

Sedimentology, Stratigraphic Evolution and Provenance of the Cambrian – Lower Ordovician Potsdam Group in the Ottawa Embayment and Quebec Basin

David G. Lowe

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Ottawa-Carleton Geoscience Centre
Faculty of Science
University of Ottawa

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Abstract

The Cambrian – Lower Ordovician Potsdam Group is a mostly siliciclastic unit that provides important insight into the paleoenvironmental, geologic and tectonic history of Early Paleozoic Laurentia. Nevertheless, in spite of 178 years of study the Potsdam in the Ottawa Embayment and Quebec Basin remains poorly understood. Also poorly understood is how the Potsdam relates with coeval strata regionally.

In this work six siliciclastic paleoenvironments are recognized: (a) braided fluvial, (b) ephemeral fluvial, (c) aeolian, (d) coastal sabkha, (e) tide-dominated marine and (f) open-coast tidal flat. Fluvial strata were examined in particular detail and interpreted to consist of two end-member kinds. Braided fluvial deposits are dominated by low-relief bars formed in wide, shallow channels; however where basement structures limited the lateral growth of channels, flows were deeper and bar deposits thicker and higher angle. In contrast, ephemeral fluvial strata are dominated by sheetflood splay sedimentation with rare preservation of scour-filling supercritical bedform strata – all later subjected to aeolian reworking. In the upper Potsdam, alternating ephemeral and braided fluvial strata provide a record of climate change, which, respectively, correlate with documented global cool (arid) and warm (humid) periods during the Late Cambrian and Early Ordovician.

Three allounits are recognized in Potsdam strata, recording regional episodes of sedimentation and facilitating correlation with coeval strata throughout eastern North America. These correlations, aided with provenance data from detrital zircons, show that changes in the areal distribution of sediment supply, accommodation and deposition/erosion were principally controlled by episodic reactivation of the Neoproterozoic Ottawa graben, which then periodically modified the stratigraphic expression of the ongoing Sauk transgression. Specifically, episodes of tectonic reactivation occurred during late Early to Middle Cambrian (allounit 1), late Middle to early Late Cambrian (allounits 2 – 3 unconformity), and Earliest Ordovician (allounits 3 – 4 unconformity). The earliest episode is correlated to regional extension of southern Laurentia, whereas the latter two are linked to peri-Laurentian accretion events that triggered reactivation of the Ottawa graben via the Missisquoi oceanic fracture zone.

Résumé

Le Cambrien - Ordovicien précoce Groupe de Potsdam est une unité silicoclastique qui fournit des informations importantes sur le paléo-environnement, l'histoire géologique et tectonique du Paléozoïque Laurentia. Néanmoins, malgré 178 années d'études, le Potsdam dans la baie d'Ottawa et le bassin du Québec demeure mal comprise. La réaction régionale du Potsdam avec les strates contemporaines est aussi peu comprise. Dans ce travail six paléo-environnements sont reconnus: (a) fluviaux entrecroisés, (b) éphémère fluviale, (c) éolien, (d) de sebkha côtière, (e) marine marémotrice et (f) ouvert de marée de la côte. Les strates fluviales ont été examinées en détails et interprétées comme étant constituées en deux types. Les dépôts fluviaux entrecroisés sont dominés par des barres en bas-relief formées dans de larges canaux peu profonds. Cependant, où les structures préexistantes ont limité la croissance latérale des canaux, les courants étaient plus profonds et les dépôts de bar plus épais, avec un angle plus raide. En contraste, les strates fluviales éphémères sont dominées par la sédimentation des épanouissements des inondations peu profondes, avec la préservation des couches rares surcritique – tous ensuite sujettes au remaniement éolien. Dans la partie supérieure du Potsdam, dépôts des fluviaux entrecroisés et éphémères fluviaux dépôts sont inter-stratifiées et fournissent un historique du changement climatique, qui correspondent respectivement à froid globalement (sec) et les périodes chaudes (humides) documentée au cours du Cambrien tardif et Ordovicien précoce.

Trois allounits sont reconnus à Potsdam strates qui donnent des preuves d'épisodes de sédimentation régionaux et à permettre la corrélation à contemporain roches stratifiées dans l'Est l'Amérique du Nord. Ces corrélations, aidées des données provenant de zircons détritiques, montrent que des changements dans la distribution locale des réserves de sédiments, accommodements et dépôts/érosions étaient contrôlés principalement par la réactivation périodique du graben d'Ottawa Néoprotérozoïque, qui, alors, modifiait périodiquement l'expression stratigraphique de la constante transgression du Sauk. Épisodes de réactivation tectoniques survenus au cours de la fin précoce à Cambrien moyen (allounit 1), fin du Cambrien moyen au début du Cambrien tardif (la discordance qui sépare allounits 1 et 2), et début du Ordovicien précoce (la discordance qui sépare allounits 2 et 3). Le

premier épisode est corrélée à l'extension régionale du sud de Laurentia, et les deux derniers sont est corrélée à des péri-laurentiennes événements d'accrétion qui ont déclenché la réactivation du graben Ottawa via le zone de fracture océanique Missisquoi.

Dedication

This thesis is dedicated to Al and Dan. Granted, it's not much in the grand scheme of things but it means a lot to me. I just wish I could have shared the excitement of finishing this piece of work with both of you.

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Chapter 1: Thesis Introduction

1.1 Thesis Rationale

The Cambrian-Ordovician Potsdam Group in the Ottawa Embayment and Quebec Basin, in Ontario, Quebec and New York State (Fig. 1.1) is a mainly siliciclastic unit that unconformably overlies rocks of the ~1.0 Ga Grenville Province. The Potsdam Group contains a wealth of geologic information, including: details pertinent to the understanding of the Paleozoic stratal and tectonic evolution of eastern North America (e.g., Salad Hersi et al., 2002; Lavoie et al., 2003; Lavoie, 2008; Landing et al., 2009), details of Early Paleozoic animal evolution and paleo-ecology (e.g., Clark and Usher, 1917; Bjerstedt and Erickson, 1989; MacNaughton et al., 2002; Hagadorn and Belt, 2008; Getty and Hagadorn, 2009; Collette and Hagadorn, 2010; Hagadorn et al., 2011), information regarding landscapes and processes of pre-vegetated continental environments (an emerging topic of study; e.g., Fuller, 1985; Long, 2006; Davies et al., 2011; Gibling and Davies, 2012; Marconato et al., 2013; Ielpi and Ghinassi, 2015; Ielpi and Rainbird, 2016), a record of Early Paleozoic climate change and its manifestation in the terrestrial sedimentary record (e.g., Lewis, 1971; Sanford and Arnott, 2010), and insights into ancient and modern intraplate tectonics of the North American craton. Furthermore, the Potsdam Group is an important aquifer in parts of Ontario, Quebec and New York State (Nastev et al., 2008; Williams et al., 2010), and much like other “basal Cambrian sandstones” (e.g., the Mount Simon Formation) is a potential reservoir for future CO₂ storage in places where it is more deeply buried (Slater et al., 2008; Medina and Rupp, 2012; Bédard et al., 2013). However, in spite of almost 180 years of study beginning with the investigations of Emmons (1838), there is still little consistency,

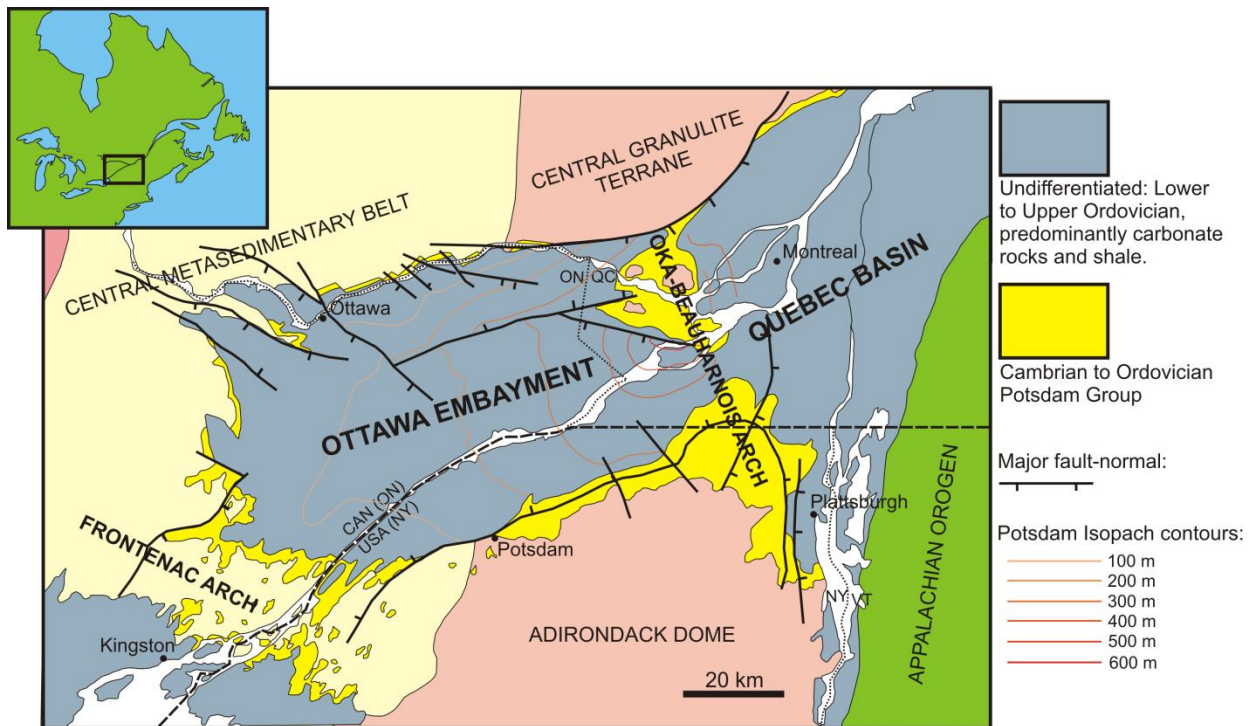


Figure 1.1 Generalized geological, structural and isopach map of the Ottawa Embayment, Quebec Basin and surrounding area, highlighting the areal distribution of the Cambrian-Ordovician Potsdam Group. Modified from Sanford and Arnott (2010).

consensus or understanding regarding the lithological correlations, depositional environments or stratigraphic nomenclature of the Potsdam in the Ottawa Embayment – Quebec Basin due to the fact that few studies extend beyond provincial or international borders. Furthermore, complex isopach and lithofacies distributions and the general lack of age-diagnostic fossils, ash beds or easily correlated stratal surfaces in a compositionally monotonous siliciclastic succession have confounded depositional age determinations and stratigraphic correlations. Additionally, earlier studies that investigated sedimentary lithofacies were either limited to small parts of the Potsdam Group (e.g., Selleck, 1975, 1978b; Bjerstedt and Erickson, 1989; Salad Hersi and Lavoie, 2000a, b; MacNaughton et al., 2002; Hagadorn and Belt, 2008; Hagadorn et al., 2011) or preceded the many major recent advances made in bedform theory and architectural analysis (e.g., Otvos, 1966). In summary, access to the wealth of

information in the Potsdam Group regarding ancient sedimentary environments, climate change, tectonics and animal evolution is limited due to a generally poorly-developed understanding of its stratal evolution and sedimentary environments.

This thesis follows the work of Sanford (2007) and Sanford and Arnott (2010). Sanford undertook the first systematic basin-wide investigation of the Potsdam, and provided a detailed description of its lithology, stratigraphy and many of the unique sedimentary structures and features of the Potsdam Group from the Ottawa Embayment and Quebec Basin in Ontario, New York State and Quebec. The work of Sanford showed that the Potsdam Group is lithologically complex unit made up of terrestrial and shallow marine strata that were deposited under tectonically-active conditions, and were interrupted by at least one major depositional hiatus. Nevertheless, this work was never published in a peer-reviewed journal, and to date has not been widely adopted. Furthermore, the work of Sanford (2007) was largely descriptive and revealed the need to better understand of the depositional and stratal evolution of the Potsdam Group. Also, Sanford relied heavily on his detailed stratigraphic framework developed locally in the southwestern Ottawa Embayment, which he used to subdivide the Potsdam succession elsewhere in the Ottawa Embayment and Quebec Basin. However, early in this investigation it became clear that there were significant differences in Potsdam stratigraphy between the western and eastern parts of the study area – differences that were not captured in Sanford’s original framework. The objective of this thesis, therefore, is to build on the work of Sanford (2007) and develop a greater understanding of the depositional and stratal evolution of the Potsdam Group by using lithofacies analysis, lithostratigraphic and allostratigraphic principles, petrography, U-Pb

detrital zircon geochronology, paleoflow analysis and biostratigraphy. Further details of the thesis objectives are given below.

1.2 Geologic Setting

The Potsdam Group is the basal sedimentary unit in the Ottawa Embayment (OE) and Quebec Basin (QB), two semi-connected fault-bounded basins filled by generally undeformed Paleozoic strata straddling the borders on Ontario, New York State and Quebec (Fig. 1.1). The OE is bounded by two structural arches, the Oka-Beauharnois and Frontenac, to the east and west, respectively, and is also bound to the south by the Adirondack Dome and to the north by the Laurentian Mountains of the Canadian Shield. The QB is bound by the Oka-Beauharnois Arch to the west, Laurentian Mountains and Adirondack highlands to the north and south, respectively, and the Appalachian Orogen to the east and southeast (Fig. 1.1). According to Sanford (1993, 2007) and Sanford and Arnott (2010), the OE-QB occupy the central part of the St. Lawrence Platform, the latter defined physiographically as the generally flat, low-lying areas of Eastern North America underlain by generally undeformed Paleozoic and younger strata. As such, the Potsdam Group in the OE-QB is central to coeval sedimentary successions in the Appalachian and Michigan basins to the west, and the St. Lawrence Lowlands and allochthons of the western Appalachian Orogen to the east.

During the Cambrian and Early Ordovician, Potsdam sedimentation occurred ~200 – 400 km inboard of the edge of the Laurentian margin, i.e. the edge of pre-Appalachian eastern North American craton. At this time, Laurentia was located along the equator and rotated 90° clockwise relative to modern North America, with Potsdam sedimentation at subequatorial latitudes (10 – 30° S) in a shelf-proximal, intracratonic location

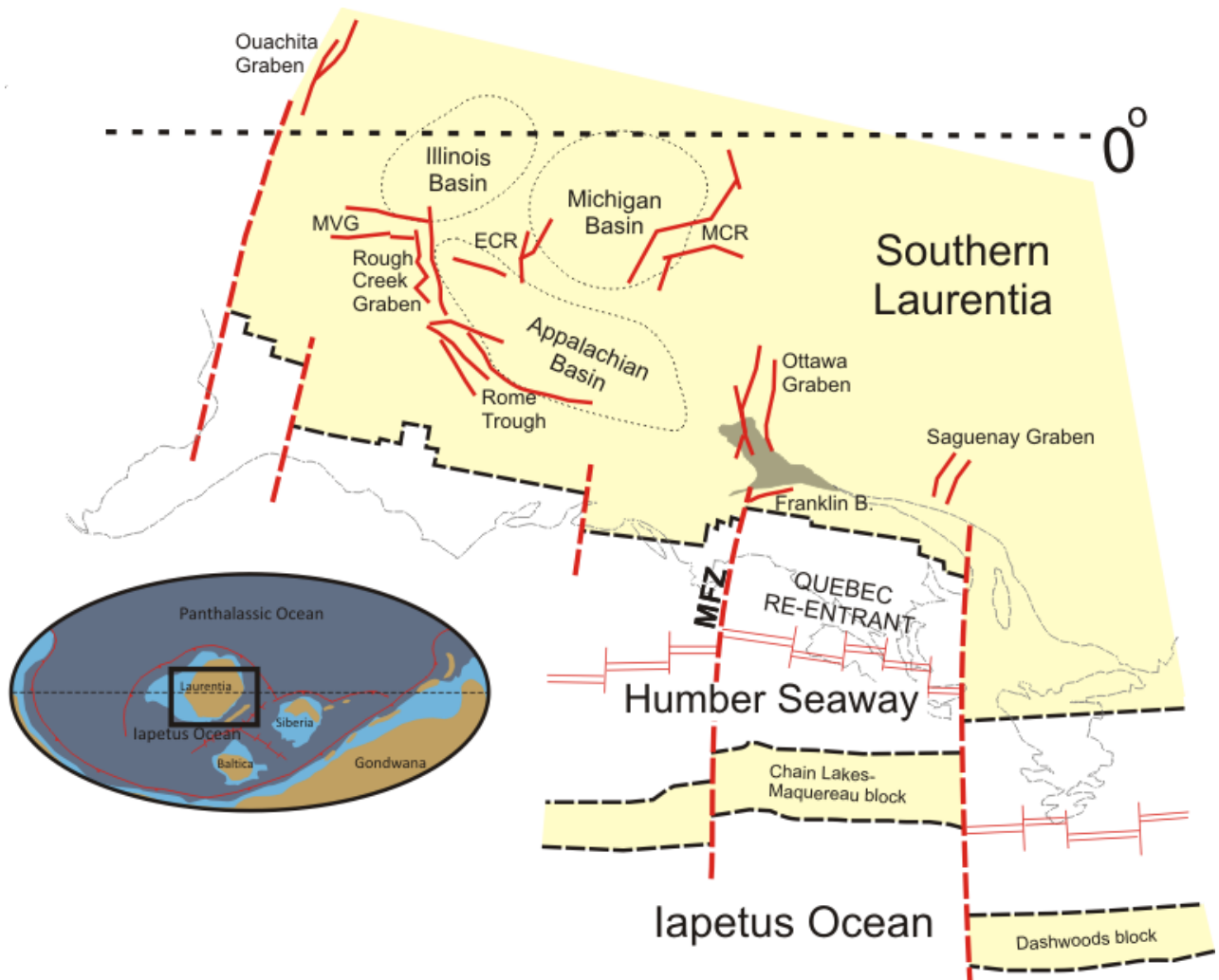


Figure 1.2 Paleogeographic and tectonic reconstruction of Early Paleozoic southern Laurentia, highlighting elements surrounding the depositional site of the Potsdam Group including mainly Proterozoic intracratonic rifts in the Laurentian craton (red lines). For reference, the shaded area shows the area covered by the Ottawa Embayment and Quebec Basin. Various tectonic features are: OG = Ottawa graben, MFZ = Missisquoi fracture zone, MCR = Mid-continent rift, ECR = East continent rift, MVG = Mississippi Valley graben, Franklin B. = Franklin Basin. Modified from Thomas (1991, 2006) and Allen et al. (2010).

(Fig. 1.2, Torsvik et al. 1996, McCausland et al. 2007, Lavoie 2008; Allen et al. 2009, 2010). Potsdam sedimentation occurred during the Early Paleozoic passive margin phase of paleo-southern Laurentia, ~15 – 20 myr after protracted rifting that led to the 570 Ma breakup of Rodinia and 535 Ma opening of the adjacent Humber Seaway (Fig. 1.2; Allen et al., 2009, 2010). The latter event led to the rifting of a number of peri-Laurentian continental fragments (e.g., Dashwoods, Chain Lakes), which came to be located ~300 – 1000 km south

of the Laurentian margin (Waldron and van Staal, 2001; van Staal et al., 2007; Allen et al., 2010). Meanwhile, a coeval high-order eustatic rise began in the Early Cambrian that eventually covered the Laurentian margin and craton with a shallow epeiric sea by the end of the Early Ordovician -- a transgressive event termed the cratonic Sauk Megasequence (Sloss, 1963; James et al., 1987). The passive margin phase ended ~7 – 10 myr after Potsdam sedimentation with the Middle Ordovician onset of Taconic foreland deformation and accretion of volcanic edifices of the Humber seaway and peri-Laurentian terranes accreted onto the Laurentian margin (Waldron and van Staal, 2001; Lavoie, 2008).

The Potsdam Group and younger Paleozoic strata onlap an earlier margin-normal rift termed the Ottawa-Bonnechere graben (Kay, 1942), or simply the Ottawa graben, that formed during late Neoproterozoic rifting (Kumarapeli and Saull, 1966; Doig and Barton, 1968; Burke and Dewey, 1973; Dewey and Burke, 1974; Doig, 1970; Kumarapeli, 1985, 1993; Kamo et al., 1995; Malka et al., 2000; Allen et al., 2010; Bleeker et al., 2011; McCausland et al., 2011) as a failed intracratonic rift arm of a plume-generated triple junction (Kay, 1942; Kumarapeli, 1985, 1993; Kamo et al., 1995; Puffer, 2002; Bleeker et al., 2011), or the cratonward extension of the Missisquoi transform fault (Dix and Al Rodhan, 2006; Allen et al., 2010). Numerous authors have provided evidence that links tectonism with deposition of parts of the Potsdam (Lewis, 1971; Salad Hersi and Dix, 2006; Landing, 2007; Landing et al., 2009; Sanford and Arnott, 2010), but details of these relationships remain poorly understood. Importantly, many of the faults in the Ottawa graben were later reactivated during the Appalachian Orogenesis (Rimando and Benn, 2005; Dix and Al Rodhan, 2006; Nurkhanuly, 2012), and mid-Mesozoic rifting and uplift of the Adirondack Dome (Crough, 1981; McHone and Butler, 1984; Hogarth et al., 1988; Heaman and

Kjarsgaard, 2000; Roden-Tice et al., 2000; Rimando and Benn, 2005; Bleeker et al., 2011), and as a consequence obscured the configuration of basement features and pattern(s) of accommodation during Potsdam sedimentation.

1.3 Study Area and Previous Work

This thesis focuses on the Potsdam Group exposed along the margins of the OE and QB in eastern Ontario, southwestern Quebec and northern New York State, essentially covering the same area as Sanford (2007) and using most of the same outcrop locations and cores. Here, the detailed bed-by-bed analysis of 296 outcrop locations (see appendix A) along the margins of the OE-QB is integrated with 12 subsurface cores that sample most of the Potsdam succession (Table 1.1). Summarized below are previous works regarding the stratigraphic framework, deposition environments, provenance and syn-sedimentary tectonic setting of the Potsdam Group in the OE and QB. Also summarized are past studies of pre-Devonian fluvial systems and the manifestation of climate change in the terrestrial sedimentary record, both of which are aspects of study in this thesis.

1.3.1 Previous stratigraphic investigations of the Potsdam Group

The Potsdam Group in the OE-QB has been the subject of stratigraphic investigations for almost 180 years, beginning with the pioneering work of Emmons (1838, 1841) in northern New York State. Soon after, Logan (1863) correlated basal Paleozoic sandstone and conglomerate in Quebec and Ontario to the Potsdam Sandstone described by Emmons. However, subsequent investigations in Canada and the U.S. confounded this correlation with

added unit names and jurisdictionally-bound stratigraphic frameworks. Many stratigraphic investigations followed in New York State, most notably Chadwick (1915, 1920), Alling (1919), Fisher (1968), Kirchgasser and Theokritoff (1971), Selleck (1975, 1978a, 1993) and Landing et al. (2009). Stratigraphic investigations in Ontario were carried out by Wilson (1946), Liberty (1971), Greggs and Bond (1972), Brand and Rust (1977), Williams et al. (1984, 1985), Williams and Wolf (1984), Wolf and Dalrymple (1984), Salad Hersi et al. (2002a) and Dix et al. (2004). In Quebec, investigations were carried out by Clark (1952, 1966, 1972), Globensky (1987), Salad Hersi and Lavoie (2000a, b) and Salad Hersi et al. (2002). For a more comprehensive account of early stratigraphic studies of the Potsdam Group the reader is referred to Sanford and Arnott (2010).

Following most of the earlier investigations, Sanford (2007) re-appraised the stratigraphy of the Potsdam Group across the entire OE-QB, formalizing his stratigraphic framework in Sanford and Arnott (2010). This was the this first time since the work of Logan (1863) that an investigation of the unit had been carried out at this scale, and the first time ever that the stratigraphy of the Potsdam Group was the focus of such a basin-wide investigation. On the basis of the investigations of Sanford (2007), the Potsdam Group was subdivided into three lithostratigraphic formations: the Abbey Dawn Formation, the Ausable and equivalent Covey Hill formations, and the Keeseville and equivalent Nepean and Cairnside formations (Fig. 1.3).

The basal Abbey Dawn Formation was defined as local occurrences of very poorly-sorted quartzite-clast boulder conglomerate along the margins of the Frontenac Arch in Ontario. Sanford (2007) interpreted the Abbey Dawn as Neoproterozoic to perhaps be an

Table 1.1 Boreholes used in this thesis and their coordinates. * Core from St. Lawrence River No. 1 could not be found, and therefore lithologic data for stratigraphic correlation is from Sanford (2007) and Sanford and Arnott (2010).

Well name	UTM location (zone 18, NAD 83)
Lanark County No.1	408825E; 4973929N
Lanark County No.2	411137E; 4974141N
AMEC MW-301 monitoring well	424622N; 5023046N
GSC Dominion Observatory No.1	443950E; 5026500N
GSC LeBreton No. 1	445500E; 5028100N
GSC Russell No.1	469150E; 5017450N
Consumers Gas No. 12023	468919E; 5011842N
GSC McCrimmon No. 1	520250E; 5030200N
Gastem Dundee No.1	544391E; 4989999N
St. Lawrence River No.1*	577025E; 5013642N
Quonto-International St. Vincent de Paul No.1	604418E; 5055374N
Quonto-International Mascouche No.1	600900E; 5066250N

earliest Cambrian syn-rift unit, deposited during the latter phase of extension of the Laurentian margin. Nevertheless, this age assignment and stratigraphic affinity was largely speculative, and based primarily on correlation to lithologically similar Neoproterozoic units in Labrador.

The Ausable Formation in New York State, and its equivalent Covey Hill Formation in Quebec and Ontario, was defined by Sanford and Arnott (2010) as “red, pink and grey to locally white sandstone and conglomerate largely of non-marine origin” that occur at the base of the Potsdam Group, except where locally underlain by the Abbey Dawn Formation. Notably, the framework of Sanford and Arnott (2010) does not use arkosic composition as a diagnostic criteria for lithostratigraphic subdivision of the Ausable/Covey Hill from other units, in spite of the fact that this was the convention used for many years (Alling, 1919;

Fisher, 1968; Clark, 1966, 1972; Lewis, 1971; Globensky, 1982; Williams et al., 1984, 1985; Wolf and Dalrymple, 1984; Landing, 2007). As a result, many sections previously defined as the Keeseville in New York or Cairnside in Quebec have been correlated to the Ausable/Covey Hill Formation in the framework of Sanford and Arnott (2010). The Ausable/Covey Hill Formation was subdivided by Sanford and Arnott (2010) into four members: the Jericho, Hannawa Falls, Chippewa Bay and Edwardsville. The basal Jericho Member is a marine unit consisting of red mudstone, siltstone, arkose and rare carbonate, and is limited to the QB. It is equivalent to the Altona Formation originally mentioned in a field trip guide by Landing et al. (2007) and soon after formalized by Landing et al. (2009). Due to the fact that the term “Altona” was formalized in a peer-reviewed publication prior to the formalization of the term “Jericho” in Sanford and Arnott (2010), the former takes precedence (NACSN, 2015, part II, article 4). The Altona is a regionally-significant unit because it provides an important depositional age constraint on overlying Potsdam Group strata. Specifically, an olenellid trilobite fragment of probable upper Lower Cambrian age was discovered in the lower part of the Altona, and multiple specimens of *Ehmaniella?* sp. were found in the upper part of the Altona, suggesting an early or middle Middle Cambrian age (Landing et al., 2009). Conformably overlying the Altona, the Hannawa Falls Member was defined by Sanford and Arnott (2010) as “salmon-pink to reddish brown” fine- to medium-grained quartz arenite or coarse-grained locally pebbly arkose, with rare conglomerate of terrestrial affinity. According to Sanford and Arnott (2010) the Hannawa Falls Member is sharply, and possibly unconformably, overlain by the Chippewa Bay Member, defined as a green-grey, pink and/or banded red and grey unit planar- and cross-

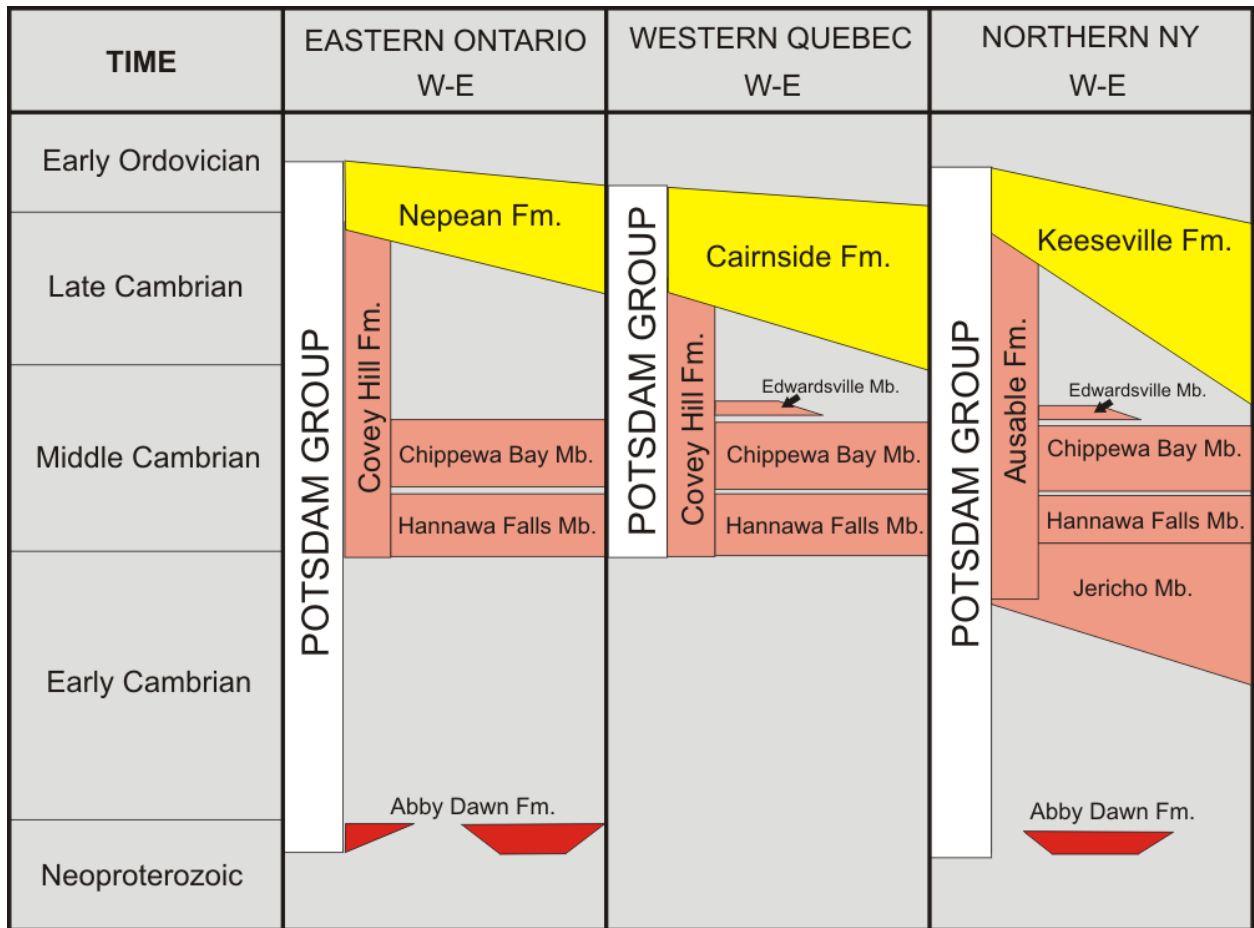


Figure 1.3 Lithostratigraphic correlation diagram of the Potsdam after Sanford and Arnott (2010).

stratified quartz or feldspathic arenite, and local pebble or cobble conglomerate of likely fluvial, but locally aeolian(?), origin. Locally capping the Chippewa Bay Member, mainly in northern New York State, is a light greenish-grey and pink to red-banded planar-stratified quartz arenite unit of presumed terrestrial affinity termed the Edwardsville Member by Sanford and Arnott (2010). Another unit, termed the Riviere Aux Outardes Member, also locally caps the Chippewa Bay Member strata in the northern OE and QB of Quebec (Clark, 1966, 1972; Salad Hersi and Lavoie, 2000b). The Riviere Aux Outardes Member consists of interbedded silica-cemented quartz arenite and dolomitic, fossiliferous quartz arenite (from Salad Hersi and Lavoie, 2000b).

Numerous earlier authors (Clark, 1966, 1972; Lewis, 1971; Selleck, 1978a, b; Wolf and Dalrymple, 1984; Sanford and Arnott, 2010) have recognized an unconformity or “significant hiatus” separating the Ausable/Covey Hill and the overlying Keeseville Formation in New York and its equivalents the Nepean and Cairnside formations in Ontario and Quebec, respectively. The best evidence of this unconformity comes from the work of Sanford (2007) and Sanford and Arnott (2010) who described the unconformity as locally angular and suggested that it represents a substantial hiatus in deposition. Although they do not specify the length of the hiatus, their age assignments and correlations (Fig. 1.3) suggest that in most places it spanned the Middle – Late Cambrian boundary. The Keeseville and equivalent Nepean and Cairnside formations overlie the unconformity, and are defined by Sanford and Arnott (2010) as white and light grey quartz arenite of mostly marine origin. The depositional age of the basal part of the Keeseville in New York State is constrained to be late Middle and Late Cambrian by sparse trilobite fauna (Walcott, 1891; Flower, 1964; Fisher, 1968; Lochman, 1968; Landing et al., 2009), but generally unconstrained elsewhere. The exact age of the uppermost Keeseville/Nepean/Cairnside is unknown due to a lack of age-diagnostic fossils, but conodonts from the basal Theresa Formation suggest that it is no younger than Early Ordovician (Greggs and Bond, 1971; Brand and Rust, 1977; Salad Hersi et al., 2002a; Dix et al., 2004). Nevertheless, Salad Hersi et al. (2002) and Dix et al. (2004) suggest that the Keeseville/Nepean/Cairnside is no younger than Upper Cambrian based primarily on the recognition of a local unconformity above the Keeseville/Nepean/Cairnside and its correlation with a well-dated unconformity in carbonate rocks on the Laurentian margin more than 100 km east of the eastern part of the Quebec Basin (palinspastically restored). Other authors, however, suggest that the uppermost Keeseville/Nepean/Cairnside

is Lower Ordovician most everywhere (Wilson, 1946; Kirwan, 1963; Clark, 1966; Greggs and Bond, 1972; Brand and Rust, 1977; Bjerstedt and Erickson 1989; Sanford and Arnott, 2010), but due to the lack of any biostratigraphic or geochronological control, the age of the uppermost unit of the Potsdam remains unresolved.

Also unresolved is the nature of the contact between the Keeseville/Nepean/Cairnside and overlying Theresa Formation. The Theresa Formation is considered to be of marine origin and composed mostly of dolomite-cemented quartz arenite beds interstratified with lesser “clean” silica-cemented quartz arenite beds (Cushing, 1908; Selleck, 1978a, 1993). The contact has been variably interpreted as unconformable (e.g., Greggs and Bond, 1972; Salad Hersi et al., 2002; Dix et al., 2004) or conformable and diachronous (Cushing, 1908; Wilson, 1946; Otvos, 1966; Clark, 1972; Brand and Rust, 1977; Sanford and Arnott, 2010). The majority of authors agree that the base of the Theresa Formation should be placed at the base of the lowest-most “dolomitic bed” (Cushing, 1908; Wilson, 1946; Greggs and Bond, 1972; Brand and Rust, 1977; Globensky, 1982, 1986; Selleck, 1978a, 1993; Williams and Wolf, 1984; Bernstein, 1992), although other authors including Clark (1966, 1972), Salad Hersi and Lavoie (2000a) and Sanford and Arnott (2010) propose that the base of the Theresa should correspond to the top of the highest clean quartz arenite bed above which the lithofacies is “subordinate or absent”. These criteria are vague, and it is unclear what thickness of layer constitutes a “bed” or what specifically is meant by “subordinate”. Furthermore, this discrepancy is not insignificant because according to the definition of Cushing (1908), “clean” silica-cemented quartz arenite are commonly intercalated with dolomitic sandstone beds throughout the Theresa Formation. Thus, depending on the criteria used, the upper Potsdam might be considered to be incorporated entirely into the Theresa (if

the base of the lowest dolomitic bed is used, and depending on what is meant by “bed”), or nearly the entire Theresa Formation might be considered a part of the Potsdam Group (if the base of the Theresa is defined as the top of the uppermost clean quartz arenite).

1.3.2 Previous facies analyses and interpretations of depositional environments of the Potsdam Group

Most authors who have conducted stratigraphic studies in strata of the Potsdam Group have made inferences about its environments of depositional (Chadwick, 1920; Lewis, 1963, 1971; Clark, 1966, 1972; Fisher, 1968; Kirchgasser and Therokritoff, 1971; Greggs and Bond, 1972; Brand and Rust, 1977; Selleck, 1978a; Salad Hersi et al., 2000; Landing et al., 2009; Sanford and Arnott, 2010), and some authors have undertaken systematic lithofacies analysis (Otvos, 1966; Selleck, 1978b; Wolf and Dalrymple, 1984; Salad Hersi and Lavoie, 2000a, b; McNaughton et al., 2002; Hagadorn and Belt, 2008; Hagadorn et al., 2011; Brink, 2014). Of those, only Otvos (1966) has described and interpreted lithofacies from across the OE and QB. The following is a summary, stratigraphically upward, of previous interpretations of the environments of deposition using the framework of Sanford and Arnott (2010).

Sanford and Arnott (2010) suggested that their Neoproterozoic(?) Abbey Dawn Formation represented the deposits of subaerial “flow debris” transported by rapid, high-energy fluvial flash floods, and therefore similar to the terrestrial talus sheet wash fans interpreted for similar strata by Otvos (1966). The late Early to Middle Cambrian Altona Formation (a.k.a. informal Jericho member) is considered marine by Landing et al. (2009)

and Sanford and Arnott (2010) based on lithology and the presence of trace fossils and rare body fossils. Recently, Brink (2014) reported hummocky- and swaley- cross-stratified sandstone and possible combined flow ripples, and therefore suggested a wave- and storm-dominated shoreface environment for the Altona. According to Brink (2014), the rare carbonate beds formed in an offshore environment and represent the maximum flooding surface of the Altona shoreface succession.

Sanford and Arnott (2010) suggested that, aside from the Altona, the Ausable Formation and correlative Covey Hill Formation consisted of a complex assemblage of interstratified aeolian and fluvial strata. Many previous authors have recognized high energy braided fluvial strata in parts of the Ausable and equivalent Covey Hill formations, particularly in northeast New York State and adjacent Quebec and locally along the Frontenac Arch, on the basis of coarse-grained, trough and planar-cross-stratified and unbioturbated sandstone and associated pebble- and/or cobble-conglomerate (Otvos, 1966; Fisher, 1968; Greggs and Bond, 1972; Lewis, 1971; Wolf and Dalrymple, 1984; Sanford and Arnott, 2010). Clark (1966, 1972), Kirchgasser and Therokritoff (1971), and Selleck (1978a, b, 1993) suggest that parts or all of this lithofacies might have been formed, instead, in a high energy littoral or shallow marine environment. Many authors, including Chadwick (1920), Wolf and Dalrymple (1984), MacNaughton et al. (2002), Sanford and Arnott (2010) and Hagadorn et al. (2011) recognize that parts of Sanford and Arnott's (2010) Hannawa Falls Member is aeolian, based on the recognition of large-scale cross-stratified, well-sorted fine- to medium-grained sandstone. Most of these aeolian strata occur along the Frontenac Arch and northwestern Adirondacks. Much of the strata in Sanford and Arnott's (2010) Chippewa Bay and Edwardsville members consist of medium and rare coarse-grained, planar-stratified

sandstone with rare, enigmatic, high- to low-angle planar- and tough cross-stratification. These strata are particularly well-exposed in northern New York State, where they have puzzled workers for many years. Many authors (e.g., Otvos, 1966; Kirchgasser and Therokritoff, 1971; Selleck, 1978a, b, 1993; Wolf and Dalrymple, 1984) who studied these strata suggested they formed in a nearshore marginal-marine environment with sedimentation driven by a combination of wind and tides, while Sanford and Arnott (2010) suggest an inland aeolian and/or ephemeral fluvial environment. However, in general there has been little systematic or critical discussion of this lithofacies, and as such its origin remains enigmatic. The “unit B” of the Riviere Aux Outardes Member in the northern OE and QB was interpreted by Salad Hersi and Lavoie (2000b) as subtidal to intertidal due to the interstratification of high-energy quartzose strata and dolomitic sandstone with features such as bioclasts, mud chips, microbial incrustations and trace fossils.

Overwhelmingly, the Keeseville and equivalent Nepean and Cairnside has been interpreted as marine. More specifically, two lithofacies seem to have been recognized: strata dominated by horizontal to low-angle planar stratified sandstone interpreted to have formed in low-relief “shoreface” or littoral, supra- or intertidal environment (Fisher, 1968; Kirchgasser and Therokritoff, 1971; Wolf and Dalrymple, 1984; Donaldson and Chiarenzelli, 2007; Hagadorn and Belt, 2008) and bioturbated cross-stratified sandstone interpreted to record high energy intertidal and/or subtidal sedimentation (Wolf and Dalrymple, 1984; Selleck, 1978a, b, 1993; Bjersetdt and Erickson, 1989; Sanford and Arnott, 2010).

1.3.3 Previous studies of sediment provenance in the Potsdam Group

Provenance of the Potsdam Group and other basal Cambrian quartz arenites in North America has long been a topic of interest but with little supporting data. The earliest provenance data come from Harding (1931) who analyzed the framework and accessory minerals of the “Potsdam Sandstone” (presumably the Nepean formation of Sanford and Arnott, 2010) and nearby paragneiss of the Grenville Province in Ontario, including analysis of detrital zircon morphology. His conclusion was that the Potsdam sediments were derived exclusively from the nearby paragneiss. Later, Lewis (1971) collected paleoflow measurements across the Ottawa Embayment and Quebec Basin and measured the framework mineral proportions and documented accessory detrital minerals from ~ 300 samples of Potsdam strata. Lewis (1971) concluded that based on feldspar content, the Ausable and equivalent Covey Hill were derived directly from nearby metamorphic and igneous rocks, probably from parts of the Adirondacks. However, based on the variability of paleoflow orientations across the study area, Lewis (1971) inferred that the sediment, although first-cycle, probably did not come from a single source area. This author also suggested that the clean quartz arenite of the Keeseville and equivalent Nepean and Cairnside formations was likely recycled from older earlier Ausable/Covey Hill strata.

Gaudette et al. (1981) published one of the earliest studies of U-Pb dating of detrital zircons from a sample of the Potsdam along the southeast margin of the Adirondacks. Although only a few grains could be dated due to limitations of the technique, it did identify a variety of Proterozoic (Grenville) and Archean (Superior) sediment sources, including sources with ages of 1180, 1320, 2100 and 2700 Ma. Later Montario and Garver (2009) measured U-Pb crystallization ages and fission-tracks from detrital zircons in two Potsdam

samples. One sample was outside of the current study area (southeast of the Adirondack Dome), but the other was from the Keeseville Formation in the southwest Ottawa Embayment. Here they identified a number of source components based on the U-Pb ages, including a ~1036, ~1161, ~1321, ~1417 and ~1667 Ma, with younger cooling ages from fission-track analysis (~540, ~780 and ~1200 Ma). They interpreted these results to suggest that the Keeseville was probably sourced from parts of the surrounding Grenville Province. Chiarenzelli et al. (2010) presented data from six additional samples of the Potsdam Group, including four from Sanford and Arnett's (2010) Ausable/Covey Hill and two from the Nepean formation in Ontario. In general, their analysis showed evidence for increasing complexity of sediment sources upward in the stratigraphic section, possibly due to expansion of the basin through time thus allowing for sourcing from more diverse regions of the Grenville Province. More specifically, they showed that three samples from the Ausable in New York along the northern and northeastern Adirondack Dome were dominated by a single age peak at around 1160 Ma suggesting derivation mainly from the nearby Adirondack basement. However, one sample from the Covey Hill and two others from the Nepean formation in Ontario along the edge of the western Ottawa Embayment show more diverse age distributions including peaks at ~1190, ~1350, ~1400, ~1450, ~1625, ~1850 and ~2700, suggesting sourcing from a number of Grenville Province and perhaps even Superior province sources to the east and northeast. Although Chiarenzelli et al. (2010) presented a substantial detrital zircon dataset, their analyses were not published in a peer-review journal, and therefore there is only limited critical discussion regarding the significance of their detrital zircon ages.

1.3.4 Previous studies of tectonics and sedimentation in the Potsdam Group

Numerous authors including Lewis (1971), Salad Hersi and Dix (2006), Landing (2007), Landing et al. (2009) and Sanford and Arnott (2010) provide evidence that syn-depositional tectonic activity had a significant influence on sedimentation of the Potsdam Group. Lewis (1971) suggested that arkosic Ausable and equivalent Covey Hill strata was deposited during active rifting due to its thickness (locally up to hundreds of metres) and lithologic uniformity. Additionally it was suggested that erosion and development of the unconformity between the Ausable/Covey Hill and Keeseville/Nepean/Cairnside was due to renewed tectonism, probably local uplift. Later, Salad-Hersi and Dix (2006) used stratigraphic evidence to suggest that Neoproterozoic faults related to the Ottawa graben were reactivated during the Late Cambrian or Early Ordovician and caused perhaps more than 100 m of Potsdam strata to be eroded.. These authors speculated that reactivation of faults in the Ottawa graben was triggered by “ocean basin tectonism” but did not elaborate on a specific event or mechanism for reactivation. Landing (2007) and Landing et al. (2009) suggested that reactivated normal faulting of the Ottawa graben likely resulted in the initiation of Potsdam sedimentation in the late Early Cambrian. Notably, this was coeval with rifting of another basin termed the Franklin Basin, which at the time was located ~80 – 100 km to the paleo-south of the eastern edge of the Quebec Basin (Landing, 2007; Landing et al., 2009). Similar to most previous authors, Sanford and Arnott (2010) suggested that tectonism was coeval with sedimentation of the Ausable and equivalent Covey Hill, and remained active from the Late Neoproterozoic to the Middle Cambrian due to extended rifting of Laurentia following the opening of the Iapetus Ocean. Significantly, Sanford and Arnott (2010) discovered that the upper part of the Ausable and equivalent Covey Hill was

locally folded and faulted prior to Keeseville/Nepean/Cairnside sedimentation, confirming the idea of Lewis (1971) that the unconformity may have been coeval with late(?) Middle Cambrian tectonism. In spite of these works, there has been little discussion of how tectonism affected the patterns of Potsdam sedimentation and accommodation or the underlying cause of intraplate tectonism during Potsdam sedimentation.

1.3.5 Previous studies of pre-Devonian fluvial sedimentary processes

It has been suggested that fluvial systems operated differently before the evolution of rooted terrestrial vegetation in the Devonian (Cotter, 1978; Davies et al., 2011; Gibling and Davies, 2012). Furthermore, pre-Devonian fluvial environments are unlikely to have any suitable modern analogues (Fuller, 1985; Davies et al., 2011). Due to the fact that much of the Potsdam has been interpreted as fluvial in origin (e.g., Sanford and Arnott, 2010, and see above for additional references), detailed facies and architectural analyses of these strata could potentially provide important insights into the sedimentary processes and architectures of pre-Devonian fluvial systems.

The study of pre-Devonian fluvial systems began with Cotter (1978) who observed a change in fluvial style in strata of the Appalachian Basin from low-relief and sheet-like in pre-Devonian strata to high-angle, with well-developed high-relief accretion sets and channel forms in Devonian and younger fluvial strata. A later comprehensive study of fluvial strata worldwide by Davies et al. (2011) further highlighted these differences, and presented a general model of the evolution of fluvial systems from the Cambrian to the Devonian. Their work and a later review paper by Gibling and Davies (2012) showed that fluvial systems

evolved from coarse-grained, mud-poor fluvial systems dominated by dune-cross stratified sheets in the Cambrian, to well-defined channel sandbodies and extensive fine-grained overbank strata with locally well-developed paleosols in the Devonian and post-Devonian. They suggested that the change was principally driven by (a) a vegetation-induced increase in the rate of chemical weathering, resulting in the influx of mud to floodplains during the Silurian, and (b) the emergence of rooted plants and thus increased bio-stabilization of floodplains by the Devonian.

Missing from this work, however, are details of pre-Devonian fluvial processes, including details of the processes of bedload transport and sedimentation. A small number of previous studies of pre-Devonian fluvial strata report accretion architectures in dune cross-stratified sandstone, suggesting sedimentation by the incremental build-up of downstream-migrating bars (Long, 2006; Marconato et al., 2013) – a pattern similar to that in modern braided rivers (Bridge and Lunt, 2006). Even more recently, Ielpi and Ghinassi (2015) and Ielpi and Rainbird (2016) provide evidence not only for the build-up and accretion of composite braid bars but also for autocyclic channel belt aggradation and abandonment in Proterozoic fluvial deposits.

The works listed above are generally limited to studies of ancient perennial fluvial systems. Much more limited are studies of pre-Devonian fluvial strata formed in ephemeral fluvial environments where discharge is marked by rare and short duration high-discharge floods. Only Hjellbakk (1997), Clemmensen and Dam (1993) and Long (2006) have described such systems, and more detailed facies and architectural analysis is needed.

1.3.6 Previous studies of climate change and its manifestation in the terrestrial sedimentary rock record

Lewis (1971) and Sanford and Arnott (2010) speculated that climate fluctuations from arid to humid conditions played an important role in the evolution of terrestrial strata in the Potsdam Group, and likely formed sharp climatic boundaries suitable for use in ‘time stratigraphic’ correlations. Nonetheless, these authors do not elaborate or fully explore this idea through comprehensive lithofacies analyses or regional correlation of climate-sensitive units, or make attempts to correlate units to documented Early Paleozoic climate events. This then presents an opportunity to (a) study the manifestation of climate change on the rock record from Early Paleozoic, pre-vegetated terrestrial environments, and (b) correlate climate change events in the Potsdam stratigraphic record to documented regional events.

Deciphering climate signals from the ancient terrestrial rock record on the basis of climate-sensitive continental lithofacies has been done with varying degrees of success by Cecil et al. (2003), Mountney (2006a), Allen et al. (2011, 2013), Foreman (2013) and Jablonski and Dalrymple (2016). Generally the best results come from interpreting variations in discharge regime from uninterrupted continental successions. The most advanced of these studies is the work of Allen et al. (2011, 2013). Those authors who use the architecture and lithofacies of fluvial strata in the Late Paleozoic equatorial Maritimes Basin as proxies for climate change, by identifying fluvial lithofacies formed under perennial, highly seasonal and ephemeral discharge regimes. They then correlated their climate-sensitive fluvial units to global climate events, specifically southern hemisphere glaciation. However, this study and others listed above deal with post-Silurian fluvial examples coexisting with plants. Therefore the lithofacies and architectural criteria used to interpret climate change from this study

probably do not apply to the strata of the Potsdam Group or other pre-Devonian, and thus pre-vegetated, examples.

1.4 Thesis Objectives and Structure

The purpose of this thesis is to investigate the stratal evolution of the Potsdam Group in the OE and QB. Specific objectives of this thesis are to investigate the lithostratigraphic framework, stratigraphic correlations, depositional environments and provenance of the Potsdam Group, as well as assess the interactions between Potsdam sedimentation, climate and tectonics. To achieve these objectives, detailed examination of sedimentary textures (grain size, sorting, etc.), sedimentary structures, stratal architectures, stratigraphic contacts and paleoflow was carried out at 296 outcrops locations. Twelve drill hole cores were also described in detail. In addition, over 200 thin sections were analyzed from representative samples in order to better characterize grain size, textures and sorting, depositional fabrics, detrital framework mineralogy, and early post-depositional and/or diagenetic textures and minerals. Finally, ten representative samples were processed for detrital zircon U-Pb dating in order to determine sediment provenance and refine stratigraphic correlations – these data were supplemented with six samples previously analyzed by Chiarenzelli et al. (2010).

This thesis is a compilation of chapters and articles that outline aspects of Potsdam stratigraphy and sedimentation, along with more general contributions to North American geologic history, fluvial sedimentology and intraplate tectonics. Chapter 2 is a detailed description of Potsdam lithofacies and their interpreted modes of deposition. Chapter 3 is a higher-level examination of six lithofacies associations, the results of which outline the

general depositional environments of the Potsdam Group. Chapter 4, then, describes the correlation of lithostratigraphic and allostratigraphic units of the Potsdam Group across the OE and QB. This chapter places the depositional environments into a regional stratigraphic context and documents revisions and details of litho- and allostratigraphic units, depositional age constraints, descriptions of major conformable contacts and internal unconformities, nature of the contact with the overlying Theresa Formation and correlation of Potsdam allounits to coeval sedimentary successions in eastern North America. Chapter 5 explores details of two fluvial lithofacies associations in the Potsdam Group: braided and sheetflood-dominated ephemeral fluvial. Discussion of these fluvial facies associations focusses on their comparison to other documented examples of pre-Devonian fluvial strata, interactions between pre-Devonian fluvial systems and basement paleo-topography, and the manifestation of climate change events in the pre-Devonian fluvial sedimentary record. This chapter also provides rare insight into the occurrence of supercritical bedform strata in fluvial deposits. Chapter 6 identifies details of the tectonic reactivation of the intra-plate Ottawa graben the Early Paleozoic from stratigraphic and provenance data from the Potsdam Group. More specifically, details of tectonic reactivation are identified by identifying changes in the patterns of sedimentation and accommodation by integrating allostratigraphy, paleoflow analysis and detrital zircon geochronology as a proxy for sediment provenance.

1.5 Statement of Contributions

Chapter 4 in large part reproduces a manuscript accepted for publication in the *Journal of Sedimentary Research*:

Lowe, D.G., and Arnott, R.W.C., accepted, Composition and Architecture of Braided and Sheetflood-Dominated Ephemeral Fluvial Strata in the Cambrian-Ordovician Potsdam Group: A Case Example of the Morphodynamics of Early Phanerozoic Fluvial Systems and Climate Change. *Journal of Sedimentary Research*.

This paper was conceived by DL and Dr. Bill Arnott in 2014 following a number of advancements in their understanding of ephemeral fluvial strata in the Potsdam Group. Perhaps most important was the recognition of features recording high energy, shallow supercritical flow conditions. Field data was compiled by DL with the assistance of Gurvir Khosa, Chris Barnes and Ed DeSantis. Architectural and lithofacies analysis and thin section petrography was carried out by DL. The original parts of the manuscript were drafted by DL, but with continuous critical discussion and editing by Dr. Bill Arnott, from which came a number of the more original ideas in the paper.

Chapter 5 is an expanded version of a manuscript in preparation for submission:

Lowe, D.G, Nowlan, G.S., McCracken, A.D., Arnott, R.W.C., and DeSantis, E., in preparation, Lithostratigraphic and allostratigraphic framework of the Cambrian-Ordovician Potsdam Group, and correlations across Early Paleozoic southern Laurentia.

This paper is based on field, subsurface and thin section investigations by David Lowe (DL), as well as biostratigraphic analysis by Drs. Godfrey Nowlan and Sandy McCracken, both of the Geologic Survey of Canada in Calgary, Alberta. The manuscript was drafted by DL, and Dr. Bill Arnott provided critical discussion and revision that significantly improved earlier drafts. Ed DeSantis provided details and interpretations of a silcrete horizon

along one of the major contacts in the Potsdam Group in an undergraduate thesis supervised by DL and Dr. Bill Arnott. Assistance with field work was provided by Gurvir Khosa, Chris Barnes, Ed DeSantis, Dr. Bruce Sanford, Mario Lacelle, Pierre Groulx, Dr. David Franz, Dr. Al Donaldson and Dr. Bill Arnott. The final version benefited from critical discussion with Dr. Bruce Sanford.

Chapter 6 is an expanded version of a manuscript in preparation for submission:

Lowe, D.G., Arnott, R.W.C, Chiarenzelli, J.R., and Rainbird, R.H., in preparation, Early Paleozoic reactivation of a passive margin intra-plate rift: insights in Ottawa graben reactivation from detrital zircon provenance signatures of the Potsdam Group.

This paper was conceived by DL with input from Dr. Bill Arnott. It is based on the same regional field and petrographic studies as chapter 4, carried out by DL with assistance from Gurvir Khosa, Chris Barnes and Ed DeSantis. It also incorporates U-Pb geochronology of detrital zircons from representative samples collected with the assistance of Chris Barnes and Ed DeSantis. Sample processing and preparation was carried out by DL with assistance from Ed DeSantis, Jiri Mrazek, Jeremy Powell and Dr. David Schneider. Zircons were analyzed and U-Pb ages calculated at the University of New Brunswick with the assistance of Drs. Chris McFarlane, Crystal Laflamme and Yan Luo. Additional U-Pb detrital zircon data from the Potsdam was graciously provided by Drs. Jeff Chiarenzelli and Robert Rainbird. Both co-authors provided correspondence regarding their data and possible source areas of the zircons. The manuscript was drafted by DL with revisions based on discussion with Dr. Bill Arnott.

Appendix B and C are reproductions of Geologic Survey of Canada Paleontological Reports produced by G. Nowlan and A.D. McCracken, respectively.

Appendix B: G.S. Nowlan, 2013. Report on two samples from Lower Ordovician strata in the vicinity of Rockland in eastern Ontario submitted for conodont analysis by David Lowe and Bill Arnott (University of Ottawa); NTS 031G/11; CON # 1777. Geological Survey of Canada, Paleontological Report 004-GSN-2013, 3 p.

Appendix C: A.D. McCracken, 2014. Report on 2 Early Ordovician conodont samples from the Potsdam Group near Saint-Chrysostome, southwestern Quebec submitted by David Lowe and Bill Arnott (University of Ottawa). NTS 031H/04. Con. No. 1791. Geological Survey of Canada, Paleontological Report 002-ADM-2014, 7 p.

Chapter 2: Lithofacies Descriptions and Interpretations

Six sedimentary facies are recognized in strata of the Potsdam Group: cross-stratified sandstone (facies 1), planar-stratified sandstone (facies 2), graded sandstone (facies 3), conglomerate (facies 4), muddy siltstone (facies 5), and dolostone (facies 6) (Table 2.1). These are then further subdivided into a number of subfacies interpreted to provide more specific detail on depositional conditions. Descriptive facies nomenclature (e.g. sets, cosets and thicknesses of units) follows the classification of McKee and Weir (1953).

2.1 F1: Cross-stratified sandstone

2.1.1 F1a: Unidirectionally cross-laminated sandstone sets and associated asymmetric formsets

Subfacies F1a consists of very thin (1 – 5 cm) unidirectionally cross-laminated sets of well-sorted, lower fine- to upper medium-grained sandstone (Fig. 2.1a). Cross-laminations are generally ≤ 2 mm thick, high angle ($\geq 20^\circ$), and are either ungraded or normally graded. Planar cross-laminated sets are common and have horizontal bases. Trough cross-laminated sets are less common and are underlain (and usually overlain) by 0.5 – 2.5 cm-deep incisional troughs. Where present, set and coset tops exhibit asymmetric formsets with heights of 0.5 – 3 cm and spacing of 3 – 10 cm (length/height ratios (L/H) range between 6 and 12, with an average of 9) (Fig. 2.1b). Formset crests have straight or broadly sinuous (2D) forms with rounded crests and uncommon bifurcation in plan view.

Table 2.1 Lithofacies and subfacies summary table, see text for more details.

Lithofacies	Sub-facies	Characteristics	Interpretation	Key references	Facies associations (Chapter 3)
F1: Cross-stratified sandstone	F1a	1-5 cm thick unidirectional high angle ($\geq 20^\circ$) trough and planar cross-laminated sets/beds and asymmetrical formsets in Uf-Lm sandstone	Current ripples formed by transport and deposition under lower flow regime unidirectional subaqueous currents	<i>Allen, 1968; Southard and Boguchwal, 1990; Baas 1994</i>	FA1, FA2, FA4, FA5
	F1b	1-2 cm thick chevron, bidirectional and unidirectional cross-laminated sets/beds and symmetrical formsets; ripple index 4-12, in Lm sandstone	Depth-limited wave ripples formed under low period (high velocity) near bed oscillatory currents propagated downwards from surface wind waves in shallow water	<i>Allen, 1976; Clifton 1976; Miller and Komar 1980</i>	FA1, FA3, FA4, FA5
	F1c	5-75 cm thick high angle ($\geq 20^\circ$) trough and planar cross-laminated sets/beds in Lm-Lvc sandstone	Subaqueous dunes formed by transport and deposition under lower flow regime, steady unidirectional subaqueous currents	<i>Ashley, 1990; Southard and Boguchwal, 1990; Vendetti et al, 2005</i>	FA1, FA2, FA4, FA5
	F1d	20 cm - 1.6 m thick, high angle ($\geq 20^\circ$) planar cross-laminated sets/beds in Um-Lvc sandstone	Unit bars formed in channels by the steady build-up of sediment under high energy currents	<i>Bridge, 2003; Reesink and Bridge 2011</i>	FA1
	F1e	5-20 cm thick low angle ($< 15^\circ$) concavo-convex trough cross-laminated sets/beds and symmetrical formsets; opposite lamina dip relative to F1a & F1c, in Um-Lvc sandstone	Antidune stratification formed under standing and breaking surface waves in high velocity and shallow ($< 50\text{cm}$) subaqueous unidirectional supercritical ($Fr > 1$) flows. Local preservation of symmetrical formsets suggests high rates of aggradation	<i>Rust and Gibling, 1990; Alexander et al., 2001; Fielding, 2006; Cartigny et al., 2014</i>	FA2
	F1f	Thin (15-30 cm), low angle to high angle ($3 - 25^\circ$), sigmoidal scour-filling cross-laminated sets/beds; sigmoidal shape defined by low angle at base laminae dip opposite relative	Chute-and-pool stratification formed under a temporary hydraulic jump in a localized scour, under high velocity and shallow ($< 50\text{cm}$) unidirectional	<i>Fralick, 1999; Alexander et al., 2001; Fielding, 2006; Cartigny et al., 2014</i>	FA2

		to F1a & F1c, in Um-Uc sandstone	supercritical ($Fr > 1$) flows; higher Fr number than F1d.		
	F1g	Thin to very thick bedded (20 cm- 1.3 m), trains of high angle ($15 - 35^\circ$), trough cross-laminated sets bound by erosional surfaces and filling large scours (35 cm – 1.2 m deep, 15 – >120 m wide, 25 – >150 m long); laminae dip opposite relative to F1a & F1c; Scours occur as regularly-spaced (~60 – 120m), isolated features along a single stratigraphic horizon. In Um-Lvc sandstone	Cyclic step stratification formed in the troughs of large, upstream-migrating cyclic steps spatially related to regularly-spaced flow-stabilized hydraulic jumps, in high velocity and shallow (<50cm) subaqueous supercritical ($Fr > 1$) flows; but higher Fr number than F1d or F1e.	<i>Winterwerp et al. 1992, Taki and Parker, 2005, Kostic et al., 2010; Cartigny et al., 2014</i>	FA2
	F1h	10-95 cm thick low angle ($< 12^\circ$) concavo-convex trough cross-laminated sets/beds and symmetrical formsets in Lv – Uf sandstone	Hummocky/swaley cross-stratification formed by transport and deposition by long period oscillatory or combined flow currents	<i>Harms et al., 1975; Duke et al., 1991; Dumas et al., 2005</i>	FA6
	F1i	1-8 cm thick discontinuous, erosionally-based and reversely-graded cross strata in Lm-Lc sandstone	Aeolian grain flow cross-strata generated by subaerial avalanching of sand on an inclined surface/ bedform	<i>Hunter, 1977; Kokerek and Dott, 1981; Legros, 2002</i>	FA3
F2: Planar-stratified sandstone	F2a	Thin (≤ 3 mm), ungraded or normally graded laminations in Uf - Lc sandstone defined by subtle grain size changes; associated with parting lineations on bed surfaces	Upper stage plane bed formed in upper flow regime, near critical ($Fr \sim 1$) subaqueous flows, possibly depth-limited, oscillatory or unidirectional flows	<i>Poala et al., 1989; Southard and Boguchwal, 1990; Best and Bridge, 1992</i>	FA1, FA2, FA4, FA5
	F2b	Thin to thick (1mm - 1cm), shallowly dipping ($\sim 1-10^\circ$) inversely graded laminations with strong grain size partitioning and low relief formsets; low relief asymmetric formsets on bedding planes; in Uf - Lc sandstone	Subcritically climbing wind ripple stratification formed by transport and deposition of bedload sand by wind in a dry, subaerial setting	<i>Hunter, 1977; Kocurek and Dott, 1981</i>	FA2, FA3, FA4
	F2c	Indistinct thick laminations to very thin beds (0.5-3 cm) with shallow (≤ 1 cm) crenulations, bumps or streamlined bumps	Adhesion stratification and associated adhesion bedforms (ripples, warts, wrinkles) formed by the adhesion of	<i>Hunter, 1980; Kocurek and Fielder, 1982; Olsen and Clemmensen, 1989</i>	FA2, FA3, FA4

		on bed surfaces; in Uf-Um sandstone	windblown sand onto damp or wet surfaces		
	F2d	0.5 – 3 cm thick, well-sorted massive or inversely-graded upper medium to lower very coarse planar sandstone strata. commonly in association with F2b and F2c.	Deflation Lags formed by windblown erosion of finer particles and subsequent surface armouring.	<i>Mountney 2006b</i>	FA2, FA3, FA4
F3: Graded sandstone beds	F3a	Very thin to thin (3 – 7 cm), normally-graded LvF-Uf sandstone with preferentially chemically-altered detrital minerals and infiltrated matrix	Subaerially-weathered waning flow deposits formed by deposition from suspension in decelerating subaqueous flows, followed by prolonged subaerial exposure in a humid setting		FA1
	F3b	1.5 - 23 cm erosionally-based beds of poorly-sorted normally-graded LvF-Uvc sandstone. Abundant mudstone matrix and pseudomatrix clasts	Rapid deposition from highly concentrated, high energy flow driven by grain-to-grain interactions and fluid turbulence	<i>Lowe, 1982; Mulder and Alexander, 2001</i>	FA6
F4: conglomerate	F4a	Thin to very thick bedded (10 cm- 2.5 m), pebble to cobble orthoconglomerate with laterally continuous and/or discontinuous trains of imbricated subangular to subround clasts	Tractional gravels deposited as bedload sheets at the base of high energy, possibly shallow unidirectional subaqueous flows	<i>Whiting et al., 1988; Southard et al., 1984</i>	FA1, FA5
	F4b	Poorly sorted, clast- to matrix-supported, cobble to boulder conglomerate, lacking internal fabric, subangular to very angular clasts. ~2-35% sandy/pebbly matrix, forms lenticular bodies against basement highs	Talus deposits deposited as accumulations of rock fall or as rock avalanches along high-relief, gravitationally-unstable basement slopes		FA1, stand-alone
F5: fine-grained siliciclastics (siltstone and mudstone)	F5a	0.5 - 5 mm thick laminations of massive silty mudstone interlaminated with thin (0.5 -1 mm) well-sorted siltstone; locally dolomitic with peloids and dolomicrite	Low but alternating energy deposition of suspended load clay and silt by decelerating flows or slack-water conditions, possible aided by flocculation and resuspended as	<i>MacQuacker et al., 2010; Plint, 2014</i>	FA1, FA5, FA6

			dense, bottom-hugging sediment gravity flows		
	F5b	0.4 - 2 cm thick unidirectional high angle ($\geq 20^\circ$) trough and planar cross-laminated sets/beds and asymmetrical or symmetrical formsets in f-c siltstone; ripple index > 15	Current and/or combined flow ripples formed by transport and deposition under moderate energy subaqueous unirectional and/or combined flow currents	<i>Allen, 1968; Southard and Boguchwal, 1990; Baas 1994, Dumas et al., 2005</i>	FA6
	F5c	Very thin (0.4 - 1 cm) chevron, bidirectional and unidirectional cross-laminated sets/beds and symmetrical formsets in f-c siltstone	Wave ripples formed by transport and deposition under near bed oscillatory currents propagated downwards from surface wind waves	<i>Allen, 1976; Clifton 1976; Miller and Komar 1980</i>	FA6
F6: dolomicrite	F6a	3 – 75 cm thick, color-mottled sucrosic dolomicrite beds, with mm - μ m scale cryptoalgal laminites, 0.1 – 0.3 silt laminae, burrows, fossil fragments, and convolute and shrinkage/injection fabrics.	Low energy accumulation of microbially-mediated dolomite is a shallow, probably peritidal and hypersaline environment. Rare siliciclastic influx.	<i>Chafetz and Buczynski, 1992; Vasconcelos et al., 1995; Pratt, 2010</i>	FA5, FA6
	F6b	~3 – 10 cm thick, variegated red and grey planar-laminated dolomicrite beds with ~5 – 40% subangular silt grains concentrated in ~0.1 – 0.3 mm thick laminae, also with <0.1 mm iron oxide-rich microbial laminites.	Moderate energy accumulation of microbially-mediated dolomite, with periodic influx of siliciclastic sediment.	<i>Chafetz and Buczynski, 1992; Vasconcelos et al., 1995; Pratt, 2010</i>	FA6

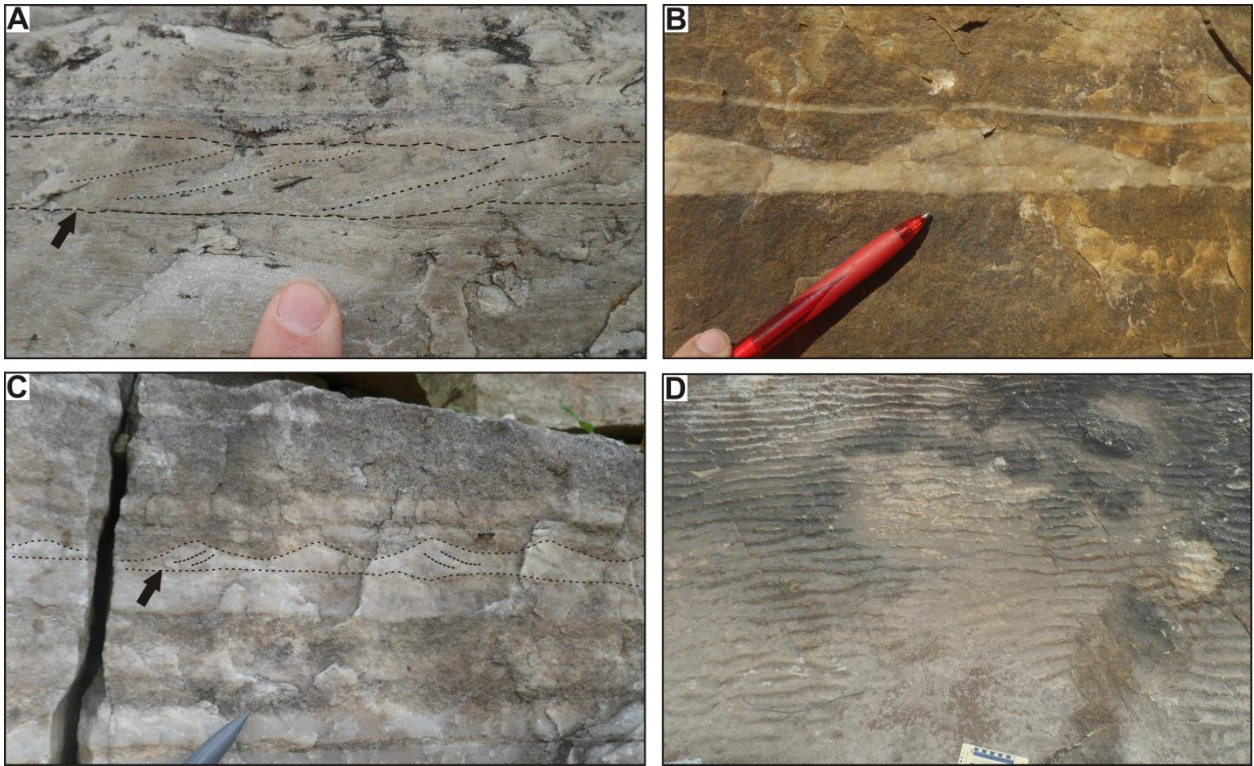


Figure 2.1 Examples of small-scale cross-stratified sandstone subfacies F1a and F1b. A) Small-scale unidirectional cross-stratified sandstone set (F1a, arrow points to base) interpreted as the deposit of a migrating current ripple in a unidirectional, low energy current. Ste. Hermas, QC (locality 235). B) Asymmetric current ripple (F1a) formset, Kanata, ON (locality 1). C) Small-scale bidirectionally cross-laminated sandstone set with symmetric formset (F1b, arrow points to beds of set) interpreted as the deposit of depth-limited wave ripples. Pencil for scale at base of photo. Kanata, ON (locality 1). D) Bedding-plane view of wave ripple (F1b) formsets, along the Great Chazy River, Altona, NY (locality 152). Divisions of scale card are in cm.

2.1.2 F1a: Interpretation: Subaqueous current ripple stratification

The thinness, unidirectional character of cross-laminations, high range of L/H ratios and asymmetric formset shape suggests deposition by current ripples under weak unidirectional subaqueous currents (Allen, 1968; Southard and Boguchwal, 1990). Planar cross-laminated ripple strata and straight to broadly sinuous crested formsets are interpreted to be the deposits of straight- or broadly sinuous- crested 2D subaqueous current ripples. Trough cross-stratified sets, on the other hand, are interpreted to represent sinuous- to linguoid-crested 3D current ripples. According to Baas (1999), 3D ripples are equilibrium

bedforms requiring sustained flow in the ripple stability field, whereas 2D ripples are incipient and transient forms. The dominance of 2D ripple stratification and formsets is therefore interpreted to record non-equilibrium ripple deposition, possibly during the final waning stages of a sedimentation event.

2.1.3 F1b: Bidirectionally cross-laminated sandstone sets with symmetric formsets

Subfacies F1b comprises very thin (1 – 2 cm) bidirectional, chevron or occasionally unidirectional cross-laminated sets of lower fine to upper medium-grained sandstone (average: lower medium) with, where observable, symmetric formsets that are 0.2 – 1.5 cm high (0.6 cm average) and spacings of 2 – 10 cm (3 cm average) (L/H ratios of 4 – 12) (Fig. 2.1c – d). Low-relief formsets (those with L/H >9) have rounded crests and few or no lateral bifurcations in plan view. Higher relief formsets (L/H <9), in contrast, have rounded or sharp crests with common bifurcations in plan view.

2.1.4 F1b: Interpretation: Depth-limited wave ripple stratification

Bidirectionally cross-laminated sandstones with symmetrical formsets are interpreted as the deposits of subaqueous wave ripples (Allen, 1982). Higher relief ripples with L/H <9 are interpreted to be orbital ripples (Allen, 1976) with bottom orbital diameters of 3 – 15 cm (4.6 cm average; based on Clifton, 1976; Miller and Komar, 1980). Low relief ripples (L/H >9) are interpreted as anorbital ripples that formed at the transition between wave ripples and oscillatory plane bed, either due to increases in near bed orbital velocity and/or decreases in water depth (Allen 1976, Clifton 1976). Based on the average grain size (lower medium

sand) and short wavelengths (average 4.6 cm), short wave periods would have been required in order to maintain sediment movement (Clifton and Dingler, 1984). These ripples, therefore, likely formed in very shallow water under short-period, short wavelength surface wind waves (i.e. depth-limited wave ripples).

2.1.5 F1c: Unidirectional, high-angle cross-stratified sandstone sets

Subfacies F1c consists of thin to thick (5 – 75 cm) sets of cross-stratified lower medium- to lower very coarse-grained, moderately- to well-sorted sandstone (Fig. 2.2a – b). Cross-strata dip at high angles ($\sim 20 - 45^\circ$), are ~ 1 mm to 2 cm thick and normally graded or ungraded. Granules and pebbles are present locally, particularly at or near the base of sets. Trough and planar cross-stratification are both observed (Fig. 2.2a – b), although trough cross-stratification is much more common. Basal bounding surfaces of trough cross-stratified sets form moderate to high relief ($15 - 45^\circ$) troughs with 4 – 45 cm of scour. Associated bedding plane exposures exhibit 20 cm to 1 m wide cusate rib-and-furrow structures.

2.1.6 F1c: Interpretation: Subaqueous dune stratification

Based primarily on the thickness of sets and unidirectional character of the cross-stratification, strata of F1c are interpreted to be the deposits of subaqueous dunes (e.g. Ashley, 1990). Most dune sets are trough cross-stratified, indicating a dominance of linguoid 3D dunes. Recent investigations suggest that 3D dunes, like 3D ripples, are equilibrium bedforms that evolve from simpler 2D dunes (Venditti et al, 2005). Therefore, their

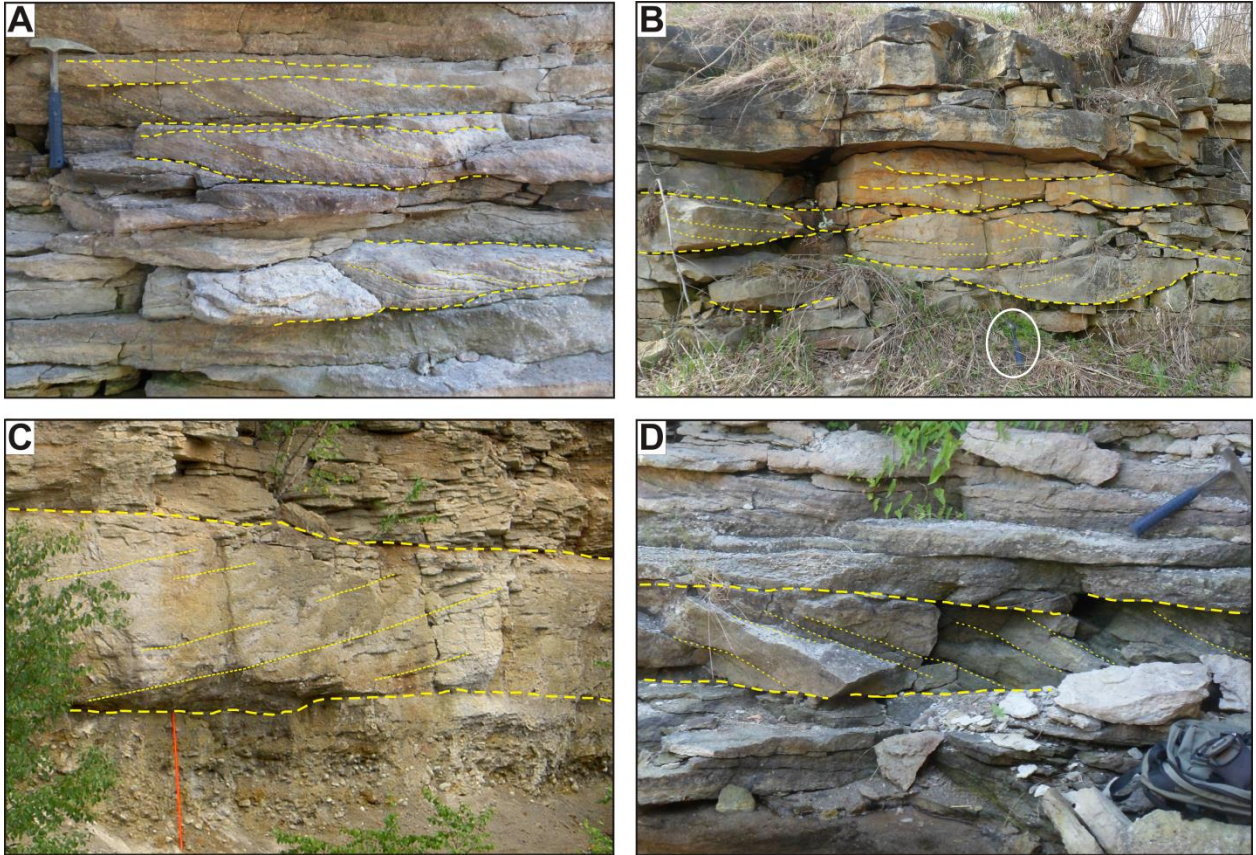


Figure 2.2 A) Coarse-grained, unidirectional, high angle planar cross-stratified sets (F1c) interpreted as the deposits of migrating 2D dunes in high-energy, unidirectional subaqueous currents. Great Chazy River, North Branch near Ellenburg, NY (locality 228). B) Coarse-grained, high angle unidirectional trough cross-stratified sandstone (F1c), exposed perpendicular to the paleoflow direction, formed by the migration of 3D dunes. Hammer is circled. South of Alexandria Bay, NY (locality 115). C) Thick planar cross-stratified set of coarse-grained sandstone (F1d) interpreted as the deposit of a solitary, lobate unit bar in a steady channelized flow. Orange staff in 1.5 m, Briton Bay, ON (locality 12). D) A thinner set of coarse-grained, plane-cross stratified unit bar cross-stratification, Great Chazy River, North Branch near Ellenburg, NY (locality 228).

dominance in strata of F1c most probably indicates prolonged periods of quasi-steady flow conditions.

2.1.7 F1d: Large-scale unidirectional planar cross-stratified sandstone sets

F1d consists of 20 cm – 1.6 m thick, planar cross-stratified sets of upper medium to lower very coarse-grained sandstone. Cross strata range in thickness from 1.5 mm to 12 cm and are defined by abrupt changes in grain size (typically alternating medium and coarse

sand). Set boundaries are planar with little evidence of scour, and cross-strata dip at angles of $20 - 45^\circ$ (average $\sim 30^\circ$) (Fig. 2.2c – d). Sets are laterally continuous over 6 m to more than 50 m in sections paralleling the dip direction of cross-strata (limited by the dimensions of the outcrops), and thicker sets are more laterally continuous. Erosional surfaces are present within sets and are steeply inclined ($15 - 40^\circ$) and truncate underlying cross-strata and are overlain by conformable or onlapping cross-strata.

2.1.8 F1d: Interpretation: Unit bar stratification

The continuous and unidirectional character of sets and the large average set thickness (70 cm) suggest avalanche deposition on the lee-side of relatively thick, elongate and persistent downflow-migrating bedforms. Furthermore, the planar, non-erosional bounding contacts indicates that the migration of these bedforms did not coincide with lee-side scour, but instead record the build-up of relatively large topographically positive features. Similar large-scale planar cross-stratification is recognized in modern fluvial systems as the deposits of unit bars – solitary lobate bars with simple lee-sides characterized by avalanche deposition (Bridge, 2003; Lunt et al., 2004; Bridge and Lunt, 2006; Reesink and Bridge 2011). The large range of observed cross-stratum thickness (1.5 mm – 12 cm) is most likely related to differences in how sediment was made available for avalanching on the bedform's leeside; (cross) laminae probably record regular grain flows from the brink of unit bars, whereas thicker layers (> 1 cm) very likely record leeside deposition related to the passage of superimposed bedforms (probably ripples and/or dunes) over the unit bar (e.g., Reesink and Bridge, 2011). Intra-set erosional surfaces are interpreted as reactivation

surfaces that probably formed during the passage of relatively large (1/4 of the unit bar height) superimposed dunes (e.g. Reesink and Bridge, 2011).

2.1.9 F1e: Low-angle trough cross-stratified sandstone sets with convex-upwards formsets

Subfacies F1d is made up of 5 – 20 cm thick lenticular sets of low angle ($\leq 15^\circ$) cross-stratified lower medium- to upper coarse-grained sandstone bounded by low-angle (5 – 15°) concave-upward scours (troughs), with uncommon low angle (10 – 15°) convex-upwards symmetrical formsets (Fig. 2.3a; see also Fig. 4.9a in chapter 4). Cross-strata are diffuse to well-defined, normally- or non-graded, defined by variations in grain size and sorting with coarser lamina having poorer sorting, and oriented either sub-parallel or dip at a low angle ($\leq 10^\circ$) to the basal set boundary. Commonly, the set bases consist of massive, poorly-sorted sandstone. Sets of cross-laminae and their associated basal scours are oriented in the opposite direction to intercalated cross-stratified sandstones of subfacies F1a and F1c, or where absent, opposite to the regional paleoflow. F1e occurs either as isolated sets, trains of 1 – 4 adjacent sets or as cosets. The observed symmetrical formsets occur within and at the top of F1e cosets. These are typically 2D in form, characterized by transverse ridges with no notable bifurcation and amplitudes of 2 – 8 cm and wavelengths of 0.5 – 1 m (Fig. 2.3c). Rarely, 3D forms are observed and are characterized by alternating low angle mounds and depressions spaced 0.8 – 1.5 m apart with relief of 5 – 10 cm (Fig. 2.3b).

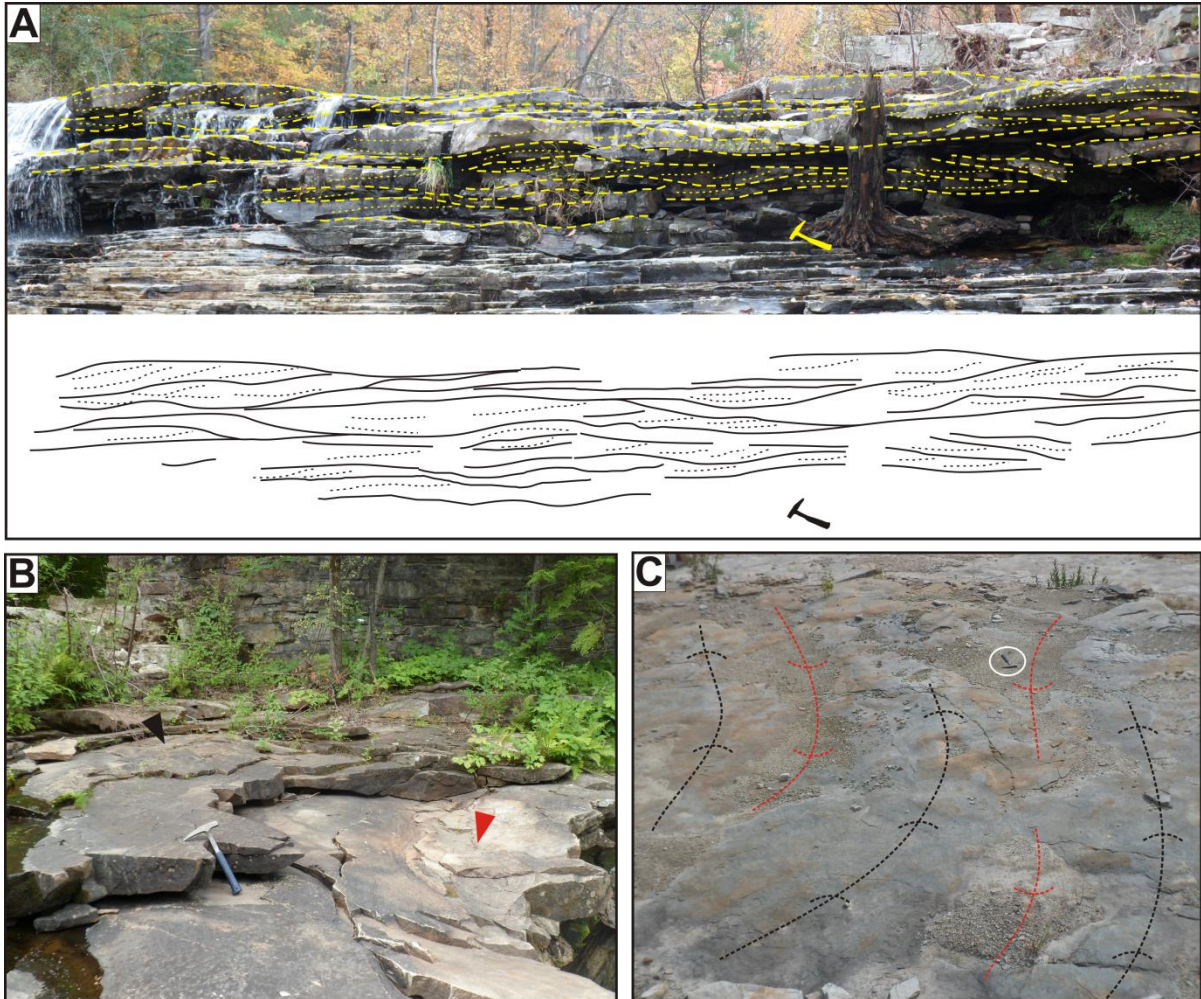


Figure 2.3 A) Coset of coarse-grained, low-angle trough cross-stratified sandstone sets with common low-angle convex-up formsets (F1e) interpreted as upstream-migrating antidune cross-stratification formed at the base of a shallow, aggradational high-energy (supercritical) subaqueous current. Located in the Great Chazy River, Woods Falls, NY (locality 148). B) Top surface of coset in A), showing 3D form of convex formsets (black arrowhead) and concave scours (red arrowhead). C) Bedding plane surface showing transverse, low-relief formsets (black lines) and intervening troughs (red lines) formed by the migration of 2D antidunes. Hammer is outlined for scale. Ducharme Quarry, QC (locality 203). See chapter 4 and figure 4.9a for a more details and an additional example.

2.1.10 F1e: interpretation: Antidune stratification

The consistently low angle of cross-strata is atypical of gravity-driven lee-side avalanche deposits formed by migrating transverse bedforms like ripples or dunes (see subfacies F1a and F1c, respectively). This, plus the dominantly opposing orientation of cross-strata and presence of convex-upward symmetrical formsets are features similar to those formed by experimental (Middleton, 1965; Alexander et al., 2001; Cartigny et al. 2013) and natural (Langford and Bracken, 1984) antidunes, and in ancient fluvial deposits have been interpreted to represent antidune cross-stratification (Rust and Gibling, 1990; Cotter and Graham, 1991; Fielding, 2006). Antidunes and their cross-stratification record transport and deposition under supercritical subaqueous flows. Under these conditions the bed is in-phase with upstream-, or less commonly, downstream-migrating surface waves, except when the standing waves break generating upstream-migrating surges (Alexander et al., 2001; Cartigny et al. 2013). Simple backset cross-stratification (opposite the paleoflow direction) indicates deposition on the bedform's stoss side and trough caused by upstream wave migration and occasionally upstream surge migration. Cosets of antidune cross-stratification that preserve formsets, on the other hand, suggest deposition under higher energy conditions in which wave breaking and upstream surge migrations were more common and rates of aggradation were higher than in cases of simple backset preservation (Alexander et al., 2001; Cartigny et al. 2013).

2.1.11 F1f: Scour-filling sigmoidal cross-stratified sandstone sets

Subfacies F1f is defined by 10 – 55 cm thick discontinuous low to high angle (5 – 25°) sigmoidal cross-stratified sets of moderately well-sorted, lower medium- to upper

coarse-grained sandstone that fill asymmetrical scours (Fig. 2.4). Cross-strata and set-bounding scours are asymmetrical and oriented opposite to intercalated cross-stratified sandstones of subfacies F1a and F1c, or where absent, opposite to the regional paleoflow. Basal bounding scours form 5 – 25° dipping, concave-up surfaces that flatten gradually downwards and laterally into a continuous and planar erosional surface. Set tops are horizontal erosional surfaces. The sets have length to height ratios of ~10 – 20 and persist laterally over distances of 3 – 15 m. Sets also exhibit a unique sigmoidal shape characterized by vertical changes in cross-stratal dip, which from bottom to top consists of: (a) a scour-draping lens of massive to low angle ($\leq 15^\circ$) cross-stratified sandstone, overlain abruptly by (b) downlapping higher angle (10 – 25°) diffuse concave to convex cross-strata, which upward is truncated by a low angle ($\leq 15^\circ$) erosional surface and overlain by (d) low angle (3 – 10°) convex-up laminae (Fig. 2.4, and see Fig. 4.9b from chapter 4).

2.1.12 F1f: Interpretation: Chute-and-pool stratification

The paleoflow-opposing direction of these sets and their occurrence within scours suggests that upstream scour migration, and soon thereafter deposition, was coupled with high energy erosional events. Additionally, their sigmoidal internal architecture with abrupt spatial changes in cross-stratal dips suggests a characteristic morphodynamic evolution with temporally fluctuating flow conditions. Similar sigmoidal scour-filling, up flow-dipping cross-stratification has been described from ancient fluvial (Fralick, 1999; Fielding, 2006) and pyroclastic (Schmincke et al., 1973) deposits, and interpreted to be the deposits of chute-and-pool structures formed under supercritical flow conditions. Additionally, the upstream migration and vertical changes in the dip of cross-strata is consistent with experimental flume

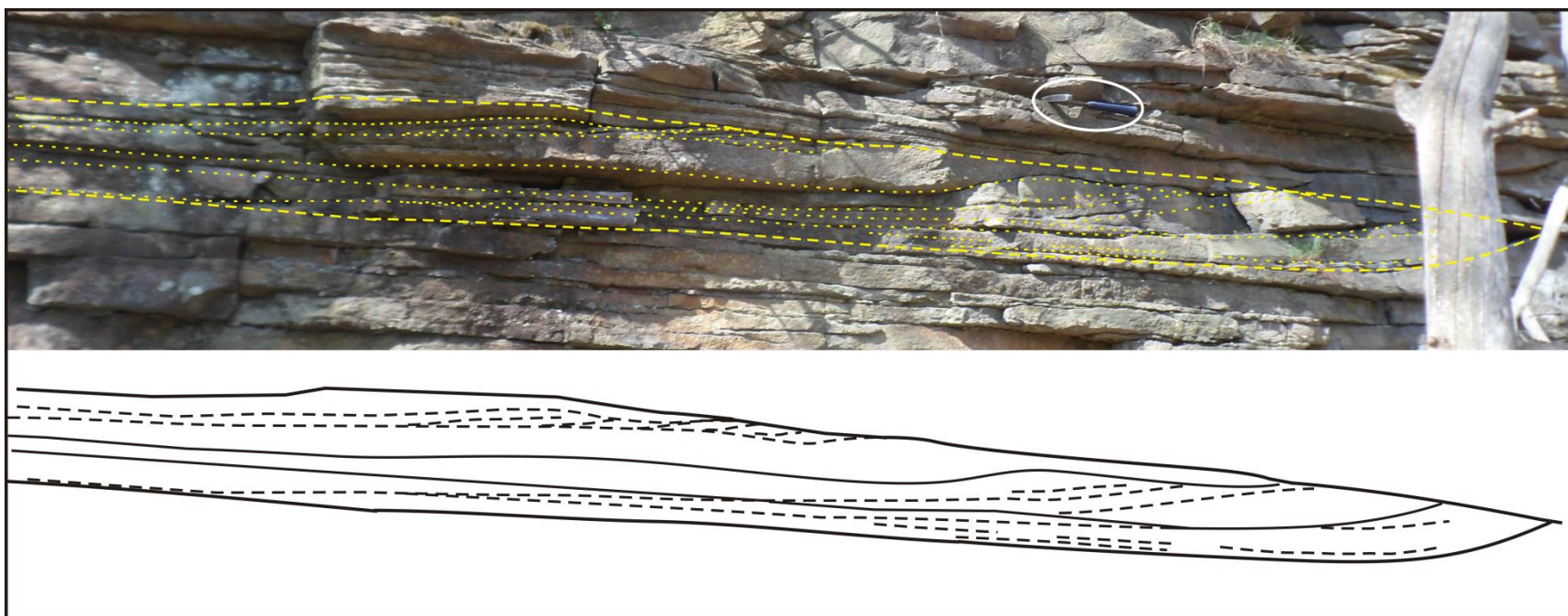


Figure 2.4 Coarse-grained, scour-filling sigmoidal cross-stratified sandstone set (F1f) interpreted as upstream-accreting chute-and-pool stratification. The solid lines demarcate discrete component parts of the set, specifically a basal scour surface overlain by a layer of strata that conform to the shape of the scour surface, in turn overlain by high-angle strata deposited under a temporarily surging hydraulic jump, and succeeded by low angle strata under re-established supercritical flow conditions. Located west of Hammond, NY (locality 95). See chapter 4 and figure 4.9c for more details and an additional example. Hammer for scale (circled).

studies of supercritical chute-and-pool bedforms, and reflects deposition under the hydraulic jump immediately downstream of an erosional supercritical flow (Alexander et al, 2001; Cartigny et al., 2013). The sigmoidal architecture is a result of a tripartite morphodynamic evolution, wherein the lowermost massive lens and low angle backsets record deposition under an upstream-migrating positive surge, while overlying higher angle backsets record rapid deposition under a stationary hydraulic jump, and finally the uppermost planar to slightly convex back- and foresets record deposition under re-established supercritical flow (Cartigny et al., 2013). Chutes-and-pools form at the transition between antidunes and cyclic steps and as such are not regarded as discrete bedforms (Cartigny et al., 2013). Nevertheless, they are interpreted to reflect highly unsteady flow conditions, most probably associated with the waning or waxing stage of flashy, shallow, high velocity subaqueous flows.

2.1.13 F1g: Unidirectional low – high angle trough cross-stratified sandstone sets with opposing paleoflow

Subfacies F1g consists of 20 cm – 1.3 m thick (average thickness: 70 cm) trough cross-stratified sets of lower medium- to upper coarse-grained sandstone with set boundaries and laminations that dip in opposing directions to those of intercalated F1a and F1c (current ripple and dune cross-strata). Set boundaries are moderate to high relief ($15 - 35^\circ$), asymmetrical erosional troughs. The sets are 2.5 – 12 m long in sections oriented parallel to the maximum dip direction of cross-strata, and 7 – 35 m across in sections perpendicular. Internal cross-strata are concave-up with dips of $15 - 35^\circ$ with tangential bases that conform

to the shape of the basal bounding surface (Fig. 2.5). Sets fill large scours (35 cm – 1.2 m deep, 15 – >120 m wide, 25 – >150 m long) and form trains of sets in which each set is truncated by the erosional trough of the succeeding set in the upcurrent direction. However, sets at the upcurrent end of each scour are not truncated and exhibit a gradual decrease in cross-stratal dip away from the high-angle side of the scour, and then are typically onlapped by planar-stratified sandstone, or in some cases, cross-stratified sandstone exhibiting paleoflow in the opposite direction (Fig 2.5, and see Figs. 4.10 – 4.11 in chapter 4).

2.1.14 F1g: Interpretation: Cyclic step stratification

Trough cross-stratification, steeply dipping and unidirectional character of cross-laminations indicates deposition by the lateral migration of stable 3D flow-transverse bedforms. Moreover, the high average thickness of sets (70 cm), indicates that the formative bedforms were large. However, the opposing dip direction of laminations relative to those formed by other transverse bedform strata such as dunes (F1c) suggests that sediment accumulated on the upstream stoss-side of the bedform, rather than the lee side. This, plus the stratal architecture of the sets (low- to high- angle concave boundary-conformable laminations and bounding troughs) are consistent with the experimentally-derived processes and deposits of cyclic steps, which are upstream-migrating flow-transverse bedforms that form in supercritical flows with Froude numbers higher than antidunes or chutes-and-pools (Kostic et al., 2010; Cartigny et al., 2013). In these very high energy flows, trains of stable hydraulic jumps persist in the troughs of cyclic steps. For each cyclic step, flows accelerate to supercritical conditions over the crest and down the leeside, favoring erosion. Further

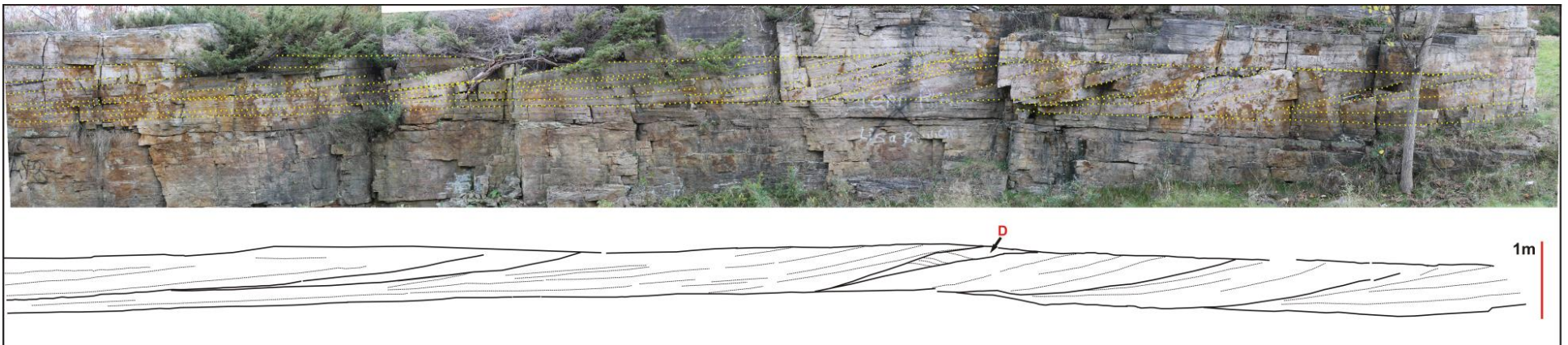


Figure 2.5 Thick set of high to low angle, coarse-grained upstream accreted cross-stratified sandstone (F1g) interpreted to have formed by the migration of quasi-stable, upstream-migrating cyclic steps, i.e., beneath stabilized upstream-migrating hydraulic jumps under flow-averaged high-energy supercritical flow conditions. The solid lines in the line diagram demarcate set boundaries. “D” indicates an isolated set of downstream-migrating dune cross-stratification. Cemetery Road, Hammond, NY (locality 85). See chapter 4 and figures 4.10 and 4.11 for more details and examples.

downstream in the troughs, however, the flow expands and forms a hydraulic jump, under which subcritical conditions persist and results in stoss-side deposition (Cartigny et al., 2014). Unlike chutes-and-pools, cyclic steps are stable supercritical bedforms, and therefore their presence is interpreted to indicate relatively sustained high velocity, shallow subaqueous flow conditions. This stability is indicated by the stacking of cyclic step deposits (i.e., cosets) and their significant lateral dimensions (some more than 60 m) compared to the smaller, isolated sets of chute-and-pool deposits.

2.1.15 F1h: Large-scale low angle concavo-convex cross-stratified sandstone

Subfacies F1h is characterized by 10 – 95 cm thick, low angle ($<10^\circ$) cross-stratified sets of boundary-parallel mm-scale laminations bounded by low-relief symmetrical concave-up basal troughs and convex –up formsets, the latter of which are sometimes truncated (Fig. 2.6). Architecturally, F1h is similar to F1e (antidune stratification, see above), but with some important differences. Firstly, F1h is much finer grain size than F1e, ranging from coarse silt to upper fine sand with an average grain size of lower fine sand. Secondly, the wavelength of low-relief formsets are much larger than those observed in F1e, generally between 2 – 4 m. Thirdly, sets and formsets are always three dimensional, whereas F1e sets and formsets are more commonly 2D and transverse, respectively. Finally, F1h is primarily associated with sparsely bioturbated mudstone (low diversity mixed *Skolithos* – *Cruziana* ichnofacies, see facies association 6, next chapter) and rare, diminutive vertical trace fossils also occur at the tops of F1h sets and cosets.

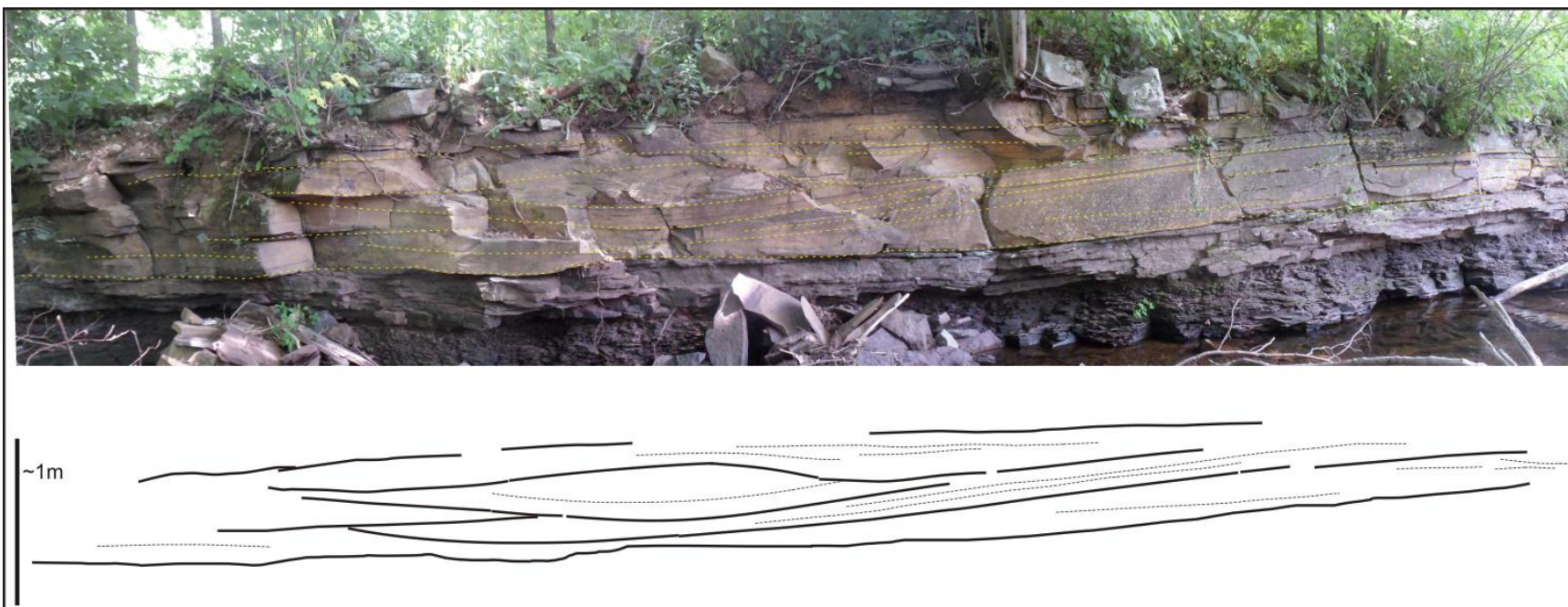


Figure 2.6 Coset of fine-grained, large-scale low angle concavo-convex cross-stratified sandstone (F1h), interpreted as hummocky cross-stratification formed by storm-driven oscillatory and/or combined flow currents. Strata underlying this coset consist of sparsely-bioturbated mudstone. Located along Stillwater Brook north of Jericho, NY (locality 138).

2.1.16 Subfacies F1h: Interpretation: Hummocky and Swaley cross-stratification

Subfacies F1h is interpreted as hummocky and swaley cross-stratification (HCS-SCS) based on its association with a low-diversity suite of mixed *Skolithos*-*Cruziana* ichnofossils in these and also intercalated strata, and also the large-amplitude alternating convex-upwards and concave-downwards 3D bounding surfaces (hummocks and swales, respectively), low angle internal truncation of laminasets, and generally fine grain size (Harms et al 1975, Dott and Bourgeois 1982; Cheel and Leckie, 1993). Based on numerous experimental and empirical studies it has become well established that HCS-SCS is deposited by large equilibrium 3D bedforms (hummocks and swales) formed under strong purely oscillatory or strongly oscillatory-dominated combined flow conditions (Southard et al., 1990; Arnott and Southard, 1990; Duke et al. 1991; Dumas et al., 2005). Typically these physical conditions occur during storms on the nearshore shelf of large basins, and accordingly HCS is usually interpreted to record deposition in this offshore setting (e.g., Dott and Bourgeois 1982, Greenwood and Sherman 1986, Duke et al., 1991, Li and Amos, 1999). However, HCS has also been reported from much shallower environments, specifically modern open-coast tidal flats in South Korea (Yang et al., 2005, 2006). Here HCS formed during storms when m-scale waves broke on the shallow, low-relief tidal flat (Yang et al., 2005, 2006). Yang et al. (2006) suggested that this intertidal form of HCS was formed by large equilibrium oscillatory bedforms (hummocks and swales), and therein similar to those described previously by Duke et al. (1991) and Dumas et al. (2005). However it is important to note that geometrical similarity does not necessitate dynamic similitude. Specifically the undulating bounding surfaces and distinctive internal characteristics of HCS/SCS can represent scour-and-drape deposition (Dott and Bourgeois 1982) or the depositional evolution of an equilibrium bed

form (Dumas et al. 2005). Differentiating between these mechanisms in the geological record is currently problematic, and beyond the scope of this thesis, but importantly is a topic that requires more extensive research.

2.1.17 F1i: Laterally discontinuous reversely-graded sandstone cross-strata

Subfacies F1i is defined by ~1 – 6 cm thick, steeply dipping ($\sim 20 - 35^\circ$) cross-strata of sandstone that occur exclusively in rare relatively thick (15 cm – 2 m) sets (see facies association 3 in next chapter). F1i cross-strata are inversely-graded normal to cross-stratal dip direction, but also coarsen in the down-dip direction (Fig. 2.7). They lack internal laminae and consist of moderately-sorted and loosely-packed lower medium to upper coarse sand. The bases of these cross-strata are commonly erosional, whereas the tops are sharp surfaces. In addition, F1i cross-strata are generally discontinuous, commonly pinching out above the base of sets and rarely below the tops of truncated sets (Fig. 2.7).

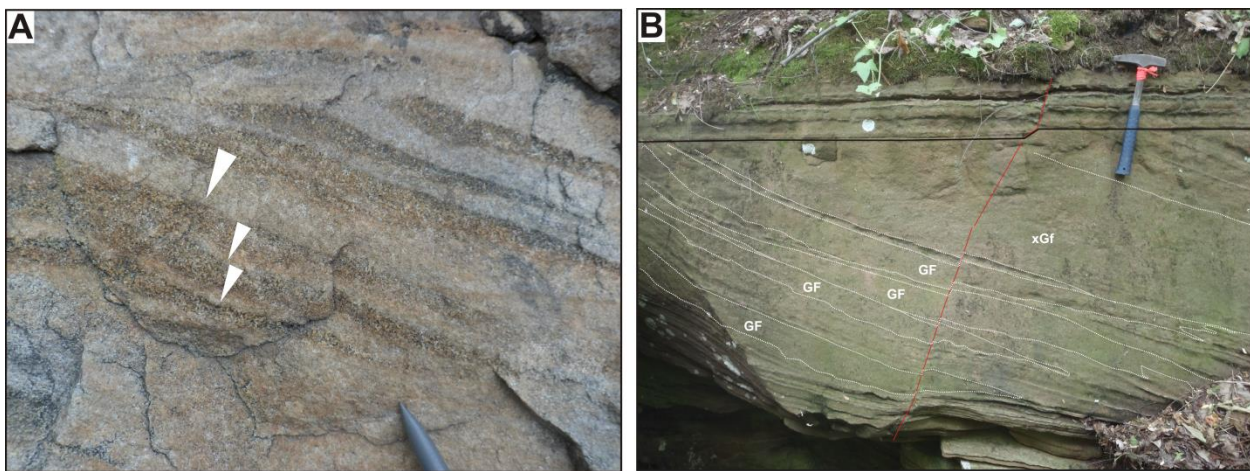


Figure 2.7 A) Centimetre-thick, laterally discontinuous reversely-graded sandstone cross-strata (F1i) interpreted as the deposits of aeolian grain flows. White arrowheads indicate reverse grading, which is sharp in this example from Kanata, ON (locality 1). Pencil tip for scale (near bottom). B) Thicker aeolian grain flow cross-strata (outlined in white and labelled “GF”) and locally amalgamated grain flow cross-strata (xGF) interbedded with inclined wind-ripple strata (F2b), Hughes Farm, ON (locality 26). Red line demarcates a fracture with minor offset.

2.1.18 F1i: Interpretation: Aeolian grain flow cross-strata

The main features of subfacies F1i, including inclined dips ($>20^\circ$), discontinuous nature, erosional bases, inverse grading, loose packing and their occurrence in thick sets suggest that they are most likely aeolian grain flow cross-strata deposited on the lee-side of steep aeolian dunes (Hunter 1977; Kocurek and Dott, 1981). The inverse grading (normal to the dip orientation) and down-dip increase in grain size are both attributed to kinetic sieving, a process in which finer grains settle to the base of the grain flow through the interstices of the larger dispersed grains (Legros 2002; Bagnold, 1954). The discontinuous nature of the grains flows is attributed to their ephemeral nature as well as their variable origins -- they may originate as coherent slumps that lose cohesion downslope or as shear surfaces that initiate and regress upslope (Hunter, 1977).

2.2 F2: Planar-stratified sandstone

2.2.1 F2a: Planar-laminated sandstone with thin normal or ungraded laminations

Strata of F2a consist of upper fine- to upper medium-grained sandstone with thin (0.4 – 3 mm) normally-graded or ungraded planar laminae (Fig. 2.8 a, c). Laminations are generally defined by subtle grain size changes and/or differences in sorting, and usually have sharp, flat contacts (Fig. 2.8c). They are horizontal, or less commonly dip at a shallow angle (generally $< 5^\circ$, but up to 10°). Straight, parallel, laterally discontinuous parting lineations, typically 0.2 – 1 cm wide, are present on bedding planes and are accentuated by slight (~ 1 mm or less) relief and/or heavy mineral streaks (Fig. 2.8 a – b).

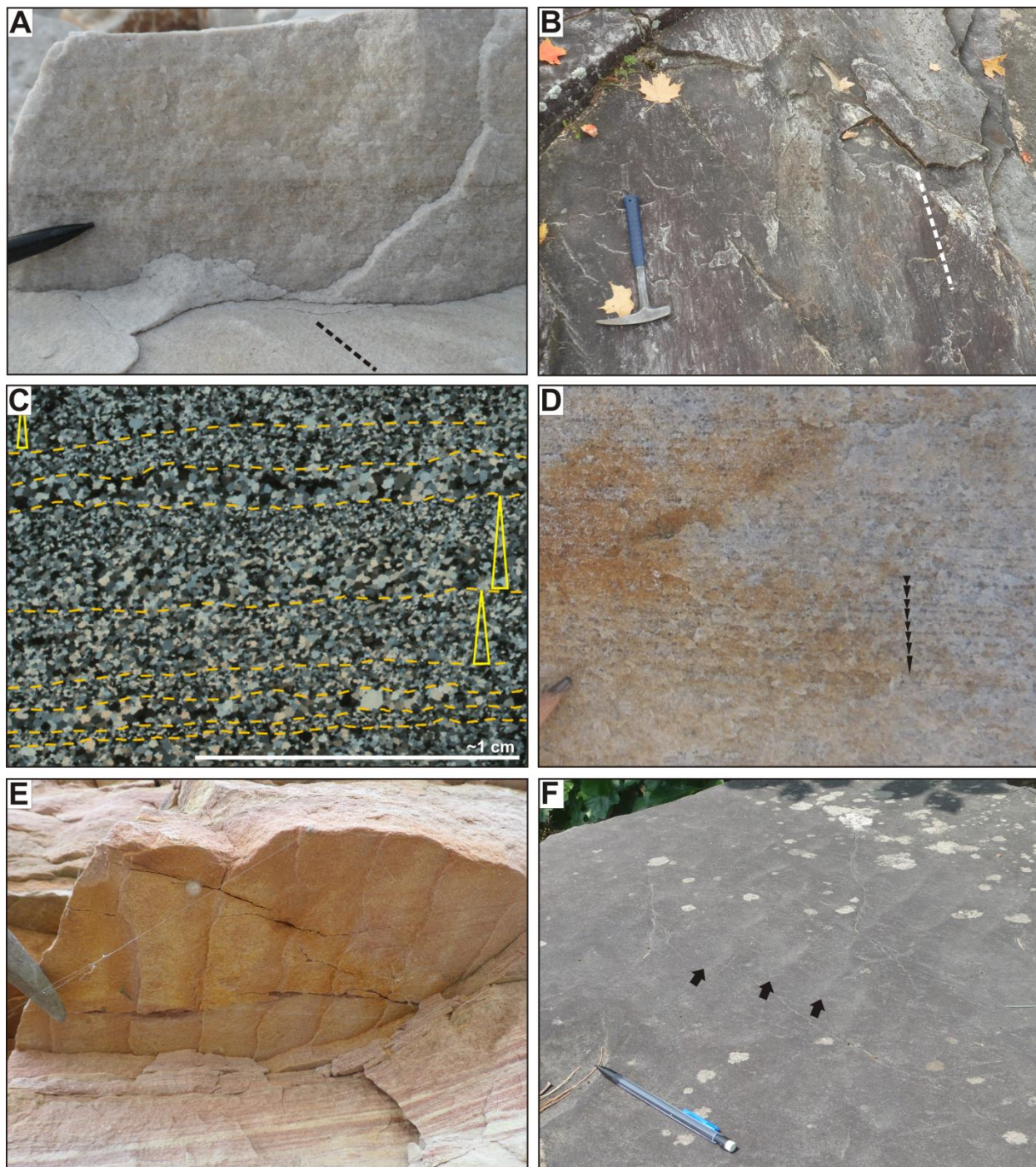


Figure 2.8 Examples of planar-stratified sandstone (F2), including F2a (A – C) and F2b (D – F). A) Upper medium-grained, planar stratified sandstone with ~mm-thick laminae, interpreted to have formed by upper stage plane bed under shallow, high-energy unidirectional and oscillating subaqueous currents. At the base of the photo is a bedding-plane ornamented with parting lineations oriented parallel to the black dashed line. Kanata, ON (locality 14). B) Parting lineations (parallel to white dashed line) on the bedding surface of a planar-laminated sandstone, Great Chazy River, Altona, NY (locality 152). C) Normal- and un-graded upper plane bed laminae in thin section, cross-polarized light, from Kanata, ON (locality 7). D) inversely-graded “pinstripe”-laminae (F2b) interpreted to be deposited by the migration of climbing wind ripples, Ducharme Quarry, QC (locality 203). Pencil tip for scale. E) Basal bedding plane of wind-ripple stratification (center of photograph) showing truncated translent strata (i.e., “pseudoripples”), Route 12 near Alexandria Bay, NY (locality 112). Hammer tip for scale. F) Bedding plane showing very low-relief wind ripple formsets, arrows mark locations of formset crests, west of Hammond, NY (locality 81).

2.2.2 F2a: Interpretation: Upper-stage plane bed stratification

Strata of F2a are interpreted to have been formed by upper stage plane bed. Sharp based, subtle normal-graded laminae were formed by flow-transverse, low amplitude (generally ≤ 6 mm) bedforms whose passage results in subtle variations in bed surface texture (e.g., Paola et al., 1989; Best and Bridge, 1992; Fielding, 2006). The common occurrence of associated parting lineations is consistent with upper-stage plane bed deposition and the effect of coherent turbulent fluid structures and their influence on the pattern of bed-surface sediment transport.

2.2.3 F2b: Planar-laminated sandstone with thin to thick reversely-graded laminations

Subfacies F2b is made up of upper fine to lower coarse sandstone with relatively thick (1 mm – 1 cm) reverse-graded laminations (Fig. 2.8d). Grading is generally even from the bottom to the top of a lamina and changes from upper fine/lower medium- to upper medium-grained sand. However in some cases, the grading is sharp with alternating millimetric fine/medium and coarse sandstone layers resulting in a “pinstripe”-like banding (Fig. 2.8d). Laminae usually dip at shallow angles ($\sim 1\text{--}5^\circ$ or less) but locally may steepen to $10\text{--}20^\circ$. Minor ($<10\%$) interstitial clay matrix is present locally in the finer-grained lower parts of laminations. Weathered bedding plane surfaces exhibit low-relief step-like features (Fig. 2.8e), or uncommonly low relief asymmetric formsets with spacing of 5 – 8 cm and heights of only a few mm (L/H of > 20) (Fig. 2.8f).

2.2.4 F2b: Interpretation: Climbing translent wind ripple stratification

The low angle inclination and association with low amplitude formsets suggests that laminae of F2b strata probably formed by the climb of low amplitude transverse bedforms. Subcritically-climbing translent wind ripple stratification, formed by the migration of low-relief wind ripples, is similarly characterized by reverse-graded, locally “pinstripe”-like and relatively thick, low-angle planar laminations (Hunter, 1977; Kocurek and Dott, 1981). The reverse grading is attributed to the structure of climbing wind ripples, with ripple crests made up of coarse-grained ballistic creep-load (>lower medium sand) migrating over finer-grained saltation load that preferentially accumulates in the ripple troughs (Hunter, 1977). The low relief step-like features observed on weathered surfaces are interpreted as pseudo-ripples generated by erosional truncation of translent strata, and are diagnostic features of wind ripple strata (Kocurek and Dott, 1981).

2.2.5 F2c: Indistinct, diffuse planar laminations and beds and associated surface crenulations and bumps

Subfacies F2c consists of diffuse and poorly-defined planar laminated to thinly bedded (0.5 – 3 cm thick) upper fine- to upper medium-grained sandstone (Fig. 2.9a). Grading is absent and grains are generally moderately sorted with up to ~10% interstitial clay and silt matrix draping grain boundaries and occluding intergranular spaces (Fig. 2.9b). Associated with these strata are a number of small and unusual surface features exposed on bedding planes, including (a) 2D features (Fig. 2.9c), (b) 3D features (Fig. 2.9d), (c)

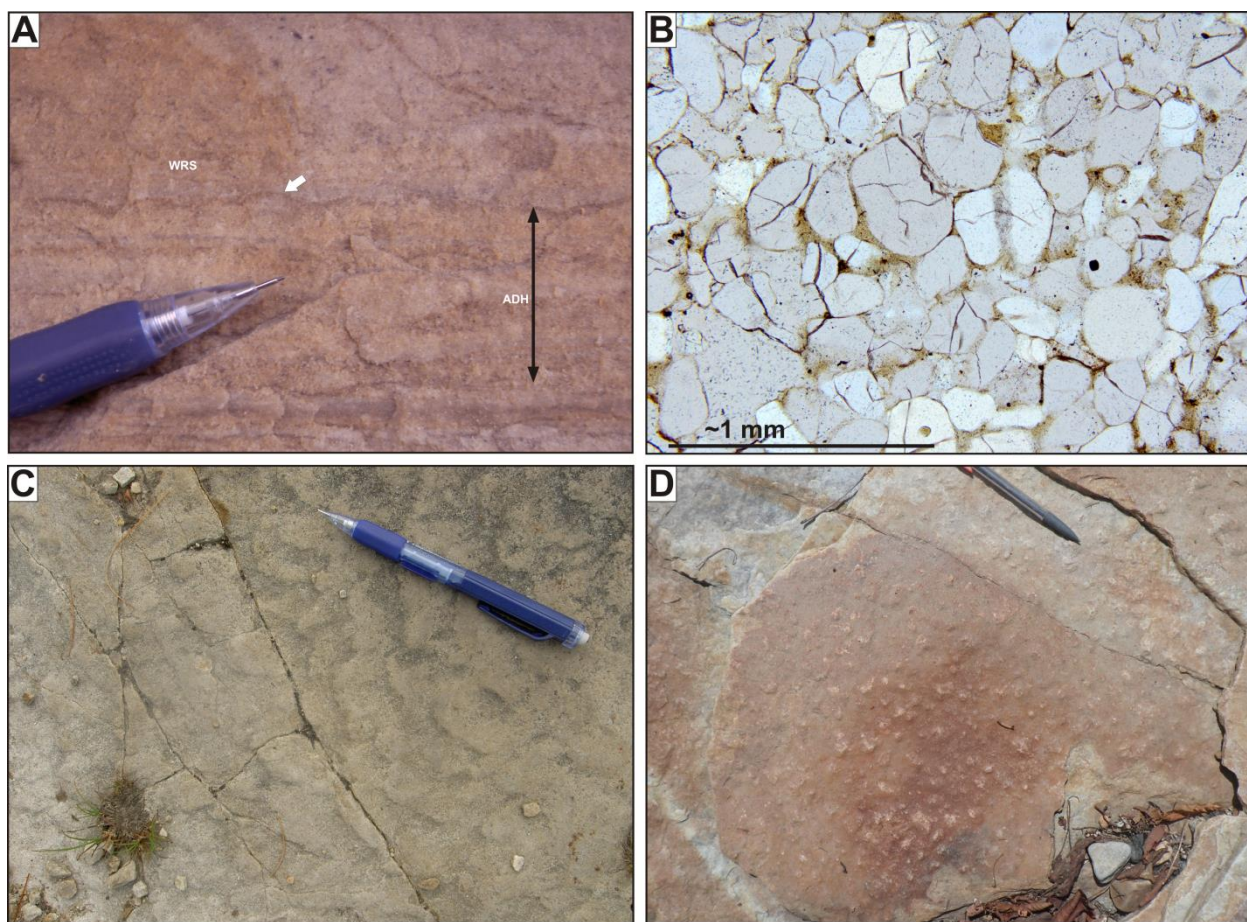


Figure 2.9 A) Indistinct, diffusely planar-stratified medium-grained sandstone (F2c) interpreted as adhesion stratification (ADH). Arrow points to crenulated upper surface of a possible adhesion ripple. Adhesion strata are overlain by medium-grained wind ripple stratification (WRS). B) Adhesion stratified quartz arenite in thin section, showing lack of discernible fabric and abundant illuvial matrix (light brown). C) Bedding surface showing adhesion ripples, with steep side facing into the paleowind toward the lower left, Kanata, ON (locality 7) D) Bedding plane ornamented with adhesion warts, Keeseville, NY (locality 244).

pockmarked surfaces and (d) featureless surfaces. 2D features occur on approximately one-tenth of F2c surfaces and consist of regularly-spaced ridge and furrows spaced of 0.5 – 3.5 cm apart (ridge to ridge) with relief of 0.5 – 4 mm (Fig. 2.9c). The ridges are either symmetrical or asymmetrical. 3D features occur on about one in five F2c surfaces and include irregularly-spaced symmetrical bumps with diametres of 0.5 – 2 cm and heights of 1 – 6 mm (Fig. 2.9d), and asymmetric (streamlined) bumps with the same dimensions except elongated up to 3 cm. Pockmarked surfaces make up approximately 1/3 of the observed surfaces and comprise surfaces covered by many small (1 – 7 mm diameter), low relief (1 – 3

mm) irregularly-spaced symmetrical bumps and depressions. Featureless surfaces are the most common and make up ~40 – 50% of the surfaces observed in F1c strata.

2.2.6 F2c: Interpretation: Adhesion stratification and associated structures

The diffuse and generally massive nature of these strata suggests that selective variations in grain size transport and deposition did not occur, indicating minimal or no influence of boundary-layer fluid shear stress or grain interactions during deposition. However, the association with surface features indicates that raised bedforms did exist on the bed surface and that deposition was not the result of simple settling from suspension (e.g., Lowe 1982). Morphologically and texturally these features are consistent with those termed adhesion stratification, which are the result of generally non-selective adhesion of saltating windblown sand onto damp or wet subaerial surfaces (Hunter, 1980; Kocurek and Fielder, 1982). The interstitial matrix is interpreted to be illuviated clay and silt that initially adhered to damp surfaces and later infiltrated during rainstorms. Surface features associated with F2c strata record a spectrum of adhesion processes and reflect variations in water saturation and interactions with raindrops. 2D features are interpreted as adhesion ripples generated by the adhesion of windblown sand onto very saturated substrates (>80% saturation; Hunter, 1980; Kocurek and Fielder 1982). Symmetric adhesion ripples are interpreted as wrinkle marks, a nascent form caused by wind shear over a damp bed and minor grain adhesion (e.g., Kocurek and Fielder 1982). Asymmetric adhesion ripples, on the other hand, probably record relatively continuous adhesion over damp surfaces leading to the buildup of steep, upwind-facing and migrating stoss sides. 3D features including small symmetrical and streamlined bumps are interpreted to be adhesion warts that originated by sand blown onto damp

protuberances inherited from rain impact structures (e.g., Olsen et al., 1989). Pockmarked surfaces are interpreted to record rain impacts on sand, while common featureless surfaces represent the adhesion of windblown sand onto substrates with <80% water saturation (Hunter, 1980; Kocurek and Fielder 1982). The preservation of these delicate surface features may be attributed to their coexistence with microbial mats (e.g., Donaldson and Chiarenzelli, 2007; Hagadorn and Belt, 2008), but nonetheless their formation is attributed purely to adhesion processes.

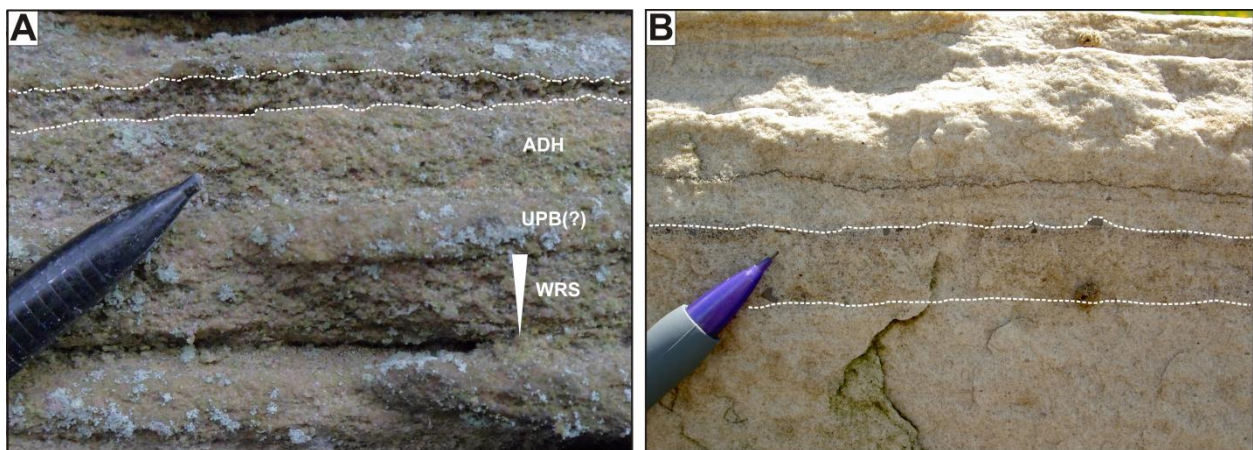


Figure 2.10 A) Bounded by white dotted lines, coarse-grained, structureless and slightly inversely-graded lamination (F2d) interpreted as a windblown deflation lag. Here it overlies common aeolian and shallow water stratification including wind ripple (WRS), upper plane bed (UPB) and adhesion (ADH) stratification. B) Poorly-sorted, structureless and inversely-graded deflation lag, Kanata, ON (locality 14).

2.2.7 F2d: Coarse-grained, massive and inversely-graded planar strata

Subfacies F2d is characterized by thick laminations to very thin beds (0.5 – 3 cm) of massive or inversely graded, well-sorted upper medium to lower very coarse sandstone (Fig. 2.10). Typically these layers are interstratified with F2b and F2c. F2d layers, commonly have diffuse bases but sharp tops, and extend laterally over at least ~55 m in some outcrops (which is the farthest an individual layer of F2d has been correlated). Coarse and very coarse grains

near the tops of the layers are well rounded with surface features including bulbous edges and concave pits that are visible under hand lens and thin section.

2.2.8 F2d: Interpretation: Deflation lags

F2d strata are interpreted as deflation lags formed by windblown erosion and bed surface armouring (e.g., Mountney, 2006b) on the basis of their association with wind ripple (F2b) and adhesion (F2c) strata and coarseness relative to these associated windblown laminae. Surface textures of grains, including bulbous edges and pits, were likely formed by abrasion due to high momentum subaerial grain impacts.

2.3 Facies 3: graded sandstone beds

2.3.1 F3a: Very thin to thinly bedded matrix-rich fine- to very fine-grained sandstone

F3a consists of very thin to thin (3 – 7 cm) beds of fine- to very fine-grained sandstone (Fig. 2.11; see also Fig. 4.4 e – f in chapter 4). Beds contain ~15 – 35% interstitial matrix, including iron-rich clays and fine to coarse silt. Where interbedded with arkose, and thus containing feldspars and other detrital minerals (besides quartz), micas are more abundant in F3a than in intercalated strata, and both detrital feldspars and micas exhibit degraded textures including skeletal remnants, embayed margins and kaolinite intergrowths in feldspar and swelling and clay intergrowths and replacement in micas. Moreover, the degree of feldspar and mica degradation is notably greater in F3a beds than in surrounding strata (see Chapters 3 and 4 for more details). Thin (1 – 3 mm) diffuse planar laminations are observed in some beds. Beds commonly grade upward from fine- to very fine-sand with an

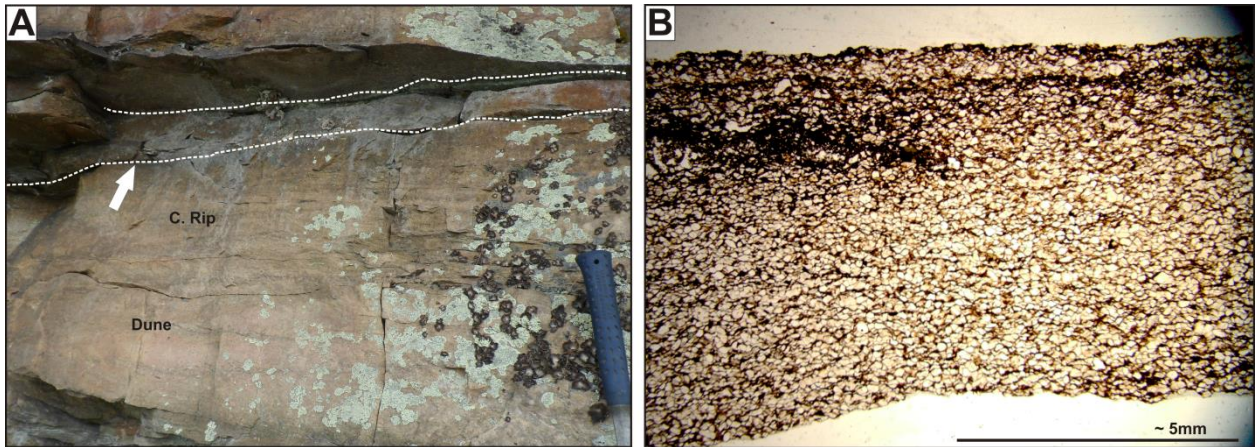


Figure 2.11 A) Bounded by white dotted lines, a thin bed of matrix-rich, fine to very fine-grained, normally-graded sandstone (F3a) interpreted as a direct-from-suspension deposit from a waning subaqueous current. Here it caps a succession of coarse-grained dune (F1c) and current ripple (C. rip, F1a) cross-stratified sandstone; Flat Rock State Forest, NY (locality 252) B) Thin section photomicrograph of a similar bed at the same location. Note the abundant matrix (dark brown), especially near top, and also normally-graded character. More details and examples are given in chapter 4 and figure 2.4 e-f.

overall increase in the proportion of silt and clay (commonly from ~15% to $\geq 35\%$) (Fig. 2.11b).

2.3.2 F3a: Interpretation: waning flow suspended-load deposits

The fine grain size, abundance of hydraulically-equivalent micas and upward-fining nature of F3a strata suggests deposition under low energy waning flow. Interstitial matrix is interpreted to be an infiltrated (eluviated) matrix, deposited by the gravity-driven transport (i.e. translocation) of fine-grained sediment by downward percolating meteoric fluids. In addition, the preferential in-situ breakdown of feldspars and micas in beds of F3a suggests that they were exposed to more extensive chemical weathering than associated facies, which in turn suggests longer periods of non-deposition and surficial exposure.

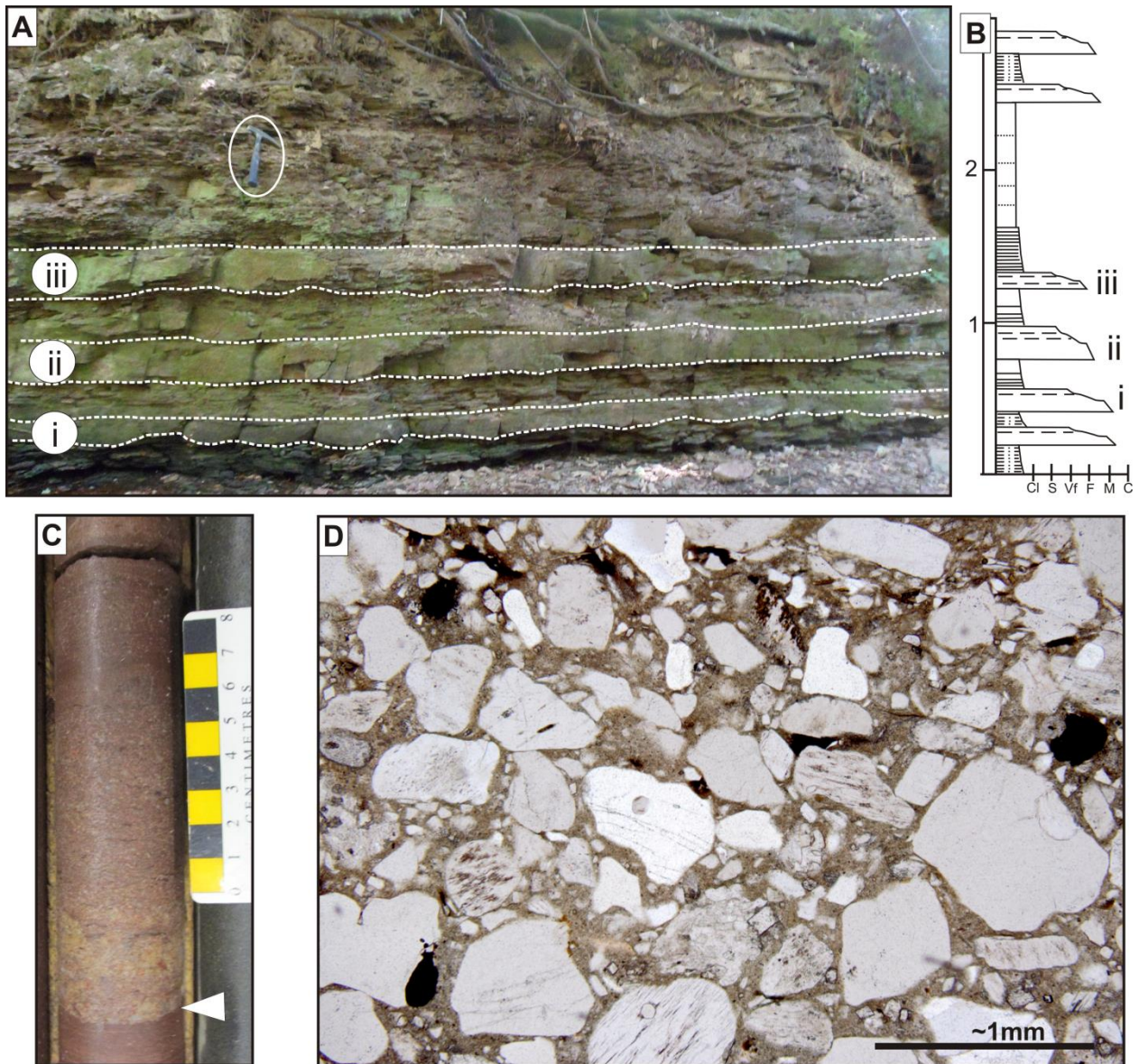


Figure 2.12 A) & B) Three structureless, erosively-based, poorly-sorted coarse- to very coarse-grained normally-graded sandstone (F3b) beds interpreted to have been deposited rapidly from highly-concentrated high-energy flows. The three beds (i – iii) correspond to those in the stratigraphic section, vertical scale in metres; Atwood Farm, near Chazy, NY (locality 233), hammer for scale (circled). B) Normally-graded concentrated flow deposit in core; Quonto St. Vincent de Paul No.1 near Montreal, QC. Note the diffuse planar laminae near the top of the bed. C) Thin section of the middle of bed ii in A). Note poorly-sorted character, very angular grain morphology and pervasive interstitial matrix (greenish brown).

2.3.3 F3b: Coarse-grained thin- to medium-bedded normally-graded sandstone

F3b is defined by 3 – 35 cm thick tabular, unlaminated, normally-graded and poorly-sorted medium- to very coarse-grained sandstone with rare floating granules and/or pebbles

(Fig. 2.12). These beds are sharp-based with local low-relief ~1 – 3 cm deep scours into underlying strata (Fig. 2.12a – b). The beds are typically coarse-tail graded, defined by the lack of granules and very coarse and coarse sand grains in the upper 1/3 – 1/6 of the bed. Diffuse planar laminae occur in the upper ~1 – 4 cm of some of the thickest F3b beds (Fig. 2.12c). Interstitial matrix, ~5 – 35% is common, particularly near the base to lower half of beds (Fig. 2.12d). In thin section, some of the matrix appears to consist of flattened and deformed sand-sized mudstone fragments, but most matrix consists of clay and minor silt that drapes and coats grain surfaces and occludes pore spaces. Also common are granule- to pebble-sized mud clasts near the base of these beds. F3b is rare, and is primarily intercalated with mudstone (see facies association 6 in next chapter).

2.3.4 F3b: Interpretation: Rapid deposition from high concentration, high-energy waning flows

The coarse grain size, locally erosive bases, poor sorting and general lack of stratification suggest rapid, non-selective sedimentation under high-energy flows. Absence of stratification indicates that bedform initiation was inhibited, most likely due to high sediment concentrations and high rates of sediment aggradation (Arnott and Hand, 1989; Leclair and Arnott, 2005; Sumner et al., 2008). Therefore, prior to deposition the flow was probably highly concentrated and thus grain transport was most probably driven by a combination of fluid turbulence, elevated pore pressure and dispersive pressure (Lowe, 1982, 1988; Smith, 1986; Mulder and Alexander, 2001). Deposition of all grain sizes likely occurred simultaneously and rapidly due to a decrease in flow velocity beyond a critical value resulting in near-complete loss of transport capacity (e.g., Lowe, 1982, 1988; Hiscott, 1994).

Diffuse coarse-tail grading present near the tops of these beds suggests that waning flow conditions prevailed for a time following rapid sedimentation and resulted in the deposition of excess finer grained sediment. Furthermore, the diffuse planar laminations at the tops of some F3b beds suggest that upper plane bed conditions occurred near the ends of some flows, probably resulting in the reworking of the tops of F3b deposits under reduced rates of bed aggradation (e.g., Sumner et al., 2008). The presence of sand to pebble sized mud fragments suggest that these flows eroded and incorporated underlying cohesive muds during sedimentation. However the matrix coating grains and occluding pore spaces in the lower parts of the beds are interpreted as illuvial matrix due to their textural relationship with coarse and very coarse sand grains and their occurrence in the lower parts of F3b beds. The occurrence of this matrix then suggests that these beds were situated generally above the groundwater table following deposition.

2.4 Facies 4: Conglomerate

2.4.1 F4a: Clast- and matrix-supported sheet-like conglomerate beds

Subfacies F4a consists of thin to thick planar beds (5 cm – 1.2 m) of clast-supported conglomerate with well-developed clast fabric (Fig 2.13). Many conglomerate beds are only 1 – 2 clasts high with a-axis perpendicular fabric (Fig. 2.13a), while others are > 2 clasts high with moderately well-developed a-axis imbricate fabric (Fig 2.13b). The dominant clast size is either pebbles or cobbles, and in individual beds commonly decreases upward. Bed



Figure 2.13 A) Photomosaic of a clast-supported cobble conglomerate beds (F4a), 1 – 2 clasts thick, showing a-axis alignment fabric, interpreted to have been deposited as tractional, low-relief bedload sheets. Hammer is circled for scale. Paleoflow is oriented away or toward the reader, Charleston Lake Provincial Park, ON (locality 57). B) Gravel bar constructed of stacked, moderately well-sorted, imbricated, clast-supported cobble conglomerate, Wellesley Island, NY (locality 117). Paleoflow toward the left. In both A) and B), white dashed lined show the boundaries of individual bedload sheets.

thickness correlates with the dominant clast size, with cobble conglomerate being 10 cm – 1.2 m thick and pebble conglomerate 5 – 20 cm thick. Clasts are moderately well sorted and subangular to subround. Matrix consists of moderately sorted medium to coarse sandstone. Beds can be traced laterally for at least ~50 m, but do pinch and swell along strike. The basal contacts are commonly planar, but with local scours ~3 – 15 cm deep.

2.4.2 F4a: Interpretation: Tractional conglomerate: bedload sheets

The well-developed fabric and moderate sorting suggests that clasts were transported as bedload. Also, the degree of clast rounding is suggestive of protracted abrasion due to bedload transport. Conglomerate beds that are 1 – 2 clasts high with a-axis perpendicular fabric like the one shown in figure 2.13a were likely deposited as low relief bedload sheets in sustained, quasi-steady subaqueous flow conditions (e.g., Whiting et al., 1988; Bridge and Lunt, 2006; Recking et al., 2009). On the other hand, conglomerate beds that are > 2 clasts high with a-axis imbricate fabric like the one shown in figure 2.13b most likely record the stacking of bedload sheets in high energy, quasi-steady subaqueous flow conditions, that ultimately built up low relief gravel bars (e.g., Hein and Walker, 1977; Bridge and Lunt, 2006).

2.4.3 F4b: Poorly-sorted, lenticular conglomerate

F4b comprises thick to very thick (1.1 – 4.5 m) beds of poorly-sorted conglomerate dominated by cobbles and boulders (~75 – 90% of clasts), but also containing granules and pebbles (Fig 2.14). Clasts are angular and show no preferred alignment or grading. Matrix makes up ~5 – 30% of these conglomerates and consists of a poorly-sorted mixture of fine- to very coarse-grained sandstone. Beds have a roughly lenticular geometry (Fig 2.14a) and are erosionally based. In addition, most directly overlie sloping ($\leq 40^\circ$) crystalline basement surfaces, or are immediately adjacent to basement highs. Strata show limited areal

distribution, extending ~25 – 40 m normal to and ~ 20 – 100 m parallel to the slope of the basement or to the basement highs.

2.4.4 F4b: Interpretation: Talus Deposits

The poor sorting and lack of grading or clast fabric indicates a non-selective style of deposition, most likely as coarse-grained sediment gravity flows. Due to the absence of clays they were unlikely to have been deposited by debris flows, but more likely were the deposits rock fall or rock avalanching in which the main mode of clast support during flow was dispersive pressure from grain-to-grain collisions. Alternatively, F4b strata may simply be accumulations of incremental rock fall talus along the margins of basement highs, which is in good accord with their lenticular geometry and proximity to basement highs.

2.5 Facies 5: Fine-grained siliciclastics (siltstone and mudstone)

2.5.1 F5a: silty mudstone, massive and rare laminated

F5a consists of structureless or rare diffusely-laminated muddy siltstone with 10 – 20% silt- and very fine sand-sized micas, 7 – 15% quartz $\pm$ feldspar silt with minor (>2%) fine grained sand and 65 – 78% clay minerals, mainly illite $\pm$ chlorite (deduced qualitatively using energy-dispersive x-ray spectra on the SEM) (Fig. 2.15). Accessory secondary hematite, pyrite and carbonate are present locally. Micas exhibit a moderately- to well-developed fabric defined by a-axis alignment of mica books. Diffuse laminae, where present, are ~0.3 – 8 mm thick and defined by variations in the abundance of silt vs. clay, or rarely the presence vs. absence of accessory hematite, pyrite or carbonate. Even rarer are thin



Figure 2.14 A) Poorly-sorted lenticular cobble and boulder conglomerate (F4b) overlying crystalline Grenville basement and interpreted as the deposit of cumulative rock fall or a rock avalanche, i.e. talus. Abbey Dawn Road, near Kingston, ON (locality 25). B) Boulder and cobble talus consisting mostly of quartzite clasts, north of Lyndhurst, ON (locality 71). C) Boulder talus along the Highway 401 west of Brockville, ON (locality 73), consisting mostly of quartzite clasts, but with a rare, exceptionally-large (> 1m diameter) granite clast (indicated by arrow). Dashed line is the contact with Grenville Province basement.

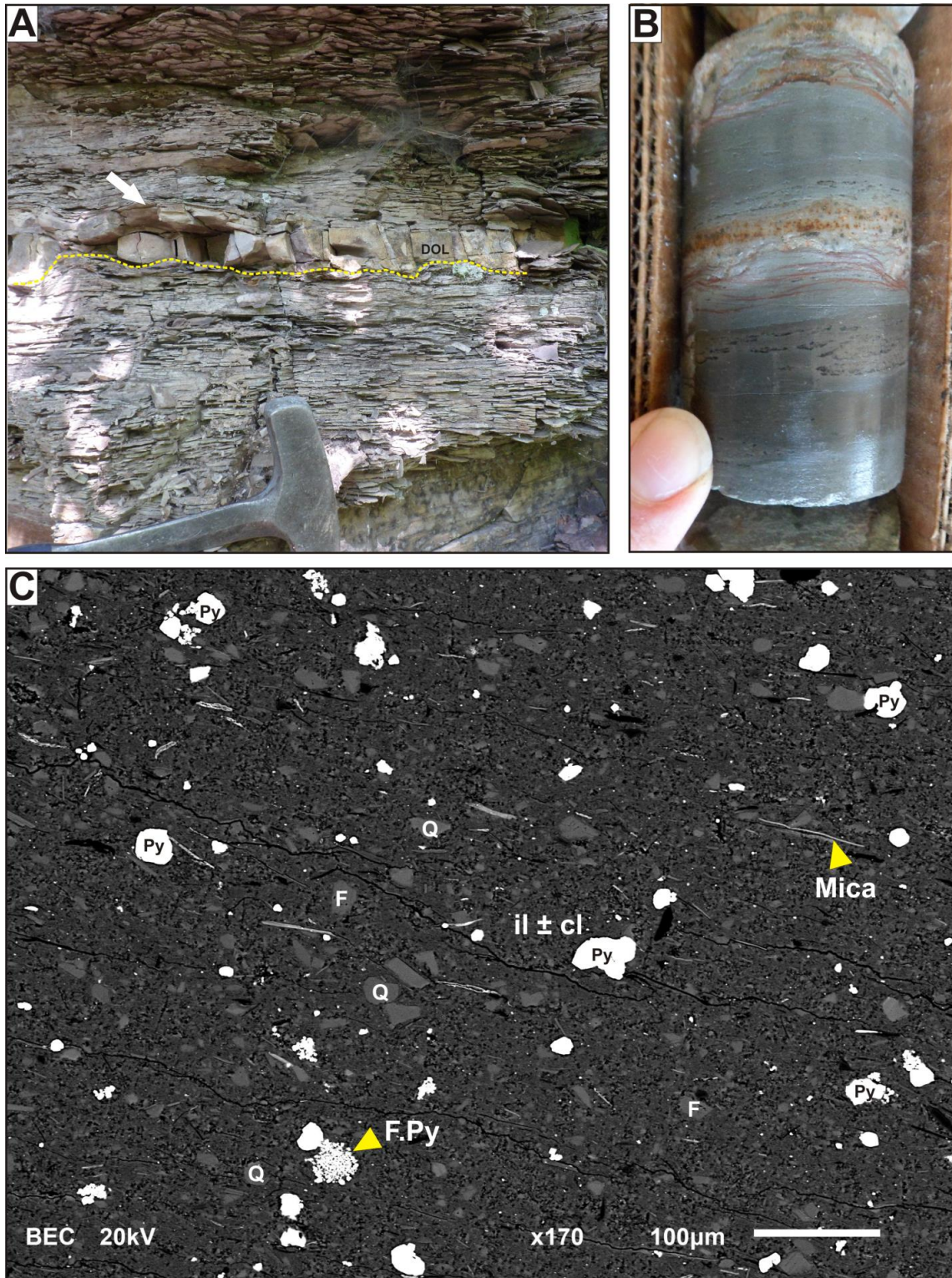


Figure 2.15 Examples of silty mudstone (F5a). A) Fissile silty mudstone with a thin dolostone interbed (facies 6), Atwood Farm, near Chazy, NY (locality 234). B) Diffusely laminated(?) and pyritic silty mudstone from GSC Dominion Observatory well in Ottawa, ON. The red streaks are secondary iron oxide. C) SEM micrograph of a thin section from a similar bed in GSC Lebreton in Ottawa, ON. Most of the finest material consists of illite $\pm$ chlorite (il $\pm$ cl), quartz silt grains are common (Q) as are aligned micas (mica) and diagenetic pyrite (Py) including uncommon framboidal pyrite (F.Py).

(~0.5 – 3.5 mm) sharply-bounded and erosionally based silt-rich laminae (~50 – 70% silt) with finer planar and/or low angle internal cross-laminae.

2.5.2 F5a: Interpretation: Hemipelagic and/or fluid mud deposition of suspended-load fines

On the basis of the fine grain size and massive or rare diffusely laminated internal structure, F5a is interpreted as suspended-load deposited in low-energy settings by slow hemipelagic sedimentation, flocculation and/or by “gelling” of high-concentration near-bed fluid sediment layers (e.g. McNally et al., 2007; Ichaso and Dalrymple, 2009). Diffuse laminae defined by variations in silt concentration are interpreted to record variations in coarse sediment availability possibly driven by seasonal sedimentation or by events such as storms, tides or floods. Rare sharp-based silt-rich laminae probably record infrequent high-energy events during which muds were resuspended and winnowed by near-bed fluid turbulence.

2.5.3 F5b and F5c: Current- and wave-rippled siltstone

F5b and F5c are the siltstone equivalent of the cross-stratified sandstone subfacies F1a (current rippled sandstone) and F1b (wave-rippled sandstone), respectively. Both F5b and F5c subfacies consist of fine to coarse siltstone (average: medium silt). Current ripple cross-stratified siltstone (F5b) differs from its sandstone equivalent (F1a) by having thinner sets (0.4 – 2 cm) and lower relief formsets that are ~0.8 – 2 cm high with ripple indexes (L/H) generally >10. Like current ripple stratification in sandstone, these are interpreted to

have formed under weak unirectional subaqueous currents (Allen, 1968; Southard and Boguchwal, 1990). Wave ripple strata in siltstone (F5c) also differs from wave ripple strata in sandstone in that its sets are thinner (0.4 – 1 cm) and formset height lower (< 1cm) resulting in higher ripple indexes (L/H) of ~10 – 20. Compared to their medium sandstone (F1b) counterparts, siltstone wave ripples formed under lower shear stresses and thus under near-bottom orbitals with longer (i.e. slower) periods, and thus may have formed in deeper water.

2.6 Facies 6: dolomicrite

2.6.1 F6a: Blocky, laminated dolomicrite beds

Strata of F6a consist of 3 – 75 cm thick well-indurated, laminated and/or color-mottled (red and grey) blocky beds of dolomicrite (Fig. 2.16). The dolomicrite has an equigranular intergranular fabric consisting of ~5 – 50 μm anhedral to subhedral ferroan dolomite rhombs (Fig 2.16d – e). Minor (<5%) floating angular to sub-angular siliciclastic silt grains are present. Accessory interstitial hematite, clays and/or organics are also present, and appear to be responsible for the red coloration present. Diffuse, mm-scale variegated laminae are common and are defined by variations in rhomb size and the occurrence of hematite and clay/organics(?). These laminations are planar or undulating, exhibiting both smooth, wavy undulations and bumpy or crinkly undulations (Fig. 2.16c). Some of these features are probably oscillation ripples due to their symmetrical form, like F1b and F5c (Fig. 2.16b). Numerous other features are present including rare possible sparse vertical burrows, fossil fragments (brachiopod and/or trilobite(?)) and possible recrystallized relics or “ghosts”

of gastropod fossils, physical shrinkage and injection structures (Fig 2.16b, c, e), bent and contorted laminae (Fig. 2.16c) and intraclasts of dolomicrite. Rare 0.5 – 1.5 mm thick sharp-based silt laminations also occur (Fig. 2.16e).

2.6.2 F6a: Interpretation: peritidal dolomite

The common laminae in F6a, with their smooth, bumpy or crinkly appearance, are interpreted as microbial laminites formed by the growth and death of microbial mats and bacterially-mediated precipitation of successive layers of dolomitic sediment (e.g., Chafetz and Buczynski, 1992; Vasconcelos et al., 1995; Pratt, 2010). The red and grey variegation of these microbial laminites, defined by alternating “clean” grey and hematite +clay/organic(?) –rich red laminae, are interpreted to have formed by successive redox fronts caused by the decay of accreted microbial mats. These microbial laminites and the dolomitic composition with no evidence of earlier calcite precipitation suggest that F6a originated as peritidal carbonates in an evaporitic shallow marine, probably intertidal environment (e.g., Purser et al., 1994; Pratt, 2010). Other features of F6a, including rare vertical burrows, shrinkage and injection structures (likely syneresis cracks due to non-polyginal distribution and both vertical and horizontal filling), bent and contorted laminae, intraclasts, wave ripples, silt grains and laminae are also consistent with intertidal peritidal carbonate sedimentation (Pratt, 2010). Floating silt grains may have been wind-transported, owing to their fine grain size and relative scarcity. Furthermore, rare bioclasts, including sparse gastropod(?), lingulid brachiopod and trilobite fragments, in addition to sparse bioturbation, suggests a stressed faunal association and thus likely restricted schizohaline conditions, consistent with intertidal and/or supratidal sedimentation.

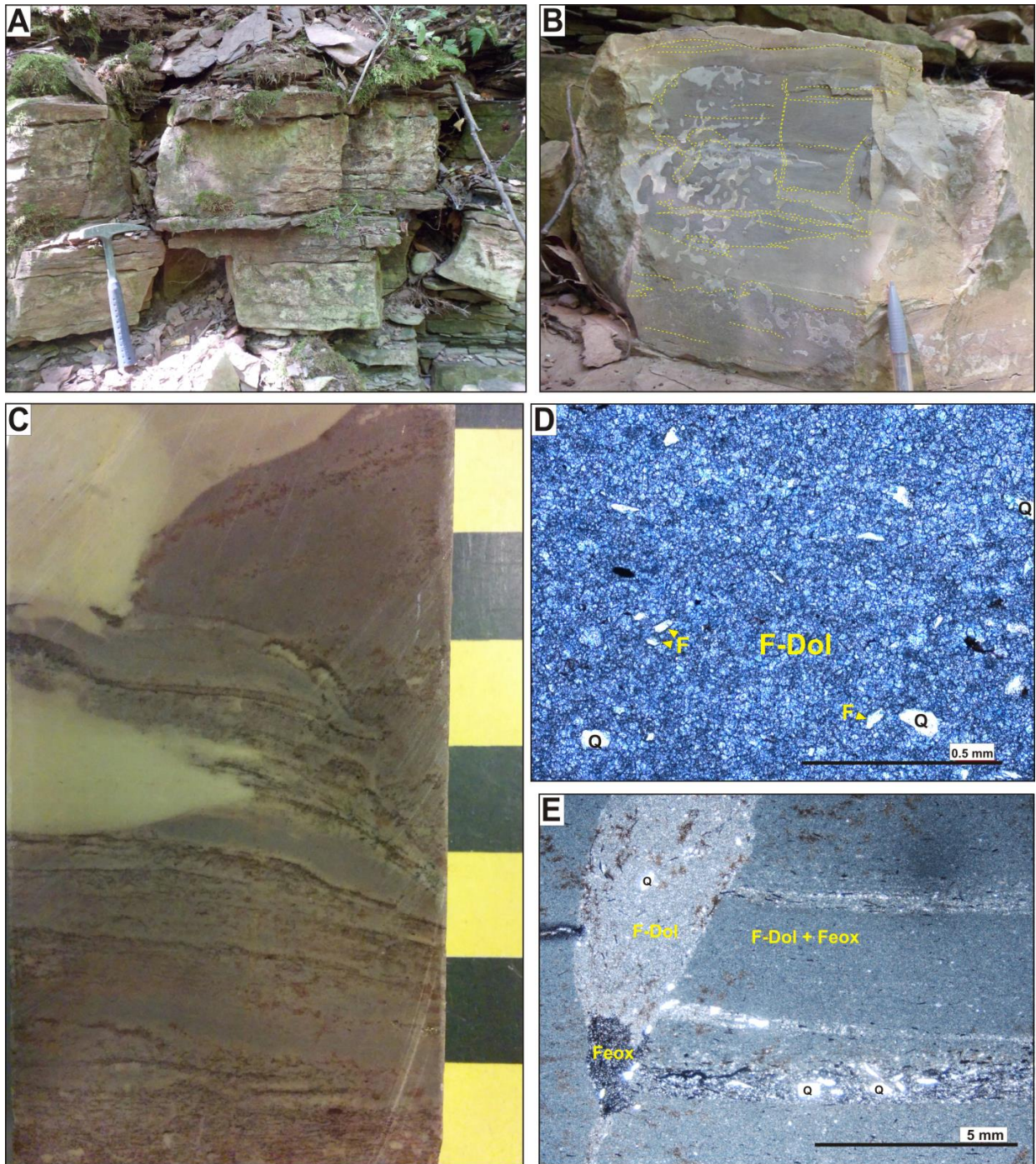


Figure 2.16 A) Blocky dolomicrite beds interpreted as peritidal dolostone, from Atwood Farm, near Chazy, NY (locality 185). B) Fresh surface of blocky dolomicrite showing possible early diagenetic shrinkage/injection fabric of lighter dolomicrite into darker (light maroon) diffusely-laminated dolomicrite. Possible wave ripple formsets cap this bed. C) Close-up of a slab cut from a similar dolomicrite bed, showing cryptically-laminated maroon dolomicrite disrupted by lighter and thicker layers of massive dolomicrite. The laminae are the result of variations in interstitial iron oxide. D) Stained thin section photomicrograph from the “light colored” material, which consists of homogeneous, fine-grained intergranular dolomicrite with rare quartz (Q) and feldspar (F) silt. E) Thin section of dolomicrite showing nature of shrinkage/injection features. Here, diffusely-laminated ferroan dolomicrite with interstitial iron oxide (F-Dol+Feox) is disrupted by injected “clean” ferroan dolomicrite (F-Dol), and iron oxide (Feox) is concentrated at the terminus of the injection feature. Q = detrital quartz.

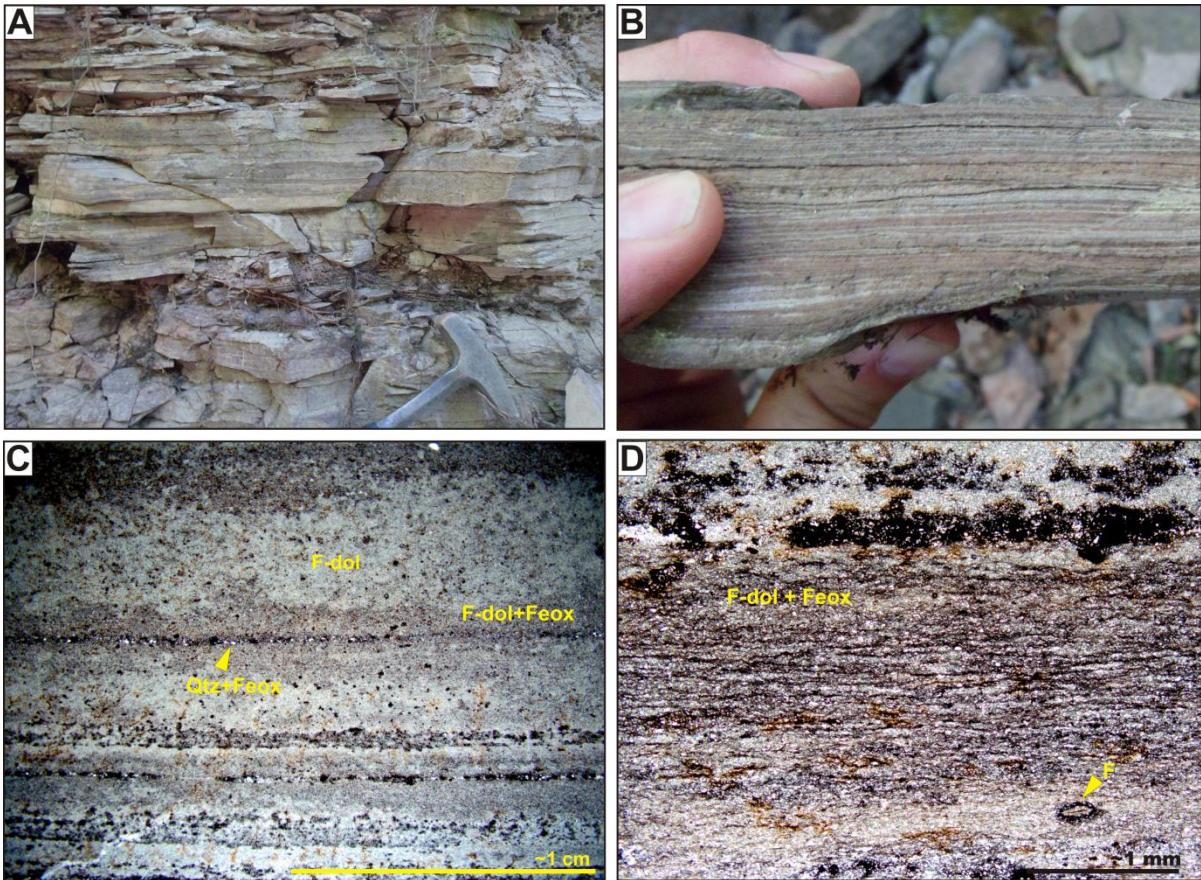


Figure 2.17 A) Fissile, planar-laminated dolomitic beds, from Atwood Farm, near Chazy, NY (locality 233). B) Close-up of laminated dolomitic showing alternating red and grey laminae. C) In thin section red laminae are shown to consist of dolomiticite with disseminated iron oxide and dispersed quartz silt (Qtz+Feox); grey laminae, on the other hand, consist of “clean” dolomiticite. D) Close-up of a red iron-oxide-rich lamina (center of photo) showing very fine (< 0.1 mm) partings of iron oxide-rich clay ± organics(?) and dolomiticite. This, then is succeeded upward by a massive discontinuous lens of opaque iron oxide, and massive dolomiticite with disseminated patches of interstitial iron oxide. F = cryptocrystalline phosphatic fossil fragment surrounded by redox front, possibly a trilobite or brachiopod fragment.

2.6.3 F6b: Fissile dolomitic beds

F6b is defined by planar-laminated, moderately well-indurated light grey to red fissile dolomite (Fig. 2.17). It consists mostly of a dolomitic microspar with ~5 – 40% angular silt grains and/or amorphous dark clay/organics(?), and minor interstitial hematite (Fig. 2.17c – d). The dolomiticite comprises an equigranular fabric of sutured ~5 – 35 μm anhedral to

subhedral ferroan dolomite rhombs. Clay/organics(?) usually occur as ~5 – 15 µm partings (Fig. 2.17d), but also as diffuse intergranular material, and silt grains commonly occur as laminae, 1 – 2 grains thick. Planar laminations in F6b are 0.1 – 1.4 mm thick and generally defined by variations in the proportions of interstitial iron oxide ± clay, and the presence or absence of silt interlaminae, which tend to coincide with higher concentrations of iron oxide (Figs. 2.17c – d). Contacts between laminations are typically diffuse, but rarely sharp, particularly at the base of silt laminae. Thin, dark brown to opaque, most likely phosphatic fossil fragments are observed in thin section (Fig. 2.17d), and lingulid brachiopod fragments have been observed in outcrop. F6b differs from F6a by (a) a greater proportion of silt, (b) fissile fabric, and (c) the presence of clearly-defined silt-rich laminae.

2.6.4 F6b: Interpretation: peritidal dolomite

Like F6a, F6b strata are also interpreted to have accumulated in a shallow- to marginal-marine peritidal setting, mainly by microbially-mediation. However, in this case the relative abundance of silt grains (~5 – 40%) and silt laminae suggest higher rates of siliciclastic input and generally higher energy conditions compared to blocky dolomicrite (F6a). Furthermore, the preferential concentration of hematite around silt laminae suggest that silt deposition was accompanied by an influx of oxygenated pore fluid, and thus these silt laminae were likely deposited by turbulent subaqueous tractional flows. Altogether, F6b is interpreted as peritidal carbonates formed in a higher energy intertidal setting than F6a.

Chapter 3: Lithofacies Associations and Depositional Environments

Previous works have recognized a wide variety of terrestrial to shallow marine depositional environments in strata of the Potsdam Group (Otvos, 1966; Clark, 1966; Fisher, 1968; Greggs and Bond, 1971; Kirchgasser and Theokritoff 1971; Lewis, 1971; Selleck, 1975; Bjerstedt and Erickson 1989; Salad-Hersi and Lavoie, 2000a and b; MacNaughton et al. 2002; Hagadorn and Belt 2008; Hagadorn et al. 2011). This section summarizes results of a systematic facies and architectural analysis of the Potsdam Group in the Ottawa Embayment and Quebec Basin based on detailed observations from 296 outcrop sections and 11 subsurface cores (see chapter 2 for details of lithofacies analysis and reference to facies codes used in this chapter). Based on this work, six facies associations representing six unique sedimentary environments are recognized.

3.1 Facies association 1 (FA1): Cross-stratified sandstone with local conglomerate

FA1 consists mostly of poorly- to moderately-sorted, coarse-grained, dune cross-stratified sandstone (F1c) with subordinate unit bar cross-stratified sandstone (F1d) and tractional conglomerate (F4a), and rare upper plane bed stratified sandstone (F2a), silty mudstone (F5a) and gravel-rich slope talus conglomerate (F4b). Grain size ranges from silt to boulders, but generally is coarse sand with scattered pebbles. Paleocurrents from cross-stratification or clast imbrication are typically tightly clustered at individual outcrops. Sets of dune and rare unit bar cross-stratified sandstone commonly form 0.5 – 5 m thick cosets that

Table 3.1 Lithofacies associations summary table, see text of chapters 2 and 3 for more details.

Facies Association	Lithofacies and subfacies present and their proportions*	Grain size (a) average, (b) total range	Other features	Architectural elements	Deposition macroform interpretation	Environment Interpretation
Facies association 1 (FA1): cross-stratified-dominated sandstone with local conglomerates	Cross-stratified sandstone (F1; 86%) Dune (F1c; 74%) Unit bar (F1d; 11.5%) Current ripple (F1a; 0.5%) Conglomerate (F3; 11%) Tractional conglomerate (F4a; 9%). Debris flow (F4b; 2%) Graded sandstone (F2; 1.5%) Suspended load sandstone, Subaerially-weathered (F3a; 1.5%) Planar-stratified sandstone (F2; 1%) Upper plane bed (F2a; 1%) Fine-grained siliciclastics (F5; 0.5%) Suspended load fallout deposits (F5c; 0.5%)	(a) coarse sand (b) mud to boulders	N/A	Compound dune/unit bar cross-stratification (84%)	Compound braid bars	Braided fluvial: migration of low relief compound braid bars in wide braided channels with quasi-steady discharge. Channels are locally abandoned and filled. Wet conditions but with little deposition prevails on floodplains. Humid climate setting.
				Channel features filled with dune sets (13%)	Abandoned and filled braided channels	
				Tabular fine-grained sandstone beds (2%)	Floodplain /overbank deposits	
				Isolated scours (1%)	Confluence scours	
Facies association 2 (FA2): Planar sandstone-dominated with	Planar-stratified sandstone (F2; 72%) Wind ripple laminations (F2b; 35%) Deflation lags (F2d; 15%) Adhesion stratification (F2c; 18%) Upper plane bed (F2a; 4%) Cross-stratified sandstone (F1;	(a) Upper medium sand (b) very fine sand to	- Illuviated matrix. - Rare isolated <i>Protichnites</i> and <i>Diplichnites</i>	Tabular sandstone beds, with wind ripple, deflation lags, ripples, upper plane bed and adhesion (80%)	Terminal Splay/ playa environment, mainly aeolian-reworked sandy splays, thin	Ephemeral fluvial: deposition of splays fed by tributary fluvial networks with episodic discharge, and near-complete reworking of

supercritical bedform strata	28%) Cyclic step (F1g; 9%) Antidune (F1e; 7%) Dune (F1c; 6%) Depth-limited wave ripple (F1b; 3%) Chute-and-pool (F1f; 2%) Current ripple (F1a; 1%)	granules (very rare pebbles and cobbles)	trackways.		aeolian sand sheets	splays by aeolian processes. Large floods are very infrequent and floodplains are generally dry. Arid or semi-arid climate setting.
				Scour-filling supercritical bedform strata (9%)	High energy sheet floods deposits	
				Channel features (9%)	Abandoned and filled distributary channels	
Facies association 3 (FA3): Large-scale cross-stratified sandstone dominated with aeolian facies	Cross-stratified sandstone (F1; 62%) Aeolian grain flow cross-strata (F1i; 60%) Depth-limited wave ripple (F1b; 2%) Planar-stratified sandstone (F2; 38%) Wind ripple lamination (F2b; 36%) Adhesion stratification (F2c; 2%)	(a) lower medium sand (b) upper fine to lower coarse sand	- Minor brittle-style Soft sediment deformation - Very rare isolated <i>Protichnites</i> trackways	Large-scale trough cross-stratified sets, with grain flow and inclined wind ripple lamina (88%)	Aeolian dunes	Aeolian dune field: Migration and deposition of sandy aeolian dunes and interdune deposits under quasi-steady regional winds in an inland arid climate setting.
				Planar stratified sandstone beds with wind ripple, adhesion, wave ripples (12%)	Dry and damp Interdune deposits	
Facies association 4 (FA4): Planar-stratified sandstone with early cements and	Planar-stratified sandstone (F2; 65%) Adhesion stratification (F2c; 35%) Wind ripple laminations (F2b; 23%) Upper plane bed (F2a; 7%) Cross-stratified sandstone (F1; 35%) Dune (F1c; 19%) Depth-limited wave ripple (F1b; 13%)	(a) Lower medium sand (b) Upper fine to upper coarse sand	- Illuviated matrix. - Early Gypsum and carbonate (weathered in outcrop)	Tabular sandstone beds with wind ripple, deflation lags, adhesion, w. and c. ripples, upper plane bed; evaporites and/or microbial mat features (12%)	Evaporitic coastal plain, sand accumulation mostly by adhesion, minor low-energy flooding from water table	Coastal Sabkha: Accumulation of windblown sand, mainly by adhesion, due to fluctuating but ultimately rising shallow water table. Evaporitic conditions and the formation of surface

binding features	Current ripple (F1a; 3.5%) Aeolian grain flow cross-strata (F1i; 0.5%)		- sandstone desiccation and intraclasts from early salt or microbial mat binding - Local sparse epifaunal trace fossil assemblage.		fluctuations	efflorescent salts and microbial mats. Common braided channels recording periods of higher discharge. Rare aeolian dunes. Arid to semi-arid inland or coastal setting.
				Channel features (18%)	Channels	
				Isolated scour elements (1.5%)	Confluence scours	
				Large-scale trough cross-stratified elements with grain flow strata (0.5%)	Aeolian dunes	
Facies association 5 (FA5): Bioturbated cross-stratified sandstone	Cross-stratified sandstone (F1; 99%) Dune (F1c; 80%) Wave ripple (F1b; 10%) Current ripple (F1a; 9%) Planar-stratified sandstone (F2; 1%) Upper plane bed (F2a; 1%) Dolomicrite (F6; <0.5%)	(a) Upper medium sand	- Abundant vertical trace fossils (mainly <i>Diplocraterion</i> , <i>Arenicolites</i> , <i>Skolithos</i>) - Inarticulate brachiopod fossils - Early carbonate cements	Medium-scale accretional elements (74%)	Intertidal to subtidal compound dunes	Tide-dominated marine: Migration and deposition of sandy tidal compound dunes in intertidal, probably estuarine environments. Larger and coarser-grained Compound dunes form sand sheets on high energy subtidal shelf.
		(b) very fine sand to granules (very rare pebbles and cobbles)		Tabular beds – ripples and plane bed, bioturbated (17%)	Troughs of compound dunes and/or low-energy intertidal sand flat	
				Large-scale accretional elements (9%)	Subtidal compound dunes	

Facies association 6 (FA6): Sparsely bioturbated mixed clastic-carbonate	Fine-grained siliciclastics (F5; 77%) WESGF deposits (F5a; 57%) Combined flow ripples (F5b; 12%) Wave ripples (F5c; 8%) Graded sandstone (F3; 16%) Concentrated flow deposits (F3b; 16%) Cross-stratified sandstone (F1; 5%) HCS/SCS (F1h; 5%) Dolomicrite (F6; 2%)	(a) medium silt (b) mud to very coarse sand	- Sparse, mainly horizontal trace fossil assemblage. -Synaeresis cracks	Fine-grained clastic successions with fine-grained w. and c. ripples (77%)	Fine-grained tidal mudflat sediments	Open-coast tidal flat: Ambient fine-grained tidal flat sedimentation driven by input of suspended load by nearby rivers. Storms and fluvial sheetfloods significantly affect tidal flat environment. Rare peritidal dolomite sedimentation away from river mouths and storm-driven currents (probably lagoonal).
				Thin (<5 cm) m.-c. grained concentrated flow strata, erosively-based (11%)	Storm-driven reworking and sedimentation	
				Thick (5-35 cm) c.-vc. grained concentrated flow strata, erosively-based (5%)	Fluvial outwash/sheetfloods (river mouth splays)	
				HCS/SCS (5%)	Coastal storm-driven sedimentation	
				Peritidal dolomicrite beds (2%)	Quiescent, lagoonal sub-environment	

exhibit low angle ($\sim 5 - 15^\circ$) downcurrent-dipping compound cross-stratification (Fig. 3.1). Also present, but rare, are compound cosets with set boundaries dipping in the up-current direction or at a high angle ($\sim 60 - 90^\circ$) to the local paleoflow direction. Locally these are incised by rare steep-sided ($15 - 25^\circ$) isolated scours (60 cm – 2 m deep, 4 – 20 m wide) filled with simple boundary-conforming cross-stratified sandstone (Fig. 3.1), or by wide ($\sim 8 - 120$ m) erosionally-based 20 cm – 2.5 m deep channel features with low relief margins (typically $< 20^\circ$) and filled with dune cosets (Fig 3.2). Thin (≥ 7 cm) laterally-continuous interbeds or laminae of normally-graded, fine-grained sandstone with illuvial clay and silt, degraded detrital feldspar and expanded (hydrated) detrital biotite (F3a) are common (Fig. 3.2 stratigraphic log; see also Figs. 2.11 and also Fig. 4.4 e – f in chapters 2 and 4). Silty mudstone is generally rare, but where present occurs as 0.5 – 4 cm thick layers; however, some cored intervals it occurs as ~ 10 cm – 1.1 m thick beds that locally are pyritic (e.g., Fig. 2.15). Bioturbation is absent. For an expanded description of FA1 and further examples, the reader is referred to chapter 4.

3.1.1 FA1: Interpretation: Braided fluvial

The dominance of unbioturbated, coarse-grained dune and lesser unit bar cross-stratified sandstone and conglomerate with unimodal local paleoflow directions suggests deposition by energetic, steady unidirectional subaqueous currents in a terrestrial, braided fluvial environment with perennial discharge in a humid climatic setting. Abundant low-angle, downcurrent-dipping compound cosets (Figs 3.1, 3.2) are interpreted as channel-filling compound braid bars formed by the mainly downstream accretion of unit bars and compound dunes (e.g., Lunt and Bridge, 2004; Bridge and Lunt, 2006). Rare upstream and lateral

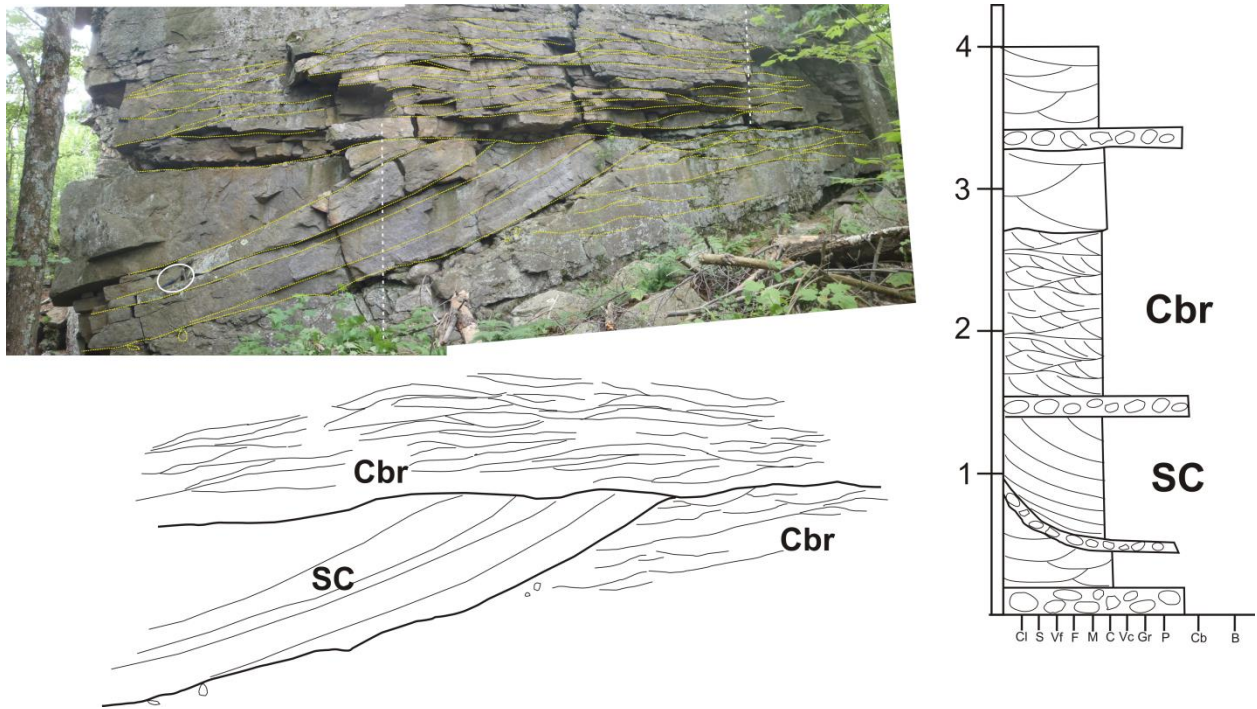


Figure 3.1 Braided fluvial (FA1) lithofacies and architecture from Charleston Lake Provincial Park, ON (locality 58). Here strata consist mostly of coarse-grained dune cross-stratified sandstone forming cosets with a downstream-accreting architecture interpreted as the deposits of compound braid bars (Cbr). Also exposed is an isolated, high-relief ~1m deep scour (SC) filled with coarse-grained boundary-conformable cross-strata interpreted to be a confluence scour and its fill. Hammer for scale (circled), measured stratigraphic section is in metres. Paleoflow from dune cross-strata is generally to the left. White dashed lines show the location of the measured section (measured in 2 parts).

accretion of compound braid bars is also evident from rare compound cosets with upcurrent and laterally accreted sets. Channelized features (Fig. 3.2) are interpreted to record the erosion, abandonment and backfilling of braided channels, whereas isolated scours (Fig. 3.1) are interpreted to have formed at the downstream end of high-angle confluences (Best, 1987; Bridge, 1993; Best and Ashworth, 1997). Thin interbeds or laminae of fine-grained sandstone with illuviated silt and hydrated biotite textures are interpreted as floodplain (overbank) deposits. Thin mudstone layers probably accumulated locally in intra-bar pools or in inactive bar-tail regions (e.g., Best et al., 2003), whereas the thicker, locally pyritic mudstone layers probably accumulated in abandoned channels or overbank ponds (e.g., S nderholm and Tirsgaard, 1998).

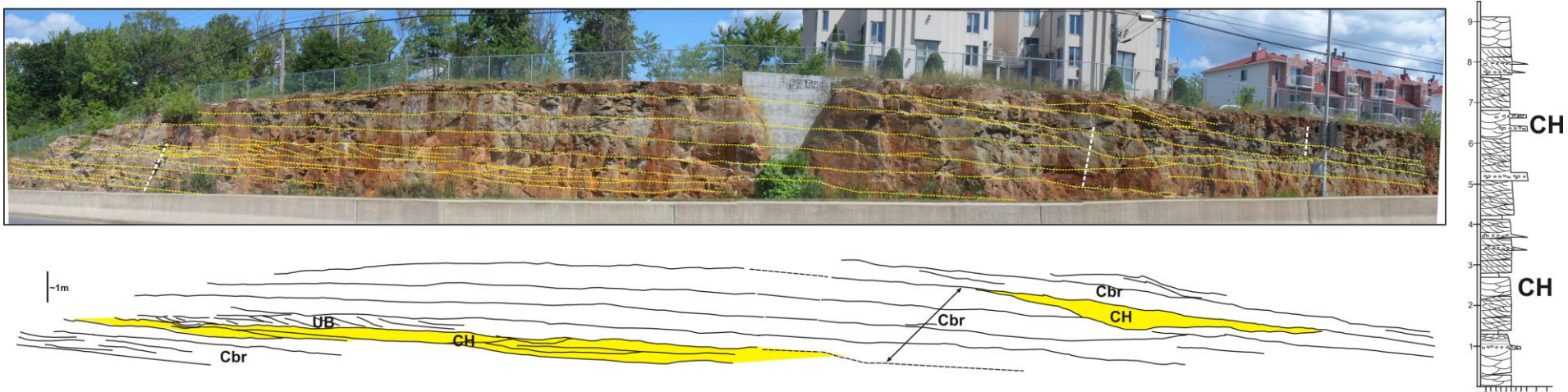


Figure 3.2 Braided fluvial (FA1) lithofacies and architecture from Ile Perrot, QC (locality 194). Paleoflow from dune cross-strata is into the page. This section exposes a stack of compound braid bars (Cbr) composed mainly of coarse-grained, downstream-accreted dune sets, and a rare, laterally-accreting unit bar (UB). Low-relief channels (CH, highlighted in yellow) filled with coarse-grained dune cross-strata locally incise compound bar deposits. White dashed lines in photo show the location of the measured section (measured in 3 parts).

3.2 Facies association 2 (FA2): Planar stratified sandstone with intercalated supercritical-flow stratification

FA2 consists mainly of moderately- to well-sorted, upper medium-grained, 10 – 95 cm thick, planar-stratified beds interbedded with lesser coarse-grained, 0.2 – 1.9 m deep, scour- and channel-filling cross-stratified sandstone (Fig. 3.3; see also Figs. 4.9 – 4.13 in the next chapter). The planar-stratified beds consist of common wind ripple (F2b) and adhesion (F2c) laminations, abundant coarse- to very coarse-grained windblown deflation lags (F2d), depth-limited wave ripple (F1b) laminations and formsets, rare polygonal desiccation cracks and uncommon upper plane bed (F2a) lamination and current ripple (F1a) strata and formsets. Illuvial matrix is ubiquitous and grains exhibit rounded and bulbous surface textures. Scour-filling cross-stratified sandstone consist of upcurrent-dipping coarse-grained antidune (F2e), chutes-and-pool (F2f) and cyclic step (F2g) deposits, collectively indicating high energy (supercritical) sheet flood conditions. In addition, rare 20 – 90 cm deep channel features filled with coarse-grained, dune cross-stratified sandstone (F1c) are present locally. Rare epifaunal traces, mostly *Protichnites* and *Diplichnites*, are observed locally on bedding surfaces of planar-stratified sandstone, mainly in association with adhesion stratification.

3.2.1 FA2: Interpretation: Semi-arid sheetflood-dominated ephemeral fluvial

The presence of supercritical bedform deposits, dunes and ripples suggest that episodic high energy sheetfloods (recurring over 100s -1000s of years; e.g., Stear, 1985; Knighton and Nanson, 1997) most likely played an important role in sedimentation, whereas

the dominant planar aeolian strata with common deflation lags record aeolian deflation and reworking of sheetflood deposits into local windblown sheets under ambient semi-arid conditions (see Chapter 4 for more details; and also Stear, 1985; Abdullatif 1989; Clemmensen and Dam; 1993; McCarthy, 1993; Knighton and Nanson, 1997; Tooth 2000a, b). Strata of FA2, therefore, are interpreted to be the deposits of ephemeral fluvial systems in which aeolian processes remolded most of the deposits of sheetfloods, save for the scour-filling supercritical bedform strata which record relatively high energy sheetflood conditions. Based on comparison with other ancient and modern analogues (Tunbridge, 1984; Abdullatif, 1989; McCarthy, 1993; Tooth, 1999; Hampton and Horton, 2007; Nichols and Fisher, 2007; Guilliford et al., 2014), these ephemeral fluvial systems likely formed distributary networks (i.e., fans) in which relatively stable but generally erosional trunk channels fed a downflow distributive network of channels and terminal splays. Abundant planar stratified beds are interpreted as terminal sheet flood splays (e.g., Tunbridge, 1984; Abdullatif, 1989; Tooth, 1999; Hampton and Horton, 2007) that were mostly reworked by the wind. The presence of illuviated matrix and common deflation lags in splay deposits suggest that surface armouring and vadose silt and clay accumulation coincided with the long recurrence intervals (10s - 1000s of years) between high energy floods (e.g. Stear, 1985; Abdullatif; 1989; McCarthy, 1993; Knighton and Nanson, 1997; Tooth 2000a). Scours filled with supercritical bedform strata record more sustained high energy sheet flood conditions, probably upstream of the terminal splays, whereas channel features filled with dune cross-stratified sandstone are interpreted to be up flow feeder channels (e.g., Abdullatif, 1989; Hampton and Horton, 2007). The occurrence of epifaunal traces is noteworthy, but currently poorly understood.



Figure 3.3 Ephemeral fluvial (FA2) lithofacies and architecture from Chateauguay High Falls, NY (locality 168). This section consists of planar-stratified aeolian sandstone lithofacies (mainly wind ripple and adhesion strata, and deflation lags) incised locally by scour-filling antidune and cyclic step cross-strata. For more details and examples of FA2 strata and its component lithofacies see chapters 2 and 4.

Nevertheless, their higher abundance and diversity locally might indicate that some ephemeral fluvial strata formed in more coastal and/or marginal marine settings.

3.3 Facies association 3 (FA3): Large-scale cross-stratified sandstone

FA3 consists of well-sorted, upper fine- to medium-grained sandstone dominated by thick to very thick (~50cm – 20m), large-scale trough cross-stratified sets interstratified with lesser thin (~5 – 40 cm), tabular planar-stratified sandstone (Fig. 3.4). Paleoflow direction measured mostly from the axes of trough cross-stratified sets is regionally variable but tightly clustered at individual outcrops. Detrital sand grains in FA3 are rounded to well-rounded with moderate sphericity. Cross-stratified sets consist of steeply-dipping ($\geq 20^\circ$) foresets of grain flow cross-strata (F1i) and shallowly-dipping ($\leq 20^\circ$) translaminar wind ripple laminated (F2b) toesets. Planar-stratified interbeds consist of horizontal to low angle ($\leq 10^\circ$) wind ripple stratification (F2b) in places interlaminated with adhesion stratification (F2c; Fig. 3.5b) and/or depth-limited wave ripple stratification (F1b). Rare soft-sediment deformation structures occur at the base of some thick cross-stratified sets and consist mostly of localized brittle structures (i.e., in-situ breccia and fractures that predate lithification, Fig. 3.5a). *Protichnites* trackways are present locally in this facies association, typically on bedding planes of planar-stratified sandstone or rarely on erosionally-exposed high angle foreset surfaces, and are described in more detail by MacNaughton et al. (2002) and Hagadorn et al. (2011).

3.3.1 FA3: Interpretation: Aeolian dune field

The dominance of thick, large-scale, step-sided trough cross-stratified sets with grain flow and wind ripple strata is interpreted to record the migration of large sinuous-crested and transverse aeolian dunes under strong unidirectional winds (McKee, 1966; Hunter, 1977; Brookfield, 1977; Kocurek and Dott, 1981; Rubin, 1987; Mountney, 2006b). Planar-stratified interbeds are interpreted as interdune sand flat deposits (e.g., Lancaster and Teller, 1988). Those dominated by wind ripple laminations record dry interdune deposition, whereas those dominated by adhesion and/or wave ripple laminations record damp to wet interdune conditions (e.g., Kocurek, 1981). Grain surface textures, including bulbous edges and concave pits, are features commonly attributed to sedimentation in subaerial windblown environments (Werner and Merino, 1997; Mahaney, 2002). Strata of FA3 were most likely deposited in arid to semi-arid inland dune fields based on the limited occurrence of interdune deposits (< 20%) and the rarity of waterlain facies, scours, or liquefaction features (Kocurek, 1981; Hummel and Kocurek, 1984; Pulvertaft, 1985; Fryberger et al., 1990). However, minor adhesion and wave ripple stratification and rare brittle-style soft sediment deformation suggest the occasional occurrence of surface water, probably due to infrequent rain storms and ephemeral interdune flooding. The rare presence of isolated *Protichnites* trackways is an interesting observation, but in light of the poor understanding of the paleoecology of the tracemakers, their rare occurrence in these strata is not considered diagnostic of any particular paleoenvironment.

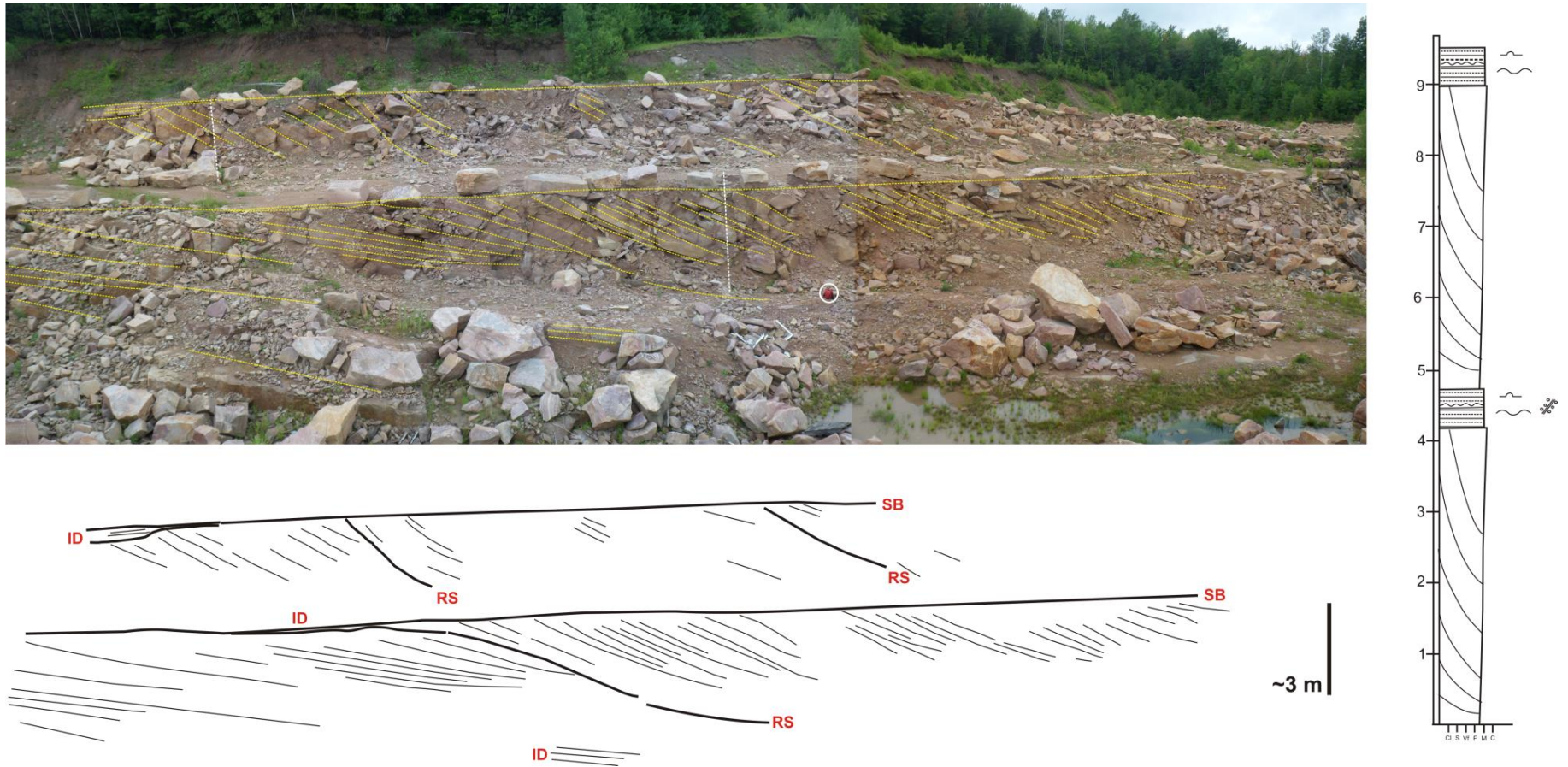


Figure 3.4 Architecture and lithofacies of aeolian erg (FA3) strata from the Rainbow Quarry, near Malone, NY (locality 188). Here, two ~4 – 4.5 m thick sets of aeolian dune cross-strata, composed of grain flow and wind ripple strata are separated by a flat, areally-extensive set boundary (SB) and a ~0.4 m thick, planar-stratified interdune (ID) deposit. Aeolian dune sets bound along strike by high- to low- angle erosional internal reactivation surfaces (RS). Red knapsack for scale (circled). White dashed lines show the location of the measured section (measured in 2 parts).

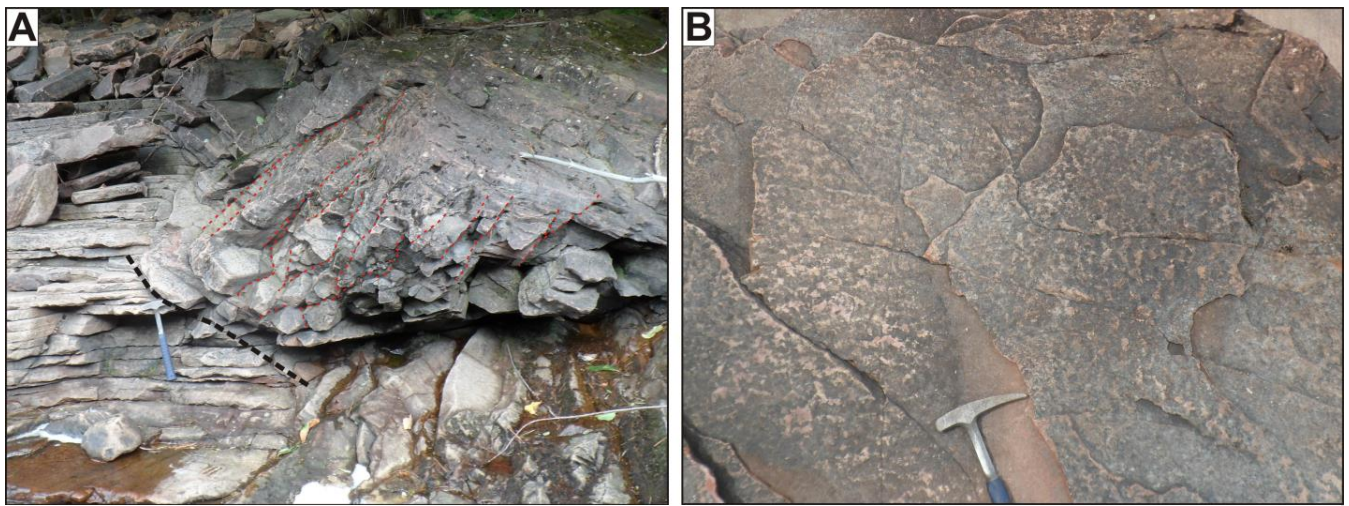


Figure 3.5 A) Localized brittle fracturing possibly induced by loading (outlined by red dashed lines) at the base of a set of high-angle aeolian dune cross-strata where it erosively truncates near-horizontal strata of the underlying set of obliquely-oriented aeolian dune bottomset (black dashed line). B) Adhesion ripples on a bedding surface of interdune strata. Both A) and B) from Hannawa Falls, NY (locality 220).

3.4 Facies association 4 (FA4): Planar-stratified sandstone with early cements and binding features

Strata of FA4 consist mainly of moderately- to well-sorted, medium-grained, planar-stratified sandstone beds with features suggestive of early cementation and/or binding.

Sandstone beds are 15 – 75 cm thick and consist of recurring 1 – 15 cm thick couplets of aeolian stratification (mainly adhesion (F2c) and/or wind ripple (F2b) laminations)

alternating with shallow subaqueous stratification (depth-limited wave ripple (F1b), current ripple (F1a) and/or upper plane bed (F2a)) (Fig. 3.6). Thin (1 – 2 mm), coarse-grained

deflation lags (F2c) are common at the tops of waterlain deposits (Fig. 3.6b), and illuvial

matrix is common in wind ripple and adhesion strata. Rare ~20 – 45 cm thick sets of cross-

strata composed mostly of aeolian grain flow strata (Fig. 3.7a) and recording the migration of

aeolian dunes (see FA3 above) occur locally. Additionally, common erosionally-based, 20

cm – 2.5 m deep channel features locally incise the planar-stratified beds of FA4 and are

filled with upper medium- to coarse-grained, dune cross-stratified sandstone (F1c) with locally tightly clustered paleoflow orientations. Rare isolated scours, similar to those described in FA2, occur at the base of some channels and scour deeply (~1.2 – 1.6 m) into underlying tabular beds (Fig. 3.7b).

Strata of FA4 also contain rare evaporite minerals, common pseudomorphs and impressions of evaporite minerals, and contorted sandstone intraclasts and polygonal desiccation cracks suggestive of early cementation and/or binding and sand layers. Weathered nodules are common in outcrop, and have left casts with unique crystalline form filled with un-lithified or poorly lithified sand preserving higher than average intergranular volumes. These include small (~4 – 9 mm) weathered nodules, leaving casts with bladed form in planar-stratified sandstone, and larger (0.7 – 2.2 cm) oblate nodules leaving casts of radial aggregates of sparry crystals (Fig. 3.8a) in coarser-grained and channelized dune cross-stratified sandstone. Although the original mineralogy is unknown, morphological comparison to “desert rose” crystal aggregates and the recognition of swallowtail twinning impressions (Fig. 3.8a) suggest that the weathered nodules were originally composed of gypsum. Rare cubic casts (Fig. 3.8b) have also been identified and may record the formation of halite based on their cubic form. In addition, very thin (~0.5 – 4 mm) sparry laminae of gypsum (Fig. 3.8c – d) and possible dolomitic pseudomorphs of earlier sulfate (Fig. 3.8 e – f) are common in cored intervals. Also present locally are rare 1 – 4 cm thick horizons of 8 – 45 cm wide of dolomite nodules, elongate parallel to bedding (Fig. 3.8 g). Both the weathered gypsum and dolomite nodules cement detrital sand grains and preserve higher than average intergranular volume, which is suggestive of shallow-burial diagenesis. Additionally, kinked and/or tightly folded, 1 – 30 mm thick and 0.5 – 7 cm long planar-laminated sandstone

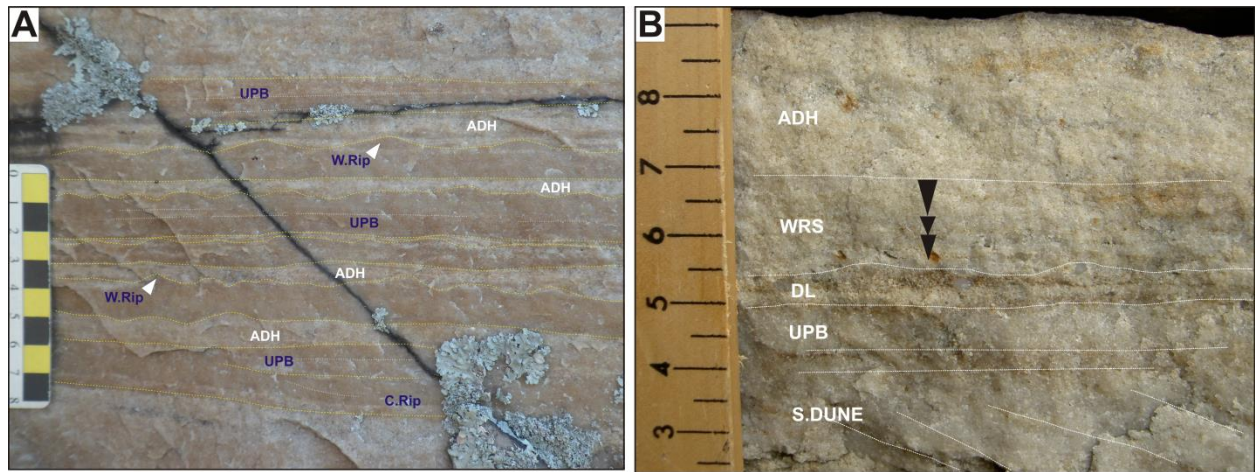


Figure 3.6 A) Alternating shallow subaqueous and adhesion stratification (ADH) in coastal sabkha (FA4) strata, Ste. Hermas, QC (locality 295). Waterlain lithofacies include current ripple (C.Rip), upper plane bed (UPB) and depth-limited wave ripple (W.Rip) stratification. The lighter hue and rougher appearance of adhesion strata is the result of a greater proportion of interstitial illuvial matrix that inhibited later quartz overgrowths. B) A ~6.5 cm succession of waterlain and aeolian lithofacies from Kanata, ON (locality 1). Here subaqueous dune cross-strata (S.DUNE) is succeeded by upper plane bed (UPB), deflation lag (DL), wind ripple (WRS) and adhesion (ADH) strata.

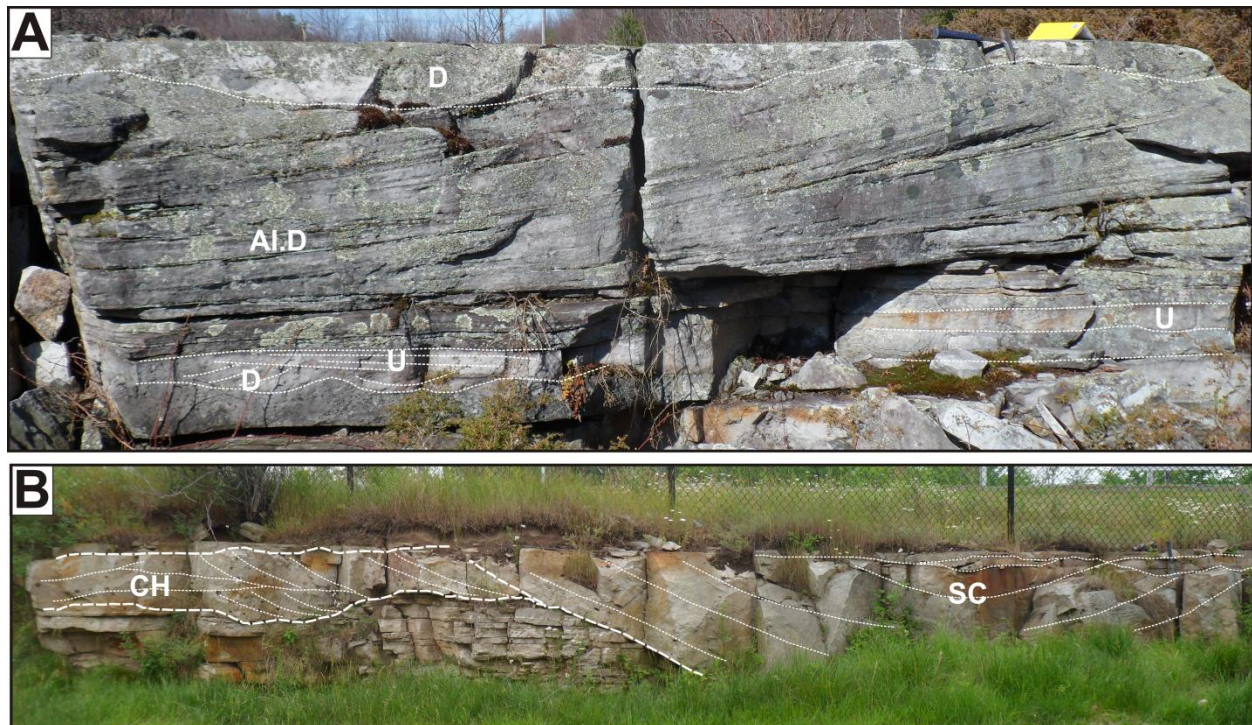


Figure 3.7 A) Coastal sabkha (FA3) strata from Kanata, ON (locality 7). Here waterlain facies, namely subaqueous dune (D) and upper plane bed (U) stratification is succeeded by a ~m-thick set of wind ripple and grain flow cross-strata formed by the migration of an aeolian dune (Al.D). This is then erosively overlain by subaqueous dune cross-strata (D). B) Coastal sabkha strata from locality 5. Here medium-grained planar-stratified aeolian and shallow waterlain sandstone lithofacies, like in figure 3.6a, are deeply scoured by coarse-grained, channel-filling (CH) dune cross-stratified and scour-filling (SC) cross-stratified sandstone.

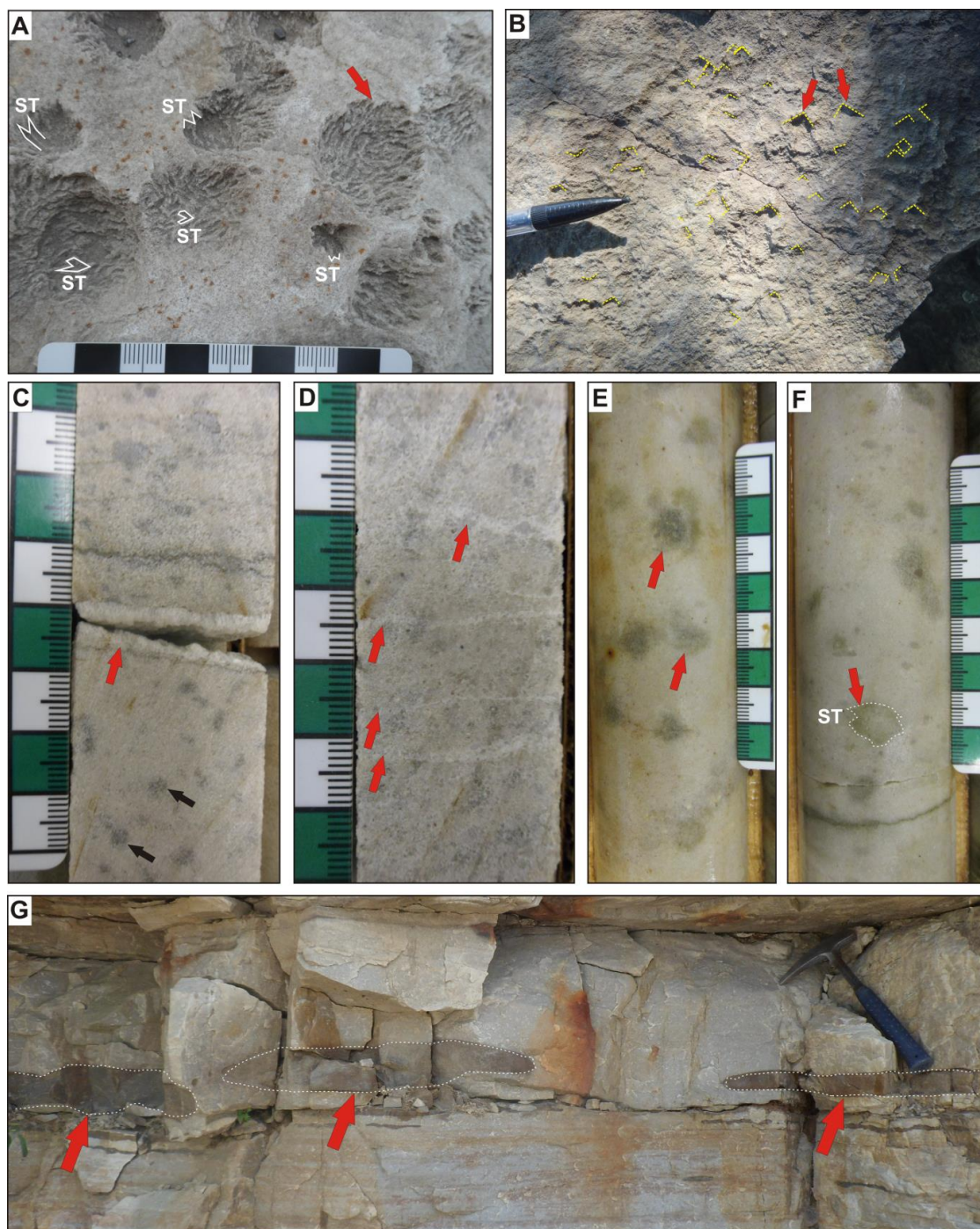


Figure 3.8 Evaporite minerals, pseudomorphs and textures in coastal sabkha (FA4) strata. **A)** Impressions of sparry, nodular radiating mineral aggregates from Kanata, ON (locality 14). Comparison to evaporitic desert rose nodules and the recognition of possible swallowtail twin textures (ST, outlined in white) suggests that the nodules were originally formed of gypsum. **B)** Cubic impressions (outlined in yellow), possibly of halite, from Ste. Clotilde, QC (locality 210). **C)** and **D)** Rare thin (≤ 5 mm) laminae of gypsum or anhydrite (indicated by red arrows) from GSC McCrimmon No.1, near Mcrimmon, ON. Blue-grey nodules are dolomite, possibly pseudomorphs of earlier sulfate nodules. **E)** and **F)**: Dolomite nodules (some indicated by red arrows), possibly pseudomorphs of earlier gypsum aggregates, from FA4 strata in Gastem Dundee No.1, near Pointe-Leblanc, QC. In **E)**, one of the nodules (indicated by the uppermost red arrow) is partially surrounded by a greenish-yellow halo, possibly disseminated pyrite from sulfate reduction. In **F)**, the outlined nodule exhibits a sparry morphology, including possible swallow-tail (ST) twinning features. **G)** Elongate dolomite nodules (circled, and indicated by arrows). Ste. Clotilde, QC (locality 209).

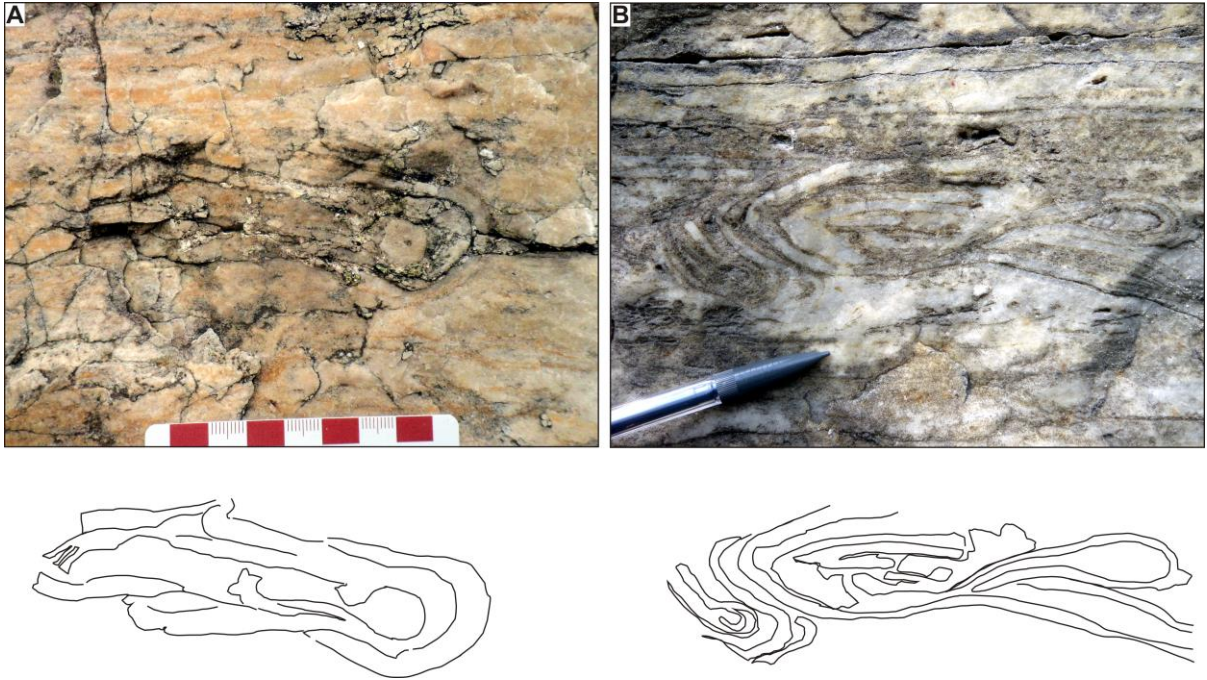


Figure 3.9 Kinked and tightly-folded sandstone intraclasts in coastal sabkha (FA4) strata, outlined below. A) From Kanata, ON (locality 222). B) From Lyn, ON (locality 20).

intraclasts are present within and near the base of planar and channelized strata (Fig. 3.9), suggesting local transport, breakage, transport and deformation of delicate by cohesive laminated sand bound by unknown early post-depositional stratiform cement or binding agent. A sparse (Bioturbation Index, or BI of 1 – 2, after Bann et al., 2008) trace fossil assemblage made up of ~1 – 4 cm long *Skolithos* and/or *Arenicolites* is present locally, but is rare. Also, rare epifaunal traces including *Protichnites*, *Diplichnites*, and *Climacticnites* are present, but only locally.

3.4.1 FA4: Interpretation: Wet evaporitic aeolian sand sheet (Sabkha/Playa)

The recurring 1 – 15 cm thick couplets of aeolian/adhesion and shallow subaqueous stratification in planar-stratified sandstone beds record dry to damp conditions alternating with shallow, low energy flooding, most likely caused by periodic fluctuations in the position of a near-surface water table. Eluviation and/or aeolian deflation occurred during dry periods when the water table was drawn down. Early gypsum and carbonate likely precipitated from evaporating pore waters during dry periods (Goudie, 1983; Atabey et al., 1998; Kendall, 2010). Furthermore, early cementation and binding indicated by the presence of fragile laminated sandstone intraclasts may have been facilitated by the mutually-inclusive precipitation of efflorescent salt crusts and growth of microbial mats (e.g., Smoot and Castens-Seidell, 1994; Pflüger and Greese, 1996; Goodall et al., 2000; Noffke et al. 2001; Donaldson and Chiarenzelli, 2007; Vogel et al. 2009; Hagadorn and McDowell 2012). Collectively, characteristics of strata of FA4 indicate deposition on a low relief sabkha or playa environment characterized by frequent water table fluctuations, precipitation of evaporites, microbial mat growth and widespread adhesion of windblown sand (e.g., Fryberger et al., 1983; Kocurek and Neilson, 1986; Fryberger et al. 1988; Goodall et al., 2000; Vogel et al. 2009). Intercalated channels and scours are interpreted to record the temporary formation of channels and confluence scours which likely formed in response to greater than usual discharge related to higher than average seasonal precipitation (if playa or sabkha) or to strong flood tides that most probably coincided with storm surges (if sabkha). A number of factors favor a coastal sabkha environment; including the occurrence of delicate

microbial/salt structures instead of thick brittle salt structures (Goodall et al., 2000; Hagadorn and McDowell, 2012) and local low diversity trace fossil assemblages.

3.5 FA5: Bioturbated cross-stratified sandstone

FA5 is dominated by moderately- to well-sorted, bioturbated, medium- to coarse-grained cross-stratified sandstone interbedded with lesser fine- to medium-grained, planar stratified sandstone beds and rare dolomicrite beds. Local 0.4 – 1.8 cm diameter nodules and rare ~0.5 – 3 cm layers of dolomite-cemented sandstone are present (including 0.4 – 1.8 cm diameter nodules or rare ~0.5 – 3 cm layers) and preserve higher than average intergranular volume suggesting shallow-burial precipitation. Medium- to coarse-grained cross-stratified sandstone commonly occur as ~0.2 – 3 m thick, low angle ($\sim 3 - 10^\circ$) compound cross-stratified cosets composed of ~2 cm – 1.1 m thick downcurrent-dipping dune (F1c) and/or current ripple (F1a) sets with local scattered pebbles and rare cobbles. Compound cross-stratified cosets then are further classified as either medium-scale (~20 cm – 1.4 m) or large-scale (~1.5 – 3 m). Medium-scale compound cosets are common and made up of medium-grained sandstone with ~2 – 15 cm thick tabular 2D dune and/or ripple sets that commonly exhibit a slight upward increase in set thickness, bidirectional (herringbone) cross-stratification and reactivation surfaces (Figs. 3.10, 3.11a, c). A sparse to moderate intensity (BI of 1 – 3) assemblage of relatively small (~1 – 3 mm diameter and ~0.5 – 3.5 cm

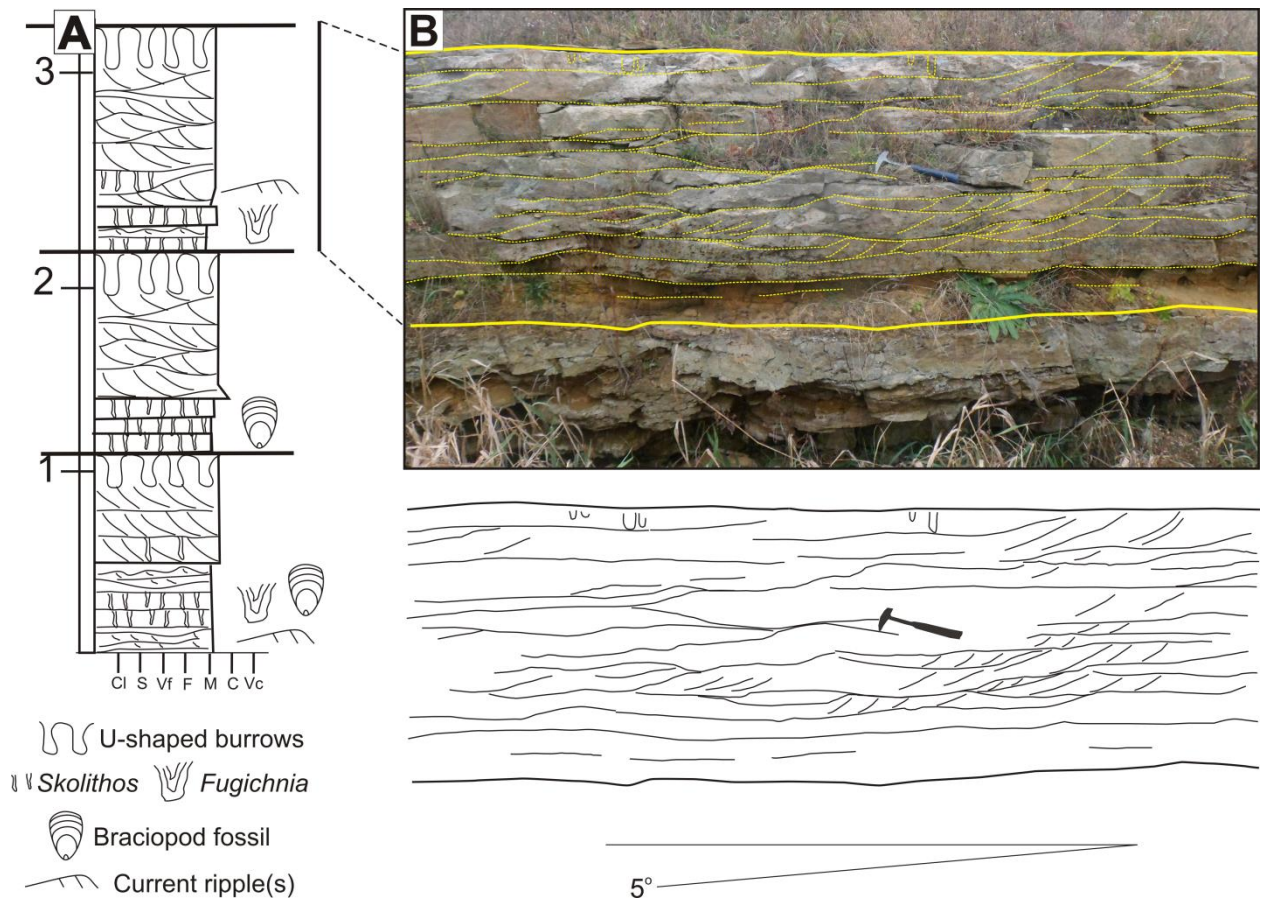


Figure 3.10 A) Stratigraphic log of 3 stacked tidal compound dunes in FA4 near Perth, ON (locality 76). Bold black lines mark the boundary between individual compound dunes. B) Photograph and sketch of the uppermost compound dune in the stratigraphic section in A), bounded by bold yellow lines. At its base the succession consists of a 10 – 15 cm layer of fine-grained, bioturbated sandstone (bottomset) overlain sharply by downcurrent-accreting dune cross-stratified sets that exhibit a shallow-angle (~5°) dip in the direction of paleoflow (to the left).

long) *Skolithos*, *Arenicolites*, *Phycodes* and/or rare *Fugichnia* traces commonly occur near the base of medium-scale compound cosets (Fig. 3.10), whereas a moderate to high intensity (BI of 2 – 4) assemblage of robust (~1.5 – 4 cm wide and ~3 – 22 cm long) protrusive

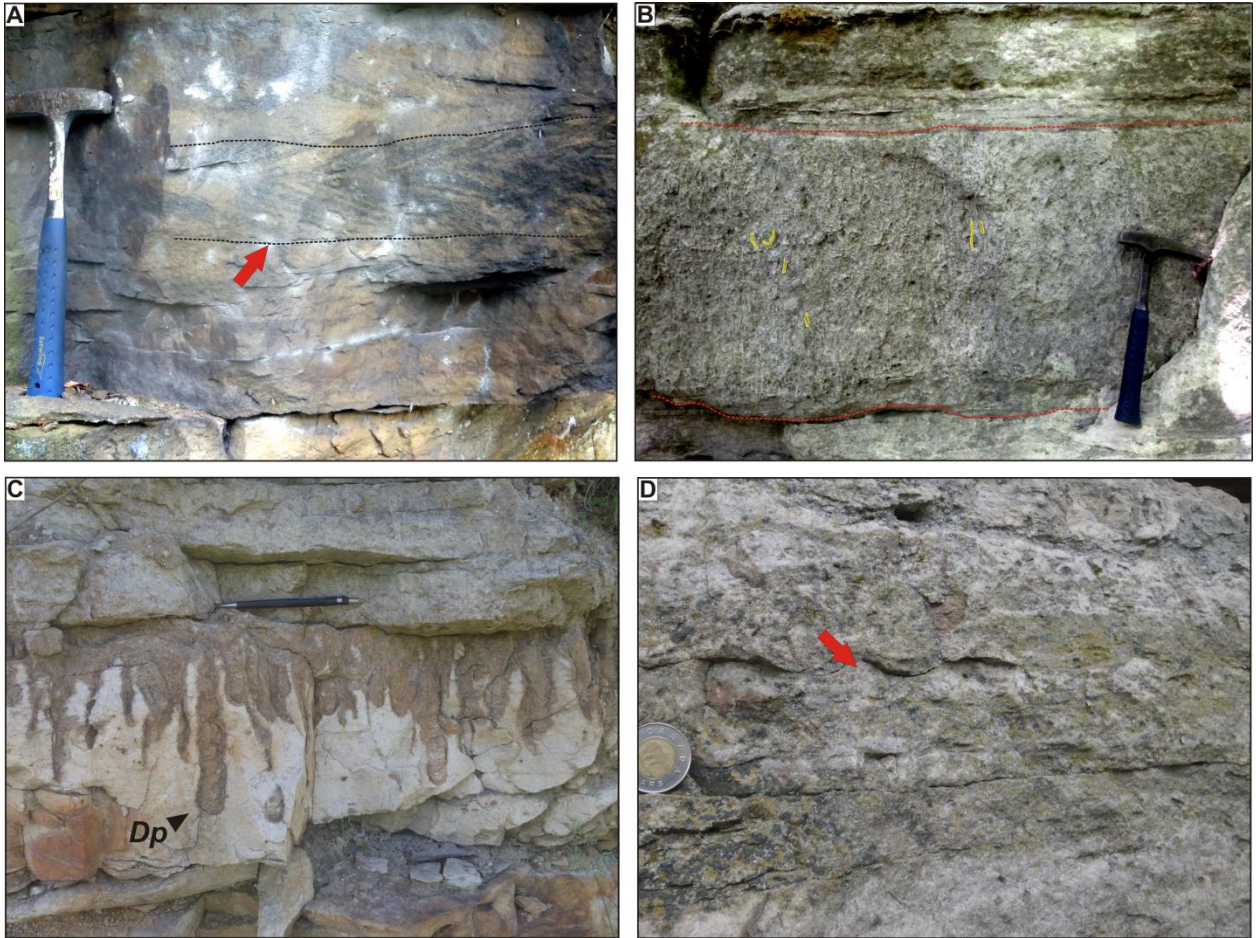


Figure 3.11 Features of tide-dominated estuary and shelf strata (FA5). A) Herringbone cross-stratification, outlined by black dotted line and arrow. Near Redwood, NY (locality 124). B) Rare thoroughly bioturbated bed (outlined in red) dominated by vertical trace fossils (several individual trace fossils are outlined in yellow). Near Blind Bay, NY (locality 87). C) Top of a compound dune deposit overlain by biomottled tabular sandstone (contact at pen). Extending downward from the surface of the compound dune are protrusive *Diplocraterion* (Dp) burrows. South of Lombardy, ON, on route 15 (locality 16). D) Bioturbated tabular beds interpreted as low-energy tidal shelf deposits. Bioturbation and patchy dolomitic cement has obscured most sedimentary features, but remnant wave ripple stratification locally discernible (indicated by arrow).

Diplocraterion and/or *Monocraterion* usually occurs at the tops (Fig. 3.11c). Medium-scale compound cosets are interstratified with ~5 cm – 2.5 m thick, fine- to coarse-grained, moderately sorted and moderately to intensely bioturbated tabular sandstone beds with sharp basal contacts and typically gradational upper contacts or rarely with ~5 – 30 cm thick dolomitic beds (F6a and F6b). Tabular sandstone beds consist of a combination of low amplitude (≤ 1.2 cm) current ripple (F1a) and wave ripple stratification (F1b) and rare planar

stratified sandstone (probably upper plane bed, F2a), as well as thin (≤ 1.2 cm) mudstone partings, though many of these structures are obscured by patchy carbonate cement and bioturbation (Fig. 3.11d). Interstitial matrix is common and in places makes up $\sim 10 - 20\%$ of the bed volume. Most of the tabular beds are sparsely to moderately bioturbated (BI of 1 – 4) with an assemblage of *Skolithos* and/or *Phycoodes*, common *Plantolites* along bedding planes and rare *Bergauria*. Rare intensely bioturbated (BI of 5 – 6) tabular beds consist mainly of retrusive *Diplocraterion* and *Fugichnia*, or densely spaced *Skolithos* (i.e., pipestone) (Fig. 3.11b). Rare inarticulate lingulid brachiopods, most likely *Lingulepis* (Wilson, 1946; Clark, 1966; Selleck, 1993) are present in some tabular beds.

Large-scale ($\sim 1.5 - 3$ m thick) compound cosets consist of ~ 10 cm – 1.1 m thick dune cross-stratified sets of coarse-grained sandstone with scattered pebbles and rare cobbles (Fig. 3.12). Herringbone cross-strata have not been observed in these large-scale compound cosets, but rare reactivation surfaces and overturned cross-strata are present. Additionally, a unique and enigmatic monospecific (?) assemblage of robust infaunal trace fossils occurs in these large-scale compound cosets (Figs. 3.13, 3.14). Traces are elliptical tube-shaped features that are 2 – 17 cm wide and at least $\sim 10 - 60$ cm long with massive fills and mm-thick lining. Individual burrows are commonly curved and variably angled, ranging from essentially vertical ($\sim 80 - 90^\circ$) to horizontal ($\sim 2 - 30^\circ$). In fact, many burrows are bent with concave-up form, changing upward from nearly-horizontal to nearly-vertical over ~ 0.5 m (Fig. 3.13b). Most burrows also show variations in morphology along their length from elliptical to circular. Furthermore, these burrows occur as solitary forms or are clustered (Fig. 3.13a).

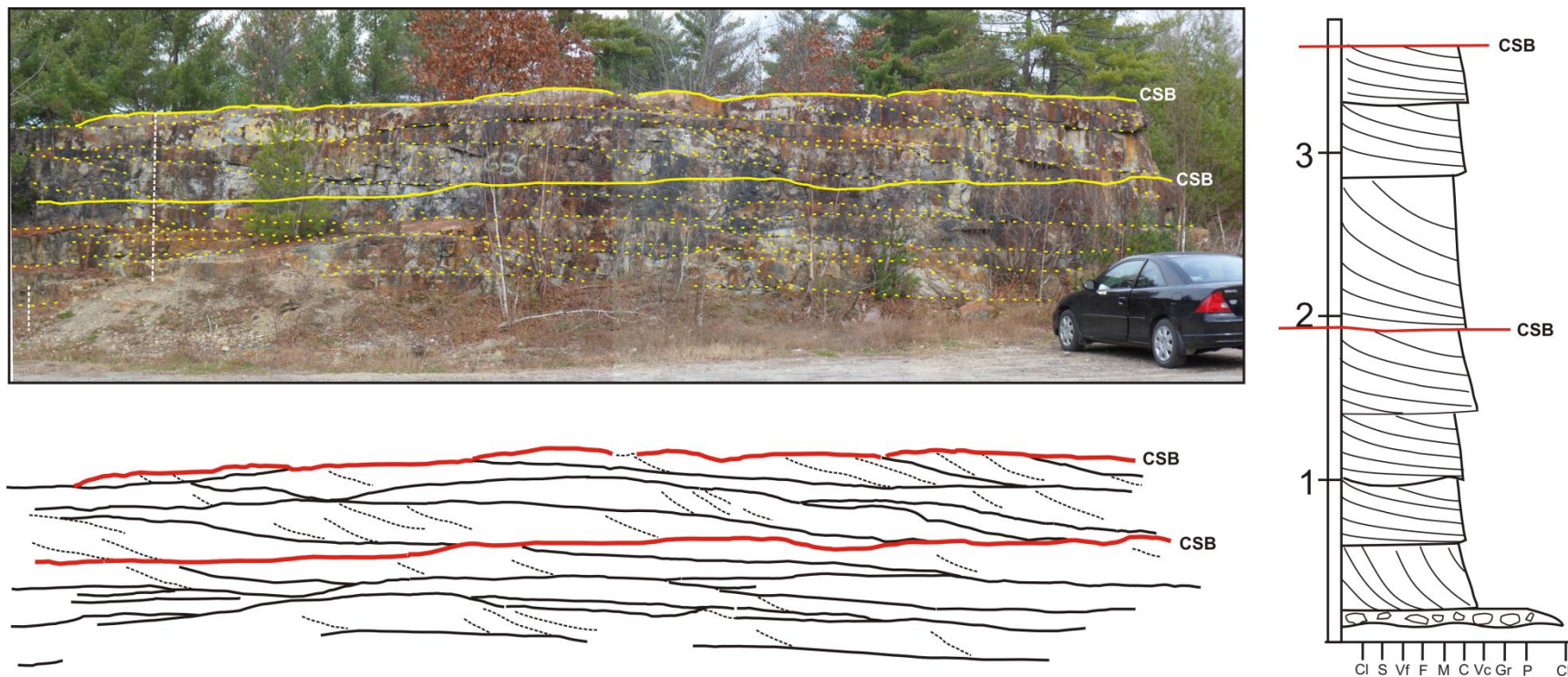


Figure 3.12 Large-scale compound cosets from Lac Beauchamp, QC (locality 8), interpreted as the deposits of high-energy, subtidal shelf compound dune field (i.e., sand sheets). Here, two compound cosets, each representing the migration of a single subtidal compound dune, are separated by a sub-horizontal coset bounding surfaces (CSB). In the top photo, dashed yellow lines trace dune set boundaries and cross strata, and these are shown by solid and dashed lines, respectively, in the outcrop trace below. White dashed line in top photo shows the location of the measured section.

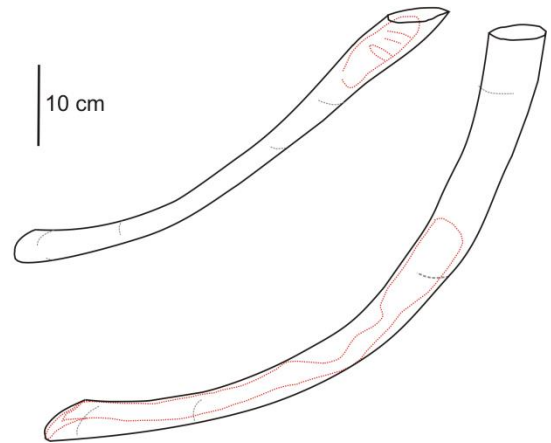
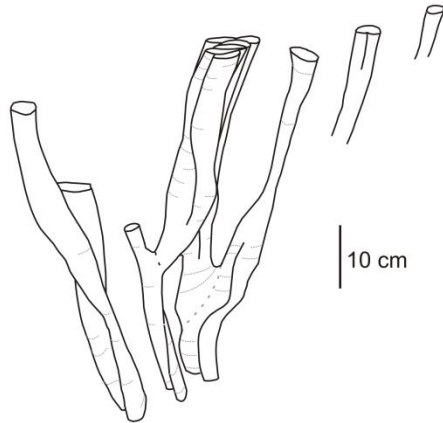
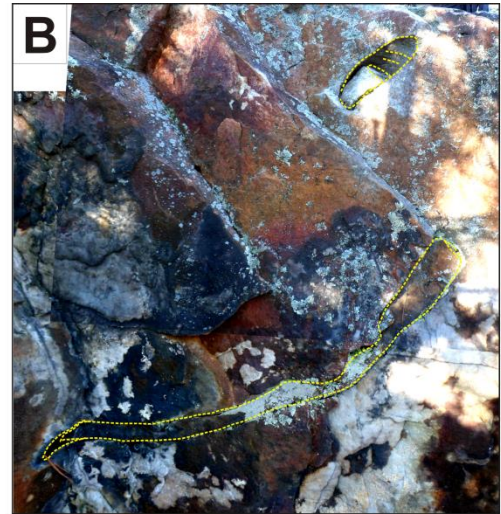


Figure 3.13 Annotated photographs (above) and interpretations (below) of the morphology of large enigmatic trace fossils in large-scale compound dunes of FA5. A) At Gatineau, QC (locality 9) numerous individual burrow tubes are clustered and appear to intertwine, merge and split from one another. Burrows commonly merge upward, but in some cases branch upward from a single large shaft to a complex array of smaller vertical shafts. B) Two large parallel burrows with concave-up form, changing upward from horizontal at their base to vertical near the top of a thick dune cross-stratified set with paleoflow toward the right. Near their base the burrows are elliptical but upwards become more circular. The burrows outlined by the yellow dashed lines in the outcrop photo, are shown in red in the line diagram. In both A) and B), grey dashed lines are drawn on the interpretations to give the reader a sense of curvature of the burrows. From Lac Beauchamp, QC (locality 8).

Clustered burrows commonly cross-cut one-another and commonly merge into a single large composite burrow (Figs 3.13a, 3.14). Typically burrows increase in width from the base the top of large-scale compound cosets, and many burrows in the lower part of a coset are truncated by downcurrent migrating dune sets.

3.5.1 FA5: Interpretation: Tide-dominated estuary and shelf

The grain size, predominance of dune cross-stratification and presence of mostly infaunal trace fossil assemblages suggest a high energy, marginal- to fully-marine depositional environment. Reliable tidal indicators such as mud drapes and tidal bundles are absent, in part because of moderate to intense ichnofabrics, but more probably as a consequence of the lack of mud in strata of FA5 and in the Potsdam as a whole (e.g., Dalrymple et al., 1985; Dott, 2003; Hagadorn and Belt, 2008). Nonetheless a tidal environment is favored based on the paucity of wave formed features like HCS or event beds potentially formed by storms (e.g., tempestites, Myrow and Southard, 1996) and also the predominance of dune cross-stratification with, albeit uncommon, bidirectional cross-stratification and reactivation surfaces (e.g., Dalrymple, 2010; Olariu et al., 2012). Downcurrent-dipping compound dune cosets are interpreted to be the deposits of tidal compound dunes (Allen and Leeder, 1980; Dalrymple, 1984; Dalrymple and Rhodes, 1995; Desjardins et al., 2012; Olariu et al., 2012), with medium-scale cosets likely deposited under lower energy, shallower flow conditions relative to large-scale cosets (Dalrymple, 2010).

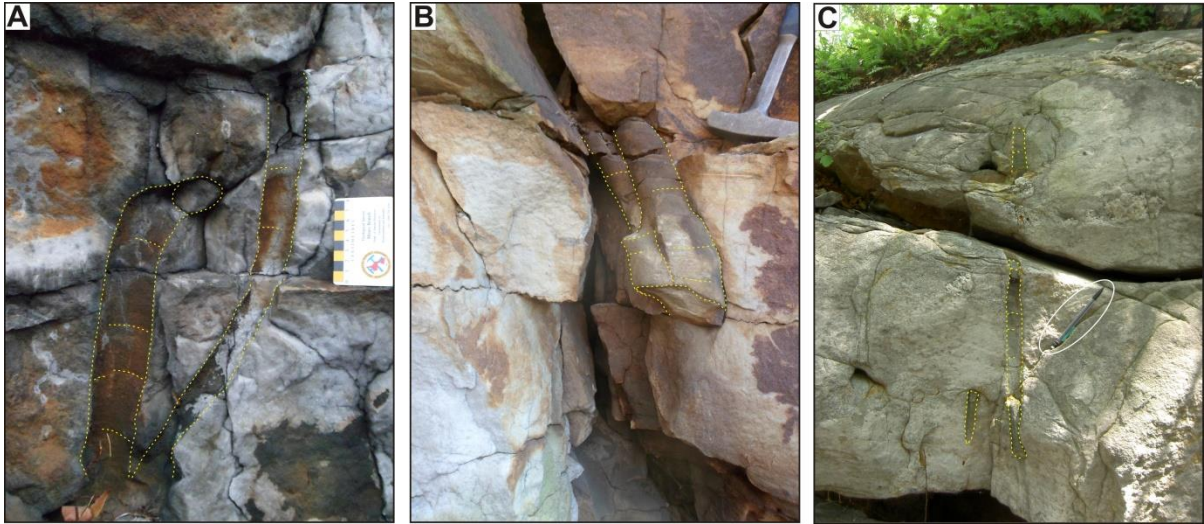


Figure 3.14 Additional examples of large, enigmatic trace fossils from FA5. A) Vertically-branching or intersecting burrows, Lac Beauchamp, QC (locality 8). B) Example of large burrows merging downward into a single amalgamated tube. C) Single straight burrow intersecting several large-scale cross-stratified sets. C) and D) are from Gatineau, QC (locality 9). Hammer for scale (circled).

Medium-scale compound dune cosets (Fig. 3.10) interbedded with bioturbated tabular beds (Fig. 3.11d) are interpreted to be compound dunes that formed in intertidal to subtidal dune fields, likely within a tidal embayment or estuary (e.g., Dalrymple, 1984; Dalrymple and Rhodes, 1995). The moderate to intense bioturbation near the bases of medium-scale of compound dunes, including escape traces and other vertical traces commonly truncated by the base of dune cross-stratified sets, suggests numerous short-lived colonization events by stress-tolerant suspension feeders or predators punctuated by episodic sedimentation events in the lee of migrating compound dunes (Selleck, 1978a; Bjerstedt and Erickson, 1989; Desjardins et al., 2010, 2012). In contrast, the middle of the compound dunes are generally devoid of trace fossils (Fig. 3.10) suggesting continuous dune sedimentation, whereas the occurrence of protrusive *Diplocraterion* and other relatively large, robust traces at the tops of compound dunes record more sustained colonization events and therefore at least short-lived episodes of stable substrate conditions (e.g., Selleck, 1978a; Desjardins et al., 2010). The

bioturbated tabular sandstone beds (Fig. 3.11b, d) and rare carbonate that are interstratified with medium-scale compound dunes are interpreted as lower energy tidal deposits that formed in interdune areas within dune fields or on the surrounding tidal shelf, and the diversity and intensity of burrows suggests continuous colonization by deposit and filter feeders that maintained equilibrium with sedimentation (Selleck, 1978a; Bjerstedt and Erickson 1989; Desjardins et al., 2010, 2012; Olariu et al., 2012).

Large-scale compound cosets in FA5 (e.g., Fig. 3.12) are interpreted to be compound dunes that formed as part of high-energy subtidal shelf sand sheets (e.g., Berné et al., 1993; Barnard et 2006; Desjardins et al., 2012); i.e., in deeper and more energetic environments than the medium-scale compound dunes. The gravel clasts and locally overturned sets in the large-scale cosets attest to the high energy conditions. The latter feature, termed “omelet structures” by Owen (1996), is formed by high rates of fluid shear stress over saturated cross-strata, inducing liquefaction and deformation. The enigmatic robust infaunal trace fossils in large-scale compound dunes (Figs. 3.13, 3.14) are unknown in the ichnological literature and are confounding given the high energy setting; the likely exertion required constructing and maintaining these burrows and a lack of evidence of any additional fauna. They are similar in size, paleoenvironment, age, burrow substrate and in some morphological features to Early Paleozoic ichnospecies of the *Daedalus* ichnogenus, in particular *Daedalus halli* or *Daedalus multiplex* (Seilacher, 2000, 2007). Much more detailed work is needed in order to make meaningful interpretations regarding the trace makers identity, behaviors and existence within such a high-energy environment, but nonetheless a few interpretations can be drawn. For example, the diameter of the burrows (~2 – 17 cm) suggest that the trace maker was relatively large, and variations in burrow shape and bending and coiling of the burrow

suggest it had the ability to conform to different shapes, and thus was likely a soft-bodied organism (rather than an arthropod, for example) and probably a large polychaete worm, such as the modern Bobbitt worm (*Eunice aphroditois*). The lining and massive internal fill of burrows suggest that they were probably stabilized dwelling burrows that were later infilled, while their common occurrence in “clusters” (Figs. 3.13) either suggest that these organisms were colonial or alternatively that individual organisms constructed elaborate intersecting burrow networks.

3.6 FA6: Sparsely bioturbated mixed clastic-carbonate

FA6 is the most lithologically diverse facies association in the Potsdam, consisting of an interbedded assemblage of siliciclastic and rare carbonate rocks. Nevertheless, FA6 is rare and only occurs within the relatively thin and areally limited Altona Member (see chapter 5). Fine-grained siliciclastic facies dominate FA6, including commonly red and locally variegated red and grey, locally dolomitic, generally massive or fissile silty mudstone (F5a; Fig. 3.15b; see also Fig. 2.15a), and erosively- or sharp-based ~0.3 – 2 cm thick layers of siltstone to lower medium-grained sandstone with planar and/or current (F1a, F5b) or wave ripple (F1b, F5c) laminations (Fig. 3.15b). A low – moderate intensity, low diversity assemblage of small vertical and horizontal burrows including *Skolithos* and/or *Cruziana* and/or *Teichichnus* and/or unidentified branching and cross-cutting horizontal burrows occur locally in the mudstones and siltstone, but generally are sparse (e.g., Fig. 3.15e – f). Small (~0.2 – 0.5 cm wide), typically curved and discontinuous intraformational cracks and injectites are also common (Fig. 3.15b). Intercalated with these low-energy, fine-grained

strata are ~3 – 35 cm thick tabular, poorly-sorted, normally-graded, locally erosively based, medium- to very coarse-grained sandstone beds (F3b), most likely deposited rapidly from concreted high-energy waning flows (Fig. 3.15c; see also Figs. 2.12 and 5.7 – 5.8). Also locally interstratified in the fine-grained strata of FA6 are ~0.9 – 2.5 m thick, sharp-based beds composed of well-sorted, fine- to medium-grained, hummocky, swaley and current-ripple cross-stratified sandstones with sparse assemblages of simple vertical burrows, probably *Skolithos*, mainly at the tops of some hummocky cross-stratified beds (Fig. 2.6). Mineralogically, all siltstones and sandstones in FA6 are composed mostly of angular, siliciclastic grains (mainly quartz and feldspar), but rounded dolomite peloids and rare glauconite grains are also present. Interstitial mud and silt matrix is common in most sandstone beds (up to ~35%). Also present in FA6 are red to grey peritidal dolomicrite strata (F6a, F6b; see chapter 2 and Figs. 2.15 – 2.17). These contain a number of cryptic features including cryptoalgal laminites, 0.1 – 0.3 mm silt laminae, rare burrows, fossil fragments (brachiopod, trilobite(?)), possible recrystallized relics or “ghosts” of gastropod fossils, and physical shrinkage and injection structures (Fig. 2.16).

3.6.1 FA6: Interpretation: Open-coast tidal flat

The dominance of sparsely bioturbated silty mudstone, intercalated with high energy sandstone beds and rare carbonate beds suggest sedimentation in a shallow marine environment dominated by low-moderate energy conditions but punctuated by high energy sedimentation events, but with local siliciclastic sediment starvation. Furthermore, the presence of hummocky and swaley cross-stratification suggests that many of the sandstone beds were deposited by episodic or periodic high energy storm-driven coastal currents (Duke

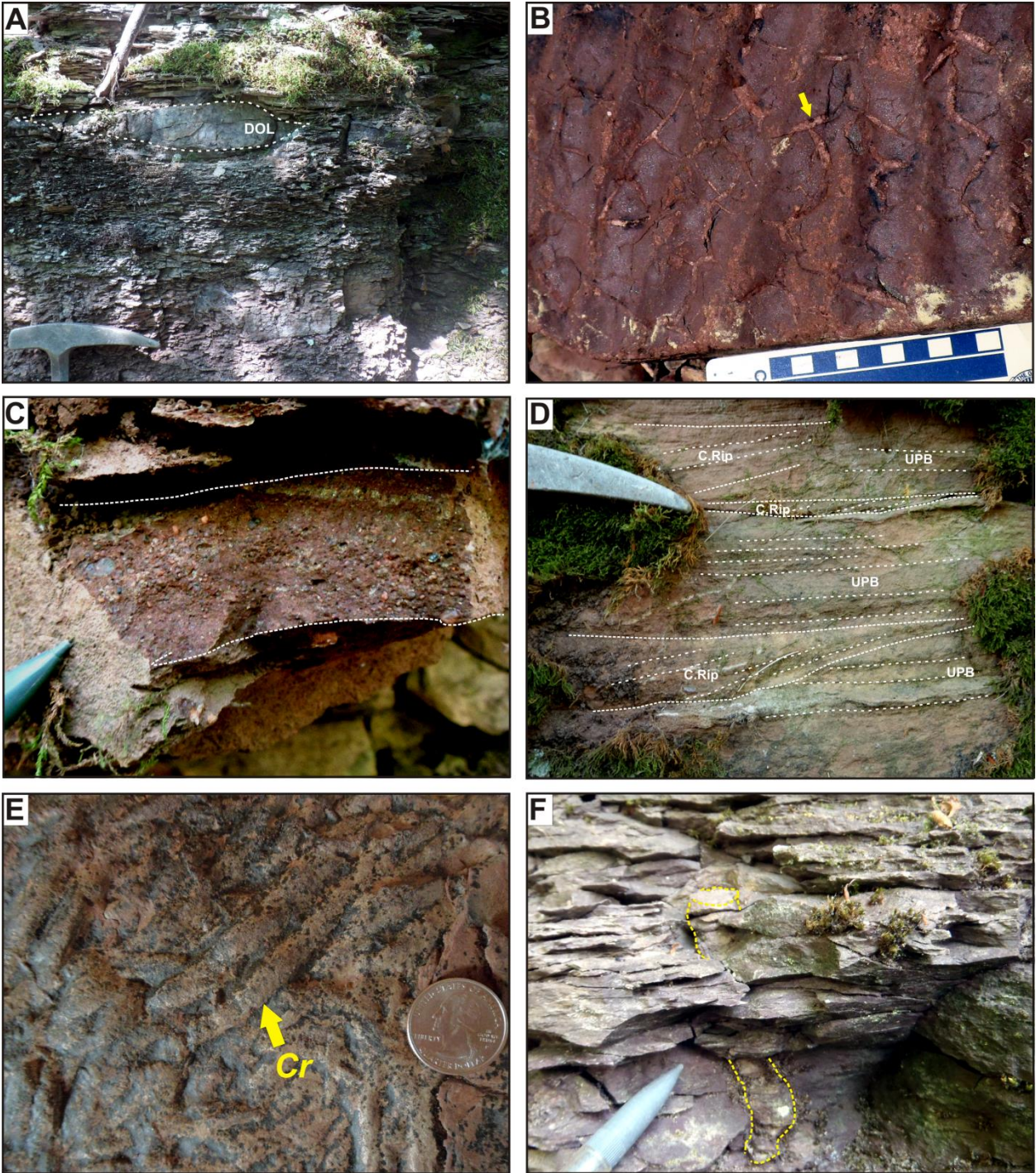


Figure 3.15 Features of the open-coast tidal flat facies association (FA3). For additional examples see figures 2.6, 2.12, 2.15 – 21.7, 5.7 and 5.8. A) Fissile, featureless variegated mudstone and an isolated displace peritidal dolostone nodule (DOL). B) Bedding plane showing low-relief symmetrical wave ripples (crests demarcated by white dashed line) in siltstone, and polygonal, discontinuous shrinkage/injection features filled with medium-grained sandstone, probably synaeresis cracks. A) and B) from Atwood Farm, near Chazy New York (locality 234). C) Poorly-sorted, coarse- to very coarse-grained matrix-rich sandstone (bounded by white dashed lines), probably deposited by rapidly-waning fluvial discharge, Atwood Farm, NY (locality 185). D) Current ripple (C.Rip) and upper plane bed (UPB) stratification in fine-grained sandstone, Atwood Farm, NY (locality 184). E) Negative epirelief *Cruziana* trace fossils from the base of a fine-grained arkose bed. F) Isolated vertical, cylindrical burrow indicated by yellow dashed lines in fissile silty mudstone. E) and F) from near Jericho, NY (locality 138).

et al., 1991; Dumas et al., 2005; Li and Amos, 1999; Yang et al., 2006). However, coarser-grained, normally-graded concentrated flow deposits (F3b) consist of a grain size that conceivably exceeds the carrying capacity of most coastal storm-driven currents (e.g., Myrow et al., 2002; Dumas et al., 2005). These beds, therefore, were instead most likely deposited by energetic, shallow, rapidly-waning, high capacity tidal currents, or fluvial sheet floods forming splays at the mouths of sandy and gravelly braided rivers. The latter fluvial interpretation is consistent with the stratigraphic occurrence of FA6, as a tongue of shallow marine strata conformably surrounded by coeval braided fluvial strata (see Chapter 5). Altogether, the character of siliciclastic FA6 strata suggest a shallow marine, fluvially- and storm- and wave-influenced coastal environment with features consistent with either a wave/storm-dominated prodeltaic shoreface (Bhattacharya, 2010; Plint, 2010) or a river-fed open-coast tidal flat (e.g., Fan et al., 2004; Yang et al., 2005, 2006). A number of features favour the latter interpretation. For example, the prominence of red coloration due to hematite with local grey mottles and lenses suggests sedimentation in a well-oxygenated shallow water environment, with local reduction driven by the decay of organic material (Retallack, 1991; Yamaguchi and Ohmoto, 2006). Also, the occurrence of interstitial clay and silt matrix in normally-graded, high-energy sandstone beds suggests that much of the clay and silt was introduced following sand deposition and by downward-percolating groundwater (eluviation) in a setting that was at least periodically subaerial. Furthermore, the low to moderate intensity, low diversity assemblage of small vertical and horizontal burrows suggest stressed faunal conditions, likely due to a combination of high rates of local aggradation during periods of fluvial influx (Fan et al., 2004), locally high near-bed fine-grained sediment concentrations (e.g., Dalrymple et al., 2003; Plint, 2014), and fluctuating

salinity due to the influence of tides and fluvial floods. Finally, microbially-laminated peritidal dolomicrite (F6a, F6b) most likely accumulated in parts of the tidal flat where sedimentation rates were low, probably in low energy lagoonal intertidal environments landward of the wave maximum (Fan et al., 2004; Yang et al., 2005, 2006) and/or in quiescent coastal areas away from sediment-laden river mouths.

Chapter 4: Composition and Architecture of Braided and Sheetflood-Dominated Ephemeral Fluvial Strata in the Cambrian-Ordovician Potsdam Group: A Case Example of the Morphodynamics of Early Phanerozoic Fluvial Systems and Climate Change

4.1 Introduction

Perennial fluvial systems are those in which discharge is semi-permanent with consistent seasonal fluctuations. Flow is confined to permanent but migrating and periodically avulsing channels on alluvial plains and fans, and includes the familiar and well-studied braided, meandering and anastomosing fluvial systems (e.g., Miall 1996, 2010, Bridge and Lunt 2006, Sambrook Smith et al. 2006). Sheetflood-dominated ephemeral fluvial systems, on the other hand, have generally negligible discharge with comparatively poorly-developed and typically dry channels. Although channels may be stable over long periods of time (e.g., Langford and Bracken 1986), rare and short duration (i.e. ephemeral) high discharge floods typically overwhelm the conveyance capacity of pre-existing channels, resulting in abrupt avulsions and poorly-confined, areally-extensive and catastrophic high energy sheet floods (McKee et al. 1967, Stear 1985, Bromley 1991). Deposition is dominated by poorly-confined sheet-like aggradation, forming fans with distributary networks (Tunbridge 1984, Hampton and Horton 2007).

Unlike their perennial counterparts, observations and data based on modern ephemeral fluvial systems are limited (e.g., McKee et al. 1967, Picard and High 1973, Stear 1985, Langford and Bracken 1986, Tooth 2000a, b) owing to the violent nature and long

recurrence interval between geologically effective high discharge events. Similarly, few ancient examples have been described (Tunbridge 1984, Olsen 1987, Bromley 1991, Hjellbakk 1997, Hampton and Horton 2007), although this may be more a consequence of their poor recognition caused by a limited understanding of the deposits that form from flashy, very high energy discharge events. However the recognition of both ephemeral and perennial fluvial deposits from the ancient rock record is important because it permits the elucidation of variations in ancient discharge regimes, and thus climate, particularly where these two types of fluvial systems are intercalated (e.g., Long 2006). Additionally, studies comparing pre-Devonian perennial and ephemeral fluvial to their younger counterparts, including modern fluvial systems, have revealed some significant differences in stratal architecture imparting differences in fluvial processes attributed primarily to the absence of bank-stabilizing vascular vegetation and associated cohesive fine-grained sediment (Cotter 1978, Long 1978, 2006, Fuller 1985, Hjellbakk 1997, Davies et al. 2011, Gibling and Davies 2012, Marconato et al. 2014, Ielpi and Ghinassi 2015). However, the specific processes of pre-vegetated systems are poorly understood due to a lack of suitable modern analogues (Fuller 1985) and a paucity of studies of pre-Devonian systems utilizing detailed facies and architectural analysis (although notable examples include Long 2006, Marconato et al. 2014 and Ielpi and Ghinassi 2015). Poorly understood also is how pre-Devonian fluvial sedimentation responded to allogenic factors such as climate or basin topography. To address these and many other outstanding questions in fluvial sedimentology, experimental flume studies have become popular for simulating fluvial processes and stratigraphy (e.g., Gran and Paola 2001, Heller et al. 2001, Paola et al. 2001, Frederici and Paola, 2003, Tal and Paola, 2007). However, as noted by Bridge and Lunt (2006), these studies are not be completely

analogous to natural systems in that they are limited to resolving only the highest orders of stratal sets formed in natural fluvial environments and are biased toward channel-fills and scours due to unrealistic rates of channel switching and abandonment. Furthermore, experiments are limited in width thus limiting the likely dispersion of discharge over non-vegetated floodplains (Wolman and Brush 1961, Fuller 1985).

The objective of this contribution, therefore, is to augment the database of pre-Devonian ephemeral and braided fluvial systems and to build on criteria for their recognition by describing their deposits from the Cambro-Ordovician Potsdam Group. Also, on the basis a comprehensive analysis of lithofacies, architectural elements and stratal stacking patterns we examine the details of fluvial morphodynamics and characteristic autogenic processes and their response to climate and basin topography in the absence of vegetation or cohesive fine-grained sediment.

4.2 Geologic Setting

The Cambrian to Ordovician Potsdam Group is a composite siliciclastic unit dominated by sandstone with subordinate conglomerate and is exposed locally along the edge of the Ottawa Embayment and Quebec Basin, an east-west extension of the St. Lawrence platform in eastern Ontario, northern New York state and western Quebec (Sanford and Arnott 2010; Fig. 4.1a). Here the Potsdam comprises the lowest part of the relatively flat-lying and undeformed Paleozoic sedimentary succession that unconformably overlies ~1 Ga rocks of the Grenville Orogen. It was deposited at subequatorial latitudes between 10° – 30° south approximately 200 – 400 km inboard of the south-facing Laurentian

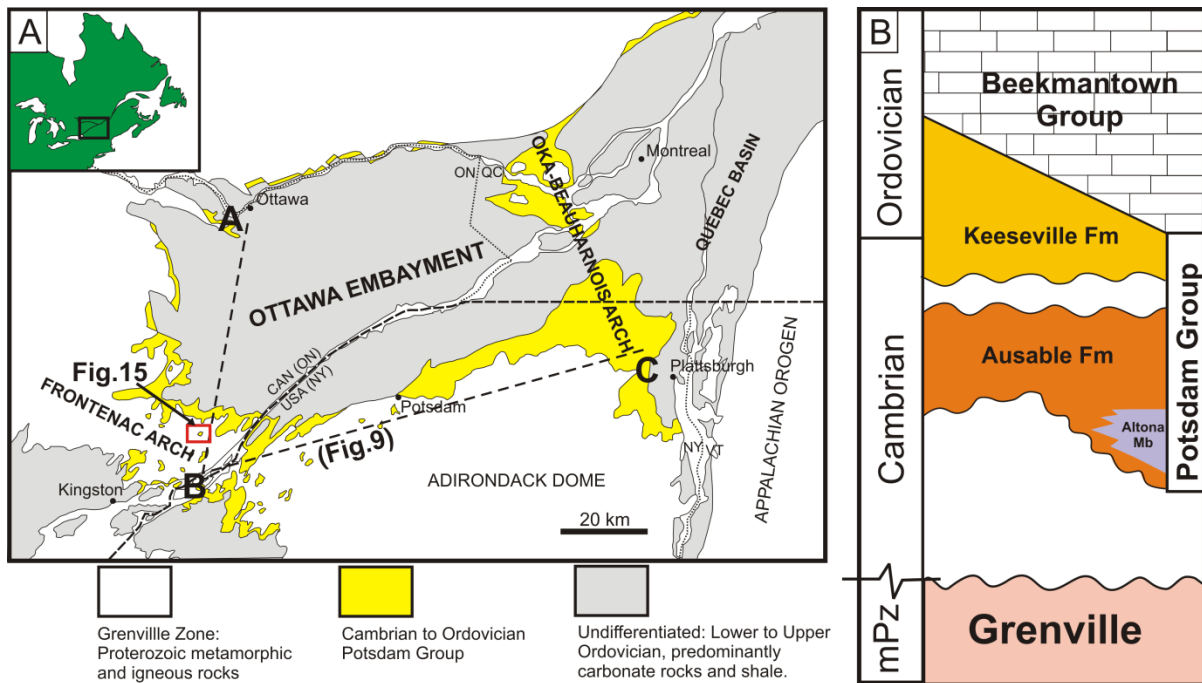


Figure 4.1 Base map showing the location and bedrock distribution of the Potsdam Group in the Ottawa Embayment and Quebec Basin. B) Generalized stratigraphic column of the Potsdam Group in the study area, adapted from Sanford and Arnott (2010). For brevity we abandon the names of units in Ontario and Quebec in favor of the earlier named equivalent units in New York State (see Sanford and Arnott (2010) for discussion of unit equivalence). Also indicated are the locations of points A, B, and C in Figure 4.3 and the location of the map in Figure 4.15 (red box).

margin during the late postrift and subsequent passive margin phase associated with the rifting and breakup of Rodinia (Torsvik et al. 1996, McCausland et al. 2007, Lavoie 2008; Allen et al. 2009). Summaries and discussions of Potsdam stratigraphy and stratigraphic nomenclature can be found in Sanford and Arnott (2010), Landing et al. (2009) and Salad-Hersi et al. (2002).

The Potsdam Group is one of the first formally-named stratigraphic units in North America. Originally recognized in 1838 as the Potsdam Sandstone by Ebenezer Emmons in northern New York State, it is now recognized as a group comprising three formations that range in age from uppermost Early Cambrian to Early Ordovician (Emmons 1838, Kirwan

1963; Clark 1966, Greggs and Bond 1972, Brand and Rust 1977, Sanford and Arnott 2010) (Fig. 4.1b). Biostratigraphic age controls of the Potsdam Group and its constituent formations come from a number of sources, but primarily from Greggs and Bond (1972), Brand and Rust (1977), Salad Hersi et al. (2002), Dix et al. (2004), Landing et al. (2009) and this study (Chapter 5; see also Nowlan, 2013). Although Salad Hersi et al. (2002) and Dix et al. (2004) argued that the uppermost Potsdam was no younger than Late Cambrian in age, biostratigraphy from this study (see Chapter 5) suggest that the upper Potsdam is Early Ordovician in age, at least across the northern and western parts of the study area. The oldest formation of the Potsdam Group is the late Early to Middle Cambrian Ausable Formation, which consists of mostly of braided fluvial arkose and rare conglomerate. An intertonguing unit of west-thinning marine siltstone, mudstone, arkose and rare dolostone occurs near the base of the Ausable, and contains fossils that constrain its depositional age (Landing et al. 2009). An unconformity, in places angular, separates the Ausable Formation from the overlying Upper Cambrian – Lower Ordovician Keeseville Formation (Clark 1966; Sanford and Arnott 2010). The Keeseville Formation consists of quartz arenites and minor conglomerate of fluvial, aeolian, marginal and shallow marine origin (Selleck 1978a, b; Bjerstedt and Erickson 1989; Sanford and Arnott 2010). The contact between the Potsdam Group and overlying Theresa Formation is defined by a change from marine siliciclastic to mixed siliciclastic/carbonate strata associated with the epeiric Sauk transgression. Age and contact relationships indicate that this contact is locally an erosional discontinuity but elsewhere conformable, and youngs progressively from the southeast to northwest (Wilson 1946, Greggs and Bond 1972, Brand and Rust 1977, Salad Hersi et al. 2002, Sanford and Arnott 2010). For more details on the stratigraphy of the Potsdam, see chapter 5.

4.3 Lithofacies associations and depositional environments

Two fluvial depositional lithofacies associations (FA1, FA2) are recognized and correlated in strata of the Potsdam Group on the basis of detailed bed-by-bed measurement of 67 outcrop sections and recognition of related facies from 12 bore holes (Table 4.1; Figs. 4.2, 4.3). For brevity, the reader is referred to chapter 2 for descriptions and interpretations of depositional lithofacies and subfacies. In addition to lithofacies, four recurring architectural elements, as defined by Miall (1996), are recognized in strata of FA1 and FA2 on the basis of architectural analysis. These include (a) *channel elements*, (b) *accretional elements*, (c) *sheet elements* and (d) *isolated scour elements* (Tables 4.1, 4.2). An even higher order stratal subdivision, here termed *stratal unit*, is recognized and defined by packages of strata bounded by continuous (beyond the scale of individual outcrops) and near-horizontal high-order surface.

4.3.1 Facies Association 1 (FA1)

Strata of FA1 dominate the Ausable Formation where they occur continuously over an area of ~15,000 – 16,000 km² and reach a maximum thickness of 550 m. However, in the southern and southwestern Ottawa Embayment FA1 strata occur as relatively small (~30 – 200 km²) ~7 – 60 m thick outliers (Fig. 4.2). Two units of FA1 are recognized in the Keeseville Formation, and are separated by a unit of facies association 2 (FA2, see next section and Figs. 4.2 – 4.3). The lower unit (FA1A on Figs. 4.2 – 4.3) has a similar

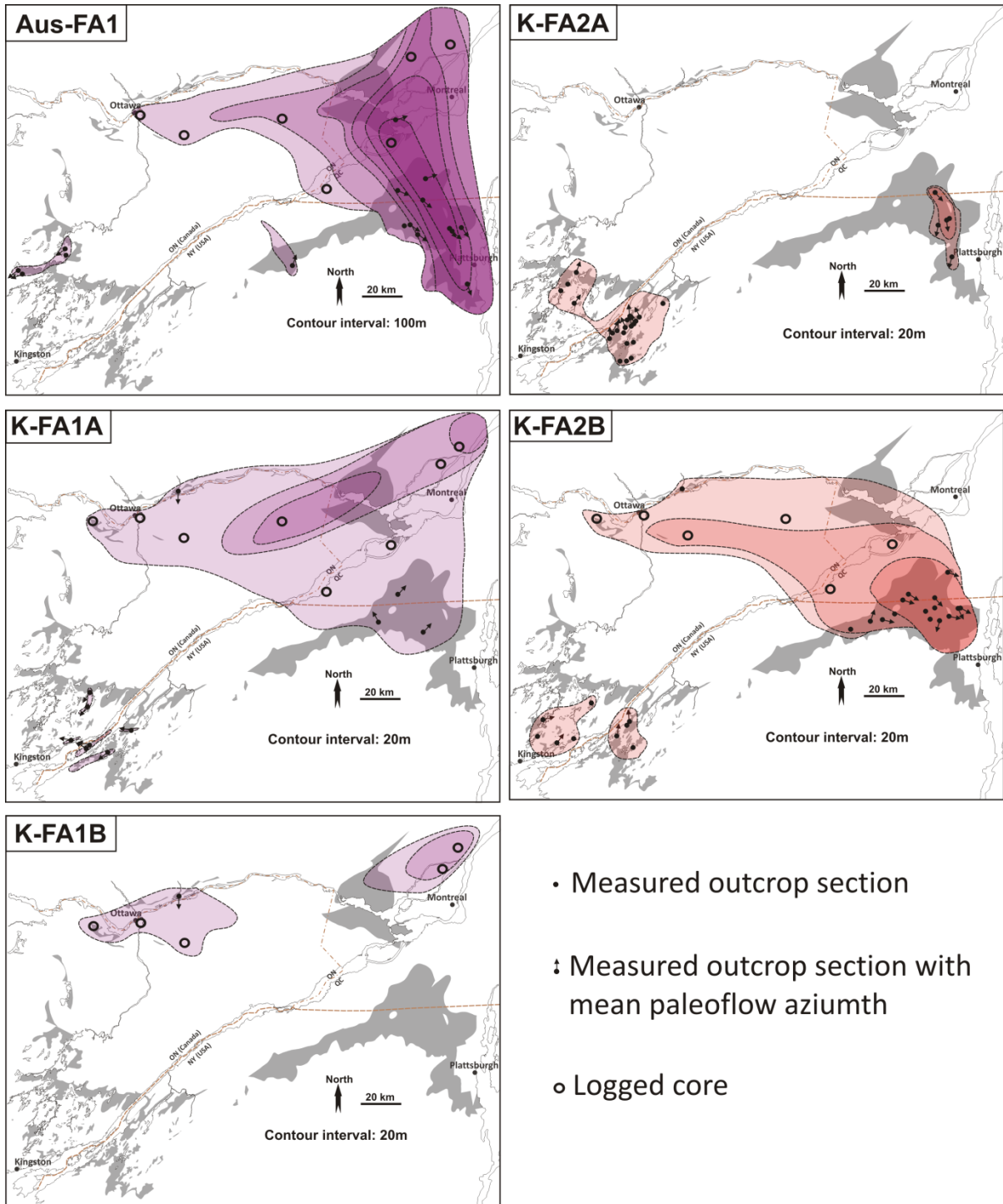


Figure 4.2 Isopach maps of braided fluvial strata in the Ausable Formation (Aus-FA1) and braided (FA1) and ephemeral (FA2) fluvial strata in the Keeseville Formation based on outcrop and core data. Keeseville fluvial units are shown from the stratigraphically lowest at top left to the stratigraphically highest at the bottom right: FA2A = ephemeral unit 1; FA1A = braided unit 1; FA2B = ephemeral unit 2; B2 FA1B = braided unit 2. Local mean paleoflow orientations measured from cross-stratified sandstone and imbricated conglomerate are indicated by arrows. Isopachs were interpolated manually by correlating unit thicknesses from 12 wellbores to one another and to unit thicknesses measured and/or calculated from the outcrop belts along the margins of the Ottawa Embayment and Quebec Basin.

distribution to FA1 strata in the Ausable Formation (Fig. 4.2) but only reaches a thickness of ~55 m. The upper FA1 unit (FA1B in Fig. 4.2 – 4.3) is confined to the northern Ottawa Embayment and Quebec Basin where it forms two ~1300 km² outcrop/subcrop belts that range from ~3 – 38 m in thickness.

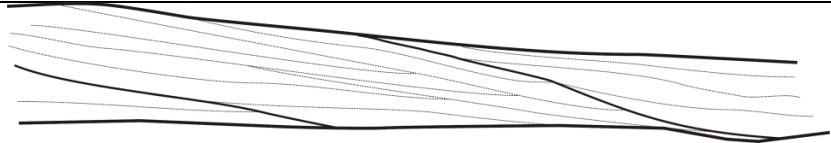
Strata of FA1 consist mostly of coarse-grained unidirectional cross-stratified sandstone (F1) formed primarily by the migration of 3D subaqueous dunes (F1c), or rarely unit bars (F1d) or very rarely current ripples (F1a; Table 4.1; Fig. 4.4a – b). Conglomerate (F4), although locally well developed, is a minor component of FA1 and consists mostly of imbricated, moderately well-sorted pebble to cobble tractional bedload conglomerate (F4a), and rare poorly-sorted cobble to boulder talus (F4b; Table 4.1; Fig. 4.4c – d). Finally, minor coarse-grained, upper plane bed stratified sandstone (F2a) and rare silty mudstone (F5a) are also present (Table 4.1). Paleocurrent directions measured from dune, unit bar and current ripple cross-strata and clast imbrication in conglomerate are typically tightly clustered at individual outcrops. Accretional elements, channel elements, isolated scour elements and sheet elements are recognized in FA1 (Table 4.1; Figs. 4.5 – 4.6). Accretional elements are ubiquitous (~84% of strata, see Table 4.1) and are generally stacked and amalgamated in FA1 strata (Figs. 4.5 – 4.7). Individual accretional elements are 0.4 – 5 m thick, extend

Table 4.1 Facies associations description and interpretation

Facies Association	Component lithofacies and subfacies and their proportions*	Grain size (a) average, (b) total range	Architectural element	Depositional macroform interpretation	Environmental Interpretation
Facies association 1 (FA1)	Cross-stratified sandstone (F1; 86%) dune (F1c; 10-95%; ave. 74%) [†] unit bar (F1d; 0-35%; ave. 11.5%) current ripple (F1a; 0-2%; ave. 0.5%) Conglomerate (F4; 11%) tractional bedload (F4a; 0-45%; ave. 9%) debris flow (F4b; 0-20%; ave. 2%) Graded sandstone (F3; 1.5%) suspended load sandstone, subaerially-weathered (F3a; 0-4%; ave. 1.5%) Planar-stratified sandstone (F2; 1%) upper plane bed (F2a; 0-6%; ave. 1%) Muddy siltstone (F5; 0.5%)	(a) lower-upper coarse sand	Accretional elements (84%)	Channel-filling compound braid bars	Braided fluvial: Buildup of channel belt during migration and deposition of low-amplitude compound braid bars in wide braided channels with quasi-steady discharge and local scouring at confluences. Channel incision and abandonment preceding avulsion, and overbank deposition following avulsion.
			Channel elements (13%)	Abandoned and filled bypass channels	
		(b) silt to boulders	Sheet elements (2%)	Bar-top and overbank deposits	
			Isolated scour elements (1%)	Confluence scours	
Facies association 2 (FA2)	Planar-stratified sandstone (F2; 72%) wind-ripple laminations (F2b; 15-74%; ave. 50%) adhesion stratification (F2c; 2-35%; ave. 18%) upper plane bed (F2a; 0-13%; ave. 4%) Cross-stratified sandstone (F1; 28%) cyclic step (F1g; 0-28%; ave. 9%) antidune (F1e; 0-40%; ave. 7%) dune (F1c; 0-23%; ave. 6%) depth-limited wave ripple (F1b; 1-16%; ave. 3%)	(a) Upper medium sand	Sheet elements (70%)	Eolian-reworked terminal or flow-margin splays	Ephemeral fluvial: Buildup of distributive channel belt (DCB) by deposition of splays fed by distributary fluvial networks with episodic discharge, and nearly complete reworking of splays by aeolian processes. High-energy sheet floods and channels override prograded DCB
		(b) very fine sand to granules (very rare pebbles and cobbles)	Isolated scour elements (18%)	Distributive high energy sheet floods	
			Channel elements (6%)	Abandoned and filled distributary channels	

	chute-and-pool (F1f; 0-7%; ave 2%) current ripple (F1a; 0-8%; ave. 1%)		Accretional elements (6%)	Terminal or flow- margin splays	preceding avulsion. Following avulsion, top of DCB is deflated and armored.
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Table 4.2 Architectural elements recognized in fluvial strata of the Potsdam Group. Modified from the scheme of Miall (1996, 2010).

Element	Form	Description
Accretional		Low-relief features ($H/L = 0.005 - 0.03$) in which low-angle to high-angle ($1-15^\circ$) dipping strata are truncated by one or more higher order of surfaces. Higher-order surfaces are dipping or nearly horizontal. Complex compound cross-stratified, implying accretion of low-order strata over time.
Channel		Erosionally based stratal features, generally with undulating bases, shallow or steep margins, and elongate with low relief ($H/L = 0.02 - 0.03$). Internal strata and low-order bounding surfaces are generally horizontal.

Sheet		Very low-relief ($H/L = 0.0001 - 0.001$), elongate tabular to lenticular layers, most commonly filled by horizontal or low-angle planar strata, in places truncated by very low-angle ($\leq 5^\circ$) high-order bounding surfaces.
Scour		Relatively high relief ($H/L = 0.1 - 0.01$), steep-sided and isolated erosionally based features. Filled by large sets or cosets of cross-strata.

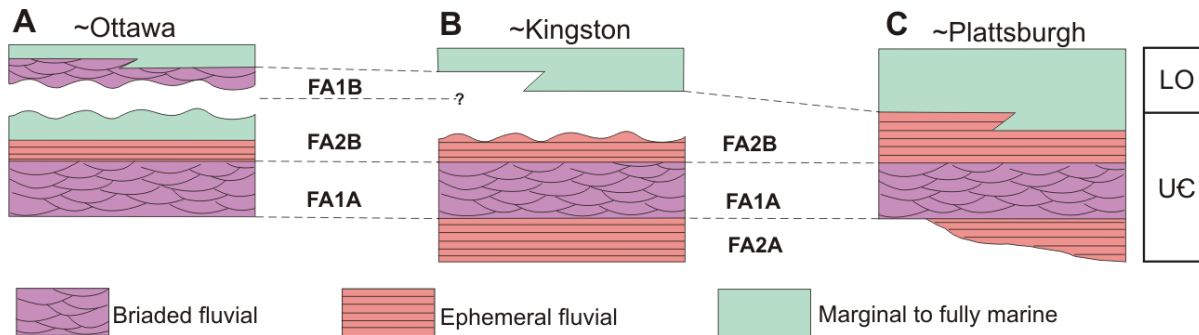


Figure 4.3 Regional correlation of interstratified ephemeral and braided fluvial units (see Figures 4.1 and 4.2) in the Keeseville Formation. The locations of A, B, and C are shown in Figure 4.1 and correspond to: the northern Ottawa Embayment (A), the southwestern Ottawa Embayment (B), and the southeastern Ottawa Embayment (C). UC = Upper Cambrian, LO = Lower Ordovician.

laterally from ~35 m to at least ~200 m, and are bound by horizontal to low angle ($\leq 10^\circ$) and locally erosional surfaces. Internally each accretional element exhibits complex compound cross-stratification consisting of dipping ($\sim 1 - 15^\circ$) sets of dune and/or rare unit bar cross-stratified sandstone, forming cosets truncated by higher order, locally erosional dipping ($\sim 1 - 35^\circ$) surfaces, which themselves are truncated by the bounding surface of each element (Figs. 4.5 – 4.6). Most of the set boundaries and internal bounding surfaces dip in the downcurrent direction, i.e. at or near the same direction as paleoflow determined from local dune cross-stratification. Notably, where present, tabular unit bar sets usually occur at the base of accretional elements (Fig. 4.5), which then is overlain by a succession of upward thinning dune cross-stratified sandstone sets. Rare accretional elements also consist wholly or partly of sets of imbricated tractional pebble to cobble conglomerate (F4a).

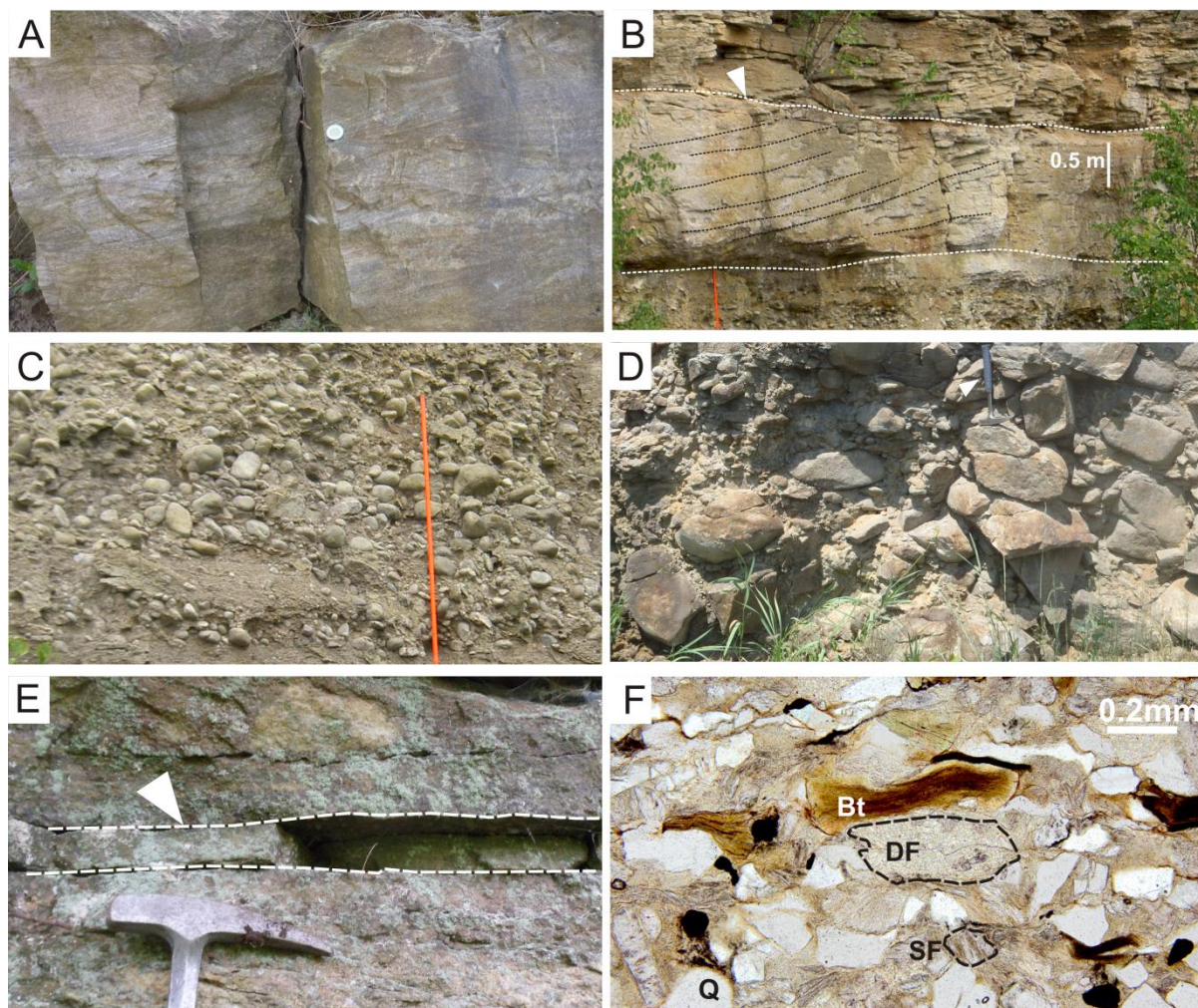
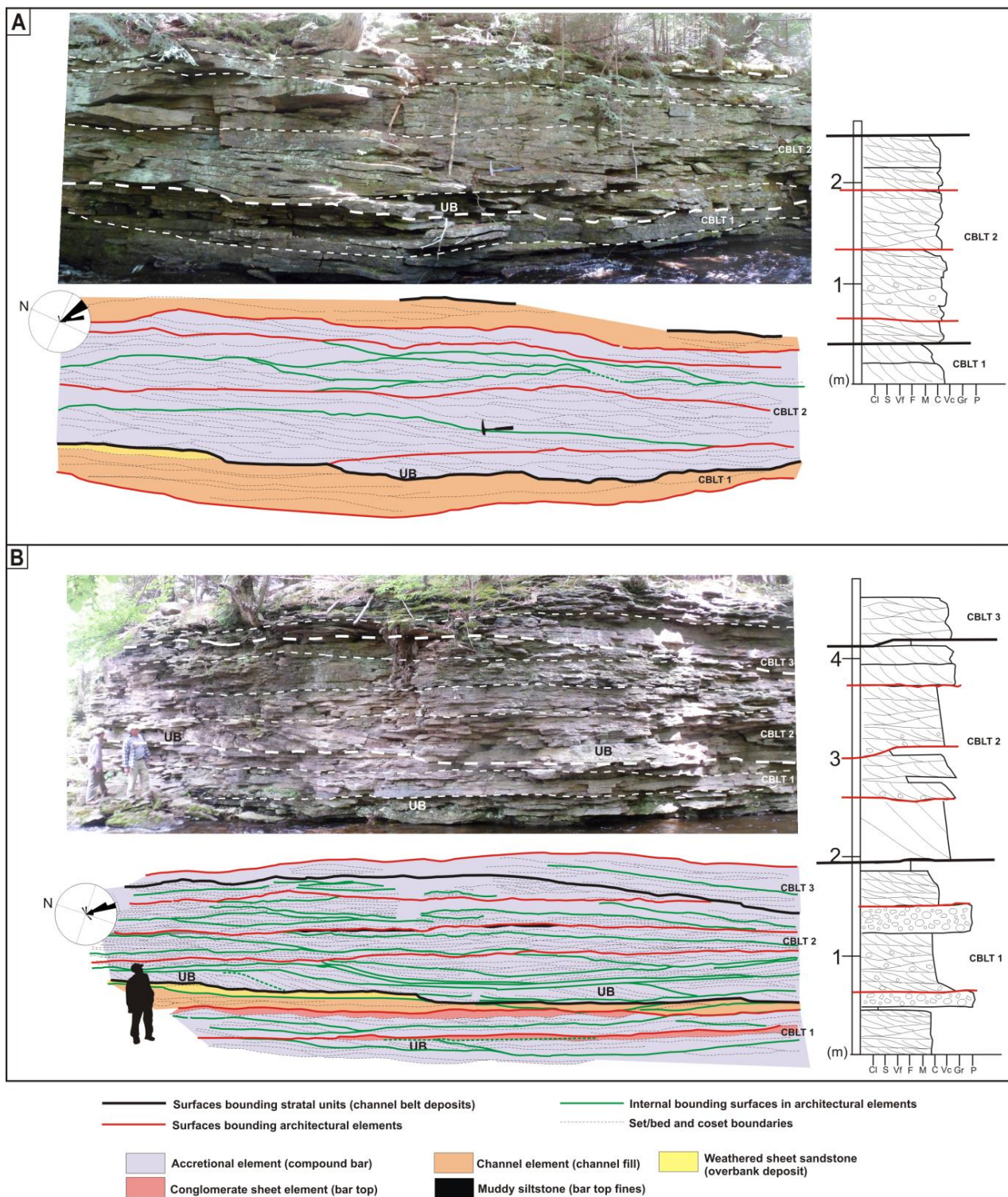


Figure 4.4 Common subfacies of FA1 (braided fluvial). A) Thin to thick (5-20 cm), high-angle trough cross-laminated sets interpreted to be formed by migrating subaqueous 3D dunes (F1c) – coin (2.8 cm diameter) for scale; Ausable Formation, Ile Perrot, QC (locality 194). B) Thick (1.7 m), high-angle planar-cross-laminated set (arrow indicates top of set) interpreted to be formed by the migration of a solitary unit bar (F1d); Ausable Formation, near Briton Bay on Big Rideau Lake, ON (locality 12). C) Imbricated cobble orthoconglomerate with rounded to subround quartzite clasts, interpreted as gravel-bedload sheet deposits (F4a); Ausable Formation, same location as B), staff is 90 cm long. D) Poorly sorted, structureless boulder conglomerate interpreted as boulder talus (F4b), hammer for scale (near top); Highway 417 near Brockville, ON (locality 73). E) Thin (3 cm), sharply bounded interbed of normally-graded, fine-grained sandstone (F3a) in a thick pile of coarse-grained sandstone (layer bounded by dashed white lines); Ausable Formation, Great Chazy River North Branch near Ellenburg, NY (locality 228). F) Photomicrograph of bed in E) showing detrital quartz (Q), and skeletal and degraded detrital feldspar (SF and DF, respectively; outlined) and expanded (hydrated) biotite (Bt).



Channel elements are rare overall (~13%) and typically incise a succession of one or more accretional elements. Channel elements are 20 cm – 3.5 m deep and bounded at their base by low angle (<20°), 20 cm – 2.5 m deep concave-up scours that extend laterally for 8 m to ≥ 120 m (maximum limited by outcrop dimensions). They are filled with coarse-grained, dune cross-stratified sandstone with horizontal set boundaries rarely interstratified with 10 – 40 cm thick horizontal beds of imbricated pebble or cobble conglomerate (Figs. 4.5, 4.7). This fill is typically normally-graded and dune cross-sets thin upward.

Isolated scour elements are even rarer than channel elements (only ~1% of FA1). Where present, they incise into amalgamated accretional elements and/or channel elements, and in turn are overlain by stacked and amalgamated accretional elements. The scour elements are bound at their base by 0.6 – 2 m deep, 4 – 20 m wide, steep-sided (15 – 25°) erosional surfaces that are symmetrical in sections oriented at a high angle to the local

Figure 4.5 (previous page) **Stratal architecture of braided fluvial (FA1) deposits from the Ausable Formation, including interpreted bounding surfaces and architectural elements. Rose diagrams show paleoflow distributions measured from dune and unit-bar cross-stratified sets. Scale of measured logs is in metres. UB = unit-bar cross-stratified sandstone. A) Outcrop along Graves Brook near Ellenburg, NY (locality 154). Here an entire channel-belt succession (i.e., stratal unit, CBLT 2) dominated by low-angle, downstream-accreting compound-bar deposits (i.e., accretional elements) and overlain by a thin abandonment channel (i.e., channel element) crops out. Dune cross-stratification dominates the facies assemblage. CBLT 2 overlies a lower channel belt (CBLT 1) that on the far left is overlain by a sheet element consisting of fine-grained, preferentially weathered overbank sandstone deposits (see Figure 4.4e - f). B) Outcrop along Great Chazy River, North Branch near Ellenburg NY (locality 228), exposing the lower part of a channel-belt succession (CBLT 1) erosionally overlain by a younger channel-belt succession (CBLT 2); both units are dominated by dune cross-stratified sandstone. The lower channel-belt succession comprises several downstream-accreting compound-bar deposits capped by bar-top sheets (i.e. conglomerate sheet elements), and overlain by abandonment channels and a subaerially weathered overbank deposit. The upper channel-belt succession is made up of unit-bar cross-stratified sandstone (UB) overlain by stacked low-angle downstream-accreting compound bars. Thin muddy siltstone layers, interpreted as bar-top fines, are present locally at the top of the second compound-bar succession.**

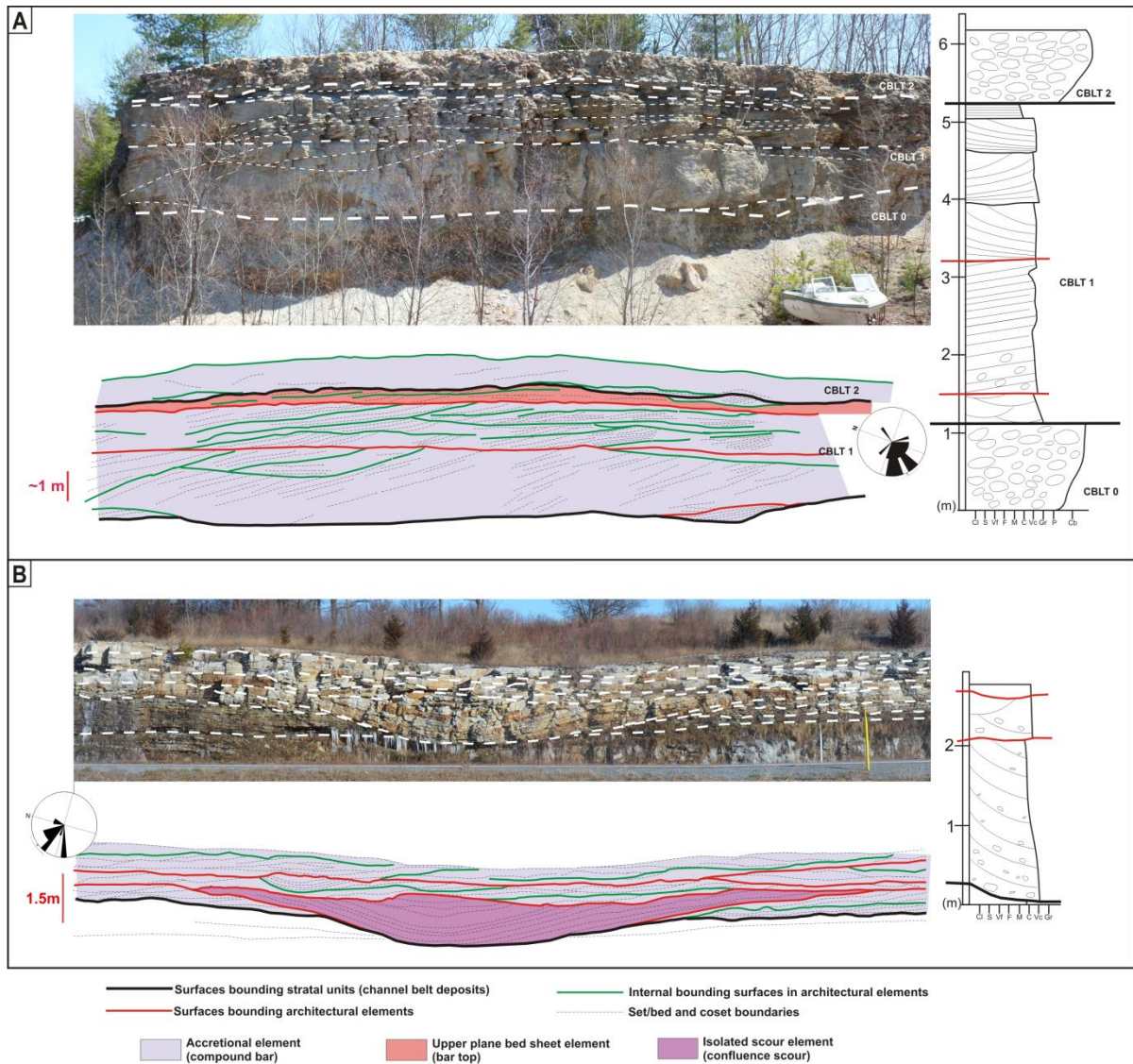


Figure 4.6 Additional examples of braided fluvial (FA1) stratal architectures. Rose diagrams show paleoflow distributions measured from dune and unit-bar cross-stratified sets and clast imbrication. A) Outcrop of the Ausable Formation in a quarry near Briton Bay on Big Rideau Lake, ON (locality 12). Here a coarse-sandstone-dominated channel-belt succession (CBLT 1) dominated by compound bars crops out. The basal bar succession consists mainly of a single, high-angle, laterally accreting unit bar with minor internal truncation surfaces; in contrast the overlying bar is made up of obliquely accreted unit bars and/or large dunes. This succession is overlain and underlain by partly exposed channel-belt successions consisting mostly of tractional conglomerates deposited by low-relief gravel bars, which provide paleoflow from clast imbrication. B) Outcrop of the Keeseville Formation along Interstate 81 on Wellesley Island, NY (locality 236). This section exposes an almost complete channel-belt succession dominated by downstream-accreted compound-bar successions with a large confluence scour filled by boundary-conformable unit-bar cross-stratified sandstone near its base.

paleoflow direction. They are filled with simple boundary-conforming cross-stratified coarse- to medium-grained sandstone, commonly with dispersed pebbles (Fig. 4.6b).

The remaining ~2% of braided fluvial strata consist of sheet elements (i.e. tabular beds), including sheets composed of coarse-grained, upper plane bed sandstone (F2a), tractional bedload pebble conglomerate (F4a), muddy siltstone (F5a) and fine to very fine normally-graded matrix-rich sandstone (F3a). The former two are 5 – 20 cm thick and cap about a third of all accretional elements (Figs. 4.5 – 4.6), whereas muddy siltstone sheets are 0.5 – 4 cm thick and overlie only about an eighth of all accretional elements (Fig. 4.5b). Sheets consisting of fine to very fine normally-graded sandstone, on the other hand, are 3 – 7 cm thick, laterally extensive (at least over 500 m), and overlie amalgamated accretional elements and/or channel elements (Figs. 4.4e – f, 5, 7). These F3a sheets contain petrographic evidence for chemical alteration not observed in adjacent strata, including degraded textures of feldspars and micas such as skeletal remnants, embayed margins and kaolinite intergrowths in feldspar and swelling and clay and iron-oxide intergrowths and replacement in micas (Fig. 4.4f). Furthermore, these sheet elements contain ~15 – 35% interstitial matrix, including iron-rich clays and fine to coarse silt that drape sand grains and occlude pore space.

4.3.2 FA1 interpretation: Braided fluvial

The large majority (~98%) of lithofacies of FA1 record coarse-grained bedload transport in energetic, steady unidirectional subaqueous currents by the migration of dunes,

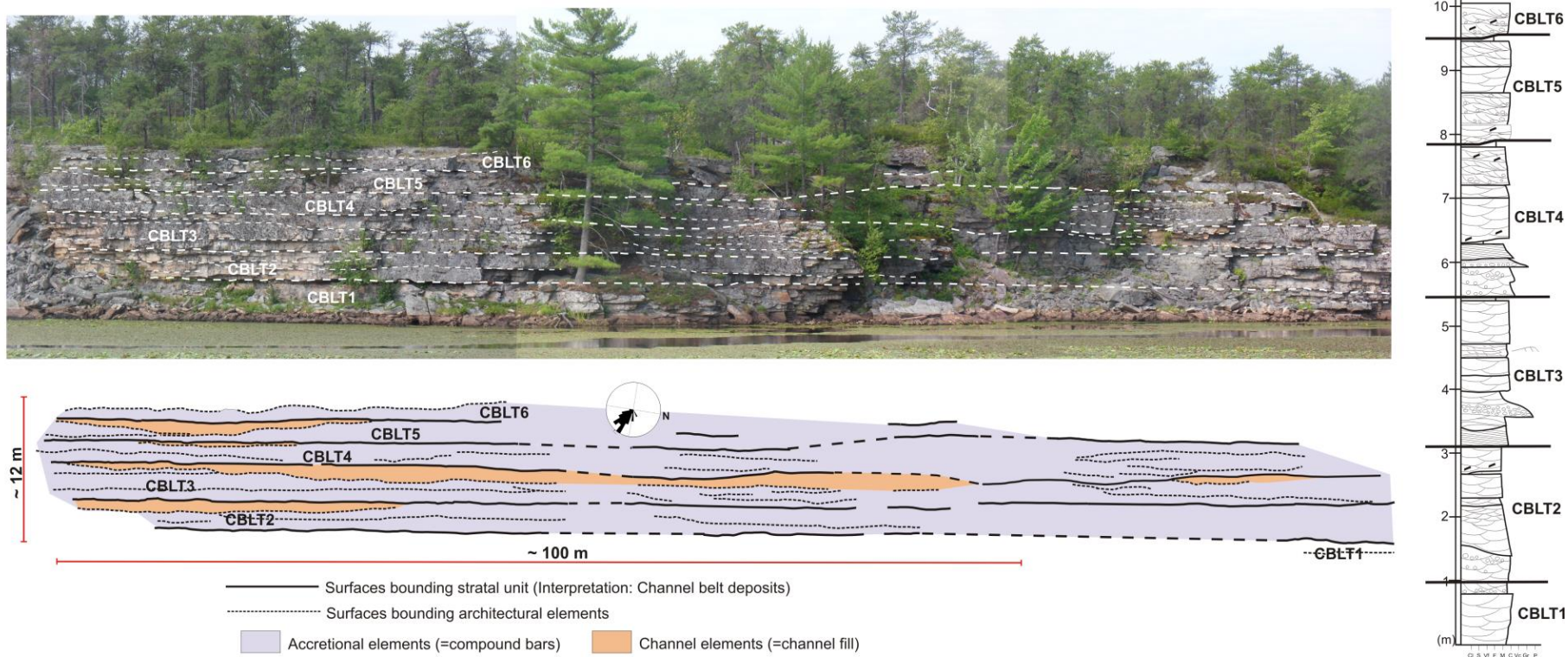


Figure 4.7 Outcrop section from Altona Flat Rock State Forest near Altona, NY (locality 252) showing large-scale architectural organization of braided fluvial (FA1) strata in the Ausable Formation. The section is subdivided by laterally continuous surfaces into six channel-belt successions (CBLT1 – CBLT6). Each channel-belt succession is dominated by multiple low-angle compound-bar deposits. These, then, are erosionally overlain by abandonment channels that mark the tops of most channel-belt deposits. The stratigraphic section shown on the right was measured along a number of smaller ledges ~ 50 m to the right of the outcrop photo and sketch.

unit bars and tractional gravel (see Table 4.1). Furthermore, the presence of complex compound dune and/or unit bar cross-stratification in accretional elements suggests the incremental build-up of bedforms into high energy composite macroforms – most likely bars or alternatively compound dunes. Furthermore the lack of bioturbation or other marine or tidal indicators suggest sedimentation in a high energy braided fluvial environment with widespread deposition of channel-filling and bar-forming sand and gravel in braided channels.

Architectural elements of FA1 are interpreted to represent the various geomorphic components common to modern and ancient braided fluvial systems. For example, the ubiquitous accretional elements of FA1 are interpreted to be in-channel and bank-attached compound bars, which are pervasive composite macroforms in modern braided rivers that consist of multiple accreted compound dunes, unit bars and rarely bedload gravels (Hein and Walker 1977, Lunt and Bridge 2004, Bridge and Lunt 2006). The lateral extent (in some cases >200 m), thickness and shallow inclination of bounding and internal surfaces (e.g., Figs 4.5, 4.6b and 4.7) suggests that the formative compound bars were mostly thin, low relief features with shallowly dipping margins. Within each compound bar deposit, each dune coset, which is truncated by locally dipping ($\sim 1 - 35^\circ$) internal surfaces (e.g., Figs. 4.5 – 4.6), is interpreted to record the accretion of bedload material during a single bankfull discharge event. Following accretion, each coset underwent a period of subsequent erosion, leading to the development of a new internal bounding surface upon which a younger accreted coset overlapped. Unit bars, which preferentially occur at the base of accretional elements, probably acted as the nuclei for the initiation and subsequent growth of compound bars as they do in modern compound bars (Bridge and Lunt 2006). By and large, accretional

elements exhibit downcurrent accretion given that set boundaries and internal bounding surfaces dip in the same general direction as local paleoflow (Fig. 4.5, 4.6b). This suggests that most compound bars experienced erosion along their heads and margins with preferential deposition on the bar tails, with very little lateral accretion or migration of bars and adjacent channels. Overall, the high relative abundance of accretional elements (~84%) suggest that braided fluvial sedimentation was dominated by the accretion and migration of bedload material in the form of low relief compound bars in laterally-extensive, shallow, low-sinuosity multi-thread braided channels. Notably however, high-order erosional channel margins are not observed, which is interpreted to be a consequence of poor preservation in the absence of bank-stabilizing vegetation or cohesive fine-grained sediment (e.g., Davies et al. 2011).

Rare isolated scour elements, high-relief scours filled by coarse-grained boundary conformable cross-stratified sandstone overlain by stacked accretional elements, are interpreted to be analogous to “hollow elements” described by Miall (2010). Accordingly, they formed from erosion downstream of high angle (generally $\geq 20^\circ$) channel confluences, in this case most likely located at the tails of large compound bars at the confluence between two anabranches of a braided river (e.g. Ashmore and Parker 1983, Best 1987, Bridge 1993, Best and Ashworth 1997, Lunt et al. 2004, Borghei and Sahebari 2010, Miall 2010). Here the formation of deeply-incised scours downstream of large mid-channel compound bars were subsequently filled by advancing tributary mouth unit bars, which later became buried by downstream-migrating compound bars (e.g., Lunt et al. 2004).

Rare erosively-based channel elements filled with simple coarse-grained dune cross-strata and incised into stacked compound bar deposits, are interpreted to record the erosion

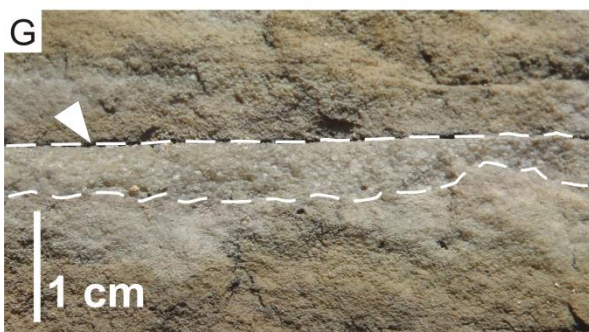
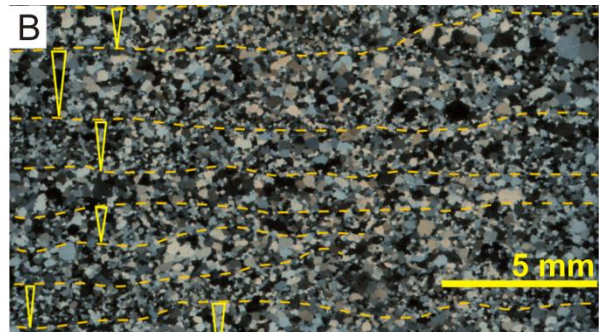
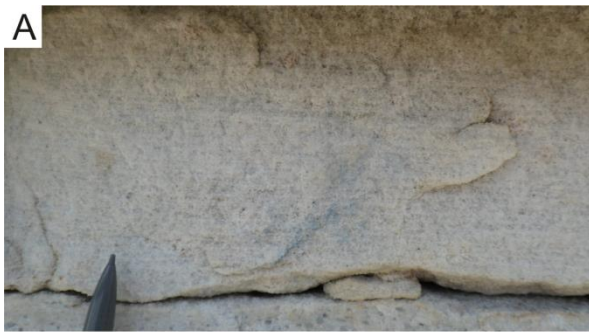
and backfill of channels without the formation of aggrading in-channel or bank-attached bars (Table 4.1). These therefore represent a special set of sedimentological conditions that deviate significantly from the deposition and migration of ubiquitous compound bars in laterally-extensive channels. Specifically, channel elements are interpreted to have formed a braided network of erosional channels that incised and reworked pre-existing compound bar deposits under conditions of net erosion or bypass. Following incision, they were aggradationally filled with coarse- to medium-grained dunes during one or more flood events under conditions of progressively decreased discharge and sediment flux, as evidenced by upward fining and decrease in dune set thickness. Channel elements therefore record the periodic and/or localized progressive shut-down of fluvial discharge, probably due to upstream avulsion (see *Stratal Elements* for more details).

Most sheet elements, including those composed of upper plane bed sandstone, tractional pebble conglomerate and muddy siltstone, are relatively thin (≤ 20 cm) and cap accretional elements. Thus, they most likely formed on the tops of compound bars. Accordingly, both upper plane bed sandstone and tractional conglomerate sheets are interpreted to record sediment winnowing by high speed, shallow water bar-top flows coinciding with waning flood flows. Muddy siltstone, on the other hand, are interpreted as fine-grained suspension deposits that accumulated in intra-bar pools, abandoned (cut-off) channels or in bar-tail regions as the mid channel bars matured and became inactive (e.g. Best et al. 2003). On the other hand, the laterally extensive 3 – 7 cm thick sheet elements consisting of normally-graded fine to very fine sandstone (F3a) and making up only ~1.5% of measured sections (Table 4.1) are not evidently genetically related to accretional elements or any other element, and thus like channel elements represent a special set of

sedimentological conditions. Based on their normally-graded character, these elements were most likely deposited from bedload and suspended load during the low energy, waning stage of a flow. Furthermore, on the basis of the evidence of preferential chemical-mineral alteration they were likely subject to prolonged near-surface weathering in which they were commonly in contact with near-surface meteoric pore water leading to hydrolysis, oxidation and hydration of labile detrital minerals. Finally, the ~15-30% interstitial matrix, capping, draping and surrounding hydraulically-unequivalent sand grains, is interpreted as an infiltrated matrix deposited in the pore space of the fine sand by illuviation. On the basis of evidence for rapid deposition, weathering and illuviation, as well as their lateral continuity (≥ 500 m), these elements are interpreted as floodplain deposits formed mainly by rapid deposition of fine-grained bedload and suspended load in waning overbank floods. Following deposition, these strata were subject to longer periods of exposure in a generally humid, water-saturated setting, before being buried by subsequent braided fluvial channel belt sedimentation.

4.3.3 Facies Association 2 (FA2)

Facies association 2 (FA2) occurs in the Keeseville Formation as two units separated by a braided fluvial unit (FA1, see previous section, Figs. 4.2 – 4.3). The lower of the two units (FA2A on Fig. 4.2 – 4.3) forms two major outcrop/subcrop belts; one along the northwestern margin of the Adirondack Lowlands over an area of ~ 1400 km² with thicknesses of ~ 3 – 17 m, and another along the northeastern margin of the Adirondacks covering an area of ~ 700 km² with thicknesses of ~ 15 – 35 m (Fig. 4.2). The upper unit of FA2 (FA2B on Fig. 4.2 – 4.3) also forms two major outcrop/subcrop belts, one along the



northwestern margin of the Adirondack Lowlands over an area of $\sim 1200 \text{ km}^2$ with thicknesses of $\sim 2 - 5 \text{ m}$, and the other covering a much larger area ($\sim 13,000 - 14,000 \text{ km}^2$) in the northern Ottawa Embayment and western Quebec Basin that thickens southeastwards from $\sim 1.5 \text{ m}$ near Ottawa to $\sim 34 \text{ m}$ along the northeastern margin of the Adirondacks (Fig. 4.2).

Strata of FA2 are dominated by moderately- to well-sorted planar-stratified medium-grained sandstone (F2, 72%) and subordinate medium- or coarse-grained cross-stratified sandstone (F1, 28%, Table 4.1). Planar stratified sandstone consist predominantly of inversely-graded wind ripple laminations (F2b), subordinate adhesion stratification (F2c), windblown deflation lags (F2d), and rare upper plane laminations (F2a) (Table 4.1; Fig. 4.8). Less abundant cross-stratified sandstone consists mostly coarse-grained, upstream-dipping supercritical bedform strata (F1e, F1f, F1g), rare coarse-grained dune cross-strata (F1c), medium-grained 2D current ripple cross-strata (F1a) and depth limited wave ripple cross-strata and formsets (F1b) (Table 4.1; Figs. 4.8 – 4.10).

Architecturally, the majority (70%) of FA2 consists of stacked and amalgamated 10 – 95 cm thick sheet elements (i.e. tabular to low-angle lenticular beds), consisting mainly of moderately well- to well-sorted medium-grained, mostly planar-stratified sandstone (Figs.

Figure 4.8 (previous page) Common planar-stratified and small-scale cross-stratified sandstone subfacies and associated features in ephemeral fluvial strata (FA2). A) Outcrop photo and B) photomicrograph of inversely graded sandstone laminae interpreted to be formed by migrating wind ripples (F2b); Keeseville Formation, Ducharme Quarry near Covey Hill, QC (locality 203). C) Low-relief wind-ripple formsets exposed on a bedding plane; Keeseville Formation, quarry near Ellisville, ON (locality 68). D) Bedding plane of low-relief, asymmetrical adhesion ripples (F2c); Keeseville Formation, Ducharme Quarry near Covey Hill, Quebec. E) Pock-like adhesion warts on the bedding surfaces of F2c sandstone; Keeseville Formation, Keeseville, NY (locality 244). F) Diffusely banded adhesion stratification (F2c); Keeseville Formation, Highway 12 near Chippewa Bay, NY (locality 86). G) Coarse-grained lamination interpreted to be a deflation lag (F2d; outlined with dashed line); Keeseville Formation, Highway 12 near Chippewa Bay, New York (locality 86). H) Polygonal desiccation cracks; Keeseville Formation, Altona, NY (locality 152). I) Very thin, cross-laminated sandstone and asymmetrical formsets (arrow) interpreted to be formed by 2D current ripples (F1a); Keeseville Formation near Elgin, ON (locality 47). J) Bedding plane of symmetrical, straight-crested formsets interpreted to be formed by depth-limited oscillation ripples (F1b); Keeseville Formation, on Highway 37 near Hammond, NY (locality 82).

4.11 – 4.13). Sheet elements appear to extend across the width of even the largest outcrops (~850 m), although low angle truncations are present locally (Figs. 4.11 – 4.13).

Nevertheless, tracing individual sheet elements laterally is difficult due to the lithological homogeneity of stacked sheet elements and the generally small size of most outcrops.

Internally, sheet elements consist mostly of planar-stratified windblown sandstone facies, primarily shallowly dipping ($\sim 1\text{--}5^\circ$) wind ripple laminations (F2b, Fig. 4.8a – c), adhesion laminations and related adhesion bedforms (F2c, Fig. 4.8d – f) and upper medium- to coarse-grained deflation lags (Table 4.1; Fig. 4.8g,). Rare depth-limited wave ripple laminations and formsets (F1b, Fig. 4.8j), upper plane bed laminations (F2a) and 2D current ripple strata and formsets (F1a; Fig. 4.8i) are also present. No consistent alternation or repetitive stacking pattern of lithofacies is observed. Furthermore, $\sim 3\text{--}12\%$ interstitial matrix is present, mainly in wind ripple and adhesion laminations, where it coats the upper parts of grain surfaces and locally inhibits silica overgrowths.

Accretional elements are rare (6%), 25 cm – 1.8 m thick lenticular packages that consist of a similar lithofacies assemblage as sheet elements, but have more internal stratal complexity and with a greater proportion of shallow waterlain deposits. Namely, wave ripples, 2D current ripples and upper plane bed laminations are comparatively more abundant. Where accretional elements are present they are commonly intercalated with sheet elements or rarely stack repetitively (Fig. 4.12). Accretional elements are bound by low angle ($2\text{--}12^\circ$) surfaces that truncate $\sim 3\text{--}9$ cm thick, dipping ($3\text{--}15^\circ$) tabular accreted strata (Fig. 4.12). These strata are composed of “drying-upward” successions consisting of a lower layer of upper plane bed and/or 2D current ripple and/or depth-limited wave ripple stratification overlain by damp adhesion (F2c) and/or dry wind ripple (F2b) stratification and/or a

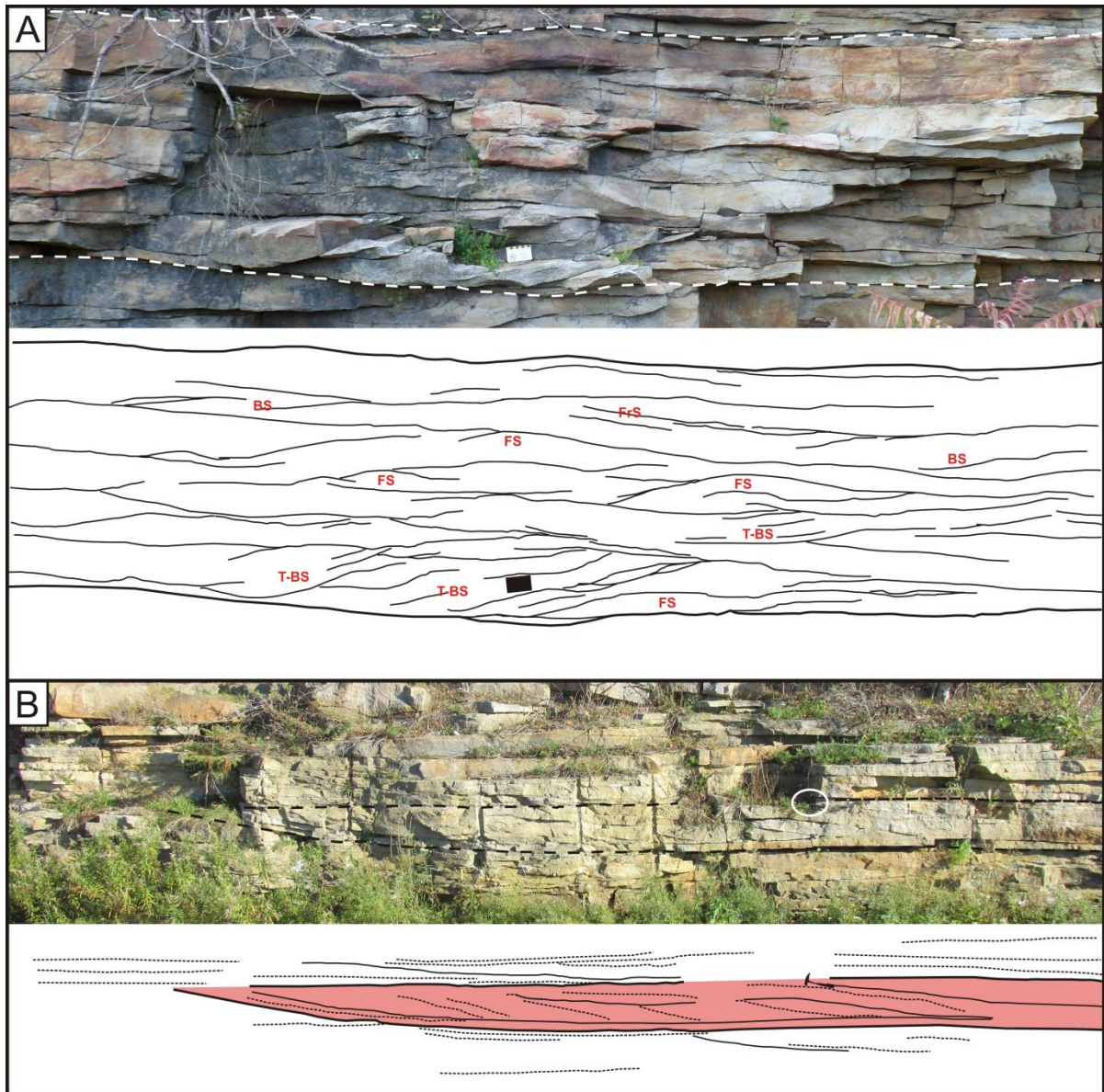


Figure 4.9 Examples of cross-stratified sandstone interpreted as supercritical bedform strata in FA2. A) Thin to thick (6-20 cm), low-angle concavo-convex trough cross-stratified sets and symmetrical formsets interpreted to have formed by migrating antidunes (F1e) under high rates of bed aggradation; on Highway 37 near Hammond NY (locality 96). Labeled here are features that correspond to documented stratal forms of antidunes from Alexander et al. (2001), including trough cross-stratified upstream-dipping backsets (T-Bs), symmetrical “hummocky” formsets (FS) and rare downstream-dipping foresets (FrS). Scale card in lower center of photo is 8 cm. B) Thick (~ 55 cm), low-angle sigmoidal scour-filling cross-stratified set interpreted to be formed by the local and temporary development of a high-energy hydraulic jump, i.e., chute-and-pool stratification. Mean local paleoflow determined from associated dune and ripple cross-strata (although not present here) is toward the left. The sigmoidal geometry is characterized by upward and lateral changes in stratal dip and is interpreted to be related to hydraulic jump surging, temporary stabilization, and subsequent wash-out (see text for details). Highway 12, near Alexandria Bay, NY (locality 100). Hammer for scale (outlined by white circle).

deflation lag in the upper 3/4 to 1/8 of the units. Polygonal desiccation features, although uncommon, are observed on the top of some units (Fig. 4.8h).

Incising into stacked sheet $\pm$ accretional elements are channel and scour elements filled with sets or cosets of upper medium to coarse-grained cross-stratified sandstone recording high-energy waterlain deposition (Tables 4.1; Figs. 4.11 – 4.13). Channel elements are rare (~6%) and are filled with moderately well-sorted, lower medium- to upper coarse-grained, 3D dune cross-stratified sandstone (F1d) bound by undulating scours at their bases and low angle ($\sim 5 - 12^\circ$) erosional surfaces along their margins (Fig. 4.11a). They range from 20 – 90 cm deep and $\sim 3 - \geq 120$ m wide (perpendicular to flow, maximum limited by outcrop dimensions). Typically, channel fills grade upward from upper to lower medium sandstone, and exhibit an upward decrease in the thickness of dune cross-bed sets.

Scour elements are more common than channel elements (~18%) and are filled by unique types of moderately well-sorted, upstream-dipping coarse-grained cross-stratified sandstone. These cross-strata are interpreted to have formed by the migration of upcurrent-accreting bedforms under flow surface instabilities (standing waves, hydraulic jumps) in shallow and high velocity supercritical flows (F1e-f; Table 4.1, Figs. 4.9 – 4.13). Specifically, antidune stratification (F1e, Figs. 4.9a, 4.11 – 4.13), chute-and-pool stratification (F1f, Figs. 4.9b, 4.11, 4.13) and cyclic step stratification (F1g, Figs. 4.10, 4.11, 4.13) are recognized (see chapter 2 for more details). Although not well represented in the sedimentary literature, these supercritical bedform strata are recognized on the basis of comparisons to rare descriptions of supercritical bedform strata from sedimentary rocks (Rust and Gibling 1990, Cotter and Graham 1991, Fralick, 1999, Fielding 2006), and to stratification produced experimentally by Alexander et al. (2001) and Cartigny et al. (2014).

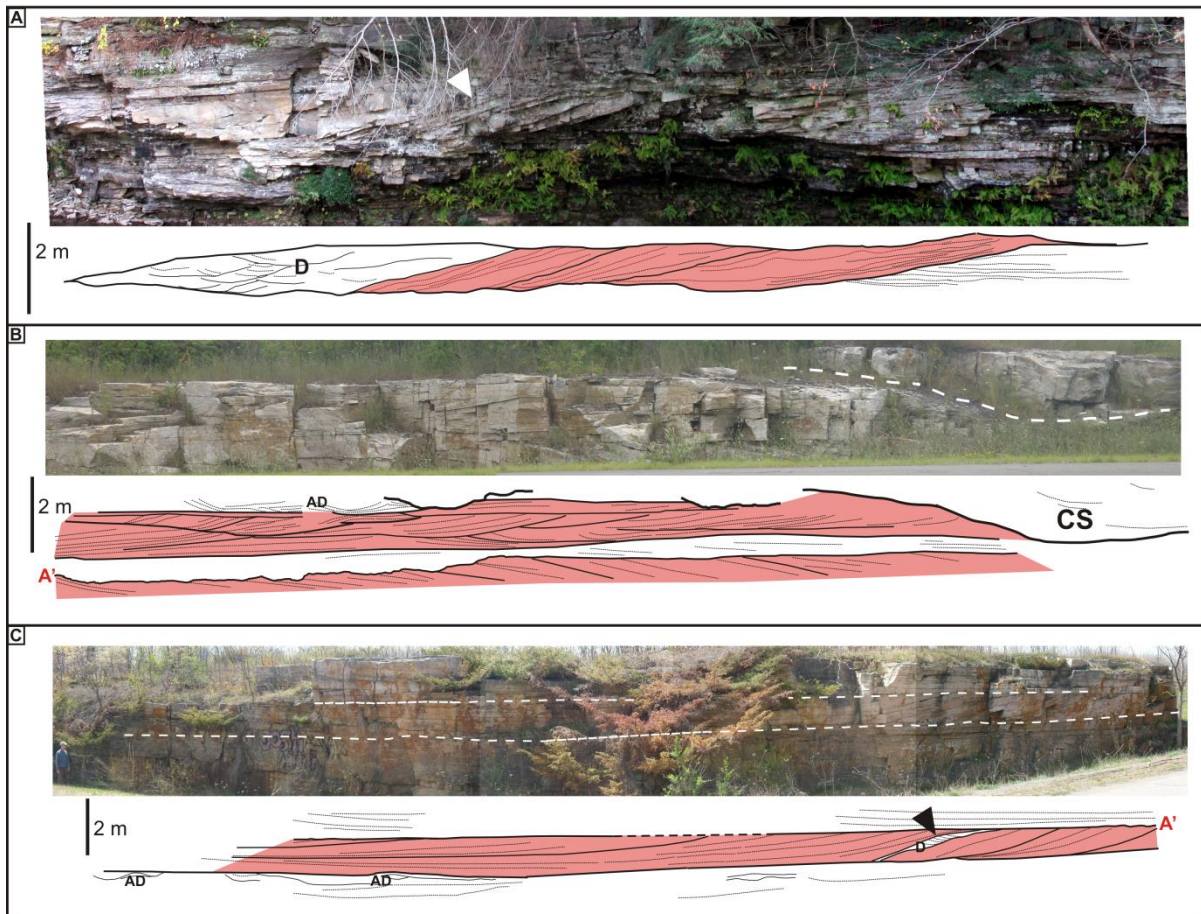


Figure 4.10 Examples of thick (1.3 – 1.5 m), high-angle trough cross-stratified sets interpreted to be formed by the migration of cyclic steps. A line tracing accompanies each photo and highlights the interpretation with cyclic-step strata in red. A) Large scour filled by upstream-dipping cyclic-step sets and, on the upstream end, a symmetrical scour (base indicated by arrow) filled by dune cross-stratified sandstone (“D” in diagram) interpreted to record the final position (and fill) of the cyclic-step trough at the onset of subcritical flow conditions. Chateauguay High Falls (above waterfall) near Chateauguay, NY (locality 168). B), C) cyclic-step cross-strata at the intersection of Cemetery Road and Highway 37 near Hammond, NY (locality 85). Part B is oriented normal to paleoflow with flow toward reader, and part C is oriented parallel to paleoflow with flow to the right. A’ on the line drawings marks where the two outcrop faces meet. The cyclic-step set is outlined by a white dashed line in part C (outcrop photo). A single downstream-migrating dune cross-stratified set (“D” in panel C and indicated by arrow) crops out on a surface that separates two cyclic step sets. Antidunes (“AD”) are interstratified with cyclic-step sets. In part B ephemeral fluvial strata, here mainly cyclic-step strata, are erosionally truncated by a deep braided fluvial confluence scour (“CS”).

Scour elements filled by antidune cosets are bounded at their lateral, upstream and downstream margins by low to high angle ($\sim 5 - 40^\circ$) scour surfaces that merge with a

generally horizontal but undulating erosional base (Figs. 4.9a, 4.11b, 4.12a, 4.13). The scours are 0.4 – 1.9 m deep, ~20 – ≥210 m wide and 70 – >400(?) m long, and antidune cosets are 2 – 12 sets thick with common convex-up antidune formsets (Fig. 4.9a, 4.11b, and 4.12a). In contrast to antidune-filled scour elements, each scour element filled by either chute-and-pool or cyclic step strata are filled with a single set. Scour-filling chute-and-pool sets are recognized as single 15 – 30 cm thick sigmoidal sets that fill isolated asymmetric upstream-dipping scours, ~3 – 15 m in length and ~8 – 25 m in width (Fig. 4.9b, 4.11a, 4.13). Finally, cyclic step strata crop out as trains of relatively high angle (15 – 35°), upstream-dipping sets that fill elongated scours 35 cm – 1.2 m deep, 15 – >120 m wide, 25 – >150 m long bounded at their lateral, upstream and downstream ends by ~5 – 40° scour surfaces that merge with a generally flat erosional base (Figs. 4.10 – 4.11, 4.13). These scours occur as isolated, regularly-spaced (~60 – 120m) features along a single stratigraphic horizon.

4.3.4 FA2 Interpretation: Sheetflood Dominated Ephemeral Fluvial

FA2 consists of ubiquitous planar-stratified and sheet and rare accretional elements, both of which are mostly aeolian with minor shallow water deposits, incised by lesser scour-filling supercritical flow strata and rare channel elements filled with dune cross-strata. This association suggests two seemingly end-member styles of deposition: dry to damp windblown sand sheet deposition and high-energy waterlain deposition. The fact that aeolian-dominated sheets make up most of the stratigraphy (Table 4.1) would intuitively suggest that aeolian processes were the primary agent for sediment transport and deposition. However, this was unlikely given the coarseness of the sediment (average upper medium sandstone), the common occurrence of coarse-grained deflation lags (F2d), and the lack of

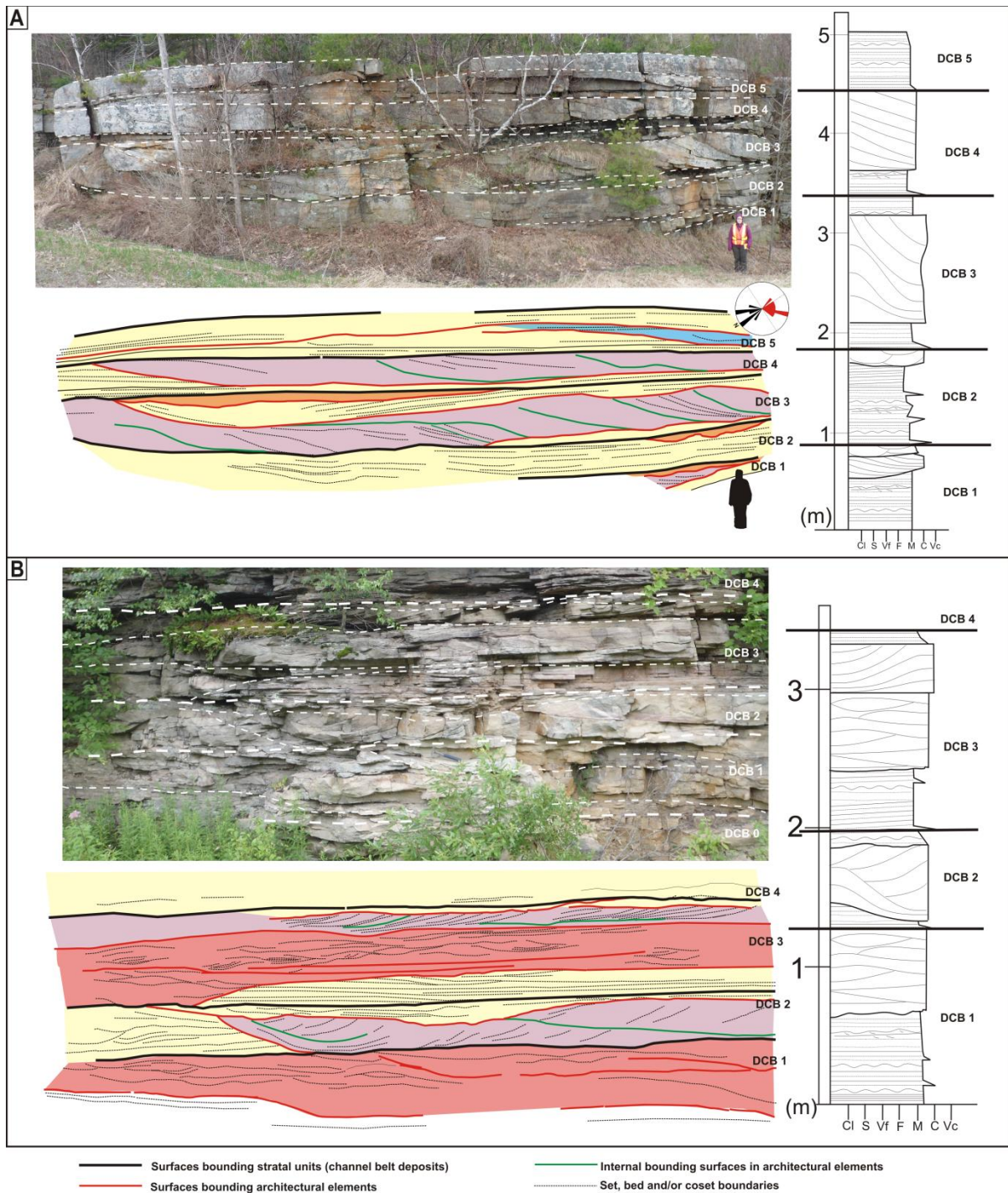


Figure 4.11 Stratigraphic architecture of ephemeral fluvial (FA2) strata from the Keeseville Formation, including interpretations of bounding surfaces and architectural elements. Rose diagrams show paleoflow distributions (black indicates measurements from ripple and dune cross-strata; red indicates supercritical-bedform strata). Vertical scale of measured logs is in metres. A) Outcrop along Highway 12 near Alexandria Bay, NY (locality 100). Here five distributive channel belt (DCB) successions crop out (DCB 1 – 5). Terminal-splay deposits (i.e., sheet elements) are erosionaly overlain by upstream-migrating, scour-filling cyclic-step sets and rare chute-and-pool sets recording high-energy sheet-flood conditions. Shallow channel elements record the incision and subsequent abandonment and filling of distributive channels. B) Outcrop along Milsap Road near Schermerhorn Landing, NY (locality 102). This section is similar to part A, but also includes erosional antidune cosets.

stratification formed by aeolian dunes, which are ubiquitous in modern and ancient aggradational aeolian sedimentary systems (i.e., dune fields, ergs; Kocurek and Havholm 1993, Mountney 2006b). These features (or their absence, as with aeolian dunes) in association with high energy sheetflood and lesser channelized waterlain strata, instead suggest conditions of windblown deflation, aeolian reworking and armouring of existing waterlain deposits with grain sizes that typically exceed the conveyance threshold of aeolian transport. Similar conditions and associated planar aeolian strata occur on the upwind margins of modern dune fields and alluvial fans where windblown reworking of pre-existing waterlain sediment dominates (e.g., Fryberger et al. 1979, Kocurek and Neilson 1986), and similar assemblages and depositional conditions have been previously described from ancient sheet-flood dominated ephemeral fluvial strata including the Lower Cambrian Nexø Formation (Clemmensen and Dam, 1993) and the Upper Triassic Blomidon Formation (Hubert and Hyde, 1982). Accordingly, FA2 is interpreted to record deposition in an ephemeral fluvial environment in which episodic, mostly unconfined sheetfloods were the principal agents of sediment transport and deposition. Following episodic high discharge events, most of the fluvial flood deposits were reworked by aeolian processes and moulded into a variety of local, low-relief windblown structures during the long recurrence intervals between floods (100 – 1000 years, Knighton and Nanson 1997). Owing to their thickness and subsurface position (i.e., occurring as scour fills), rare high energy supercritical bedform strata in FA2 were less susceptible to aeolian reworking and thus provide a direct record of depositional sheetflood events.

Modern ephemeral fluvial systems are characterized by episodic floods with downstream declining discharge due by transmission loss from infiltration, overbank

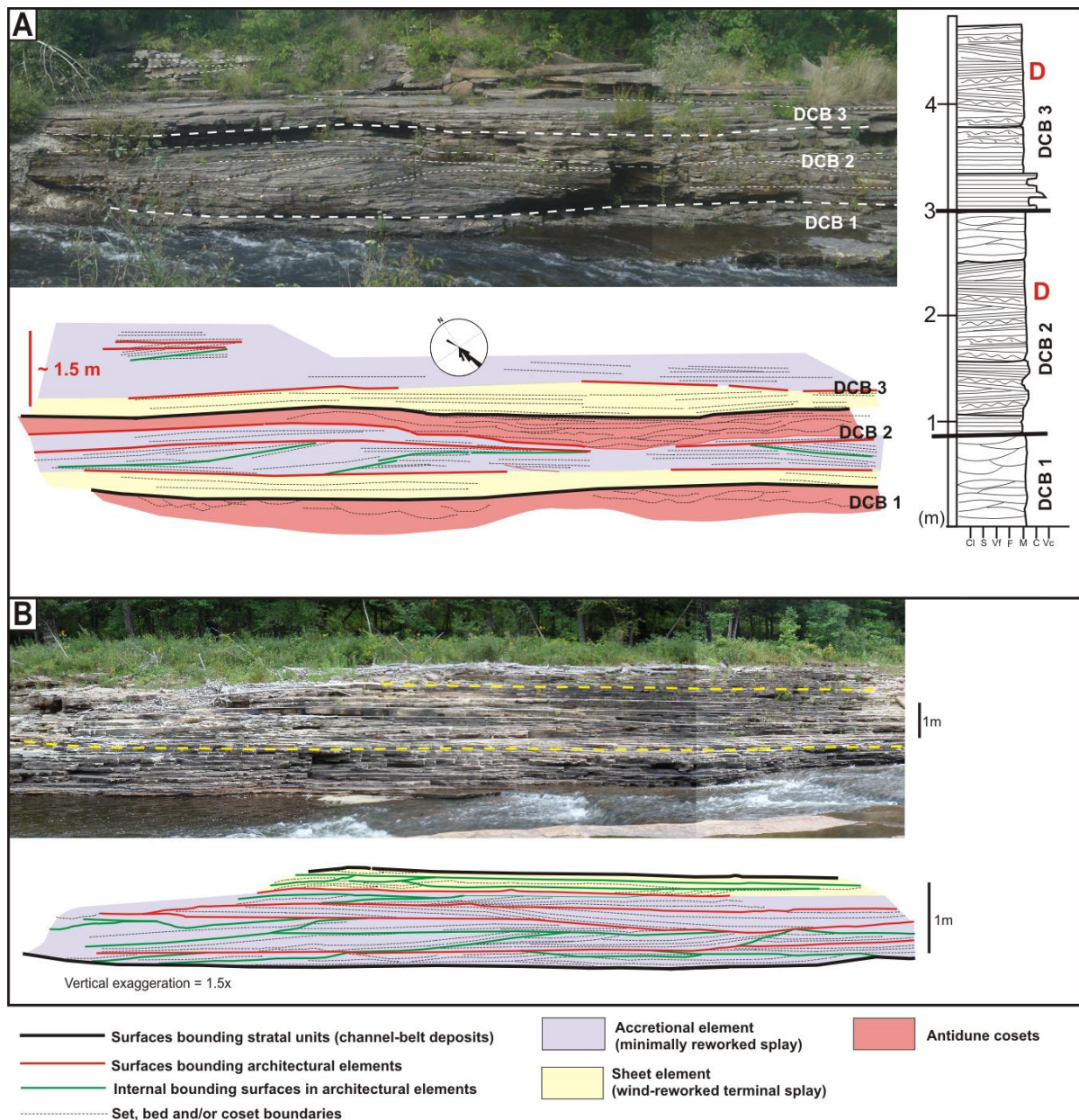


Figure 4.12 Additional examples of ephemeral fluvial (FA2) deposits in the Keeseville Formation along the Great Chazy River in Altona, NY (locality 152). Rose diagrams show paleoflow distributions from dune cross-strata. Vertical scale of measured logs is in metres, D = desiccation cracks. Here low-angle accretional elements dominate and are interpreted to be splays subject to more frequent sheet flooding (i.e., shorter recurrence interval) compared to sheet elements (see text for details). **A**) Section consisting of three DCB successions (DCB 1 – 3). The middle DCB succession is complete and consists of an eolian-reworked splay (i.e., sheet element) overlain by a splay with minimal eolian reworking (i.e., accretional element), which then is incised by an erosional antidune coset. Angles of accretion on the left side of the middle splay (accretional element) are exaggerated due to outcrop relief. **B**) An ephemeral fluvial DCB succession (bounded by yellow dashed lines in photo and by solid black lines in sketch) that is dominated by minimally reworked splay deposits (i.e., accretional elements) capped by a single more pervasively eolian-reworked splay (i.e., sheet element).

flooding and evaporation (Knighton and Nanson 1997, Tooth 2000a). Due to the episodic and rapidly declining nature of ephemeral floods, most ancient and modern sheetflood-dominated ephemeral fluvial systems form distributary networks (i.e., fans) in which relatively stable but generally erosional trunk channels feed a distributive network of channels and further down flow (depositional) splays (i.e., “floodouts”; e.g., Tunbridge 1984, Abdullatif 1989, McCarthy 1993, Tooth 2000a, b, Hampton and Horton 2007, Nichols and Fisher 2007, Guilliford et al. 2014).

Accordingly, the ubiquitous planar-stratified, mostly aeolian sheet elements are interpreted as lobate splays deposited along the terminus or margins of high-energy sheetfloods with downflow-declining discharge, which were subsequently reworked into windblown sheets. Rare waterlain 2D current ripple and upper plane lamination are the remnants of water transported sediment deposited under poorly-confined or unconfined flows. On the basis of these waterlain bedforms, the depositing flows were likely very shallow (e.g., Southard and Boguchwal 1990), but not necessarily high speed due to the paucity of supercritical bedform stratification. Rare depth-limited wave ripples record shallow wave reworking of sheet surfaces during episodes with standing water during post-flood conditions, whereas abundant adhesion stratification records damp, partially-saturated surface conditions following floods and/or rainstorms. The ~3 – 12% matrix present in sheet and accretional elements is interpreted to be an infiltrated (illuviated) matrix deposited by the gravity-driven transport (i.e., translocation) of fine-grained sediment by downward percolating meteoric fluids, most likely occurring during rainstorms. Due to their lithologic similarity to sheet elements, the rare accretional elements are also interpreted as aeolian-reworked splays. However, on the basis of a greater proportion of waterlain deposits and the

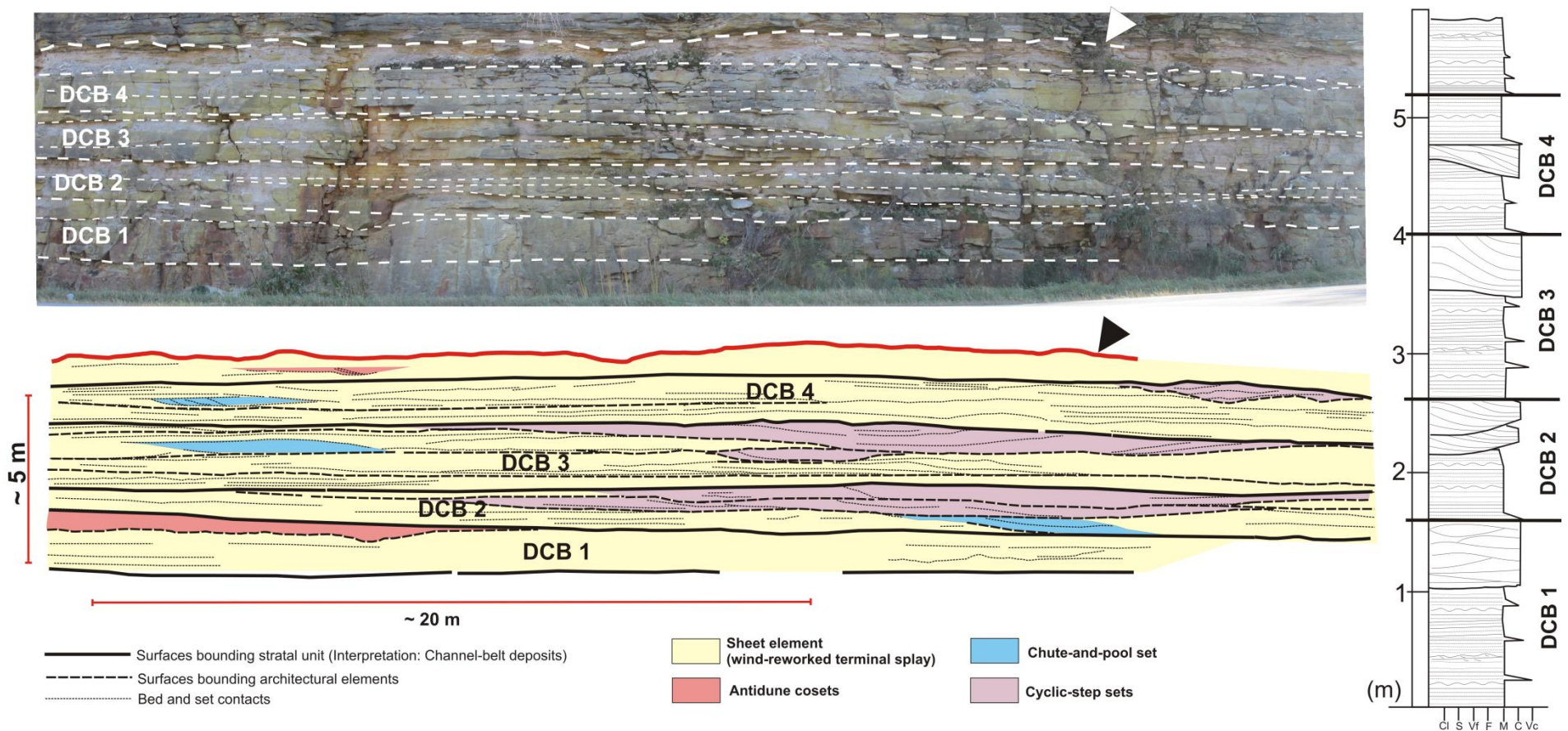


Figure 4.13 Outcrop section along Highway 12 near Alexandria Bay, NY (locality 112), showing typical large-scale architectural organization of ephemeral fluvial strata in the Keeseville Formation. Laterally continuous surfaces subdivide the section into four distributive channel belt (DCB) successions (DCB 1 – 4). Each DCB is dominated by stacked eolian-reworked terminal-splay deposits (sheet deposits) overlain erosionally by local scour-filling supercritical-bedform strata. The solid red line at the top of the section is the erosional base of an overlying succession of braided fluvial deposits (also indicated by arrow on photo and line drawing).

preservation of internal, low-angle ($2 - 12^\circ$) accreted “drying-upward” lithofacies successions, accretional elements likely record splays that were less reworked by the wind, perhaps because they formed in locations with shorter recurrence intervals between floods. Each of the accreted “drying-upward” successions is interpreted to record waterlain accretion from a single terminal sheetflood onto the surface of a low relief ($\leq 12^\circ$) lobate splay.

Rare channel elements, filled with upper medium- to coarse-grained 3D dune cross strata and incised into sheet and/or accretional splay deposits are interpreted as abandoned and backfilled distributary channels, common features of modern and ancient ephemeral fluvial systems (e.g., Tunbridge 1984, McCarthy 1993, Tooth 2000b, Hampton and Horton 2007). Individual channels probably formed and acted as a discharge conduit for numerous erosional/bypass floods before being abandoned and filled. The horizontal architecture of channel-filling dune sets suggest a simple vertically aggrading channel fill and the upward fining and decrease in dune thickness suggests progressively lower energy flow conditions, most likely related to gradual diversion of upstream fluid discharge (e.g., Tunbridge 1984; Hampton and Horton 2007).

Finally, scour-filling supercritical bedform strata record high energy sheetflood events, and were likely upstream from the terminal sheetfloods that deposited the sheet and accretional elements farther downflow or on the margins of large floods. Flow conditions in this setting were more sustained (i.e., longer duration), steadier and higher energy than their downstream terminal sheetflood equivalents, most likely due to lower rates of discharge loss through infiltration or minor evaporation. The type of stratification preserved reflects the energy of the formative flow, i.e. with lower stream-averaged Froude numbers and discharge per unit area recorded by antidunes, to higher Froude numbers and discharges recorded by

chutes-and-pools and ultimately cyclic steps (Alexander et al. 2001, Cartigny et al. 2014). Scours filled with coarse-grained antidune cosets are areally extensive (up to at least ~400 m long and ~200 m wide), with steep margins but horizontal, undulating bases. Due to the high rates of aggradation required to deposit antidune cosets (e.g., Cartigny et al. 2014), and also the generally unsteady nature of formative sheetfloods (Hogg 1982), these scours were very probably formed and rapidly filled by antidune cosets during a single flood event. However, due to the shallow and unconfined nature of the formative sheetflood it is unlikely that the scours were formed by focused erosion or channelization. Instead, the scours are interpreted as composite scours (i.e. stratigraphic surfaces; e.g. Sylvester et al. 2011) formed by the successive amalgamation of antidune troughs during erosional flood conditions. Following erosion of the composite scour, waning aggradational sheetflood conditions resulted in their filling with antidune cosets. Relatively small (~3 – 15 m in length and ~8 – 25 m in width) isolated scours filled by coarse-grained, upstream-dipping sigmoidal chute-and-pool sets occur in sheetfloods with higher Froude number compared to antidunes. In this case, the erosion of a localized scour probably promoted local flow expansion and the temporary development of a hydraulic jump, resulting in local deposition (Alexander et al. 2001; Cartigny et al. 2014). Scours filled by cyclic step strata, on the other hand, record a more expansive stabilization of hydraulic jumps within regularly-spaced (every ~60 – 120 m) elongated scours (35 cm – 1.2 m deep, 15 – >120 m wide, 25 – >150 m long) under sustained flows at even higher Froude numbers (Winterwerp et al. 1992, Taki and Parker 2005, Kostic et al. 2010, Cartigny et al. 2014). Each scour records the upstream-migration of the erosional trough of a cyclic step bedform. On the upstream side of each trough the flow accelerated causing erosion, while further downflow on the downstream side the flow expanded under a

stable hydraulic jump resulting in relatively high angle (15 – 35°) stoss-side deposition of upstream-dipping sets (e.g. Cartigny et al. 2014).

4.3.5 Stratal Units

Stratal units are at the highest order of stratal subdivision recognized in outcrops and are generally tabular, repetitively stacked packages of strata bounded by continuous, more or less horizontal planar surfaces that truncate lower order lithofacies and architectural elements (Figs. 4.7, 4.13). Stratal units are recognized both in braided (FA1) and ephemeral (FA2) fluvial strata, and in each lithofacies association consist of a typical vertical succession of lithofacies and architectural elements (Figs. 4.7, 4.13).

Stratal units in braided fluvial (FA1) deposits are 1.3 – 7 m thick and can be correlated over distances of 500 m to 3 km – their maximum extent being constrained by availability of large outcrops and also recognizable surfaces that can be confidentially correlated. Confluence scours and unit bar sets, although rare, typically occur at the base of stratal units (Fig. 4.6b). Stacked and amalgamated compound bar deposits and associated interstratified bar top lithofacies form the core of all stratal units. These, then, are incised by abandoned bypass channels (channel elements) near the top of about half of the measured stratal units (Figs. 4.5, 4.7). About a third of all measured stratal units are capped by thin (≥ 7 cm) overbank deposits (i.e. weathered fine-grained sandstone, F2d; Figs. 4.4e– f, 4.5, 4.7).

In ephemeral fluvial (FA2) strata, stratal units are 0.4 – 2.6 m thick and can be traced across the most laterally continuous outcrops (>850 m) and correlated over 1 – 3 km between outcrops (Figs. 4.11 – 4.13). They are bound at their base by sharp, generally horizontal

surfaces and commonly at their top by a deflation lag consisting of coarse and (locally) very coarse sandstone (Fig. 4.8g). Each stratal unit typically comprises 2 – 10 stacked aeolian-reworked terminal/overbank splay deposits (sheet elements) and/or rare lobate splay deposits (accretional elements). These are then typically erosively overlain by one or more scours filled with antidune or cyclic step strata and/or dune-filled abandoned distributary channels (Fig. 4.11 – 4.13). Where present, the scours/channels commonly erode 30 – 50% of the thickness of the underlying stratal unit, and in some places erode it completely, and even parts of underlying strata.

4.3.6 Stratal units: Interpretation: Channel Belt and Distributive Channel Belt

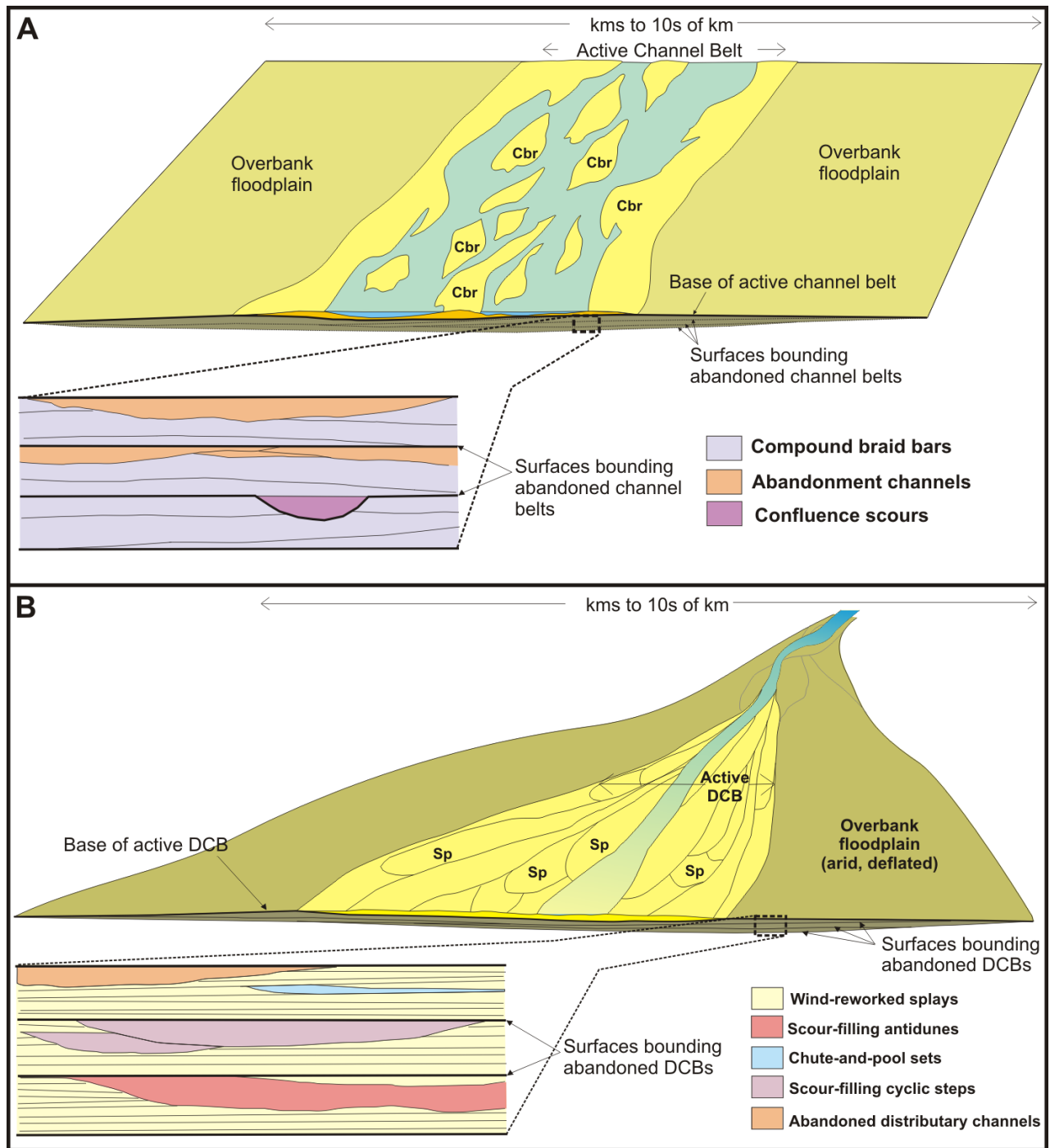
Successions

Based on their high stratal order and repetitive stacking pattern the deposition of stratal units is interpreted to have been controlled by recurring autogenic processes in both FA1 and FA2. Specifically, in both fluvial environments they are interpreted to be deposits of discrete channel belts that formed between periods of avulsion and thus bounded by avulsive surfaces (e.g., Hubert and Hyde 1982, Skelley et al. 2003, Lunt et al. 2004, Lunt and Bridge 2004, Bridge and Lunt 2006, Nichols and Fisher 2007, Payenburg et al. 2011, Guilliford et al. 2014; Fig. 4.14). In braided fluvial (FA1) environments, each channel belt was defined by the stream-parallel elongated area of active channel migration and bar deposition (Fig. 4.14a; Lunt et al. 2004, Bridge and Lunt 2006), whereas each ephemeral fluvial (FA2) stratal unit most likely records sedimentation in an active lobate or fan-shaped distributive channel belt (DCB), owing to the distributive nature of ephemeral discharge (DCBs; Fig. 4.14b; e.g., Hubert and Hyde, 1982; Nichols and Fisher 2007, Guilliford et al.

2014). The arrangement of component architectural elements in channel belt and DCB successions in FA1 and FA2, respectively, record three sequential stages of channel belt development: (a) aggradation, (b) erosion /bypass, and (c) avulsion. These three stages represent a balance between stream power (the product of discharge and slope) and critical power, and the progressive attainment of critical power threshold conditions (i.e., equilibrium (graded) conditions of bypass; Bull 1979) during aggradation and ultimately its exceedance leading to channel belt avulsion.

In braided fluvial (FA1) environments channel belt aggradation was manifest by the build-up, migration and amalgamation of sandy and local gravelly compound bars within wide, shallow braided channels with local confluence scouring at the tails of large compound bars (Figs. 4.6b, 4.14a). However, progressive build-up resulted in a progressive increase in downstream slope, and accordingly stream power, which finally came to exceed the critical power threshold. This then resulted in net bypass and/or erosion, forming incised channels (channel elements) at or near the top of many channel belt successions. The aggradational fill and preservation of each channel element indicates a decrease in local discharge and sediment flux, which most probably signals the early stages of progressive avulsion and the diversion of fluid and sediment flow into a topographically lower, more hydrodynamically favorable part of the floodplain (e.g., Qian 1990, Bryant et al. 1995, Mohrig et al. 2000, Törnqvist and Bridge 2002, Leeder, 2011). Abandoned channel belts were then overlain by the thin, laterally-extensive fine-grained overbank sandstone that accumulated on the floodplain along the margins of subsequent active channel belts.

In each ephemeral fluvial DCB aggradation occurred by the vertical, downstream and lateral build-up of successive splay deposits (Fig. 4.14b). As with braided fluvial channel



belts, the progradation of each DCB resulted in increased downstream and cross-stream slopes, and in turn, stream power. Eventually a critical power threshold was exceeded

followed by net bypass and/or erosion, resulting in scour and local deposition under high energy supercritical sheetflood conditions and/or the incision and filling of distributary channels. This was then followed by avulsion at a node located somewhere upstream of each DCB that diverted subsequent floods to a new, topographically lower position on the alluvial plain (e.g. Nichols and Fisher 2007, Guilliford et al. 2014). Unlike abandoned braided fluvial strata channel belts, which experienced overbank flooding and sedimentation, deflation lags cap ephemeral fluvial DCBs suggesting that the tops of abandoned DCBs were subject to extended periods of subaerial exposure and erosion. Preservation of DCBs from complete aeolian deflation was likely promoted by the armouring of the surface with a coarse-grained deflation lag as well as the progressive but intermittent rise of the water table (e.g. Fryberger et al. 1988, Kocurek 1988; Clemmensen and Dam 1993).

Figure 4.14 (previous page) Conceptual model for the deposition of A) braided and B) ephemeral fluvial strata. In each, the sketch in the lower left summarizes the typical architecture and stacking pattern of fluvial strata. A) Braided fluvial channel belt successions are made up mostly of stacked compound bars deposited during channel-belt aggradation. These, then, are incised by abandonment channels and their fill, which formed during progressive channel-belt avulsion and subsequent abandonment. The upper diagram shows the spatial distribution of the various stratal elements. Within the active channel belt, downstream-migrating in-channel and bank-attached compound bars (Cbr) migrate and are deposited in a network of wide, shallow braided channels. At the same time, overbank floods deposit thin, fine-grained sandstone over the adjacent floodplain that overlies abandoned channel belts. The repeated buildup, followed by avulsion and abandonment of active channel belts, resulted in the stacking of channel-belt successions and the typical architecture and stacking pattern shown schematically in the lower panel. B) Ephemeral fluvial strata consist of stacked distributive channel belt (DCB) successions separated by surfaces formed by avulsion. Most DCB successions are made up of stacked splays deposited during DCB progradation that later were incised by distributary channels and/or scour-filling supercritical-bedform strata deposited by sustained, high-energy sheet floods (see text for discussion). The upper diagram shows how discharge and sediment are distributed across an ephemeral floodplain. Within the active DCB, lobate splays (Sp) are deposited during episodic sheet floods and reworked locally into eolian sand sheets between floods. At the same time the adjacent floodplain is deflated by wind until the surface becomes armored with coarse-grained detritus. The typical architecture and stacking pattern shown in the lower panel is formed by the stacking of DCB successions due to repeated aggradation followed by avulsion and abandonment of active DCBs.

4.4 Discussion

4.4.1 Pre-Vegetated Fluvial Morphodynamics and Interactions with Floodplain

Topography

Previous studies of the Potsdam Group suggest that basement topography including bedrock ridges, localized knolls, hills and cliffs were present along the southwestern Ottawa Embayment during Potsdam sedimentation (Lewis 1963, Kirwan 1963, Otvos 1966, Wolf and Dalrymple 1984, Bjerstedt and Erickson 1989, Sanford and Arnott 2010). In contrast farther east along the eastern Ottawa Embayment and into the Quebec Basin, sediments were deposited on a relatively open and flat alluvial plain (Fig. 4.2). These topographical differences provide a basis for understanding interactions between paleotopography and fluvial sedimentation in the absence of floodplain-stabilizing vegetation and associated cohesive fine-grained floodplain sediment (e.g., Long 1978, Dalrymple et al. 1985, Fuller 1985).

In the eastern Ottawa Embayment and Quebec Basin thick (~50 – 550 m) sandy braided fluvial deposits of the Ausable and Keeseville Formations typically occur over a large area (~15,000 km², Fig. 4.2) and are subdivided by avulsion surfaces into many (~25 – 200) stacked 1.3 – 3.3 m thick channel belt successions. These strata record deposition on areally-expansive, featureless floodplains with possible alluvial plain widths of ~60 – 120 km, and show little evidence for interaction with antecedent basement topography. The ubiquitous 0.4 – 2.2 m thick compound bar deposits described here have high aspect (width: depth) ratios of $\geq 80:1$ and are bounded by $\leq 5^\circ$ surfaces and internally subdivided by $\leq 15^\circ$ accretion surfaces (Figs. 4.5, 4.6b, 4.7). This low-relief architecture is consistent with the so-called low relief “sheet-braided” architectural style reported from pre-Devonian fluvial strata

(Cotter 1978, Fuller 1985, Davies et al. 2011), which contrasts patterns reported from post-Silurian to modern braided fluvial systems that generally consist of higher relief macroforms (e.g., Cotter 1978, Ashworth et al. 2000, Best et al. 2003, Bridge and Lunt 2006, Davies et al., 2011). Nevertheless, like many of their documented modern counterparts (e.g., Skelly et al., 2003, Lunt et al. 2004, Bridge and Lunt 2006, Horn et al., 2012), braided pre-Devonian braided fluvial strata in the Potsdam, like some earlier documented examples (Long 2006, Marconato et al. 2014, Ielpi and Ghinassi 2015), formed mainly by the build-up, migration and amalgamation of coarse-grained compound bars composed internally of accreted unit bars and dune cosets. However the compound bars described here, like those in other pre-Devonian examples, are thinner and have more shallowly-inclined margins and higher aspect ratios than their modern counterparts. Notable also is the lack of large-scale erosional channel margins bounding channel-filling compound bar successions that commonly bound post-Silurian fluvial sand bodies (e.g., Leleu et al. 2010, Davies et al. 2011). Although never fully observed in strata of the Potsdam, or rarely elsewhere in pre-Devonian strata for that matter, large, formative aggrading channels in pre-vegetated fluvial systems were probably very wide and shallow features, with aspect ratios of $\sim 200:1$ to potentially as high as $1000:1$ (Fuller 1985, Ielpi and Ghinassi 2015). Certainly, channels here were likely no more than one or maybe two metres deep, given that the thickness of dune sets are commonly ≤ 8 cm thick and unit bar sets are ≤ 40 cm (see Table 4.3). Such shallow braided fluvial systems dominated by low relief compound bars are interpreted to reflect the manner in which pre-vegetated braided fluvial systems adjusted to increases in discharge. Most likely, the lack of rooted vegetation and paucity of organically-bound cohesive fine-grained deposits prevented the stabilization of erosional channel margins (Schumm 1960,

Table 4.3 Dune-set, unit-bar and compound-bar thicknesses and estimated channel depths of braided fluvial systems in the eastern Ottawa Embayment/Quebec Basin and the paleotopographically complex southwestern Ottawa Embayment. Estimates of channel depth based on published scaling relationships between stratal set thickness and flow depth (see references 1, 2, 3 for details).

	Dune set thickness (range; average)	Flow depth from dune-set thicknesses ¹	Unit-bar set thickness (range; average)	Flow-depth from unit bar set thickness ²	Compound-bar thickness (range; average)	Flow depth from compound-bar thickness ³	Range of possible channel depth
Eastern Ottawa Embayment and Quebec Basin	5 – 12 cm; 6.5 cm	~0.9 – 1.5 m	15 – 65 cm; 33 cm	0.13 – 0.65 m	0.4 – 2.2 m; 1.4 m	0.4 – 2.2 m	0.1 – 2 m
Southeastern Ottawa Embayment	10 – 30 cm; 16 cm	~3 – 5 m	0.7 – 2 m;	0.7 – 2 m	1.2 – 3.5 m; 2.1 m	1.2 – 3.5 m	0.7 – 5 m

1: Yalin, 1964; Ashworth et al., 2000; Bridge and Tye, 2000; Leclair and Bridge, 2001; Leclair, 2002; Best et al., 2003

2: Bridge, 2003; Reesink and Bridge, 2011

3: Mohrig et al., 2000; Hajek and Heller, 2012

Davies et al. 2011), and as a consequence channels generally underwent continuous lateral migration and expansion with little or no change in flow depth (e.g., Wolman and Brush 1961, Fuller 1985, S nderholm and Tirsgaard 1998) while being progressively filled with low relief downstream-accreting compound bars.

In the paleotopographically-complex southwest Ottawa Embayment braided fluvial strata are more lithologically diverse. Here braided fluvial strata of the Ausable and Keeseville occur as relatively thin (≤ 15 m) and small ($2 - 200 \text{ km}^2$) outliers (Fig. 4.2) subdivided internally by avulsion surfaces into only a few ($\sim 2 - 4$) stacked channel belt successions that are relatively thick (2.2 – 7 m). These strata are bound laterally by topographically-elevated and well-indurated basement highs composed of granite and quartzite. Within $\sim 50 - 300$ m of the basement highs flow-oblique boulder talus with rapidly decreasing clast size and abundance crop out (Fig. 4.15), suggesting that the basement highs were present during fluvial sedimentation and contributed locally-derived coarse-grained detritus (cobbles, boulders). More importantly, they formed barriers to lateral channel and channel belt migration, resulting in a patchy distribution of relatively narrow ($\sim 2 - 10$ km) floodplain segments. Here, internal accretion surfaces of compound bar deposits are typically steep, reaching angles of 35° , and thus recording generally steep-sided compound bars, some of which showing evidence of lateral accretion, and thus possibly meandering (Fig. 4.6a). Furthermore, the thicknesses of compound bar deposits (1.2 – 3.5 m), unit bar sets (0.7 – 2 m) and dune sets (10 – 30 cm) suggest flow depths of $\sim 1 - 5$ m, which are notably deeper than those in poorly-confined floodplains to the east (see Table 4.3 and its caption for more details). The lateral confinement of channels by well-indurated basement features was probably the cause of deeper channel depths and the development of thick and steep-sided

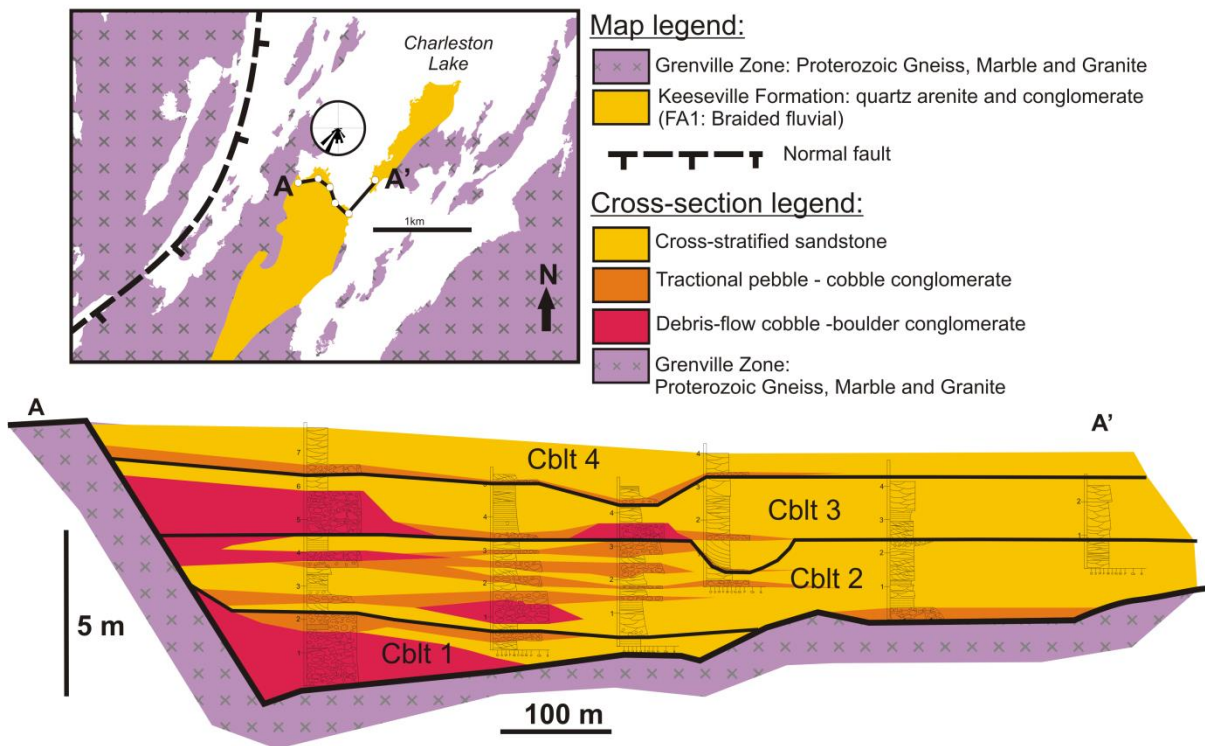


Figure 4.15 Map and cross section of one of the many isolated outliers of braided fluvial strata that occur in the paleotopographically complex southwestern Ottawa Embayment, Charleston Lake Provincial Park, ON (localities 55 – 60, 235, 241; see Figure 4.1). Here, an ~ 2 km² outlier of braided fluvial strata, consisting of sandstone and conglomerate of the Keeseville Formation, abuts a basement high on its western margin, which is in close proximity to a mapped normal fault. Local paleoflow is mostly toward the southwest (see rose diagram on map). Flow-oblique boulder talus crop out near the basement high but then thin and pass laterally (eastward) into tractional cobble and pebble conglomerate and cross-stratified sandstone. The entire succession thins from ~ 8 m along the margin of the basement high to ~ 4.5 m, and consists of four channel-belt successions (Cblt 1 – Cblt 4).

compound bars during peak discharge events; features more similar to post-Silurian and modern braided fluvial compound bars.

Ephemeral fluvial deposits throughout the study area thin over paleotopographic highs and thicken into the adjacent lows. In the paleotopographically complex southwest Ottawa Embayment ~5 – 20 m thick ephemeral fluvial strata cover a total area of ~1200 – 1400 km² where they overlie small (~30 – 100 km²) isolated topographic highs and lows with ~10 – 15 m of differential relief. Everywhere else this relationship is similarly exhibited,

but over a much broader area -- relatively thin (≤ 40 m) deposits over an area of $\sim 12,000$ km² throughout the northern Ottawa Embayment and Quebec Basin thicken southeastward to a maximum of ~ 85 m in an area of ~ 1400 km² in the northern Champlain Valley (Fig. 4.2). Nevertheless, irrespective of location (i.e. the paleotopographically complex southwest or elsewhere) no significant variation in grain size or thickness of cross-strata, architectural elements or distributive channel belt successions (DCB) is noted. However, throughout the entire study area splay deposits are more common in paleotopographic lows (ave. $\sim 81\%$ compared to ave. $\sim 64\%$ on highs), whereas scour-based high energy supercritical bedform strata are more common over and along paleotopographic highs. This is spatially consistent with the downflow reduction in discharge and flow capacity/competence from highlands to lowlands reported from modern and ancient distributive ephemeral fluvial systems (Tunbridge 1984, Abdullatif 1989, McCarthy et al. 1991, Tooth 2000a, b, Hampton and Horton 2007, Nichols and Fisher 2007, Gulliford et al. 2014). However, in many modern (Abdullatif 1989, McCarthy et al. 1991, Tooth 2000a, b) and post-Silurian (Hubert and Hyde 1982, Hampton and Horton 2007, Gulliford et al. 2014) systems splay deposits are complexly intercalated with fine-grained playa lake, vegetated floodplain and/or swamps deposits, and supercritical bedform strata have not been documented. Potsdam and other documented pre-Devonian ephemeral fluvial deposits (e.g., Clemmensen and Dam 1993), on the other hand, were comparatively drier and interbedded with deflated aeolian sand flat deposits. These drier conditions were likely the result of higher rates of flood-water infiltration in the absence of low permeability fine-grained deposits and the absence of a sheltering mechanism from erosional winds and evaporation before the evolution of rooted vegetation. It is possible that supercritical conditions like those in Potsdam strata formed

more easily during pre-vegetated times due to the greater propensity for floodplain erosion and the lateral spreading of discharge resulting in shallow, areally-extensive unconfined flows. Alternatively, the paucity of documented supercritical bedform strata may instead be a function of their lack of recognition in the rock record (Fielding, 2006), and thus further documentation of supercritical bedforms in the fluvial sedimentary record is needed.

4.4.2 Climate Fluctuations Recorded by Fluvial Strata in the Potsdam Group

In the Keeseville Formation ephemeral fluvial deposits (FA2A) are overlain by a basal braided fluvial unit (FA1A), capped by an upper ephemeral fluvial unit (FA2B), in turn overlain an upper braided fluvial unit (FA1B) (Figs. 4.2 – 4.3). The contacts between fluvial units are marked only by an abrupt change in facies and stratal architecture (Figs. 4.10b, 4.13, 4.16). The change from ephemeral fluvial to braided fluvial and vice versa indicates fundamental changes in the style, magnitude, but most importantly, the frequency of bankfull fluvial discharge events due to variations in climate. Specifically, braided fluvial systems likely formed in humid settings with seasonal peaks in precipitation and related fluvial discharge (e.g. Ashworth et al. 2000, Lunt et al. 2004, Marconato et al. 2013), whereas sheetflood-dominated ephemeral fluvial systems formed in arid or semi-arid settings characterized by episodic uncharacteristically high volume precipitation events and related high volume fluvial discharge separated by ambient dry climate conditions (e.g. Stear 1985, Abdullatif 1989, McCarthy 1993, Tooth 2000a, b). However, due to the likelihood that aeolian processes probably spanned a wider range of climatic conditions before the evolution of land plants, these fluvial facies associations are probably not fully analogous to those in



Figure 4.16 Examples of the abrupt contact between ephemeral and braided fluvial units. A) and B) Contact between ephemeral (FA2) and braided (FA1) units in the southwestern Ottawa Embayment near Alexandria Bay, NY (locality 115). Here the contact shows minor (~10 – 20 cm) relief; C) and D) Contact between the lower braided unit (FA1A) and the upper ephemeral unit (FA2B) in the southeastern Ottawa Embayment at the Chateaugay High Falls Park in Chateaugay, NY (locality 168). Here the contact is sharp and horizontal with minor relief (the apparent slope on the contact in C) is due to perspective of the photographer, and the apparent undulations in D) are due to relief on the outcrop face.

the modern or post-vegetated world (Sønderholm and Tirsgaard 1998, Long 2011).

Therefore, the facies criteria used here should be considered to record fluctuations in climate from humid (braided) to at least semi-arid (ephemeral) in the pre-Devonian. Also, it is likely that these climate changes affected an area at least the size of the study area (33,000 km²), and therefore contacts between ephemeral and braided fluvial units can be considered isochrones (i.e., time lines) and therein provide a means for time-significant regional stratigraphic correlation.

Based on regional correlations of ephemeral and braided fluvial units, the Keeseville Formation records one and a half climate cycles (i.e., from semi-arid to humid to semi-arid and finally humid again) in the Ottawa Embayment and Quebec Basin before being transgressed by the epeiric Sauk seaway in the Early Ordovician. Unfortunately, the general lack of age control in terrestrial quartz arenite of the Potsdam makes estimates of the absolute or even relative timing of the periods of climate cycles problematic. Models examining how allogenic forces like climate are recorded in the rock record may provide some insight, as these suggest that the frequency and duration of climate changes must be lower and longer, respectively, than those of the highest order autocyclic process in order to be preserved (Jerolmack and Paola 2010; Ganti et al. 2013). In this case the highest order autocyclic process is avulsion, which here is recorded by the deposition of many (~25 – 40) individual channel belt successions (i.e., stratal units). Törnqvist and Bridge (2002) provide evidence to suggest that the modern Rhine-Meuse delta avulses every ~1000 – 1400 years; however, the recurrence interval of avulsion cycles is poorly constrained and nevertheless this example is probably a poor analogue for the non-vegetated, equatorial examples described here. In any case, a probable upper limit for the duration of the climate fluctuations is provided by

available ages and stratigraphic relationships in the Potsdam Group. The marine Altona member, interfingering with the Ausable Formation near its base, has a minimum age of about lower Middle Cambrian based on trilobite faunas (Landing et al. 2009). The Ausable Formation is then separated from the overlying late Middle Keeseville Formation by a regional and in places angular unconformity (Sanford 2007; Sanford and Arnott 2010). Biostratigraphy from the lower part of the Keeseville suggest that it is uppermost Middle Cambrian to early Late Cambrian in age (Walcott, 1981; Flower, 1964; Lochman, 1968; Fisher, 1968). Marine strata of the Keeseville Formation that overlie the intercalated ephemeral and braided fluvial succession are Early Ordovician (Arenigian) based on conodont faunas (Brand and Rust 1977; this study, Chapter 5). Therefore braided and ephemeral fluvial strata of the Keeseville were likely deposited throughout the Late Cambrian until the Earliest Ordovician over a period as short as ~4 to as much as 12 myr (using dates from the 2015 ICS International Chronostratigraphic Chart, Cohen et al. 2013), suggesting that a single full climate cycle (assuming equal duration for each part of the cycle and also for individual cycles) recorded by Keeseville fluvial strata had a period of just over ~ 2.5 myr to as much as 8 myr.

Although poorly resolved, the temporal range of climate cycles recorded in the Keeseville Formation overlap with the timing of documented global climate cycles in the Late Cambrian, which averaged about 2.5 myr (Cherns et al. 2013; Fig. 4.17). These climate cycles are correlated mainly to periglacial facies, paleo-geomorphologic features and $\delta^{13}\text{C}$ isotopic excursions from Cambro-Ordovician strata deposited in Baltica and parts of Gondwana, as well as global sea level fluctuations (Cherns et al., 2013). The global climate model of Cecil et al. (2003), although based on Late Permian cyclothems, provides a basis to

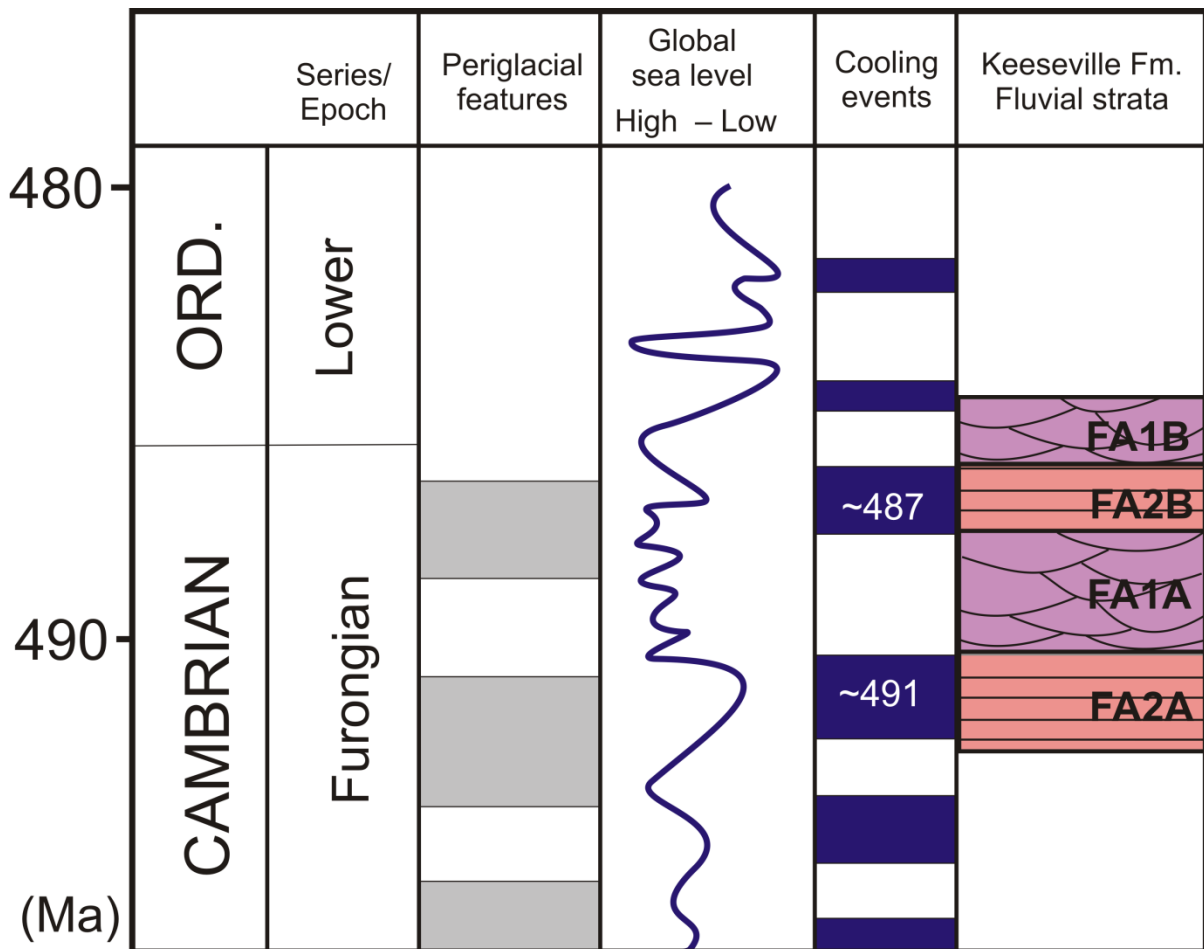


Figure 4.17 Postulated correlation of intercalated ephemeral and braided fluvial strata in the Keeseville Formation with interpreted episodes of Late Cambrian-Early Ordovician global climate change and associated eustatic and glacial fluctuations reported by Cherns et al. (2013; see text for details; global sea-level curve is from Haq and Schutter, 2008). Ephemeral fluvial units (FA2A and FA2B) are interpreted to correlate with cool periods at ~ 491.5 and ~ 487 Ma, respectively, whereas braided fluvial deposits (FA1A and FA1B) coincided with the intervening warm periods at ~ 490 – 488 and ~ 486 – 484 Ma, respectively.

explain the climate cycles in the subequatorial region where Keeseville fluvial sedimentation took place (Torsvik et al. 1996, McCausland et al. 2007). The model predicts that episodes of global cooling inhibited the southward excursion of the humid intertropical convergence zone (ITCZ; i.e., doldrums), which would have resulted in semi-arid conditions over the Ottawa Embayment and Quebec Basin and consequently ephemeral fluvial conditions (Fig. 4.18). Conversely, global warming periods resulted in a seasonal southward excursion of the

ITCZ, and as a consequence development of a humid and seasonal, likely monsoonal, climate over the Ottawa Embayment and Quebec Basin and braided fluvial sedimentation. Based on this model and correlation to documented Late Cambrian climate cycles, ephemeral fluvial units FA2A and FA2B are correlated to cooling events at ca. 491 and 487 Ma (Cherns et al. 2013; Fig. 4.17), suggesting that the Late Cambrian climate cycle recorded by Keeseville fluvial strata lasted approximately 4 myr. The nature of the contacts between braided and ephemeral fluvial units suggest that low frequency global climate fluctuations can be expressed as sharp but conformable changes in the fluvial style in the pre-vegetated fluvial rock record, and provide a means not only for relative but also absolute time correlation in pre-Devonian continental strata.

4.5 Summary and conclusions

Detailed facies and architectural analysis of the sandstone-dominated Potsdam Group reveal the presence of two fluvial facies associations: braided fluvial and ephemeral fluvial. Although specific sedimentary processes vary between these two fluvial end-members, both consist of stacked dm- to m-scale stratal units recording recurring autogenic cycles of channel belt aggradation/progradation, the attainment of critical threshold conditions followed by avulsion and abandonment.

Braided fluvial strata of the Potsdam Group consist mostly of coarse-grained, dune- and unit bar-cross coarse-grained stratified sandstone and local conglomerate. Deposition of compound braid bars by the accretion of dunes and unit bars and rare confluence scouring occurred during periods of channel belt aggradation, typically succeeded by the incision of

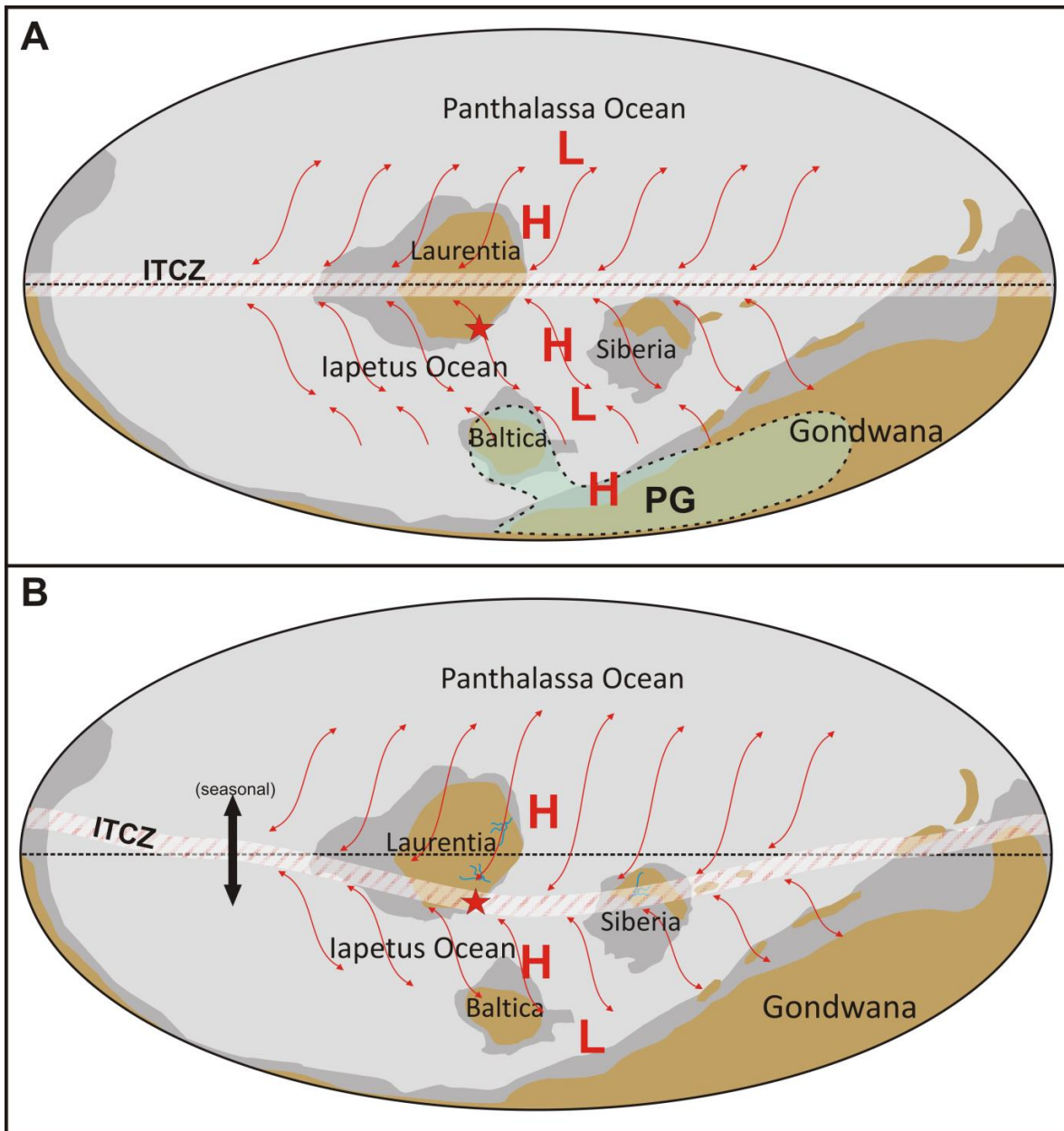


Figure 4.18 Conceptual global atmospheric climate model depicting the surface winds and the location of the intertropical convergence zone (ITCZ) during the Late Cambrian. H = areas of high atmospheric pressure; L = areas of low atmospheric pressure. Paleogeography is modified from Scotese (2001), and the atmospheric climate model is modified from Cecil et al. (2003). The red star indicates the approximate location of the Ottawa Embayment and Quebec Basin near the southern edge of Laurentia at 10° – 30° south latitude. A) Global climate and surface winds during cool periods when periglacial conditions (PG) persisted in Baltica (e.g., Cherns et al., 2013) and perhaps southern Gondwana. During these times minimal atmospheric heating occurred during summers in the southern hemisphere, resulting in a persistent zone of high atmospheric pressure over high southern latitudes. This high-pressure zone limited the southward excursion of the ITCZ, which resulted in humid conditions at the equator but semiarid to arid conditions, and thus ephemeral fluvial sedimentation, at 10° – 30° south over the Ottawa Embayment and Quebec Basin. In contrast, part B illustrates atmospheric conditions during global warm periods, when pressure belts expanded northwards and southwards and seasonal variations in solar heating in the northern and southern hemispheres caused the ITCZ to seasonally fluctuate north and south of the equator. At the low southern latitudes of the Ottawa Embayment and Quebec Basin, this resulted in a seasonal monsoonal climate and the development of perennial braided rivers with seasonal fluctuations in discharge.

dm-deep erosional braided channels into the tops of channel belts when critical threshold conditions were exceeded. Channels were later filled by vertically-aggraded dune cross-strata during progressive channel belt avulsion and capped by thin (≤ 7 cm) floodplain (overbank) deposits following abandonment. The low-relief compound bar deposits and channel elements that characterize braided fluvial strata here are similar to those described as “sheet-braided” by Cotter (1978) and others (Fuller 1985, Davies et al. 2011) to describe braided fluvial strata deposited before the evolution of floodplain-stabilizing rooted vegetation or cohesive fine-grained sediment. The low-relief architecture is interpreted to be the result of lateral expansion of channels and compound braid bars without increases in channel depth. However where the lateral expansion of channel belts was locally limited by basement topography, channels were deeper and braided fluvial deposits consist of steeper angle forms more similar to their post-Silurian and modern counterparts.

Sheetflood-dominated ephemeral fluvial strata consist mostly of medium- to coarse-grained, planar stratified sandstone deposited by aeolian and supercritical subaqueous flows. Distributive channel belts prograded mostly by the deposition of terminal splays during rare episodic sheet floods, which later were reworked into local windblown sheets during the long recurrence interval between floods. Splays preferentially accumulated in topographic lows where sheet floods terminated as floodwaters rapidly attenuated because of infiltration and/or evaporation. High energy (supercritical) sheet flows and/or distributary channels incised splay deposits preferentially on the relatively steep slopes along the margins of basement highs, and in particular at the top of distributive channel belts where the steepest slopes and critical threshold conditions prevailed. Moreover, the sheet-like architecture of ephemeral fluvial strata has changed little through geologic time despite the evolution of vegetation.

Nevertheless, these and other pre-Devonian examples (e.g. Clemmensen and Dam 1993) are characterized by considerably more aeolian reworking of splays than in post-Silurian or modern counterparts, which most likely relates to greater rates of infiltration and a lack of sheltering from wind before the evolution of land plants. Furthermore, supercritical bedform strata are present in the Potsdam ephemeral fluvial strata, but are not widely recognized in most other documented ephemeral fluvial strata or fluvial strata in general. This may be due to the greater tendency for sheet floods in pre-Devonian systems, or alternatively a paucity of recognition of supercritical bedform strata in the fluvial rock record.

The presence of interstratified braided fluvial and ephemeral fluvial units in the Keeseville Formation records one and a half climate cycles in the Late Cambrian and Earliest Ordovician. The cyclicity of fluctuations is correlated to climate cycles in the Late Cambrian (see Cherns et al. 2013), with semi-arid conditions and related ephemeral fluvial systems coinciding with global cool periods at ca. 491 and 487 Ma, which then suggests an ~4 myr duration for a full climate cycle. The contacts separating ephemeral and braided fluvial systems (and vice versa) suggest that low frequency global climate fluctuations can be expressed as sharp, conformable changes in the fluvial style in the fluvial rock record, and therein provide a readily identified surface for relative and absolute chronostratigraphic correlation within the pre-Devonian continental rock record. The lack of evidence of gradational climate-driven contacts in the fluvial record of the Potsdam Group is attributed to the autocyclic nature of sedimentation, which results in periodic channel belt (or DCB) sedimentation separated by regularly-spaced temporal gaps in the sedimentary record at any given location.

Chapter 5: Lithostratigraphic and allostratigraphic framework of the Cambrian-Ordovician Potsdam Group, and correlations across Early Paleozoic southern Laurentia

5.1 Introduction

In east-central North America siliciclastic sedimentary rocks of the Cambrian to Ordovician Potsdam Group unconformably overlie rocks of the 1 – 1.5 Ga Grenville Orogen and crop out locally along the margins of the fault-bounded Ottawa Embayment and Quebec Basin (Fig. 5.1). The Potsdam Group, perhaps more commonly known as the “Potsdam Sandstone”, is one of the first proposed names in the geological literature in North America (from Emmons, 1838) and for almost 200 years has been studied locally in New York State, Ontario and Quebec (Logan, 1863; Alling, 1919; Chadwick, 1920; Wilson, 1946; Clark, 1966; 1972; Otvos, 1966; Fisher, 1968; Greggs and Bond, 1971, 1972; Brand and Rust, 1977; Selleck 1978a & b; Wolf and Dalrymple, 1984; Globensky, 1987; Salad Hersi et al. 2002; Dix et al. 2004; Landing et al. 2009; Sanford, 2009; see also Sanford and Arnott, 2010 for detailed discussion). Nevertheless, in spite of its long history there is still little consistency or consensus regarding the lithological correlations, depositional environments or stratigraphic nomenclature of the Potsdam in the Ottawa Embayment – Quebec Basin due to the fact that few studies extend beyond provincial or international borders (however, see Sanford 2007; Sanford and Arnott, 2010). Furthermore, complex isopach and lithofacies distributions and the general lack of age-diagnostic fossils, ash beds or easily correlated stratal surfaces in a compositionally monotonous, mostly continental siliciclastic succession have confounded depositional age determinations and stratigraphic correlations.

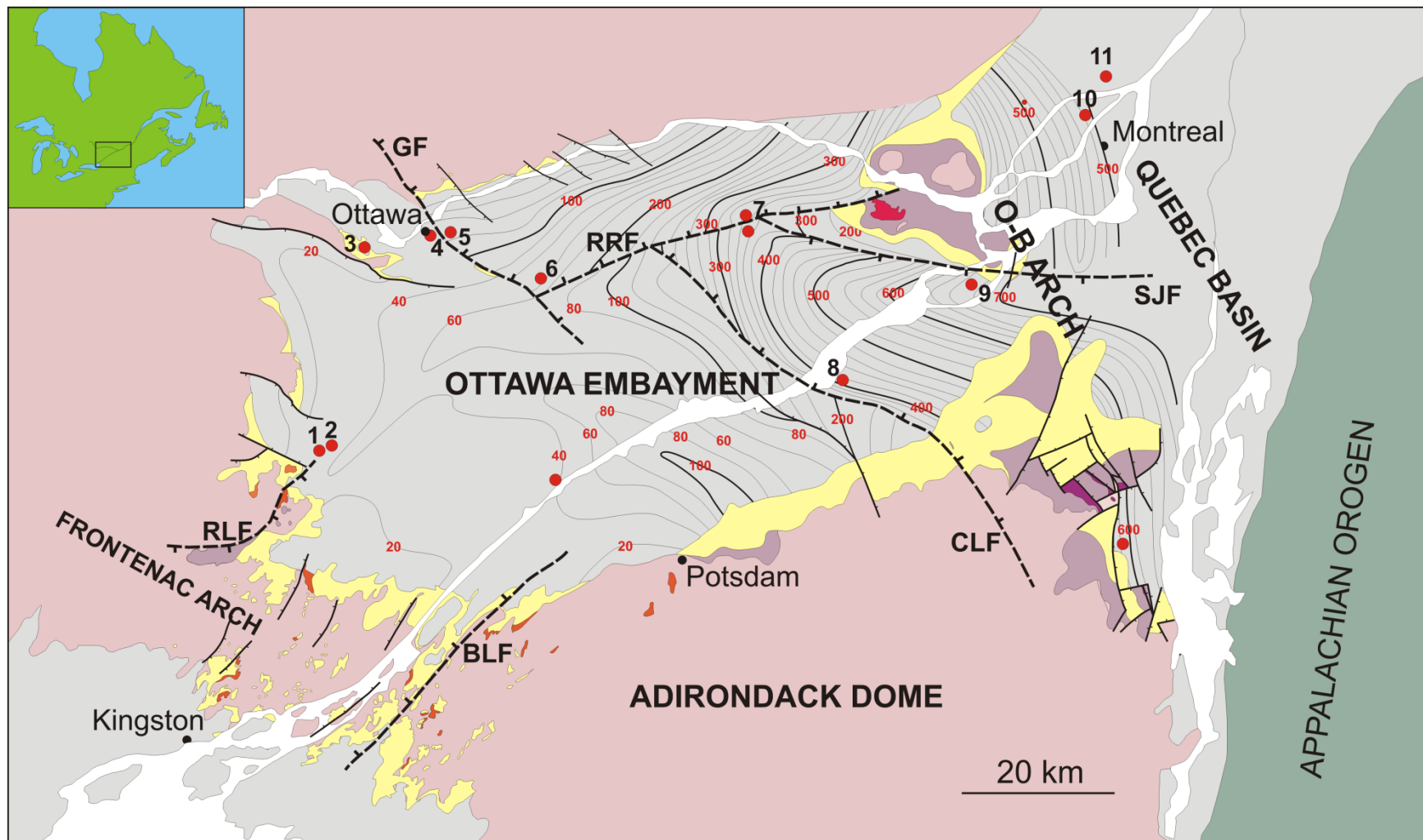


Figure 5.1 Geologic and isopach map of the Potsdam Group in the Ottawa Embayment and Quebec Basin. Isopach thickness is in metres. These two semi-connected basins are separated by the Oka-Beauharnois Arch. A second arch, the Frontenac Arch, bounds the southeastern margin of the Ottawa Embayment. A number of normal faults occur within this area and exert a strong influence on the Potsdam isopach and lithofacies distributions (see text for more details). Some particularly important faults that are mentioned in the text are shown, and include the Gloucester fault (GF), Rideau Lakes fault (RLF), Black Lake fault (BLF), Rideau-Rockland Fault (RRF), Chateaugay Lake fault (CLF) and Ste. Justine fault (SJF). Red dots and numbers mark the location and identity (respectively) of wellbores used for isopach interpolation and regional correlation. Stratigraphy and correlation of cores from wellbores are shown in figure 5.4.

Nevertheless, disentangling the existing inconsistencies and complexities of Potsdam Group stratigraphy and lithofacies remains important for gaining a better understanding of the Early Paleozoic history of North America and also providing context to studies of the paleoecology of Early Paleozoic microbial and metazoan life including the earliest reported terrestrial animal life on Earth (Clark and Usher, 1917; Bjerstedt and Erickson, 1989; MacNaughton et al., 2002; Hagadorn and Belt, 2008; Collette and Hagadorn, 2010; Hagadorn et al., 2011). In addition, the location of the Potsdam Group between the Laurentian margin succession to the east and the interior cratonic basins to the west (Fig. 5.2, Sanford and Arnott, 2010), makes the Potsdam Group an important key for regional correlations of Lower Paleozoic strata of the Sauk Megasequence (e.g. Sloss, 1963) across eastern North America. Such regional correlations are needed to better elucidate and constrain geologically-significant events that occurred in Early Paleozoic Laurentia, including a regionally complex and poorly-understood combination of eustatic fluctuations, climate changes and tectonic events (Lavoie, 2008; Landing et al., 2003, 2009; Cherns et al., 2013).

The purpose of this chapter, therefore, is to critically evaluate previous depositional and stratigraphic frameworks and to clarify details of the Potsdam stratal succession. This is done by independently undertaking systematic and detailed lithofacies analysis and lithostratigraphic and allostratigraphic correlations of the Potsdam Group based on study of 296 outcrop locations and 12 fully-cored drill holes (see appendix A and Table 1.1) including many of the same outcrops and cores used by Sanford and Arnott (2010) across the Ottawa Embayment and Quebec Basin. Furthermore, new age constraints using conodont biostratigraphy to better constrain stratigraphic correlations are described. Finally, regional

correlations with coeval strata of the northeastern North American Sauk Megasequence deposited on the paleo-southern Laurentian margin and craton interior are proposed.

5.2 Paleogeographic and tectonic setting

The Ottawa Embayment and Quebec Basin are semi-connected basins filled by lower Paleozoic strata and located at the southeastern end of rift structure termed the Ottawa graben (a.k.a., the Ottawa-Bonnechere graben; Kay, 1942; Fig 5.2). The Ottawa graben originated in the Latest Neoproterozoic (ca. 590 Ma) during rifting and breakup of the supercontinent Rodinia (Kumarapeli, 1985, 1993; Kamo et al., 1995; Allen et al., 2010; Burton and Southworth, 2010; Bleeker et al., 2011). Accordingly, during the Cambrian and Ordovician Potsdam sedimentation occurred in and along the margins of the eastern (paleo-southern) part of this pre-existing rift, which at that time was located at ca. 10° – 30° south latitude and ca. 200 – 400 km inboard of the Quebec Re-entrant portion of the south-facing passive Laurentian margin (Torsvik et al. 1996; Landing, 2007; Landing et al., 2009; McCausland et al. 2007, 2011; Lavoie, 2008; Allen et al., 2009; Fig 5.2). Numerous authors, including Lewis (1971), Salad Hersi and Dix (2006), Landing et al. (2009) and Sanford and Arnott (2010), suggest that intra-plate tectonism played an active role in Potsdam sedimentation, however the connection between tectonic reactivation of the Ottawa graben and Potsdam sedimentation, if true, is poorly resolved. Furthermore, Potsdam sedimentation was coeval with siliciclastic and carbonate sedimentation across the passive Laurentian shelf and slope (Lavoie et al., 2003; Landing, 2007; Lavoie, 2008); all of which was influenced by a high-order sea level rise across Laurentia that began in the Early Cambrian and eventually covered

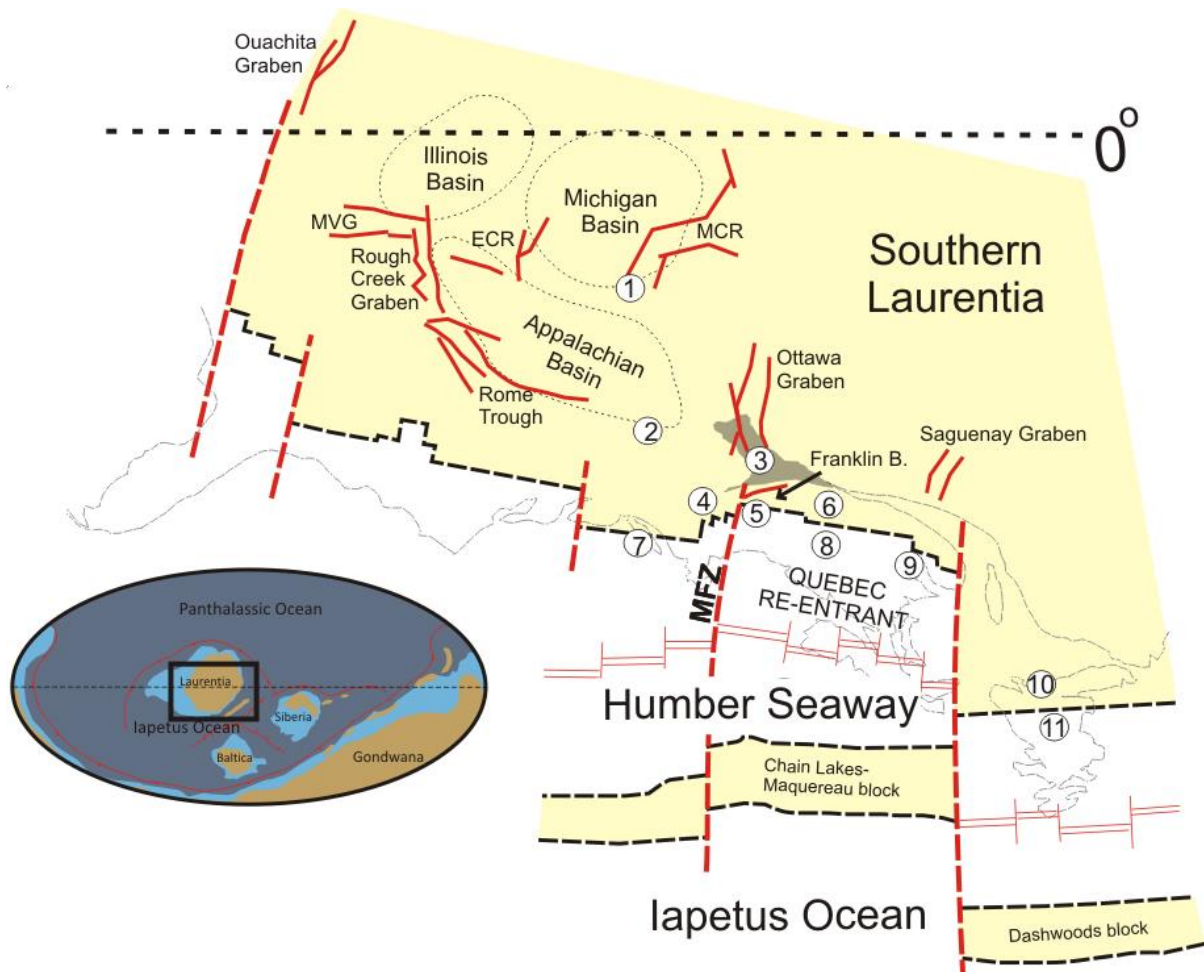


Figure 5.2 Paleogeographic and tectonic map of Southern Laurentia during the Cambrian and earliest Ordovician, modified from Thomas (2006) and Allen et al. (2010), with the modern North American coastline overlain for reference. Dashed black lines correspond to the presumed margin of the Laurentian continental crust, and dashed red lines correspond to major oceanic transform faults. Faults bounding the Ottawa graben, along with related intracratonic rifts such as the Saguenay graben, Rome trough, Mid-continent rift (MCR), East continent rift (ECR), Mississippi Valley graben (MVG), Oachita graben and Rough Creek graben. The shaded area indicates the known distribution of the Potsdam Group in the Ottawa Embayment and Quebec Basin, at the paleo-southern end of the Ottawa Graben. The numbers correspond to the locations of the different the cratonic, shelf and slope successions across southern Laurentia stratigraphic shown in figure 5.30.

the Laurentian margin and craton with a shallow epeiric sea by the end of the Early Ordovician. This transgressive event is termed the cratonic Sauk Megasequence, which in turn is divided into smaller divisions representing lower order transgressive-regressive cycles (Sauk I, II and III, among others; Sloss, 1963; James et al., 1986).

5.3 Depositional environments

Previous works have recognized a wide variety of terrestrial to shallow marine depositional environments in strata of the Potsdam Group (Otvos, 1966; Clark, 1966; Fisher, 1968; Greggs and Bond, 1971; Kirchgasser and Theokritoff 1971; Lewis, 1971; Selleck, 1975; Bjerstedt and Erickson 1989; Salad-Hersi and Lavoie, 2000a and b; MacNaughton et al. 2002; Hagadorn and Belt 2008; Hagadorn et al. 2011). In this study, detailed facies analysis (see chapters 2 and 3) recognizes six terrestrial to shallow marine environments, which are: braided fluvial (FA1), ephemeral fluvial (FA2), aeolian (FA3), coastal sabkha (FA4), tidal marine (FA5) and open-coast tidal flat (FA6). These are described in chapter 3, and their distribution within the Potsdam sedimentary pile is given in the next section and in Figure 5.3. The facies association of each outcrop location in this study is given in appendix A, and their occurrence in drill core is shown in Figure 5.4.

5.4 Lithostratigraphic revisions and depositional ages

5.4.1 Potsdam Group

The term Potsdam Group herein formally follows the definition of Sanford and Arnott (2010), although with some revision and redefinition of its constituent units. Accordingly, the Potsdam Group encompasses all siliciclastic and rare carbonate strata that unconformably overlie metamorphic and igneous rocks of the Proterozoic Grenville Province and underlie mixed carbonate and siliciclastic strata of the Theresa Formation. The Potsdam Group (Potsdam) has a highly uneven isopach, which in large part reflects changes across

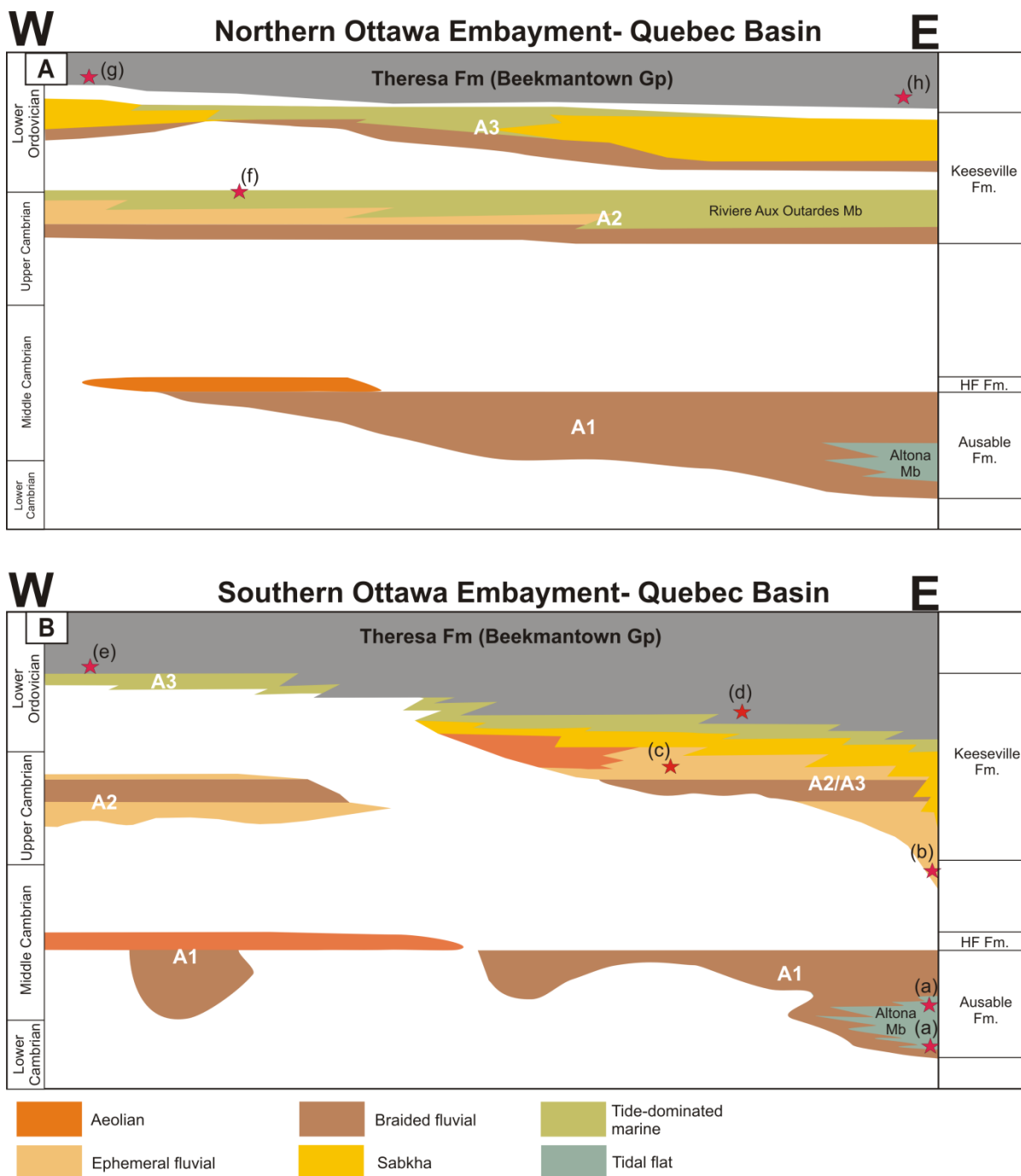


Figure 5.3 Stratigraphic correlation of units and lithofacies across the northern and southern parts of the Ottawa Embayment and Quebec Basin. Locations of biostratigraphic age control are indicated by the red stars, and are from: (a) Landing et al. (2009), (b) Walcott (1891), Flower (1964), Lochman (1968), Landing et al. (2009) (c) Fisher (1968), (d) this study, Salad Hersi et al. (2003), (e) Greggs and Bond (1971), (f) this study, (g) Brand and Rust (1977), Dix et al. (2004) and (h) Salad Hersi et al (2002a). See text for details regarding the correlation and age of Potsdam strata.

intrabasinal faults (Figs. 5.1, 5.4; Sanford, 2007; Sanford and Arnott, 2010). Accordingly, it is thickest in the southwestern Ottawa Embayment and southern Quebec Basin where it reaches a maximum thickness of at least 630 m thick (Figs. 5.1, 5.4), but then thins continuously to the northwest and abruptly to the west across a series of faults to only ~10 – 40 m thick throughout the western Ottawa Embayment. In this work the Potsdam comprises three formations, which stratigraphically upward are: Ausable, Hannawa Falls and Keeseville (Fig. 5.3). Names of units from Ontario and Quebec (Nepean, Covey Hill and Cairnside formations) are here abandoned and replaced by the names of equivalent units in New York State, which predate Canadian formation names (originally from Emmons (1841) and Alling (1919)). The abandonment of the Canadian formation names is in accordance with the North American Stratigraphic Code (Article 7(e) from NACSN, 2005) and is intended to mitigate uncertainty regarding unit equivalence across borders and to promote an internationally-recognized stratigraphic framework. Nevertheless the Canadian terms are well-established local names and therefore may be used informally so long as the priority of the U.S. names for equivalent units are stated in published literature. The main changes made here from the frameworks of Landing et al. (2009) and Sanford and Arnott (2010) are:

- 1) abandonment of Canadian formation names;
- 2) abandonment of the Abbey Dawn Formation (Sanford and Arnott, 2010) due to the occurrence of boulder conglomerate (talus) at multiple stratigraphic positions within the Potsdam (see F4b in chapter 2), and lack of evidence to support its Proterozoic age;

- 3) modification of the rank of the Altona Formation (Landing et al., 2009) to Altona Member, due to its intertonguing relationship with the more extensive Ausable Formation;
- 4) redefinition of the Ausable Formation to include only arkose;
- 5) elevate the Hannawa Falls from member to formation status, and redefine it to include only aeolian quartz arenites that occur above arkose of the Ausable Formation (e.g. the “Lower Hannawa Falls Member” of Sanford and Arnott, 2010);
- 6) abandonment of the Chippewa Bay and Edwardsville members, and
- 7) recognition of an unconformity separating the lower and upper parts of the Keeseville Formation over much of the study area.

The existing age diagnostic fossil data, including new fossil ages presented here, suggest that the Potsdam Group ranges in age from uppermost Lower Cambrian to Lower Ordovician (Fig. 5.3). Details of the studied outcrop locations are given in appendix A, and detailed descriptions and interpretations of taxa used for age determinations are provided in appendices B and C.

5.4.2 Ausable Formation

The Ausable Formation comprises mostly grey to red, coarse- to very coarse-grained, pebbly, silica- and/or rarely kaolinite/sericite/feldspar-cemented arkose and pebble to boulder conglomerate with arkose matrix (Fig 5.5). On the basis of lithofacies analysis described in chapters 1 and 2, the Ausable consists mostly of braided fluvial deposits (FA1). However, the

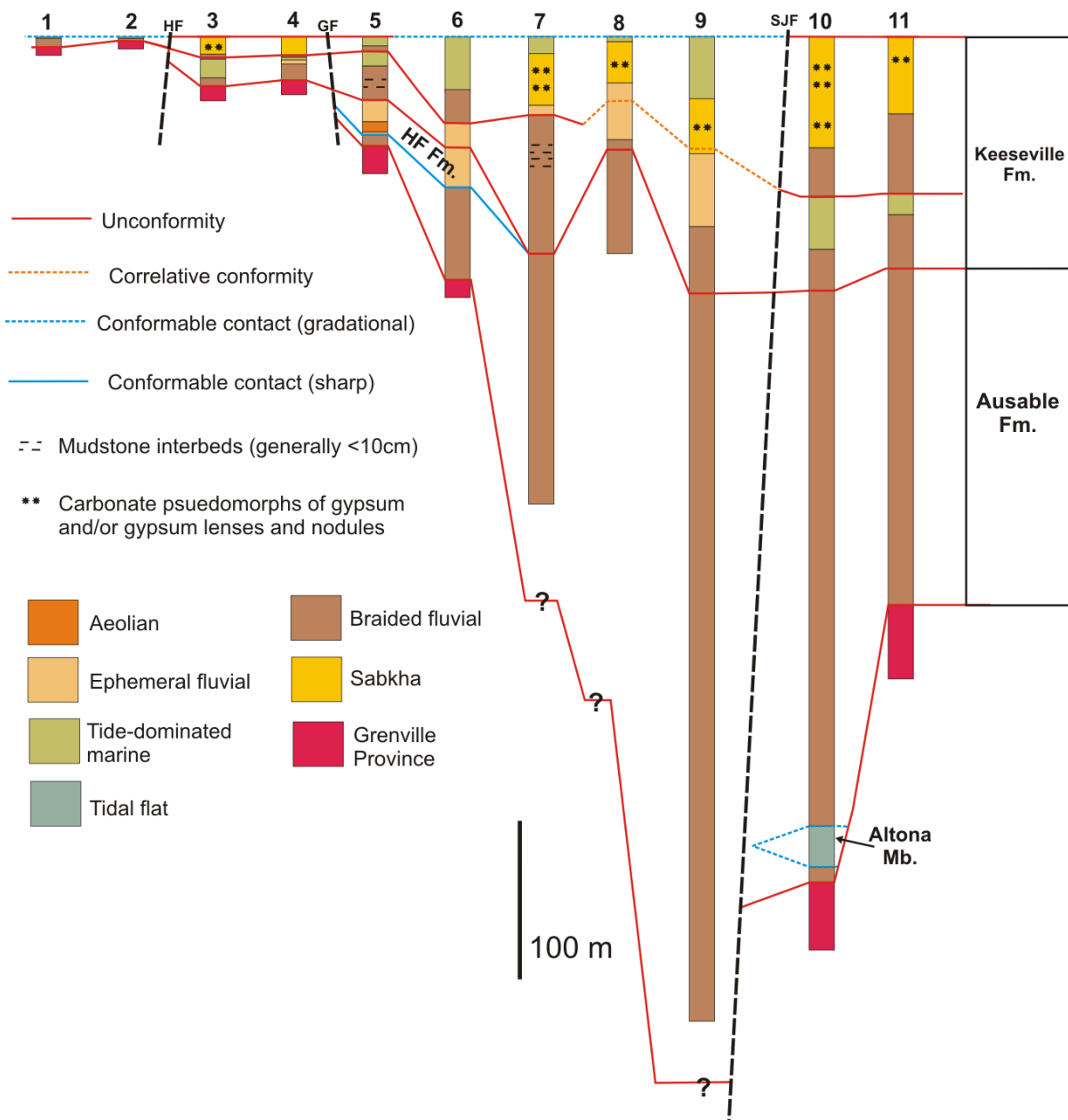


Figure 5.4 East to west correlation of units and lithofacies associations from cores of the Potsdam Group across the Ottawa Embayment and Quebec Basin. Numbers correspond to wellbore locations on Figure 5.1. The cores are from: (1) Lanark County No.1, (2) Lanark County No.2, (3) AMEC MW-301 monitoring well, (4) Dominion Observatory No.1, (5) GSC LeBreton No. 1, (6) GSC Russell No.1 and Consumers No. 12023, (7) GSC McCrimmon No. 1, (8) Gastem Dundee No.1, (9) St. Lawrence River No.1, (10) Quonto-International St. Vincent de Paul No.1, (11) Quonto-International Mascouche No.1. Faults shown here are the Hazeldean fault (HF), Gloucester fault (GF) and Ste. Justine fault (SJF).

Ausable also includes rare boulder talus (F4b, see chapter 2) and rare red mudstone, feldspathic siltstone, arkose and carbonate of open-coast tidal flat (FA6) origin in the intertonguing Altona Member (Figs. 5.6 – 5.8; see definition below). The Ausable Formation, as formally defined here, includes: all strata formerly assigned to the arkosic Ausable Member in New York (Alling, 1919; Fisher 1968; and revised by Sanford and Arnott, 2010); the informal Nicholsville and Allens Falls Conglomerate in northeastern New York (Chadwick, 1920; Reed, 1934; Postel et al., 1959; Fisher, 1968); the arkosic Covey Hill Formation in Quebec (Clark, 1966, 1972; Sanford and Arnott, 2010; here abandoned), and the arkosic “lower Hannawa Falls Member” (Sanford and Arnott, 2010; page 28). However, this definition does not include quartz arenite exposed in the lower part of the Potsdam succession along the Frontenac Arch in New York and Ontario, termed the Chippewa Bay Member by Sanford and Arnott (2010) (i.e., Potsdam I of Kirchgasser and Theokritoff, 1971; Selleck, 1975, 1978a, b, 1993). Instead, these quartz-rich strata are considered part of the Keeseville Formation (see below). The Ausable Formation defined here also excludes red quartz arenitic parts of the “Hannawa Falls Member” of Sanford and Arnott (2010), which is redefined below.

Based on this redefinition, the Ausable Formation covers a large area of the Ottawa Embayment and Quebec Basin (~15,000 – 16,000 km²) and exhibits a highly uneven isopach and distribution closely tied to regional faults (Fig. 5.4), occurring mainly in fault-bounded grabens in the northern and eastern parts of the Ottawa Embayment and western Quebec Basin (i.e., on the down-dropped sides of the Gloucester, Russell-Rigaud, Ste. Justine, Rideau Lakes and Chateauguay Lake faults, Figs. 5.1, 5.4). Strata are thickest (up to 450 m, or more) immediately south of the Ste. Justine Fault, approximately ~40 km southwest of the



Figure 5.5 Representative strata of the Ausable Formation. Braided fluvial strata consisting of (A) coarse- and very coarse-grained arkose interstratified cobble conglomerate (FA1); Briton Bay, ON (locality 12), and pinkish cross-stratified, pebbly coarse-grained arkose with rare pebble conglomerate and thin silty mudstone beds (FA1) that crop out at (B) Flat Rock State Forest, NY (locality 251); arrow points to sitting field assistant for scale, and (C) Ile Perrot, QC (locality 194); hammer for scale, circled.

island of Montreal, and remain thick (typically ~300 – 400 m thick) south- and northwards along the western Quebec Basin and axis of the Oka-Beauharnois Arch. In the northern

Ottawa Embayment, Ausable strata thin continuously eastward to ~8 m in the hanging wall trough of the Gloucester Fault (Figs. 5.1, 5.4). In the southwest Ottawa Embayment, the Ausable is generally absent except for isolated, ~0.5 – 25 m thick accumulations along the northern Adirondacks (e.g., Allens Falls and Nicholville, NY), immediately east and south of the Rideau Lake Fault in Ontario (Fig. 5.1), and locally along faults in the Frontenac Arch (e.g., Abbey Dawn Formation of Sanford and Arnott, 2010). Based on biostratigraphic control from strata in the intertonguing Altona Member near its base in the southern Quebec Basin (Landing et al., 2009; summarized below), and also in the overlying Keeseville Formation (Walcott, 1891; Fisher, 1955; Flower, 1964), a Middle Cambrian depositional age is proposed for the Ausable Formation. Multiple possible stratotypes exist for the Ausable Formation, including exposures at Lapham Mills NY, Altona Flat Rock State Forest, Ile Perrot QC, Franklin QC, Nicholville NY and at the head of Briton Bay on the Big Rideau Lake, ON (localities 245, 251-253, 194, 176, 246 and 12, respectively).

5.4.3 Altona Member

The Altona Member (revised from the Altona Formation of Landing et al., 2009) is an intertonguing unit near the base of the Ausable Formations, consisting mostly of red to light grey arkose, mudstone, siltstone and rare peritidal carbonate interbeds deposited on an open-coast tidal flat (FA6, see chapter 3) in the eastern Ottawa Embayment and western Quebec Basin (Figs. 5.1, 5.3, 5.4, 5.6). The Altona was originally considered to be the basal

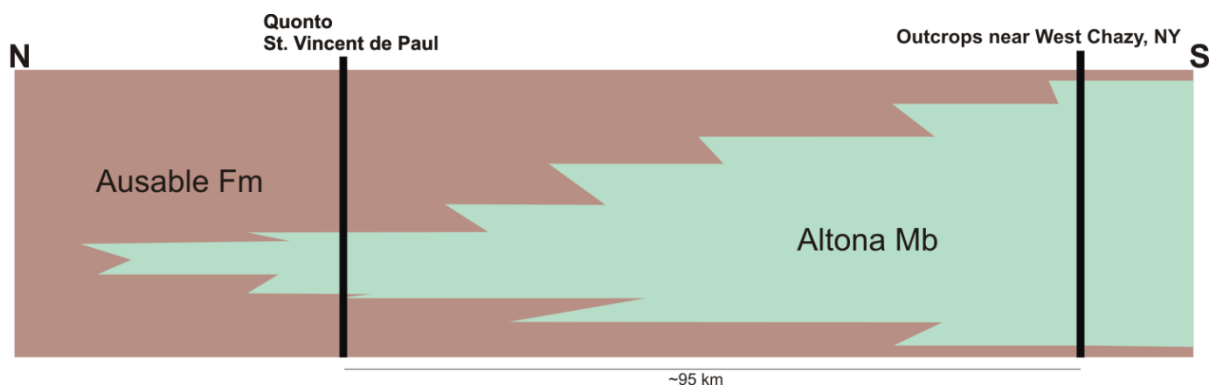


Figure 5.6 Correlation of Altona Member strata from its type locality near Chazy, NY (see Landing et al. (2009) for more details) northward to Quonto St. Vincent de Paul No.1 near Montreal, QC. Datum at the base is the contact with ~1.0 Ga Grenville basement.

unit of the Potsdam with a thin (~3-4 m thick) package of coarse-grained fluvial arkose at its base. However, correlation of Altona strata from its type locality near West Chazy NY ~60 km to the north near Laval, QC (Quonto-International St. Vincent De Paul No. 1) reveals that the basal fluvial arkose thickens northward from ~3.5 m to ~17 m whereas the overlying tidal flat strata thins from ~80.5 m to only ~20 m (Fig. 5.6). This suggests that the Altona is a northward thinning tongue of coastal marine strata bounded above and below by coarse-grained braided fluvial arkose of the Ausable, and it is this relationship that forms the primary justification for modifying its status to member of the Ausable Formation (Article 25(b) from NACSN, 2005). The basal contact of the Altona Member with underlying braided fluvial arkose is conformable and gradational. The nature of this contact is best captured in core, where tidal flat facies sharply overlie coarse-grained arkose of the Ausable, which then are overlain by a 12 cm thick bed of coarse-grained arkose succeeded upward by a more continuous section of tidal flat facies (Fig. 5.7a). Above this contact, the lower 2/3–1/2 of the tidal flat succession is dominated by sparsely bioturbated tidal flat mudstone and siltstone intercalated with rare ~1.5 – 16 cm thick, normally-graded structureless fluvial sheetflood and/or storm/wave-generated arkose beds (Figs. 5.7b – c; see also Landing et al., 2009; Brink, 2014). A ~0.8 – 6 m thick interval of hummocky and/or swaley cross-stratified,

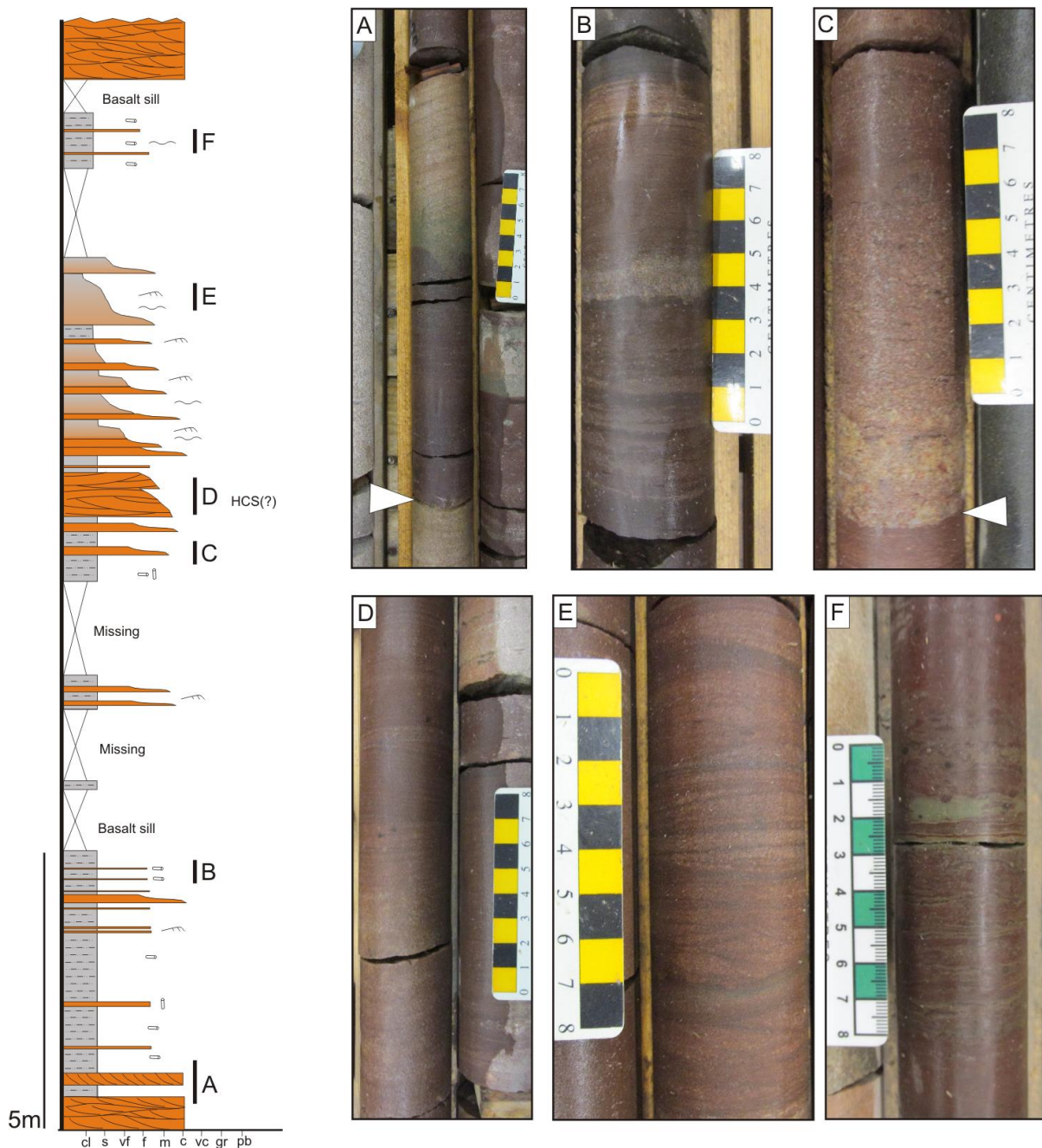


Figure 5.7 Detailed stratigraphic log of the Altona Member from Quonto St. Vincent de Paul No.1, and core photographs showing important features. A) Gradational basal contact of the coastal tidal flat strata (FA6) of the Altona with underlying braided fluvial arkose, see text for details. Arrow marks the base of the Altona Member. B) Red silty tidal flat mudstones interstratified with a thin ($\leq 1\text{cm}$) erosively-based upper medium-grained arkose, possibly deposited by strong wave and/or tidal currents. C) Erosively-based, normally-graded coarse- to medium-grained arkose, possibly an event bed deposited rapidly by a high-energy waning current, possibly a fluvial sheetflood onto the tidal flat, or a high-energy storm/wave-driven flood. D) Well-sorted, fine- to medium-grained, low angle cross-stratified arkose, interpreted as hummocky cross-stratification. E) fine- to very-fine grained planar- and ripple cross-stratified arkose. F) Mottled and variegated red and green silty mudstone.

locally dolomitic arkose beds sharply overlies the lower part of the tidal flat succession (e.g., Brink, 2014, Figs. 5.7d – e, 5.8a; see also Fig 3.15d), and probably represents storm-related deposition on the lower intertidal zone (e.g., Yang et al., 2006). This interval is succeeded by mixed intertidal mudstone, siltstone and rare lagoonal, peritidal dolostone beds with common microbial laminites, shrinkage and injection features, and rare burrows (Fig. 5.7b – c; see chapter 2 and figures 2.16 – 2.17 for more details). The latter beds are only known from one location near Chazy, New York (Atwood Farm, locality 185) and most likely accumulated in parts of the tidal flat where sedimentation rates were low, probably in low energy lagoonal intertidal environments landward of the wave maximum (Fan et al., 2004; Yang et al., 2005, 2006) and/or in quiescent coastal areas away from sediment-laden river mouths. In turn, these carbonate strata are overlain by intertidal mudstone and siltstone interbedded with ~3 – 23 cm thick, normally-graded, coarse- to very coarse-grained arkosic river-mouth-splay deposits, representing a progradation of fluvial terminal fluvial systems over the tidal flat (Fig. 5.8d). The upper contact of the Altona is similarly conformable and gradational (e.g. Landing et al., 2009). A number of ~3 – 23 cm thick, coarse-grained fluvial river-mouth splays interbeds occur in the upper few metres of the Altona (Fig. 5.8d), and are succeeded abruptly by coarse-grained and locally pebbly braided fluvial strata of the Ausable Formation, recording progradation of fluvial systems over the tidal flat. The depositional age of the Altona is constrained by two trilobite occurrences in the southern Quebec Basin – an olenellid trilobite fragment of probable upper Lower Cambrian age in the lower part of the Altona tidal flat succession, and multiple specimens of *Ehmaniella?* sp. from just below the uppermost intertidal/river mouth deposits, suggesting an early or middle Middle Cambrian age (Landing et al., 2009).

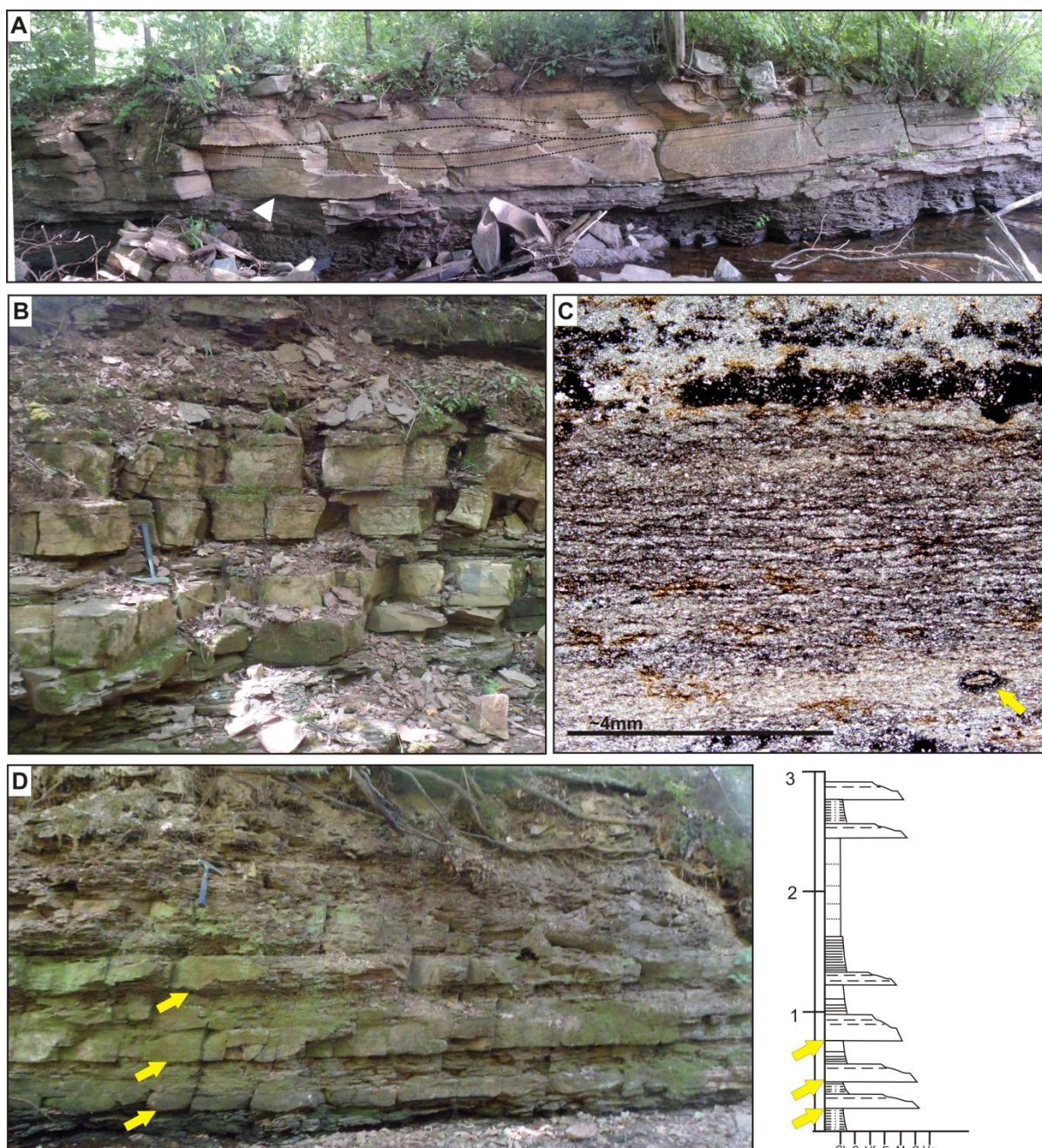


Figure 5.8 Features of the Altona Member in outcrop near Chazy, NY. A) Arrow points to the contact between sparsely bioturbated red silty mudstone (below) and fine-grained hummocky cross-stratified sandstone; located in Stillwater Creek near Jericho, NY (locality 138). B) Blocky and laminated peritidal dolostone exposed at Atwood Farm near Chazy NY (locality 185). C) Thin section photomicrograph of laminated dolostone. This image is centered on very fine (< 0.1 mm) partings of iron oxide-rich clay $\pm$ organics(?) and dolomicrite, interpreted as the by-product of the growth and decay of successive microbial mats. The red arrow points to a fossil fragment surrounded by a redox halo. D) Massive, coarse-grained normally graded sandstone beds interstratified with red mudstone, near the top of the Altona Member at Atwood Farm (locality 233). The sandstone beds are interpreted to have been deposited quickly from high-energy, high-concentration rapidly-waning fluvial sheetfloods near the mouth of a nearby braided river.

5.4.4 Top of the Ausable Formation

The Ausable Formation is conformably overlain by quartz arenite aeolian (FA1) strata of the Hannawa Falls Formation in the western and southwest Ottawa Embayment (localities 54 and 124). The contact between these units is marked by a ~0.3 – 1.9 m thick unit of ephemeral fluvial deposits (FA3) that caps the braided fluvial strata of the Ausable and underlies aeolian strata of the Hannawa Falls (Figs. 5.9, 5.10). This ephemeral fluvial unit consists of massive, cobble-pebble conglomerate lags interbedded with upper medium- to coarse-grained planar stratified sandstone consisting of inversely-graded wind ripple strata, illuviated matrix and common coarse- and very coarse sandstone deflation lags (Figs. 5.9, 5.10). Clasts in the conglomerate exhibit pitted and grooved surfaces suggesting aeolian abrasion (Fig. 5.9b). Feldspar content decreases across this interval from ~30% in the Ausable to $\leq 5\%$ (visually estimated). This conformable transition from braided fluvial to aeolian strata is interpreted to record reworking and local deflation and armouring of upper Ausable braided fluvial strata by ephemeral sheet floods and wind as a result of a progressive but major shift in climate from humid to arid.

In the eastern Ottawa Embayment and Quebec Basin the Hannawa Falls Formation is absent, so that the Ausable Formation is separated from overlying fluvial quartz arenite of the lower Keeseville Formation by a cryptic unconformity (Fig. 5.11). The unconformity is exposed along the axis of the southern Oka-Beauharnois Arch near Franklin, QC (locality 176), and also in several cores from southern Quebec (e.g. Gastem Dundee No.1). Here, the top of the Ausable is a low-relief undulating erosional surface with ~10 – 25 cm of relief and capped by a ~4 – 10 cm thick massive and preferentially silicified pebble and granule

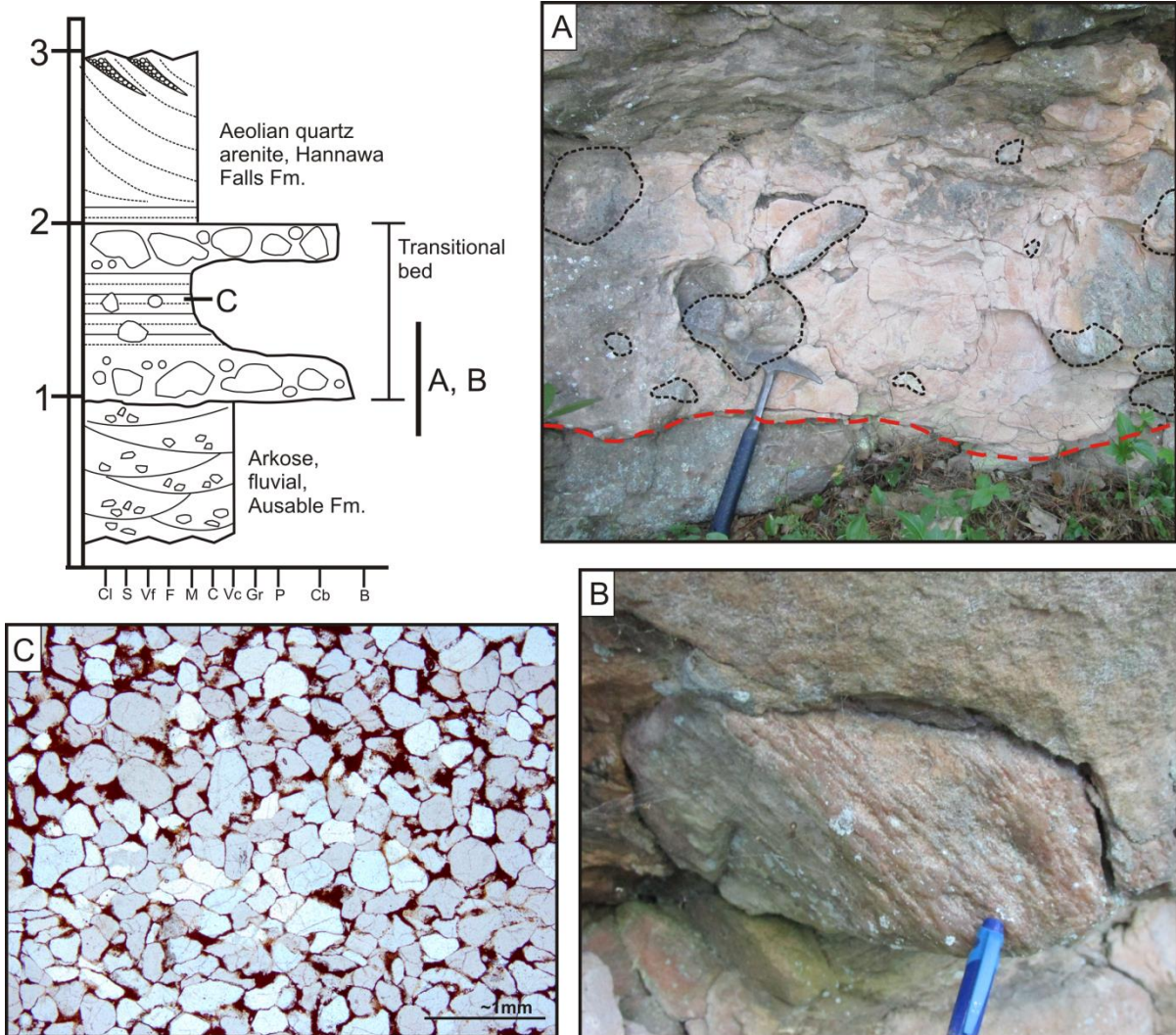


Figure 5.9 Contact between arkosic fluvial strata of the Ausable Formation and overlying quartz arenites of the aeolian Hannawa Falls Formation at Jones Falls Locks, ON (locality 53). These formations are separated here by a ~1m thick transitional unit consisting of massive boulder lags and planar wind ripple stratified sandstone. Vertical scale in stratigraphic log is in metres. A) Sharp contact between the Ausable and the transitional bed (red dashed line). Subangular boulders and cobbles are outlined in black in the transitional bed. B) Close-up of quartzite cobble showing pitted and striated surface texture interpreted to have formed by prolonged windblown abrasion. C) Thin section photomicrograph of wind-ripple stratified sandstone from the transitional unit; note abundant interstitial illuviated matrix.



~1m

Figure 5.10 Contact between arkosic fluvial strata of the Ausable Formation and overlying quartz arenites of the aeolian Hannawa Falls Formation: GSC Lebreton No.1, Ottawa, ON. TB= transitional bed.

conglomerate with coarse- to medium-grained sandstone matrix (Fig. 5.11). This capping conglomerate is preferentially cemented by pore-filling silica cement that preserves anomalously high intergranular volume ($\sim 22 - 26\%$ ¹, compared to $\sim 5 - 15\%$ for most silica-cemented Potsdam Group beds) and contains illuviated matrix (Fig. 5.12a-b). Additionally, detrital feldspar grains in the uppermost $\sim 1.5 - 2$ m of the Ausable are preferentially degraded and illuviated matrix is also present (Fig. 5.12). Collectively these features suggest the development of an initial lag, probably by aeolian deflation, followed by development of a silcrete paleosol with an upper duricrust and underlying illuvial horizon (e.g., Thiry, 1999). Silica was probably sourced from the breakdown of detrital feldspars beneath the silcrete, and was mobilized by upward-migrating groundwater driven by surface evaporitic pumping. Evaporation also served to concentrate the dissolved silica, which upon reaction with atmospheric CO₂, reduced the pH of the silica-bearing groundwater and promoted silica precipitation (e.g., Selleck, 1978b).

5.4.5 Hannawa Falls Formation

The Hannawa Falls Formation, conformably overlying the Ausable Formation and unconformably overlain by the Keeseville Formation, is defined by mainly large-scale cross-stratified aeolian quartz arenite with a pervasive red coloration (Fig. 5.13). Here the Hannawa Falls Formation is a revision of the Hannawa Falls Member as described by Sanford and Arnott (2010) and typified by the well-known large-scale cross-stratified red bed exposures along the Raquette River south of the town of Potsdam (localities 192 and 220, see Fig.

¹ Calculated from thin section photomicrographs using ImageJ

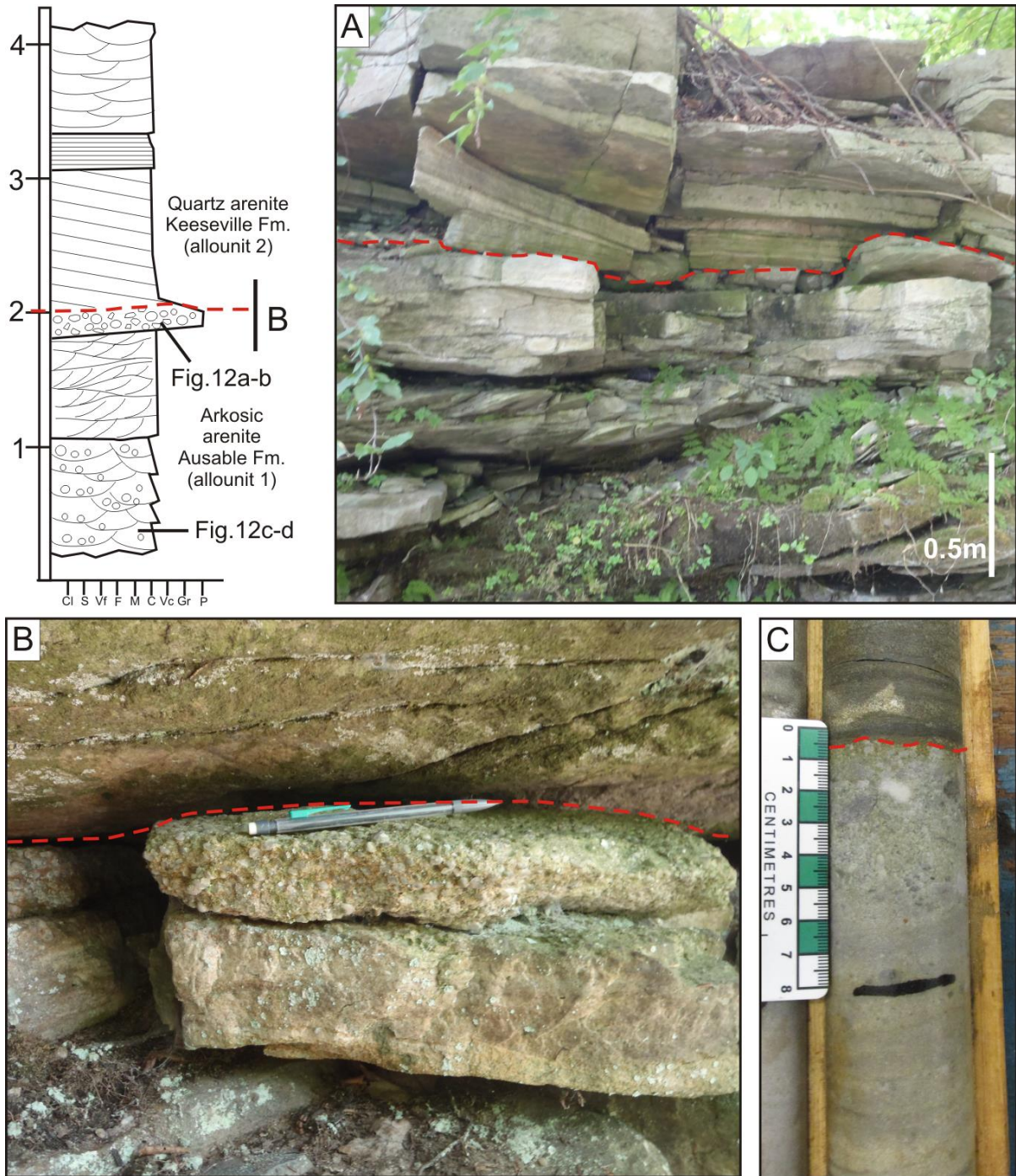


Figure 5.11 The contact (red dashed line) between fluvial arkoses of the Ausable Formation and fluvial quartz arenites of the Keeseville formations: (A) in the eastern Ottawa Embayment and Quebec Basin, near Franklin, QC (locality 176) – here the contact is a cryptic unconformity with an ~10 – 15 cm thick massive and silicified granule to pebble lag at the top of the Ausable (B). (C) Contact in the Gastem Dundee No. 1 well, southern Quebec.

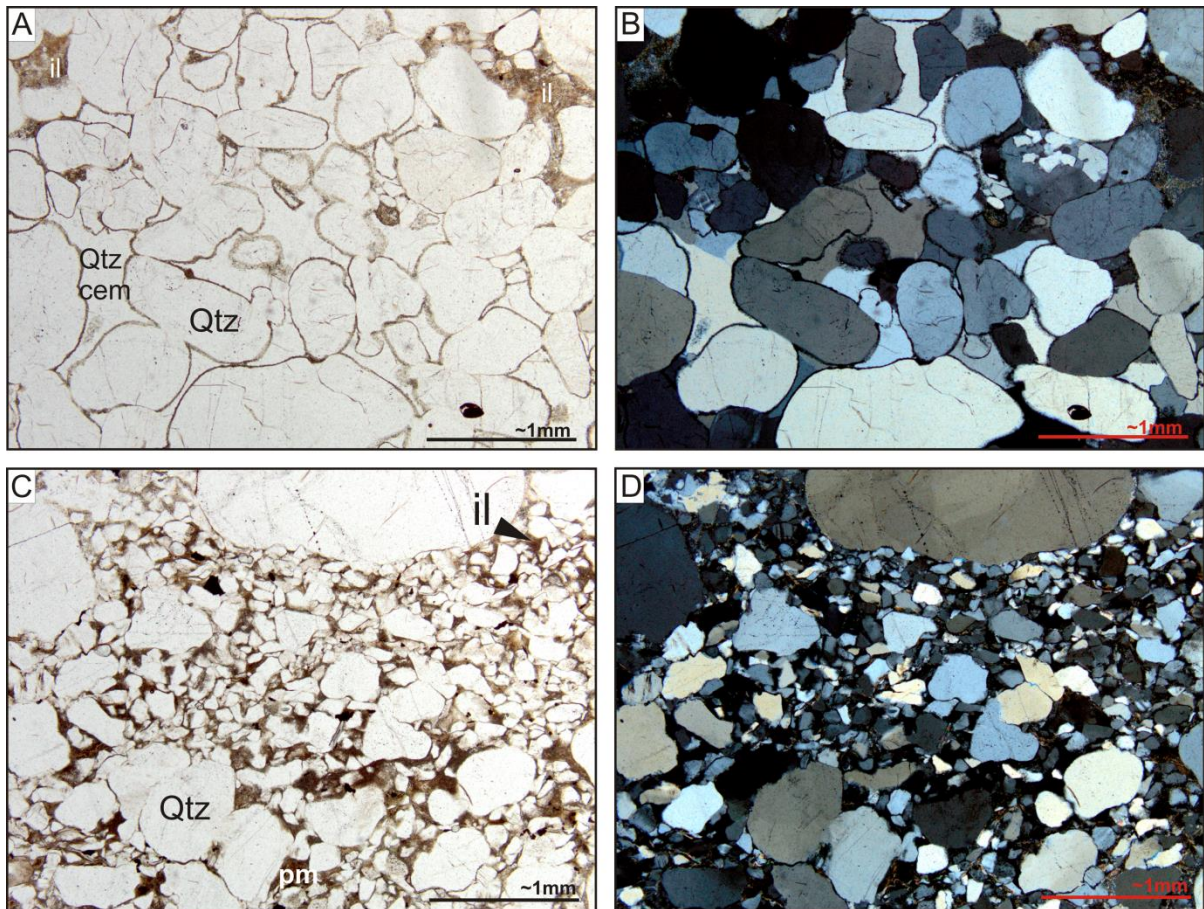


Figure 5.12 Thin section photomicrographs showing characteristics of the silcrete that caps Ausable strata at the outcrop section from figure 11 (locality 176). A) & B) taken from the capping conglomerate where early pore-filling non-syntaxial silica cements and minor illuvial matrix are present. Qtz = quartz grain, Qtz cem = quartz cement, il = illuvial matrix. C) & D) photomicrographs of a sample taken ~1.5 m beneath the capping conglomerate. In contrast to the overlying conglomerate, early silica cement is absent but illuvial matrix (il) is abundant with possible pseudomatrix from the breakdown of feldspar (pm- for pseudomatrix).

5.13a): these were first described by Emmons (1838) and deemed the type section of the “Potsdam Sandstone”. Here, it is deemed the type section of the Hannawa Falls Formation.

Sanford and Arnott (2010) used red colouration as a primary criterion for the definition and recognition of the Hannawa Falls, thus extending this unit to all basal sandstone and conglomerate strata of the Potsdam Group with a red coloration regardless of

mineralogical composition. Notably, at its type section in Hannawa Falls, New York and elsewhere a pervasive red coloration certainly characterizes the Hannawa Falls due to pervasive grain-rimming iron oxide cement that texturally pre-date silica cements (Fig 5.13b). Therefore, this cement likely originated as primary or early diagenetic clay rims, possibly caused by the breakdown of rare ferromagnesian silicate minerals and/or iron-oxide rich clays during aeolian transport followed by precipitation of iron oxides in well-oxygenated meteoric pore water (e.g. Wilson, 1992; Bietler et al., 2005). However, red coloration does not everywhere characterize Hannawa Falls strata (e.g., Fig. 5.10), as red coloration also occurs locally in strata of the Ausable and Keeseville formations where redox fronts commonly cross-cut primary sedimentary structures (Fig. 5.14). Furthermore, petrographic studies of the aeolian Navajo Sandstone by Chan et al. (2000) and Beitler et al. (2005), for example, suggest that early iron oxide cements are susceptible to diagenetic remobilization by reducing fluids. Therefore, red coloration is probably a questionable attribute for lithostratigraphic correlation given that its presence or absence may or may not be reflective of depositional origin. Accordingly, the Hannawa Falls Formation is defined here on the basis of four diagnostic criteria, which in order of importance are: (a) quartz arenite composition, (b) recognizable unconformable contact with the overlying Keeseville Formation, (c) well-sorted medium sand size, (d) aeolian sedimentary fabrics including inversely-graded laminae and large-scale cross-stratification and (d) common pervasive red coloration due to grain rimming hematite cements (Fig. 5.13).

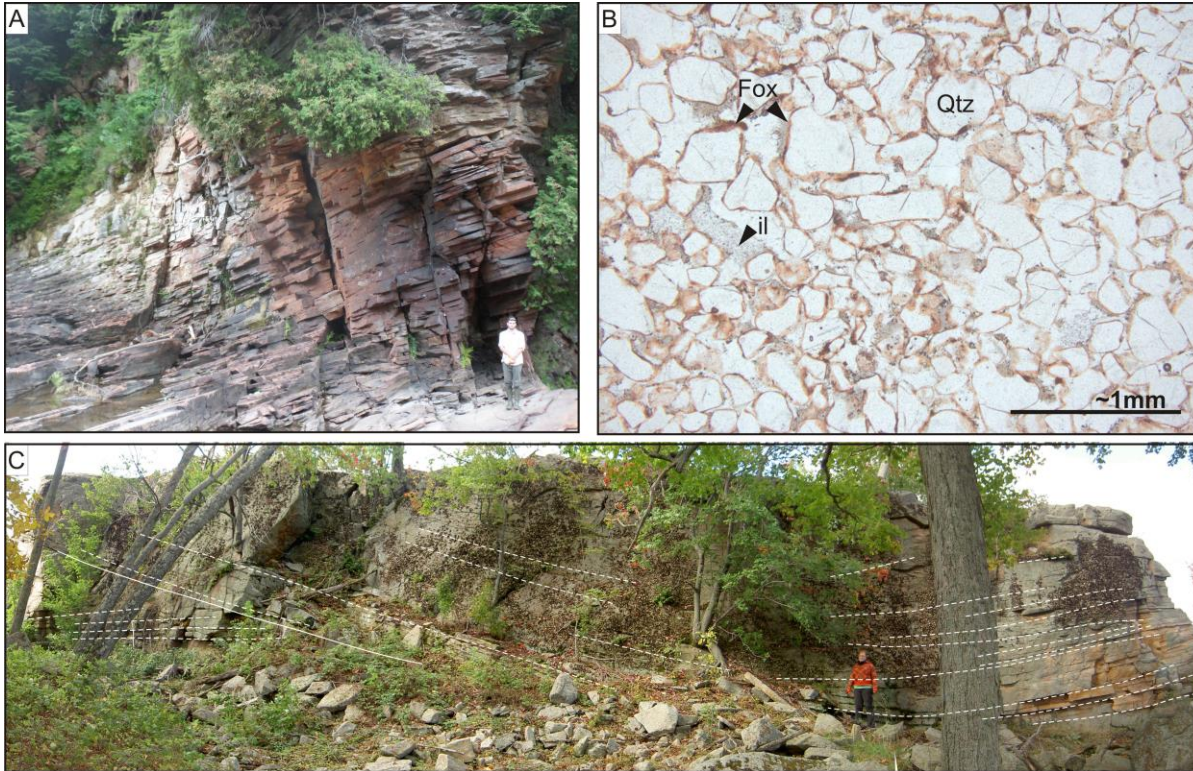


Figure 5.13 Examples of the Hannawa Falls Formation. A) Red, well-sorted, medium-grained, large-scale cross-bedded aeolian (FA3) sandstone at its type section in the Raquette River in Hannawa Falls, NY (locality 220). B) Photomicrograph of sample taken from the same location. Note the pervasive, red coloured, early diagenetic iron-oxide rims that surround the quartz grains. Fox= iron oxide, Qtz = quartz grain; il= illuvial matrix. C) Large-scale aeolian dune cross-stratification, Sloan Quarry, ON (locality 27).

The Hannawa Falls is here upgraded to formation status on the basis of its wide areal distribution (correlated over 19,600 km²) and recognizable combination of lithologic features, noted above (Fig. 5.13). The Hannawa Falls is therefore easily identified by its lithologic characteristics and is a mappable tabular unit on the Earth's surface, thus satisfying the conditions for a formation rank (Article 24 from NACSN, 2005). On the basis of these criteria, strata of the Hannawa Falls Formation range from ~ 2 – 25 m thick and crop out mainly in stratigraphic outliers throughout the Frontenac Arch/Adirondack Lowlands in eastern Ontario and northern New York, but also are present in the subsurface of the northwestern Ottawa Embayment on the eastern side of the Gloucester Fault (Figs. 5.1, 5.4,

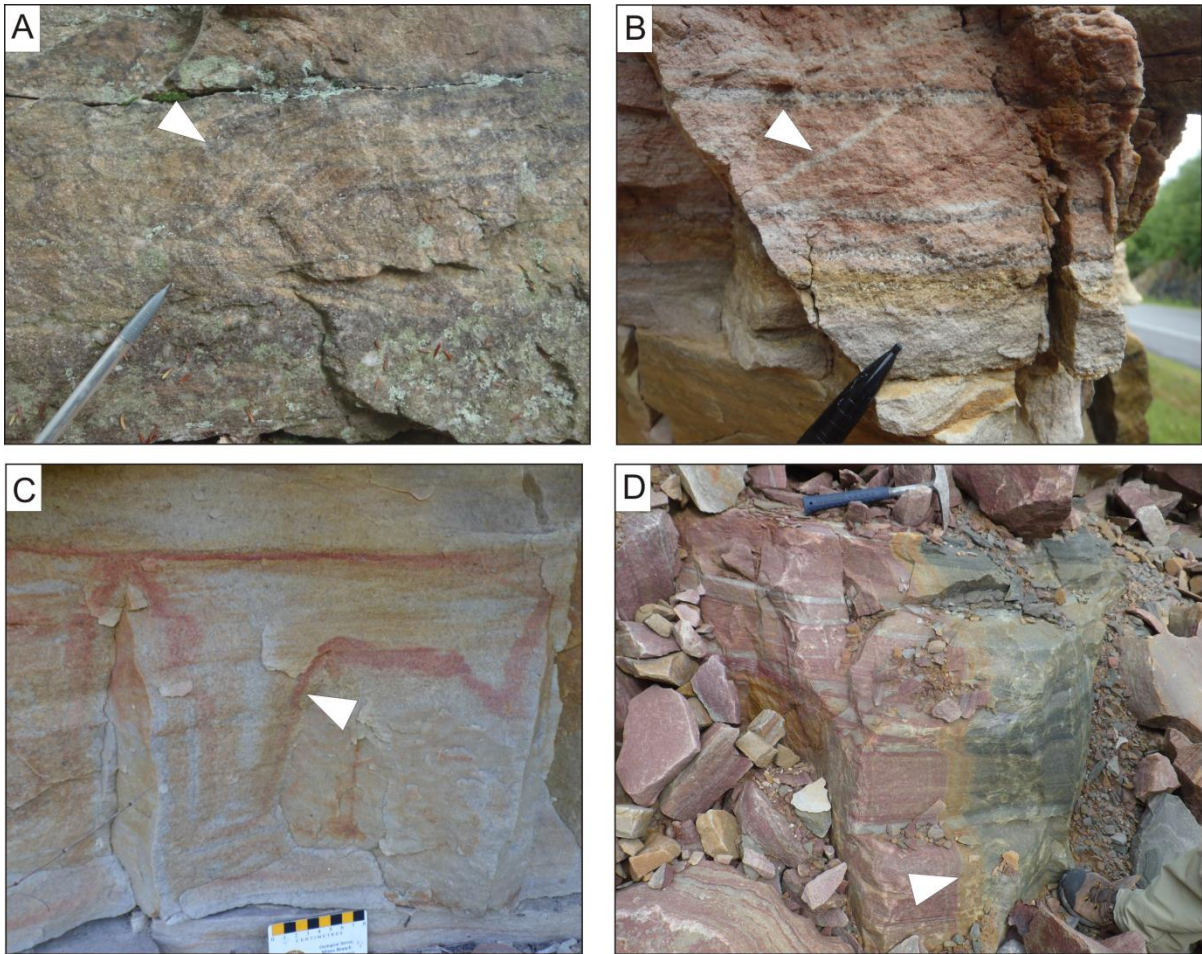


Figure 5.14 Examples of red coloration in the Ausable and Keeseville formations. A) Liesegang banding in coarse-grained pebbly arkose of the Ausable Formation in Graves Brook near Ellenburg, NY (locality 154). B) Secondary red and grey streaks cross-cutting primary stratification in ephemeral fluvial (FA2) quartz arenites of the Keeseville Formation along Highway 12 near Alexandria Bay, NY (locality 112). C) Irregular liesegang banding in ephemeral fluvial strata of the Keeseville Formation, exposed along highway 12 near Alexandria Bay, NY (locality 102). D) Vertical redox front cross-cutting primary stratification in aeolian (FA3) strata of the Keeseville Formation, Rainbow Quarry, NY (locality 188).

5.10). The Hannawa Falls Formation consists mostly of aeolian (FA1) strata that thicken southward from ~5.5 m in the subsurface near Ottawa, to ~ 22 m near Hannawa Falls NY, to ~95 km in the SSW. These strata are overlain locally by ephemeral fluvial strata (FA3) that over the same area thicken northward from ~2 m to ~25 m. The contact between aeolian erg and ephemeral fluvial strata is sharp and marked by a ~5 – 8 cm thick pebble conglomerate.

The Hannawa Falls Formation is undated, but most likely is middle or upper Middle Cambrian based on its conformable relationship with the underlying Middle Cambrian Ausable Formation. Rare and poorly-understood *Protichnites* and *Diplichnites* have been described by MacNaughton et al. (2002) and are the earliest evidence for terrestrial animal life known so far (specimens from localities 27 and 28). Though MacNaughton et al. (2002) suggested that the aeolian strata of the Hannawa Falls must have been close to a marine system, evidence here, primarily the extent of aeolian strata with no correlative marine or littoral strata, rare waterlain facies, thin interdune strata (~ 5 – 40 cm) and wide areal extent of correlative aeolian strata suggest that strata of the Hannawa Falls accumulated in an inland erg under arid or semi-arid conditions (see FA3 in Chapter 3 for more details).

The unconformity that separates the Hannawa Falls and Keeseville formations is expressed in most places as an erosional disconformity (Fig. 5.15), but locally as an angular unconformity where the underlying Hannawa Falls Formation has been folded and faulted (Fig. 5.16; e.g., Sanford, 2007; Sanford and Arnott, 2010; unconformity exposed at localities 27, 28, 41, 54, 74, 86, 124 and 129). Locally, a ~15 – 25 cm thick, massive and anomalously coarse-grained (pebble-cobble) regolithic conglomerate is present (Fig. 5.15c). The structural deformation of Hannawa Falls is characterized by broad localized synclines, half-synclines, low- to high-angle normal faults, rare thrust faults and otherwise massive and/or convolute stratification (e.g., Fig. 5.16). According to Sanford and Arnott (2010), this structural deformation was related to extension oriented sub-parallel or oblique to the trend of the Ottawa Embayment. In addition to erosion and structural deformation, the upper ~0.3 – 2 m of the Hannawa Falls Formation is exceptionally red (Fig. 5.15a -b). The red colouration and

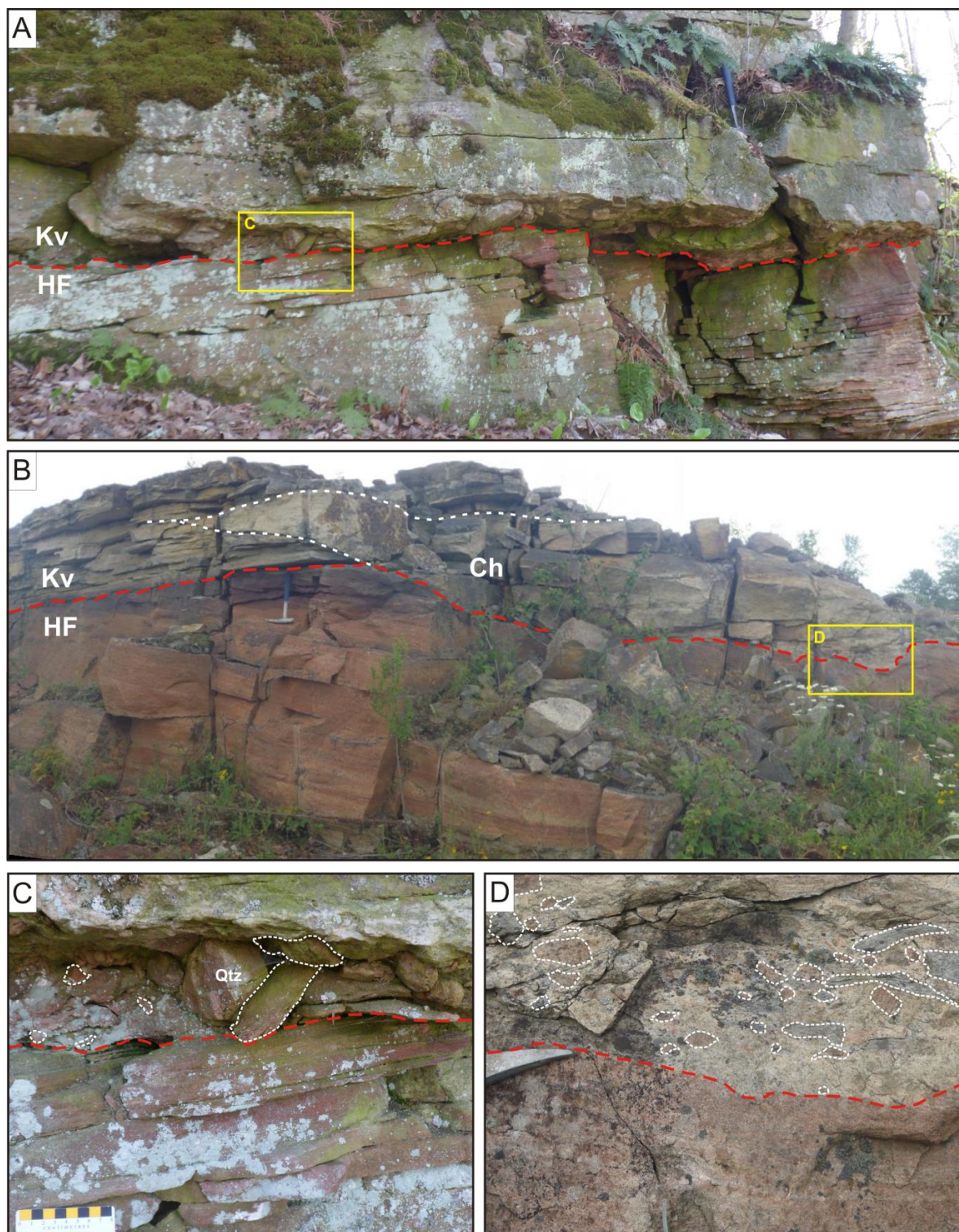


Figure 5.15 Examples of the erosional unconformity separating Hannawa Falls Formation (HF) and Keeseville Formation (KV) strata. A) Erosional unconformity (red dashed line) with minor (≤ 10 cm) erosional relief near Millsite Lake, Redwood, NY (locality 124). B) Same surface but at Sloan Quarry, ON (locality 27). Here, the unconformity is mostly flat with an abrupt upward-reddening of the underlying Hannawa Falls (left side of photo). Note the channel (Ch) in basal ephemeral fluvial strata of the Keeseville that locally incises Hannawa Falls strata. C) & D) close-up photos of the unconformity in the yellow inset boxes in A) and B), respectively. C) At Millsite Lake, NY, a $\sim 5 - 10$ cm thick lag caps the Hannawa Falls, and includes clasts of the red Hannawa Falls sandstone (outlined in white). D) At Sloan Quarry, ON, abundant clasts of pink to red, finely-laminated Hannawa Falls sandstone in white-coloured channel-fill sandstone at the base of the Keeseville (outlined in white).

associated poor induration increases upward towards the unconformity, and generally abruptly (Fig. 5.15b) defining zonation. In thin section, the red colouration and poor induration are related to intergranular hematite and fibrous, void-filling illite cements that preserve higher than normal primary intergranular volumes ($\sim 26 - 28\%^2$; Fig. 5.17). In addition, angular clasts eroded from this horizon are common in the lower $\sim 1 - 2$ m of the overlying Keeseville Formation, suggesting that near-surface cementation predated deposition of the overlying Keeseville (Figs. 5.15, 5.16). Based on high intergranular volumes, crude zonation and presence of clasts of Hannawa Falls in the base of the Keeseville, this hematite- and illite-cemented horizon is interpreted to have formed as an early (pre-burial) near-surface paleosol horizon. Specifically, it is interpreted as a ferric oxisol (classification of Mack et al., 1993), or laterite, and reflects groundwater leaching of alkali elements and silica and near-surface precipitation of residual hematite and kaolinite (Singer, 1975; Mack et al., 1993). Kaolinite, however, was later recrystallized to illite during burial diagenesis. Requisite Fe and Al for lateritization was most likely sourced from leached clay grain coatings, rare detrital feldspar grains, and/or perhaps nearby basement.

² Calculated from thin section photomicrographs using ImageJ

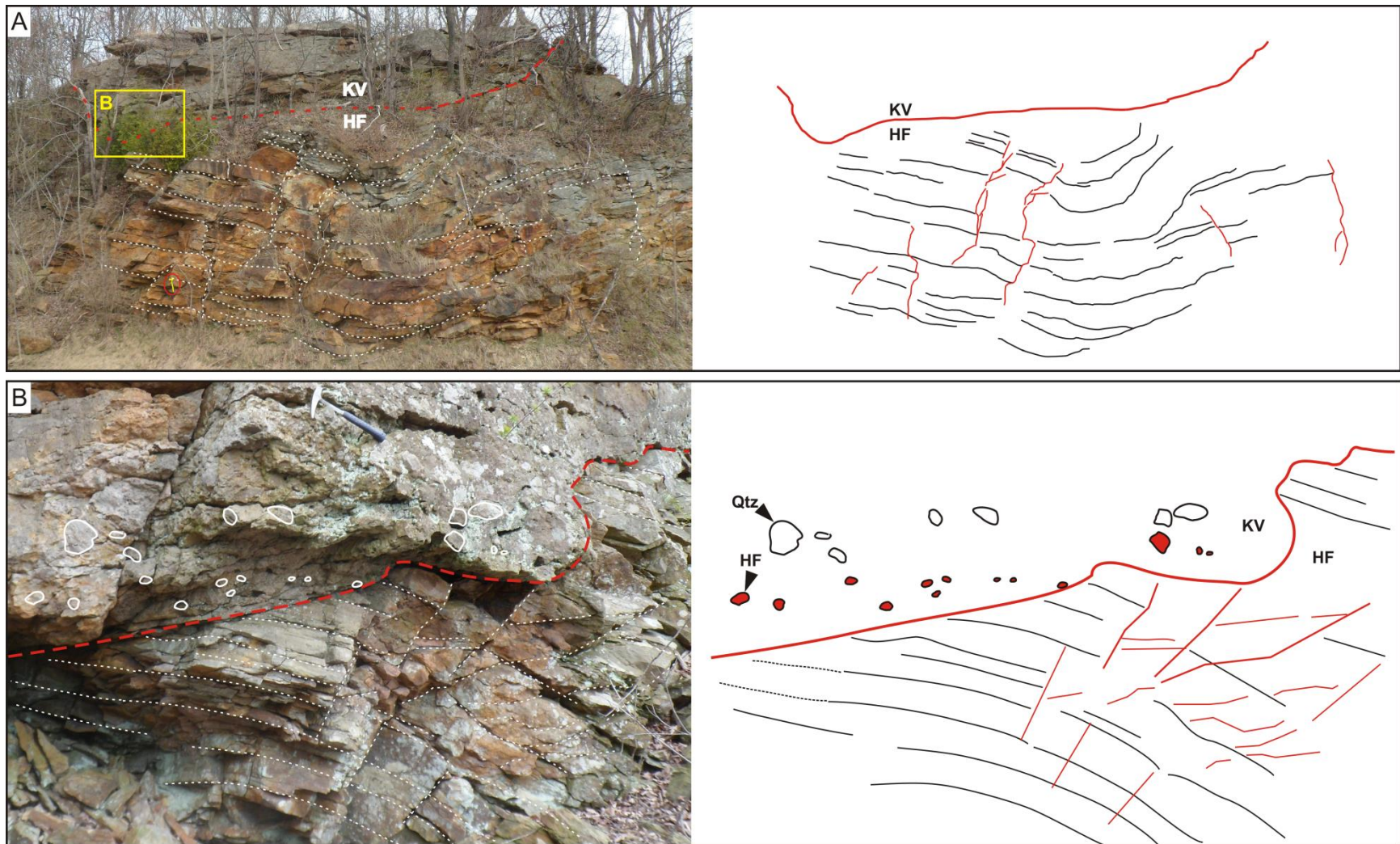


Figure 5.16 Example of the angular unconformity locally developed between the Hannawa Falls Formation (HF) and the Keeseville Formation (KV), exposed along route 42 east of Phillipsville, ON (locality 41). A) View of the section from the roadside, here Hannawa Falls strata exhibit minor folding and/or slumping and brittle faulting, compared to the flat-lying and undeformed Keeseville strata. Red circle shows rock hammer for scale. B) Close-up of the angular unconformity at the same location, location given in the yellow inset box in figure 16a. Here, fractured and folded Hannawa Falls strata are truncated by relatively undeformed Keeseville strata. Here, like at Sloan Quarry (figure 15 b), the base of the Keeseville is channelized and clasts of eroded Hannawa Falls strata (HF, in red) and quartzite clasts (Qtz) are mixed into the channel fill.

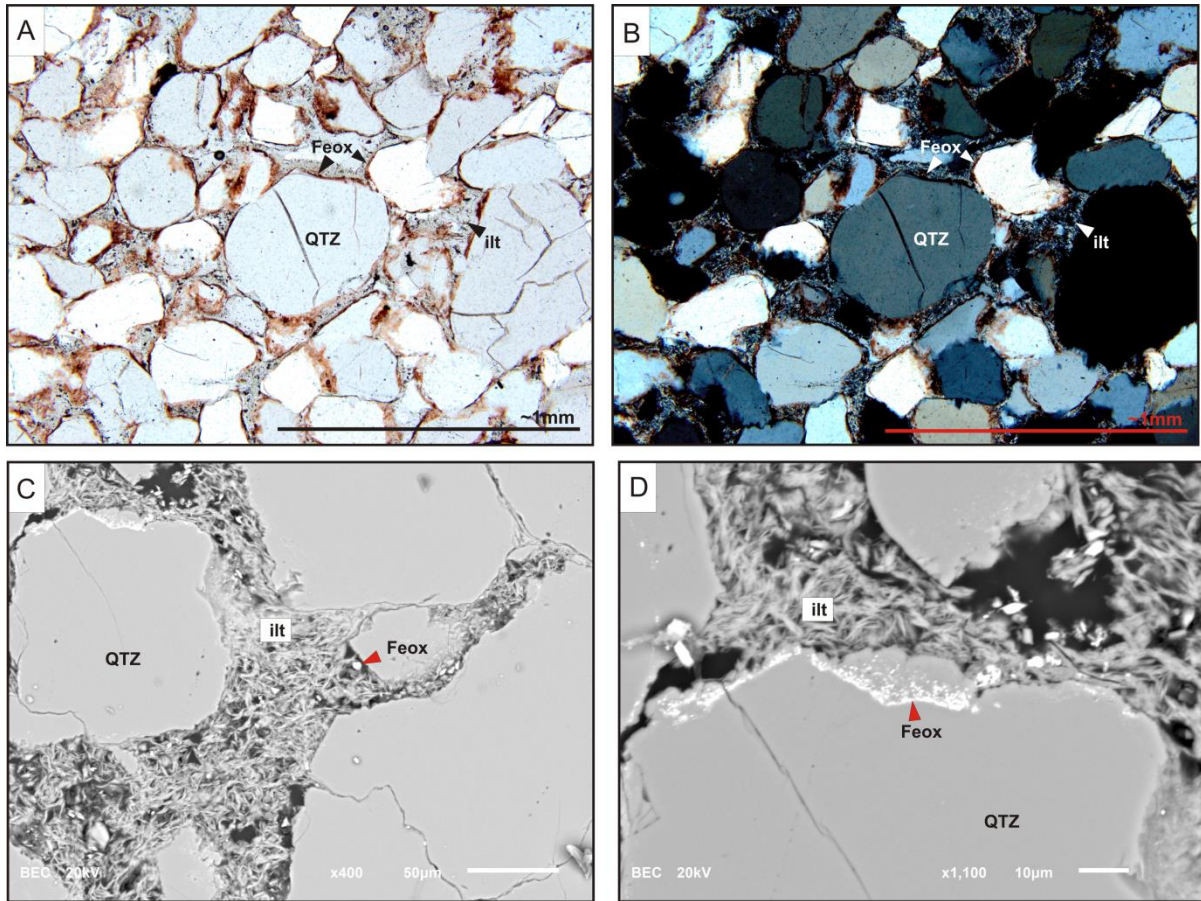


Figure 5.17 Photomicrographs of Hannawa Falls strata immediately below the unconformity at Millsite Lake (locality 124, see Figure 5.15a). A) & B) thin section photomicrographs in plane- (A) and cross-polarized (B) light. Quartz grains (Qtz) are rimmed by iron oxide cements (Feox), and surrounded by intergranular illite (ilt) and disseminated iron oxide cements. C) & D) are scanning electron microscopical images of the same horizon, showing the fibrous nature of illite (ilt) cements and iron oxide cement (Feox; the brighter material).

5.4.6 Keeseville Formation

The Keeseville Formation is the uppermost unit of the Potsdam Group and consists primarily of buff to white, generally silica-cemented quartz arenite, although rarely and locally strata exhibit a red colour. Included also are rare quartzite-clast cobble-boulder conglomerate and carbonate beds (Fig. 5.18). The Keeseville Formation (from Sanford and Arnott, 2010) replaces the Keeseville Member in New York (from Emmons, 1841; Fisher



Figure 5.18 Examples of the Keeseville Formation from across the study area. A) Mostly planar-stratified coastal plain ephemeral fluvial strata (FA2) exposed in the Great Chazy River in Woods Falls, NY (locality 148). Arrows demarcate the top and base of a coset of hummocky-looking antidune stratification. B) Aeolian dune cross-stratification (FA3) exposed in the Rainbow Quarry, Near Malone, NY (locality 188). C) Planar- and cross-stratified coastal sabkha (FA4) strata exposed in the Melocheville Quarry, near Melocheville, QC (locality 275). D) ephemeral fluvial strata (FA2) exposed along highway 12 near Alexandria Bay, NY (locality 100). The high-angle set at the base is interpreted as a high-angle, upstream-dipping cyclic step set. E) Gravelly braided fluvial strata (FA1) exposed in Charleston Lake Provincial Park, ON (locality 57). F) Bioturbated, mostly dune cross-stratified tide-dominated marine strata (FA5) exposed along highway 15 southwest of Smiths Falls, ON (locality 16). Circle in A), C), E) and F) outlines hammer for scale.

1968) and its stratigraphic equivalents named the Nepean Formation (Wilson, 1946) and Cairnside Formation (Clark, 1966; 1972) in Ontario and Quebec, respectively. It here also includes the quartz arenite and quartzose conglomerate strata previously assigned to the Chippewa Bay Member exposed in parts of northern New York and eastern Ontario, primarily over the Frontenac Arch (Sanford and Arnott, 2010; termed also the Potsdam I by Kirchgasser and Theokritoff, 1971; e.g., localities 20, 22, 52, 55-56, 68, 78, 81, 82, 84-88, 95-112; Figs. 5.14b – c, 5.18d). This revision is consistent with the original definition of the Keeseville by Emmons (1841) and later by Fisher (1968) in New York. Due to its wide extent and lithofacies variability it is not feasible to propose a single stratotype locality for the Keeseville Formation, and instead many localities should be considered as representative including the Ausable Chasm (locality 190), outcrops in and around the town of Altona NY (e.g., 154, 187; Fig. 5.18a), Ducharme Quarry (200, 201, 203; Fig. 5.19), outcrops and quarries near Melocheville QC (e.g., 206, 207, 210; Fig. 5.18c), outcrops along Highway 12 near Alexandria Bay, NY (e.g., 86, 87, 100, 104, 112; Fig. 5.18d), near Perth ON (e.g. 16, 76), near Gananoque ON (e.g., 22, 68), near Brockville, ON (e.g., 20, 223), in Nepean and Kanata, ON (e.g., 1, 5, 222) and in Gatineau, QC (e.g., 8, 9). The sections at Ducharme Quarry (200, 201, 203; Fig. 5.19) provide the best coverage of the Keeseville Formation and provide representative examples of most of its lithofacies; however these sections occur on private land with limited access, and also occur on an active quarry with constantly changing exposures. A more appropriate type section of the Keeseville Formation is therefore the Ausable Chasm, where over a hundred metres of representative strata is exposed (locality 190), and is easily accessed and well-known, satisfying at least some of the conditions of a type section (Article 8(a) from NACSN, 2005). However, it does not represent the complete

lithofacies variability of the Keeseville, and at this location the boundaries between the Keeseville and other units are not exposed. The most complete and easily-accessed sections of the Keeseville Formation crop out along Highway 12 in northern New York State, between Alexandria Bay and Blind Bay (e.g., 86, 87, 100, 104, 112; Fig. 5.18d). Together these closely-spaced outcrops should be considered a composite stratotype of the Keeseville Formation (see Article 8(d) from NACSN, 2005), as they expose the entire Keeseville Formation in this area, including its lower and upper contacts. Additionally most of the lithofacies that make up the Keeseville Formation are well exposed and easily accessed.

The Keeseville Formation is the most areally expansive unit in the Potsdam Group, cropping out across the entire Ottawa Embayment and Quebec Basin -- an area of at least 26,000 km². Like the Ausable Formation, it has an uneven regional isopach, ranging in thickness from only ~8 m to 180 m. In addition, it consists of a complexly interstratified and regionally-variable assemblage of depositional facies, and is commonly, but not everywhere, subdivided by an internal unconformity. However, in spite of its stratal complexity a number of characteristics permit basin-wide correlation of the Keeseville succession. Firstly, the conformable interstratification of braided and ephemeral deposits in the non-marine part of the Keeseville provides a record of climate change across the region from humid to semi-arid, respectively. This forms the basis of the relative chronostratigraphic correlation of two ephemeral and two braided fluvial units across the basin (see Fig. 5.3 and chapter 4, specifically Fig. 4.3), which further aids in correlation of the terrestrial parts of the Keeseville succession. Furthermore, the Keeseville succession is capped everywhere by a sabkha and/or tide-dominated marine unit.

The best exposed, but also most geographically-isolated exposures of the Keeseville, occur in Ausable Chasm in the southernmost part of the Quebec Basin. Here a ~140 m thick section from the lower – middle part of the Keeseville in this area exposes mostly supratidal sabkha deposits (FA4) with microbial surface features and rare epifaunal traces (*Protichnites*, *Diplichnites*, and *Climacticnites*) and scyphomedusae impressions (FA4; see Hagadorn and Belt, 2008), locally intercalated with erosionally-based antidune sets and cosets (previously interpreted to be marine HCS by Hagadorn and Belt, 2008), suggesting an intimate association of marginal marine and sheetflood-dominated ephemeral fluvial systems (FA2). An uppermost Middle Cambrian *Crepicephalus* Zone trilobite assemblage has been described in the lower parts of the Chasm section (Walcott, 1891; Flower, 1964; Lochman, 1968; Landing et al., 2009), whereas the middle and upper parts of the section are most probably Upper Cambrian (e.g. Hagadorn and Belt, 2008). Much of the Ausable Chasm section is coeval with marine “Potsdam Formation” strata ~110 km to the south near Whitehall-Fort Ann (a probable Keeseville Formation equivalent, but outside of the current study area, see Landing et al., 2007) and most likely with the terrestrial (braided and ephemeral fluvial) Keeseville section farther to the north in the Ottawa Embayment and Quebec Basin.

About ~45 – 60 km north of Ausable Chasm, strata of the Keeseville Formation are well-exposed over a ~2000 km² area that straddles the New York Quebec Border north of the Adirondack highlands, east of the Chateaugay Fault and south of the Ste. Justine Fault in the southeastern Ottawa Embayment and southern Quebec Basin (Fig. 5.1). An Upper Cambrian age for the majority of Keeseville strata in this area is supported, in part, by Upper Cambrian trilobites (Fisher, 1968), and similarity of the paleomagnetic poles from samples

taken from the Keeseville with other documented Late Cambrian North American paleopoles (Seguin et al., 1981). A Tremadocian depositional age of the conformably overlying Theresa Formation in this area (this study, see details below) substantiates this age correlation. In this area, the Keeseville is ~65 – 120 m thick and made up of ~50 – 100 m of ephemeral (FA2) and minor braided fluvial strata (FA1) and rare aeolian strata (FA3) capped everywhere by sabkha facies (FA4; ~10 – 40 m thick) and overlain gradationally by tide-dominated marine strata (FA5; ~9 – 17 m thick) (Figs. 5.3 – 5.4). The fluvial systems that formed in this area likely transported sediment to the supratidal environments farther south (mentioned above), and occasionally may have been inundated by coastal flooding based on the rare occurrence of *Proticnites*, *Diplichnites* and *Climacticnites*. Hagadorn et al. (2011) also reported rare occurrences of *Proticnites* in aeolian strata in the same area (locality 166). Coastal fluvial strata in this area are gradationally overlain by marine strata, and the nature of this contact is well-exposed in the upper part of Ducharme Quarry in southern Quebec (locality 201, Fig. 5.19). Here, strata of likely coastal ephemeral fluvial (FA2) affinity are separated from overlying tide-dominated marine strata by a ~1.8 m thick transitional section (Fig 5.19). This section consists mostly of current ripple and dune-cross-stratified sabkha sandstone with rare weathered gypsum nodules (FA4) intercalated with six cm-scale pebble conglomerate beds (Fig. 5.19c-d), each generally capped by a thin (≤ 1 cm) drape of bioturbated silty mudstone containing a low diversity assemblage of abundant solitary and branching horizontal burrows of the *Cruziana* ichnofacies (Fig. 5.19b). Each conglomerate bed is interpreted to be a transgressive lag, recording shoreline retrogradation and erosion followed by a period of low energy marine sedimentation amenable to deposit feeders and mud deposition. Each retrogradation was then followed by progradation, resulting the deposition of coastal

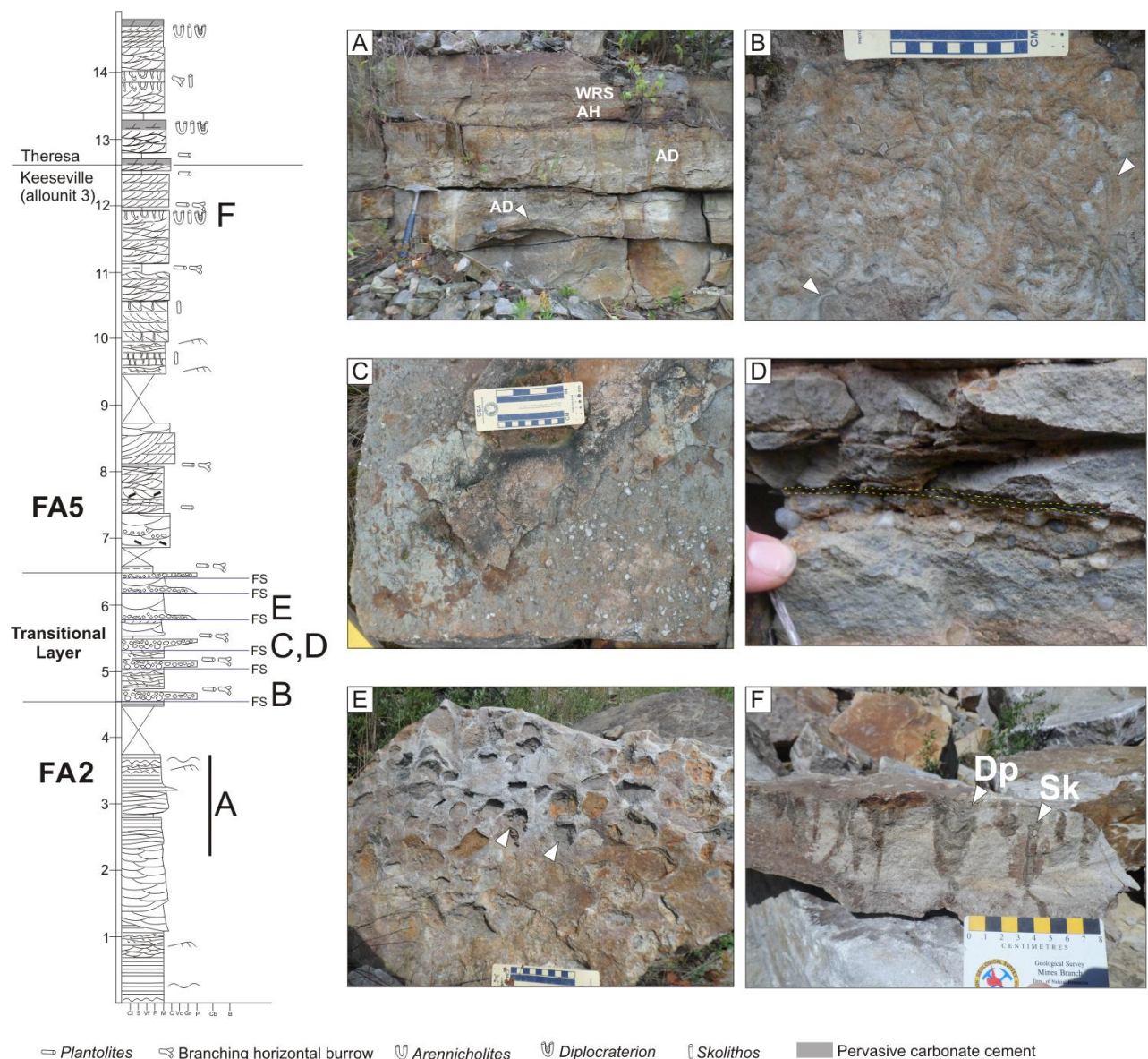


Figure 5.19 Coastal ephemeral fluvial (FA2) to tide-dominated marine (FA5) transition exposed in the upper part of Ducharme Quarry, QC (locality 201). Units of measure are metres. The section below 4 m is dominated by coastal ephemeral fluvial strata (FA2) shown in more detail in A: exposed here are low relief antidune cosets (AD), including rare convex-up formsets (white arrow). Also present are low angle climbing wind ripple laminae (WRS) and diffuse adhesion lamination (AH). The base of the ~1.8 m transitional layer occurs at ~4.6 m (lower FS). This layer contains six thin, massive pebble conglomerates, each interpreted as a transgressive lag. B) Each lag is capped by thin (≤ 1 cm) burrowed silty mudstone containing a simple *Cruziana* ichnofacies, interpreted to record deposit feeders in flooded, sediment-starved conditions (shown in view from top bedding surface). C) & D) show a close-up of one of these pebble lags and capping mudstone, from a bedding plane view and in vertical section, respectively. In D) the capping mudstone is outlined in yellow, and is locally eroded (red dashed line) E) Strata between each lag and capping mudstone in the transitional layer is mostly medium- to lower coarse-grained coastal sabkha (FA4) strata, and record coastal progradation after each flooding event. The voids exposed here (arrows) are interpreted as weathered evaporitic nodules. F) Vertical filter feeders of the *Skolithos* ichnofacies in tide-dominated marine (FA5) strata exposed above the transitional section. Trace fossils include *Diplocraterion* (Dp) and *Skolithos* (Sk). Also shown on the stratigraphic section is the conformable Keeseville – Theresa contact, defined by the lowest carbonate cemented bed ≥ 4 cm thick.

sabkha facies. This transitional interval is then capped by a ~10 – 30 cm thick bioturbated mudstone overlain by high energy subtidal and/or intertidal, locally bioturbated, cross-stratified sandstone (FA5), which record the final coastal retrogradation in this part of the basin.

In the northern Ottawa Embayment and Quebec Basin the Keeseville thins westward from ~180 m near Montreal to ~30 m near Ottawa and is subdivided into two units by an internal unconformity (Figs. 5.3, 5.4, 5.20). The lower unit is ~15 – 90 m thick (thinning westward) and is made up of an ~4.5 – 60 m thick succession of ephemeral and braided fluvial strata (FA2 and FA1) capped locally by a ~2 – 33 m thick tide-dominated marine (FA5) unit with rare peritidal dolostone interbeds, here called the Riviere aux Outardes Member (from Clark, 1966; Salad Hersi and Lavoie, 2000b). The unconformity that truncates the Riviere Aux Outardes Member exhibits local erosional relief of ~5 – 10 cm (Fig. 5.20). Rip-up clasts of peritidal dolostone and dolomite-cemented marine sandstone occur in the basal ~0.1 – 1.1 m of the overlying upper unit of the Keeseville, suggesting early carbonate cementation and cannibalization of parts of the upper Riviere Aux Outardes Member (Fig. 5.20b). New conodont data from a dolostone bed in the Riviere Aux Outardes Member, located ~90 cm below the intra-Keeseville disconformity, support a Lower Ordovician depositional age for the upper Keeseville (Fig. 5.20). This bed yielded numerous *Variabiloconus bassleri* specimens and a single *Cordylodus(?)* specimen, in addition to fragments of phosphatic inarticulate brachiopods, indicating an upper Skullrockian (i.e., lowermost Ordovician) age (Appendix B). The overlying upper unit of the Keeseville consists locally of 3.5 – 30 m of braided fluvial strata (FA1) capped by ~6 – 72 m of sabkha deposits (FA4). In most places the latter are generally capped by ~5 – 42 m of tide-

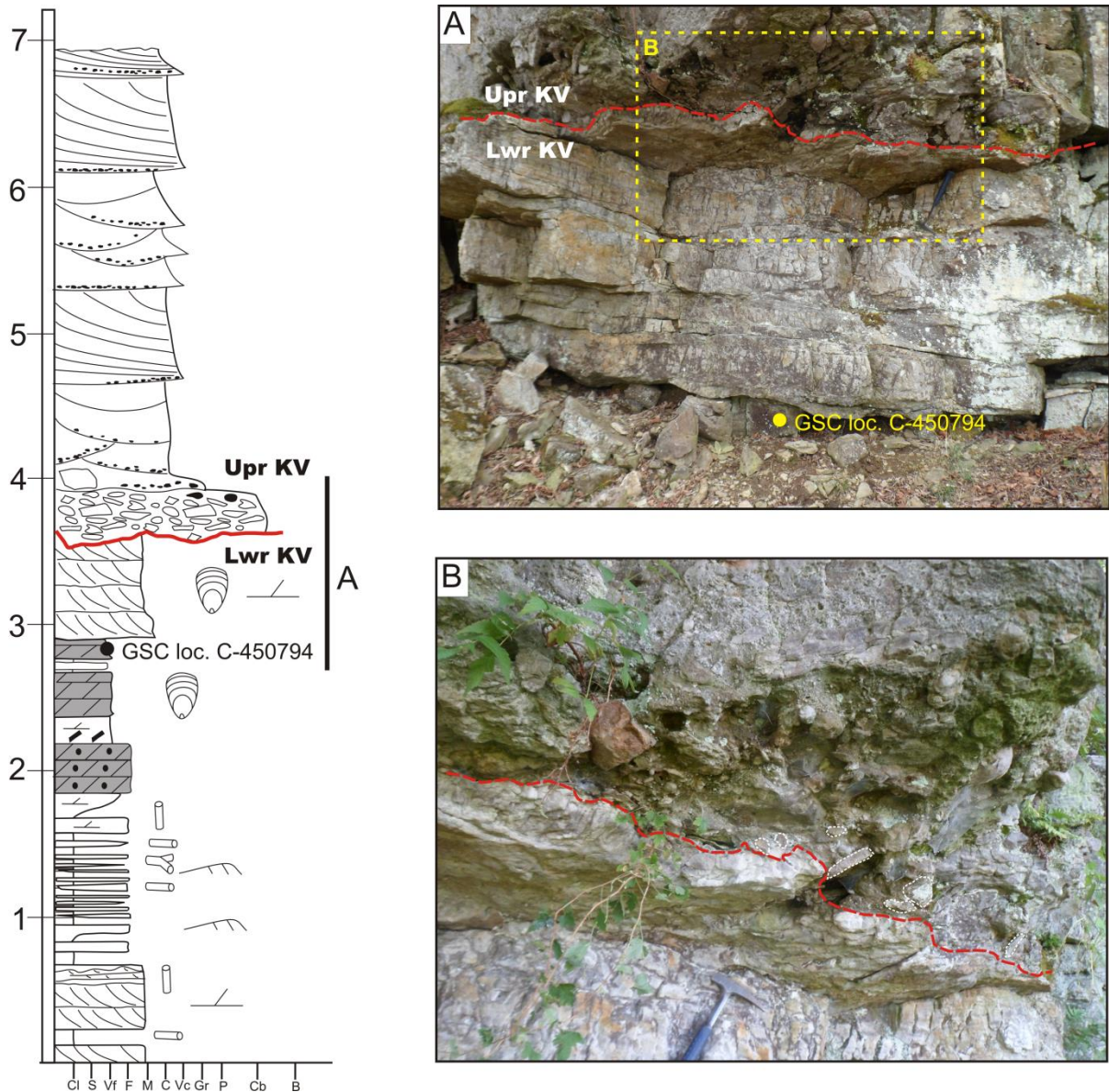


Figure 5.20 Unconformity (red line) between the lower and upper parts of the Keeseville Formation, exposed in Rockland, ON (locality 2). Conodonts from this locality occur in rare dolostone beds in tide-dominated marine (FA5) strata ~0.9 m beneath the unconformity, and suggesting an earliest Ordovician depositional age (see text and appendix B for details). A) The unconformity is erosional with ~5 – 10 cm of erosional relief. Immediately above the unconformity is a ~30 cm thick massive conglomerate, succeeded by braided fluvial strata (FA1) of the upper Keeseville. B) Close-up of the unconformity showing clasts. Most clasts are quartzite, but several near the base of the layer are dolomitic sandstone fragments from the underlying lower Keeseville (outlined in white).

dominated marine strata (FA5), except on the footwall side of regional normal faults near Montreal and Ottawa (the St. Justine and Gloucester faults, respectively Figs. 5.1, 5.4).

Soft-sediment deformation structures are common in the upper unit of the Keeseville in the northern Ottawa Embayment and Quebec Basin, and are particularly well-exposed in the sabkha strata west of Ottawa (Fig. 5.21). Here, deformed strata within a single $\sim 0.5 - 2.2$ m thick horizon are correlated over an area of at least $\sim 70 \text{ Km}^2$ directly east of the Hazeldean fault (Fig. 5.1). The deformation structures in this horizon include (a) convolute, tightly folded and locally overturned $\sim 2 - 6$ cm thick laminated sandstone layers set in a massive sandstone, (b) intraclast breccia consisting of broken and contorted pieces of the same sandstone layers in massive matrix, and (c) isolated lenses or bodies of massive sandstone, $\sim 0.9 - 2.2$ m thick, with low- to high angle ($\sim 10 - 60^\circ$) erosional margins (Fig. 5.21). However, owing to the grain size (i.e., medium sand) and well-sorted nature of these strata, it is doubtful that these features represent load structures related to an inverted density profile (e.g., Owen, 1996; Bridge and Demicco, 2008). Instead, these features are interpreted to be the products of differential liquefaction; i.e., where some layers are mobilized by excess pore water while others are not, and are similar in form to features produced experimentally by Nichols et al. (1994). The resistance of some layers to liquefaction probably stems from their preferential evaporitic cementation and/or microbial binding in the shallow subsurface, consistent with the sabkha environment of deposition (see FA4 in chapter 3). Presumably these liquefaction features formed suddenly and probably at the same time over the $\sim 70 \text{ km}^2$ east of the Hazeldean Fault in Kanata, given their occurrence in a single correlative stratum. On the basis of this inference, the large area covered and proximity to major faults these features are interpreted to have been triggered by an earthquake (Wheeler, 2002;

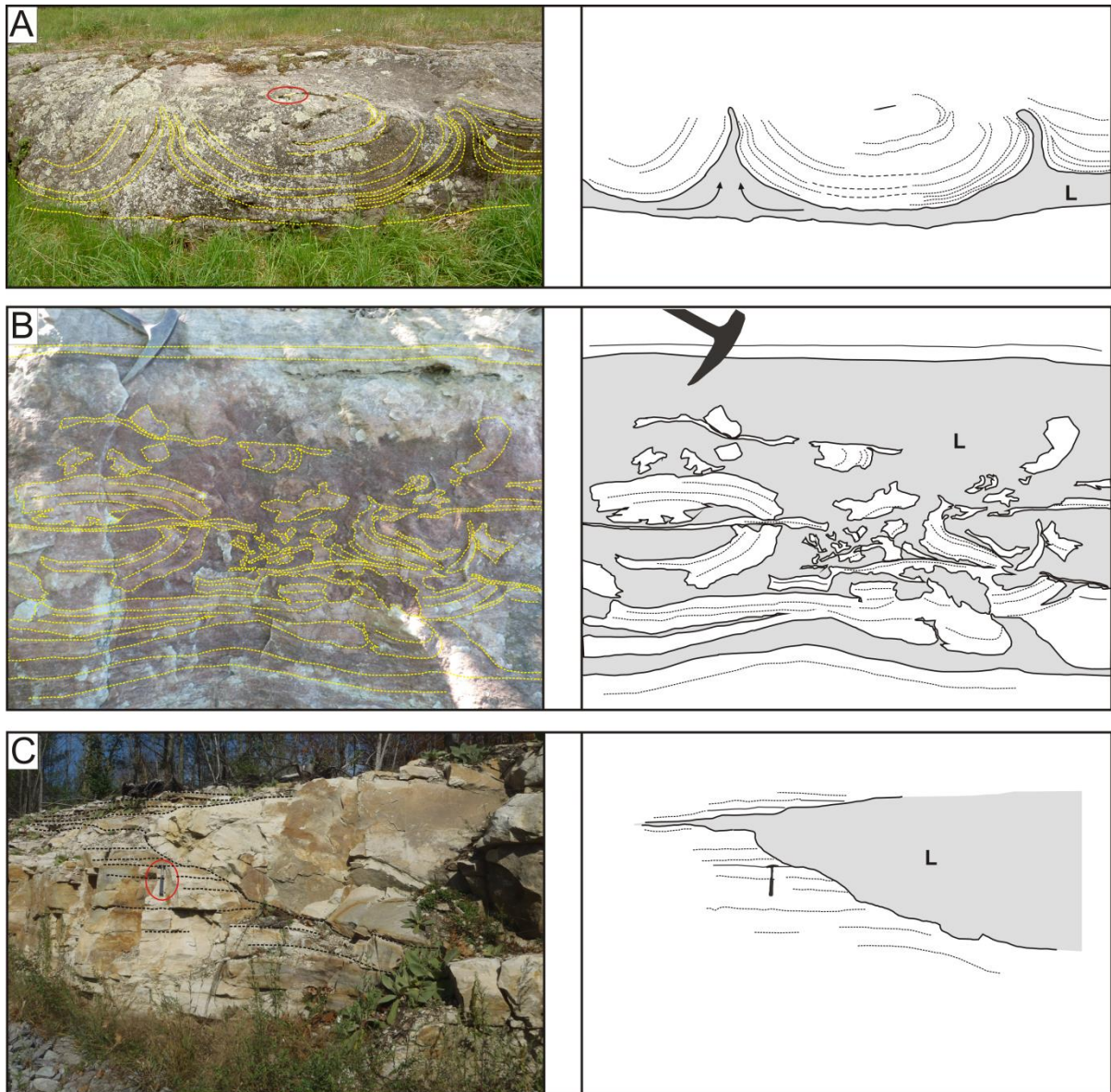


Figure 5.21 Soft-sediment deformation fabrics exposed in Kanata, ON, just east of the Hazeldean Fault. A) Tight isoclinal folding of planar-stratified sabkha sandstone facies (FA4) overlying a massive sandstone, near Hazeldean Road, Kanata (locality 4). Pen for scale. This feature is interpreted to be the result of preferential liquefaction and dewatering of an underlying bed. Arrows show the proposed movement of pore fluid (see text for more detail). B) Intraclast breccia composed of contorted, planar-stratified sabkha sandstone (outlined in yellow) surrounded by massive sandstone matrix, exposed in the Centrum Mall complex, Kanata, ON (locality 221). This feature is interpreted to record a progression of the preferential liquefaction process from A). Here, non-liquefied layers have ruptured, allowing the release and flow of underlying and/or interstratified liquefied sand. C) Lens of massive, erosively-based sandstone truncating planar- and cross-stratified sabkha sandstone (FA4) in Kanata, ON (locality 193). Rock hammer for scale. This feature is interpreted as a further progression of selective liquefaction, in which liquefied sand is extruded and/or intruded into adjacent undeformed strata.

Obermeier et al., 2002; Montenat et al., 2007). Other triggers for such widespread

liquefaction, including rapid sedimentation, storm-driven wave impact, common high shear stress flow conditions, are less plausible in this coastal sabkha environment, further supporting a seismic origin (Owen et al., 2011).

In the southwestern Ottawa Embayment, the Keeseville Formation is relatively thin (~8 – 26 m) and, like in the north, intersected by an internal unconformity (Figs. 5.22, 5.23). Here strata underlying the unconformity consist of ~4 – 22 m thick ephemeral and local braided fluvial strata (Chippewa Bay Member of Sanford and Arnott, 2010; and Potsdam I of Kirchgasser and Theokritoff, 1971; Selleck, 1975, 1978a, b, 1993). In places the braided fluvial strata contain cobble traction-transport conglomerates and are interstratified with coeval cobble-boulder debrites along the margins of basement highs. In most parts of the southwest Ottawa Embayment strata in the uppermost ~1.5 m of these fluvial strata below the unconformity show evidence of possible incipient paleosol development. Specifically, chloritic and/or Fe-rich clays coat round and subround sand grains, and thus appear to have inhibited the ubiquitous silica cements present in over- and underlying Keeseville strata. Furthermore, primary sedimentary stratification is absent in these illuvial horizons (Fig. 5.23b). Therefore, the presence clay coats and disruption of stratification in strata beneath the unconformity suggests intense near-surface illuviation, and more specifically, the formation of an argillitic inceptisol (e.g., Gile and Grossman, 1968; Mack et al., 1993). However, sections located in the south-westernmost Ottawa Embayment, specifically directly south of the St. Lawrence River and on the north side of the Black Lake Fault (Fig. 5.1) expose a 0.3 – 1.2 m thick nodular or

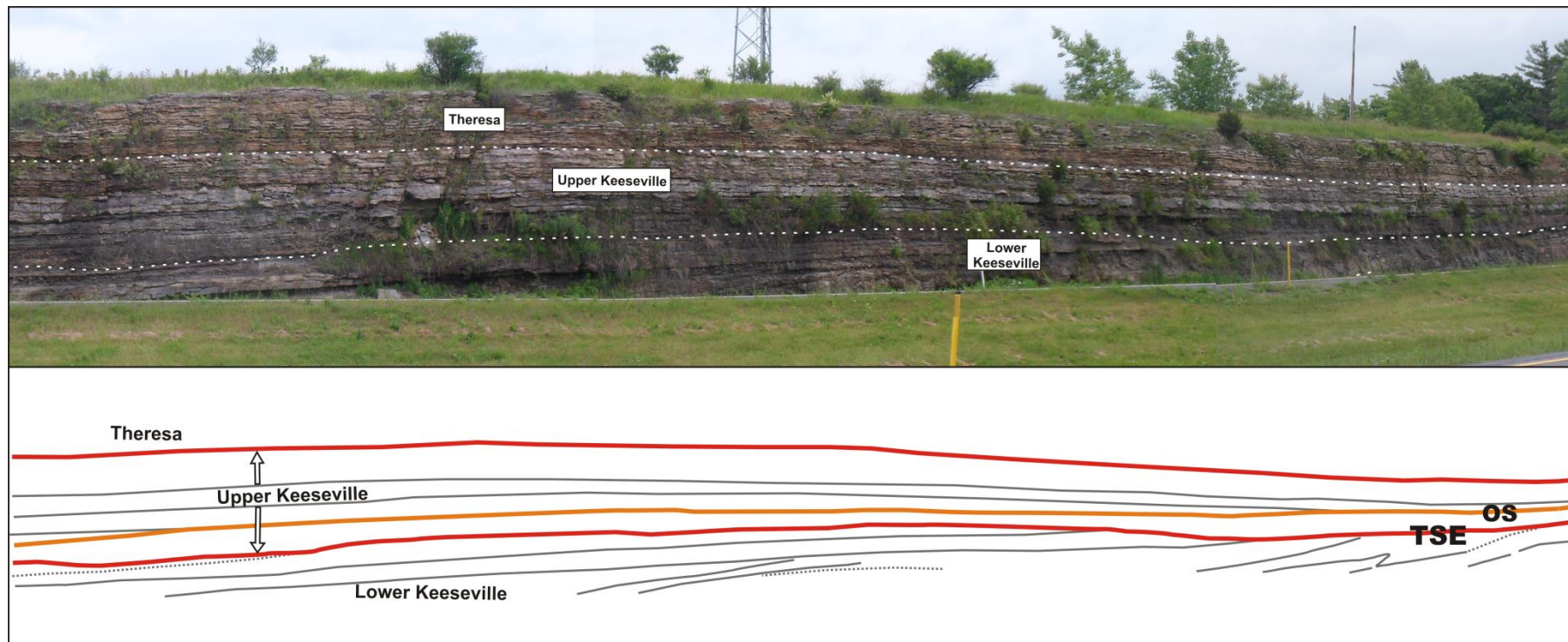


Figure 5.22 Contacts between the fluvial lower Keeseville, marine upper Keeseville and overlying Theresa Formation, exposed along Interstate 81 on Wellesley Island, NY (locality 236). Here, strata of the lower Keeseville are truncated by an erosional surface capped by a massive cobble conglomerate. This surface is interpreted as a transgressive surface of erosion (TSE), and the overlying conglomerate is interpreted as a transgressive lag. The lag is overlain by a subtle onlap surface (OS), over which tide-dominated marine strata of the upper Keeseville onlap at a very low angle ($\leq 5^\circ$). The base of the Theresa is defined by the lowest carbonate-cemented bed (≥ 4 cm thick), and here conformably overlies the upper Keeseville (see figure 27 and text for more details).

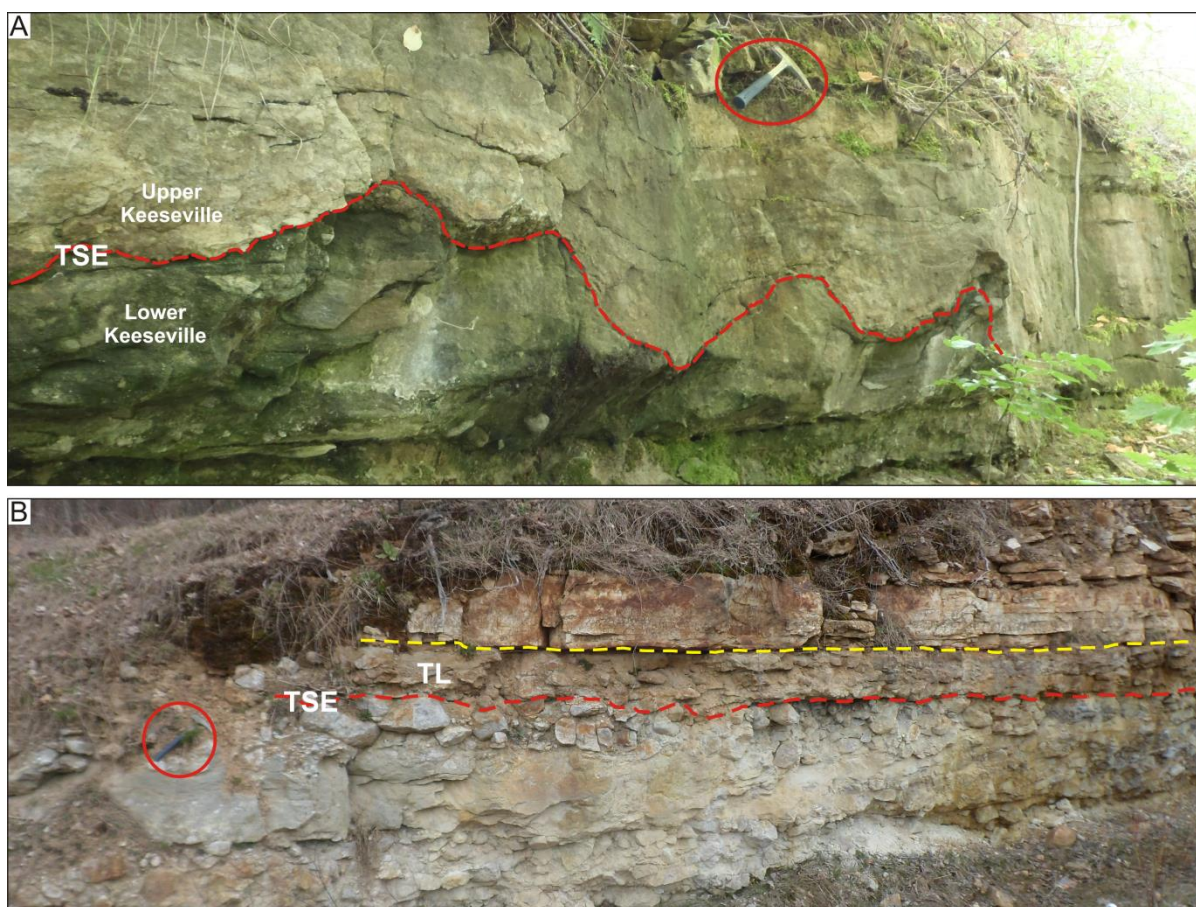


Figure 5.23 Examples of the unconformity separating the fluvial lower Keeseville and marine upper Keeseville Formation in the western Ottawa Embayment. A) Localized, high-relief undulations characterize the erosive basal transgressive surface of erosion of the tide-dominated marine upper Keeseville, exposed on Wellesley Island, NY (locality 117). B) Contact exposed along Highway 15, southwest of Smiths Falls, ON. Here, fluvial strata of the lower Keeseville are poorly indurated due to the presence of pore-occluding illuvial clay, interpreted to represent srigillic inceptisol development. Strata of the lower Keeseville are erosively overlain by a transgressive surface of erosion (TSE) and capped by a cobble conglomerate transgressive lag (TL). Hammer for scale (circled in A) and B)).

massive preferentially silicified horizon in the uppermost part of these fluvial strata (Fig. 5.24), parts of which were described earlier by Selleck (1978b). Silica cement in this horizon occurs as syntaxial quartz overgrowths that preserve higher intergranular volumes compared to adjacent strata (on average ~31% compared to 17%³; Fig. 5.25). Additionally, the lack of

³ Calculated from thin section photomicrographs using ImageJ

pressure solution or grain suturing suggests that the cement formed during early (pre-compaction) diagenesis, and may represent part of a silcrete horizon (Watson and Nash, 1997). However, the massive silicified horizons and isolated nodules do not contain grain-coating clay argillans (Fig. 5.25), suggesting that silicification pre-dated illuviation, and primary sedimentary structures are preserved, suggesting that this silcrete most likely formed in the shallow subsurface as a groundwater silcrete (Thiry, 1999; Nash and Ullyott, 2007), rather than a pedogenic silcrete. More importantly, this locally developed groundwater silcrete formed a well-indurated substrate that resisted erosion and preserved lower parts of the Keeseville in this area.

Keeseville strata overlying the unconformity in the southwestern Ottawa Embayment consist of a ~3.5 – 10 m thick tide-dominated marine succession. The base of this marine unit is sharp and erosional, with local erosional scours and commonly with a ~5 – 15 cm thick massive pebble/cobble transgressive lag (Figs. 5.22, 5.23). Minor erosional relief of ~10 – 50 cm is locally developed over the disconformity, and marine strata of the upper unit commonly onlap the surface at a shallow angle ($\leq 5^\circ$; Figs. 5.22, 5.23b).

5.4.7 Keeseville – Theresa Contact and Age of the Uppermost Potsdam

The Keeseville Formation is everywhere overlain by the Theresa Formation, however definition and placement of the Keeseville – Theresa contact remains problematic despite many years of study. The contact has been variably interpreted as unconformable (e.g., Gregg and Bond, 1973; Salad Hersi et al., 2002; Dix et al., 2004) or conformable (Cushing,



Figure 5.24 Groundwater silcrete horizon that locally caps the lower Keeseville in the southwest Ottawa Embayment, along the southern Frontenac Arch (see text for details). A) Massive silicified horizon with its base outlined by a yellow dashed line, white triangle points to it also. Hammer for scale (circled). Exposed along highway 12 in Chippewa Bay, NY (locality 86). B) Round silicified nodules exposed in strata of the uppermost lower Keeseville Formation, on Wellesley Island, NY (locality 118).

1908; Wilson, 1946; Clark, 1972; Brand and Rust, 1977; Sanford and Arnott, 2010).

Although variably defined in the past, the general consensus of earlier workers across the

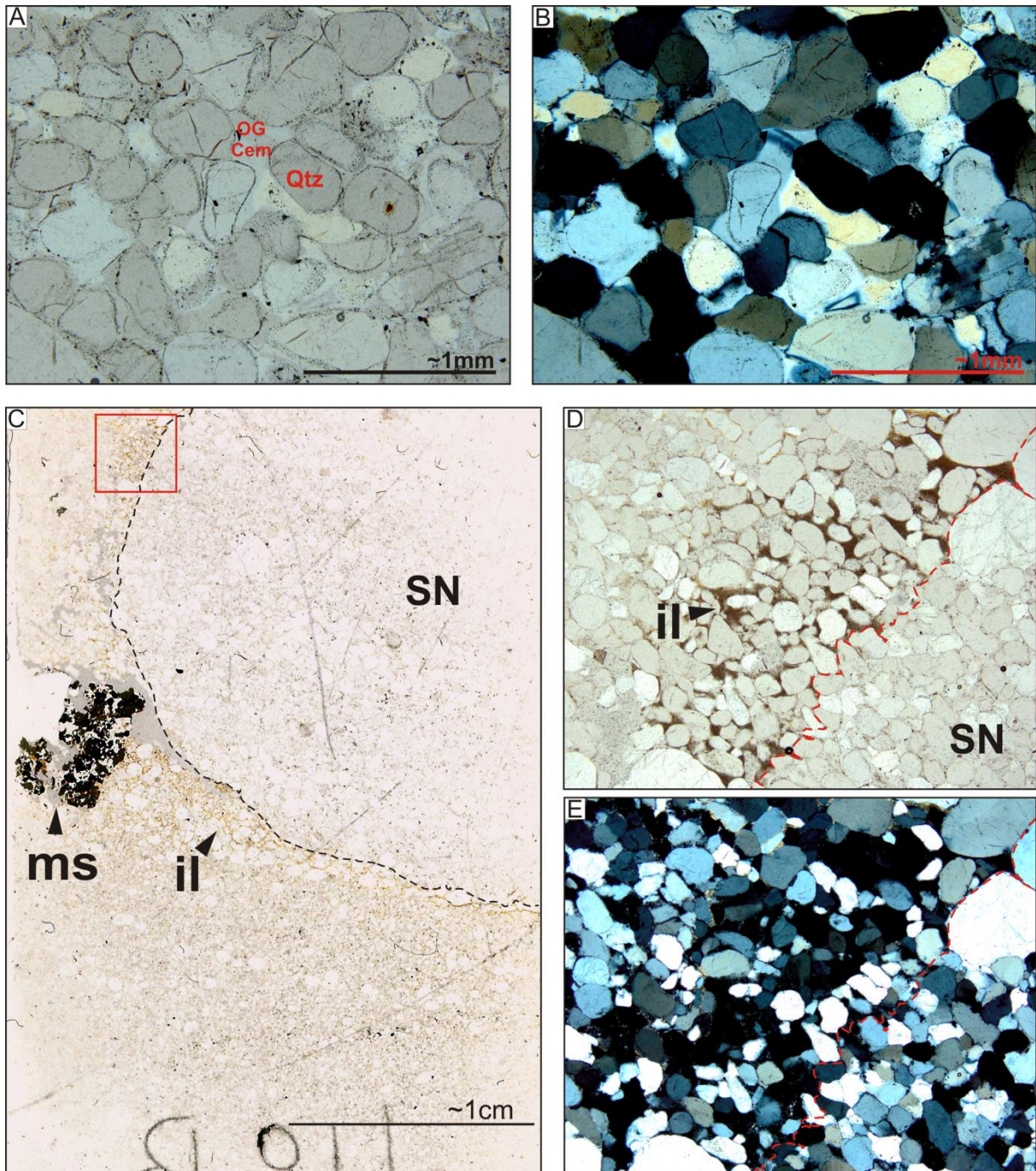


Figure 5.25 Petrographic characteristics of the upper Keeseville groundwater silcrete shown in Figure 24. A) & B) Plane- and cross-polarized photomicrograph of the massive silicified horizon from Figure 24a (locality 86). Sample consists of a quartz arenite (Qtz = quartz grain) cemented by syntaxial overgrowths (OG cem) that preserve higher than normal intergranular volumes. Also, compared to strata above and below, compaction features such as sutured or embayed grain contacts are absent. C) Thin section scan of a sample taken from the nodular silicified horizon (locality 118, from figure 24b). SN = silicified nodule, il= illuvial matrix, ms= tourmaline-rich metasedimentary fragment. Note the clarity within the nodule, which is due to the absence of illuvial matrix, which instead preferentially coats the margin of the nodule. D) & E) Plane- and cross-polarized light photomicrographs of the inset box in C). Note the preferential accumulation of illuvial matrix along the upper margin of the nodule, suggesting that the nodule predated development of the lower – upper Keeseville unconformity.

Ottawa Embayment and Quebec Basin is that the Theresa Formation (and equivalent March Formation, now abandoned, see Dix et al., 2004) follows the original definition of Cushing (1908) to consist of a generally bioturbated “grey calcareous sandstone and interbedded clean, white quartz sandstone of marine origin that overlie the Keeseville everywhere”. Accordingly, the Keeseville – Theresa contact is taken to be marked by the lowermost pervasively carbonate-cemented bed (e.g. Cushing, 1908; Wilson, 1946; Globensky, 1982; Brand and Rust, 1977; Williams and Wolf, 1984). Although the term “bed”, as defined by McKee and Weir (1953), is defined to be any layer thicker than 1 cm, it is considered here to be a layer at least 4 cm thick, and therefore distinct from mm- to a few cm-thick, discontinuous lenses of carbonate cemented sandstone that are common in the upper part of the Keeseville Formation. Although the 4 cm thickness limit is arbitrary, it permits consistent definition of the base of the Theresa Formation, and from careful measurement of many sections seems to adequately define the point above which a mixed carbonate-siliciclastic succession consistent with the definition of the Theresa persists. Also, the locally dolomitic Riviere Aux Outardes member complicates use of the lowermost carbonate-cemented bed; however, this unit is easily distinguished from the Theresa Formation by the presence of relatively thick (~20 – 80 m) and conspicuous silica-cemented terrestrial sandstone and conglomerate that immediately and disconformably overlie it.

Based on this definition, the nature of the Keeseville – Theresa contact apparently depends on its location relative to regional faults, the thickness of the underlying Keeseville and the facies association above and below the contact. For example, in the central Ottawa embayment and farther southeast, in the area south of the St. Justine fault and east of the Chateauguay Fault (Fig. 5.1) where Keeseville strata are thickest, the uppermost Keeseville

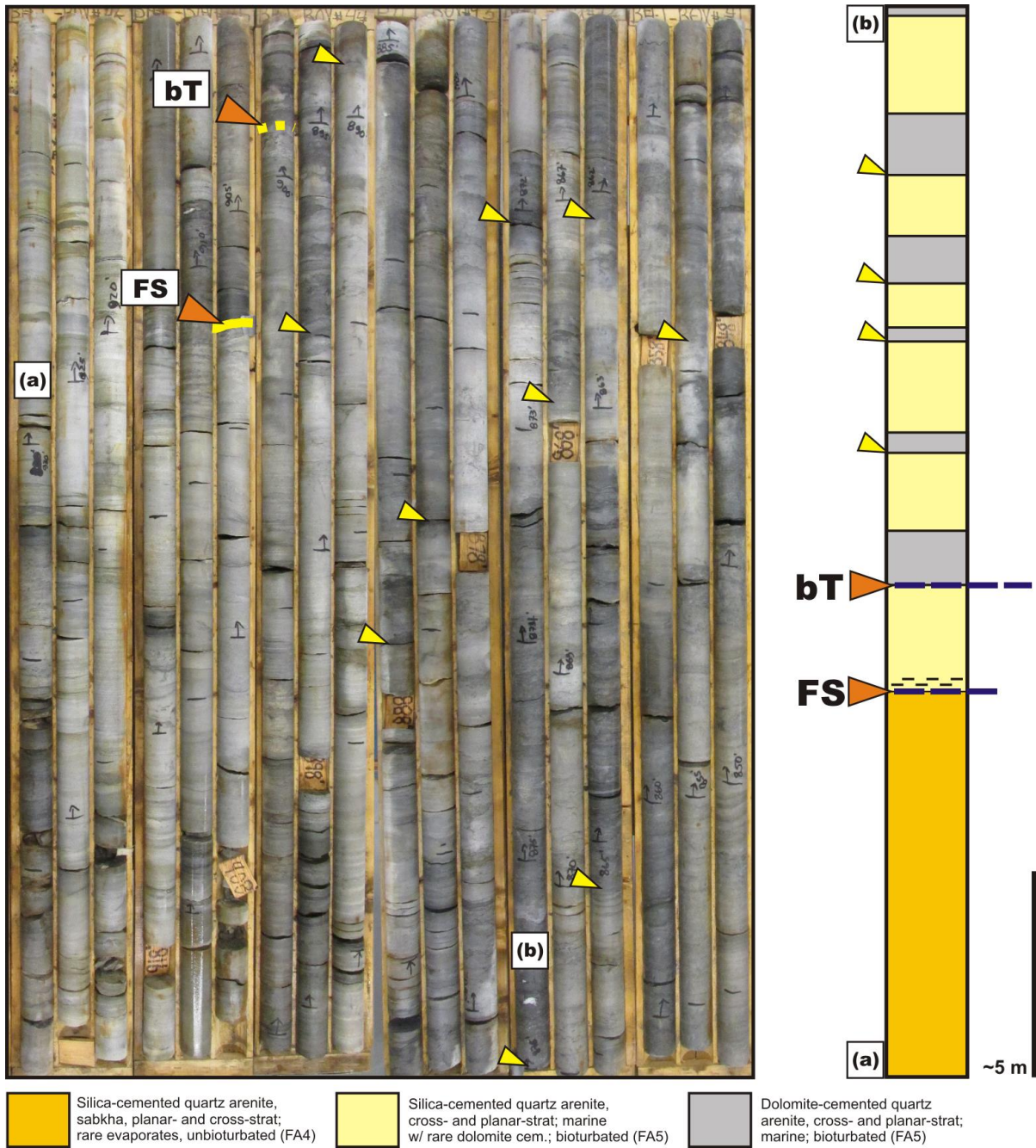


Figure 5.26 Keeseville-Theresa contact from Quonto Gastem No.1 in southern Quebec. Here, quartz arenitic sabkha (FA4) strata are overlain by a flooding surface (FS) and drill core ~2.5 m of bioturbated marine quartz arenite (FA5) before the lowest carbonate-cemented bed >4 cm thick is encountered, thus defining the base of the Theresa Formation (bT). Here the Keeseville-Theresa contact is conformable with little change in lithofacies across the contact, except for the occurrence of pervasively carbonate-cemented arenite beds in the lower Theresa Formation. See also figure 19. Yellow arrows indicate the base of a carbonate cemented bed. Measured section on left side is the interval between (a) and (b) in core.

consists of inter/subtidal marine facies and the Keeseville – Theresa contact is conformable and gradational. In these areas the change to strata dominated by carbonate cement is marked by a progressive increase in the abundance and thickness of carbonate-cemented beds above the contact (Fig. 5.26). This suggests continuous sedimentation during an episode of gradual flooding on the hanging wall sides of these regional normal faults. In contrast, on the footwall side of regional normal faults in the northwest Ottawa Embayment near Ottawa (Gloucester Fault) or the northern Quebec Basin near Montreal (Fig. 5.1), the contact truncates coastal sabkha or locally aeolian facies of the upper Keeseville and is defined by a sharp and erosional contact (Figs. 5.27c-d; Fig. 5.28) typically with minor relief (~5 – 10 cm) and evidence of pedogenic alteration including locally concentrated illuvial matrix and rare void-filling spherulitic chalcedony. This contact is likely an intra-Early Ordovician disconformity of unknown duration, consistent with the observations and interpretations of Salad Hersi et al. (2002) and Dix et al. (2004), and records a period of non-deposition, minor erosion and pedogenesis followed by marine flooding. Finally, in parts of the southwest Ottawa Embayment, Keeseville strata are comparatively much thinner and the contact with the Theresa Formation is marked by an abrupt change from silica- to carbonate- cemented strata (e.g., Greggs and Bond; Selleck, 1978a, 1993; Bjerrestedt and Erickson, 1989; Sanford and Arnott, 2010; Fig 5.27a). Here also the uppermost ~5 – 12 cm of the Keeseville is locally to pervasively cemented by dolomite (increasing toward the contact) and robust vertical trace fossils filled with sediment sourced from above the contact, and therefore quite possibly representative of a firmground *Glossifungites* ichnofacies, are observed (Fig. 5.27b). Collectively these features suggest a hiatus in sedimentation, but without subaerial erosion or

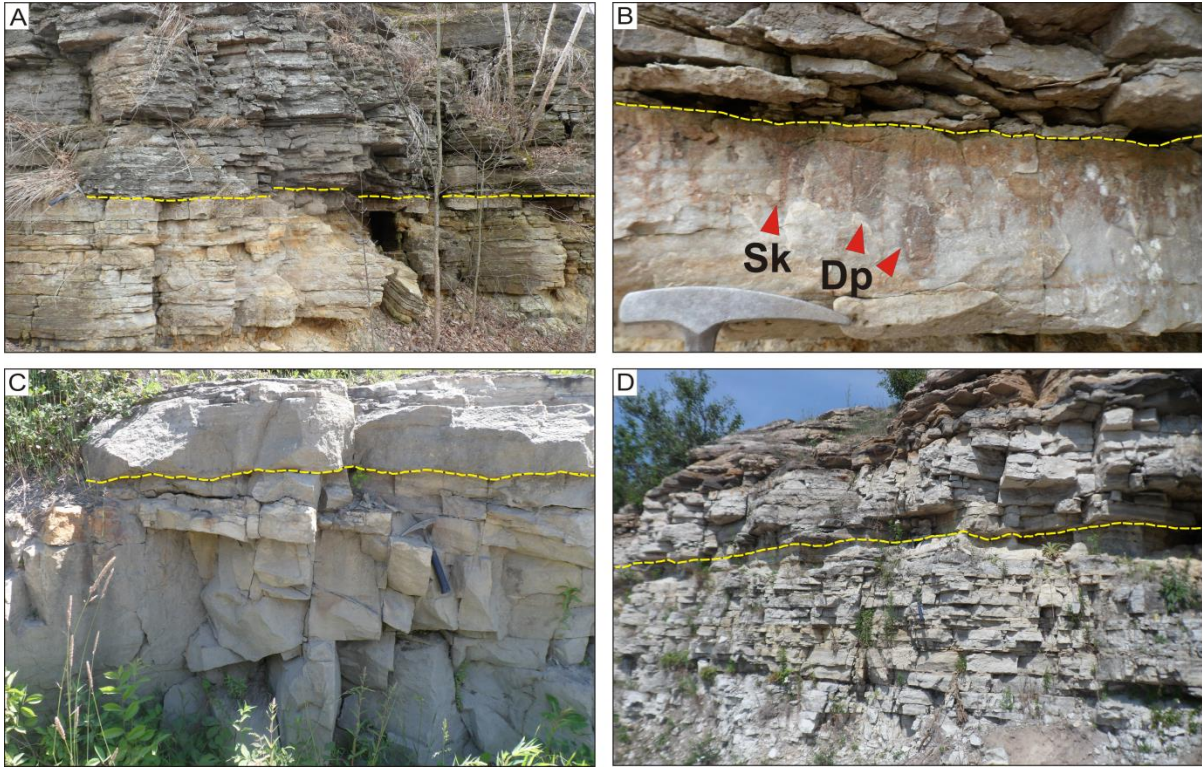


Figure 5.27 Keeseville-Theresa contact from the western Ottawa Embayment. A) and B) outcrop along the Thousands Island Parkway and originally described by Gregg and Bond (1971) (locality 223). Here the contact is interpreted as a sharp flooding surface coeval with retrogradation, siliciclastic sediment and locally well-developed *Glossifunghites* ichnofacies (as in B; Sk = *Skolithos*, Dp = *Diplocraterion*). C) Sharp, subtle erosional unconformity locally developed between aeolian dune strata of the upper Keeseville (below) and pervasively dolomite-cemented arenite of the Theresa Formation (above), exposed along Hawthorne Road, south of Ottawa, immediately on the footwall side of the Gloucester Fault (locality 3). D) Cryptic paraconformity between sabkha facies of the upper Keeseville (below) and locally bioturbated tide-dominated marine strata of Theresa Formation (above) at the type locality of the “Nepean Formation” along Highway 417 in Ottawa (locality 222). The base of the Theresa is defined by the lowest dolomite-cemented bed, following Dix et al. (2004). Slight preferential weathering of the uppermost ~20 cm of the Keeseville is attributed to an interstitial illuvial matrix that inhibited the silica or dolomite cementation present in adjacent strata. Hammer for scale in A), C) and D).

pedogenesis. These contacts, therefore, most likely record a rise of relative sea level that temporarily overwhelmed local sediment supply.

The age of the uppermost part of the Potsdam regionally can be constrained by conodont biostratigraphy (Fig. 5.29) previously reported from the lowermost part of the

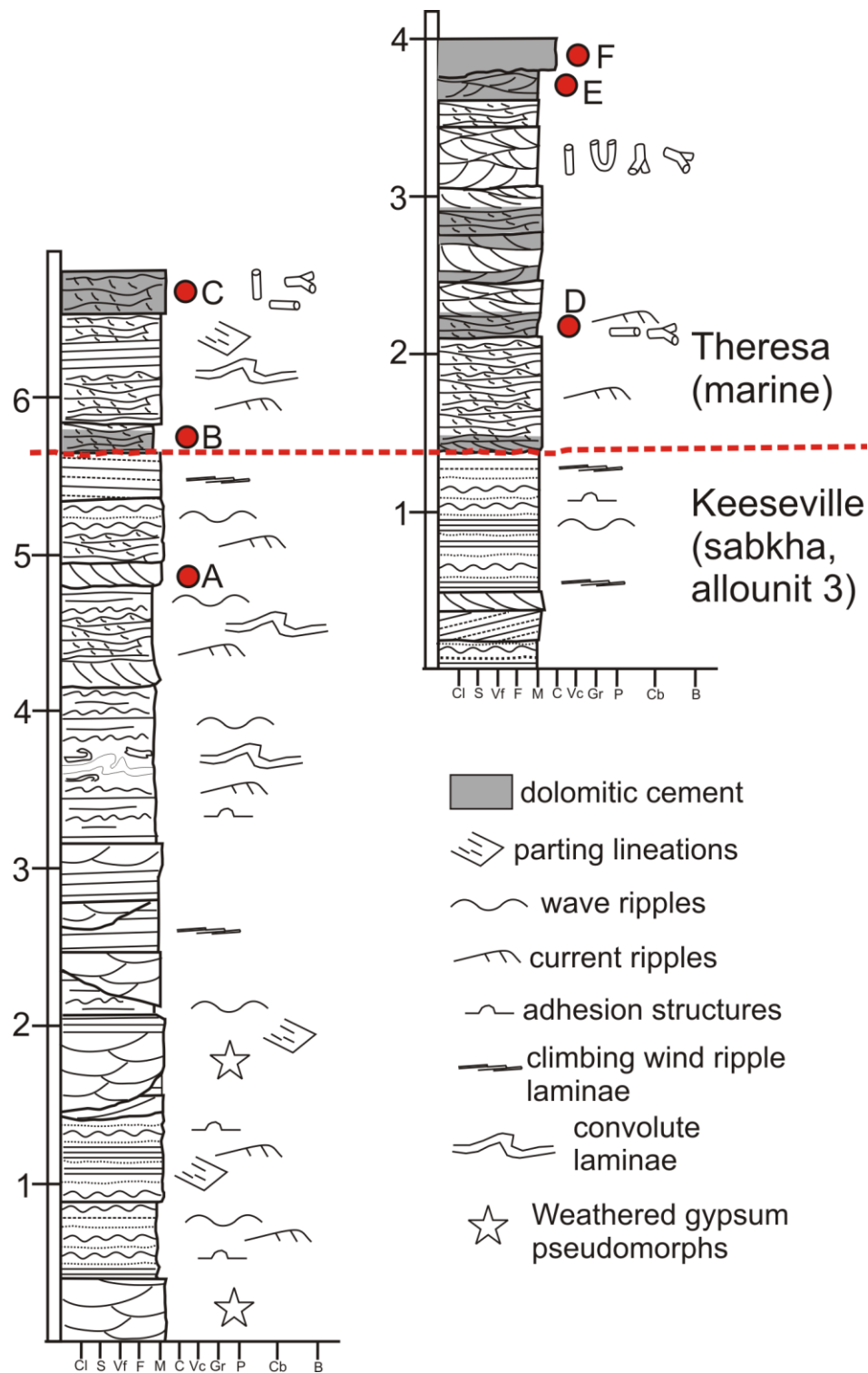


Figure 5.28 Stratigraphic log of the “Nepean Formation” (here abandoned) type section along highway 417 in Ottawa (locality 222, see figure 27d). Red dashed line marks the paraconformity between the Keeseville and Theresa formations. A- F show the approximate locations of samples used for conodont biostratigraphy by Dix et al. (2004) (A-C) and by Brand and Rust (1977) (D-F).

Theresa Formation in the southwest where the contact is a sharp but conformable flooding surface (Greggs and Bond, 1971), in the northeast and northwest where the contact is a localized disconformity (Brand and Rust, 1977; Salad Hersi et al., 2002, 2003; Dix et al., 2004), and a pre-existing (Salad-Hersi et al., 2003) and a newly collected sample from the southwestern Quebec Basin (near Ste. Clotilde, QC; GSC- 450797), ~15 – 30 m above the base of the Theresa where the Potsdam-Theresa contact is conformable and gradational. This latter sample yielded over 100 conodont specimens including many *Drepanoistous gracilis* and *Colaptoconus quadriplicatus* (Appendix C) suggesting a large probable age range of lower Stairsian to mid Blackhillsian stages (see Ross et al., 1997), or Upper Tremadocian to Lower Arenigian, overlapping with the age of the Theresa Formation throughout most of the Ottawa Embayment and Western Quebec Basin (Greggs and Bond, 1972; Brand and Rust, 1977; Salad Hersi et al., 2002, 2003; Dix et al., 2004). Though the precision of the biostratigraphic data is low, the collective age determinations from at or near the base of the Theresa Formation suggest that the basal part of the Theresa is diachronous (e.g., Salad Hersi et al., 2003) and youngs slightly from the southeast to the southwest from as old as Late Skullrockian (i.e., Early-Middle Tremadocian) in the southeastern Quebec Basin and southeastern Ottawa Embayment (Salad Hersi et al., 2003; Salad Hersi and Dix, 2006) to as young as Early Arenigian in the northwestern Ottawa Embayment (Brand and Rust, 1977; Dix et al., 2004) (Fig. 5.29).

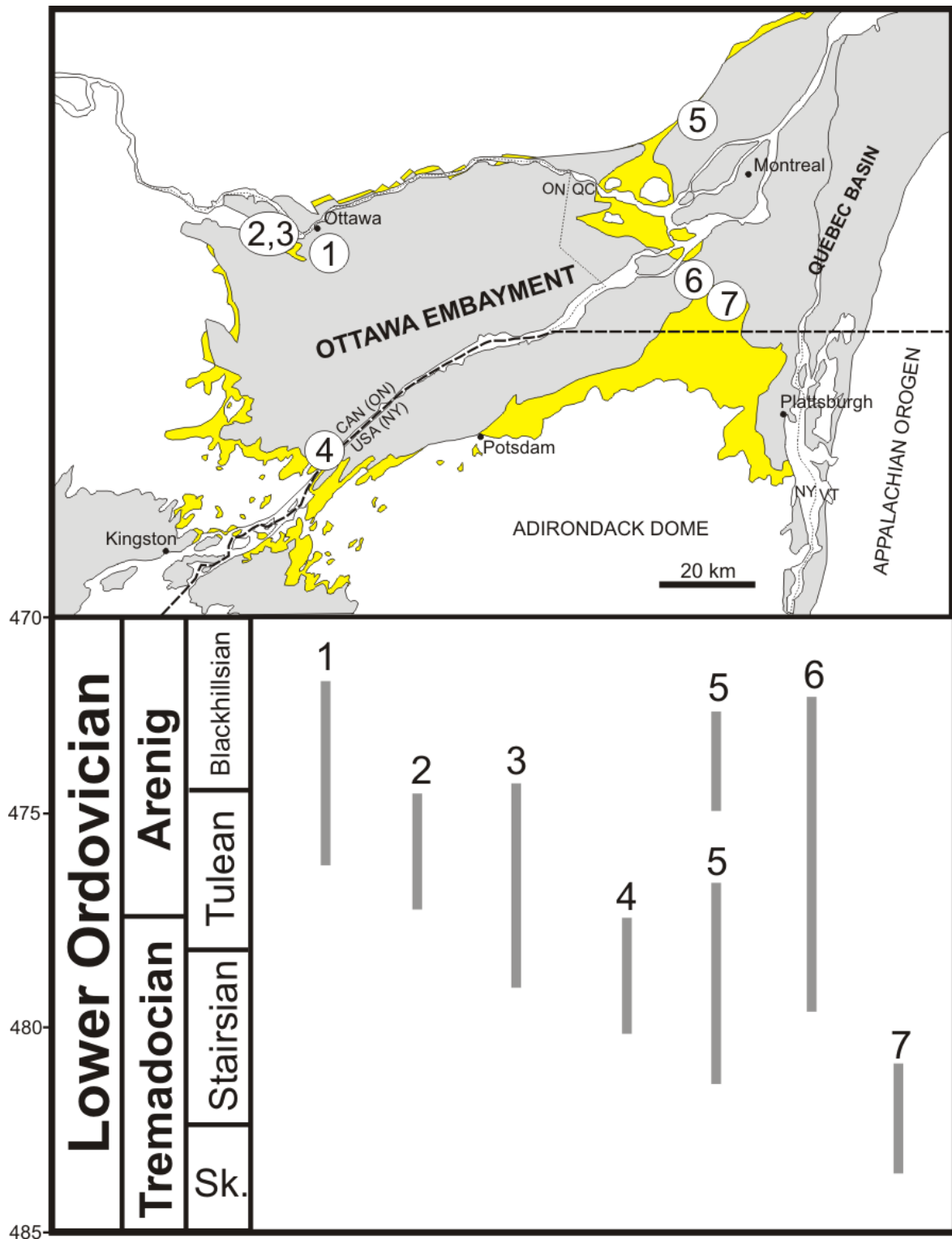


Figure 5.29 New and previously published biostratigraphic age control on the basal and medial parts of the Theresa Formation. (1) Nowlan (2003) and Salad Hersi and Dix (2006), basal Theresa; (2) Brand and Rust (1977), basal Theresa (*their* upper Nepean Formation); (3) Dix et al. (2004), basal Theresa; (4) Greggs and Bond (1971), basal Theresa; (5) Salad Hersi et al. (2002); basal and medial Theresa; (6) this study, medial Theresa; (7) Salad Hersi et al. (2003), basal Theresa. Stages of the Ordovician Period are given as well as stages of the Ibeixian conodont series from Ross et al. (1997). Sk. = Skullrockian. Numbers on the left x-axis are millions of years ago.

5.5 Allostratigraphic Framework and Regional Correlations

Regardless of its lithostratigraphic subdivisions the Potsdam Group is internally subdivided by unconformities into three allounits that record discrete sedimentation events in the eastern (paleo-southern) part of the Ottawa Graben (Figs. 5.3, 5.30). The sedimentary record of each event is summarized and regional stratigraphic correlations are proposed that link them with successions in the cratonic Appalachian, Michigan and Illinois basins to the west (~500 – 1100 km paleo-northwest of the Ottawa graben), Laurentian margin shelf and slope successions of the New York Promontory and Quebec Re-entrant to the east, northeast and southeast (~80 – 800 km paleo-south, southeast and southwest), and also the St. Lawrence Promontory margin succession to the northeast (~1500 – 2000 km paleo-southeast) (Fig. 5.30).

5.5.1 Allounit 1

Allounit 1 includes the arkosic Ausable Formation and red quartz arenitic Hannawa Falls Formation (Figs. 5.3, 5.30). Near the base of the mostly braided fluvial Ausable Formation, and limited to the easternmost (pale-southernmost) Ottawa Graben, the Altona Member forms a conformable tongue of marine tidal flat strata. Accordingly braided fluvial strata of the Ausable and tidal flat strata of the Altona are interpreted to have formed a single genetically-linked depositional system, with mud and sand on the Altona tidal flats sourced from fluvial discharge of coeval Ausable braided rivers to the paleo-north. Existing fossil ages suggest that the onset of mineralogically-immature (i.e., arkosic) braided fluvial sedimentation in the basal part of the Ausable Formation probably occurred during the

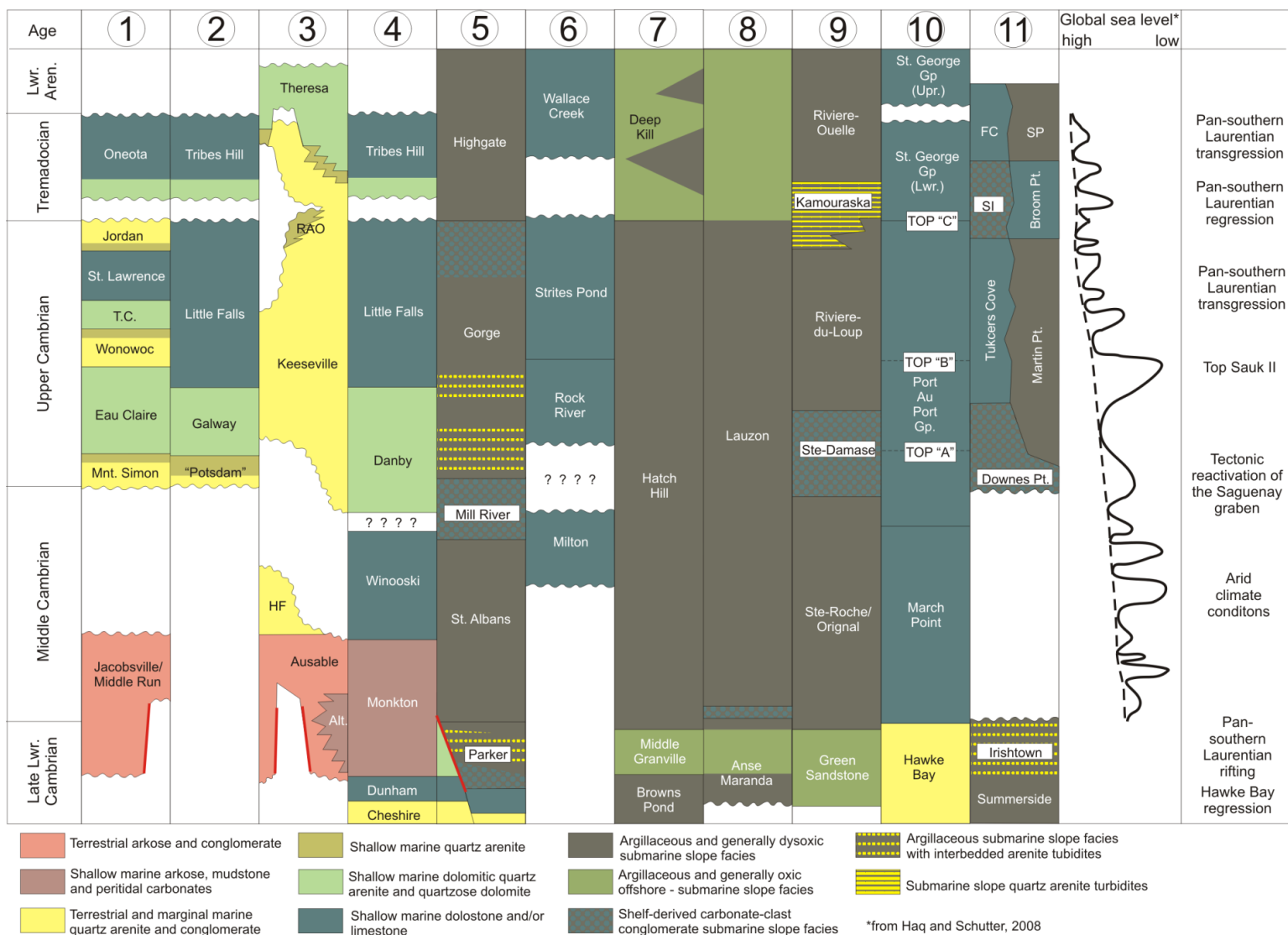


Figure 5.30 Correlation of Potsdam strata with coeval strata deposited across Southern Laurentia. (1) Michigan and northern Appalachian basins; (2) Mohawk Valley and southern Lake Champlain Valley in New York State; (3) Potsdam Group in the Ottawa Embayment and Quebec Basin; (4) Laurentian shelf succession in western Vermont and southeastern New York State.; (5) Franklin Basin succession in northern Vermont and Quebec; (6) Laurentian shelf succession of the Phillipsburg slice in southern Quebec and northern Vermont; (7) Laurentian slope succession in the allochthons of southwestern Vermont and eastern New York State; (8) Laurentian slope succession of the Bacchus nappe in southeastern Quebec; (9) Laurentian slope succession of the Riviere-Boyer Nappe in southeastern Quebec; (10) Laurentian shelf succession of the St. Lawrence Promontory, western Newfoundland; (11) Laurentian slope succession of the St. Lawrence Promontory, western Newfoundland. See text for details and references. Alt. = Altona Member, HF = Hannawa Falls Formation, RAO = Riviere aux Outardes Member, SI = Stearing Island Member, FC = Facotry Cove Member, SP = Saint Pauls Member.

middle or late Early Cambrian, whereas the intertonguing marine Altona Formation records a latest Early Cambrian westward (paleo-northward) marine transgression followed by an early-mid Middle Cambrian regression. Sometime during the mid to late Middle Cambrian, Ausable braided fluvial sedimentation ceased and strata of the Ausable Formation were then deflated, eroded and in places conformably overlain by the Hannawa Falls Formation. The Hannawa Falls then records quartz-rich aeolian erg sedimentation to the southwest (paleo-northwest) of the thickest, most areally extensive parts of the Ausable. The change from braided fluvial to aeolian erg sedimentation quite possibly reflects a Middle Cambrian climate change from humid to arid conditions. Similarly, the change in composition -- from arkose to quartz arenite -- most probably reflects the loss of labile feldspar during highly corrasive windblown transport and reworking of pre-existing arkose. Furthermore, the dispersal of windblown sediment from the paleo-south to the paleo-northwest is consistent the prevailing wind direction (expected southeast to northwest) given the location of the Ottawa Graben at $\sim 10^\circ$ south of the equator.

Allouit 1 sedimentation in the Ottawa graben is also coeval with faulting and subsidence in the Franklin Basin, $\sim 80 - 90$ km to the paleo-south of the Ottawa graben where debris flow deposits overlain by dysoxic, deep marine mudstones of the Parker Formation were deposited over shallow marine strata (Shaw, 1958; Stanley, 1999; Landing 2007; Landing et al., 2009). Landing (2007) and Landing et al. (2009) suggested that late Early Cambrian Franklin Basin faulting extended paleo-northward into the Ottawa graben and resulted in the initiation of local fault-bounded grabens. The resulting differential topography in the Ottawa graben would have limited paleo-northward transgression of the Altona and also resulted in the observed uneven isopach and distribution of Ausable strata accumulating

in syn-sedimentary fault-bounded grabens. This interpretation is supported by the mineralogical immaturity of the locally thick (≥ 450 m) Ausable succession, which contains ~10 – 40% euhedral, unaltered feldspar grains (Lewis, 1971) suggesting derivation from rapidly exhumed, minimally weathered and nearby cratonic granites and gneisses (e.g., the “basement uplift” field of Dickinson and Suczek, 1979; also see Dickinson et al., 1983; Cox and Lowe, 1995).

The Ausable Formation is correlated to coeval arkosic and rare carbonate strata of the Monkton Formation, recording tide-dominated sedimentation on the nearby Laurentian shelf. It is also correlated to the mudstone and rare arkose of the Parker Formation recording coeval deep marine turbidite sedimentation in the Franklin Basin (Cady, 1945; Landing, 2007). The transgression and regression recorded by strata of the marine Altona Member cannot be unequivocally correlated to other successions in northeastern North America. This suggests that it may have been driven by tectonism with local transgressive conditions caused by an exceedance in rift-generated accommodation over the rate of sediment supply, followed by regression related to an increase in the rate of sedimentation or reduced rate of rift generated accommodation.

Of note also is evidence of potentially coeval (late Early – Middle(?) Cambrian) and perhaps related cratonic rifting throughout eastern and central North America, including in the Midcontinent and East Continent Rifts, the Mississippi Valley and Rough Creek grabens and Rome Trough (Woodward, 1961; Thomas, 1991). In fact, Sanford (2007) and Sanford and Arnott (2010) correlated the Ausable Formation to the lithologically-similar but undated synrift Middle Run and Jacobsville formations that overly Proterozoic strata in the fault-bounded East Continent and Midcontinent rift systems beneath the Appalachian and

Michigan basins and across the Cincinnati Arch (Brown et al, 1982; Shrake, 1991; Shrake et al., 1991; Drahovzal, 1997; Baranoski et al., 2009). These units have previously been interpreted to be Proterozoic Grenville foreland basin strata (Santos et al., 2002; Baranoski et al., 2009) or the fills of even earlier rift basins (Brown et al., 1982). However, a recent combined geochronological, stratigraphic and paleomagnetic study by Malone et al. (in press) suggest that the Jacobsville in the Midcontinent rift was deposited after the late Neoproterozoic Snowball earth event (~632 Ma) and possibly in the earliest Cambrian. Furthermore, Drahovzal (1997) interprets the upper sequence of the Middle Run Formation in the East Continent rift zone as ‘post-Grenville’, including two unconformity-bound units interpreted as Late Neoproterozoic and Cambrian in age. Therefore, there is a plausible correlation of the Ausable Formation to the Jacobsville and Middle run formations proposed by Sanford and Arnott (2010), inasmuch as all or parts of these units are Ausable equivalents, in particular the upper rift sequences in the Midcontinent and East Continent Rifts (Drahovzal, 1997; Santos et al., 2002; Baranoski et al., 2009). Cambrian syn-rift arkosic sandstones in the Mississippi Valley and Rough Creek grabens and the Rome Trough (Drahovzal 1995; Thomas, 1991, and references therein) are also possible stratigraphic equivalents of the synrift Ausable Formation. Notably, rifting of the Ottawa graben and elsewhere across Southern Laurentia was coeval with the late Early Cambrian Hawke Bay regression that affected the entire southern Laurentian Margin at the end of the Sauk I sequence (Palmer and James, 1979; James et al., 1986; Landing et al., 2002; Lavoie et al., 2003; Landing, 2007; Lavoie, 2008; Fig. 5.30). It is unclear if any relationship exists between pan-continental rifting and regression, however as Weisel and Karner (1989) suggest, rifting and extension can lead to mechanical unloading and isostatic rebound of continental

lithosphere, thus providing a possible mechanism for the observed coeval rifting and regression.

There are no known lithologic equivalents of the mostly aeolian mid(?) Middle Cambrian Hannawa Falls Formation that caps allounit 1. However, coeval Middle Cambrian strata on the Laurentian shelf record sedimentation on relatively narrow (<200 km wide), high-energy carbonate platforms (e.g., the Winooski and March Point formations; Cady, 1945; James et al., 1986; Knight, 1991; Knight and Boyce, 1991; Landing, 2007) and slow sedimentation of thin intervals of black mudstone, calcitubidites and local glauconitic sandstone on the Laurentian slope (i.e., the Orignal/St. Roch, Lauzon and Hatch Hill formations; Landing, 1993, 2007; Landing et al., 2002; Lavoie et al., 2003; Lavoie, 2008). These siliciclastic-poor depositional conditions are consistent with arid climate conditions recorded by the Hannawa Falls Formation, which conceivably would have significantly reduced the occurrence and discharge of fluvial systems and thus delivery of siliciclastic sediment to the continental shelf and slope.

5.5.2 Allounit 1 – Allounit 2 contact

The timing and duration of the unconformity that separates allounits 1 and 2 is poorly constrained. Nonetheless, the available geochronological control and stratigraphic relationships suggest that it is a diachronous surface that incorporates much of the late Middle Cambrian (~1 – 5 Myr) in the southernmost Quebec Basin (i.e. in the vicinity of the Ausable Chasm) to possibly as much as ~4 – 10 Myr, and therefore the Middle – Late Cambrian, farther north throughout most of the Ottawa graben. In the eastern (paleo-

southern) Ottawa graben a deflation lag and silcrete horizon caps the Ausable braided fluvial strata of allounit 1 and records probable late Middle Cambrian aeolian deflation and paleosol development under an arid climate. At the same time, aeolian erg sedimentation (Hannawa Falls Formation) was ongoing in the southwestern (paleo-northwestern) Ottawa graben and as a consequence the unconformity developed later there, most likely during the latest Middle Cambrian. A possible laterite horizon (a.k.a. oxisol) caps the Hannawa Falls aeolian succession in this area and indurated clasts at the base of allounit 2 indicates local erosion of pedogenically-cemented Hannawa Falls strata. Moreover, Sanford (2007) and Sanford and Arnott (2010) noted that in the same area Hannawa Falls strata beneath the unconformity are locally folded and faulted, suggesting an episode of tectonic reactivation of the Ottawa graben and related structural deformation coincident with, or following, the allounit 1-2 unconformity.

The subaerial unconformity separating allounits 1 and 2 is correlated with a late Middle to early Late Cambrian regression across southern Laurentia (Chow and James, 1987; James et al., 1986; Lavoie et al., 2003). Notably, this regression is not recorded in coeval strata in northern Laurentian margin (modern western North America), and thus was most likely controlled by local conditions in southern Laurentia rather than eustasy (James et al., 1986). On the nearby Laurentian shelf and craton interior this regression was manifest by a Middle Cambrian unconformity overlain by latest Middle Cambrian or earliest Late Cambrian regressive quartz arenites (the Danby, “Potsdam” and Mount Simon formations; Cady, 1945; Mehrtens and Butler, 1989; Sharke et al, 1991; Landing, 2007). These regressive quartz arenites are slightly older than the base of allounit 2 (Keeseville Formation) throughout most of the Ottawa graben but are coeval with erosion of the Hannawa Falls

Formation and also with coastal sabkha sedimentation of allounit 2 in the paleo-southwesternmost Ottawa graben (i.e., the Keeseville Formation at Ausable Chasm). This suggests that erosion of the Hannawa Falls, and perhaps part of the older Ausable, may have supplied much of the siliciclastic sediment to terrestrial, coastal and marine environments along the margins of the Ottawa graben (i.e., at the Ausable Chasm) and on the nearby Laurentian shelf, ~150 – 350 km to the paleo-southwest and southeast (represented by the Danby Formation in Vermont and sandstone interbeds of the Strites Pond formations in Quebec; Cady, 1945; Mehrtens and Butler, 1989; Salad Hersi et al., 2002; Landing, 2007). It is also conceivable that erosion of allounit 1 contributed sediment to coeval terrestrial and shallow marine environments in the Appalachian and Michigan basins some ~450 – 1200 km to the paleo-northwest (i.e. the Mount Simon Formation, Catacosinos, 1973; Dott et al., 1986; Medina and Rupp, 2012). This would be consistent with the paleoflow direction of basal fluvial strata of allounit 2, which suggest southeastward drainage into the Appalachian Basin and toward the Michigan Basin (see Lewis, 1963 and Chapter 6 for more details).

In the nearby and more distal parts of the coeval Laurentian continental slope, ~100 – 1600 km to the paleo-south and southeast, this regression resulted in the progradation of shelf carbonates and/or the local occurrence of regressive slope conglomerates containing shelf carbonate platform clasts recording erosion and/or collapse of the shelf-slope break (e.g., Mill River and Ste. Damase formations and Downes Point Member of the Cow Head Group; James and Stevens, 1986; Chow and James, 1987; James et al., 1986; Lavoie et al., 2003; Landing, 2007; Lavoie, 2008). The most notable example of the slope conglomerate facies is the St. Damase Formation, deposited ~800 km to the paleo-southeast of the Ottawa graben. This unit records localized and anomalously deep erosion and collapse of parts of the Quebec

Re-entrant shelf which is thought to have been related to tectonic reactivation of the nearby Saguenay graben (Lavoie, 1997, 1998, 2008; Lavoie et al., 2003). As noted above, evidence from the Potsdam Group suggests that the Ottawa graben was also reactivated at about this time. This suggests that tectonic activity was probably widespread across Southern Laurentia at this time, however, the nature and underlying cause of tectonic activity, and possible links to coeval regression, are unknown.

5.5.3 Allounit 2

Allounit 2 consists of the lower part of the Keeseville Formation (Figs. 5.3, 5.30). Accordingly, sedimentation of allounit 2 began during the latest Middle Cambrian in the paleo-southwesternmost Ottawa graben (i.e., Ausable Chasm) in a coastal sabkha environment. Later, during the early – middle Late Cambrian, alternating ephemeral and braided fluvial and local aeolian sedimentation was established throughout the paleo-southern Ottawa graben. Terrestrial sedimentation continued in the southern Ottawa graben until the Early Ordovician. However, in the paleo-southeastern Ottawa graben, fluvial sediments were transgressed in the latest Cambrian resulting in deposition of tide-dominated marine strata (Riviere Aux Outardes Member), including lowermost Ordovician peritidal carbonates.

Events recorded by allounit 2 strata, specifically, widespread quartzose sedimentation and marine drowning, are well represented by generally more fully marine strata in the coeval Laurentian Shelf and cratonic basin successions that record a Late Cambrian to earliest Ordovician(?) marine transgression and highstand event. Fluvial strata deposited

during the Late Cambrian throughout the Ottawa graben were most likely the source for at least some, if not most of the quartzose detritus supplied to coastal and marine environments outside of the Ottawa graben (e.g., Salad-Hersi et al., 2002). However, as southern Laurentia and the Ottawa graben became flooded during the latest Cambrian this and perhaps other siliciclastic sources became progressively diminished, resulting mainly in carbonate sedimentation across Southern Laurentia by the end of the Late Cambrian. In the Mohawk and southern Champlain valleys this sedimentation history is recorded by a conformable succession consisting of the basal Potsdam Formation – a quartz arenite that is a likely Keeseville Formation equivalent, plus the overlying Galway (lithologically similar but not correlated with the Theresa Formation) and Little Falls formations (Landing et al., 2003; Landing, 2007). In Vermont these events are recorded by the Danby Formation sandstone and overlying Little Falls Formation carbonate (Landing, 2007).

In the adjacent parts of the Appalachian and Michigan basins two cycles of quartzose sedimentation followed by marine transgression occurred in the Late Cambrian (i.e., coeval with allounit 2). Each of these cycles consists of a basal unit of terrestrial to shallow marine quartz sandstone (i.e. the Mount Simon and Wonowoc formations; see Driese et al., 1981; Dott et al., 1986). These, then, are succeeded by shallow marine dolomitic sandstone interstratified with mudstone and local carbonate (the Eau Claire, Tunnel City/Franconia and St. Lawrence formations, Fig. 5.30). The base of the second cycle (i.e., the Wonowoc Formation) coincides with the top of the Sauk II sequence, and additionally the top of “Grand Cycle B”, and represents a regressive surface recognized throughout the St. Lawrence Promontory shelf (~1500 – 1600 km to the paleo-southeast of the Ottawa graben) and also across North America, and is interpreted to be associated with a eustatic fall during the

middle Late Cambrian (James et al., 1986; Lavoie, 2008). Interestingly, these two cycles, in addition to the top boundary of the Sauk II sequence that separates them, are not recorded in allounit 2 of the Ottawa graben or in the nearby New York Promontory or Quebec Re-entrant shelf successions, the reasons for which are currently unknown, but may be related to higher rates of subsidence in these latter areas.

5.5.4 Allounit 2 – Allounit 3 contact

The contact separating allounits 2 and 3 is a Late Cambrian to earliest Ordovician unconformity throughout most of the Ottawa graben, except for the paleo-southwestern Ottawa graben where it is a correlative conformity recording a continuous history of fluvial sedimentation through the Late Cambrian and Early Ordovician. This contact correlates to a well-documented Cambrian – Ordovician stage boundary eustatic fall that resulted in an unconformity that truncates Upper Cambrian strata in successions deposited on the nearby Laurentian shelf and the Appalachian, Michigan and Illinois basins (Chow and James, 1987; James et al., 1986; Landing, 1993; Salad-Hersi et al., 2002; Landing et al., 2003). Curiously however, the Ottawa graben was still undergoing transgression during the Cambrian – Ordovician stage boundary, and thus experienced a delayed earliest Ordovician regression relative to other parts of nearby Southern Laurentia. This delay in regression may have been the result of locally elevated rates of subsidence exceeding the rate of eustatic fall in the Ottawa graben, related to reactivation of faults inherited from earlier episodes of rifting (e.g., as suggested by Salad Hersi and Dix (2006) for younger stratal units in the Ottawa graben).

Strata deposited on the deep marine Laurentian slope show little stratigraphic evidence of this eustatic Cambrian – Ordovician stage boundary regression, although the Uppermost Cambrian – Lower Ordovician Kamouraska Formation in the Rivière-Boyer Nappe of the central Quebec Re-entrant is a localized exception. This latter unit consists of turbidites, which unlike lithic wackes of under- and overlying units, are quartz arenites quite possibly sourced from eroded quartzose Keeseville and/or Hannawa Falls strata, or contemporary equivalent siliciclastic units deposited in parts of the Laurentian margin and craton closer to the Rivière-Boyer Nappe (Lavoie et al., 2003; Lavoie, 2008; Malhame and Hesse, 2015). This interpretation is supported not only by compositional similarities between the Kamouraska and Keeseville/Hannawa Falls and also by surface texture analysis of grains in the Kamouraska that strongly suggests inherited windblown transport (Malhame and Hesse, 2015), consistent with cannibalization of aeolian and ephemeral fluvial strata of the Hannawa Falls and Keeseville formations, or equivalents.

5.5.5 Allounit 3

Allounit 3 is made up of the upper part of the Keeseville Formation, and records the final phase of siliciclastic-dominated sedimentation in the Potsdam Group before an Early Ordovician (Tremadocian – earliest Arenigian) marine transgression culminating in the deposition of mixed siliciclastic-carbonate marine strata of the Theresa Formation throughout the southern Ottawa graben. This transgression was more regionally extensive than earlier transgressive events (Altona or Rivière Aux Outardes), and correlates with a Lower Ordovician (Tremadocian) eustatic rise (James et al., 1986; Lavoie et al., 2003; Landing et al., 2003; Landing, 2007; Lavoie, 2008).

However, unlike most areas in Laurentia, where transgression was rapid and isochronous, age and contact relationships (outlined in the previous section and on Figs. 26-29) suggest that transgression in the Ottawa graben initiated in the mid-Tremadocian and was slow and diachronous toward the paleo-northeast. Stratigraphically this event is represented by a sabkha – intertidal – subtidal facies coastal facies belt in the upper Keeseville and Lower Theresa formations. By the latest Tremadocian or earliest Arenigian the southern Ottawa graben was fully transgressed. Structural and stratigraphic evidence suggest that the protracted and diachronous nature of this transgression may have been due to variations in accommodation space related to topography associated with faults that were active before or during sedimentation. For example, in the southeasternmost (paleo-southwesternmost) Ottawa graben, located within a graben feature bounded by the Ste. Justine and Chateauguay faults (Fig. 5.1), the Keeseville – Theresa contact is gradational and conformable (Fig. 5.26), recording gradual flooding that kept pace with siliciclastic sedimentation under relatively high accommodation and rates of sedimentation. Conversely, in the paleo-west Ottawa graben, a sharp flooding surface with minor *Glossifungites* and early carbonate cements (Fig. 5.27a – b) records an abrupt late Tremadocian flooding, most likely caused by eustatic rise that rapidly inundated a large area and temporarily overwhelmed the local sediment supply. Finally, on the footwall sides of major faults in the paleo-eastern Ottawa graben the Keeseville-Theresa contact is an intra-Early Ordovician unconformity (Figs. 5.27c – d, 5.28). This suggests that these areas were subaerially exposed, essentially existing as fault-bounded islands during most of the Tremadocian eustatic transgression. Whether these faults were active during transgression or were instead the topographic remnants of earlier faulting is unknown, however syn-transgressive movements on these faults could explain how these

areas remained subaerially exposed and were locally eroded while most of the Laurentian shelf, cratonic basins and nearby areas of the southern Ottawa Graben were flooded. It would also be consistent with the observed soft-sediment deformation features that can be correlated over a large area ($\sim 70 \text{ km}^2$) and are located next to the Hazeldean Fault, which collectively suggest that deformation was triggered by an earthquake.

5.6 Summary and Conclusions

The Cambrian-Ordovician Potsdam Group in the Ottawa Embayment and Quebec basin in the easternmost Ottawa Graben is here divided into three formations and two members. With minor nomenclatural modification, this work largely confirms conclusions of the earlier basin-scale investigations of Sanford (2007) and Sanford and Arnott (2010) inasmuch as the Potsdam Group is a complex composite Cambrian and Upper Ordovician siliciclastic unit dissected by at least one, and probably two major unconformities. From the base upward the Potsdam sedimentary pile consists of the arkosic Ausable Formation, which in the eastern part of the study area intertongues with the Altona Member, conformably succeeded by the red, quartz arenitic Hannawa Falls Formation. These, then, are unconformably overlain by the quartz arenitic Keeseville Formation, which locally is intercalated with the Riviere Aux Outardes Member.

In addition to these proposed lithostratigraphic revisions, the Potsdam Group is also subdivided into three allounits recording three distinct episodes of regional sedimentation. Allostratigraphic correlation of the Potsdam Group in the Ottawa graben to coeval southern Laurentian successions, and summarized below, places these sedimentation episodes into

regional context and further elucidates the combined effects of eustasy, tectonics and climate on the sedimentation history of the Potsdam Group.

Allouit 1 comprises the Ausable and Hannawa Falls Formations. Initial sedimentation records the onset of Early Cambrian rifting and deposition of mineralogically immature (arkosic) braided fluvial strata of the Ausable Formation in fault-bounded sub-basins of the Ottawa Graben. Significantly, this syn-rift sedimentation event in the Ottawa Graben also coincided with rifting and syn-rift sedimentation reported elsewhere throughout southern Laurentia, including in the Franklin Basin, Rome Trough, Rough Creek graben and rift basins underlying parts of the Michigan and Appalachian basins and intervening arches. Moreover, this late Early Cambrian pan-Laurentian rifting and sedimentation event was coincident with the craton-wide Hawke Bay regression, marked by siliciclastic sedimentation across Southern Laurentia. In the nearby Laurentian shelf succession the equivalent Monkton Formation records coeval arkosic tide-dominated marine sedimentation, while in the deep marine Franklin Basin the Parker Formation records deep marine siliciclastic sedimentation of sand-rich turbidites. The Altona Member, a tidal flat succession intertonguing locally with the Ausable Formation in the Ottawa graben, records late Early Cambrian transgression and early Middle Cambrian regression into the paleo-southernmost part of the Ottawa graben. Presumably, transgression occurred where rift-generated accommodation exceeded the sedimentation rate from Ausable braided rivers. Regression then was driven by an increase in the rate of sediment supply and/or reduction in the rate of rift-generated accommodation.

Later in the Middle Cambrian, a major climate change from humid to arid conditions resulted in the cessation of fluvial sedimentation, deflation and unconformity/paleosol development in the paleo-southernmost Ottawa graben, and the formation of an aeolian erg

system (Hannawa Falls Formation) that accumulated mainly in the paleo-central/western Ottawa Graben under prevailing southeasterly winds. These windblown sediments also marked a shift in the detrital composition from arkose to quartz arenite, most probably due to a combination of sedimentary recycling and corrasion of feldspars during windblown transport. Coeval shelf sedimentation was carbonate-dominated (e.g., the Winooski, March Point formations) and slope sediments consisted mainly of thin intervals of slowly accumulated black mudstone, calcitubidites and local glauconitic sandstone (i.e., the Orignal/St. Roch, Lauzon and Hatch Hill formations). These siliciclastic-starved marine sediments are consistent with the arid climate recorded by the Hannawa Falls Formation in which the shutdown of fluvial sediment delivery systems prevented siliciclastic sediments from reaching the continental margin to the south of the Ottawa graben.

Erg sedimentation of the Hannawa Falls was followed by the development of a graben-wide subaerial unconformity by the latest Middle Cambrian to earliest Late Cambrian, marking the end of Allounit 1 sedimentation. At the same time or soon after, local structural deformation affected Allounit 1 strata in parts of the Ottawa Graben, particularly in the vicinity of the Frontenac Arch, suggesting focused tectonic reactivation. Coincident with this period of subaerial exposure and tectonic deformation in the Ottawa graben was reactivation of the related Saguenay graben and non-eustatic regression across all parts of southern Laurentia. Coeval regressive sediments on the Laurentian shelf and craton were mainly terrestrial and shallow marine quartz arenites (the Danby, “Potsdam” and Mount Simon formations). Sediment supply for these regressive sandstones likely consisted, at least in part, of sediment eroded from exposed allounit 1 strata.

Allounit 2 consists of the uppermost Middle Cambrian to lowermost Ordovician basal part of the Keeseville Formation, which unconformably overlies Ausable strata in the Quebec Basin and eastern and northern Ottawa Embayment, and Hannawa Falls strata in the western Ottawa Embayment. Allounit 2 records Upper Cambrian quartzose fluvial sedimentation followed by eustatic transgression in the paleo-eastern Ottawa graben (Riviere Aux Outardes Member), culminating in rapid earliest Ordovician regression and subaerial erosion across most of the Ottawa graben. The transgression and regression recorded by allounit 2 strata is well-represented by coeval strata deposited on the Laurentian shelf, all of which record an upward-decrease in siliciclastic sedimentation due to Late Cambrian eustatic rise and are capped by a regressive Cambrian – Ordovician stage boundary unconformity (e.g. the “Potsdam”-Galway-Little Falls formations in central New York, Danby-Little Falls formations in Vermont and Rock River-Strites Pond formations in Quebec). Regression in the Ottawa graben appears to have been delayed relative to most other parts of southern Laurentia, perhaps as a result of locally elevated rates of subsidence and thus accommodation space generation in the Ottawa graben that outpaced the rate of relative sea level fall.

Allounit 3 records a protracted and diachronous northwestward (paleo-northeastward) eustatic transgression across the southern Ottawa graben that eventually culminated in widespread mixed carbonate-siliciclastic, shallow marine sedimentation (Theresa Formation). This early Ordovician transgression occurred rapidly over most of Southern Laurentia, resulting in the widespread development of epeiric seas. The comparatively protracted eustatic rise over the Ottawa graben was due to the persistence of fault-bounded topographic highs, which formed islands and/or coastal salients during sea level rise. The occurrence of soft-sediment deformation features correlated over a large area ($\sim 70 \text{ km}^2$) near

Ottawa suggests that the faults bounding these paleo-topographic highs may have been episodically reactivated.

Chapter 6: Early Paleozoic reactivation of a passive margin intra-plate rift: insights into reactivation of the Ottawa graben from detrital zircon provenance signatures of the Potsdam Group

6.1 Introduction

The Ottawa-Bonnechere graben (Kay, 1942), or for brevity the Ottawa graben, is an enigmatic intracratonic fault-bounded rift in northeastern North America oriented approximately normal to the modern St. Lawrence River Valley and Atlantic continental margin and extends northeastward from Montreal, QC over ~700 km to Sudbury, ON (Fig. 6.1). It, along with a number of other margin-normal rifts in eastern North America, including the Saguenay graben, the Southern Oklahoma fault zone and the Rough Creek graben, originated in the Late Neoproterozoic during intracratonic rifting leading to the breakup of Rodinia (Kumarapeli and Saull, 1966; Doig and Barton, 1968; Doig, 1970; Burke and Dewey, 1973; Dewey and Burke, 1974; Currie, 1976; Kumarapeli, 1985, 1993; Thomas, 1991; Kamo et al., 1995; Malka et al., 2000; Salad-Hersi and Dix, 2006; Allen et al., 2010; McCausland et al., 2011) (Fig. 6.2). Subsequently, the Ottawa graben persisted as a zone of crustal weakness that was reactivated during major plate tectonic events like the Appalachian Orogeny, culminating in the assembly of Pangea (Rimando and Benn, 2005; Dix and Al Rodhan, 2006; Nurkhanuly, 2012), and mid-Mesozoic rifting that culminated in the breakup of Pangea and opening of the Atlantic Ocean (Crough, 1981; McHone and Butler, 1984; Hogarth et al., 1988; Rimando and Benn, 2005; Bleeker et al., 2011). These reactivation events are unsurprising given their proximity to active margins. Less expected however, is

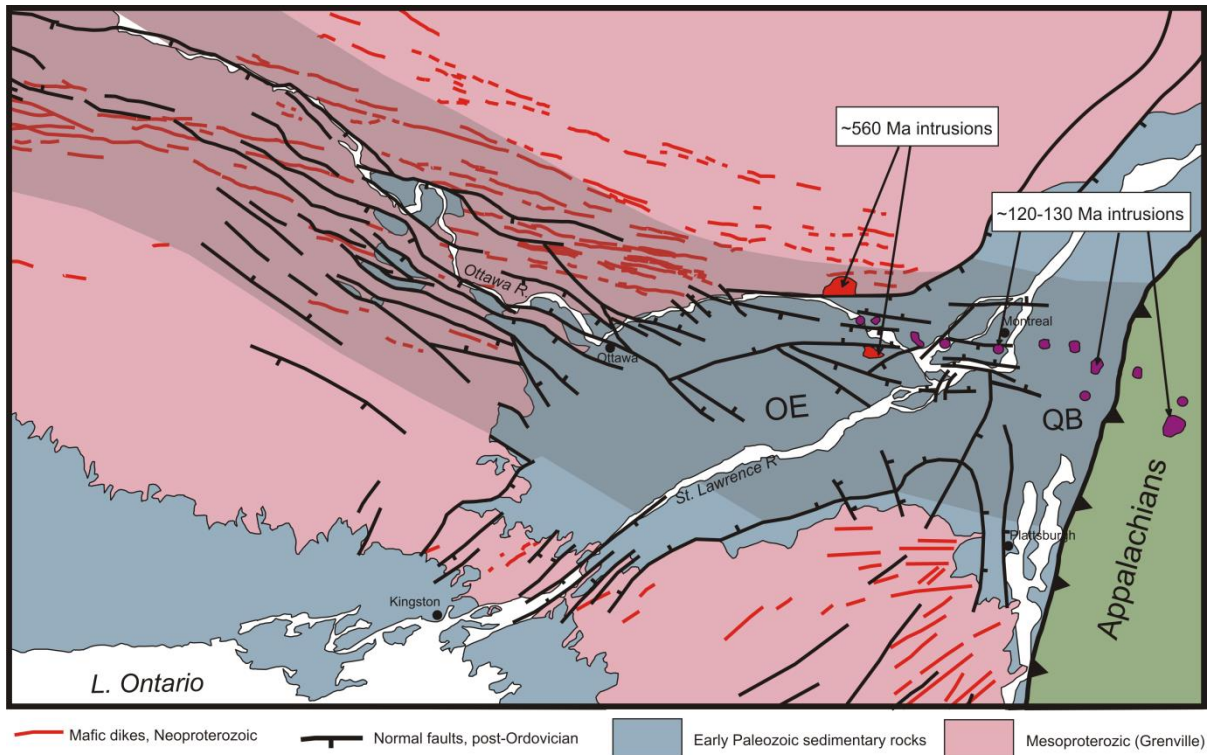


Figure 6.1 Structural and geologic map of the Ottawa graben. The approximate boundaries of the graben are shown in the shaded area. OE = Ottawa Embayment, QB = Quebec Basin. Modified from Bleeker et al. (2011). Areas shaded in red are latest Neoproterozoic Chatham-Grenville and Mont Rigaud intrusions, and areas in purple are Mesozoic intrusions of the Monteregian alkaline province.

the occurrence of Cenozoic faulting (Rimando and Benn, 2005), uplift of the adjacent Adirondack Dome (Isachsen, 1975, 1981) and modern seismicity (Aylesworth et al., 2000; Bleeker et al., 2011; Ma and Audet, 2015) suggesting that the Ottawa Graben continues to be active in spite of being far removed (~3500 – 4000 km) from any tectonically-active plate margin. This type of intraplate tectonic activity, which is clearly unrelated to hotspots, remains enigmatic, and a topic of continuing research (Zoback and Zoback, 1981; Braile, 1982; Zoback, 1992; Grollmund and Zoback, 2001; Mazzotti and Townend, 2010; Hurd and Zoback, 2012; Ma and Audet, 2015).

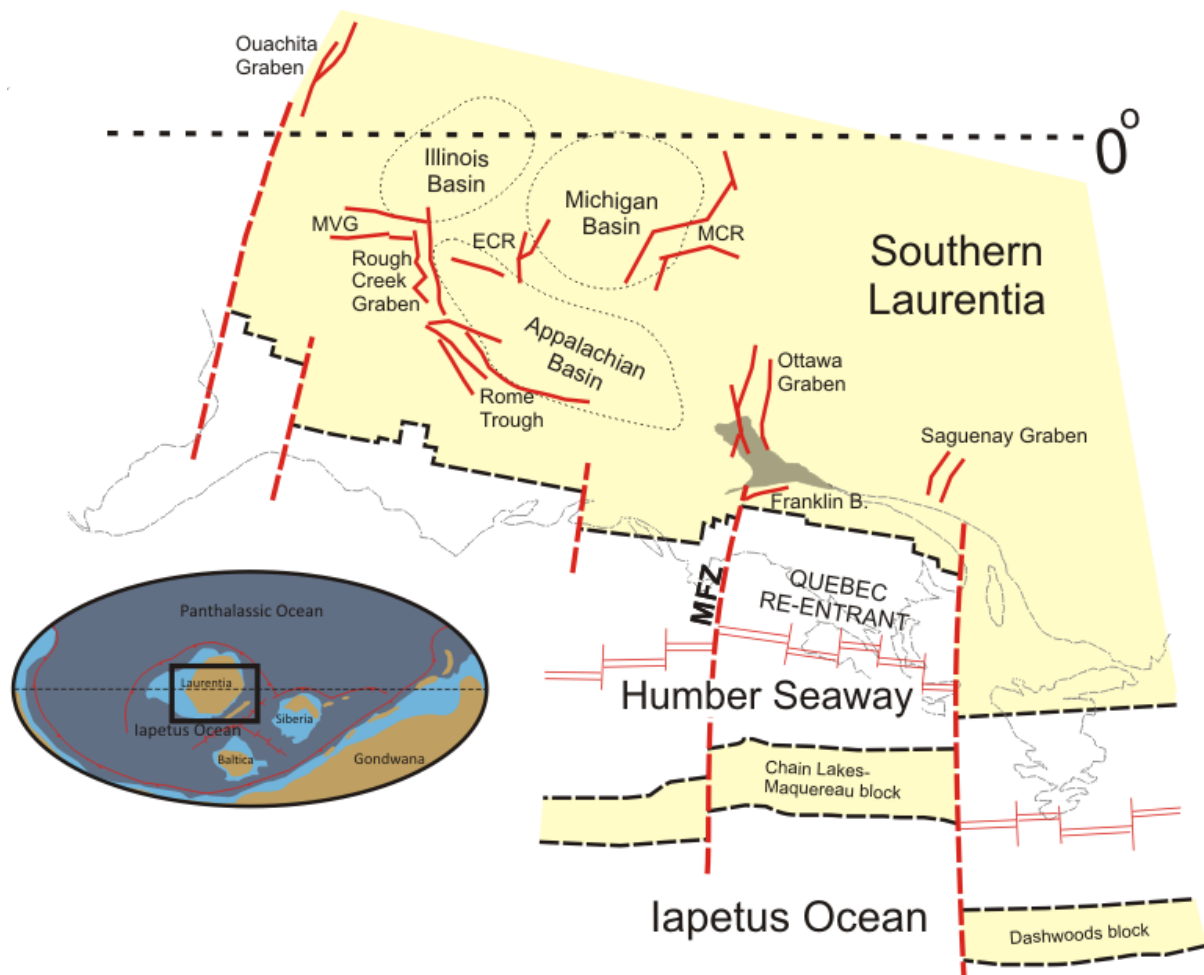


Figure 6.2 Paleogeographic and tectonic reconstruction of Early Paleozoic southern Laurentia. The areas shaded in light yellow represent continental crust of Laurentia and its rifted fragments to the paleo-south. Red lines on southern Laurentia indicate the locations of various Neoproterozoic structures: Ottawa graben, Saguenay graben, MFZ = Missisquoi fracture zone, Rome trough, Rough Creek graben, MVG = Mississippi Valley graben, Oachita graben, MCR= Mid-continent rift, ECR=East-continent rift, Frabklin B. = Franklin Basin.. Dashed red lines represent oceanic fracture zones connected to active transforms on the mid-oceanic ridge of the Humber Seaway. Thin double red lines show the location of the spreading ridge of the Humber Seaway. Dashed box shows location of paleogeographic reconstructions in Figure 6.7.

Like the Cenozoic, the reactivation of the Early Paleozoic Ottawa graben under intra-plate, passive margin conditions has previously been reported based on the study of strata from within and surrounding the Ottawa graben (Lewis, 1971; Salad Hersi and Dix, 2006; Landing, 2007; Landing et al., 2009; Sanford and Arnott, 2010; chapter 5). In fact, a number

of studies of the Potsdam Group, a Cambrian to Lower Ordovician, mostly terrestrial siliciclastic unit in the easternmost part of the Ottawa Graben, suggest that the development of internal unconformities, changes in detrital mineralogy, syn-sedimentary structural deformation and highly irregular isopach distribution are tied to syn-sedimentary tectonic activity (Lewis, 1971; Sanford and Arnott, 2010; chapter 5). However, due to the mainly terrestrial and lithologically monotonous character of the Potsdam and a historical lack of any systematic, cross-border studies, details about the timing and location of potential tectonically-linked changes in accommodation and sedimentation patterns remain poorly developed. Furthermore, although Salad Hersi and Dix (2006) suggested that reactivation of the Ottawa graben in the Early Ordovician was related to stresses generated by ocean basin tectonic activity in the adjacent Humber Seaway, the exact source(s) of stresses and the mechanism(s) by which they were transmitted to the graben were not addressed.

This study of the Lower Cambrian to Lower Ordovician Potsdam Group helps unravel details of the timing, location and orientation of tectonic reactivation of the Ottawa graben during the Cambrian and Early Ordovician. It specifically integrates the existing stratigraphic and sedimentological framework of the Potsdam Group from chapter 5 with new and existing U-Pb detrital zircon geochronology and paleoflow data in order to identify variations in sediment dispersal patterns, which are interpreted to reflect spatial changes in sediment source to sink caused by tectonic reactivation of the Ottawa graben. Furthermore, a discussion of possible sources of tectonic stress as well as possible mechanisms for the transmission of these stresses to the Ottawa graben is also offered.

6.2 Late Neoproterozoic to Early Paleozoic Laurentia, and the Ottawa graben

The Ottawa graben is part of the St. Lawrence Rift System (Kumarapeli and Saull, 1966) which in addition to the Saguenay graben, originated during a prolonged multi-phase intracratonic rifting event in ancient North America that lasted from the Late Neoproterozoic until the near the end of the Early Cambrian (Cawood et al., 2001; Waldron and van Staal, 2001; Lavoie, 2008; Allen et al., 2010). The Ottawa graben was initiated during an episode of Neoproterozoic rifting (~600 – 570 Ma) that eventually culminated in the breakup of Rodinia and opening of the Iapetus Ocean. Rifting also coincided with the emplacement of the ~590 – 577 Ma Grenville dyke swarm and related alkaline intrusions (Doig and Barton, 1968; Doig, 1970; Kumarapeli, 1985; Kamo et al., 1995; Cawood et al., 2001; Allen et al., 2010; McCausland et al., 2011) (Fig. 6.1). Numerous authors, including Burke and Dewey (1973), Dewey and Burke (1974), and Kumarapeli (1985, 1993) suggest that the Ottawa graben originated as an aulocogen – the failed arm of an Iapetan rift triple junction located at the head of a mantle plume. More recently, Allen et al. (2010) argued that the Ottawa graben formed instead by transtension related to the cratonward propagation of Iapetan transform faults, similar to the modern Benue Trough in West Africa (e.g., Benkhelil, 1989). Notwithstanding details of its earliest inception, following the breakup of Rodinia at ~570 Ma a second phase of rifting affected nascent southern Laurentia, but this time inboard of the original margin along the Iapetus Ocean. This second rift phase culminated in the ~ 550 – 530 Ma (late Ediacaran to earliest Cambrian) opening of a narrow (~300 km) seaway termed the Humber seaway and paleo-southward drifting of fragments of the Laurentian margin (e.g., the Dashwoods, Chain Lakes-Maquereau, Shelburne Falls “arc” and other unnamed

peri-Laurentian terranes; Karabinos et al., 1998; Cawood et al., 2001; Waldron and van Staal, 2001; Hibbard et al., 2007; Allen et al., 2010) (Fig. 6.2). During this phase, the Ottawa graben was also reactivated with the emplacement of localized syenitic intrusions of the Mont Rigaud (533 ± 1 Ma) and Chatham-Grenville (531 ± 3 Ma) stocks (Malka et al., 2001; McCausland et al., 2007). Subsequently, a third post-breakup phase of rifting, termed the “end-rift/early drift” by James et al. (1986), affected the entire Laurentian margin during the Early Cambrian ($\sim 530 - 510$ Ma) resulting in widespread but uneven syn-rift sedimentation (e.g., the Pinnacle and Chilhowee formations) and local volcanism on the Laurentian margin (James et al., 1989; Thomas, 1991; Cherichetti et al., 1998; Landing, 2007; Lavoie, 2008; Allen et al., 2009, 2010). Following this terminal phase of extension the Laurentian margin became a passive margin characterized by widespread, generally shallow marine carbonate and rare siliciclastic shelf sedimentation. This phase lasted from the late Early Cambrian until the Middle Ordovician when peri-Laurentian fragments collided with Laurentia, closing the Humber seaway (James et al., 1986; Waldron and van Staal, 2001; Lavoie, 2008; Landing, 2007; Allen et al., 2010).

In the Ottawa graben deposition of the Potsdam Group over ~ 1 Ga Grenville Province basement began in the mid-late Early Cambrian near the end of the “end-rift/early drift” phase and continued, albeit punctuated by two major periods of non-deposition and erosion, until the Early Ordovician (Landing et al., 2009; Sanford and Arnott, 2010; chapter 5). During all this time, Laurentia was located along the equator and rotated $\sim 90^\circ$ clockwise relative to present day North America (Torsvik et al. 1996; McCausland et al. 2007, 2011). In addition its south-facing margin consisted of a series of promontories and embayments bounded laterally by major fracture zones linked to active oceanic transforms in the Humber

seaway (Thomas, 1991, 2006; Allen et al., 2009, 2010) (Fig. 6.2). The Ottawa graben, in turn, was located 10° – 30° south latitude and ca. 200 – 400 km inboard of the edge of the continental margin, approximately at the intersection of the New York promontory and Quebec embayment, where the proposed Missisquoi fracture zone intersected the Laurentian Margin (Cherichetti et al., 1998; Lavoie, 2008; Allen et al., 2009, 2010). The peri-Laurentian terranes described above (i.e., Dashwoods, Chain Lakes and Shelburne Falls) were located ~300 – 1000 km to the paleo-south of the Laurentian margin (Fig. 6.2). During the early Late Cambrian, Iapetus oceanic crust obducted paleo-northward over these terranes, setting into motion the closing of the Humber Seaway that would culminate in the Middle Ordovician Taconic orogeny (Waldron and van Staal, 2001; van Staal et al., 2007).

6.3 Allostratigraphy of the Potsdam Group

The Cambrian – Early Ordovician Potsdam Group is a mainly siliciclastic unit that crops out along the margins of the Ottawa Embayment and Quebec Basin; two semi-connected fault-bounded Paleozoic basins located at the eastern end of the Ottawa graben (i.e., paleo-southern Ottawa graben, or SOG for brevity) (Fig. 6.3). The Potsdam Group unconformably overlies metamorphic and igneous rocks of the ~1 Ga Grenville Province, and in turn is overlain by the mixed siliciclastic and carbonate rocks of the Theresa Formation, the basal unit of the Beekmantown Group (Sanford and Arnott, 2010; chapter 5). According to the stratigraphic model in chapter 5, the Potsdam Group is subdivided into three allounits recording discrete episodes of sedimentation (Fig. 6.4).

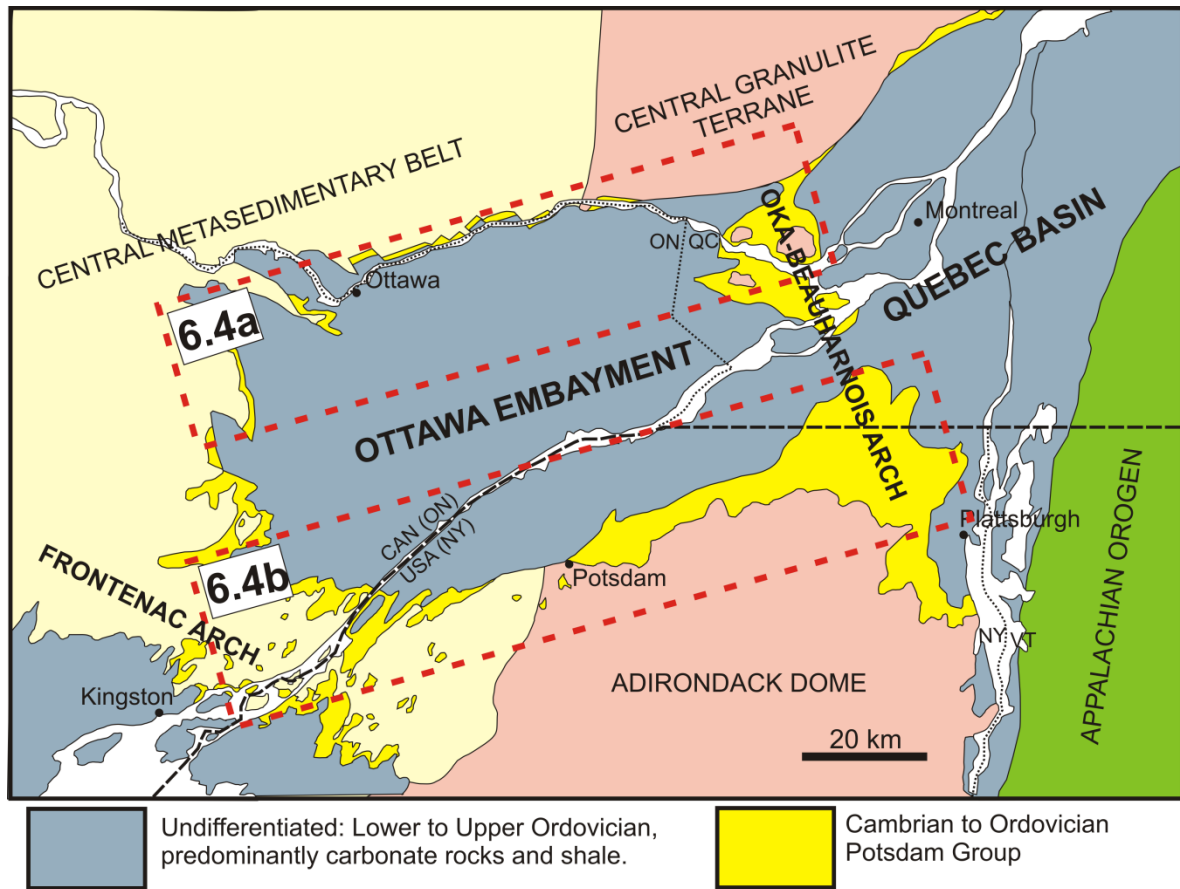


Figure 6.3 Simplified geologic map of the Ottawa Embayment and Quebec Basin showing the distribution of Potsdam Group and younger Paleozoic strata. The inset dashed boxes indicate the areas corresponding to the stratigraphic correlations shown in figure 6.4a and 6.4b.

Allouit 1, at the base of the Potsdam Group, consists of mainly braided fluvial arkose of the Ausable Formation overlain locally by aeolian red bed quartz arenite of the Hannawa Falls Formation (Fig. 6.4). The basal Ausable Formation occurs mainly in fault-bounded grabens in the eastern and northern parts of study area where locally it is ≥ 450 m thick, but also occurs as thin (≤ 25 m) areally-limited, fault-bounded outliers in the southern and southwestern Ottawa Embayment. In the eastern part of the study area the Altona member, a northward thinning, $\sim 20 - 80$ m thick intertongue of marine strata consisting mostly of mudstone and siltstone with rare sandstone and carbonate, occurs near the base of the Ausable Formation and provides a record of a minor marine incursion into the SOG.

Importantly the Altona contains trilobite fauna indicating a late Early Cambrian to early or mid-Middle Cambrian age (Landing et al., 2009). This then, along with age constraints from the overlying units described next, suggests a late Early to Middle Cambrian age for Allounit 1. The aeolian Hannawa Falls Formation, which conformably overlies the Ausable Formation, is limited to the southwestern parts of the Ottawa Embayment where it occurs as ~ 2 – 25 m thick outliers. An erosional and locally angular unconformity caps allounit 1 strata, representing a depositional hiatus and coeval erosion and paleosol development that persisted for as much as ~10 Myr from the mid-Middle Cambrian until the early Late Cambrian (chapter 5). The locally angular nature of the unconformity is attributed to local drag-folding and faulting of Allounit 1 strata (e.g., figure 5.16), which according to Sanford and Arnott (2010) was related to extension oriented sub-parallel or oblique to the trend of the Ottawa Embayment.

Allounit 2 consists of the lower part of the Keeseville Formation, a unit composed mostly of quartz arenite with rare quartzite-clast conglomerate and carbonate. A number of age-diagnostic fossils, including sparse trilobite faunas locally near its base and conodonts near its top, suggest that Allounit 1 was deposited from the late Middle Cambrian until the earliest Ordovician, with most sedimentation taking place during the Late Cambrian (Walcott, 1891; Flower, 1964; Lochman, 1968; Fisher, 1968; Landing et al., 2009; chapter 5, appendices B, C). The oldest strata in Allounit 2 are limited to the southernmost Quebec Basin and consist of late Middle Cambrian quartz arenite deposited in marginal marine and coastal fluvial environments. Younger, most probably Upper Cambrian braided and ephemeral fluvial quartz arenite and local conglomerate are widespread across the SOG, blanketing earlier allounit 1 strata and Grenville basement with thicknesses varying from ~50

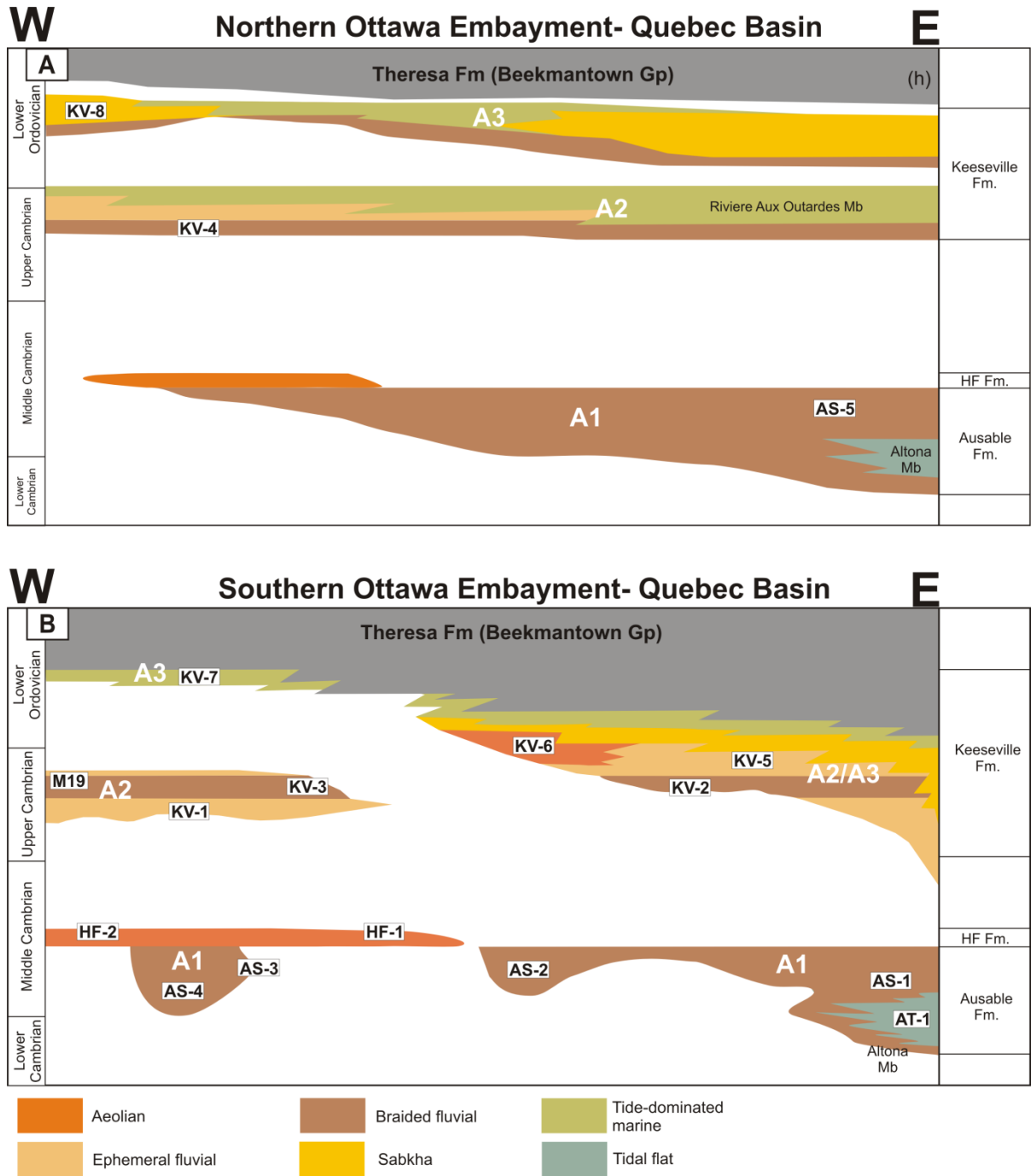


Figure 6.4 Stratigraphic correlation of Potsdam strata across the northern (A) and southern (B) Ottawa Embayment and Quebec Basin. Text in white (A1 – A3) outlines the allostratigraphic units described in the text. The text in inset boxes (e.g., AT-1) correspond to the approximate stratigraphic location of detrital zircon samples (see Table 6.1 for more details).

– 100 m in the southeast, ~5 – 60 m in the north and ~4 – 22 m in the southwest parts of the study area. In the northern Ottawa Embayment and adjacent northern Quebec Basin, Upper

Cambrian fluvial strata are capped by uppermost Cambrian to lowermost Ordovician tidal marine strata, including rare carbonate rocks of the Riviere Aux Outardes Member, recording marine transgression. Allounit 2 strata are then truncated by an erosional unconformity over most of the Ottawa Embayment and Quebec Basin, recording an intra-Ordovician break in sedimentation coinciding with local marine regression, erosion and paleosol development. In the northern Ottawa Embayment, vertical joint sets occur in allounit 1 strata immediately beneath the unconformity (e.g., Fig. 5.20) suggesting subtle structural deformation of the uppermost allounit 1 either preceding or during unconformity development. However, this unconformity is absent in the southeastern Ottawa Embayment and adjacent southern Quebec Basin; where, instead, coeval ephemeral fluvial and supratidal sabkha quartz arenite strata record uninterrupted terrestrial to marginal marine sedimentation. Thus, the allounit 1 – allounit 2 contact in this area is a correlative conformity located within these fluvial and marginal marine strata, however, the exact position of the contact is unknown.

Allounit 3 consists of the early Ordovician upper part of the quartz arenitic Keeseville Formation, generally comprising basal ephemeral or braided fluvial strata capped by coastal sabkha and/or subtidal fully marine strata, recording marine transgression of the entire basin, coinciding with the regional Sauk III transgression. Throughout most of the southern and central Ottawa Embayment and Quebec Basin, allounit 3 strata are conformably overlain by subtidal, mixed carbonate and quartz arenite strata of the Theresa Formation. Over much of the northern Ottawa Embayment and adjacent Quebec Basin on the other hand, Allounit 3 strata and the Theresa Formation are separated by a sharp, locally erosive unconformity (Salad Hersi et al., 2002; Dix et al., 2004; chapter 5). Conodont specimens from the lowermost Theresa Formation across the basin suggest that marine transgression over the

SOG was diachronous, with marine flooding first in the southwest and progressing north- and northwestward (modern configuration) throughout the Tremadocian (Greggs and Bond, 1972; Brand and Rust, 1977; Salad Hersi et al., 2002; chapter 5).

6.4 Detrital zircon provenance

6.4.1 Methods

Sandstone provenance and regional sedimentation patterns were evaluated based on detrital zircon age assemblages from the three allounits of the Potsdam Group across the Ottawa Embayment and Quebec Basin. Samples were strategically located both geographically and stratigraphically in order to supplement the existing detrital zircon database from earlier studies, namely Chiarenzelli et al. (2010) and Montario and Garver (2009). Figure 6.4 shows the stratigraphic distribution of detrital zircon samples and Table 6.1 provides details on their locations.

Samples were first disaggregated and sieved to isolate grains with the $63\ \mu\text{m} < \text{c-axes} < 125\ \mu\text{m}$ (i.e., coarse silt to very fine sand fraction). This is a standard size fraction that captures detrital zircons from all sources (Poldervaart, 1955) and thus is considered to eliminate size fractionation of provenance components caused by differences in hydraulic conditions during deposition (Morton and Hallsworth, 1994; Morton et al., 1996; Fedo et al., 2003). Next, heavy minerals from disaggregated samples were separated by hydraulic gravity separation using a Wilfley table, and then further separated by settling through methylene iodide, a heavy liquid with a specific gravity of $3.34\ \text{g/cm}^3$. Zircons were then picked from the final heavy fraction and mounted in epoxy and polished flat to expose zircon grain

interiors. For each sample at least 100 detrital zircons were picked for U-Pb dating in order to reduce the probability (to <1%) of missing an age population making up 5% of the total sample (Dodson et al., 1988; Morton et al., 1996; Fedo et al., 2003). The U-Pb ages of detrital zircon grains were determined by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) using a 193 nm excimer laser for ablation at the University of New Brunswick (UNB, the 10 new samples; see McFarlane and Luo (2012) for details of analytical setup) and the Arizona LaserChron Centre (6 samples from Chiarenzelli et al., 2010; see Gehrels et al., 2006, 2008, and Gehrels and Pecha, 2014 for details of analytical setup). Ablation pits were 30 – 35 μm in diameter and $\sim 15 \mu\text{m}$ in depth, and ablation frequency was 5 Hz at a radiant fluence of 5 J/cm^2 . Ablated material was carried from the sample cell using a He-Ni-Ar carrier gas (UNB), or He carrier gas (LaserChron), to the ICPMS where the isotopes Pb^{204} , Pb^{206} , Pb^{207} , Pb^{208} , Th^{232} and U^{238} were measured during 15s of background followed by 15s of sample ablation and 30s of delay for purging for each analysis. At both labs replicate measurements of zircon and glass reference materials of known composition and age were used to correct for instrumental mass bias to monitor accuracy and reproducibility of analyses. These included Harvard 91500, (Wiedenbeck et al., 1995), FC-1, (Paces and Miller, 1993) and NIST 610 glass (Jochum et al., 2011) at UNB and Sri Lankan standard zircon at the Arizona LaserChron Lab. At UNB, reduction of mass spectrometry data and calculation of U-Pb ages was carried out using Visualage, a data reduction scheme developed for Iolite, a general program designed to process mass spectrometric data (Paton et al., 2011; Petrus and Kamber, 2012). At the LaserChron lab, data were reduced and ages were calculated using an in-house Excel routine (E2agecalc; Gehrels et al., 2008). Following data reduction, zircons ages were filtered by removing those

with > 10% discordance (e.g., Fedo et al., 2002; Gehrels, 2012). Next, the ISOPLOT/Excel add-on program of Ludwig (2003) was used to plot relative age probability distribution curves of $\text{Pb}^{206}/\text{Pb}^{207}$ ages in Ma and 2 standard deviations from the mean in each sample (Fig. 6.5). Finally, age modes of each probability distribution and their contributing analyses were identified in each sample using the “Age Peak” routine of Gehrels (2012).

6.4.2 Results

Results of detrital zircon geochronology are summarized in tables 6.1 and 6.2 and Figure 6.5, and tabulated in appendix D. Based on major and minor age probability modes (Table 6.1), and graphical comparison of the relative probability plots (Fig. 6.5), a number of common age modes have been identified, and are considered to represent the most common detrital zircon source components for the Potsdam Group (Table 6.2). The most common zircon source component has an average age mode of ~ 1176 Ma, and consists of >20% of detrital zircon ages in 13 of the 17 samples, with age modes ranging from 1157 to 1195 (Fig. 6.5 and Table 6.1). A second common source component occurs at ~ 1442 Ma and consists of >20% of zircon ages in 4 samples, with age modes ranging between 1417 and 1467 Ma. Additionally a number of younger zircon source components are identified, and in order of decreasing abundance occur at ~ 1095 Ma, occurring in 5 samples with modes ranging between 1089 – 1104 Ma; at ~ 1054 Ma, occurring in 4 samples with modes between 1052 – 1057 Ma; and at ~ 1074 Ma, occurring in 3 samples with modes between 1073 – 1075 Ma. A number of younger, generally major age modes are also present at 1018 Ma, 1034 Ma, 1036 Ma and 1043 Ma (Table 6.1). The least common source components are represented by older

Sample, <i>n</i> analyses	Formation, Allounit (locality)	Location (locality #)	Facies	Major age modes >20% (Ma)	Minor age modes 5 – 20% (Ma)	Small age groupings <5% (Ma)
AT-1 [‡] (<i>n</i> =96)	Altona Mb., A1	West Chazy, NY (233)	Tidal flat	1157(82%)	--	--
AS-1 [‡] (<i>n</i> =96)	Ausable Fm., A1	West Chazy, NY (251)	Braided fluvial	1168(80%)	--	--
AS-2 (<i>n</i> =96)	Ausable Fm., A1	Nicholsville, NY (246)	Braided fluvial	1167(59%); 1089(25%)	1052(15%)	1403(5%)
AS-3 (<i>n</i> =102)	Ausable Fm., A1	Butternut Bay, HWY 401, ON (73)	Talus	1182(82%)	--	1065(4%)
AS-4 (<i>n</i> =99)	Ausable Fm., A1	Briton Bay, ON (12)	Braided fluvial	1183(67%)	1094(14%)	1633(3%)
AS-5 (<i>n</i> =122)	Ausable Fm., A1	Ile Perrot, QC (194)	Braided fluvial	1175(33%); 1182(31%); 1098(22%); 1073(20%); 1462(20%)	1256(13%); 1313(10%)	1632(3%); 1721(2%)
HF-1 [‡] (<i>n</i> =97)	Hannawa Falls Fm., A1	Hannawa Falls, NY (220)	Aeolian erg	1175(77%)	1343(6%)	1513(3%)
HF-2 (<i>n</i> =91)	Hannawa Falls Fm., A1	Theresa, NY (129)	Aeolian erg	1190(24%); 1443(22%); 1073(20%)	1384(18%); 1252(7%)	1671(3%)
KV-1 [‡] (<i>n</i> =95)	Keeseville Fm., A2	Sunbury quarry, ON	Ephemeral fluvial	1180(52%); 1054(39%); 1018(36%)	1467(9%)	1547(3%); 1662(3%); 2720(3%)
KV-2 (<i>n</i> =111)	Keeseville Fm., A2	Chateauguay High Falls, NY (168)	Braided fluvial	1172(48%); 1043(25%)	1432 (9%)	1720(3%)
KV-3 [‡] (<i>n</i> =91)	Keeseville Fm., A2	Charleston Lake Park, ON (55)	Talus, Braided fluvial	1057(55%); 1327(34%)	--	2721(3%)
M19†	Keeseville Fm., A2	Fishers Landing, NY (116)	Braided fluvial	1036, 1161	1417, 1321	1667
KV-4	Keeseville Fm., A2	Masson-Angiers, QC	Braided fluvial	1184(37%); 1034(31%)	1309(10%);	--

(n=101)		(18)			1381(7%)	
KV-5 (n=119)	Keeseville Fm., A3	Altona, NY (152)	Ephemeral fluvial	1195(33%); 1104 (23%); 1453(21%); 1090(20%)	1269(16%); 1332(12%);	2680(2%)
KV-6 (n=97)	Keeseville Fm., A3	Rainbow quarry, NY (188)	Aeolian erg	1154(34%)	1053(15%); 1441(15%); 1422(12%); 1359(9%)	1489(3%); 2623(3%)
KV-7 (n=119)	Keeseville Fm., A3	Blind Bay, NY (87)	Subtidal marine	1074(45%)	1369(15%); 1309(8%)	1481(3%); 1655(2%), 1883(2%); 2695(5%)
KV-8 [‡] (n=100)	Keeseville Fm., A3	Kanata, ON	Sabkha	1075(53%); 1161(41%)	1351(14%); 1440(11%)	2767(4%)

Table 6.1 Detrital zircon samples and constituent age modes. [‡] indicate samples from Chiarenzelli et al. (2010). † indicates samples from Montario and Garver (2009). Age modes are defined as the most commonly occurring Pb²⁰⁶/Pb²⁰⁷ ages in the probability distribution for each sample identified using the “agepick” routine of Gehrels (2012). Major and minor modes represent >20% and 15-20%, respectively, of the detrital zircon populations in a single sample. “Small age groupings” are very minor modes (<5%) with questionable statistical significance. Note that the percentages do not necessarily add to 100% because some dated grains are outliers, and therefore do fall into any age cluster (< 100%), or a single grain can contribute to two closely-spaced probability modes (resulting in >100%).

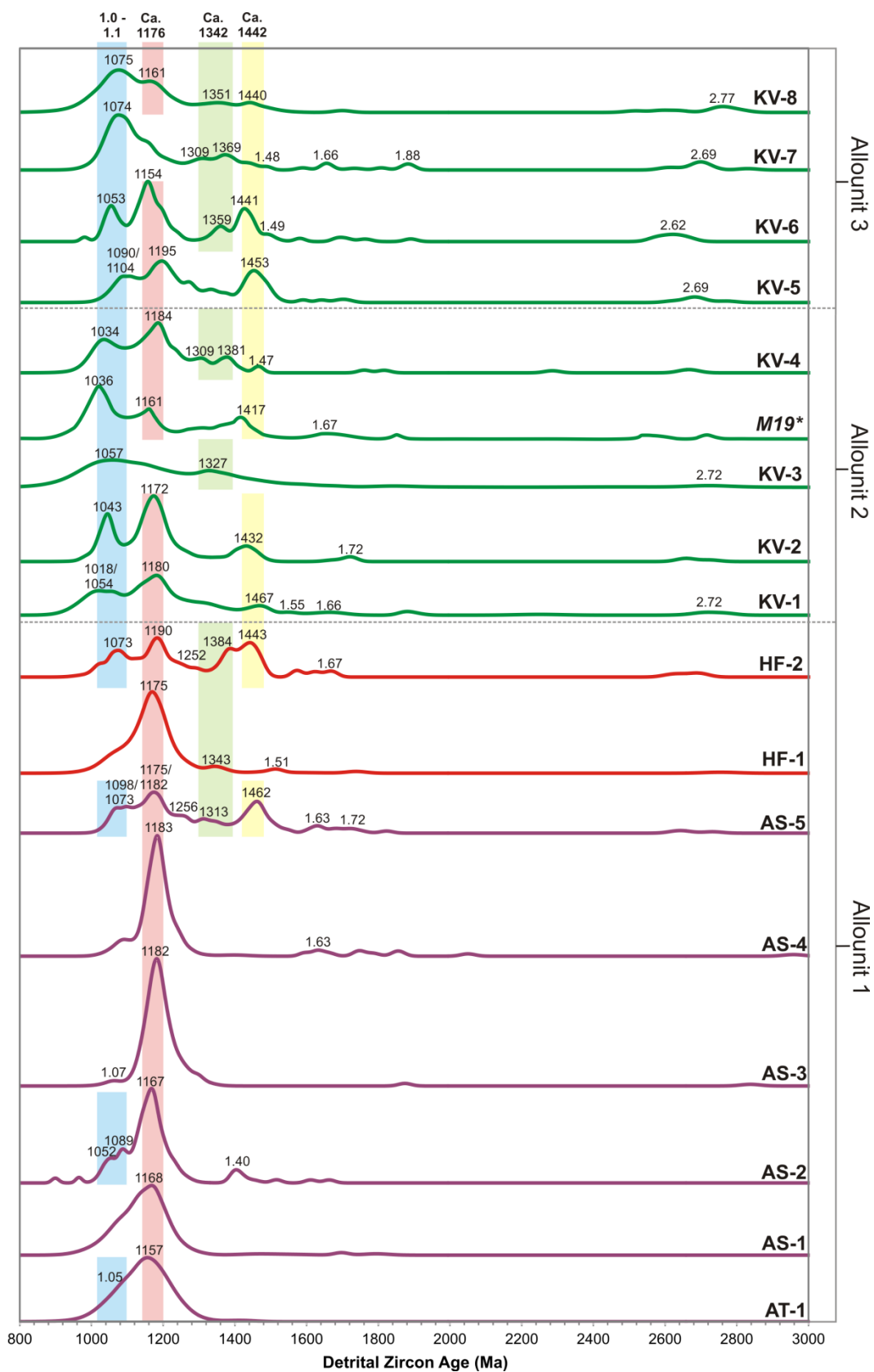


Table 6.2 **Age components and potential sources for detrital zircons.**

Age component	Potential source(s)
Ca. 1176 Ma (13 major modes, 1195 – 1157 Ma)	(1) 1200 – 1160 Ma quartz monzonites and granites in the Frontenac terrane, including the Frontenac, Hyde School, Rockport and Hermon intrusive complexes and the Rossie diorite – Antwerp granodiorite. Cropping out 0 – 50 km southwest and west of the OE, covering an area of ~ 7800 km² and likely extending beneath the western OE (McLelland et al., 1988; van Breeman and Davidson, 1988; Marcantonio et al., 1990; Wasteneys et al., 1999; Carr et al., 2000; Davidson and van Breeman, 2000; McLelland et al., 2004; Heumann et al., 2006). (2) 1170 – 1160 Ma Chevreuil suite: monzonite, gabbro and diabase cropping out 0 – 170 km north and northwest of the Ottawa Embayment in the Quebec CMB (Carr et al., 2000; Corriveau and van Breeman, 2000). (3) 1160 – 1135 Ma AMGC intrusions of the Adirondacks in New York and Morin terrane in Quebec, covering large areas (~ 27,000 km²) immediately south and north of eastern OE and western QB, and likely extending beneath (Doig, 1991; Emslie and Hunt, 1990; Friedman and Martignole, 1995; McLelland et al., 1988, 2004).
Ca. 1442 Ma (4 major and 5 minor modes, 1467 – 1417 Ma)	(1) 1450 – 1420 Ma plutons and orthogneiss covering an area of 48,000 km², ~ 120 – 300 km west and northwest of the OE (Culshaw et al., 1997; Timmerman et al., 1997; Nadeau and van Breeman, 1998). (3) Rare 1415 – 1500 Ma detrital zircons in metasedimentary rocks of the Frontenac terrane of the CMB in Ontario, immediately to the southwest and perhaps beneath the western OE (Sager-Kinsman and Parrish, 1993; Friedman and Martignole, 1995). (2) ~1.39 Ma Bondy Gneiss complex, ~ 70 km north of the western OE (Wodicka et al., 2004; Blein et al., 2003).

Ca. 1095 Ma (5 major modes, 1089 – 1104 Ma)	(1) 1103 – 1090 Ma Hawkeye Granite, ~ 60 – 80 km south of the western OE in the northwest Adirondacks (McLelland et al., 2004). (2) 1090 – 1075 Ma Skootamata suite, syenite and granite in the CMB, immediately southwest of the OE over an area of ~ 6000 km² and possibly extending beneath the western OE (Marcantonio et al., 1990; Davidson and van Breeman, 2000). (3) 1090 – 1075 Kensington suite, syenite intrusions in the CMB in Quebec, ~ 20 – 120 km north and northwest of the OE (Corriveau et al., 1990).
Ca. 1074 Ma (3 major modes 1073 – 1074)	(1), (2) and (3) from above, mixed with: (2) 1070 – 1066 Ma granites in the CMB in Ontario, immediately along the southwest margin of the OE (Davidson and van Breeman, 2000). (3) 1070 – 1060 Ma Guenette suite, rare granite intrusions in the CMB in Quebec ~ 100 - 120 km north and northwest of the OE (Corriveau and van Breeman, 2000).
Ca. 1054 Ma (2 major and 2 minor modes, 1052 – 1057 Ma); and younger outliers (1043, 1034, 1036 and 1043)	(1) 1050 – 1030 Lyon Mountain Granite, in the northern Adirondacks immediately south of the eastern OE and western QB (McLelland et al., 2001; Selleck et al., 2004; Valley et al., 2011) (2) Rare ca. 1054 Ma post-tectonic aplite dykes in the CMB of Quebec, ~ 60 km north of the western OE.
Ca. 1342 Ma	(1) Rare granitoids and gneisses throughout the CMB (Elsevir terrane) and GGB of Ontario, 10 – 160 km to the west of the

(1 major and 7 minor modes, 1309 – 1381 Ma)	OE (van Breeman and Davidson, 1990; van Breeman et al., 1996; Wodicka et al., 1996; Timmerman et al., 1997; Carr et al., 2000). (2) The ca. 1386 ± 10 Ma tonalities of the Bondy Gneiss complex, ~ 70 km north of the OE (Blein et al., 2003). (3) 1350 – 1250 Ma Royal Mountain tonalites and granodiorites, ~ 160 - 170 km south of the OE (McLelland et al., 2004). (4) 1400 – 1360 quartz diorites and tonalites of the La Bostonnais complex, ~ 160 km northwest of the western QB (Nadeau and van Breeman, 1998; Corrigan, 1995; Sappin et al., 2009).
Ca. 1259 Ma (3 minor modes, 1252 – 1269 Ma)	(1) Abundant 1280 – 1240 Ma tonalites and granites over a large area (~12,000 km²) of the CMB of Ontario (Elsevier terrane), 10 – 160 km west of the OE (Lumbers et al., 1990; Easton, 1992; Carr et al., 2000). (2) 1275 – 1200 Ma detrital zircons in metasedimentary rocks of the in the CMB in Quebec ~ 50 – 100 km north and northwest of the OE (Friedman and Martignole, 1995).
Minor age groupings (1.51, 1.66, 2.70 Ga)	(1) Distant igneous suites in the western margin of the CGB, ~ 320 - 400 km west of the OE (Nadeau and van Breeman, 1998; Carr et al., 2000). (2) Common 1700 – 1900 Ma and rare 2000 – 2700 Ma detrital zircons in metasedimentary rocks of the Frontenac terrane of the CMB in Ontario, immediately to the southwest and perhaps beneath the western OE (Sager-Kinsman and Parrish, 1993).

and generally minor modes with averages of ~ 1342 Ma represented by modes from 1309 to 1381 Ma, and ~ 1259 Ma with modes from 1252 to 1269 Ma. In addition, rare small age groupings made up of ≤ 5 zircon grains occur at ~ 1.51 , 1.66 and 2.70 Ga. Due to the inherently large analytical uncertainties in the LA-ICPMS technique of dating, outlying individual U-Pb ages that are not part of any major or minor age modes or small groupings are not considered further in the discussion of provenance. From the base to the top of the Potsdam Group, the detrital zircon signature of samples changes considerably (Fig 6.5, Table 6.1). The Lower to Middle Cambrian allounit 1, including the arkosic, mainly fluvial Ausable Formation overlain by the quartzose aeolian Hannawa Falls Formation, contain detrital zircons that overwhelmingly come from ~ 1176 Ma sources. In fact, ~ 1176 Ma modes dominates in five samples from the Ausable (including the marine Altona Member) and one from the Hannawa Falls, representing $\geq 55\%$ to as much as 82% of the dated grains with little or no contribution from other age modes. Nevertheless, two samples, one from the Ausable in the northeastern Ottawa Embayment (AS-5) and one from the Hannawa Falls in the southwestern Ottawa Embayment (HF-2), show a more varied source signature in which only 24 – 34% of the detrital zircons contribute to the ~ 1176 Ma source component, and with additional major contributions from ~ 1442 Ma, ~ 1074 Ma, 1095 Ma sources and minor contributions from ~ 1342 Ma and ~ 1259 Ma sources (Fig 6.5, Table 6.1). Detrital zircons in the arkosic Ausable Formation (including the Altona Member) are generally euhedral to subhedral.

Figure 6.5 (page 251) Probability distribution curves of detrital zircon ages from each of the detrital zircon samples used in this study, from the base to the top of the Potsdam sedimentary pile (defining the vertical axis). Sample names are given on the right side of each curve, and age in Ma is given on the x-axis. Also, curves are colour-coded based on their lithologic unit: purple = Ausable Formation, red = Hannawa Falls Formation, green = Keeseville Formation. Distribution of samples in terms of allounits is shown on the y-axis. Peaks in the probability distribution represent the modes of the main source components, and the coloured vertical bars indicate the most commonly occurring (four) major age modes (note that the blue shaded area actually includes 3 recurring modes at ~1095, ~1074 and ~1054 Ma, but these are too close in age to be separated on the diagram; see table 6.2).

Allounit 2, consisting of Upper Cambrian quartz arenite of the basal part of the Keeseville Formation, contain mostly rounded to well-rounded detrital zircons yielding generally more diverse detrital age spectra than allounit 1. The main distinguishing feature of these age assemblages is the ubiquitous presence of young age modes, including the major ~ 1054 Ma component and minor younger 1018Ma, 1043 Ma, 1036 Ma and 1034 Ma modes. The ~ 1176 Ma is still a common major source, but in some samples is minor or absent. Minor contributions of grains from ~ 1342 Ma and ~ 1442 sources are common, and contributions from ~ 1.66 and 2.70 Ga age groupings are rare.

Strata of allounit 3, consisting of the Early Ordovician upper part of the quartz arenitic Keeseville Formation, also contain rounded to well-rounded detrital zircons with contributions from a variety of source components (Fig 6.5, Table 6.1). Age assemblages from the lower part of allounit 3 (KV-5, KV-6) are similar to those from parts of allounit 1 (AS-5 and HF-1), with major contributions from ~ 1176 Ma, 1442 Ma, 1054 Ma and 1095 Ma sources. In contrast, zircon age spectra from the upper part of allounit 3 consist of a major contribution from ~ 1074 Ma sources with only minor contributions from ~ 1176 Ma, 1442 Ma and 1342 Ma sources. Small groups of detrital zircons at ~ 2.70 Ga are present in all allounit 3 samples.

6.4.3 Potential sources of detrital zircons

Potential sources of the most common occurring age modes (e.g. ~ 1176 Ma, 1143 Ma, 1095, 1074, etc.) as well as lesser age modes (1.51, 1.66 and 2.7 Ga) are present in the nearby Grenville Province, mostly within 300 km of the Ottawa Embayment (Table 2, Fig. 6.6). Nevertheless, some caution should be exercised when correlating potential zircon sources with the present-day exposed surface of the Grenville Province, especially considering Hyodo et al. (1993) suggested that as much as 5 km of vertical erosion in parts of the Grenville Province since the Early Paleozoic. Nevertheless, magmatic suites in the Grenville Province, effectively the potential sources of detrital zircons in the Potsdam, occur in linear and thus predictably distributed lithotectonic domains (e.g., the Central Metasedimentary Terrane and its subdivisions). Moreover, the crust of the Grenville Province is $\sim 30 - 35$ km thick (Ludden and Hynes, 2000), and therefore 5 km of local erosion since the Early Paleozoic should not have significantly changed the spatial distribution of exposed magmatic suites relative to the Ottawa graben following deposition of the Potsdam Group. Therefore the modern distribution of exposed magmatic suites is considered representative of those exposed during the Cambrian and Ordovician for the purpose of source-to-sink correlation.

Zircons comprising the common ~ 1176 Ma component can be traced to widespread $\sim 1200 - 1160$ Ma quartz monzonites and granites in the Frontenac terrane along the southwestern margin of the Ottawa Embayment on the Frontenac Arch and Adirondack lowlands, including the Frontenac, Hyde School, Rockport and Hermon intrusive complexes and the Rossie diorite – Antwerp granodiorite (McLelland et al., 1988; van Breeman and

Davidson, 1988; Marcantonio et al., 1990; Wasteneys et al., 1999; Carr et al., 2000; Davidson and van Breeman, 2000; McLelland et al., 2004; Heumann et al., 2006). Slightly younger sources may also have contributed zircons to the ~ 1176 Ma source component, but are too young to have been its main source. These include monzonite, gabbro and diabase of the ~ 1170 – 1160 Ma Chevreuil igneous suite in the Central Metasedimentary Belt (CMB), cropping out immediately northwest of the Ottawa Embayment (Carr et al., 2000; Corriveau and van Breeman, 2000), and ~ 1160 – 1135 Ma anorthosite-mangerite-charnockite-granite (AMGC) intrusions of the Adirondacks (McLelland et al., 1988, 2004) in the Central Granulite terrane (CGT) in Quebec (Emslie and Hunt, 1990; Doig, 1991; Friedman and Martignole, 1995), located directly south and north, respectively, of the Ottawa Embayment and Quebec Basin. The most probable source of zircons comprising the common ~ 1442 Ma source component are ~ 1450 – 1420 plutons and orthogneiss that cover a large area (48, 000 km²) in the western part of the Central Gneiss Belt (CGB), ~ 120 – 300 km to the northwest and west of the edge of the Ottawa Embayment (Culshaw et al., 1997; Timmerman et al., 1997; Nadeau and van Breeman, 1998) (Fig. 6.6). Other possible sources for these zircons include metasedimentary rocks from the Frontenac terrane that crop out immediately to the southwest and west, and the CMB northwest of the Ottawa Embayment (Sager-Kinsman and Parrish, 1993; Friedman and Martignole, 1995). Additionally, metasedimentary rocks and/or ~ 1.39 Ga tonalite intrusions of the Bondy Gneiss complex, located ~ 70 km north of the Ottawa Embayment (Blein et al., 2003; Wodicka et al., 2004), and/or the ~ 1.45 Ga metavolcanic rocks in the Montauban Group, located ~ 160 km northeast of the western Quebec Basin (Nadeau and van Breeman, 1998; Sappin et al., 2009) are also potential sources. However, these latter sources are considered minor compared to the CGB owing to

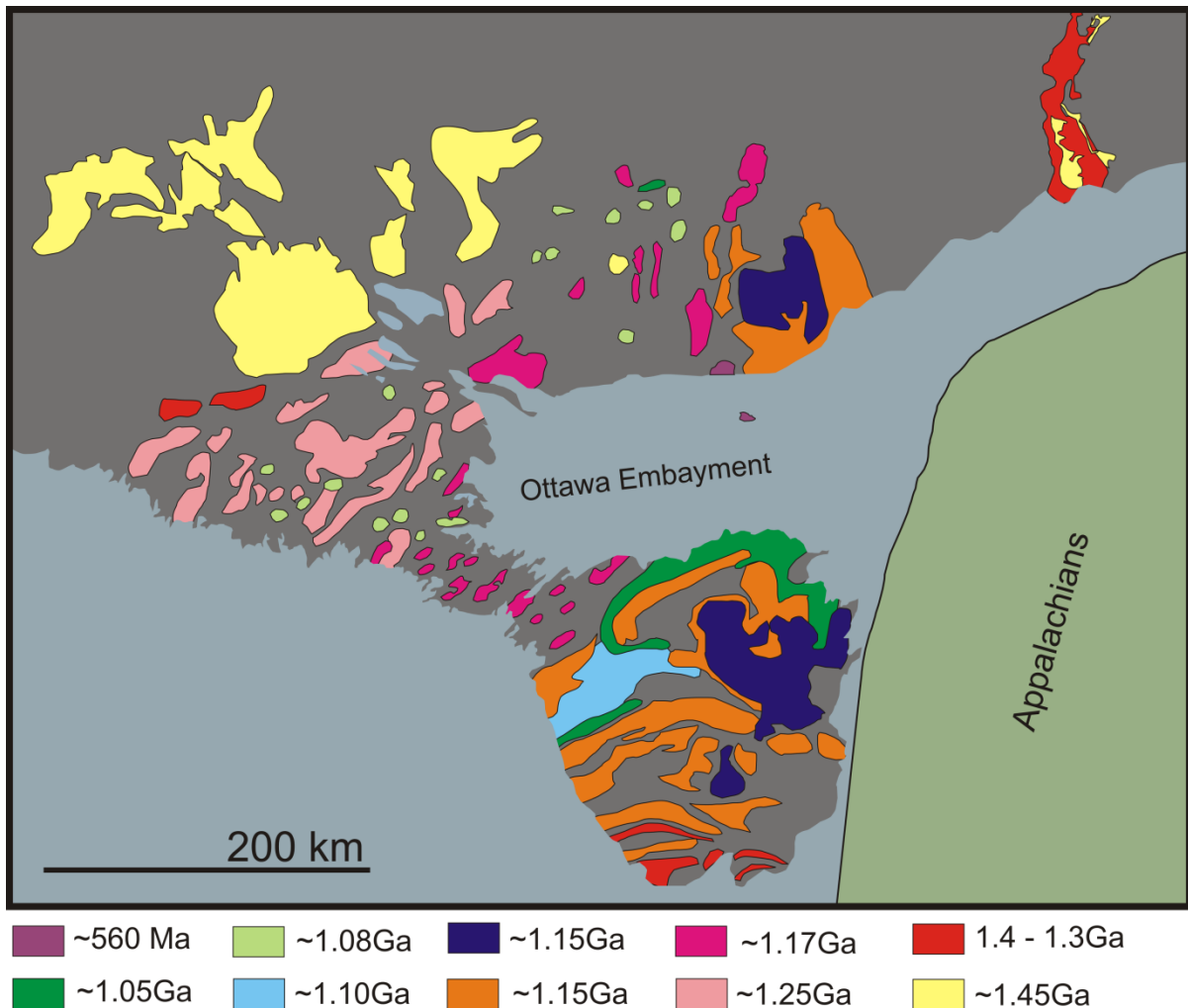


Figure 6.6 General geology of the Grenville Province of eastern Ontario, western Quebec and northern New York State, highlighting potential sources of zircons identified in the detrital zircon analysis. See text and table 6.2 for more detailed discussion of source areas.

their limited areal extent and also that they consist of rock types that are generally zircon-poor.

Younger age components (i.e., ~ 1095 Ma, 1074 Ma and 1054 Ma) were likely sourced from igneous intrusions in the CMB, CGT and Adirondack dome that surround the Ottawa Embayment and Quebec Basin. The tightly constrained source for zircons in the ~ 1095 Ma component is the ~ 1090 – 1103 Ma Hawkeye granite, located in the northwestern Adirondacks (McLelland et al., 2004). Younger magmatic suites may have also contributed

zircons to the ~ 1095 Ma component, and include the ~ 1090 – 1075 Ma Kensington suite in the CMB in Quebec (Corriveau et al., 1990) and/or the coeval Skootamatta suite in the CMB of Ontario (Marcantonio et al., 1990; Davidson and van Breeman, 2000). Zircons of the ~ 1074 Ma component were likely sourced from a combination of the ~1090 – 1075 Ma sources mentioned above with younger but geographically overlapping granitoid rocks of ~ 1070 – 1060 Ma Guenette suite in the CMB of Quebec (Corriveau and van Breeman, 2000) and/or ~ 1070 – 1066 Ma leucogranites in the CMB of Ontario (Davidson and van Breeman, 2000). lastly, zircons that make up the ~ 1054 Ma component and some younger age modes (1043, 1036 and 1034 Ma) were most likely sourced from the ~ 1050 – 1030 Ma Lyon Mountain Granite exposed throughout the northern Adirondacks (McLelland et al., 2001; Selleck et al., 2004; Valley et al., 2011) (Table 2, Fig. 6.6).

Zircons from the minor ~ 1342 component, comprising a wide range of age modes from 1309 to 1381 Ma, have numerous nearby potential sources including granitoids and gneisses throughout parts of the CGB and western CMB (i.e., the Elzevir terrane), ~10 – 160 km west of the Ottawa Embayment (van Breeman and Davidson, 1990; van Breeman et al., 1996; Wodicka et al., 1996; Timmerman et al., 1997; Carr et al., 2000) and ~ 1386 Ma tonalites in the Bondy Gniess complex, ~70 km north of the Ottawa Embayment (Blein et al., 2003). More distant ~ 1350 – 1250 Ma tonalites and granodiorites in the southernmost Adirondacks are also possible sources (McLelland et al., 2004), in addition to more distant quartz diorites and tonalites of the ~ 1400 – 1360 Ma La Bostonnais complex, located ~ 160 km northwest of the western Quebec Basin (Corrigan, 1995; Nadeau and van Breeman, 1998; Sappin et al., 2009). Zircons making up the minor and generally negligible ~ 1259 Ma source component may have been sourced from ~ 1280 – 1240 Ma tonalites and granites of the

CMB, ~10 – 160 km west of the Ottawa Embayment (Lumbers et al., 1990; Easton, 1992; Carr et al., 2000), or from metasedimentary rocks in the Quebec CMB directly north of the Ottawa Embayment (Friedman and Martignole, 1995). Finally, zircons comprising the small age groupings at ~ 1.51, 1.66 and 2.70 Ga may have been sourced from more distant Grenville sources ~ 320 - 400 km to the west along the margins of the CMB (Nadeau and van Breeman, 1998; Carr et al., 2000), from nearby metasedimentary rocks in the Frontenac terrane immediately west and southwest of the Ottawa Embayment (Sager-Kinsman and Parrish, 1993), or from parts of the Bondy Gneiss complex, ~ 70 km north of the western Ottawa Embayment (Wodicka et al., 2004).

6.5 Patterns of Sedimentation and Accommodation

6.5.1 Allounit 1

The locally thick (up to 450 m) upper Lower to Middle Cambrian fluvial arkose of the Ausable Formation, including locally intercalated marine strata of the Altona Member, occur at the base and make up most of Allounit 1. This unit exhibits a highly irregular, fault-bounded isopach across the paleo-southern Ottawa graben (SOG) (chapter 5), suggesting that faults were either active during sedimentation or were activated following Ausable deposition but before sedimentation of the more areally extensive strata of Allounit 2. Syn-sedimentary faulting is more likely given localized coarse boulder debris along faults and abundant detrital feldspar in the Ausable (~ 12 – 41%, Lewis, 1971), together suggesting rapid exhumation and erosion of local sources and deposition in adjacent, rapidly subsiding

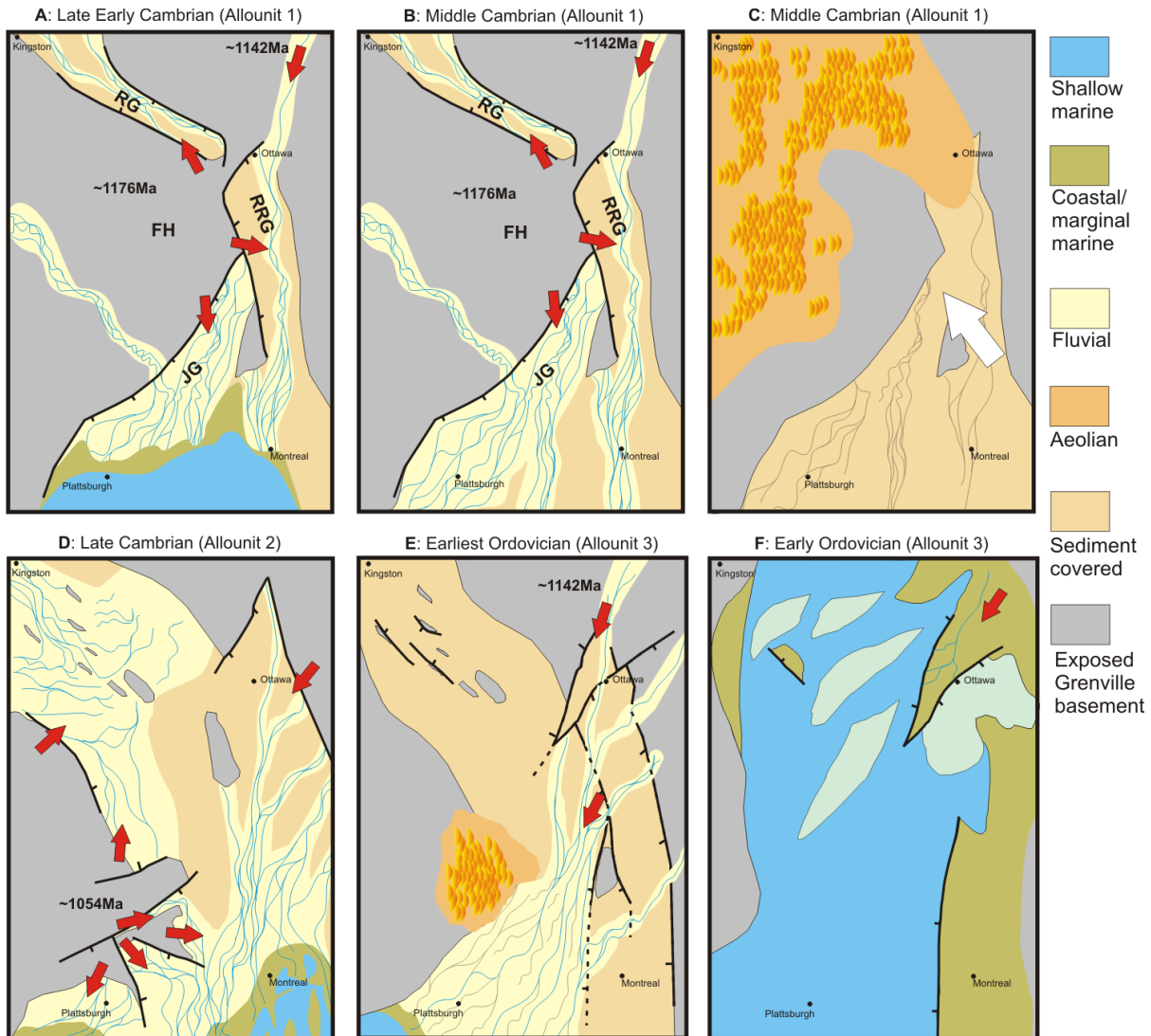


Figure 6.7 Paleogeographic and tectonic reconstruction of the paleo-southern Ottawa graben (SOG) (location given in Figure 6.2), compiled using detrital zircon provenance, paleoflow and the depositional and stratigraphic framework developed in chapters 2 – 5. Major cities in the area are shown for reference. Red arrows indicate the general direction of fluvial paleoflow and white arrows the prevailing wind (see Appendix E for paleoflow dataset). Active faults are shown in bold – hanging wall side indicated by the short dashes. The ages (in Ma) correspond to the age components identified in Table 6.2. A) and B): reconstruction of the SOG during Ausable Formation sedimentation of Allounit 1, including late Early Cambrian marine inundation recorded by the Altona Member (A). JG = Jericho half-graben, RRG = Rigaud-Rockland graben, RG = Rideau half-graben, FH = Frontenac horst. Numbers in “Ma” show the location or direction of zircon age source components. B) Reconstruction during Middle Cambrian Hannawa Falls Formation sedimentation (upper Allounit 1). C) Reconstruction during Late Cambrian Allounit 2 sedimentation (lower Keeseville Formation). E) Earliest Ordovician reconstruction during the earliest part of Allounit 3 sedimentation (upper Keeseville). F) Early Ordovician (Late Tremadocian) reconstruction during the late stages of marine flooding of the SOG.

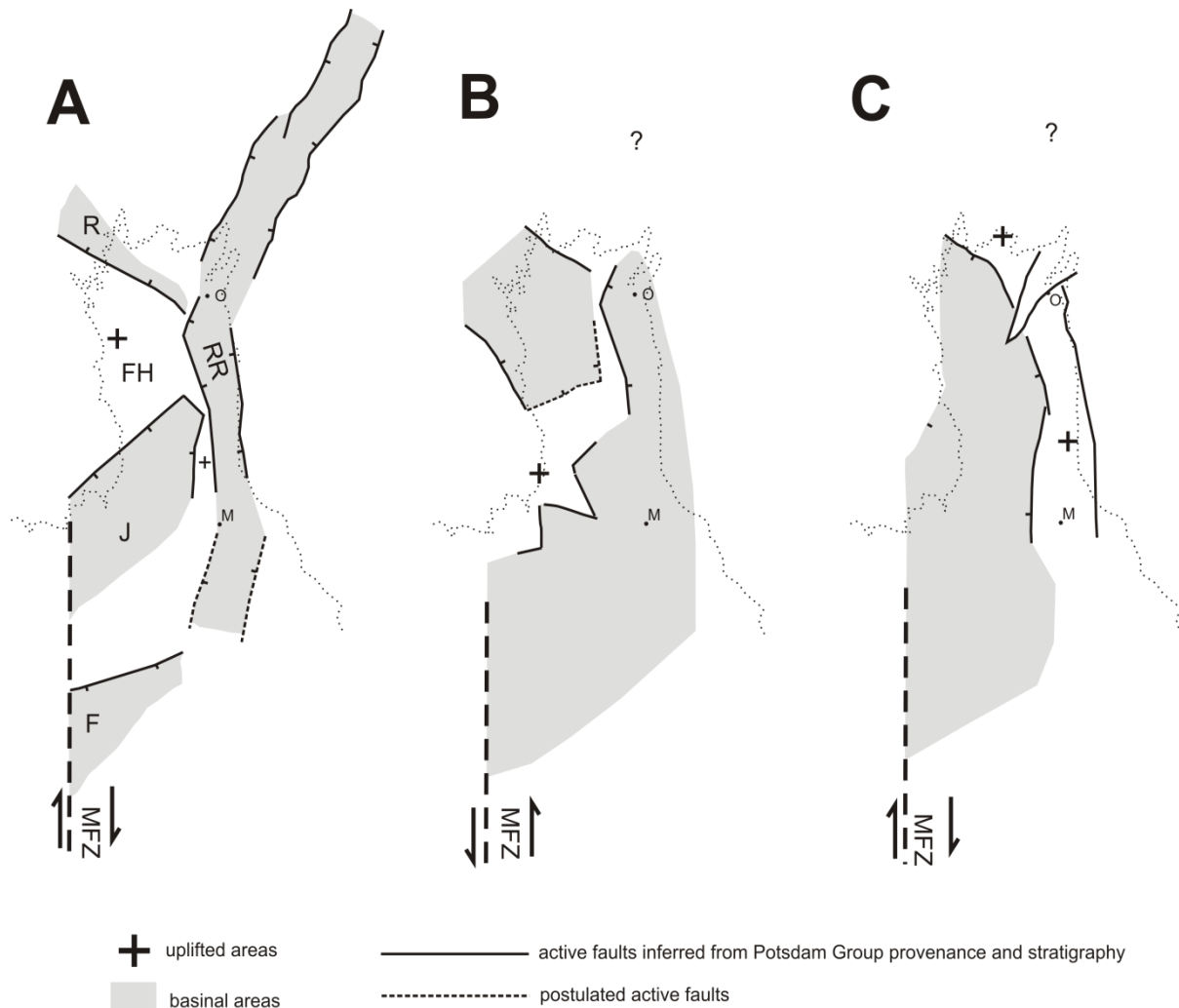


Figure 6.8 Tectonic reconstruction of the three episodes of tectonic reorganization that formed allounits 1, 2 and 3. Letters O and M indicate the location of Ottawa and Montreal, respectively. Dashed lines show the shape of the Ottawa Embayment and Quebec Basin, for reference and scale. A) Late Early to Middle Cambrian rifting, including opening of the Franklin (F), Jericho (J) and Rideau (R) half-grabens and uplift of the Frontenac horst (FH) oblique to the main trend of the Ottawa graben (see Fig. 6.1), and opening of the Rigaud-Rockland graben (RR) parallel to the trend of the Ottawa graben. It is here proposed that dextral movement on the adjoining Missisquoi fracture zone (MFZ) accommodated opening of the half-grabens (see text for details). B) Late Middle to early Late Cambrian tectonic reorganization of the Ottawa graben. Here, transtension caused by sinistral reactivation of the MFZ has resulted in tectonic inversion immediately paleo-east of the MFZ. Specifically, the area previously underlain by the Jericho graben has been uplifted and the Frontenac horst subsided. C) Earliest Ordovician reorganization of the Ottawa graben. At this time, areas to the paleo-east have been exhumed, while the pre-existing basement high in B) has subsided, most likely resulting from dextral reactivation of the MFZ.

grabens (Dickinson and Suczek, 1979; Dickinson et al., 1983; Cox and Lowe, 1995; chapter 5). This interpretation is supported by the dominance of euhedral – subhedral detrital zircons belonging to the ~ 1176 Ma source component. These zircons were most probably sourced locally from the 1200 – 1160 Ma igneous and high-grade metamorphic rocks in the Frontenac terrane (McLelland et al., 1988; van Breeman and Davidson, 1988; Marcantonio et al., 1990; Wasteneys et al., 1999; Carr et al., 2000; Davidson and van Breeman, 2000; McLelland et al., 2004; Heumann et al., 2006), and deposited in adjacent fault-bounded depocentres of the Ausable (Table 2, Figs. 6.6, 6.7a – c). Based on the distribution of Ausable strata, a likely paleogeographic reconstruction of the SOG during the late Early Cambrian and Middle Cambrian is shown in figures 6.7a – b and 6.8a, and illustrates three large half-grabens and grabens: (a) an ~ 6500 km² paleo-southwest-to-northeast-oriented Jericho half-graben in the paleo-southern SOG, (b) an ~ 5000 km² paleo-north-to-south-oriented Rigaud-Rockland graben in the paleo-eastern SOG and (c) an ~ 600 km² paleo-southeast-to-northwest oriented Rideau half-graben in the paleo-northern SOG (Fig. 6.8a). The variable orientation of these grabens suggest a complex extensional setting with opening oriented both parallel and at a high angle (~ 35 – 50°) to the trend of the Ottawa graben.

Fluvial drainage within the half-grabens was generally axial, with paleo-southwest and south flow in the Jericho half-graben and Rigaud-Rockland graben and paleo-northwest flow in the Rideau half-graben (Fig. 6.7a – b; see Appendix E). In the Jericho and Rideau half-grabens the dominance of ~ 1176 Ma zircons suggests direct sourcing from the adjacent footwall region dominated by 1200 – 1160 Ma igneous and metamorphic rocks, here termed the Frontenac horst (Figs. 6.6, 6.7a – b, 6.8a). However, detrital zircons from the Rigaud-Rockland graben (AS-5; Fig. 6.5, Table 6.1) are more diverse with major contributions from

the ~ 1176 Ma, 1074 Ma, 1095 Ma and 1442 Ma source components. This more diverse signature suggests contributions from more distant sources, specifically the 1450 – 1420 Ma igneous rocks in the CGB, ~ 120 – 300 km to the paleo-north and -northeast of the SOG, and younger zircons (~ 1095 and 1074 Ma) sourced from granitoids in the CMB, ~ 20 – 120 km to the paleo-northeast (Fig.6.6, table 2). This sediment provenance suggests the regional drainage system extended well to the paleo-north of the SOG and flowed into the Rigaud-Rockland graben along a path that parallels the modern Ottawa graben (Fig. 6.7a – b). This suggests that late Early to Middle Cambrian rifting likely involved the entire Ottawa graben to the paleo-north of the SOG, which then acted as a conduit for regional paleo-southward fluvial discharge and sediment dispersal (Fig. 6.8a). The Franklin Basin, located ~ 80 km to the paleo-south of the SOG, also became active at this time, and therefore likely represents an extension of the Ottawa graben but on the Laurentian margin (e.g., Landing, 2007; Landing et al., 2009; chapter 5) (Fig. 6.8a). Significantly, ~ 580 – 535 Ma zircons are absent in samples of the Ausable, indicating that Ediacaran to earliest Cambrian alkaline rift intrusions in the Ottawa graben (i.e., the Rigaud, Chatham-Grenville stocks and Callander Complex; Kamo et al., 1995; Malka et al., 2000; McCausland et al., 2007) were not exposed during this Early – Middle Cambrian pan-Ottawa graben episode of rifting and syn-rift fluvial sedimentation.

A major Middle Cambrian climate change resulted in the shut-down of Ausable river systems throughout the SOG, and the initiation of aeolian sedimentation of the Hannawa Falls Formation in the paleo-northwestern SOG (Fig. 6.7c; chapter 5). This climate change also coincided with a change in detrital composition from arkose to quartz arenite, presumably due largely to aeolian destruction of feldspar grains during transport of recycled

arkosic sand (chapter 5). The spatial distribution of the Hannawa Falls erg sediments and their paleoflow (i.e., toward the paleo-northwest; Appendix E) suggest that prevailing southeasterly winds eroded and reworked sediment from the Ausable fluvial deposits in the Jericho and Rigaud-Rockland grabens, and redeposited it in the paleo-northwest as the Hannawa Falls. This interpretation is corroborated by the subrounded to rounded detrital zircons in the Hannawa Falls with age distributions similar to those in rocks of the older Ausable Formation (Fig. 6.5, Table 6.1).

6.5.2 Allounit 2

Following a significant late Middle Cambrian depositional hiatus, quartz sand and rare quartzite boulders were dispersed across the SOG and marked the initiation of latest Middle to Late Cambrian sedimentation of allounit 2 (i.e., lower Keeseville Formation, chapter 5). The thickest accumulations of quartz arenite (~65 – 180 m) occur in the paleo-southern and paleo-eastern parts of the SOG, roughly overlying parts of the pre-existing Jericho and Rigaud-Rockland grabens. Along the paleo-southwest margin of the SOG, thick (up to 180 m) quartz sands accumulated in upper intertidal to supratidal coastal flats fed locally by braided and ephemeral fluvial systems (Hagadorn and Belt, 2008; chapters 4 and 5). Meanwhile, in the paleo-eastern part of the SOG, Late Cambrian eustatic rise had drowned continental environments by the earliest Ordovician and replaced it with subtidal sedimentation (chapter 5). In contrast, continental conditions prevailed in the paleo-northwest SOG, and deposited a thin (≤ 22 m) succession of quartzose fluvial strata over a wide area ($\sim 8000 \text{ km}^2$).

Differences in stratal distribution, paleoflow directions and detrital zircon populations of allounit 2 strata suggest major changes in the pattern of accommodation and sediment dispersal following deposition of allounit 1 and development of the allounit 1 – 2 unconformity, with new sediment sources and sinks emerging (Figs. 6.5, 6.7d). The prominence of young zircons with modes of 1018 – 1057 Ma, plus locally significant contributions from the ~ 1176 Ma component and minor contributions from the ~ 1442 Ma component, suggest the influx of sediment derived from the ~ 1050 – 1030 Ma Lyon Mountain Granite and eroded Allounit 1 strata in the Adirondack Dome plus ongoing contributions from 1200 – 1160 Ma Adirondack Lowland and Frontenac terrane sources. Minor ~ 1342 Ma components were likely derived from rare distant sources, ~160 – 170 km to the paleo-west (i.e., Mount Royal tonalites and granites; McLelland et al., 2004). Thus the main source area was along the southwestern margin of the SOG where newly-unroofed Lyon Mountain Granite and strata of allounit 1 in the Jericho graben were eroded, but with minor contributions (~ 1342 Ma) from distant sources in the paleo-west (Figs. 6.6, 6.7d). The main source area in the southwestern SOG, previously a Middle Cambrian topographic low underlain by the Jericho graben, must have been tectonically inverted and uplifted following allounit 1 deposition (Fig. 6.8b). Correspondingly, strata deposited along the paleo-southwest margin of the SOG exhibit a radial fluvial paleodrainage pattern away from this source area, with flow toward the paleo-east, paleo-southeast and paleo-southwest (Fig. 6.7d; Appendix E). Rivers also carried sediment from this source area ~ 40 – 200 km to the paleo-northwest, where ~ 4 – 22 m of fluvial sediment covered an area of ~ 8000 km² in the paleo-northwest SOG, much of which had been the Frontenac horst – i.e., the main source area of ~ 1176 Ma allounit 1. Therefore, this previously elevated source area had apparently subsided following

deposition of allounit 1, providing further evidence of tectonic inversion (Fig. 6.7d). Tectonic inversion was therefore widespread in the paleo-western SOG, with uplift in the paleo-southwest and subsidence in the paleo-northwest (Fig. 6.8b), which may have been coincident with the localized folding and faulting of parts of the Allounit 1 (Hannawa Falls Formation) described by Sanford and Arnott (2010) (their Hannawa Falls Member).

At the same time, the paleo-east SOG was being flooded by the ongoing eustatic rise, suggesting that this area continued to be a topographically low area in the Late Cambrian like it was during deposition of allounit 1 in the late Early and Middle Cambrian. However differences in detrital zircons suggest that this area it was no longer connected to the same distant sources located in the paleo-north. Instead, detrital zircons in a braided fluvial succession along the paleo-eastern margin of the SOG, with flow toward the paleo-west (KV-4, Figs. 6.4, 6.7d), have a similar age assemblage to the rest of allounit 2 strata, with major modes at 1034 and 1186 Ma (Fig 6.5). Nevertheless, an Adirondack source can be ruled out for this interval due to its location and paleoflow. Instead, the zircons were likely sourced from ~ 1054 Ma aplite dykes and related intrusions and 1170 – 1160 Ma granitoids in the CMB of Quebec, ~ 60 km to the paleo-east (Friedman and Martignole, 1995).

6.5.3 Allounit 3

Deposition of allounit 2 was followed by marine regression, depositional hiatus and development of an intra-early Ordovician unconformity in the paleo-northern and paleo-eastern parts of the SOG. However, in the paleo-southwest SOG, quartzose fluvial sedimentation continued, resulting in a correlative conformity between allounits 2 and 3

(chapters 4 and 5). Basal allounit 3 strata in this area consists of ephemeral fluvial strata deposited on a wide (~ 70 – 100 km) alluvial plain (chapter 4) that drained toward the paleo-southwest and south into supra- to intertidal coastal environments at the paleo-southwest edge of the SOG (Fig. 6.7e; Hagadorn and Belt, 2008; chapter 5; Appendix E). Rare aeolian dune strata record coeval windblown sedimentation locally along the paleo-northern margin of coastal ephemeral floodplains (Fig. 6.7e; Hagadorn et al., 2011; chapter 5). Detrital zircons from these fluvial and aeolian strata (KV-5 and KV-6, Fig. 6.5, Table 6.1) indicate the reappearance of the 1176 and 1442 Ma – dominated zircon assemblage observed in fluvial arkose of allounit 1 in the Rigaud-Rockland graben, in addition to younger source components (sample AS-5, Fig. 6.5, Table 6.1). The reappearance of this detrital zircon source signature suggests one of two possible provenance scenarios: (a) exhumation, erosion and recycling of Middle Cambrian Rigaud-Rockland graben allounit 1 Ausable strata from the paleo-east, and/or (b) direct, long-distance sourcing from parts of the Grenville CGB, at least 300 km to the paleo-northeast. In either case this suggests an inversion of the paleo-eastern SOG from a topographically-low depocentre during allounit 2 sedimentation, to a sediment source area and/or a zone of fluvial bypass. Meanwhile, continuous sedimentation in the paleo-southwest suggests that this area was probably subtly inverted from a low-accommodation source area to a subsiding sink for sediment accumulation (Figs. 6.7e, 6.8c). Notwithstanding, the occurrence of zircons comprising younger source components (~1000 – 1100 Ma) suggest some mixing with more local Adirondack sources. Fluvial strata contain a ~ 1104 Ma mode suggesting partial sourcing from the 1103 – 1090 Ma Hawkeye Granite, ~ 150 km to the paleo-north (McLelland et al., 2004), plus an 1195 Ma mode suggestive of a direct sourcing from ~ 1200 – 1160 Ma granitoids in the same area and/or recycling of

allunit 1 or allunit 2 strata to the paleo-northeast (Fig. 6.7e). The aeolian sample, on the other hand, contains modes at ~ 1053 Ma and 1154 Ma, which suggest partial sourcing from the nearby 1050 – 1030 Ma Lyon Mountain Granite (McLelland et al., 2001; Selleck et al., 2004; Valley et al., 2011) and 1160 – 1135 Ma AMGC intrusions, ~10 – 100 km to the paleo-west, consistent with the observed paleo-northeastward direction of dune migration (Fig. 6.7e).

Fluvial sedimentation become more widespread in the SOG following the initial quartzose sedimentation in the southwestern SOG, but ultimately the entire SOG was slowly transgressed from the paleo-southwest to the paleo-northeast during the Tremadocian (chapter 5). By the end of the Tremadocian the SOG was covered almost completely by a shallow epeiric seaway with widespread subtidal to intertidal, mixed siliciclastic and carbonate sedimentation. However, in parts of the paleo-eastern and paleo-northern SOG, supratidal sabkha and coastal aeolian environments persisted on fault-bounded islands and/or peninsulas connected to the margins of the SOG (Fig. 6.7f; chapter 5). Marine transport, most likely related to tidal currents, was generally to the paleo-south or paleo-southwest. Similarly, flow in fluvial and tidal channels in coastal environments was generally to the paleo-south, but with local deviations presumably due to discharge and tidal flow over complex topography (Fig. 6.7f). Detrital zircons collected from coastal and intertidal strata along the paleo-northern margin of SOG (KV-7 and KV-8) include major contributions from the ~ 1074 Ma source component with notably subordinate or minor contributions from the ~ 1176 Ma component, and minor contributions from the ~ 1342 Ma and 1442 Ma components. This suggests sourcing mainly from 1100 – 1060 Ma igneous rocks common along the paleo-northwestern and paleo-northeastern margins of the SOG (e.g., 1095 – 1075

Skootamata suite and 1070 – 1066 Ma intrusions in the paleo-northwest, and 1090 – 1075 Ma Kensington and 1070 – 1060 Ma Guenette suites in the paleo-northeast; Corriveau et al., 1990; Marcantonio et al., 1990; Corriveau and van Breeman, 2000; Davidson and van Breeman, 2000). Sources of the other minor components include the 1170 – 1160 Ma Chevriél suite and 1386 Ma Bondy Gneiss located ~70 km to the paleo-northeast (Wodicka et al., 2004), 1350 – 1250 Ma Royal Mountain tonalites and granodiorites ~ 160 - 170 km to the paleo-west (McLelland et al., 2004), reworking of earlier Potsdam strata and possible contributions from metasedimentary rocks in the CMB (Sager-Kinsman and Parrish, 1993, Table 6.2). In general, therefore, the provenance of these coastal sands was simple, being sourced mainly from areas along the periphery of the basin.

6.6 Early Paleozoic Tectonic Reactivation of the Ottawa Graben

Stratigraphic relationships and U-Pb zircon provenance signatures in strata of the Potsdam Group suggest deposition associated with three Early Paleozoic episodes of tectonic reorganization of the Neoproterozoic Ottawa graben. From oldest to youngest these occurred during: (a) late Early to Middle Cambrian, resulting in the deposition of allounit 1; (b) late Middle to earliest Late Cambrian, coinciding with the unconformity that separates allounits 1 and 2; and (c) earliest Ordovician and coinciding with the unconformity separating allounits 2 and 3 (Fig. 6.7). Each reactivation episode coincided with tectonic reconfiguration of the Ottawa graben due to movements along unique sets of faults oriented nearly parallel or oblique ($\sim 40 - 70^\circ$) to the general trend of the Ottawa Graben (Figs. 6.7, 6.8).

During the late Early to Middle Cambrian, reactivation of the Ottawa graben resulted in the opening of a number of smaller half-grabens located immediately to the paleo-east and oriented obliquely ($\sim 40 - 70^\circ$) to the paleo-eastern margin of the Ottawa graben (i.e., the Franklin, Jericho and Rideau half-grabens; Figs. 6.7, 6.8). At the same time, the Frontenac horst, located paleo-north of the Jericho half-graben and paleo-south of the Rideau half-graben was uplifted and eroded providing arkosic sediment and ca. 1176 Ma zircons to the adjacent subsiding half-grabens (Figs. 6.7a – b, 6.8a). To the paleo-east of these structural features, a more extensive paleo-north to –northeast trending graben, here termed the Rigaud-Rockland graben, extended ~ 350 km to the paleo-north-northwest and formed a rift-generated transport corridor for more regional ~ 1442 Ma sediment sources (Figs. 6.7a – b, 6.8a). Notably the orientation of the Rigaud-Rockland graben and Jericho and Rideau half-grabens subparallel the trend of Neoproterozoic dykes (Fig 6.1), which are the only preserved remnants of the initiation of the Ottawa graben, suggesting that they most likely formed by reactivation of the main bounding faults of the older Ottawa graben.

The late Middle to earliest Late Cambrian reactivation episode coincided with the unconformity that separates allounits 1 and 2 and tectonic inversion of structural features in the paleo-east (Figs. 6.7d, 6.8b). Specifically, the Jericho half-graben was uplifted, while most of the pre-existing Frontenac horst immediately to the paleo-north subsided. This inversion resulted in the introduction of a new sediment source component (the ~ 1054 Ma Lyon Mountain granite) and also local structural deformation of allounit 1 strata (e.g., Sanford and Arnott, 2010). Meanwhile, the Rigaud-Rockland graben remained topographically low (Figs. 6.7d, 6.8b) but no longer provided a corridor for long-distance

sediment transport, suggesting that the feature had become inactive, and thus drainage was diverted elsewhere.

The final reactivation episode during the earliest Ordovician coincided with another tectonic inversion of structural features in the Ottawa graben. This time, unroofing and erosion of parts of the previously topographically depressed Rigaud-Rockland graben occurred, as well as subsidence of previously-uplifted areas in the paleo-east that provided sediment from the Lyon Mountain granite (Figs. 6.7e –f, 6.8c). This topographic inversion resulted in the reappearance of sediment from regional ~1442 Ma sources.

6.7 Tectonic Implications

The episodes of Early Paleozoic tectonic activity outlined above are notable since they occurred in an intraplate setting on the passive margin of Laurentia (Fig. 6.2). As such, the source of lithospheric and/or sub-lithospheric stress(es) and the mechanism for the transmission of those stress(es) cannot to easily identified. However, like modern zones of intraplate activity, such as the New Madrid and West Quebec seismic zones, the Early Paleozoic Ottawa graben probably persisted as a zone of weakness following its initiation by Late Neoproterozoic rifting and in which pre-existing faults were episodically reactivated (Zoback and Zoback, 1981; Braile, 1982; Zoback, 1992; Mazzotti and Townend, 2010). Evidence provided here suggests at least three discrete episodes of reorganization of the Ottawa graben and significant plate margin or intracratonic tectonic activity. Possible drivers include (a) the passage of a sub-lithospheric hotspot, (b) protracted intracratonic extension

akin to the modern East African rift, and (c) the propagation of far-field stresses from Peri-Laurentian plate-margin tectonics.

The presence of a sub-lithospheric hotspot has been hypothesized for the Late Neoproterozoic (~600 Ma) initiation of the Ottawa graben (e.g. Burke and Dewey, 1973; Dewey and Burke, 1974; Kumarapeli, 1985, 1993), and may have persisted into the Earliest Cambrian (~535 – 530 Ma) during the second rift phase in Southern Laurentia and the emplacement of syenetic stocks (Mont Rigaud, Chatham-Grenville; Malka et al., 2000; McCausland et al., 2007). However, a hotspot is unlikely for any of the Early Paleozoic reorganization episodes coeval with Potsdam sedimentation, given the absence of coeval igneous rocks. Intracratonic extension, on the other hand, likely contributed to the late Early to Middle Cambrian episode of reorganization (Fig. 6.8a). This inference is based on the stratigraphic correlations of Sanford and Arnott (2010) (and chapter 5) who suggest that Early to Middle Cambrian reactivation of Proterozoic rifts and syn-rift sedimentation may have occurred throughout southern Laurentia, including in the Rome Trough, Rough Creek and Mississippi Valley grabens and the East Continent and Midcontinent rifts (Thomas, 1991; Drahovzal, 1997; Malone et al., in press). Therefore it is likely that a late Early to Middle Cambrian phase of regional extension affected all of Southern Laurentia, which then resulted in widespread reactivation of Neoproterozoic structures. By analogy with modern and ancient intraplate rifts (e.g., Burke, 1977; Leeder, 1995; Sengor, 1995; Gawthorpe and Leeder, 2000), the primary extensional stress field was likely oriented normal to the Laurentian margin and therefore consistent with the generally margin-parallel orientation of many of the Proterozoic rifts throughout southern Laurentia and the newly-activated faults in the Ottawa graben (i.e. those bounding the Rideau, Jericho and Franklin half-grabens).

However, Neoproterozoic faults bounding the Rigaud-Rockland graben were oriented normal (i.e., $\sim 90^\circ$) to the Laurentian margin and thus unfavourably oriented to the regional stress field. Nevertheless, as pointed out by Henry et al. (2000), Mazotti and Townend (2010) and Ma and Audet (2015), pre-existing faults can be reactivated even where they are not favorably oriented to the prevailing stress field.

Following the Middle Cambrian, evidence of regional extension of the Laurentian margin is lacking, suggesting that later episodes of tectonic reorganization in the Ottawa graben were related to other processes. Of note then is the initiation of peri-Laurentian accretional plate tectonic activity during the early Late Cambrian ($\sim 495 - 490$ Ma) and related to the paleo-northward obduction of Iapetan oceanic crust over peri-Laurentian terranes across the Humber seaway, $\sim 300 - 1000$ km paleo-south of the Laurentian margin (Waldron and van Staal, 2001; Gerbi et al., 2006; van Staal et al., 2007). This event coincided with the timing of the Middle to early Late Cambrian reorganization event in the Ottawa graben (Fig. 6.8b), suggesting that the two may in fact be related. Similarly, the Saguenay graben, a Neoproterozoic margin-normal rift located ~ 400 km to the paleo-northeast (Fig. 6.2), was also reactivated and inverted, resulting in the erosion of a significant volume of earlier Paleozoic and Proterozoic strata (Lavoie, 1997, 1998, 2008; Lavoie et al., 2003). The final reorganization of the Ottawa graben during the earliest Ordovician (Fig. 6.8c) was also coeval with a major peri-Laurentian event, specifically the initiation of the paleo-southward subduction of the Humber seaway beneath peri-Laurentian terranes (Waldron and van Staal, 2001; Gerbi et al., 2006; van Staal et al., 2007). At the same time, the Southern Oklahoma Fault System, yet another margin-normal Neoproterozoic rift located

~1800 km to the paleo-west, experienced tectonic reactivation (Johnson et al., 1988; Salad Hersi and Dix, 2006).

On the basis of the overlap in timing of peri-Laurentian plate-margin events and the reactivation episodes of the Ottawa graben and other margin-normal Neoproterozoic rifts, it is proposed that compressive stresses were propagated across the ~300 – 1000 km Humber seaway during plate-margin events in the early Late Cambrian and earliest Ordovician. These stresses preferentially affected margin-normal Neoproterozoic rifts in Laurentia, but apparently did not affect other parts of the Laurentian margin (Waldron and van Staal, 2001) or reactivate other Neoproterozoic rifts. Unknown however is the mechanism by which peri-Laurentian plate-margin stresses were propagated to the Ottawa graben and other margin-normal grabens. Although far-field compressional stresses can propagate long distances through continental crust (up to 1500 km; Giles et al., 2002), the postulated ~300 – 1000 km of oceanic crust separating the peri-Laurentian terranes from the Ottawa graben was likely too weak to propagate stress over such a distance. With limited alternatives, two possible mechanisms are examined: (a) peri-Laurentian plate-margin stresses resulted in changes in the prevailing regional intraplate stress field, or (b) stress from peri-Laurentian tectonic events were propagated along oceanic fracture zones and into margin-normal Neoproterozoic rifts. It is likely that peri-Laurentian plate-margin events caused significant changes in the orientation and/or magnitude of the prevailing intraplate stress, and thus reactivation of different sets of pre-existing faults in the Ottawa graben and other weakened margin-normal Neoproterozoic rifts (e.g. Zoback and Zoback, 1981; Zoback, 1992; Mazzotti and Townend, 2010; Hurd and Zoback, 2012; Ma and Audet, 2015). However, it is unknown if intraplate stresses alone could have been of sufficient magnitude to cause the profound tectonic

reorganizations that took place during the Late Cambrian and Early Ordovician. Although seismically active, fault offsets in reactivated zones like the New Madrid seismic zone have been minor since the Cretaceous (Hamilton and Zoback, 1982; Grollimund and Zoback, 2001), suggesting that significant reorganization of the Ottawa graben in just $\sim 2 - 5$ Myr during the Early Paleozoic by intraplate stresses is problematic. Nevertheless, modern eastern North America is tectonically quiescent, with the nearest active plate margin ~ 3500 km from the modern Ottawa graben. By contrast, the active spreading ridge of the Humber Seaway was located as little as ~ 200 km from the Ottawa graben, and after the early Late Cambrian the peri-Laurentian convergent margin was as near as ~ 400 km (van Staal et al., 2007). Therefore, by contrast to modern North America, the intraplate stresses were much stronger and more dynamic, thus plausibly accounting for the observed reactivation events. However, reactivation by this mechanism cannot explain why only margin-normal Neoproterozoic rifts, like the Ottawa graben, were reactivated during the Late Cambrian and Early Ordovician, with no documented evidence of coeval reactivation of other Neoproterozoic rifts.

Finally, we consider the possibility that oceanic transform zones connected to the active spreading ridge of the Humber Seaway acted as conduits for tectonic stress. This is based on the observations of earlier authors (Thomas, 1991, 2006; Allen et al., 2009, 2010) who noted that margin-normal grabens on the Laurentia occurred where hypothetical oceanic fracture zones intersected continental crust (Fig. 6.2). Such a condition would help explain the preferential reactivation of margin-normal rifts during the Late Cambrian and Early Ordovician compared to margin-parallel Neoproterozoic rifts. It could also explain the Early Paleozoic relationship between the Ottawa graben and the proposed Missisquoi fracture zone (MFZ), a remnant Neoproterozoic transform fault which is postulated to have remained an

active paleo-topographic and –bathymetric component of the Laurentian Shelf and slope during the Early Paleozoic (Landing, 2007; Landing et al., 2009; Brink, 2014). The MFZ is believed to have been an extension of the active Missisquoi transform on the Humber seaway spreading ridge, and intersected the Laurentian margin approximately along the southern (paleo-western) margin of the Ottawa graben (Cherichetti et al., 1998; Allen et al., 2010; Burton and Southworth, 2010) (Figs. 6.2, 6.8). At that time the MFZ was a prominent, possibly active, paleo-topographic ridge that exerted control over the isopach of rift clastics and separated shallow shelf environments to the paleo-east from submarine slope facies of the active Franklin Basin to the paleo-west (Cherichetti et al., 1998; Landing, 2007; Landing et al., 2009) (Fig 6.8a). The MFZ also likely formed the paleo-eastern (modern southern) margin of the Jericho Basin, since its trend coincides with the southernmost limit of allounit 1 rift clastics (Figs. 6.7a – b). To accommodate opening of the Jericho and Franklin basins during the late Early Cambrian, the MFZ must have been reactivated with a dextral sense of motion (Fig. 6.8a).

Based on this connection between the MFZ and Ottawa graben during the Early and Middle Cambrian, it is hypothesized here that the MFZ continued to be genetically linked to the Ottawa graben during the latter two episodes of reactivation (early Late Cambrian and earliest Ordovician). Specifically, we posit that peri-Laurentian tectonic stress was focussed and propagated along the MFZ, resulting in transtensional/transpressional reactivation of faults in the Ottawa graben (e.g., Benkhelil, 1989; Umhoefer et al., 2007). Although oceanic fracture zones are typically tectonically inactive (Bergman and Solomon, 1992), evidence from the modern Indian Ocean (Bull, 1990) and Tasman Sea (Robinson, 2011) suggest that strong and spatially dynamic intraplate stresses can be reactivated by oceanic fracture zones.

As noted above, similarly strong and dynamic intraplate stresses were very likely present in the crust that underlay the post-Late Cambrian Humber seaway (e.g., van Staal et al., 2007), and thus transmission of plate tectonic stress along the MFZ and other fracture zones was also likely. Once propagated into the Ottawa graben, stress was relieved by reactivating pre-existing faults. A plausible configuration for the Ottawa graben is analogous to that described by Umhoefer et al. (2007) who described “strike-slip fault termination basins” from the Gulf of California and elsewhere (e.g., Aegean Sea basins, eastern Death Valley basins and the Fundy Basin). Strike-slip fault termination basins are complex, composite strike-slip features at the terminations of large strike slip faults and where remnant strike-slip stress are relieved by forming new or reactivating pre-existing faults. Furthermore, many stratigraphic characteristics of the Early Paleozoic Ottawa graben are consistent with such a terminal strike-slip basin setting, including the occurrence of thick, areally-restricted stratal units, localized unconformities, structural deformation of basin strata, a history of repeated reactivation and inversion of grabens and horsts, and complex patterns of uplift with rifting oriented oblique or normal to an associated major strike-slip fault (Crowell 1974a,b; Benkhelil, 1989; Nilson and Sylvester, 1995; Umhoefer et al., 2007). Like the Ottawa graben, the Saguenay graben may also have occurred at the termination of a hypothetical oceanic fracture zone (the Saguenay-Montmorency fracture zone (SMFZ), Allen et al., 2010) and may also represent a strike-slip fault termination basin.

On the basis of this model, the location of the Ottawa graben immediately to the paleo-east of the MFZ suggests right lateral displacement of faults off the MFZ (Fig. 6.8) similar to the grabens and horsts in the North Anatolian transtensional fault termination basins system (Koukouvelas and Ayden, 2002; Umhoefer et al., 2007). Right-lateral

displacement, caused by sinistral movement on the MFZ, would result in transpression and uplift with peripheral flexural subsidence, whereas dextral movement on the MFZ would result in transtension and mainly subsidence along the margin of the MFZ, with erosion and unroofing of areas farther to the paleo-east and north (Crowell 1974a, b). Therefore, the early Late Cambrian reorganization event, which was characterized by uplift of the Jericho half-graben bordered to the paleo-north by subsidence of the Frontenac horst, was most probably driven by sinistral reactivation of the MFZ. In contrast, the later earliest Ordovician event, being characterized by subsidence along the MFZ and peripheral unroofing and erosion of the paleo-eastern Ottawa graben (i.e., the earlier Rigaud-Rockland graben), suggests dextral reactivation of the MFZ (Fig. 6.8c).

6.8 Conclusions

It has been understood for some time that intra-plate tectonism related to reactivation of the Neoproterozoic Ottawa graben strongly influenced Potsdam Group sedimentation (e.g., Lewis, 1971; Salad Hersi and Dix, 2006). Here, U-Pb geochronology has been integrated with the allostratigraphic framework and paleoflow data to identify three episodes of sedimentation driven by tectonic reorganization of the Ottawa graben.

The earliest episode of reorganization was coeval with late Early to Middle Cambrian deposition of allounit 1. At this time a number of half-grabens opened along the paleo-western (modern southern) margin of the Ottawa graben, bound to the paleo—west (modern south) by the hypothesized Neoproterozoic Missisquoi fracture zone (MFZ), including the Rideau, Jericho and Franklin half-grabens. The former two were filled by arkose sourced

directly from nearby ~1176 Ma granitoids in the Frontenac terrane, which were rapidly exhumed by the uplift of the Frontenac horst directly paleo-north of the Jericho and paleo-south of the Rideau half-graben. Meanwhile another more extensive graben just to the paleo-east of the half-grabens, here termed the Rigaud-Rockland graben, was also opened, thus providing a fault-bounded, strike-slip generated conduit for both local horst-derived sediment with ~1176 Ma sources and sediment from ~1442 Ma sources from ~350 km to the paleo-northeast. This episode of reactivation of Neoproterozoic faults may have been linked to a late Early to Middle Cambrian period of lithospheric extension across southern Laurentia, based on correlation of allounit 1 rift clastics to similar syn-rift units throughout eastern North America and a lack of other plausible mechanisms including nearby plate-margin tectonic activity or the presence of a mantle hotspot. The hypothetical MFZ was the paleo-west (modern south) limit of rifting of the half-grabens, which suggest that it had to have experienced dextral reactivation in order to accommodate opening of the rifts.

The next episode of tectonic reorganization occurred during the late Middle to early Late Cambrian, following allounit 1 sedimentation and either preceding or coeval with the initiation of allounit 2 sedimentation. This episode resulted in inversion of pre-existing features, specifically the uplift of much of the Jericho half-graben with coincident subsidence of the Frontenac horst located immediately paleo-north. Uplift of the Jericho graben caused reworking of allounit 1 strata and the introduction of sediment sourced from the ~1050 – 1030 Ma Lyon Mountain granite. Meanwhile, subsidence of the Frontenac horst resulted in local structural deformation of allounit 1 strata followed by the paleo-northwest paleoflow of fluvial systems carrying Lyon Mountain and reworked allounit 1 sediment. This episode of reactivation is coeval with the initiation of compressional plate margin stresses in peri-

Laurentian terranes, located ~300 – 1000 km to the paleo-south, and also with reactivation of the margin-normal Saguenay graben. It is suggested that abrupt changes to the intraplate stress field were compensated by reactivation of Humber seaway fracture zones. These, then, resulted in the reactivation of the margin-normal Ottawa and Saguenay grabens, both located at the terminus of Humber seaway fracture zones, in a manner analogous to modern “strike-slip termination basins” in the Gulf of California and elsewhere.

The final episode of reorganization described here occurred during the earliest Ordovician, during the hiatus that separates allounit 2 and 3 strata across much of the basin. This episode resulted in a second period of inversion, this time with renewed subsidence of the Jericho half-graben and peripheral exhumation and erosion of parts of the paleo-eastern Ottawa graben, specifically the former Rigaud-Rockland graben. The result of this reorganization was the re-appearance of ~1442 Ma sources in allounit 3 strata from direct sourcing from distant (~350 km) Grenville sources to the paleo-northeast and/or from further reworking of allounit 1 strata from the peripherally-exhumed parts of the basin. Furthermore, the peripherally-exhumed Rigaud-Rockland graben remained a topographically-positive feature where terrestrial and coastal environments persisted during the final phase of the Sauk transgression in the Ottawa graben. The timing of this reorganization event coincided with the timing of the initiation of paleo-south directed subduction of the Humber seaway beneath the peri-Laurentian terranes, and also reactivation of the margin-normal Southern Oklahoma fault zone. Like the preceding episode, the peri-Laurentian events likely altered intra-plate stresses, resulting in the strike-slip reactivation of oceanic fracture zone and margin-normal fault-bounded basins, including the Ottawa graben.

Thesis conclusions, contributions and areas for future research

7.1 Conclusions

Six lithofacies are identified in the Potsdam Group, which are then further subdivided into unique subfacies that record specific depositional processes:

Facies 1 consists of medium- to coarse-grained cross-stratified sandstone recording the formation and migration of a number of different bedforms under unique flow conditions, including: current ripples, depth-limited wave ripples, subaqueous dunes, unit bars, antidunes, chutes-and-pools, cyclic steps, wave/storm-formed hummocks and swales, and aeolian grain flow strata.

Facies 2 is made up of medium- to coarse-grained planar stratified sandstone formed by upper plane bed in critical subaqueous flows, migration of wind ripples, adhesion processes and aeolian deflation;

Facies 3 consists of graded sandstone including thin (≤ 7 cm) fine-grained layers formed by suspension deposition in decelerating flows, and also thick (up to 23 cm) poorly-sorted, coarse-grained layers recording rapid deposition from highly concentrated, high energy flows;

Facies 4 consists of conglomerate, including imbricated pebble to cobble orthoconglomerate deposited as bedload sheets at the base of high-energy subaqueous flows, and massive, poorly-sorted cobble to boulder conglomerate deposited as slope talus;

Facies 5 comprises rare fine-grained siliciclastics, including muddy siltstone deposited by hemipelagic settling and/or flocculation and “gelling” and movement of fluid muds, and current- and wave-ripple cross-stratified siltstone;

Facies 6 consists of rare, diffusely-stratified and sparsely-bioturbated peritidal dolomicrite with associated features such as crenulated laminae, shrinkage and injection fabrics, and rare burrows.

At the next highest level of stratal observation six lithofacies associations are identified that represent the ancient depositional environments of Potsdam strata. These are:

Facies association 1 (FA1), braided fluvial: Made up of poorly- to moderately-sorted, coarse-grained, dune cross-stratified sandstone with subordinate unit bar cross-stratified sandstone and tractional conglomerate, and rare planar stratified sandstone, silty mudstone and gravel-rich slope talus conglomerate, recording deposition of coarse bedload in high-energy braided rivers and minor overbank sedimentation.

Facies association 2 (FA2), ephemeral fluvial: Consisting of medium-grained aeolian and shallow water planar-stratified sandstone lithofacies recording deposition of terminal splays subject to aeolian reworking. These are locally incised by coarse-grained supercritical bedform strata recording high energy sheetflood conditions.

Facies association 3 (FA3), aeolian: Consists predominantly of medium-grained, large-scale trough cross-stratified sets made up mostly of aeolian grain-flow strata interpreted to record the sedimentation by the migration of aeolian dunes. These sets are interbedded with lesser aeolian and shallow water planar stratified sandstone recording interdune sedimentation.

Facies association 4 (FA4), coastal sabkha: Made up mostly of medium-grained, aeolian and shallow water sandstone lithofacies recording alternating wet and dry conditions. Evaporite

minerals, pseudomorphs or their eroded remnants and contorted intraclasts suggesting early cementation and/or binding indicate the presence of evaporites and microbial mats.

Facies association 5 (FA5), tide-dominated marine: Dominated by moderately- to well-sorted, bioturbated, medium- to coarse-grained compound dune cross-stratified sandstone recording sedimentation by the migration of tidal compound dunes. These are interbedded with lesser fine- to medium-grained, planar and ripple cross-stratified sandstone beds and rare dolomicrite beds recording low energy subtidal interdune sedimentation.

Facies association 6 (FA6), open-coast tidal flat: consists mostly of sparsely bioturbated tidal flat siltstone and mudstone intercalated with lesser fine-grained upper plane bed and hummocky-cross stratified sandstone deposited by coastal storm currents, as well as rare coarse-grained normally-graded sandstone deposited at the mouths of braided rivers and rare peritidal carbonate formed in quiet lagoonal sub-environments.

Chapter 4 provides an expanded investigation of the composition and architecture of braided (FA1) and ephemeral (FA2) fluvial strata. The expanded analysis shows that both fluvial facies associations consist of stacked dm- to m-scale stratal units that record recurring autogenic cycles of channel belt buildup, the attainment of critical threshold conditions and finally, avulsion and abandonment.

In braided fluvial systems (FA1), channel belt buildup was manifest by the aggradation of downstream-accreting compound braid bars made up of accreted dunes, unit bars and rare conglomerate. Rare confluence scours also formed at the tail of some compound bars. Aggradation resulted in an increase in downstream slope and thus stream

power, ultimately resulting in the incision of dm-deep erosional braided channels into the tops of channel belts when critical threshold conditions were exceeded. Channels were later filled by vertically-aggraded dune cross-strata during progressive channel belt avulsion and capped by thin (≤ 7 cm) floodplain (overbank) deposits following abandonment.

Low-relief ($\leq 5^\circ$) compound bar deposits and channel elements characterize the thickest ($\sim 50 - 550$ m) and most areally extensive ($\sim 15,000$ km²) accumulations of braided fluvial strata where fluvial sedimentation presumably occurred over wide ($\sim 60 - 120$ km) floodplains generally unconstrained by basement topography. These strata are similar to those described as “sheet-braided” by Cotter (1978) and others (Fuller 1985, Davies et al. 2011) to describe braided fluvial strata deposited before the evolution of floodplain-stabilizing rooted vegetation and with a paucity of cohesive fine-grained floodplain sediment. Owing to their easily-eroded channel margins, channels accommodated increases in discharge by lateral expansion with negligible change in channel depth, resulting in the deposition of low-relief downstream-accreting compound braid bars in potentially very wide ($\sim 200 - 1500$ m) and shallow (≤ 1.5 m) channels. However, in areas where lateral channel belt expansion was limited by local basement topography, channels tended to be deeper ($\sim 2 - 5$ m) and compound bars steeper (up to 35°) and also locally migrated laterally rather than solely downstream, thus showing similarities with their post-Silurian and modern counterparts wherein channels are naturally “fixed” by cohesive floodplain sediment and rooted vegetation.

Ephemeral fluvial systems (FA2) were characterized by the incremental buildup of terminal splays during rare episodic sheet floods, which were largely reworked into local windblown sheets during the long recurrence interval between floods. The accumulated

splays formed a distributive channel belt (i.e., fan) hypothetically fed by an upstream trunk channel. Eventually, the accumulation of deflated and reworked splays in one area resulted in the attainment critical threshold conditions during floods, and thus the incision of scour-filling, high-energy supercritical bedform strata and/or distributary channels. Finally, an upstream avulsion diverted subsequent floods to a new, topographically lower position on the alluvial plain. Once abandoned, distributive channel belts remained dry and were subjected to windblown deflation and armoring.

Unlike braided fluvial strata, variations in basement topography did not affect flow depths or the relief of macroforms in ephemeral fluvial systems. Nevertheless, splays preferentially accumulated in topographic lows and high energy (supercritical) sheet flows and/or distributary channels preferentially incised splay deposits along the relatively steep margins of basement highs. Moreover, the sheet-like architecture of ephemeral fluvial strata and unconfined deposition from terminal splays documented from Potsdam strata is also common to many documented post-Silurian and modern examples (i.e., after the evolution of land plants). However, the Potsdam example and other pre-Devonian examples (e.g., Clemmensen and Dam 1993) are characterized by more extensive aeolian reworking of splays compared to their post-Silurian or modern counterparts, likely relating to greater rates of direct infiltration of overland flow and a lack of sheltering from wind in the absence of land plants and associated fine-grained sediment. Furthermore, supercritical bedform strata are present in Potsdam ephemeral fluvial strata, but have not been recognized in most other documented ephemeral fluvial strata or fluvial strata in general.

The presence of interstratified braided fluvial and ephemeral fluvial units in the upper Potsdam records one and a half climate cycles in the Late Cambrian and Earliest Ordovician.

These repetitive fluctuations are correlated to climate cycles in the Late Cambrian, with semi-arid conditions and related ephemeral fluvial systems correlated to documented global cool periods at ca. 491 and 487 Ma. The contacts separating ephemeral and braided fluvial deposits (and vice versa) suggest that low frequency global climate fluctuations can be expressed as sharp, conformable changes in the fluvial style in the fluvial rock record, and therein provide a readily identified surface for relative and absolute chronostratigraphic correlation within the pre-Devonian continental rock record.

Chapter 5 places the facies associations discussed in the previous chapters into a lithostratigraphic and allostratigraphic framework. From the base to the top of the Potsdam Group (modified from Landing et al., 2009; Sanford and Arnott, 2010) is summarized as follows:

The late Early to Middle Cambrian Ausable Formation consisting of braided fluvial arkose (FA1) with a highly uneven, fault-bounded isopach that ranges from ~0.5 – 450 m. Near the base of the Ausable Formation, but limited to the eastern part of the study area, is an ~20 – 80 m thick north- and eastward-pinching of tongue of open coast tidal flat (FA6) strata here named the Altona Member.

The Middle Cambrian Hannawa Falls Formation is a ~ 2 – 25 m thick, generally red quartz arenite of aeolian (FA3) origin that conformably overlies the Ausable formation in the western part of the study area.

The Ausable and Hannawa Falls formations are unconformably overlain by the generally white quartz arenitic, latest Middle Cambrian to Early Ordovician strata of the Keeseville Formation. The Keeseville Formation is ~8 m to 180 m thick and consists of a diverse assemblage of lithofacies associations including braided fluvial (FA1), ephemeral

fluvial (FA2), aeolian erg (FA3), sabkha (FA4) and high-energy inter- to subtidal marine (FA5) strata. Except in the southeastern part of the study area, an unconformity divides the Keeseville into an upper and lower part. In the northern part of the study area, an earliest Ordovician marine unit that locally caps the lower Keeseville unit, named The Riviere Aux Outardes Member. The Keeseville Formation is in places conformably or unconformably overlain by the dolomite-cemented quartz sandstone of the Theresa Formation.

In addition to these proposed lithostratigraphic revisions, the Potsdam Group is also subdivided into three allounits that record three distinct episodes of regional sedimentation, which then is used for correlation with other stratal units in eastern North America. Allounit 1 comprises the Ausable and Hannawa Falls Formations. Therefore, the initiation of allounit 1 sedimentation records the onset of Early Cambrian rifting and deposition of mineralogically immature (arkosic) braided fluvial strata of the Ausable Formation in fault-bounded sub-basins of the Ottawa graben. In the eastern (paleo-southern) part of the Ottawa graben, however, fluvial sedimentation was temporarily interrupted by transgression and deposition of the marine (tidal flat) Altona Member. Significantly, this episode of syn-rift sedimentation in the Ottawa Graben coincided with rifting and syn-rift sedimentation reported elsewhere throughout southern Laurentia. Later in the Middle Cambrian, a major climate change from humid to arid conditions resulted in the cessation of fluvial sedimentation and the formation of an aeolian erg (Hannawa Falls Formation) that accumulated mainly in the paleo-central/western Ottawa Graben under prevailing southeasterly winds. These wind-blown sediments marked a shift in the detrital composition from arkose to quartz arenite, most probably due to a combination of sedimentary recycling and mechanical attrition of feldspars by wind-blown transport. Coeval shelf sedimentation

was carbonate-dominated (e.g., the Winooski, March Point formations) and slope sediments consisted mainly of thin intervals of slowly accumulated black mudstone, calcitubidites and local glauconitic sandstone (i.e., the Orignal/St. Roch, Lauzon and Hatch Hill formations), consistent with the climate-driven shutdown of fluvial sediment delivery systems to the Laurentian margin.

Hannawa Falls sedimentation was followed in the latest Middle Cambrian to earliest Late Cambrian by the development of a subaerial unconformity, marking the end of Allounit 1 sedimentation. At the same time, or soon after, local structural deformation affected Allounit 1 strata in parts of the Ottawa graben, particularly in the vicinity of the Frontenac Arch, suggesting focused tectonic reactivation and transpression. Coincident with this period of subaerial exposure and tectonic deformation in the Ottawa graben was reactivation of the related Saguenay graben and non-eustatic regression across all parts of southern Laurentia.

Allounit 2 consists of the uppermost Middle Cambrian to lowermost Ordovician basal part of the Keeseville Formation, and records Upper Cambrian quartzose fluvial sedimentation, and eustatic transgression of the paleo-eastern (modern northern) Ottawa graben (Riviere Aux Outardes Member). In the earliest Ordovician, transgression was followed by regression and subaerial erosion across most of the Ottawa graben. Both the transgression and regression recorded by Allounit 2 strata are well-represented in coeval strata deposited on the Laurentian shelf; all of which record an upward-decrease in siliciclastic sedimentation caused by a Late Cambrian eustatic rise followed by a regressive Cambrian – Ordovician stage boundary unconformity (e.g. the “Potsdam”-Galway-Little Falls formations in central New York, Danby-Little Falls formations in Vermont and Strites Pond-Wallace Creek formations in Quebec).

Allouit 3 consists of the upper Keeseville Formation, which records a protracted and diachronous northwestward (paleo-northeastward) eustatic transgression across the southern Ottawa graben that eventually culminated in widespread mixed carbonate-siliciclastic, shallow marine sedimentation (Theresa Formation). This early Ordovician transgression occurred rapidly over most of Southern Laurentia, resulting in the widespread development of epeiric seas and carbonate sedimentation in adjacent parts of the Laurentian margin and the cratonic interior (i.e., the Oneota, Tribes Hill and Wallace Creek formations). However, in the Ottawa graben the persistence of fault-bounded topographic highs which formed localized islands and/or coastal salients stalled sea level rise and resulted in the development of a localized unconformity separating the Keeseville and Theresa formations. The occurrence of soft-sediment deformation features correlated over a large area ($\sim 70 \text{ km}^2$) near Ottawa suggests that the faults bounding these paleo-topographic highs may have been episodically reactivated.

In chapter 6, evidence suggesting tectonic reactivation of Neoproterozoic faults in the Ottawa graben during Cambrian to Early Ordovician Potsdam sedimentation (chapter 5; Lewis, 1971; Salad Hersi and Dix, 2006; Sanford and Arnott, 2010) is further investigated using U-Pb geochronology of detrital zircons and paleoflow. Detrital zircon geochronology of the Potsdam show it consists of sediment derived from various parts of the Grenville Province, with recurring age major probability peaks at $\sim 1176 \text{ Ma}$, $\sim 1095 \text{ Ma}$, $\sim 1442 \text{ Ma}$, $\sim 1074 \text{ Ma}$, $\sim 1054 \text{ Ma}$, $\sim 1342 \text{ Ma}$ and $\sim 1259 \text{ Ma}$ (in order of decreasing abundance). Most of these peaks record basement sources along the margins or underlying parts of the modern Ottawa Embayment ($\sim 1176 \text{ Ma}$, $\sim 1095 \text{ Ma}$, $\sim 1074 \text{ Ma}$, and $\sim 1054 \text{ Ma}$) while others record more distant sourcing, i.e., $\sim 100 - 350 \text{ km}$ from the margins of the Ottawa Embayment

(~1442 Ma, ~1342 Ma and ~1259 Ma). The variations in the presence and relative distribution of zircon age peaks throughout the Potsdam sedimentary pile, along with the existing stratigraphic framework and paleoflow, elucidate the configurations and reactivation of the Ottawa graben during Potsdam sedimentation. Three episodes of tectonic reorganization are recognized here: (a) late Early to Middle Cambrian, during deposition of Allounit 1; (b) late Middle to earliest Late Cambrian, coinciding with the unconformity that separates Allounits 1 and 2; and (c) earliest Ordovician and coinciding with the unconformity separating Allounits 2 and 3.

During the earliest episode (late Early to Middle Cambrian) reactivation of Neoproterozoic faults resulted in opening of a number of half-grabens, specifically the Franklin, Jericho and Rideau half-grabens. At the same time the Frontenac horst, an intervening basement high located between the Jericho and Rideau half-grabens, was uplifted and eroded providing local arkosic sediment and ~1176 Ma zircons to the adjacent subsiding half-grabens. To the paleo-east of these structural features, a more extensive paleo-north to – northeast trending graben, here termed the Rigaud-Rockland graben, extended ~350 km to the paleo-north-northwest and formed a rift-generated transport corridor for the supply of more regional ~1442 Ma sediment sources.

The second reorganization episode (late Middle to earliest Late Cambrian) coincided with the unconformity that separates allounits 1 and 2, and tectonic inversion of the Jericho and Rideau half-grabens and the Frontenac horst. This inversion resulted in the introduction of a new sediment source component (the ~1054 Ma Lyon Mountain granite) and also local extensional structural deformation of allounit 1 strata (e.g., Sanford and Arnott, 2010). Meanwhile, the Rigaud-Rockland graben remained topographically low but no longer

provided a corridor for long-distance sediment transport, suggesting that the feature had become inactive, with drainage diverted elsewhere.

The final reactivation episode occurred during the earliest Ordovician and coincided with another tectonic inversion of structural features in the Ottawa graben, specifically unroofing and erosion of parts of the previously topographically depressed Rigaud-Rockland graben and subsidence of previously-uplifted areas in the paleo-southeast. This topographic inversion resulted in the reappearance of sediment from regional ~1442 Ma sources that spread to the paleo-southeast.

The episodes of Early Paleozoic tectonic activity outlined above are notable since they occurred in an intraplate setting on the passive margin of Laurentia. As such, the source of lithospheric and/or sub-lithospheric stress(es) and the mechanism for the transmission of those stress(es) cannot be easily identified. The first episode of reactivation (late Early to Middle Cambrian) was roughly coeval with proposed rifting and syn-rift sedimentation documented elsewhere in eastern North America, suggesting that reactivation was the result of a regional late Early to Middle Cambrian period of lithospheric extension that affected much of paleo-southern Laurentia. The second and third periods of reactivation, in the late Middle to earliest Late Cambrian and earliest Ordovician, respectively, coincide with the timing of peri-Laurentian accretional tectonic events, ~300 – 1000 km to the paleo-south of the Ottawa graben. It is here suggested that dramatic changes in the intraplate stress field due to peri-Laurentian events triggered the reactivation of the hypothetical Mississquoi fracture zone, which was spatially connected to the Ottawa graben. The Ottawa graben and perhaps other margin-normal grabens (Saguenay, Ouachita) likely behaved like strike-slip

termination basins, in which remnant strike-slip stress in the adjoining fracture zone was dissipated by reactivating pre-existing faults in the margin-normal grabens.

7.2 Contributions

This thesis contributes new knowledge and ideas having both academic significance and broader economic and/or societal appeal. The academic contributions are evident from the conclusions above, and are also highlighted below. From a broader economic and societal perspective, this project provides details of the stratal architecture and stratigraphy of an important groundwater and potential future CO₂ reservoir, insight into intraplate tectonics and seismicity, and constraints of the frequency of ancient climate cycles and their effects on fluvial discharge and sedimentation. More specifically, the most significant contributions of this thesis are:

The advancement of understanding the processes governing fluvial sedimentation before the Devonian evolution of land plants. Few such studies exist, and most do not use detailed architectural analysis to unravel geomorphic details of the fluvial environments. This thesis highlights some of the differences and similarities between the fluvial systems in the Potsdam Group and their documented post-Silurian and modern fluvial counterparts. It also highlights how basement topography affected fluvial sedimentation and stratal architecture in the absence of flood-plain stabilizing vegetation.

Rare examples are shown here of supercritical bedform strata, including the only documented examples of cyclic step stratification in the fluvial rock record to date.

Deciphering climate signals from sedimentary successions presents an opportunity to understand modern climate change from the perspective of ancient natural climate cycles. However, deciphering climate signals from the sedimentary rock record is difficult, particularly for the pre-Devonian terrestrial rock record which has no suitable modern analogues and contains no climate proxies beyond sedimentary structures. This thesis provides an example of Early Paleozoic climate change and its manifestation in the fluvial rock record on the basis of detailed facies and architectural analysis and stratigraphic correlation of fluvial strata in the Potsdam Group.

In spite of almost 200 years of study, a lithostratigraphic framework that accounts both for discrepancies across borders and for natural variations in the Potsdam stratal pile in the eastern Ottawa graben has remained elusive. Stratigraphic correlations from outcrop sections and drill core in this thesis and new biostratigraphic analyses by Nowlan (2013) and McCracken (2014) have been used to revise previous frameworks and provide additional details of the lithostratigraphy and age of the Potsdam Group.

Similarly, correlation of Potsdam strata to coeval Laurentian strata in North America is problematic given the uncertainty regarding the age and lithostratigraphy of the Potsdam Group. However, given the central location of the Potsdam Group in the Ottawa graben, situated between craton interior successions to the west and Laurentian shelf and slope successions to the east, the Potsdam is a keystone in the correlation of Early Paleozoic strata across eastern North America. The identification of three allounits recording three distinct episodes of regional sedimentation permits the correlation of Potsdam strata with other successions in eastern North America. Moreover, the regional correlations developed in this

thesis help unravel the tectonic, eustatic and climate forces acting upon the Potsdam and coeval Laurentian successions.

The Neoproterozoic stage of the Ottawa graben is one of a number of ancient structural features that has been and continues to be reactivated by intraplate stresses. Similarly, previously documented stratigraphic evidence suggested that intraplate tectonic reactivation was coincident with Potsdam sedimentation, but details of this activity and its effects on the patterns of sedimentation and accommodation were poorly-constrained. In this thesis, U-Pb detrital zircon geochronology was used to better constrain sediment provenance and thus isolate changes in the pattern of sedimentation and accommodation driven by tectonic reactivation of the Ottawa graben. The results suggest a correlation between tectonic reorganization and major plate tectonic events, including Early – Middle Cambrian extension and late Middle Cambrian to Early Ordovician accretional tectonic events in peri-Laurentian continental fragments, ~300 – 1000 km outboard of the Laurentian margin. Not only does this illuminate the origins of the stratal complexity of the Potsdam Group, it also provides an example of: (a) the use of detrital zircon geochronology in unraveling complex tectonic histories of sedimentary basins, (b) intraplate reactivation of pre-existing structures due to far-field tectonic events, and (c) the geodynamic evolution of the passive Laurentian margin.

7.3 Areas for future research

Many features and facets of the Potsdam Group remain poorly-understood and understudied, and further study of these would undoubtedly advance the existing depositional, stratigraphic, diagenetic and paleontological framework of the Potsdam Group,

as well as contribute to the field of sedimentology and geology in general. Listed below are suggested topics for future research.

There is significant opportunity to further study supercritical bedform strata identified in this thesis, in order to reveal details of the hydro- and morphodynamic evolution of these features. This is particularly important for strata interpreted to have been deposited by cyclic steps, as no other examples of this feature have been reported from the ancient fluvial sedimentary record (existing examples are instead from the deep marine or subglacial environments and thus formed by sediment-gravity flows). The best exposures of these features are at localities 85, 95, 96, 100 and 102 near Alexandria Bay, New York, and 168 near Chateauguay New York.

In chapter 3, an enigmatic monospecific(?) assemblage of robust infaunal trace fossils were described from high-energy subtidal compound dune facies (FA5). These are similar in size, paleoenvironment, age, burrow substrate and in some morphological features to Early Paleozoic ichnospecies of the *Daedalus* ichnogenus, in particular *Daedalus halli* or *Daedalus multiplex* (Seilacher, 2000, 2007). However, much more detailed work is needed to make more meaningful interpretations regarding the trace makers identity, behaviors and occurrence within such a high-energy environment. The best places to study these enigmatic trace fossils are at localities 8 and 9 in Gatineau, Quebec.

The Altona Member is an important stratigraphic unit due to its fossil record, which therein constrains the age of early Potsdam sedimentation in the Ottawa graben. However, it is a generally poorly-exposed unit with features common to at least two marine environments, specifically wave- and storm-dominated shoreface (Brink, 2015) and open-coast tidal flat (this thesis). The difference in interpretation hinges on rare dolostone beds.

Brink (2015) interpreted these as offshore pelagic algal carbonates, originally limestone but later dolomitized, citing their structureless fabric. However, this study identifies cryptic laminae among other primary features such as crinkled laminae and shrinkage and injection fabrics, more suggestive of a peritidal, perhaps evaporitic origin. Also, no evidence was found to suggest that the original composition was limestone, also consistent with a peritidal setting where microbial mediation and possibly hypersalinity would enhance the precipitation of primary dolomite. Nevertheless, the regional nature of this project did not permit the time for a more comprehensive petrographic analysis of these rare dolostone beds, which remains an opportunity for future study. The dolostone beds are exposed at localities 185 and 234, at the Atwood Farm location near Chazy, New York.

Although not the focus of this study, note was taken of epifaunal trace fossils including *Protichnites*, *Diplichnites* and *Climactichnites*. As noted by many previous workers including MacNaughton et al. (2002), Hagadorn and Belt (2008) and Hagadorn et al. (2011), these fauna had a remarkable ability to travel over subaerial surfaces, and thus are candidates for the earliest animals to inhabit terrestrial environments. On the basis of casual observation of these trace fossils, it was notable that *Protichnites*, *Diplichnites* and *Climactichnites* most commonly occur on bedding planes of coastal sabkha strata (e.g., localities 190, 207, 210, 295) and in coastal plain ephemeral fluvial strata, which based on stratigraphic correlation may have been perhaps ~5 – 50 km from a coeval coastline or intertidal zone (e.g., localities 148, 152, 200 – 203). However, comparatively rare but seemingly larger *Protichnites* and *Diplichnites* were also present in aeolian and ephemeral fluvial strata farther removed from any possible nearby coastal environment (likely ~ 50 km or more; e.g. localities 27, 28, 68, 166). This casual observation suggests that perhaps some

organisms, in particular large arthropods, developed the ability to move farther inland than others. However more work is needed in order to correctly identify and systematically catalogue the occurrence, morphology and size of these trace fossils across the study area in order to assess any correlation between depositional environments, estimated proximity to coeval marine environments and trace fossil diversity and abundance.

Structural deformation of Hannawa Falls Formation strata was mentioned in chapters 5 and 6; however systematic structural measurements were not made in this study. Instead, results of the few measurements made by Sanford and Arnott (2010) were cited. Further detailed structural analysis of the deformation fabrics of Hannawa Falls (i.e., upper Allounit 1) strata, therefore, would be beneficial for three reasons. Firstly, it would be beneficial to test the structural interpretation of Sanford and Arnott (2010), which was that this structural deformation was related to extension oriented sub-parallel or oblique to the trend of the Ottawa Embayment. Although this is in accord with the detrital zircon provenance data in Chapter 6, it is still based on relatively few structural measurements. Secondly, it is unclear how well-indurated Hannawa Falls strata was at the time it was deformed, and therefore a detailed examination of structural fabrics, with a focus on identifying soft-sediment structural fabrics such as hydroplastic fractures, slump folds and pinch-and-swell structures, would help assess this question, and ultimately the timing of structural deformation relative to Hannawa Falls sedimentation. Finally, parts of the overlying Keeseville Formation have also undergone localized structural deformation, particularly along the axis of the Frontenac Arch, and therefore future study of Allounit 1 structural deformation needs to determine if there have been later phases of structural deformation that may have affected the Potsdam elsewhere in the Ottawa Embayment.

Soft-sediment deformation features from the Keeseville Formation near Ottawa were briefly described in chapter 5, and interpreted as seismites. However, the description and interpretation of these features in this thesis offers only a brief discussion of these soft-sediment features, and therefore an opportunity exists to further study these features and test the hypothesis presented here.

Sedimentary petrography played a minor but important part in this thesis, and was mainly used to make qualitative granulometric, textural and mineralogical observations pertinent to understanding details of sedimentation, provenance, pedogenesis and early diagenesis; in other words, it was focused on features related to syn- and early post-deposition. Nevertheless, strata of the Potsdam Group clearly have experienced burial diagenesis based on the presence of compaction features such as stylolites, sutured grain contacts and generally negligible intergranular volume. However, the diagenetic history of the Potsdam is only well known locally (e.g., Salad Hersi et al., 2002), and in general the paragenetic sequence and maximum burial depths and thus maximum thickness of overburden is unknown. Also poorly understood is the relative timing and cause of diagenetic iron oxide formation, or whether some parts of the Potsdam underwent numerous cycles of burial diagenesis, as suggested by Salad Hersi et al. (2002). Therefore a possible avenue of future research would be to undertake a regional and systematic paragenetic study of the Potsdam Group in order to gain a better understanding of many of its diagenetic features, including the paleopedological and early diagenetic features illustrated in this thesis. Finally, enigmatic, vertical large-scale cylindrical structures, originally described in the Potsdam Group by Hawley and Hart (1932) and later by Sanford and Arnott (2010), occur in parts of the Potsdam Group, mainly along the Frontenac Arch but also locally along the

northern Adirondacks. Although initially a focus of investigation in this project, these features were superseded by other components of this project. Nevertheless, these features are striking, unique and poorly-understood and present an opportunity for future research. Most likely they are fluidization structures; however unraveling details of the mechanism by which they formed would require extensive study. They are exposed at many localities, but most notably localities 26 – 29, 54, 58, 68, 220 and 264.

References

- Abdullatif, O.M. 1989. Channel-fill and sheet-flood facies sequences in the ephemeral terminal River Gash, Kassala, Sudan. *Sedimentary Geology*, **63**: 171-184.
- Alexander, J., Bridge, J.S., Cheel, R.J., and Leclair, S.F. 2001. Bedforms and associated sedimentary structures formed under supercritical water flows over aggrading sand beds. *Sedimentology*, **48**: 133-152.
- Allen, J.R.L. 1968. Current ripples; their relation to patterns of water and sediment motion. North Holland Publishing Company, Amsterdam.
- Allen, J.R.L. 1979. A model for the interpretation of wave ripple-marks using their wavelength, textural composition, and shape. *Journal of the Geological Society of London*, **136, Part 6**: 673-682.
- Allen, J.R.L. 1982. Sedimentary structures, their character and physical basis; *Developments in Sedimentology*, **30**; I. Elsevier Sci. Publ. Co., Amsterdam, Netherlands.
- Allen, J.R.L., and Leeder, M.R. 1980. Criteria for the instability of upper-stage plane beds. *Sedimentology*, **27**: 209-217.
- Allen, J.S., Thomas, W.A., and Lavoie, D. 2009. Stratigraphy and structure of the Laurentian rifted margin in the Northern Appalachians; a low-angle detachment rift system. *Geology (Boulder)*, **37**: 335-338.
- Allen, J.S., Thomas, W.A., and Lavoie, D. 2010. The Laurentian margin of northeastern North America. *In* *Rodinia to Pangea; the lithotectonic record of the Appalachian region*, Edited by Tolio, R., Bartholelew, M.J., Hibbard, J.P., Karabinos, P.M. *Memoir - Geological Society of America*, **206**: 71-90.
- Allen, J.P., Fielding, C.R., Gibling, M.R., and Rygel, M.C. 2011. Fluvial response to paleo-equatorial climate fluctuations during the late Paleozoic ice age. *Geological Society of America Bulletin*, **123**: 1524-1538.
- Allen, J.P., Fielding, C.R., Rygel, M.C., and Gibling, M.R. 2013. Deconvolving signals of tectonic and climatic controls from continental basins; an example from the late Paleozoic Cumberland Basin, Atlantic Canada. *Journal of Sedimentary Research*, **83**: 847-872.
- Alling, H.L. 1919. Geology of the Lake Clear region (parts of Saint Regis and Saranac quadrangles). *Bulletin - New York State Museum and Science Service*, **207**: 111-145.
- Arnott, R.W., and Southard, J.B. 1990. Exploratory flow-duct experiments on combined-flow bed configurations, and some implications for interpreting storm-event stratification. *Journal of Sedimentary Petrology*, **60**: 211-219.

- Arnott, R.W.C., and Hand, B.M. 1989. Bedforms, primary structures and grain fabric in the presence of suspended sediment rain. *Journal of Sedimentary Petrology*, **59**: 1062-1069.
- Ashley, G.M. 1990. Classification of large-scale subaqueous bedforms; a new look at an old problem. *Journal of Sedimentary Petrology*, **60**: 160-172.
- Ashmore, P., and Parker, G. 1983. Confluence Scour in coarse braided streams. *Water Resources Research*, **19**: 392-402.
- Ashworth, P.J., Best, J.L., Roden, J.E., Bristow, C.S., and Klaassen, G.J. 2000. Morphological evolution and dynamics of a large, sand braid-bar, Jamuna River, Bangladesh. *Sedimentology*, **47**: 533-555.
- Atabey, E., Atabey, N., and Kara, H. 1998. Sedimentology of caliche (calcrete) occurrences of the Kirsehir region. *Bulletin of the Mineral Research and Exploration Institute of Turkey*, **120**: 69-80.
- Aylsworth, J.M., Lawrence, D.E., and Guertin, J. 2000. Did two massive earthquakes in the Holocene induce widespread landsliding and near-surface deformation in part of the Ottawa Valley, Canada? *Geology*, **28**: 903-906.
- Baas, J.H. 1999. An empirical model for the development and equilibrium morphology of current ripples in fine sand. *Sedimentology*, **46**: 123-138.
- Bagnold, R.A. 1954. The physical aspects of dry deserts. *In* *Biology of Desserts*, *Edited by* Cloudsley-Thompson, J.L. Institute of Biology, London. pp. 7-12.
- Bann, K.L., Tye, S.C., MacEachern, J.A., Fielding, C., and Jones, B.G. 2008. Ichnological and sedimentologic signatures of mixed wave- and storm-dominated deltaic deposits; examples from the Early Permian Sydney Basin, Australia. *In* *Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy*, *Edited by* Hampson, G.J., Steel, R.J., Burgess, P.M., and Dalrymple, R.W. Special Publication - Society for Sedimentary Geology, **90**: 293-332.
- Baranoski, M.T., Dean, S.L., Wicks, J.L., and Brown, V.M. 2009. Unconformity-bounded seismic reflection sequences define Grenville-age rift system and foreland basins beneath the Phanerozoic in Ohio. *Geosphere*, **5**: 140-151.
- Barnard, P.L., Hanes, D.M., Rubin, D.M., and Kvitek, R.G. 2006. Giant sand waves at the mouth of San Francisco Bay. *Eos*, **87**: 287-289.
- Benkhelil, J. 1989. The origin and evolution of the Cretaceous Benue Trough (Nigeria). *Journal of African Earth Sciences*, **8**: 251-282.
- Bergman, E.A., and Solomon, S.C. 1992. On the strength of oceanic fracture zones and their influence on the intraplate stress field. *Journal of Geophysical Research*, **97**: 15,365-15,377.

Berne, S., C.P., Le Drezen, E., and Lericolais, G. 1993. Morphology, internal structure, and reversal of asymmetry of large subtidal dunes in the entrance to Gironde Estuary (France). *Journal of Sedimentary Petrology*, **63**: 780-793.

Best, J., and Bridge, J. 1992. The morphology and dynamics of low amplitude bedwaves upon upper stage plane beds and the preservation of planar laminae. *Sedimentology*, **39**: 737-752.

Best, J.L., and Ashworth, P.J. 1997. Scour in large braided rivers and the recognition of sequence stratigraphic boundaries. *Nature*, **387**: 275-7.

Best, J.L. 1987. Flow dynamics at river channel confluences; implications for sediment transport and bed morphology. Special Publication - Society of Economic Paleontologists and Mineralogists, **39**: 27-35.

Best, J.L., Ashworth, P.J., Bristow, C.S., and Roden, J. 2003. Three-dimensional sedimentary architecture of a large, mid-channel sand braid bar, Jamuna River, Bangladesh. *Journal of Sedimentary Research*, **73**: 516-530.

Bhattacharya, J.P. 2010. Deltas. *In Facies Models 4 Edited by N.P. James and R.W. Dalrymple*. Geological Association of Canada, St. John's, Canada, pp. 233-264.

Bjerstedt, T.W., and Erickson, J.M. 1989. Trace fossils and bioturbation in peritidal facies of the Potsdam-Theresa formations (Cambrian-Ordovician), Northwest Adirondacks. *Palaios*, **4**: 203-224.

Bleeker, W., Dix, G.R., Davidson, A., and LeCheminant, A. 2011. Tectonic Evolution and Sedimentary Record of the Ottawa-Bonnechere Graben: Examining the Precambrian and Phanerozoic History of Magmatic Activity, Faulting and Sedimentation. *In Geological Association of Canada - Mineralogical Association of Canada - Society of Economic Geologists - Society for Geology Applied to Mineral Deposits Joint Annual Meeting, Guidebook to Fieldtrip 1A*, Ottawa, Canada, pp. 98.

Blein, O., Lafleche, M.R., and Corriveau, L. 2003. Geochemistry of the granulitic Bondy gneiss complex; a 1.4 Ga arc in the Central Metasedimentary Belt, Grenville Province, Canada. *Precambrian Research*, **120**: 193-217.

Borghei, S.M., and Sahebari, A.J. 2010. Local scour at open-channel junctions. *Journal of Hydraulic Research*, **48**: 538-542.

Braile, L.W., Keller, G.R., Hinze, W.J., and Lidiak, E.G. 1982. An ancient rift complex and its relation to contemporary seismicity in the New Madrid seismic zone. *Tectonics*, **1**: 225-237.

Brand, U., and Rust, B.R. 1977. The age and upper boundary of the Nepean Formation in its type section near Ottawa, Ontario. *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre*, **14**: 2002-2006.

Bridge, J.S. 2003. *Rivers and Floodplains: Forms, Processes, and Sedimentary Record*. Wiley-Blackwell Publishing, Oxford, United Kingdom.

Bridge, J.S. 1993. The interaction between channel geometry, water flows, sediment transport and deposition in braided rivers. *In Braided Rivers, Edited by Best, J.L.* Geological Society Special Publications, **75**: 13-71.

Bridge, J.S., and Tye, R.S. 2000. Interpreting the dimensions of ancient fluvial channel bars, channels, and channel belts from wireline-logs and cores. *AAPG Bulletin*, **84**: 1205-1228.

Bridge, J.S., and Lunt, I.A. 2006. Depositional models of braided rivers. *In Braided Rivers: Process, Deposits, Ecology and Management, Edited by Sambrook Smith, G.H., Best, J.L., Bristow, C.S. and Petts, G.E.* Special Publication of the International Association of Sedimentologists, **36**: 11-50.

Bridge, J.S., and Demicco, R.V. 2008. *Earth surface processes, landforms and sediment deposits*. Cambridge University Press, Cambridge, United Kingdom, .

Brink, R.A. 2015. Sedimentologic Comparison of The Late/lower Early Middle Cambrian Altona Formation And The Lower Cambrian Monkton Formation. MSc thesis, Department of Geology, University of Vermont, Burlington, Vermont.

Bromley, M.H., 1991, Variations in fluvial style as revealed by architectural elements, Kayenta Formation, Mesa Creek, Colorado, USA: evidence for both ephemeral and perennial fluvial processes, in A. D. Miall and N. Tyler, eds., *The three-dimensional facies architecture of terrigenous clastic sediments and its implications for hydrocarbon discovery and recovery: SEPM Concepts in Sedimentology and Paleontology*, v. 3, p. 94–103.

Brookfield, M.E. 1977. The origin of bounding surfaces in ancient aeolian sandstones. *Sedimentology*, **24**: 303-332.

Brown, L., Jensen, L., Oliver, J., Kaufman, S., and Steiner, D. 1982. Rift structure beneath the Michigan Basin from COCORP profiling (USA). *Geology*, **10**: 645-649.

Bryant, M., Falk, P., and Paola, C. 1995. Experimental study of avulsion frequency and rate of deposition. *Geology*, **23**: 365-368.

Bull, J.M. 1990. Structural style of intra-plate deformation, central Indian Ocean Basin; evidence for the role of fracture zones. *Tectonophysics*, **184**: 213-228.

Bull, W.B. 1979. Threshold of critical power in streams. *Geological Society of America Bulletin*, **90**: 453-464.

Burke, K. 1977. Aulacogens and continental breakup. *Annual Review of Earth and Planetary Sciences*, **5**: 371-396.

Burke, K., and Dewey, J.F. 1973. Plume-generated triple junctions: key indicators in applying plate tectonics to old rocks. *Journal of Geology*, **81**: 406-433.

Burton, W.C., and Southworth, S. 2010. A model for Iapetan rifting of Laurentia based on Neoproterozoic dikes and related rocks. In Tolio, R., Bartholelew, M.J., Hibbard, J.P., Karabinos, P.M., *From Rodinia to Pangea; the lithotectonic record of the Appalachian region*; Memoir - Geological Society of America, **206**: 455-476.

Cady, W.M. 1945. Stratigraphy and structure of west-central Vermont. *Bulletin of the Geological Society of America*, **56**: 515-587.

Carr, S.D., Easton, R.M., Jamieson, R.A., and Culshaw, N.G. 2000. Geologic transect across the Grenville orogen of Ontario and New York. *Canadian Journal of Earth Sciences*, **37**: 193-216.

Carr, S.D., Easton, R.M., Jamieson, R.A., and Culshaw, N.G. 2000. Geologic transect across the Grenville Orogen of Ontario and New York. *Canadian Journal of Earth Sciences*, **37**: 193-216.

Cartigny, M.J.B., Ventra, D., Postma, G., and van, d.B. 2014. Morphodynamics and sedimentary structures of bedforms under supercritical-flow conditions; new insights from flume experiments. *Sedimentology*, **61**: 712-748.

Cawood, P.A., McCausland, P.J.A., and Dunning, G.R. 2001. Opening Iapetus: Constraints from the Laurentian margin in Newfoundland. *Bulletin of the Geological Society of America*, **113**: 443-453.

Cecil, C.B., Dulong, F.T., West, R.R., Stamm, R.G., Wardlaw, B.R., and Edgar, N.T. 2003. Climate controls on the stratigraphy of a Middle Pennsylvanian cyclothem in North America. *Special Publication - Society for Sedimentary Geology*, **77**: 151-180.

Chadwick, G.H. 1915. Post-Ordovician deformation in the Saint Lawrence Valley, New York. *Bulletin of the Geological Society of America*, **26**: 287-294.

Chadwick, G.H. 1920. The Paleozoic rocks of the Canton Quadrangle. *New York State Museum Bulletin* 217-218. University of the State of New York, Albany, New York.

Chafetz, H.S., and Buczynski, C. 1992. Bacterially induced lithification of microbial mats. *Palaaios*, **7**: 277-293.

Cheel, R.J., and Leckie, D.A. 1993. Hummocky cross-stratification. *Sedimentology Review*, **1**: 103-122.

- Cherichetti, L., Doolan, B., and Mehrtens, C. 1998. The Pinnacle Formation; a late Precambrian rift valley fill with implications for Iapetus rift basin evolution. *Northeastern Geology and Environmental Sciences*, **20**: 175-185.
- Cherns, L., Wheelley, J.R., Popov, L.E., Ghobadi Pour, M., Owens, R.M., and Hemsley, A.R. 2013. Long-period orbital climate forcing in the early Palaeozoic? *Journal of the Geological Society*, **170**: 707-710.
- Chiarenzelli, J., Aspler, L.B., Donaldson, J.A., Rainbird, R., Mosher, D., Regan, S.P., Ibanez-Mejia, M., and Franzi, D.A. 2010. Detrital zircons of Cambro-Ordovician sandstone units in eastern Ontario and northern New York. *Abstracts with Programs - Geological Society of America*, **42**: 118.
- Chiarenzelli, J.R., and McLelland, J.M. 1991. Age and regional relationships of granitoid rocks of the Adirondack highlands. *Journal of Geology*, **99**: 571-590.
- Chow, N., and James, N.P. 1987. Cambrian grand cycles; a Northern Appalachian perspective. *Geological Society of America Bulletin*, **98**: 418-429.
- Clark, T.H. 1966. Châteauguay Area; Châteauguay, Huntingdon, Beauharnois, Napierville and St. Jean counties. 122, Québec Department of Natural Resources Geological Report 122, Québec Department of Natural Resources, Québec, Québec.
- Clark, T.H. 1952. Montreal Area, Laval and Lachine Map-Areas. Quebec Dept. Mines, Geol. Surveys Br. Geol. Rept. 46.
- Clark, T.H. 1972. Region de Montreal--Montreal area. Québec Geological Exploration Service Geological Report 122, Québec Department of Natural Resources, Québec, Québec.
- Clark, T.H., and Usher, J.L. 1948. The sense of Climactichnites. *American Journal of Science*, **246**: 251-253.
- Clemmensen, L.B., and Dam, G. 1993. Aeolian sand-sheet deposits in the Lower Cambrian Nekso sandstone formation, Bornholm, Denmark; sedimentary architecture and genesis. *Sedimentary Geology*, **83**: 71-85.
- Clifton, H.E. 1976. Wave-formed sedimentary structures; a conceptual model. *In Beach and Nearshore Sedimentation, Edited by Davis, R.A., and Ethington, R.L. Special Publication - Society of Economic Paleontologists and Mineralogists*, **24**: 126-148.
- Clifton, H.E., and Dingler, J.R. 1984. Wave-formed structures and paleoenvironmental reconstruction. *Marine Geology*, **60**: 165-198.
- Cohen, K.M., Finney, S.C., Gibbard, P.L., and Junxuan, F. 2013. The ICS international chronostratigraphic chart. *Episodes*, **36**: 199-204.

Collette, J.H., and Hagadorn, J.W. 2010. Three-dimensionally preserved arthropods from Cambrian Lagerstaetten of Quebec and Wisconsin. *Journal of Paleontology*, **84**: 646-667.

Corrigan, D. 1995. Mezoproterozoic evolution of the south-central Grenville orogen: structural, metamorphic, and geochronologic constraints from the Mauricie transect. PhD thesis, Carleton University, Ottawa, Canada.

Corriveau, L., Heaman, L.M., Marcantonio, F., and Van Breemen, O. 1990. 1.1 Ga K-rich alkaline plutonism in the SW Grenville Province; U-Pb constraints for the timing of subduction-related magmatism. *Contributions to Mineralogy and Petrology*, **105**: 473-485.

Corriveau, L., and van Breeman, O. 2000. Docking of the Central Metasedimentary Belt to Laurentia in Geon 12; evidence from the 1.17-1.16 Ga Chevreuil Intrusive Suite and host gneisses, Quebec. *Canadian Journal of Earth Sciences*, **37**: 253-269.

Cotter, E., 1978, The evolution of fluvial style, with special reference to the Central Appalachian Paleozoic, in Miall, A.D., ed., *Fluvial Sedimentology: Memoir - Canadian Society of Petroleum Geologists*, v. 5, p. 361-383.

Cotter, E., and Graham, J.R. 1991. Coastal plain sedimentation in the late Devonian of southern Ireland; hummocky cross-stratification in fluvial deposits? *Sedimentary Geology*, **72**: 201-224.

Cox, R., and Lowe, D.R. 1995. Compositional evolution of coarse clastic sediments in the Southwestern United States from 1.8 to 0.2 Ga and implications for relationships between the development of crustal blocks and their sedimentary cover. *Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes*, **65**: 477-494.

Crough, S.T. 1981. Mesozoic hotspot epeirogeny in eastern North America. *Geology*, **9**: 2-6.

Crowell, J.C. 1973. Origin of late Cenozoic basins in southern California. *The American Association of Petroleum Geologists Bulletin*, **57**: 774.

Crowell, J.C. 1974. Sedimentation along the San Andreas Fault, California. *In Tectonics and Sedimentation, Edited by Dickinson, W.R. Special Publication - Society of Economic Paleontologists and Mineralogists*, **19**: 292-303.

Cuadrado, D.G., Carmona, N.B., and Bournod, C. 2011. Biostabilization of sediments by microbial mats in a temperate siliciclastic tidal flat, Bahia Blanca Estuary (Argentina). *Sedimentary Geology*, **237**: 95-101.

Culshaw, N.G., Jamieson, R.A., Ketchum, J.W.F., Wodicka, N., Corrigan, D., and Reynolds, P.H. 1997. Transect across the northwestern Grenville Orogen, Georgian Bay, Ontario; polystage convergence and extension in the lower orogenic crust. *Tectonics*, **16**: 966-982.

Currie, K.L. 1976. The alkaline rocks of Canada. Geological Survey of Canada Bulletin 239, Geological Survey of Canada, Ottawa, ON, Canada.

Cushing, H.P. 1908. Lower portion of the Paleozoic section in northwestern New York. Bulletin of the Geological Society of America, **19**: 155-176.

Daidu, F., Congxian, L., Dejie, W., Wang, P., Archer, A.W., and Greb, S.F. 2004. Morphology and sedimentation on open-coast intertidal flats of the Changjiang Delta, China. Journal of Coastal Research, **43**: 23-35.

Dalrymple, R.W. 2010. Tidal Depositional Systems. In *Facies Models 4 Edited by N.P. James and R.W. Dalrymple*. Geological Association of Canada, St. John's, Canada, pp. 201-231.

Dalrymple, R.W., and Rhodes, R.N. 1995. Estuarine Dunes and Bars. In *Geomorphology and Sedimentology of Estuaries Edited by G.M.E. Perillo*. Elsevier Science, Amsterdam, pp. 359-422.

Dalrymple, R.W., Narbonne, G.M., and Smith, L. 1985. Eolian action and the distribution of Cambrian shales in North America. *Geology*, **13**: 607-610.

Dalrymple, R.W. 1984. Morphology and internal structure of sandwaves in the Bay of Fundy. *Sedimentology*, **31**: 365-382.

Dalrymple, R.W., Baker, E.K., Harris, P.T., and Hughes, M.G. 2003. Sedimentology and stratigraphy of a tide-dominated, foreland-basin delta (Fly River, Papua New Guinea). Special Publication - Society for Sedimentary Geology, **76**: 147-173.

Davidson, A., and van Breeman, O. 2000. Late Grenvillian granite plutons in the Central Metasedimentary Belt, Grenville Province, southeastern Ontario. Current Research 2000-F5, Geological Survey of Canada, Ottawa, Canada.

Davies, N.S., Gibling, M.R., and Rygel, M.C. 2011. Alluvial facies evolution during the Palaeozoic greening of the continents: Case studies, conceptual models and modern analogues. *Sedimentology*, **58**: 220-258.

Desjardins, P.R., Gabriela Mangano, M., Buatois, L.A., and Pratt, B.R. 2010. Skolithos pipe rock and associated ichnofabrics from the southern Rocky Mountains, Canada; colonization trends and environmental controls in an Early Cambrian sand-sheet complex. *Lethaia*, **43**: 507-528.

Desjardins, P.R., Buatois, L.A., Pratt, B.R., and Mangano, M.G. 2012. Sedimentological-ichnological model for tide-dominated shelf sandbodies; Lower Cambrian Gog Group of western Canada. *Sedimentology*, **59**: 1452-1477.

- Dewey, J.F., and Burke, K. 1974. Hot Spots and Continental Break-up; implications for Collisional Orogeny. *Geology*, **2**: 57-60.
- Dickinson, W.R., and Suczek, C.A. 1979. Plate tectonics and sandstone compositions. *AAPG Bulletin*, **63**: 2164-2182.
- Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., and Ryberg, P.T. 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin*, **94**: 222-235.
- Dix, G.R., and Al Rodhan, Z. 2006. A new geological framework for the Middle Ordovician Carillon Formation (uppermost Beekmantown Group, Ottawa Embayment): Onset of Taconic foreland deposition and tectonism within the Laurentian platform interior. *Canadian Journal of Earth Sciences*, **43**: 1367-1387.
- Dix, G.R., Salad Hersi, O., and Nowlan, G.S. 2004. The Potsdam-Beekmantown Group boundary, Nepean Formation type section (Ottawa, Ontario): A cryptic sequence boundary, not a conformable transition. *Canadian Journal of Earth Sciences*, **41**: 897-902.
- Dodson, M.H., Compston, W., Williams, I.S., and Wilson, J.F. 1988. A search for ancient detrital zircons in Zimbabwean sediments. *Journal of the Geological Society of London*, **145**: 977-983.
- Doig, R. 1970. An alkaline rock province linking Europe and North America. *Canadian Journal of Earth Sciences*, **7**: 22-28.
- Doig, R. 1991. U-Pb zircon dates of Morin anorthosite suite rocks, Grenville Province, Quebec. *Journal of Geology*, **99**: 729-738.
- Doig, R., and Barton, J.M., Jr. 1968. Ages of carbonatites and other alkaline rocks in Quebec. *Canadian Journal of Earth Sciences*, **5**: 1401-1407.
- Donaldson, J.A., and Chiarenzelli, J.R. 2007. 8(b) Disruption of mats by seismic events. *In* Atlas of Microbial Mat Features Preserved within the Siliciclastic Rock Record. *Edited by* Schieber, J., Bose, P., Erksson, P.G., Banerjee, S., Sarkar, S., Altermann, W., and Cataneanu, O. *Atlases in Geoscience*, **2**, Elsevier, Amsterdam, the Netherlands. pp. 244-248.
- Dott, R.H., J. 2003. The importance of eolian abrasion in supermature quartz sandstones and the paradox of weathering on vegetation-free landscapes. *Journal of Geology*, **111**: 387-405.
- Dott, R.H., J., and Bourgeois, J. 1982. Hummocky stratification; significance of its variable bedding sequences. *Geological Society of America Bulletin*, **93**: 663-680.

- Dott, R.H., Jr., Byers, C.W., Fielder, G.W., Stenzel, S.R., and Winfree, K.E. 1986. Aeolian to marine transition in Cambro-Ordovician cratonic sheet sandstones of the northern Mississippi Valley, U.S.A. *Sedimentology*, **33**: 345-367.
- Drahovzal, J.A. 1995. Exploration strategies and possible submarine fan complexes in the Rough Creek Graben, western Kentucky. *AAPG Bulletin*, **79**: 1412.
- Drahovzal, J.A. 1997. Proterozoic sequences and their implications for Precambrian and Cambrian geologic evolution of western Kentucky; evidence from seismic-reflection data. *Seismological Research Letters*, **68**: 553-566.
- Driese, S.G., Byers, C.W., and Dott, R.H., Jr. 1981. Tidal deposition in the basal Upper Cambrian Mt. Simon Formation in Wisconsin. *Journal of Sedimentary Petrology*, **51**: 367-381.
- Duke, W.L., Arnott, R.W.C., and Cheel, R.J. 1991. Shelf sandstones and hummocky cross-stratification; new insights on a stormy debate. *Geology*, **19**: 625-628.
- Dumas, S., Arnott, R.W.C., and Southard, J.B. 2005. Experiments on oscillatory-flow and combined-flow bed forms; implications for interpreting parts of the shallow-marine sedimentary record. *Journal of Sedimentary Research*, **75**: 501-513.
- Easton, R.M. 1992. The Grenville Province and the Proterozoic history of central and southern Ontario. *Ontario Geological Survey Special Volume*, **4**, 715-904.
- Emmons, E. 1838. Report of the second geological district of the State of New York. *New York Geological Survey, Annual Report*, **2**: 185-252.
- Emmons, E. 1841. Fifth annual report of the survey of the second geological district of New York]. *New York Geological Survey, Annual Report*, **5**: 113-136.
- Emslie, R.F., and Hunt, P.A. 1990. Ages and petrogenetic significance of igneous mangerite-charnockite suites associated with massif anorthosites, Grenville Province. *Journal of Geology*, **98**: 213-231.
- Fedo, C.M., Sircombe, K.N., and Rainbird, R.H. 2003. Detrital zircon analysis of the sedimentary record. *Reviews in Mineralogy and Geochemistry*, **53**: 277-303.
- Fielding, C.R. 2006. Upper flow regime sheets, lenses and scour fills; extending the range of architectural elements for fluvial sediment bodies. *Sedimentary Geology*, **190**: 227-240.
- Fisher, D.W. 1968. Geology of the Plattsburgh and Rouses Point, New York–Vermont, quadrangles. *Special Bulletin no.1*, Vermont Geological Survey, Burlington, Vermont.

- Fisher, D.W. 1955. Time span of the Theresa and Potsdam formations in the region peripheral to the Adirondack Mountains, New York. *Bulletin of the Geological Society of America*, **66**: 1558-1559.
- Flower, R.H. 1963. A paleocurrent study of the Potsdam Sandstone of New York, Quebec, and Ontario. Unpublished PhD thesis, Ohio State University. 174 p.
- Flower, R.H. 1964. The nautiloid order Ellesmeroceratida (Cephalopoda). New Mexico Bureau of Mines and Mineral Resources Memoir 12, Socorro, New Mexico.
- Fralick, P. 1999. Paleohydraulics of chute-and-pool structures in a Paleoproterozoic fluvial sandstone. *Sedimentary Geology*, **125**: 129-134.
- Friedman, R.M., and Martignole, J. 1995. Mesoproterozoic sedimentation, magmatism, and metamorphism in the southern part of the Grenville Province (western Quebec): U-Pb geochronological constraints. *Canadian Journal of Earth Sciences*, **32**: 2103-2114.
- Fryberger, S.G., Ahlbrandt, T.S., and Andrews, S. 1979. Origin, sedimentary features, and significance of low-angle eolian "sand sheet" deposits, Great Sand Dunes National Monument and vicinity, Colorado. *Journal of Sedimentary Petrology*, **49**: 733-746.
- Fryberger, S.G., Al-Sari, A., and Clisham, T.J. 1983. Eolian dune, interdune, sand sheet, and siliciclastic sabkha sediments of an offshore prograding sand sea, Dhahran area, Saudi Arabia. *AAPG Bulletin*, **67**: 280-312.
- Fryberger, S.G., Schenk, C.J., and Krystinik, L.F. 1988. Stokes surfaces and the effects of near-surface groundwater-table on aeolian deposition. *Sedimentology*, **35**: 21-41.
- Fryberger, S.G., Krystinik, L.F., and Schenk, C.J. 1990. Tidally flooded back-barrier dunefield, Guerrero Negro area, Baja California, Mexico. *Sedimentology*, **37**: 23-43.
- Fuller, A.O. 1985. A contribution to the conceptual modelling of pre-Devonian fluvial systems. *Verhandelinge van die Geologiese Vereniging van Suid Afrika = Transactions of the Geological Society of South Africa*, **88**: 189-194.
- Ganti, V., Lamb, M.P., and McElroy, B. 2014. Quantitative bounds on morphodynamics and implications for reading the sedimentary record. *Nature Communications*, **5**, 1-7.
- Gaudette, H.E., Vitrac-Michard, A., and Allegre, C.J. 1981. North American Precambrian history recorded in a single sample; high-resolution U-Pb systematics of the Potsdam Sandstone detrital zircons, New York State. *Earth and Planetary Science Letters*, **54**: 248-260.
- Gawthorpe, R.L., and Leeder, M.R. 2000. Tectono-sedimentary evolution of active extensional basins. *Basin Research*, **12**: 195-218.

- Gehrels, G.E., Valencia, V., and Ruiz, J. 2008. Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation–multicollector–inductively coupled plasma–mass spectrometry. *Geochemistry, Geophysics, Geosystems*, **9**: 1525-2027.
- Gehrels, G., and Pecha, M. 2014. Detrital zircon U-Pb geochronology and Hf isotope geochemistry of Paleozoic and Triassic passive margin strata of western North America. *Geosphere*, **10**: 49-65.
- Gehrels, G., Valencia, V., and Pullen, A. 2006. Detrital zircon geochronology by laser-ablation multicollector ICPMS at the Arizona Laserchron Center. *The Paleontological Society Papers*, **12**: 67-76.
- Gerbi, C.C., Johnson, S.E., Aleinikoff, J.N., Bedard, J.H., Dunning, G.R., and Fanning, C.M. 2006. Early Paleozoic development of the Maine-Quebec boundary Mountains region. *Canadian Journal of Earth Sciences*, **43**: 367-389.
- Getty, P.R., and Hagadorn, J.W. 2009. Palaeobiology of the *Climactichnites* tracemaker. *Palaeontology*, **52**: 753-778.
- Gibling, M.R., and Davies, N.S. 2012. Palaeozoic landscapes shaped by plant evolution. *Nature Geoscience*, **5**: 99-105.
- Gile, L.H., and Grossman, R.B. 1968. Morphology of the argillic horizon in desert soils of southern New Mexico. *Soil Science*, **106**: 6-15.
- Giles, D., Betts, P., and Lister, G. 2002. Far-field continental backarc setting for the 1.80-1.67 Ga basins of northeastern Australia. *Geology*, **30**: 823-826.
- Globensky, Y. 1982. Lachute region; Region de Lachute. Rapport Geologique - Ministere de l'Energie et des Ressources 200, Ministere de l'Energie et des Ressources, Quebec, Québec.
- Globensky, Y. 1987. Geology of the Saint Lawrence Lowlands; Geologie des basses-terres du Saint-Laurent. MM 85-02, Ministere de l'Energie et des Ressources, Québec, Québec.
- Goodall, T.M., North, C.P., and Glennie, K.W. 2000. Surface and subsurface sedimentary structures produced by salt crusts. *Sedimentology*, **47**: 99-118.
- Goudie, A.S. 1983. Calcrete. *In* Chemical sediments and geomorphology; precipitates and residua in the near-surface environment, *Edited by* Goudie, A.S., and Pye, K. Academic Press, Cambridge, MA. p. 93-131.
- Greenwood, B., and Sherman, D.J. 1986. Hummocky cross-stratification in the surf zone; flow parametres and bedding genesis. *Sedimentology*, **33**: 33-45.
- Greggs, R.G., and Bond, I.J. 1971. Conodonts from the March and Oxford formations in the Brockville area, Ontario. *Canadian Journal of Earth Sciences*, **8**: 1455-1471.

- Greggs, R.G., and Bond, I.J. 1972. A Principal Reference Section Proposed for the Nepean Formation of Probable Tremadocian Age Near Ottawa, Ontario. *Canadian Journal of Earth Sciences*, **9**: 933-941.
- Greggs, R.G., and Bond, I.J. 1973. Erratum; A Principal Reference Section Proposed for the Nepean Formation of Probable Tremadocian Age near Ottawa, Ontario. *Canadian Journal of Earth Sciences*, **10**: 329.
- Grollimund, B., and Zoback, M.D. 2001. Did deglaciation trigger intraplate seismicity in the New Madrid seismic zone? *Geology (Boulder)*, **29**: 175-178.
- Gulliford, A.R., Flint, S.S., and Hodgson, D.M. 2014. Testing applicability of models of distributive fluvial systems or trunk rivers in ephemeral systems: Reconstructing 3-D fluvial architecture in the Beaufort Group, South Africa. *Journal of Sedimentary Research*, **84**: 1147-1169.
- Hagadorn, J.W., and Belt, E.S. 2008. Stranded in upstate New York; Cambrian scyphomedusae from the Potsdam Sandstone. *Palaaios*, **23**: 424-441.
- Hagadorn, J.W., and McDowell, C. 2012. Microbial influence on erosion, grain transport and bedform genesis in sandy substrates under unidirectional flow. *Sedimentology*, **59**: 795-808.
- Hagadorn, J.W., Collette, J.H., and Belt, E.S. 2011. Eolian-aquatic deposits and faunas of the Middle Cambrian Potsdam Group. *Palaaios*, **26**: 314-334.
- Hajek, E.A., and Heller, P.L. 2012. Flow-depth scaling in alluvial architecture and nonmarine sequence stratigraphy: Example from the castlegate sandstone, Central Utah, U.S.A. *Journal of Sedimentary Research*, **82**: 121-130.
- Hamilton, R.M., and Zoback, M.D. 1982. Tectonic features of the New Madrid seismic zone from seismic-reflection profiles. *In* Investigations of the New Madrid, Missouri, Earthquake Region. U.S. Geological Survey Professional Paper, 1236: pp. 55-82.
- Hampton, B.A., and Horton, B.K. 2007. Sheetflow fluvial processes in a rapidly subsiding basin, Altiplano plateau, Bolivia. *Sedimentology*, **54**: 1121-1147.
- Haq, B.U., and Schutter, S.R. 2008. A chronology of paleozoic sea-level changes. *Science*, **322**: 64-68.
- Harding, W.D. 1931. The relations of the Grenville sediments and the Potsdam sandstone in eastern Ontario. *American Mineralogist*, **16**: 430-436.
- Harms, J.C., Southard, J.B., Spearing, D.R., and Walker, R.G. 1975. Depositional environments as interpreted from primary sedimentary structures and stratification sequences. Society of Sedimentary Geology Short Course No.2, Tulsa, OK, United States.

- Hein, F.J., and Walker, R.G. 1977. Bar evolution and development of stratification in the gravelly, braided, Kicking Horse River, British Columbia. *Canadian Journal of Earth Sciences*, **14**: 562-70.
- Henry, C., Das, S., and Woodhouse, J.H. 2000. The great March 25, 1998, Antarctic Plate earthquake; moment tensor and rupture history. *Journal of Geophysical Research*, **105**: 16,097-16,118.
- Hibbard, J.P., van Staal, C.R., and Rankin, D.W. 2007. A comparative analysis of pre-Silurian crustal building blocks of the northern and the southern Appalachian orogen. *American Journal of Science*, **307**: 23-45.
- Hiscott, R.N. 1994. Loss of capacity, not competence, as the fundamental process governing deposition from turbidity currents. *Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes*, **64**: 209-214.
- Hjellbakk, A. 1997. Facies and fluvial architecture of a high-energy braided river: the Upper Proterozoic Segloddan Member, Varanger Peninsula, northern Norway. *Sedimentary Geology*, **114**: 131-161.
- Hogarth, D.D., Rushforth, P., and McCorkell, R.H. 1988. The Blackburn carbonatites, near Ottawa, Ontario; dikes with fluidized emplacement. *The Canadian Mineralogist*, **26, Part 2**: 377-390.
- Hogg, S.E. 1982. Sheetfloods, sheetwash, sheetflow, or...? *Earth Science Reviews*, **18**: 59-76.
- Horn, J.D., Fielding, C.R., and Joeckel, R.M., 2012, Revision of Platte River alluvium facies model through observations of extant channels and barforms, and subsurface alluvial valley fills. *Journal of Sedimentary Research*, v. 82, p. 72-91.
- Hummel, G., and Kocurek, G. 1984. Interdune areas of the back-island dune field, North Padre Island, Texas. *Sedimentary Geology*, **39**: 1-26.
- Hunter, R.E. 1977. Basic types of stratification in small eolian dunes. *Sedimentology*, **24**: 361-387.
- Hunter, R.E. 1980. Quasi-planar adhesion stratification; an eolian structure formed in wet sand. *Journal of Sedimentary Petrology*, **50**: 263-266.
- Hurd, O., and Zoback, M.D. 2012. Intraplate earthquakes, regional stress and fault mechanics in the central and eastern U.S. and Southeastern Canada. *Tectonophysics*, **581**: 182-192.
- Hyodo, H., York, D., Dunlop, D.J. 1993. Tectonothermal History in the Mattawa Area, Ontario, Canada, Deduced From Paleomagnetism and $^{40}\text{Ar}/^{39}\text{Ar}$ Dating of a Grenville Di. *Journal of Geophysical Research*, **98**, 18,001-18,010.

- Ichaso, A.A., and Dalrymple, R.W. 2009. Tide- and wave-generated fluid mud deposits in the Tilje Formation (Jurassic), offshore Norway. *Geology*, **37**: 539-542.
- Ielpi, A., and Rainbird, R.H. 2016. Highly Variable Precambrian Fluvial Style Recorded In the Nelson Head Formation of Brock Inlier (Northwest Territories, Canada). *Journal of Sedimentary Research*, **86**: 199-216.
- Ielpi, A., and Ghinassi, M. 2015. Planview style and palaeodrainage of Torridonian channel belts; Applecross Formation, Stoer Peninsula, Scotland. *Sedimentary Geology*, **325**: 1-16.
- Isachsen, Y.W. 1975. Contemporary arching along the eastern flank of the Adirondack Dome, and possible implications for tectonics and seismicity. *Abstracts with Programs - Geological Society of America*, **7**: 79.
- James, N.P., and Stevens, R.K. 1986. Stratigraphy and correlation of the Cambro-Ordovician Cow Head Group, western Newfoundland. *Bulletin - Geological Survey of Canada* 366. Geological Survey of Canada, Ottawa, Ontario.
- James, N.P., Botsford, J.W., and Williams, S.H. 1987. Allochthonous slope sequence at Lobster Cove Head; evidence for a complex Middle Ordovician platform margin in western Newfoundland. *Canadian Journal of Earth Sciences*, **24**: 1199-1211.
- Jerolmack, D.J., and Paola, C. 2010. Shredding of environmental signals by sediment transport. *Geophysical Research Letters*, **37**.
- Jochum, K.P., Weis, U., Stoll, B., Kuzmin, D., Yang, Q., Raczek, I., Jacob, D.E., Stracke, A., Birbaum, K., Frick, D.A., Gunther, D., and Enzweiler, J. 2011. Determination of reference values for NIST SRM 610-617 glasses following ISO guidelines. *Geostandards and Geoanalytical Research*, **35**: 397-429.
- Johnson, K.S., Amsden, T.W., Denison, R.E., Dutton, S.P., Goldstein, A.G., Rascoe, B., Jr., Sutherland, P.K., and Thompson, D.M. 1988. Southern Midcontinent region. *In* *Sedimentary cover; North American Craton: U.S., Edited by Sloss, L.L.* Geological Society of America, DNAG, *Geology of North America*, Vol. D-2, pp. 307-359.
- Kamo, S.L., Krogh, T.E., and Kumarapeli, P.S. 1995. Age of the Grenville dyke swarm, Ontario - Quebec: implications for the timing of Iapetan rifting. *Canadian Journal of Earth Sciences*, **32**: 273-280.
- Karabinos, P., Samson, S.D., Hepburn, J.C., and Stoll, H.M. 1998. Taconian orogeny in the New England Appalachians: Collision between Laurentia and the Shelburne Falls arc. *Geology*, **26**: 215-218.
- Kay, G.M. 1942. Ottawa-Bonnechere graben and Lake Ontario homocline. *Bulletin of the Geological Society of America*, **53**: 585-646.

Kendall, A.C. 2010. Marine Evaporites. *In Facies Models 4 Edited by N.P. James and R.W. Dalrymple*. Geological Association of Canada, St. John's, Canada, pp. 505-539.

Kirchgasser, W., and Theokritoff, G. 1971. Precambrian and lower Paleozoic stratigraphy, northwest Saint Lawrence and north Jefferson counties, New York. Guidebook - New York State Geological Association 43rd Annual Meeting, B1-B24.

Kirwan, J.L. 1963. Age of Nepean (Potsdam) sandstone in Eastern Ontario. *American Journal of Science*, **261**: 108-110.

Knight, I., and Boyce, W.D. 1991. Deformed Lower Paleozoic Platform Carbonates, Goose Arm - Old Man's Pond. Current Research, Report 91-1, Newfoundland Department of Mines and Energy, Geological Survey Branch, St. John's, Canada.

Knight, I. 1991. Geology of Cambro-Ordovician rocks in the Port Saunders (NTS 12I/11), Castors River (NTS 12I/15), St. John Island (NTS 12I/14) and Torrent River (NTS 12I/10) map areas. Geological Survey, Department of Mines and Energy, Geoscience Publications and Information Section, St John's, NL, Canada.

Knighton, A.D., and Nanson, G.C., 1997, Distinctiveness, diversity and uniqueness in arid zone river systems, *in* Thomas, D.S.G., *Arid Zone Geomorphology: Process, Form and Change in Drylands*, second Edition. Chichester, Wiley, p. 185–203.

Kocurek, G., and Dott Jr, R.H. 1981. Distinctions and uses of stratification types in the interpretation of eolian sand. *Journal of Sedimentary Petrology*, **51**: 579-596.

Kocurek, G., and Fielder, G. 1982. Adhesion structures. *Journal of Sedimentary Petrology*, **52**: 1229-1241.

Kocurek, G., and Nielson, J. 1986. Conditions favourable for the formation of warm-climate aeolian sand sheets. *Sedimentology*, **33**: 795-816.

Kocurek, G. and Havholm, K.G., 1993, Eolian sequence stratigraphy - a conceptual framework, *in* Weimer, P., and Posamentier, H.W., eds., *Siliciclastic Sequence Stratigraphy: Recent Developments and Applications*: American Association of Petroleum Geologists, Memoir 58, p. 393-409.

Kocurek, G. 1981. Significance of interdune deposits and bounding surfaces in aeolian dune sands. *Sedimentology*, **28**: 753-780.

Kocurek, G., 1988, First-order and super bounding surfaces in eolian sequences – Bounding surfaces revisited: *Sedimentary Geology*, v. 56, p. 193-206.

Kostic, S., Sequeiros, O., Spinewine, B., and Parker, G. 2010. Cyclic steps: A phenomenon of supercritical shallow flow from the high mountains to the bottom of the ocean. *Journal of Hydro-Environment Research*, **3**: 167-172.

- Koukouvelas, I.K., and Aydin, A. 2002. Fault structure and related basins of the North Aegean Sea and its surroundings. *Tectonics*, **21**: 10-1 - 10-17.
- Kumarapeli, P.S. 1985. Vestiges of Iapetan rifting in the craton west of the Northern Appalachians. *Geoscience Canada*, **12**: 54-59.
- Kumarapeli, P.S. 1993. A plume-generated segment of the rifted margin of Laurentia, southern Canadian Appalachians, seen through a completed Wilson Cycle. *Tectonophysics*, **219**: 47-55.
- Kumarapeli, P.S., and Saull, V.A. 1966. St. Lawrence valley system -- North American equivalent of east African rift valley system. *Canadian Journal of Earth Sciences*, **3**: 639-658.
- Lancaster, N., and Teller, J.T. 1988. Interdune deposits of the Namib Sand Sea. *Sedimentary Geology*, **55**: 91-107.
- Landing, E. 1993. Cambrian-Ordovician boundary in the Taconic allochthon, eastern New York, and its interregional correlation. *Journal of Paleontology*, **67**: 1-19.
- Landing, E. 2007. Ediacaran-Ordovician of east Laurentia; geologic setting and controls on deposition along the New York Promontory region. *Bulletin - New York State Museum* (1976), **510**: 5-24.
- Landing, E., Geyer, G., and Bartowski, K.E. 2002. Latest Early Cambrian small shelly fossils, trilobites, and Hatch Hill dysaerobic interval on the Quebec continental slope. *Journal of Paleontology*, **76**: 287-305.
- Landing, E., Westrop, S.R., and van, A.H. 2003. Uppermost Cambrian-Lower Ordovician faunas and Laurentian Platform sequence stratigraphy, eastern New York and Vermont. *Journal of Paleontology*, **77**: 78-98.
- Landing, E., Amati, L., and Franz, D.A. 2009. Epeirogenic transgression near a triple junction; the oldest (latest Early-Middle Cambrian) marine onlap of cratonic New York and Quebec. *Geological Magazine*, **146**: 552-566.
- Landing, E., Franz, D.A., Hagadorn, J.W., Westrop, S.R., Kroger, B., and Dawson, J.C. 2007. Cambrian of east Laurentia; field workshop in eastern New York and western Vermont. *Bulletin - New York State Museum* (1976), **510**: 25-80.
- Langford, R., and Bracken, B. 1987. Medano Creek, Colorado, a model for upper-flow-regime fluvial deposition. *Journal of Sedimentary Petrology*, **57**: 863-870.
- Langford, R., and Bracken, B. 1987. Medano Creek, Colorado, a model for upper-flow-regime fluvial deposition. *Journal of Sedimentary Petrology*, **57**: 863-870.

Lavoie, D. 1997. Cambrian–Ordovician slope conglomerates in the Humber Zone, Québec Reentrant, Québec. *In* Current research 1997-D, Geological Survey of Canada, Ottawa, Ontario. pp. 9-20.

Lavoie, D. 1998. Along strike Upper Cambrian – Lower Ordovician stratigraphic nomenclature and framework for the external Humber Zone, from Québec City to Gaspé. *In* Current research 1998-D, Geological Survey of Canada, Ottawa, Canada. pp. 11-18.

Lavoie, D. 2008. Appalachian foreland basin of Canada. *In* The sedimentary basins of the United States and Canada. *Edited by* Miall, A.D. Sedimentary Basins of the World, Vol. 5, Elsevier, The Netherlands. pp. 65-103.

Lavoie, D., Burden, E., and Lebel, D. 2003. Stratigraphic framework for the Cambrian-Ordovician rift and passive margin successions from southern Quebec to western Newfoundland. *Canadian Journal of Earth Sciences*, **40**: 177-205.

Lebel, D., and Kirkwood, D. 1998. Nappes and melanges in the Quebec-Bellechasse area; their regional tectonic and stratigraphic significance in the Humber Zone. Geological Association of Canada/Mineralogical Association of Canada, joint annual meeting, Quebec 1998; field trip guidebook A5.

Leclair, S.F., and Bridge, J.S. 2001. Quantitative interpretation of sedimentary structures formed by rivers dunes. *Journal of Sedimentary Research*, **71**: 713-716.

Leclair, S.F. 2002. Preservation of cross-strata due to the migration of subaqueous dunes; an experimental investigation. *Sedimentology*, **49**: 1157-1180.

Leclair, S.F., and Arnott, R.W. 2005. Parallel lamination formed by high-density turbidity currents. *Journal of Sedimentary Research*, **75**: 1-5.

Leeder, M. 2011. *Sedimentology and Sedimentary Basins: From Turbulence to Tectonics*. Wiley-Blackwell, Chichester, West Sussex, UK.

Leeder, M.R. 1995. Continental Rifts and Proto-Oceanic Rift Troughs. *In* Tectonics of sedimentary basins *Edited by* C. Busby and R.V. Ingersoll. Blackwell Science, Cambridge, MA, pp. 119-148.

Legros, F. 2002. Can dispersive pressure cause inverse grading in grain flows? *Journal of Sedimentary Research*, **72**: 166-170.

Leleu, S., Van Lanen, X.M.T., and Hartley, A.J. 2010. Controls on the architecture of a Triassic sandy fluvial system: Wolfville Formation, Fundy Basin, Nova Scotia, Canada: Implications for the interpretation and correlation of ancient fluvial successions: *Journal of Sedimentary Research*, **80**, p.867-883.

Lewis, T.L. 1963. A paleocurrent study of the Potsdam Sandstone of New York, Quebec, and Ontario. PhD thesis, Ohio State University, 174p.

Li, M.Z., and Amos, C.L. 1999. Sheet flow and large wave ripples under combined waves and currents: Field observations, model predictions and effects on boundary layer dynamics. *Continental Shelf Research*, **19**: 637-663.

Liberty, B.A. 1971. Paleozoic geology of Wolfe Island, Bath, Sydenham and Gananaque map areas. Geologic Survey of Canada, Paper 17-35.

Lochman, C. 1968. *Crepicephalus* faunule from the Bonnetterre Dolomite (Upper Cambrian) of Missouri. *Journal of Paleontology*, **42**: 1153-1162.

Logan, W.E. 1863. Geology of Canada. Geological Survey of Canada Report of Progress from Commencement to 1863, Dawson Brothers, Montreal, Quebec.

Long, D.G.F., 1978, Proterozoic stream deposits: some problems of recognition and interpretation of ancient sandy fluvial systems, in Miall, A.D., ed., *Fluvial Sedimentology*: Canadian Society of Petroleum Geologists Memoir 5, p. 313-341.

Long, D.G.F. 2006. Architecture of pre-vegetation sandy-braided perennial and ephemeral river deposits in the Paleoproterozoic Athabasca Group, northern Saskatchewan, Canada as indicators of Precambrian fluvial style. *Sedimentary Geology*, **190**: 71-95.

Lowe, D.R. 1982. Sediment gravity flows; II, Depositional models with special reference to the deposits of high-density turbidity currents. *Journal of Sedimentary Petrology*, **52**: 279-297.

Lowe, D.R. 1988. Suspended-load fallout rate as an independent variable in the analysis of current structures. *Sedimentology*, **35**: 765-776.

Ludden, J., and Hynes, A. 2000. The Lithoprobe Abitibi–Grenville transect: two billion years of crust formation and recycling in the Precambrian Shield of Canada. *Canadian Journal of Earth Sciences*, **37**, 459-476.

Ludwig, K.R. 2003. User's manual for Isoplot 3.00, A geochronological toolkit for Microsoft Excel: Berkeley Geochronology Center Special Publication 4.

Lumbers, S.B., Tsai-Way Wu, Heaman, L.M., Vertolli, V.M., and MacRae, N.D. 1991. Petrology and age of the A-type Mulock granite batholith, northern Grenville Province, Ontario. *Precambrian Research*, **53**: 199-231.

Lunt, I.A., and Bridge, J.S. 2004. Evolution and deposits of a gravelly braid bar, Sagavanirktok River, Alaska. *Sedimentology*, **51**: 415-432.

- Lunt, I.A., Bridge, J.S., and Tye, R.S. 2004. A quantitative, three-dimensional depositional model of gravelly braided rivers. *Sedimentology*, **51**: 377-414.
- Ma, S., and Audet, P. 2014. The 5.2 magnitude earthquake near Ladysmith, Quebec, 17 may 2013: Implications for the seismotectonics of the Ottawa-Bonnechere Graben. *Canadian Journal of Earth Sciences*, **51**: 439-451.
- Mack, G.H., James, W.C., and Monger, H.C. 1993. Classification of Paleosols. *Geological Society of America Bulletin*, **105**: 129-136.
- MacNaughton, R.B., Cole, J.M., Dalrymple, R.W., Braddy, S.J., Briggs, D.E.G., and Lukie, T.D. 2002. First steps on land; arthropod trackways in Cambrian-Ordovician eolian sandstone, southeastern Ontario, Canada. *Geology*, **30**: 391-394.
- Mahaney, W.C. 2002. Atlas of sand grain surface textures and applications. Oxford University Press, Oxford, United Kingdom.
- Malhame, P., and Hesse, R. 2015. Quartz arenites of the cambroordovician kamouraska formation, quebec appalachians, canada: II. eolian sands in deep-sea sedimentary gravity-flow depositssup1/sup. *Canadian Journal of Earth Sciences*, **52**: 261-277.
- Malka, E., Stevenson, R.K., and David, J. 2000. Sm-Nd geochemistry and U-Pb geochronology of the Mont Rigaud stock, Quebec, Canada: A late magmatic event associated with the formation of the Iapetus Rift. *Journal of Geology*, **108**: 569-583.
- Malone, D.H., Stein, C.A., Craddock, J.P., Kley, J., Stein, S., and Malone, J.E. 2016. Maximum depositional age of the Neoproterozoic Jacobsville Sandstone, Michigan: Implications for the evolution of the Midcontinent Rift. *Geosphere*, **12**: 1271-1282.
- Marcantonio, F., McNutt, R.H., Dickin, A.P., and Heaman, L.M. 1990. Isotopic evidence for the crustal evolution of the Frontenac Arch in the Grenville Province of Ontario, Canada. *Chemical Geology*, **83**: 297-314.
- Marconato, A., de Almeida, R.P., Turra, B.B., and Fragoso-Cesar, A. 2014. Pre-vegetation fluvial floodplains and channel-belts in the late Neoproterozoic-Cambrian Santa Barbara Group (southern Brazil). *Sedimentary Geology*, **300**: 49-61.
- Mazzotti, S., and Townend, J. 2010. State of stress in central and eastern North American seismic zones. *Lithosphere*, **2**: 76-83.
- McAnally, W.H., Friedrichs, C., Hamilton, D., Hayter, E., Shrestha, P., Rodriguez, H., Sheremet, A., and Teeter, A. 2007. Management of fluid mud in estuaries, bays, and lakes. I: Present state of understanding on character and behavior. *Journal of Hydraulic Engineering*, **133**: 9-22.

- McCarthy, T.S. 1993. The great inland deltas of Africa. *Journal of African Earth Sciences and the Middle East*, **17**: 275-291.
- McCarthy, T.S., Stanistreet, I.G., and Cairncross, B. 1991. The sedimentary dynamics of active fluvial channels on the Okavango Fan, Botswana. *Sedimentology*, **38**: 471-487.
- McCausland, P.J.A., Van, d.V., and Hall, C.M. 2007. Circum-Iapetus paleogeography of the Precambrian-Cambrian transition with a new paleomagnetic constraint from Laurentia. *Precambrian Research*, **156**: 125-152.
- McCausland, P.J.A., Hankard, F., Van, d.V., and Hall, C.M. 2011. Ediacaran paleogeography of Laurentia: Paleomagnetism and ⁴⁰Ar-³⁹Ar geochronology of the 583Ma Baie des Moutons syenite, Quebec. *Precambrian Research*, **187**: 58-78.
- McFarlane, C.R.M., and Luo, Y. 2012. U-Pb geochronology using 193 nm excimer LA-ICP-MS optimized for in situ accessory mineral dating in thin sections. *Geoscience Canada*, **39**: 158-172.
- McHone, J.G., and Butler, J.R. 1984. Mesozoic igneous provinces of New England and the opening of the North Atlantic Ocean. *Geological Society of America Bulletin*, **95**: 757-765.
- McKee, E.D., and Weir, G.W. 1953. Terminology for stratification and cross-stratification in sedimentary rocks. *Geological Society of America -- Bulletin*, **64**: 381-389.
- McKee, E.D., Crosby, E.J., and Berryhill, H.L., J. 1967. Flood deposits, Bijou Creek, Colorado. *Journal of Sedimentary Petrology*, **37**: 829-851.
- McKee, E.D. 1966. Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas). *Sedimentology*, **7**, 3-69.
- McLelland, J., Hamilton, M., Selleck, B., McLelland, J., Walker, D., and Orrell, S. 2001. Zircon U-Pb geochronology of the Ottawa Orogeny, Adirondack Highlands, New York; regional and tectonic implications. *Precambrian Research*, **109**: 39-72.
- McLelland, J.M., Chiarenzelli, J., Whitney, P., and Isachsen, Y. 1988. U-Pb zircon geochronology of the Adirondack Mountains and implications for their geologic evolution. *Geology (Boulder)*, **16**: 920-924.
- McLelland, J.M., Bickford, M.E., Hill, B.M., Clechenko, C.C., Valley, J.W., and Hamilton, M.A. 2004. Direct dating of Adirondack Massif anorthosite by U-Pb SHRIMP analysis of igneous zircon; implications for AMCG complexes. *Geological Society of America Bulletin*, **116**: 1299-1317.

Medina, C.R., and Rupp, J.A. 2012. Reservoir characterization and lithostratigraphic division of the Mount Simon Sandstone (Cambrian); implications for estimations of geologic sequestration storage capacity. *Environmental Geosciences*, **19**: 1-15.

Mehrtens, C.J., and Butler, R.J. 1989. Sedimentology of the Upper Cambrian Danby Formation, western Vermont: an example of mixed siliciclastic and carbonate sedimentation. *Northeastern Geology*, **11**: 84-97.

Miall, A.D., 1996, *The Geology of Fluvial Deposits; Sedimentary Facies, Basin Analysis, and Petroleum Geology*. Springer-Verlag, Berlin.

Miall, A.D. 2010. Alluvial Deposits. *In Facies Models 4 Edited by N.P. James and R.W. Dalrymple*. Geological Association of Canada, St. John's NL, pp. 105.

Middleton, G.V. 1965. Antidune cross-bedding in a large flume. *Journal of Sedimentary Petrology*, **35**: 922-927.

Miller, M.C., and Komar, P.D. 1980. Oscillation sand ripples generated by laboratory apparatus. *Journal of Sedimentary Petrology*, **50**: 173-182.

Mohrig, D., Heller, P.L., Paola, C., and Lyons, W.J. 2000. Interpreting avulsion process from ancient alluvial sequences: Guadalupe-Matarranya system (Northern Spain) and Wasatch formation (Western Colorado). *Bulletin of the Geological Society of America*, **112**: 1787-1803.

Montario, M.J., and Garver, J.I. 2009. The thermal evolution of the Grenville Terrane revealed through U-Pb and fission-track analysis of detrital zircon from Cambro-Ordovician quartz arenites of the Potsdam and Galway Formations. *Journal of Geology*, **117**: 595-614.

Montenat, C., Barrier, P., Ott d'Estevou, P., and Hibsich, C. 2007. Seismites; an attempt at critical analysis and classification. *Sedimentary Geology*, **196**: 5-30.

Morton, A.C., and Hallsworth, C. 1994. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. *Sedimentary Geology*, **90**: 241-256.

Morton, A.C., Claoue-Long, J., and Berge, C. 1996. SHRIMP constraints on sediment provenance and transport history in the Mesozoic Statfjord Formation, North Sea. *Journal of the Geological Society of London*, **153**: 915-929.

Mount, J.F. 1984. Mixing of siliciclastic and carbonate sediments in shallow shelf environments. *Geology (Boulder)*, **12**: 432-435.

Mountney, N.P. 2006. Eolian facies models. *Special Publication - Society for Sedimentary Geology*, **84**: 19-83.

- Mountney, N.P. 2006. Periodic accumulation and destruction of aeolian erg sequences in the Permian Cedar Mesa Sandstone, White Canyon, southern Utah, USA. *Sedimentology*, **53**: 789-823.
- Mulder, T., and Alexander, J. 2001. The physical character of subaqueous sedimentary density flows and their deposits. *Sedimentology*, **48**: 269-299.
- Myrow, P.M., Fischer, W., and Goodge, J.W. 2002. Wave-modified turbidites; combined-flow shoreline and shelf deposits, Cambrian, Antarctica. *Journal of Sedimentary Research*, **72**: 641-656.
- Nadeau, L., and van Breemen, O. 1998. Plutonic ages and tectonic setting of the Algonquin and Muskoka allochthons, Central Gneiss Belt, Grenville Province, Ontario. *Canadian Journal of Earth Sciences*, **35**: 1423-1438.
- Nash, D.J., and Ulliyott, J.S. 2007. Silcrete. *In* *Geochemical sediments and landscapes*, Edited by Nash, D.J., and McLaren, S.J. Wiley-Blackwell, Oxford, UK. pp. 95-148.
- Nichols, G.J., and Fisher, J.A. 2007. Processes, facies and architecture of fluvial distributary system deposits. *Sedimentary Geology*, **195**: 75-90.
- Nichols, R.J., Sparks, R.S.J., and Wilson, C.J.N. 1994. Experimental studies of the fluidization of layered sediments and the formation of fluid escape structures. *Sedimentology*, **41**: 233-253.
- Nilson, T.H., and Sylvester, A.G. 1995. Strike-Slip Basins. *In* *Tectonics of Sedimentary Basins* Edited by C.J. Busby and R.V. Ingersoll. Blackwell Science, Cambridge, MA, pp. 425-458.
- Noffke, N., Gerdes, G., Klenke, T., and Krumbein, W.E. 2001. Microbially induced sedimentary structures; a new category within the classification of primary sedimentary structures. *Journal of Sedimentary Research*, **71**: 649-656.
- North American Commission on Stratigraphic Nomenclature. 2005. North American Stratigraphic Code. *The American Association of Petroleum Geologists Bulletin*, **89**: 1547-1591.
- North, C.P., and Taylor, K.S. 1996. Ephemeral-fluvial deposits: integrated outcrop and simulation studies reveal complexity. *American Association of Petroleum Geologists Bulletin*, **80**: 811-830.
- Nurkhanuly, U. 2012. Structurally controlled hydrothermal dolomite, Eganville-Douglas Paleozoic outlier, Ottawa-Bonnechere Graben, eastern Ontario. MSc Thesis, Carleton University, Ottawa, ON, Canada.

Obermeier, S.F., Pond, E.C., Olson, S.M., and Green, R.A. 2002. Paleoliquefaction studies in continental settings. Special Paper - Geological Society of America, **359**: 13-27.

Olariu, C., Steel, R.J., Dalrymple, R.W., and Gingras, M.K. 2012. Tidal dunes versus tidal bars: The sedimentological and architectural characteristics of compound dunes in a tidal seaway, the lower Baronia Sandstone (Lower Eocene), Ager Basin, Spain. *Sedimentary Geology*, **279**: 134-155.

Olsen, H. 1987. Ancient ephemeral stream deposits; a local terminal fan model from the Bunter sandstone formation (L. Triassic) in the Tonder-3, -4, and -5 wells, Denmark. Geological Society Special Publications, **35**: 69-86.

Olsen, H., Due, P.H., and Clemmensen, L.B. 1989. Morphology and genesis of asymmetric adhesion warts - a new adhesion surface structure. *Sedimentary Geology*, **6**: 277-285.

Otvos, J., E.G. 1966. Sedimentary structures and depositional environments, Potsdam Formation, Upper Cambrian. American Association of Petroleum Geologists -- Bulletin, **50**: 159-165.

Owen, G. 1996. Experimental soft-sediment deformation; structures formed by the liquefaction of unconsolidated sands and some ancient examples. *Sedimentology*, **43**: 279-293.

Owen, G., Moretti, M., and Alfaro, P. 2011. Recognising triggers for soft-sediment deformation; current understanding and future directions. *Sedimentary Geology*, **235**, 133-140.

Paces, J.B., and Miller, J.D., Jr. 1993. Precise U-Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota; geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagnetic processes associated with the 1.1 Ga

Palmer, A.R., and James, N.P. 1980. The Hawke Bay Event; a circum-Iapetus regression near the lower Middle Cambrian boundary. *In* The Caledonides in the U.S.A., Proceedings. Edited by Wones, D.R. Memoir 1, Virginia Polytechnic Institute and State University Department of Geological Sciences, Blacksburg, Virginia. pp. 15-18.

Paola, C., Wiele, S.M., and Reinhart, M.A. 1986. Upper-regime parallel lamination as the result of turbulent sediment transport and low-amplitude bed forms. Abstracts - SEPM Midyear Meeting, **1986**, Vol. 3: 87.

Paola, C., Wiele, S.M., and Reinhart, M.A. 1989. Upper-regime parallel lamination as the result of turbulent sediment transport and low-amplitude bed forms. *Sedimentology*, **36**: 47-59.

- Paton, C., Hellstrom, J., Paul, B., Woodhead, J., and Hergt, J. 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry*, **26**: 2508-2518.
- Payenberg, T., Willis, B., Bracken, B., Posamentier, H.W., Pyrcz, M., Pusca, V., and Sullivan, M.D., 2011, Revisiting the subsurface classification of fluvial sandbodies: American Association of Petroleum Geologists, Search and Discovery Article #90124, 2011 AAPG Annual Convention and Exhibition, April 10–13, 2011, Houston, Texas.
- Petrus, J.A., and Kamber, B.S. 2012. VizualAge: A Novel Approach to Laser Ablation ICP-MS U-Pb Geochronology Data Reduction. *Geostandards and Geoanalytical Research*, **36**: 247-270.
- Pflueger, F., and Gresse, P.G. 1996. Microbial sand chips; a non-actualistic sedimentary structure. *Sedimentary Geology*, **102**: 263-274.
- Plint, G.A. 2010. Wave- and Storm-Dominated Shoreline and Shallow-Marine Systems. *In Facies Models 4 Edited by N.P. James and R.W. Dalrymple*. Geological Association of Canada, St. John's, Canada, pp. 167-200.
- Plint, G.A. 2014. Mud dispersal across a Cretaceous prodelta; storm-generated, wave-enhanced sediment gravity flows inferred from mudstone microtexture and microfacies. *Sedimentology*, **61**: 609-647.
- Poldervaart, A. 1955. Zircons in rocks. *American Journal of Science*, **253**: 433-461.
- Postel, A.W., Nelson, A.E., and Wiesnet, D.R. 1959. Geologic map of the Nicholasville quadrangle, New York. Map GQ-123, United States Geological Survey, Reston, Virginia.
- Pratt, B.R. 2010. Peritidal Carbonates. *In Facies Models 4 Edited by N.P. James and R.W. Dalrymple*. Geological Association of Canada, St. John's, Canada, pp. 401-420.
- Puffer, J.H. 2002. A late Neoproterozoic eastern Laurentian superplume; location, size, chemical composition, and environmental impact. *American Journal of Science*, **302**: 1-27.
- Pulvertaft, T.C.R. 1985. Aeolian dune and wet interdune sedimentation in the middle Proterozoic Dala Sandstone, Sweden. *Sedimentary Geology*, **44**: 93-111.
- Purser, B., Tucker, M., and Zenger, D. 1994. Dolomites; a volume in honour of Dolomieu. Blackwell, Oxford, International, .
- Qian, N. 1990. Fluvial processes in the lower Yellow River after levee breaching at Tongwaxiang in 1855. *International Journal of Sediment Research*, **5**: 1-13.

- Recking, A., Frey, P., Paquier, A., and Belleudy, P. 2009. An experimental investigation of mechanisms involved in bed load sheet production and migration. *Journal of Geophysical Research*, **114**.
- Reed, J.C. 1934. Geology of the Potsdam Quadrangle. *In* New York State Museum Bulletin 297, State Department of Education, Albany, NY, United States. pp. 5-65.
- Reesink, A.J.H., and Bridge, J.S. 2011. Evidence of bedform superimposition and flow unsteadiness in unit-bar deposits, South Saskatchewan River, Canada. *Journal of Sedimentary Research*, **81**: 814-840.
- Retallack, G.J. 1991. Untangling the effects of burial alteration and ancient soil formation. *Annual Review of Earth and Planetary Sciences*, **19**: 183-206.
- Rimando, R.E., and Benn, K. 2005. Evolution of faulting and paleo-stress field within the Ottawa Graben, Canada. *Journal of Geodynamics*, **39**: 337-360.
- Robinson, D.P. 2011. A rare great earthquake on an oceanic fossil fracture zone. *Geophysical Journal International*, **186**: 1121-1134.
- Roden-Tice, M., Tice, S.J., and Schofield, I.S. 2000. Evidence for differential unroofing in the Adirondack Mountains, New York State, determined by apatite fission-track thermochronology. *Journal of Geology*, **108**: 155-169.
- Ross Jr., R.J., Hintze, L.F., Ethington, R.L., Miller, J.F., Taylor, M.E., Repetski, J.E., Sprinkle, J., and Guensburg, T.E. 1997. The Ibexian, lowermost series in the North American Ordovician. *US Geological Survey Professional Paper*, 1579: 1-50.
- Rust, B.R., and Gibling, M.R. 1990. Three-dimensional antidunes as HCS mimics in a fluvial sandstone; the Pennsylvanian South Bar Formation near Sydney, Nova Scotia. *Journal of Sedimentary Petrology*, **60**: 540-548.
- Sager-Kinsman, E., and Parrish, R.R. 1993. Geochronology of detrital zircons from the Elzevir and Frontenac terranes, Central Metasedimentary Belt, Grenville Province, Ontario. *Canadian Journal of Earth Sciences*, **30**: 465-473.
- Salad Hersi, O., Lavoie, D., and Nowlan, G.S. 2003. Reappraisal of the Beekmantown Group sedimentology and stratigraphy, Montreal area, southwestern Quebec; implications for understanding the depositional evolution of the Lower-Middle Ordovician Laurentian passive margin of Eastern Canada. *Canadian Journal of Earth Sciences*, **40**: 149-176.
- Salad Hersi, O., Lavoie, D., Hilowle Mohamed, A., and Nowlan, G.S. 2002. Subaerial unconformity at the Potsdam–Beekmantown contact in the Quebec Reentrant: regional significance for the Laurentian continental margin history. *Bulletin and Canadian Petroleum Geology*, **50**: 419-440.

Salad Hersi, O., and Lavoie, D. 2000. Lithostratigraphic revision of the Upper Cambrian Cairnside Formation, upper Potsdam Group, southwestern Quebec. Current Research 2000-D4, Geological Survey of Canada, Ottawa, ON, Canada.

Salad Hersi, O., and Lavoie, D. 2000. Pre-Cairnside Formation carbonate-rich sandstone: evidence for a Cambrian carbonate platform in southwestern Quebec? Current Research 2000-D3, Geological Survey of Canada, Ottawa, ON, Canada.

Salad Hersi, O., and Dix, G.R. 2006. Precambrian fault systems as control on regional differences in relative sea level along the Early Ordovician platform of eastern North America. *Journal of Sedimentary Research*, **76**: 700-716.

Sambrook Smith, G.H., Ashworth, P.J., Best, J.L., Woodward, J., and Simpson, C.J. 2006. The sedimentology and alluvial architecture of the sandy braided South Saskatchewan River, Canada. *Sedimentology*, **53**: 413-434.

Sanford, B.V. 2007. Stratigraphic and structural framework of the Potsdam Group in eastern Ontario, western Quebec and northern New York State. Ph.D. thesis, Department of Earth Sciences, University of Ottawa, Ontario.

Sanford, B.V., and Arnott, R.W.C. 2010. Stratigraphic and Structural Framework of the Potsdam Group in eastern Ontario, western Quebec and northern New York State. Geological Survey of Canada Bulletin 5907, Geological Survey of Canada, Ottawa, Ontario.

Santos, J.O.S., Hartmann, L.A., McNaughton, N.J., Easton, R.M., Rea, R.G., and Potter, P.E. 2002. Sensitive high resolution ion microprobe (SHRIMP) detrital zircon geochronology provides new evidence for a hidden neoproterozoic foreland basin to the Grenville Orogen in the eastern Midwest, U.S.A. *Canadian Journal of Earth Sciences*, **39**: 1505-1515.

Sappin, A., Constantin, M., Clark, T., and van Breemen, O. 2009. Geochemistry, geochronology, and geodynamic setting of Ni-Cu + or - PGE mineral prospects hosted by mafic and ultramafic intrusions in the Portneuf-Mauricie Domain, Grenville Province, Quebec. *Canadian Journal of Earth Sciences*, **46**: 331-353.

Schmincke, H.-., Fisher, R.V., and Waters, A.C. 1973. Antidune and chute and pool structures in the base surge deposits of the Laacher See area, Germany. *Sedimentology*, **20**: 553-574.

Schumm, S.A., 1960, The shape of alluvial channels in relation to sediment type: U.S. Geological Survey, Professional Paper 352-B, p. 17-30.

Scotese, C.R. 2001. Atlas of Earth History, Volume 1, Paleogeography, PALEOMAP Project. Arlington, Texas.

Seguin, M.K., Rao, K.V., and Arnal, P. 1981. Paleomagnetic study of Cambrian Potsdam Group sandstones, St. Lawrence Lowlands, Quebec. *Earth and Planetary Science Letters*, **55**: 433-449.

Seilacher, A. 2000. Ordovician and Silurian arthropycid ichno-stratigraphy. *In Geological exploration in the Murzuk Basin. Edited by M.A. Sola and D. Worsley. Elsevier, Amsterdam*, pp. 237-258.

Seilacher, A. 2007. Trace fossil analysis. Springer, Berlin.

Selleck, B.W. 1978. Syndepositional brecciation in the Potsdam Sandstone of northern New York State. *Journal of Sedimentary Petrology*, **48**: 1177-1184.

Selleck, B., McLelland, J., and Hamilton, M.A. 2004. Magmatic-hydrothermal leaching and origin of late to post-tectonic quartz-rich rocks, Adirondack Highlands, New York. *In Proterozoic Tectonic Evolution of the Grenville Orogen in North America, Edited by Tollo, R.P., McLelland, J., Corriveau, L., and Bartholomew, M.J. Memoir - Geological Society of America*, **197**: 379-390.

Selleck, B.W. 1975. Paleoenvironments and petrography of the Potsdam Sandstone, Theresa Formation and Ogdensburg Dolomite (U. Camb. - L. Ord.) of the southwestern St. Lawrence Valley, New York. Ph.D. thesis, Department of Geology, University of Rochester, Rochester, New York.

Selleck, B.W. 1978. Paleoenvironments of the Potsdam Sandstone and Theresa Formation of the southwestern St. Lawrence Lowlands. *Guidebook - New York State Geological Association, Meeting*: 173-188.

Selleck, B.W. 1993. Sedimentology and diagenesis of the Potsdam Sandstone and Theresa Formation, southwestern St. Lawrence Valley. *In Field Trip Guidebook - New York State Geological Association, 65th Annual Meeting, Canton, New York*. pp. 219-228.

Sengor, A.M.C. 1995. Sedimentation and Tectonics of Fossil Rifts. *In Tectonics of Sedimentary Basins Edited by C.J. Busby and R.V. Ingersoll. Blackwell Science, Cambridge, MA*, pp. 53-118.

Shaw, A.B. 1958. Stratigraphy and structure of the Saint Albans area, northwestern Vermont. *Bulletin of the Geological Society of America*, **69**: 519-567.

Shrake, D.L. 1991. The Middle Run Formation; a subsurface stratigraphic unit in southwestern Ohio. *The Ohio Journal of Science*, **91**: 49-55.

Shrake, D.L., Carlton, R.W., Wickstrom, L.H., Potter, P.E., Richard, B.H., Wolfe, P.J., and Sitler, G.M. 1991. Pre-Mount Simon basin under the Cincinnati Arch. *Geology*, **19**: 139-142.

Singer, A. 1975. A Cretaceous laterite in the Negev Desert, southern Israel. *Geological Magazine*, **112**: 151-162.

Skelly, R.L., Bristow, C.S., and Ethridge, F.G. 2003. Architecture of channel-belt deposits in an aggrading shallow sandbed braided river: The lower Niobrara River, northeast Nebraska. *Sedimentary Geology*, **158**: 249-270.

Sloss, L.L. 1963. Sequences in the cratonic interior of North America. *Geological Society of America Bulletin*, **74**: 93-113.

Sloss, L.L. 1959. Sequences in the cratonic interior of North America. *Bulletin of the Geological Society of America*, **70**: 1676-1677.

Smith, G.A. 1986. Coarse-grained nonmarine volcanoclastic sediment; terminology and depositional process. *Geological Society of America Bulletin*, **97**: 1-10.

Smoot, J.P., and Castens-Seidell, B. 1994. Sedimentary features produced by efflorescent salt crusts, Saline Valley and Death Valley, California. *In Sedimentology and Geochemistry of Modern and Ancient Saline Lakes, Edited by Renaut, R.W., and Last, W.M. Special Publication - Society for Sedimentary Geology*, **50**: 73-90.

Sonderholm, M., and Tirsgaard, H. 1998. Proterozoic fluvial styles; response to changes in accommodation space (Rivieradal sandstones, eastern North Greenland). *Sedimentary Geology*, **120**: 257-274.

Southard, J.B., and Boguchwal, L.A. 1990. Bed configuration in steady unidirectional water flows; Part 2, Synthesis of flume data. *Journal of Sedimentary Petrology*, **60**: 658-679.

Southard, J.B., Lambie, J.M., Federico, D.C., Pile, H.T., and Weidman, C.R. 1990. Experiments on bed configurations in fine sands under bidirectional purely oscillatory flow, and the origin of hummocky cross-stratification. *Journal of Sedimentary Petrology*, **60**: 1-17.

Stanley, R. 1999. The Champlain thrust fault at Lone Rock Point. Annual Meeting - New England Intercollegiate Geological Conference, **91**: 359-364.

Stear, W.M. 1985. Comparison of the bedform distribution and dynamics of modern and ancient sandy ephemeral flood deposits in the southwestern Karoo region, South Africa. *Sedimentary Geology*, **45**: 209-230.

Sumner, E.J., Amy, L.A., and Talling, P.J. 2008. Deposit structure and processes of sand deposition from decelerating sediment suspensions. *Journal of Sedimentary Research*, **78**: 529-547.

Sylvester, Z., Pirmez, C., and Cantelli, A. 2011. A model of submarine channel-levee evolution based on channel trajectories: Implications for stratigraphic architecture. *Marine and Petroleum Geology*, **28**: 716-727.

Thiry, M. 1999. Diversity of continental silicification features; examples from the Cenozoic deposits in the Paris Basin and neighbouring basement. *In* Palaeoweathering, palaeosurfaces and related continental deposits, *Edited by* Thiry, M., Simon-Coincon, R. Special Publication of the International Association of Sedimentologists 27, International Association of Sedimentologists, Ghent, Belgium. pp. 87-127.

Thomas, W.A. 1991. The Appalachian-Ouachita rifted margin of southeastern North America. *Geological Society of America Bulletin*, **103**: 415-431.

Thomas, W.A. 2006. Tectonic inheritance at a continental margin. *GSA Today*, **16**: 4-11.

Timmermann, H., Parrish, R.R., Jamieson, R.A., and Culshaw, N.G. 1997. Time of metamorphism beneath the Central Metasedimentary Belt boundary thrust zone, Grenville Orogen, Ontario: accretion at 1080 Ma? *Canadian Journal of Earth Sciences*, **34**: 1023-1029.

Tooth, S. 1999. Floodouts in central Australia. *Geomorphology Publication - International Association of Geomorphologists*, **7**: 219-247.

Tooth, S. 2000. Process, form and change in dryland rivers; a review of recent research. *Earth-Science Reviews*, **51**: 67-107.

Tooth, S. 2000. Downstream changes in dryland river channels; the Northern Plains of arid central Australia. *Geomorphology*, **34**: 33-54.

Tornqvist, T.E., and Bridge, J.S. 2002. Spatial variation of overbank aggradation rate and its influence on avulsion frequency. *Sedimentology*, **49**: 891-905.

Torsvik, T.H., Smethurst, M.A., Meert, J.G., and Van, D.V. 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic - A tale of Baltica and Laurentia. *Earth Science Reviews*, **40**: 229-229.

Tunbridge, I.P. 1984. Facies model for a sandy ephemeral stream and clay playa complex; the Middle Devonian Trentishoe Formation of North Devon, UK. *Sedimentology*, **31**: 697-715.

Umhoefer, P.J., Schwennicke, T., Del Margo, M.T., Ruiz-geraldo, G., Ingle, J.C., and McIntosh, W. 2007. Transtensional fault-termination basins: An important basin type illustrated by the Pliocene San Jose Island basin and related basins in the southern Gulf of California, Mexico. *Basin Research*, **19**: 297-322.

Valley, P.M., Hanchar, J.M., and Whitehouse, M.J. 2011. New insights on the evolution of the Lyon Mountain Granite and associated Kiruna-type magnetite-apatite deposits, Adirondack Mountains, New York State. *Geosphere*, **7**: 357-389.

van Breemen, O., and Davidson, A. 1988. Northeast extension of Proterozoic terranes of mid-continental North America. *Geological Society of America Bulletin*, **100**: 630-638.

van Breemen, O., and Davidson, A. 1990. U-Pb zircon and baddeleyite ages from the Central Gneiss Belt, Ontario. Paper - Geological Survey of Canada, **89-02**: 85-92.

van Breemen, O., Davidson, A., Loveridge, W.D., and Sullivan, R.W. 1986. U-Pb zircon geochronology of Grenville tectonites, granulites and igneous precursors, Parry Sound, Ontario. Special Paper - Geological Association of Canada, **31**: 191-207.

van Staal, C.R., Whalen, J.B., McNicoll, V.J., Pehrsson, S., Lissenberg, C.J., Zagorevski, A., van Breemen, O., and Jenner, G.A. 2007. The Notre Dame Arc and the Taconic Orogeny in Newfoundland. *In* 4-D Framework of Continental Crust, *Edited by* Hatcher, R.D., Carlson, M.P., McBride, J.H., and Martinez Catalan, J.R. Memoir - Geological Society of America, **200**: 511-552.

Venditti, J.G., Church, M., and Bennett, S.J. 2005. On the transition between 2D and 3D dunes. *Sedimentology*, **52**: 1343-1359.

Vogel, M.B., Des Marais, D.J., Turk, K.A., Parenteau, M.N., Jahnke, L.L., and Kubo, M.D.Y. 2009. The role of biofilms in the sedimentology of actively forming gypsum deposits at Guerrero Negro, Mexico. *Astrobiology*, **9**: 875-893.

Walcott, C.D. 1891. Correlation papers, Cambrian. U.S. Geological Survey Bulletin 81, U.S. Geological Survey, Reston, VA, United States.

Waldron, J.W.F., and van Staal, C.R. 2001. Taconian Orogeny and the accretion of the Dashwoods Block; a peri-Laurentian microcontinent in the Iapetus Ocean. *Geology*, **29**: 811-814.

Wasteneys, H., McLelland, J., and Lumbers, S. 1999. Precise zircon geochronology in the Adirondack Lowlands and implications for revising plate-tectonic models of the Central Metasedimentary Belt and Adirondack Mountains, Grenville Province, Ontario and New York. *Canadian Journal of Earth Sciences*, **36**: 967-984.

Watson, A., and Nash, D.J. 1997. Desert crusts and varnishes. *In* Arid zone geomorphology; process, form and change in drylands, *Edited by* Thomas, D.S.G. Wiley-Blackwell, Oxford, UK. pp. 69-107.

Weissel, J.K., and Karner, G.D. 1989. Flexural uplift of rift flanks due to mechanical unloading of the lithosphere during extension. *Journal of Geophysical Research*, **94**: 13,919-13,950.

Werner, B.T., and Merino, E. 1997. Concave sand grains in eolian environments; evidence, mechanism, and modeling. *Journal of Sedimentary Research*, **67**: 754-762.

Wheeler, R.L. 2002. Distinguishing seismic from nonseismic soft-sediment structures; criteria from seismic-hazard analysis. *In* Ancient Seismites, *Edited by* Etensohn, F.R., Rast, N., and Brett, C.E. Special Paper - Geological Society of America, **359**: 1-11.

Whiting, P.J., Dietrich, W.E., Leopold, L.B., Drake, T.G., and Shreve, R.L. 1988. Bedload sheets in heterogeneous sediment. *Geology*, **16**: 105-108.

Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Von Quadt, A., Roddick, J.C., and Spiegel, W. 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. *Geostandards Newsletter*, **19**: 1-23.

Wiesnet, D.R., and Clark, T.H. 1966. The bedrock structure of Covey Hill and vicinity, northern New York and southern Quebec. U.S.Geological Survey Professional Paper 550-D: D35-D38.

Williams, D.A., and Wolf, R.R. 1984a. Paleozoic geology of the Westport area, southern Ontario. Ontario Geological Survey, Map P.2723.

Williams, D.A., Rae, A.M., and Wolf, R.R. 1984. Paleozoic geology of the Ottawa area, southern Ontario. Ontario Geological Survey, Map P.2716.

Williams, D.A., Rae, A.M., and Wolf, R.R. 1985. Paleozoic geology of the Russell-Thurso area, southern Ontario. Ontario Geological Survey, Map P.2717.

Wilson, M.D. 1992. Inherited grain-rimming clays in sandstones from eolian and shelf environments: their origin and control on reservoir properties. *In* Origin, diagenesis, and petrophysics of clay minerals in sandstones *Edited by* D.W. Houseknecht and E.D. Pittman. SEPM, pp. 209-225.

Wilson, A.E. 1946. Geology of Ottawa–St. Lawrence lowland, Ontario and Quebec. Geological Survey of Canada Memoir 241, Geological Survey of Canada, Ottawa, Ontario.

Wodicka, N., Parrish, R.R., and Jamieson, R.A. 1996. The Parry Sound domain: a far-travelled allochthon? New evidence from U-Pb zircon geochronology. *Canadian Journal of Earth Sciences*, **33**: 1087-1104.

Wodicka, N., Corriveau, L., and Stern, R.A. 2004. SHRIMP U-Pb zircon geochronology of the Bondy gneiss complex; evidence for circa 1.39 Ga arc magmatism and polyphase Grenvillian metamorphism in the Central Metasedimentary Belt, Grenville Province, Quebec. *In* Proterozoic Tectonic Evolution of the Grenville Orogen in North America, *Edited by* Tollo, R.P., McLelland, J., Corriveau, L., and Bartholomew, M.J. Memoir - Geological Society of America, **197**: 243-266.

Wolf, R.R., and Dalrymple, R.W. 1984. Sedimentology of the Cambro-Ordovician sandstones of eastern Ontario. *In* Geoscience Research Grant Program Summary of Research 1983 – 1984. *Edited by* Milne, V.G. Ontario Geological Survey Miscellaneous Paper 121, Ontario Geological Survey, Sudbury, Ontario. pp. 240-252.

Wolman, M.G., and Brush, L.M., Jr, 1961, Factors controlling size and shape of stream channels in coarse noncohesive sands: U.S. Geological Survey, Professional Paper 282-G, p. 191-210.

Woodward, H.P. 1961. Preliminary subsurface study of southeastern Appalachian Interior Plateau. Bulletin of the American Association of Petroleum Geologists, **45**: 1634-1655.

Yalin, M.S. 1964. Geometrical properties of sand waves. ASCE -- Proceedings, Journal of the Hydraulics Division, **90**: 105-119.

Yamaguchi, K.E., and Ohmoto, H. 2006. Geochemical and isotopic constraints on the origin of Paleoproterozoic red shales of the Gamagara/Mapedi Formation, Postmasburg Group, South Africa. South African Journal of Geology, **109**: 123-138.

Yang, B.C., Dalrymple, R.W., and Chun, S.S. 2005. Sedimentation on a wave-dominated, open-coast tidal flat, south-western Korea; summer tidal flat-winter shoreface. Sedimentology, **52**: 235-252.

Yang, B.C., Dalrymple, R.W., Chun, S.S., and Lee, H.J. 2006. Transgressive sedimentation and stratigraphic evolution of a wave-dominated macrotidal coast, western Korea. Marine Geology, **235**: 35-48.

Yang, B., Dalrymple, R.W., and Chun, S. 2006. The significance of hummocky cross-stratification (HCS) wavelengths; evidence from an open-coast tidal flat, South Korea. Journal of Sedimentary Research, **76**: 2-8.

Zoback, M.D., and Zoback, M.L. 1981. State of stress and intraplate earthquakes in the United States. Science, **213**: 96-1904.

Zoback, M.L. 1992. Stress field constraints on intraplate seismicity in eastern North America. Journal of Geophysical Research, **97**: 11761-82.

Zoback, M.L. 1992. Stress field constraints on intraplate seismicity in eastern North America. Journal of Geophysical Research, **97**: 11761-82.

Zoback, M.D., and Zoback, M.L. 1981. State of stress and intraplate earthquakes in the United States. Science, **213**: 96-104.

Appendix A: Outcrop locations (UTM Zone 18)

Station	Easting	Northing	Lithostratigraphic unit(s)	Allounit(s)	Facies association(s)
1	428410E	5017535N	Keeseville	A3	FA4
2	476500E	5041500N	Keeseville, Riviere Aux Outardes Mb	A2,A3	FA5,FA2
3	456144E	5017333N	Keeseville, Theresa	A3	
4	431613E	5016545N	Keeseville	A3	FA4
5	428366E	5017546N	Keeseville	A3	FA4
6	433101E	5019021N	Keeseville	A3	FA4
7	432561E	5019471N	Keeseville	A3	FA4
8	451415E	5037084N	Keeseville	A3	FA5
9	446257E	5038385N	Keeseville	A3	FA5
10	434158E	5016130N	Keeseville	A3	FA4
11	404625E	5007425N	Keeseville/Theresa	A3	FA4
12	406309E	4958089N	Ausable	A1	FA2
13	424892E	5021437N	Keeseville	A3	FA4
14	428532E	5017954N	Keeseville	A3	FA4
15	432100E	5018900N	Keeseville	A2,A3	FA5,FA4
16	412659E	4959755N	Keeseville	A2,A3	FA2,FA5
17	409459E	4943600N	Theresa		
18	466858E	5043335N	Keeseville	A2,A3	FA1,FA2, FA5
19	466735E	5043381N	Keeseville	A2,A3	FA1,FA2, FA5
20	438347E	4936282N	Keeseville	A3	
21	437243E	4936854N	Keeseville	A3	
22	409758E	4910883N	Keeseville	A2	FA1,FA2
23	409935E	4911053N	Keeseville	A2	FA2
24	400334E	4907867N	Keeseville	A2	FA2
25	394883E	4905508N	Ausable	A1	FA1 (talus)
26	389520E	4912016N	Hannawa Falls	A1	FA3
27	390789E	4912949N	Hannawa Falls, Keeseville	A1,A2	FA3,FA2,FA5
28	393900E	4916616N	Hannawa Falls, Keeseville	A1,A2	FA3,FA2
29	388789E	4915324N	Hannawa Falls, Keeseville	A1	FA3
30	420310E	4916935N	Keeseville	A3	FA5
31	418837E	4918914N	Keeseville	A3	FA5
32	414065E	4918878N	Keeseville	A3	FA5
33	411073E	4934054N	Keeseville	A2(?)	FA1(?)
34	411723E	4935120N	Keeseville	A2, A3	FA1/FA2(?),FA5

Station	Easting	Northing	Lithostratigraphic unit(s)	Allounit(s)	Facies association(s)
35	41128E	4934508N	Keeseville	?	?
36	411789E	4935700N	Keeseville	A2,A3	FA1,FA5
37	413074E	4938852N	Keeseville	A3	FA5
38	412637E	4939140N	Hannawa Falls, Keeseville	A1,A3	FA3(?),FA5
39	410906E	4941216N	Keeseville	A2	FA2
40	410302E	4942614N	Theresa, Keeseville(?)	A3(?)	FA5
41	410200E	4926500N	Hannawa Falls, Keeseville	A1,A2	FA3,FA2
42	400801E	4942483N	Keeseville	A3	FA5
43	400635E	4942884N	Keeseville	A3	FA5
44	408050E	4952939N	Keeseville	A3	FA4
45	410236E	4943153N	Theresa		
46	406186E	4938443N	Keeseville	A2	FA2
47	406002E	4936441N	Keeseville	A2	FA2
48	406107E	4937167N	Keeseville	A2	FA2
49	406436E	4938186N	Keeseville	A2	FA2
50	405868E	4938840N	Keeseville	A2	FA2
51	403630E	4939348N	Keeseville, Theresa	A3	FA5
52	404090E	4934500N	Ausable(?), Keeseville	A1(?), A2	
53	401924E	4933165N	Ausable, Hannawa Falls, Keeseville	A1,A2,A3	FA1,FA3,FA2
54	392520E	4919926N	Hannawa Falls, Keeseville	A1,A2	FA3(?),FA2
55	417600E	4928400N	Keeseville	A2	FA1
56	418797E	4929750N	Keeseville	A2	FA1
57	419185E	4929705N	Keeseville	A2	FA1
58	419237E	4929533N	Keeseville	A2	FA1
59	419377E	4929413N	Hannawa Falls, Keeseville	A1,A2	FA3(?), FA1
60	417986E	4928498N	Keeseville	A2	FA1
61	402834E	4940012N	Keeseville	A3	FA5
62	419020E	4934942N	Hannawa Falls(?)/Keeseville(?)	A1(?)/A2(?)	FA3 or FA2
63	419521E	4936705N	Keeseville	A3	FA5
64	418470E	4937296N	Keeseville	A3	FA5
65	416993E	4937131N	Theresa		
66	409120E	4943496N	Theresa		
67	397051E	4936100N	Hannawa Falls	A1	FA3
68	408560E	4926077N	Hannawa Falls, Keeseville	A1,A2	FA3,FA2
69	439420E	4934025N	Theresa		
70	427442E	4937404N	Keeseville, Theresa(?)	A2,A3	FA1,FA5
71	411723E	4935120N	Keeseville	A2	FA1 (talus)
72	439028E	4932723N	Theresa		

Station	Easting	Northing	Lithostratigraphic unit(s)	Allounit(s)	Facies association(s)
73	436810E	4929860N	Ausable	A1	FA1 (talus)
74	408423E	4967610N	Hannawa Falls, Keeseville	A1,A2	FA3,FA2
75	405884E	4967820N	Hannwa Falls, Keeseville	A1,A3	FA3,FA5
76	405560E	4969200N	Keeseville	A3	FA5
77	445044E	4918560N	Theresa		
78	445882E	4922357N	Keeseville	A2	FA2,FA1
79	446373E	4922953N	Keeseville	A2,A3	FA2,FA1,FA5
80	446578E	4923110N	Keeseville	A2	FA2(?)
81	443393E	4918878N	Keeseville	A2	FA2
82	443719E	4919166N	Keeseville	A2	FA2
83	443794E	4919361N	Theresa		
84	442480E	4917865N	Keeseville	A2	FA1
85	441971E	4916836N	Keeseville	A2	FA2,FA1
86	437384E	4917814N	Hannawa Falls, Keeseville	A1, A2, A3	FA3,FA2,FA5
87	439288E	4924031N	Keeseville, Theresa	A2,A3	FA2,FA5
88	438760E	4925121N	Keeseville, Theresa	A2,A3	FA2,FA5
89	445809E	4934582N	Theresa		
90	446606E	4935379N	Theresa		
91	451726E	4934628N	Theresa		
92	451129E	4934422N	Theresa		
93	445752E	4927775N	Keeseville	A2	FA2
94	445788E	4927349N	Keeseville	A2	FA2
95	440606E	4915124N	Keeseville	A2	FA2
96*	439850E	4914411N	Keeseville	A2	FA2
97*	439147E	4903800N	Hannawa Falls, Keeseville	A1,A2,A3	FA3,FA2,FA5
98	433100E	4906750N	Keeseville	A2	FA2
99	433345E	4909883N	Keeseville	A2	FA2
100	432072E	4912176N	Keeseville	A2	FA1,FA2
101	433061E	4913021N	Keeseville	A2	FA2
102	438315E	4919418N	Keeseville	A2	FA2
103	438570E	4919804N	Keeseville	A2	FA2
104	440433E	4921840N	Keeseville	A2,A3	FA2,FA5
105	437087E	4908957N	Hannawa Falls(?), Keeseville	A1(?),A2	FA3(?),FA2
106	437437E	4908477N	Keeseville	A2	FA2
107	437279E	4908026N	Hannawa Falls	A1	FA3(?),FA2(?)
108	435928E	4912880N	Keeseville	A2	FA2
109	435692E	4911863N	Keeseville	A2	FA2
110	435716E	4910730N	Keeseville	A2	FA2
111	439278E	4919731N	Keeseville	A2	FA2

Station	Easting	Northing	Lithostratigraphic unit(s)	Allounit(s)	Facies association(s)
112	430118E	4910676N	Keeseville	A2	FA2, FA1
113	428485E	4910354N	Keeseville	A2	FA2
114	427991E	4907977N	Keeseville	A2	FA2
115	428384E	4907702N	Keeseville	A2	FA2, FA1
116	420262E	4902815N	Keeseville	A2	FA1
117	419813E	4907507N	Keeseville	A2,A3	FA1,FA5
118	419304E	4907018N	Keeseville	A2	FA1
119	420556E	4905987N	Keeseville	A2	FA1
120	42096E	4906258N	Keeseville	A2	FA1
121	428739E	4905147N	Ausable	A1	FA1
122	459204E	4935637N	Keeseville	A2	FA2
123	435912E	4906623N	Keeseville	A3	FA5
124	436930E	4904803N	Ausable, Hannawa Falls, Keeseville	A1, A2, A3	FA3,FA1,FA2,FA5
125	438709E	4902532N	Keeseville	A2	FA1,FA2
126	438835E	4903238N	Keeseville	A2	FA2
127	438035E	4901897N	Keeseville	A2	FA1,FA2
128	436662E	4901203N	Keeseville	A3	FA5
129	436714E	4896198N	Hannawa Falls, Keeseville	A1,A2	FA3,FA2
130	434488E	4897850N	Keeseville	A2	FA2
131	434524E	4898624N	Keeseville	A2	FA2(?)
132	444644E	4919555N	Keeseville	A2	FA2
133	441881E	4925625N	Keeseville, Theresa	A2,A3(?)	FA2,FA5(?)
134	438818E	4911917N	Keeseville	A2	FA2
135	438131E	4910922N	Keeseville	A2,A3	FA2,FA5
136	453297E	4930718N	Keeseville, Theresa	A2	FA2
137	609246E	4951133N	Keeseville	A2 or A3 (?)	FA2
138	605142E	4962498N	Ausable (Altona Mb)	A1	FA6
139	604306E	4964042N	Ausable	A1	FA1
140	606289E	4965515N	Ausable	A1	FA1
141	613796E	4964152N	Ausable	A1	FA1
142	616944E	4968144N	Ausable	A1	FA1
143	615550E	4977500N	Ausable	A1	FA1
144	614909E	4972049N	Ausable	A1	FA1
145	612041E	4979382N	Keeseville	A2	FA1
146	613126E	4979347N	Keeseville	A2/A3(?)	FA2
147	607190E	4978930N	Theresa		
148	607489E	4975630N	Keeseville	A3(?)	FA2
149	607362E	4975009N	Keeseville	A2/A3(?)	FA2

Station	Easting	Northing	Lithostratigraphic unit(s)	Allounit(s)	Facies association(s)
150	607553E	4975171N	Keeseville	A2/A3(?)	FA2
151	606954E	4971427N	Keeseville	A2/A3(?)	FA2
152	606129E	4970511N	Keeseville	A3	FA2
153	601528E	4968118N	Keeseville	A2	FA1
154	593181E	4965010N	Ausable	A1	FA1
155	596018E	4968465N	Keeseville	A2	FA1
156	602060E	4971946N	Keeseville	A2/A3(?)	FA2
157	602346E	4973096N	Keeseville	A2/A3(?)	FA2
158	599828E	4974794N	Ausable	A1	FA1
159	599432E	4975691N	Keeseville	A2/A3(?)	FA1/FA2(?),FA5
160	599401E	4979574N	Keeseville	A3	FA2,FA4/FA5(?)
161	590915E	4979343N	Keeseville	A2/A3(?)	?
162	595059E	4974729N	Keeseville	A2	FA1
163	596210E	4973222N	Keeseville	A2	FA1
164	553696E	4971879N	Keeseville	A2/A3(?)	FA2
165	555281E	4968634N	Keeseville	A2/A3(?)	FA2
166	566954E	4967703N	Keeseville	A3	FA3
167	565785E	4971310N	Keeseville	A2/A3(?)	FA2
168	571974E	4972971N	Keeseville	A2,A3(?)	FA1,FA2
169	578785E	4976078N	Keeseville	A2/A3(?)	FA2
170	578778E	4979604N	Theresa		
171	594549E	4985748N	Ausable	A1	FA1
172	591513E	4987598N	Ausable	A1	FA1
173	591518E	4987409N	Ausable	A1	FA1
174	596274E	4988706N	Ausable	A1	FA1
175	591518E	4987409N	Ausable	A1	FA1
176	582697E	4986664N	Ausable, Keeseville	A1,A2	FA1,FA2
177	587545E	4996190N	Keeseville	A2	FA1
178	588478E	4995998N	Keeseville	A2/A3(?)	FA1/FA2(?)
179	597337E	4994954N	Ausable	A1	FA1
180	605274E	4969400N	Keeseville	A3	FA2
181	594313E	4983944N	Ausable	A1	FA1
182	596999E	4982373N	Keeseville	A3	FA4
183	596829E	4982215N	Ausable	A1	FA1
184	613811E	4964510N	Ausable (Altona Mb)	A1	FA6
185	613697E	4964682N	Ausable (Altona Mb)	A1	FA6
186	613609E	4964838N	Ausable (Altona Mb)	A1	FA6
187	606790E	4971231N	Keeseville	A3	FA2
188	567998E	4968956N	Keeseville	A3	FA3
189	618328E	4972073N	Keeseville	A2	FA1

Station	Easting	Northing	Lithostratigraphic unit(s)	Allounit(s)	Facies association(s)
190	622110E	4931262N	Keeseville	A2/A3(?)	FA4
191	614416E	4942797N	Keeseville	A2/A3(?)	FA2/FA4(?)
192	502050E	4941190N	Hannawa Falls	A1	FA3
193	426429E	5021230N	Keeseville	A3	FA4
194	581384E	5026425N	Ausable	A1	FA1
195	406748E	4987293N	Theresa		
196	410500E	4931581N	Keeseville	A3	FA5
197	402960E	4994955N	Theresa		
198	410267E	4943141N	Theresa		
199	609922E	4985482N	Theresa		
200	598852E	4985199N	Keeseville	A3	FA2
201	598892E	4984397N	Keeseville	A3	FA4,FA5
202	583224E	4983511E	Keeseville	A3	FA2,FA1
203	599473E	4984382E	Keeseville	A2,A3	FA2,FA3
204	582677E	4986297N	Keeseville	A2	FA1
205	580882E	5018775N	Keeseville	A3	FA4?
206	582693E	5018872N	Theresa		
207	583452E	5018314N	Keeseville	A3	FA4
208	584834E	5018560N	Theresa		
209	606640E	4999246N	Keeseville	A3	FA2,FA4
210	606398E	4998249N	Keeseville	A3	FA2,FA4
211	413363E	4898029N	Keeseville	A2,A3	FA1,FA5
212	438023E	4895608N	Keeseville	A2	FA2
213	438224E	4895489N	Keeseville	A2	FA2
214	433832E	4895554N	Keeseville	A2	FA2
215	440768E	4905993N	Keeseville	A2,A3	FA2,FA4
216	456401E	4926435N	Keeseville	A2	FA2
217	456684E	4926584N	Hannawa Falls, Keeseville	A1,A2	FA3,FA1
218	463886E	4915571N	Grenville, Potsdam(?)		
219	463703E	4922376N	Keeseville	A2	FA1,FA2
220	501982E	4940024N	Hannawa Falls	A1	FA3
221	428581E	5017967N	Keeseville	A3	FA4
222	432025E	5019788N	Keeseville, Theresa	A3	FA4, FA5
223	435048E	4926711N	Keeseville, Theresa	A3	FA5
224	410540E	4932214N	Keeseville	A3	FA5
225	408856E	4943563N	Theresa		
226	590138E	4969888N	Ausable	A1	FA1
227	589065E	4972039N	Ausable	A1	FA1
228	588932E	4970698N	Ausable	A1	FA1
229	585834E	4970134N	Ausable	A1	FA1

Station	Easting	Northing	Lithostratigraphic unit(s)	Allounit(s)	Facies association(s)
230	585361E	4970054N	Ausable	A1	FA1
231	581656E	4971334N	Keeseville	A2	FA1
232	613553E	4964937N	Ausable (Altona Mb)	A1	FA6
233	613507E	4964930N	Ausable (Altona Mb)	A1	FA6
234	613695E	4964708N	Ausable (Altona Mb)	A1	FA6
235	418867E	4929772N	Keeseville	A2	FA1
236	419593E	4907399N	Keeseville	A2,A3	FA1,FA5
237	598869E	4978700N	Keeseville	A2	FA4
238	598187E	4981380N	Keeseville	A3	FA4
239	607972E	4975007N	Theresa		
240	437567E	5016003N	Theresa		
241	419635E	4929836N	Keeseville	A2	FA1
242	610377E	4963628N	Ausable	A1	FA1
243	601718E	5000408N	Theresa		
244	620920E	4929374N	Keeseville	A2	FA4
245	619411E	4938962N	Ausable	A1	FA1
246	527007E	4949163N	Ausable	A1	FA2
247	593625E	4971348N	Keeseville	A2/A3(?)	FA4(?)
248	594515E	4970959N	Keeseville	A2/A3(?)	FA4(?)
249	593134E	4976793N	Keeseville	A2/A3(?)	FA4
250	594572E	4978219N	Keeseville	A2	FA1
251	611651E	4966942N	Ausable	A1	FA1
252	611039E	4967555N	Ausable	A1	FA1
253	611507E	4967118N	Ausable	A1	FA1
254	611451E	4966948N	Ausable	A1	FA1
255	611470E	4967221N	Ausable	A1	FA1
256	612969E	4965082N	Ausable (Altona Mb)	A1	FA6,FA1
257	612135E	4961074N	Ausable (Altona Mb)	A1	FA6
258	607422E	4970155N	Ausable/Keeseville	A1/A2	FA1/FA2
259	608632E	4969178N	Ausable	A1	FA1
260	523192E	4949375N	Keeseville	A2	FA2
261	522532E	4950295N	Keeseville	A2	FA2
262	512010E	4944717N	Ausable	A1	FA1
263	583425E	4985478N	Keeseville	A2	FA1
264	461662E	4917918N	Keeseville	A2	FA2
265	623408E	4972301N	Ausable	A1	FA1
266	612817E	4942641N	Keeseville	A2	FA1
267	595257E	4973408N	Keeseville	A2	FA1
268	594708E	4973110N	Keeseville	A2	FA2
269	589648E	5024071N	Keeseville	A3	FA4

Station	Easting	Northing	Lithostratigraphic unit(s)	Allounit(s)	Facies association(s)
270	582629E	5025250N	Ausable	A1	FA1
271	582128E	5020372N	Ausable	A1	FA1
272	583763E	4985439N	Keeseville	A2	FA2
272	584159E	4985505N	Keeseville	A3	FA2, FA4
273	584861E	5020399N	Keeseville	A2	FA2
274	587817E	5018305N	Keeseville	A2	FA3
275	584229E	5018019N	Keeseville	A3	FA4
276	599568E	4771806N	Galway		
277	624473E	4809849N	"Potsdam"/Keeseville		FA5
278	629392E	4823707N	"Potsdam"/Keeseville		FA4
279	628073E	4843876N	Galway(?)		
280	628335E	4846028N	Ausable	A1	FA1
281	626965E	626965N	"Potsdam"/Keeseville		FA4
282	582586E	5020461N	Ausable	A1	FA1
283	431772E	5020145N	Keeseville	A3	FA4
284	418558E	4929140N	Keeseville	A2	FA1
285	437746E	4898717N	Hannawa Falls, Keeseville	A1,A2	FA3,FA2
286	396072E	4968341N	Keeseville	A3	FA5
287	402586E	4969931N	Keeseville	A3	FA5
288	399173E	4962399N	Keeseville	A3	FA5
289	397831E	4961590N	Hannawa Falls	A1	FA3
290	396844E	4949974N	Keeseville	A2	FA2
291	383376E	4945381N	Ausable	A1	FA1
292	381535E	4945977N	Ausable	A1	FA1
293	447399E	5041600N	Keeseville	A3	FA5
294	445667E	5040881N	Keeseville	A3	FA5
295	562758E	5049488N	Keeseville	A3	FA4
296	564490E	5058740N	Keeseville	A3	FA4

Appendix B: Biostratigraphic analysis from the Riviere Aux Outardes Member, Rockland, ON.

Report No. 004-GSN-2013

Report on two samples from Lower Ordovician strata in the vicinity of Rockland in eastern Ontario submitted for conodont analysis by David Lowe and Bill Arnott (University of Ottawa); NTS 031G/11; CON # 1777.

All references to age determinations and paleontological data must quote the authorship of the report, and the unique GSC Curation Number of the fossil collection. If the report is cited in a publication, it should be included in the References Cited section as:

"Nowlan, G.S., 2013. Report on two samples from Lower Ordovician strata in the vicinity of Rockland in eastern Ontario submitted for conodont analysis by David Lowe and Bill Arnott (University of Ottawa); NTS 031G/11; CON # 1777. Geological Survey of Canada, Paleontological Report 004-GSN-2013, 4 p."

Reference to, or reproduction of, paleontological data and age determinations in publications must be approved by the author of the Paleontological Report prior to manuscript submission. If the author is not available, the Chief Paleontologist, Geological Survey of Canada (Calgary) should be consulted for possible revision. Substantial use of paleontological and age data in publications should be reflected in the publications' authorship.

Material: Two rocks samples processed completely in the GSC Calgary Conodont Laboratory. The first sample was submitted by David Lowe and Bill Arnott from the University of Ottawa and the second sample was collected by the author and David Lowe, taking advantage of a visit to Ottawa by the author. The samples, both from the same unit, broke down very slowly but completely in acid; however, the separation of the residue resulted in extremely large heavy fractions to be picked for conodonts. Both samples were picked for about ten hours each until a point was reached that no conodonts were observed on the picking tray for five consecutive trays. Much heavy residue remains for both samples, but we believe we have recovered a majority of specimens in the samples.

1. Locality: GSC loc. C-450794; Chippewa Bay Member of the Covey Hill Formation; isolated outcrop in north Rockland, Ontario: outcrop is west of Edward Street and northwest of Woods Street at the south end of an apartment building; latitude 45°33'10.0"N; longitude 075°17'53.22W; NTS 031G/11.

Mass dissolved: 2512 g (99% breakdown)

Fauna: The sample yielded 2 fragmentary conodont elements (CAI 3)

assignable as follows:

?*Cordylodus* sp.: 1

Variabiloconus bassleri (Furnish): 1

Remarks: The presence of specimens of *V. bassleri* indicates an Early Ordovician age. In North American stage terminology, it indicates a late Skullrockian age in the *Rossodus manitouensis* Zone (Ross et al., 1997). In international terms, the age is Early Tremadocian. The specimen assigned to *V. bassleri* is reasonably well preserved and possesses a short cusp that shows evidence of repair after breakage in life. The specimen tentatively assigned to the genus *Cordylodus* is fragmentary with a broken posterior process and anterobasal corner; it most resembles *Cordylodus angulatus* Pander.

2. Locality: GSC loc. C-450795; field sample no. **NI-2012-1;** Chippewa Bay Member of the Covey Hill Formation; isolated outcrop in north Rockland, Ontario; outcrop west of Edward Street and northwest of Woods Street at the south end of an apartment building; sample is 52 m WSW of C-450794 around the small cliff towards the Ottawa River; latitude 45°33'10.13"N; longitude 075°17'55.64"W; NTS 031G/11.

Mass dissolved: 2550 g (99% breakdown)

Fauna: The sample yielded 7 fragmentary to moderately well preserved conodont elements (CAI 3) assignable as follows:

Variabiloconus bassleri (Furnish): 6

Denticle fragment: 1

The sample also yielded fragments of phosphatic inarticulate brachiopods.

Remarks: As with the previous sample (C-450794) the presence of *V. bassleri* indicates an Early Ordovician age for the sample. Several well preserved specimens are represented in the fauna. The denticle fragment is likely a part of a *Cordylodus* specimen. In North American stage terminology, it indicates a late Skullrockian age in the *Rossodus manitouensis* Zone (Ross et al., 1997). In international terms, the age is Early Tremadocian.

General Comments

These two samples, not surprisingly, produced similar results. The samples are from a relatively well exposed section of the Chippewa Member of the Covey Hill Formation as defined by Sanford and Arnott (2010). In other places, the Covey Hill Formation is thought to be Late Cambrian (see for example, Salad Hersi et al., 2002a). The specimens recovered Draft Report 004-GSN-2013, page 3 from the Covey Hill Formation in this

report are few in number but do appear to be within the range of variation of *V. bassleri* a species indicative of late Skullrockian (Early Ordovician) age. The presence of fragments of probable *Cordylodus* being additionally suggestive of this age.

The age of the samples is older than those found in the March Formation above the Nepean Formation type section (Brand and Rust 1977; Dix et al. 2004) and in the March Formation of the Brockville area to the south (Greggs and Bond 1971). In both of these areas, specimens of *Colaptoconus quadraplicatus* (Branson & Mehl) are present in the samples and this species, although long-ranging, does not appear until the Stairsian. Specimens were not illustrated by Brand and Rust (1977) and so evaluation of their faunas is necessarily limited, as noted by Dix et al. (2004). Dix et al. (2004) recovered very few specimens, but those present indicate a Stairsian - Tulean age for the March Formation.

A fauna similar to that reported from the Covey Hill Formation herein was recovered from the Wallace Creek Formation in the Philipsburg slice in Quebec (Salad Hersi et al., 2007). It includes *Variabiloconus bassleri* but is much more diverse than the samples reported herein.

The Wallace Creek Formation overlies the Strites Pond Formation, which yields a Late Cambrian fauna but the immediately overlying basal Wallace Creek Formation yields a restricted fauna with specimens of *V. bassleri* and possible *Cordylodus angulatus* (Salad Hersi et al. 2002b), similar to those reported herein from the Covey Hill Formation. Almost all of the biostratigraphic data from this region of eastern Canada are from relatively poorly sampled sections. It is clear that many more biostratigraphic data are needed before the age relationships of mapped units in the Ottawa region and their broader regional relationships can be fully understood.

Thermal Alteration

Specimens from both samples in this report record the prevailing thermal alteration for the Ottawa region as reported by Legall et al. (1981). Rockland is located about exactly on their CAI 3 isograd and these specimens reflect that level of thermal maturity exactly. A CAI value of 3 indicates heating in the 110° to 200°C range (Nowlan and Barnes 1987).

References Cited

- Brand, U. And Rust, B.R. 1977. The age and upper boundary of the Nepean Formation in its type section near Ottawa, Ontario. Canadian Journal of Earth Sciences, v. 14, p. 2002-2006.
- Dix, G.R., Salad Hersi, O. and Nowlan, G.S. 2004. The Potsdam - Beekmantown Group boundary, Nepean Formation type section (Ottawa, Ontario): a cryptic sequence boundary, not a conformable transition. Canadian Journal of Earth Sciences, v. 41, p. 897-902.

Greggs R.G. and Bond, I.J. 1971. Conodonts from the March and Oxford formations in the
Draft Report 004-GSN-2013, page 4

Brockville area, Ontario. Canadian Journal of Earth Sciences, v. 8, p. 1455-1471. Legall, F.D., Barnes, C.R. and Macqueen, R.W. 1981. Thermal maturation, burial history and hotspot development, Paleozoic strata of southern Ontario - Quebec, from conodont and acritarch colour alteration studies. Bulletin of Canadian Petroleum Geology, v. 29, p. 492-539.

Nowlan, G.S. and Barnes, C.R. 1987. Application of conodont colour alteration indices to regional and economic geology. *In* Conodonts: Investigative Techniques and Applications, R.L. Austin (editor), Ellis Horwood, p. 188-202.

Ross, R.J., Hintze, L.F., Ehtington, R.L., Miller, J.F., Taylor, M.E. and Repetski, J.E. 1997. The Ibexian, lowermost series in the North American Ordovician. U.S. Geological Survey Professional Paper 1579, p.1-84.

Salad Hersi, O., Lavoie, D., Mohamed, A.H. and Nowlan, G.S. 2002a. Subaerial unconformity at the Potsdam - Beekmantown contact in the Quebec Reentrant: regional significance for the Laurentian continental margin history. Bulletin of Canadian Petroleum Geology, v. 50, p. 419-440.

Salad Hersi, O., Lavoie, D. And Nowlan, G.S. 2002b. Stratigraphy and sedimentology of the Upper Cambrian Strites Pond Formation, Philipsburg Group, southern Quebec, and implications for the Cambrian platform in eastern Canada. Bulletin of Canadian Petroleum Geology, v. 50, p. 542-565.

Salad Hersi, O., Nowlan, G.S. and Lavoie, D. 2007. A revision of the stratigraphic nomenclature of the Cambrian-Ordovician strata of the Philipsburg tectonic slice, southern Quebec. Canadian Journal of Earth Sciences, v. 44, p. 1775-1790.

Sanford, B.V. and Arnott, R.W.C. 2010. Stratigraphic and structural framework of the Potsdam Group in eastern Ontario, western Quebec and northern New York State. Geological Survey of Canada Bulletin 597.

Report prepared by:

Godfrey S. Nowlan
Micropaleontologist
18 March 2013
Paleontology Subdivision
Geological Survey of Canada – Calgary

Appendix C: Biostratigraphic analysis from the Keeseville Formation at Ducharme Quarry, QC, and the lower Theresa Formation, Ste. Chrysostome, QC.

2-ADM-2014

Report on 2 Early Ordovician conodont samples from the Potsdam Group near Saint Chrysostome, southwestern Quebec submitted by David Lowe and Bill Arnott (University of Ottawa). NTS 031H/04. Con. No. 1791

A. D. McCracken

All references to age determinations and paleontological data must quote the authorship of the report, and the unique GSC Curation Number of the fossil collection. If the report is cited in a publication, it should be included in the References Cited section as:
“McCracken, A.D., 2014. Report on 2 Early Ordovician conodont samples from the Potsdam Group near Saint-Chrysostome, southwestern Quebec submitted by David Lowe and Bill Arnott (University of Ottawa). NTS 031H/04. Con. No. 1791; Geological Survey of Canada, Paleontological Report 2-ADM-2014, 7 p.”

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The two samples are part of David Lowe and Bill Arnott's study on the Cambrian Ordovician Potsdam Group in the Ottawa Embayment and Quebec Basin in Ontario, Quebec and adjacent New York State. They wrote (External Request for Laboratory Consultative Services 330403-007-14-EXT) “This project is an integrative sedimentology and stratigraphy project spearheaded by David Lowe (PhD Candidate, University of Ottawa) and uses facies analysis, sequence stratigraphic correlations, petrography, detrital zircon dating and biostratigraphic ages to build a comprehensive depositional model for the Potsdam Group. We are requesting the use of the lab as well as the expertise of biostratigrapher Godfrey Nowlan to obtain conodont specimens and age correlations from two samples in the Potsdam Group. Nowlan (2013) (GSC report #004-GSN-2013) has already provided a very useful and informative age determination from a sample in Eastern Ontario, that has helped immensely in understanding the complexities of this unit.”

The samples were processed in the GSC Calgary Conodont Laboratory. Both were huge in comparison to our lab's usual sample size. One sample, GSC C-450796 was barren - this was processed at our usual 2.5 kg sample size, and essentially did not dissolve. Even so, the little residue there was picked to completion. The second sample (GSC C-450797) was processed in its entirety - 9.6 kg. The sample went through 6 weeks of digestions, and processing was stopped at 63% dissolution. However, over 6 kg were dissolved - over twice the standard amount. The heavy liquid residue of this sample was picked for 4 hours, also twice the standard amount. There is some residue left, but I believe that there is no point in doing more work - the second phase of picking brought only more of the same, but smaller (which is typical of a "repick").

The study and report were completed by Sandy McCracken. The taxonomic identifications and biostratigraphy was done in consultation with Godfrey Nowlan. Material: 2 rock samples processed completely in the GSC laboratory.

GSC Curation Number: C-450796

Sample 201-A; Ducharme Quarry (carrières Ducharme) near New York border; uppermost Potsdam Group, upper ca. 20 m of Cairnside Formation; latitude 45° 00' 23.03" N; longitude 73° 44' 44.48" W; NAD83; NTS 031-H-04. Con. No. 1791-1: Mass in 2500 g, out 2483 g, 0.7 % breakdown, 0 slide, Barren.

Fossils: Barren

GSC Curation Number: C-450797

Sample 243-A; Sainte Clotilde de Châteauguay, Rivière Châteauguay and QC Rt 209; Potsdam Group, Lower Theresa Formation; latitude 45° 08' 59.51" N; longitude 73° 42' 21.48" W; NAD83; NTS 031-H-04. Con. No. 1791-2: Mass in 9609 g, out 3581 g, 62.7 % breakdown, 2 slides, repicked.

Fossils:

Acodus? sp. - 3 specimens

Colaptoconus quadriplicatus (Branson & Mehl 1933) - 108 specimens

Drepanodus? sp. - 1 specimen

Drepanoistodus gracilis (Branson & Mehl 1933) - 46 specimens

Oneotodus costatus Ethington & Brand 1981 - 14 specimens

Thermal: CAI 3.

Remarks: Probable age range: Ibexian Series, *Acodus deltatus*-*Oneotodus costatus* Zone (lower Stairsian Stage) through to about mid *Reutterodus andinus* Zone (mid Blackhillsian Stage) based on *Drepanoistodus gracilis*, but in part supported by the other taxa.

Discussion

Colaptoconus quadriplicatus (Branson & Mehl) is the most abundant taxon in sample C-450797. The range of this species, as reported by Ross et al. (1997) is from the lower

“Low diversity interval” (lower Stairsian Stage, Ibexian Series) through to about mid *Reutterodus andinus* Zone (mid Blackhillsian Stage, Ibexian Series). McCracken (in Desbiens et al. 1996) identified this species in the lower Beauharnois Formation of Quebec (see table of stages and zones).

Drepanoistodus gracilis (Branson & Mehl) has been assigned previously to *Drepanodus*, but this collection clearly (and fortunately) includes two *q* (suberectiform) elements. In retrospect, the elements McCracken (in Desbiens et al. 1996) called *Drepanoistodus angulensis* (Harris) from the lower Beauharnois Formation are more likely this species because of the similar *r* (oistodiform) element.

Ross et al. (1997) give the range of this species (their *Drepanodus gracilis*) from the *Acodus deltatus*-*Oneotodus costatus* Zone [lower Stairsian (Ibexian)] through to about mid *Reutterodus andinus* Zone [mid Blackhillsian (Ibexian)].

Oneotodus costatus Ethington & Brand is represented by a few costate and short specimens. Two are reminiscent of the symmetrical quadricostate element of *Colaptoconus quadriplicatus* but are thought to be part of *O. costatus* because of their short, squat nature (as opposed to long and thin). The species has a range from the base of the *Acodus deltatus*-*Oneotodus costatus* Zone [lower Stairsian (Ibexian)] through to about mid *Reutterodus andinus* Zone [mid Blackhillsian (Ibexian)] (Ross et al. 1997).

The three specimens assigned to *Acodus?* sp. are oistodiform elements. These are not part of *Drepanoistodus*, and are not compressed enough to be considered oistodiform elements of *Oepikodus communis* (see below).

The collectors previously submitted two samples from the Covey Hill Formation near Rockland, Ontario. Nowlan (2013) reported that these were from the upper Skullrockian Stage of the Ibexian Series. He (2013) also commented on the occurrences of *Colaptoconus quadriplicatus* in the Nepean and March formations of the Ottawa area and the March and Oxford formations of the Brockville area (Brand & Rust 1977; Dixon et al. 2004; Greggs & Bond 1971). There are no other forms in common with those occurrences, and none at all with Nowlan’s (2013) study.

McCracken’s (in Desbiens et al. 1996) work in Montreal, Quebec was mentioned above. Although *Colaptoconus quadriplicatus* and *Drepanoistodus gracilis* (as *D. angulensis*) were present, the fauna also contained *Oepikodus communis* (Ethington & Clark) which ranges from the *O. communis* Zone (mid Tulean Stage, Ibexian Series) through the *Reutterodus andinus* Zone (top of the Blackhillsian Stage, Ibexian Series). At this location, the Beauharnois Formation overlay the Theresa Formation.

This sample from the Lower Theresa Formation thus is older than the Desbiens et al. (1996) Beauharnois material and younger than Nowlan’s (2013) Covey Hill Formation material. It does not have anything in common with the faunas from the Nepean Formation type section but it overlaps in age - Nowlan (in Dix et al. 2004) interpreted the fauna of the Nepean Formation type section as ranging from Stairsian to Tulean stages.

References cited

Brand, U. and Rust, B.R. 1977: The age and upper boundary of the Nepean Formation in its type section near Ottawa, Ontario. *Canadian Journal of Earth Sciences*, v. 14, no. 9, p. 2002-2006.

Desbiens, S., Bolton, T.E., and McCracken, A.D. 1996: Fauna of the lower Beauharnois Formation (Beekmantown Group, lower Ordovician), Grande-île, Quebec. *Canadian Journal of Earth Sciences*, v. 33, p. 1132-1153.

Dix, G.R., Salad Hersi, O., and Nowlan, G.S. 2004: The Potsdam-Beekmantown Group boundary, Nepean Formation type section (Ottawa, Ontario): a cryptic sequence boundary, not a conformable transition. *Canadian Journal of Earth Sciences*, v. 41, no. 8, p. 897-902.

Greggs, R.G. and Bond, I.J. 1971: Conodonts from the March and Oxford Formations in the Brockville area, Ontario. *Canadian Journal of Earth Sciences*, v. 8, no. 11, p. 1455-1471.

Ross, R.J.Jr., Hintze, L.F., Ethington, R.L., Miller, J.F., Taylor, M.E., and Repetski, J.E. 1997: The Ibexian, lowermost series in the North American Ordovician. *In* Early Paleozoic biochronology of the Great Basin, western United States. Taylor, M.E. (ed.). United States Geological Survey, Professional Paper 1579-A, p. 1-50.

Nowlan, G.S. 2013: Report on two samples from Lower Ordovician strata in the vicinity of Rockland in eastern Ontario submitted for conodont analysis by David Lowe and Bill Arnott (University of Ottawa); NTS 031G/11; CON # 1777. Geological Survey of Canada, Paleontological Report 004-GSN-2013, 3 p.

Author	A.D. McCracken
Geological Survey of Canada (Calgary)	Chief Paleontologist GSC (Calgary)
June 6, 2014	

System Series	Stage	Formation	Shelly Fossil Zones (this report)	Conodont Zones (this report)	Shelly Fossil Zones		Conodont Faunas
					N. Utah - SE. Idaho Ross (1951, 1968)	W. Utah Hintze (1953)	W. Utah Ethington & Clark (1971)
White-rockian Series	Rangerian	Wah Wah Fm.	PO <i>Paralenorthis-Orthidiella</i>	TI <i>Tripodus laevis</i>	L	L	E
Lower Ordovician Ibexian Series	Blackhillian	Fillmore Formation	Hm <i>Hesperonomiella minor</i>	Ra <i>Reutterodus andinus</i>	K	"K"	
			Pn <i>Pseudocybele nasuta</i>		J	J	
			Pi <i>Presbynileus ibexensis</i>	Oc <i>Oepikodus communis</i>	I	I	
			Tt <i>Trigonocerca typica</i>		H	H	
	Tulean	Fillmore Formation	Pc <i>Protopliomerella contracta</i>	AO <i>Acodus deltatus - Oneotodus costatus</i>	G-2	G-2	D
			Hc <i>Hintzeia celsaora</i>		G-1	G-1	
			Rs <i>Rossaspis superciliosa</i>	Md <i>Macerodus diana</i>	F	F	
			Te <i>Tesselacauda</i>	LD "Low diversity interval"	E	E	
	Skullrockian	House Ls.	LK <i>Leiostegium-Kainella</i>	Rm <i>Rossodus manitouensis</i>	D	D	C
			Pa <i>Paraplethopeltis</i>	Ca <i>Cordylodus angulatus</i>	C	C	
		Notch Peak Formation	BX <i>Bellefontia-Xenostegium</i>	la <i>lapetognathus</i> n. sp.	A + B	B	B
			Sy <i>Symphysurina</i>	CI <i>Cordylodus lindstromi</i>			
			Mi <i>Missisquoia</i>	CI <i>Cordylodus intermedius</i>		Not Studied	A
			Ea <i>Eurekia apopsis</i>	Cp <i>Cordylodus proavus</i>			
Up. C Croixian Series	Tremp.	Notch Peak Formation	Ss <i>Saukiella serotina</i>	Eo <i>Eoconodontus</i>	St. Charles Dol.	Not Studied	Not Studied
			Sj <i>Saukiella junia</i>				

Figure: Stages of the Ibexian Series showing the shelly fossil and conodont zones by which they are characterized. Also shown are correlations with previous zones and faunas. From Ross et al. 1997.

PLATE 1

All specimens are from GSC Curation No. C-450797

Figs. A-C. *Drepanoistodus gracilis* (Branson & Mehl 1933)

Fig. D. *Drepanodus?* sp. (upper left), *Acodus?* sp. (3 oistodiform elements on right)

Fig. E. *Oneotodus costatus* Ethington & Brand 1981

Figs. F-H. *Colaptoconus quadriplicatus* (Branson & Mehl 1933)

2-ADM-2014 Plate 1



Appendix D: Detrital zircon geochronological data

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
AT-1													
ADAT09-1	12.953	0.325	1126	50	2.121	0.078	1156	26	0.199	0.005	1171	29	0.00
ADAT09-2	12.792	0.230	1151	36	2.162	0.058	1169	19	0.201	0.004	1179	22	0.00
ADAT09-3	12.688	0.239	1168	37	2.165	0.095	1170	30	0.199	0.008	1171	42	0.00
ADAT09-4	12.633	0.244	1176	38	2.224	0.086	1189	27	0.204	0.007	1196	36	0.00
ADAT09-6	12.444	0.256	1206	41	2.348	0.050	1227	15	0.212	0.001	1239	5	0.00
ADAT09-7	11.970	0.273	1282	44	2.554	0.074	1287	21	0.222	0.004	1291	21	0.00
ADAT09-8	13.162	0.237	1094	36	1.957	0.076	1101	26	0.187	0.006	1104	35	0.00
ADAT09-9	12.218	0.247	1242	40	2.405	0.052	1244	15	0.213	0.002	1246	8	0.00
ADAT09-10	12.408	0.271	1212	43	2.367	0.054	1233	16	0.213	0.001	1245	7	0.00
ADAT09-11	12.533	0.217	1192	34	2.255	0.067	1198	21	0.205	0.005	1202	27	0.00
ADAT09-12	12.694	0.275	1167	43	2.216	0.055	1186	17	0.204	0.003	1197	13	0.00
ADAT09-13	12.416	0.578	1210	92	2.414	0.114	1247	34	0.217	0.002	1268	10	0.00
ADAT09-14	12.690	0.179	1167	28	2.142	0.052	1163	17	0.197	0.004	1160	21	0.60
ADAT09-15	13.460	0.306	1050	46	1.848	0.059	1063	21	0.180	0.004	1069	22	0.00
ADAT09-16	13.193	0.127	1090	19	1.915	0.042	1086	15	0.183	0.004	1085	19	0.46
ADAT09-17	12.837	0.215	1144	33	2.088	0.049	1145	16	0.194	0.003	1145	18	0.00
ADAT09-18	12.471	0.321	1202	51	2.316	0.083	1217	25	0.209	0.005	1226	28	0.00
ADAT09-20	12.749	0.256	1158	40	2.104	0.049	1150	16	0.195	0.002	1146	12	1.06
ADAT09-21	13.067	0.517	1109	79	1.588	0.093	966	36	0.151	0.006	904	36	18.48
ADAT09-22	13.206	0.239	1088	36	1.893	0.042	1079	15	0.181	0.002	1074	13	1.24
ADAT09-23	13.875	0.541	988	79	1.696	0.067	1007	25	0.171	0.001	1016	5	0.00
ADAT09-24	12.634	0.602	1176	94	2.107	0.102	1151	33	0.193	0.002	1138	9	3.23
ADAT09-25	12.562	0.374	1187	59	2.171	0.066	1172	21	0.198	0.001	1163	7	2.01

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
ADAT09-26	12.507	0.215	1196	34	2.270	0.048	1203	15	0.206	0.003	1207	14	0.00
ADAT09-27	12.864	0.310	1140	48	2.016	0.049	1121	17	0.188	0.001	1111	5	2.55
ADAT09-28	12.207	0.408	1244	65	2.466	0.083	1262	24	0.218	0.001	1273	3	0.00
ADAT09-29	13.500	0.448	1044	67	1.887	0.066	1076	23	0.185	0.002	1093	11	0.00
ADAT09-30	13.473	0.600	1048	90	1.835	0.082	1058	29	0.179	0.001	1063	4	0.00
ADAT09-31	12.801	0.200	1150	31	2.158	0.034	1168	11	0.200	0.000	1177	2	0.00
ADAT09-32	12.747	0.232	1158	36	1.983	0.037	1110	13	0.183	0.001	1085	4	6.33
ADAT09-33	12.912	0.258	1133	40	1.932	0.047	1092	16	0.181	0.003	1072	14	5.37
ADAT09-34	12.952	0.599	1127	92	2.030	0.101	1126	34	0.191	0.004	1125	19	0.15
ADAT09-35	12.752	0.449	1157	70	2.136	0.081	1161	26	0.198	0.003	1162	15	0.00
ADAT09-36	12.778	0.325	1153	50	2.142	0.056	1162	18	0.198	0.001	1167	6	0.00
ADAT09-37	12.889	0.235	1136	36	1.847	0.070	1062	25	0.173	0.006	1027	32	9.65
ADAT09-38	13.389	0.362	1060	54	1.634	0.060	983	23	0.159	0.004	949	22	10.44
ADAT09-39	12.597	0.328	1182	51	2.210	0.059	1184	19	0.202	0.001	1186	7	0.00
ADAT09-40	12.693	0.223	1167	35	2.112	0.039	1153	13	0.194	0.001	1145	6	1.85
ADAT09-41	13.244	0.339	1082	51	1.756	0.047	1029	17	0.169	0.001	1005	7	7.13
ADAT09-42	13.374	0.360	1062	54	1.710	0.053	1012	20	0.166	0.003	989	14	6.88
ADAT09-43	12.604	0.461	1181	72	2.093	0.078	1146	26	0.191	0.001	1128	8	4.43
ADAT09-44	13.675	0.324	1017	48	1.744	0.042	1025	16	0.173	0.001	1028	4	0.00
ADAT09-45	13.563	0.214	1034	32	1.755	0.029	1029	11	0.173	0.001	1027	4	0.69
ADAT09-46	12.550	0.257	1189	40	2.297	0.049	1211	15	0.209	0.001	1224	7	0.00
ADAT09-47	12.680	0.377	1169	59	2.184	0.074	1176	24	0.201	0.003	1180	18	0.00
ADAT09-48	12.762	0.306	1156	48	2.181	0.053	1175	17	0.202	0.001	1185	5	0.00
ADAT09-49	12.414	0.312	1211	49	2.249	0.058	1196	18	0.202	0.001	1189	5	1.81
ADAT09-50	12.626	0.290	1177	46	2.170	0.057	1171	18	0.199	0.003	1168	14	0.76
ADAT09-51	12.739	0.270	1160	42	2.106	0.046	1151	15	0.195	0.001	1146	6	1.16
ADAT09-52	12.802	0.242	1150	38	1.727	0.037	1019	14	0.160	0.002	959	9	16.59
ADAT09-53	12.920	0.425	1131	66	2.156	0.077	1167	25	0.202	0.003	1186	14	0.00
ADAT09-54	13.395	0.236	1059	35	1.881	0.033	1074	12	0.183	0.000	1082	3	0.00

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
ADAT09-56	13.271	0.317	1078	48	1.966	0.048	1104	16	0.189	0.001	1117	4	0.00
ADAT09-57	13.427	0.314	1054	47	1.903	0.058	1082	20	0.185	0.004	1096	20	0.00
ADAT09-58	12.180	0.182	1248	29	2.396	0.037	1241	11	0.212	0.001	1237	3	0.84
ADAT09-59	12.993	0.351	1120	54	2.095	0.058	1147	19	0.197	0.001	1161	7	0.00
ADAT09-60	12.809	0.382	1149	59	2.155	0.065	1167	21	0.200	0.001	1176	4	0.00
ADAT09-61	12.442	0.311	1206	49	2.359	0.061	1230	18	0.213	0.001	1244	7	0.00
ADAT09-62	12.633	0.398	1176	62	2.235	0.076	1192	24	0.205	0.003	1201	14	0.00
ADAT09-63	12.143	0.219	1254	35	2.436	0.056	1253	17	0.215	0.003	1253	16	0.07
ADAT09-64	13.129	0.377	1099	57	1.996	0.059	1114	20	0.190	0.001	1122	7	0.00
ADAT09-65	12.966	0.252	1124	39	2.056	0.040	1134	13	0.193	0.001	1139	3	0.00
ADAT09-66	12.983	0.538	1122	83	1.898	0.094	1081	33	0.179	0.005	1060	26	5.49
ADAT09-67	12.681	0.206	1169	32	2.178	0.041	1174	13	0.200	0.002	1177	10	0.00
ADAT09-68	12.280	0.258	1232	41	2.353	0.053	1228	16	0.210	0.002	1226	10	0.46
ADAT09-69	12.558	0.260	1188	41	2.255	0.048	1198	15	0.205	0.001	1204	5	0.00
ADAT09-70	12.795	0.333	1151	52	2.177	0.064	1174	20	0.202	0.003	1186	14	0.00
ADAT09-71	12.480	0.157	1200	25	1.939	0.112	1095	39	0.176	0.010	1043	54	13.14
ADAT09-72	11.141	0.237	1420	41	3.096	0.069	1432	17	0.250	0.002	1439	9	0.00
ADAT09-73	12.400	0.216	1213	34	2.227	0.041	1190	13	0.200	0.001	1177	7	2.98
ADAT09-74	12.908	0.232	1133	36	1.727	0.039	1019	14	0.162	0.002	966	12	14.77
ADAT09-75	12.594	0.449	1182	70	2.272	0.082	1204	25	0.208	0.001	1215	6	0.00
ADAT09-76	12.931	0.163	1130	25	1.942	0.058	1096	20	0.182	0.005	1079	27	4.52
ADAT09-77	12.339	0.241	1223	38	2.151	0.053	1165	17	0.192	0.003	1135	16	7.17
ADAT09-78	13.410	0.235	1057	35	1.757	0.045	1030	16	0.171	0.003	1017	17	3.76
ADAT09-79	13.035	0.309	1114	47	1.926	0.049	1090	17	0.182	0.002	1079	9	3.17
ADAT09-80	12.761	0.393	1156	61	1.949	0.063	1098	22	0.180	0.002	1069	9	7.54
ADAT09-81	12.819	0.179	1147	28	1.886	0.063	1076	22	0.175	0.005	1041	29	9.23
ADAT09-82	12.962	0.324	1125	50	1.912	0.100	1085	35	0.180	0.008	1065	45	5.30
ADAT09-83	12.513	0.460	1195	72	1.577	0.112	961	44	0.143	0.009	862	49	27.86
ADAT09-84	12.784	0.204	1152	32	2.047	0.039	1131	13	0.190	0.002	1120	11	2.80

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
ADAT09-85	13.562	0.286	1034	43	1.677	0.040	1000	15	0.165	0.002	984	10	4.84
ADAT09-86	12.618	0.310	1178	49	2.172	0.065	1172	21	0.199	0.003	1169	19	0.81
ADAT09-87	12.504	0.201	1196	32	2.197	0.040	1180	13	0.199	0.002	1171	9	2.10
ADAT09-88	13.036	0.295	1114	45	1.918	0.053	1087	18	0.181	0.003	1074	16	3.54
ADAT09-89	12.810	0.159	1148	25	2.045	0.037	1131	12	0.190	0.003	1121	14	2.36
ADAT09-90	12.906	0.404	1134	62	2.031	0.066	1126	22	0.190	0.002	1122	9	1.05
ADAT09-91	12.464	0.200	1203	32	2.137	0.043	1161	14	0.193	0.002	1139	13	5.31
ADAT09-92	12.997	0.246	1120	38	1.994	0.042	1114	14	0.188	0.002	1111	9	0.80
ADAT09-93	12.473	0.634	1201	100	2.048	0.107	1132	36	0.185	0.002	1096	12	8.78
ADAT09-95	13.175	0.182	1092	28	1.938	0.039	1094	13	0.185	0.003	1095	15	0.00
ADAT09-94	12.727	0.253	1161	39	2.106	0.061	1151	20	0.194	0.004	1145	22	1.41
ADAT09-96	13.288	0.238	1075	36	1.838	0.040	1059	14	0.177	0.002	1051	12	2.23
ADAT09-97	12.681	0.277	1169	43	2.185	0.053	1176	17	0.201	0.002	1181	12	0.00
ADAT09-99	12.930	0.261	1130	40	1.900	0.058	1081	20	0.178	0.004	1057	23	6.46
ADAT09-100	13.374	0.192	1062	29	1.864	0.039	1068	14	0.181	0.003	1071	15	0.00
AS-1													
ADAS09-2	12.714	0.422	1163	66	2.074	0.069	1140	23	0.191	0.001	1128	4	3.05
ADAS09-3	9.118	0.184	1794	37	4.663	0.114	1761	20	0.308	0.004	1733	21	3.42
ADAS09-4	13.106	0.410	1103	63	2.021	0.076	1123	26	0.192	0.004	1133	22	0.00
ADAS09-5	13.522	0.346	1040	52	1.817	0.047	1051	17	0.178	0.000	1057	2	0.00
ADAS09-6	12.552	0.196	1189	31	2.193	0.036	1179	11	0.200	0.001	1173	6	1.29
ADAS09-7	13.039	0.472	1113	72	2.088	0.077	1145	25	0.197	0.002	1162	8	0.00
ADAS09-8	13.002	0.326	1119	50	2.079	0.076	1142	25	0.196	0.005	1154	28	0.00
ADAS09-9	13.424	0.514	1055	77	1.924	0.081	1090	28	0.187	0.003	1107	18	0.00
ADAS09-10	12.444	0.303	1206	48	2.219	0.056	1187	18	0.200	0.001	1177	7	2.43
ADAS09-11	12.964	0.443	1125	68	2.100	0.075	1149	25	0.197	0.002	1162	11	0.00
ADAS09-12	12.766	0.152	1155	24	2.115	0.039	1154	13	0.196	0.003	1153	15	0.19
ADAS09-13	12.789	0.200	1152	31	2.119	0.034	1155	11	0.197	0.001	1157	3	0.00
ADAS09-14	12.487	0.395	1199	62	2.178	0.070	1174	22	0.197	0.001	1160	6	3.22

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
ADAS09-15	13.429	0.352	1054	53	1.748	0.055	1027	20	0.170	0.003	1014	16	3.83
ADAS09-16	13.116	0.295	1102	45	1.853	0.043	1065	15	0.176	0.001	1047	6	4.98
ADAS09-17	13.473	0.278	1048	42	1.795	0.041	1044	15	0.175	0.002	1042	10	0.56
ADAS09-18	13.254	0.348	1080	53	1.981	0.055	1109	19	0.190	0.002	1124	10	0.00
ADAS09-20	13.599	0.385	1029	57	1.769	0.053	1034	19	0.174	0.002	1037	9	0.00
ADAS09-21	12.864	0.276	1140	43	2.109	0.045	1152	15	0.197	0.000	1158	3	0.00
ADAS09-23	12.068	0.316	1266	51	2.586	0.071	1297	20	0.226	0.002	1315	10	0.00
ADAS09-24	12.536	0.172	1191	27	2.187	0.031	1177	10	0.199	0.001	1169	4	1.87
ADAS09-25	12.531	0.467	1192	74	2.029	0.091	1125	31	0.184	0.005	1091	25	8.47
ADAS09-26	12.817	0.190	1147	30	2.107	0.053	1151	17	0.196	0.004	1153	21	0.00
ADAS09-27	13.242	0.175	1082	26	1.898	0.042	1081	15	0.182	0.003	1080	18	0.24
ADAS09-29	12.883	0.175	1137	27	1.987	0.036	1111	12	0.186	0.002	1098	12	3.45
ADAS09-30	13.092	0.296	1105	45	1.970	0.050	1105	17	0.187	0.002	1105	12	0.00
ADAS09-31	9.612	0.107	1697	20	4.014	0.061	1637	12	0.280	0.003	1590	15	6.30
ADAS09-32	12.769	0.259	1155	40	2.023	0.060	1123	20	0.187	0.004	1107	22	4.14
ADAS09-33	12.560	0.146	1188	23	2.191	0.036	1178	11	0.200	0.002	1173	12	1.24
ADAS09-34	12.524	0.372	1193	59	2.155	0.070	1167	23	0.196	0.003	1152	14	3.44
ADAS09-35	12.552	0.255	1189	40	2.215	0.055	1186	17	0.202	0.003	1184	16	0.39
ADAS09-36	12.974	0.132	1123	20	1.941	0.029	1095	10	0.183	0.002	1082	11	3.70
ADAS09-37	13.015	0.163	1117	25	1.937	0.037	1094	13	0.183	0.003	1082	15	3.11
ADAS09-38	12.745	0.181	1159	28	2.095	0.051	1147	17	0.194	0.004	1141	20	1.52
ADAS09-39	12.649	0.082	1174	13	2.132	0.019	1159	6	0.196	0.001	1151	7	1.89
ADAS09-40	13.132	0.176	1099	27	1.823	0.037	1054	13	0.174	0.003	1032	15	6.12
ADAS09-41	12.643	0.328	1175	51	2.185	0.057	1176	18	0.200	0.000	1177	2	0.00
ADAS09-42	13.247	0.457	1082	69	1.951	0.072	1099	25	0.187	0.002	1108	13	0.00
ADAS09-44	12.692	0.458	1167	72	2.102	0.084	1150	27	0.194	0.003	1140	18	2.27
ADAS09-45	12.817	0.202	1147	31	2.139	0.037	1161	12	0.199	0.001	1169	8	0.00
ADAS09-46	12.793	0.196	1151	30	2.055	0.034	1134	11	0.191	0.001	1125	6	2.26
ADAS09-47	12.748	0.237	1158	37	2.142	0.040	1163	13	0.198	0.001	1165	3	0.00

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
ADAS09-48	12.659	0.239	1172	37	2.125	0.045	1157	15	0.195	0.002	1149	10	1.97
ADAS09-49	12.922	0.237	1131	36	2.095	0.038	1147	13	0.196	0.000	1156	1	0.00
ADAS09-50	13.187	0.516	1091	78	1.933	0.084	1093	29	0.185	0.003	1094	19	0.00
ADAS09-51	13.140	0.648	1098	99	1.953	0.103	1100	35	0.186	0.003	1100	19	0.00
ADAS09-52	12.881	0.453	1137	70	2.003	0.076	1117	26	0.187	0.003	1106	15	2.77
ADAS09-53	12.859	0.298	1141	46	2.073	0.053	1140	18	0.193	0.002	1140	11	0.12
ADAS09-54	12.837	0.415	1144	64	1.697	0.126	1008	48	0.158	0.011	946	59	17.35
ADAS09-55	12.903	0.111	1134	17	2.025	0.029	1124	10	0.189	0.002	1119	12	1.36
ADAS09-56	13.020	0.316	1116	48	2.078	0.060	1142	20	0.196	0.003	1155	16	0.00
ADAS09-57	13.298	0.263	1074	40	1.859	0.039	1067	14	0.179	0.001	1063	6	1.02
ADAS09-58	13.286	0.141	1076	21	1.844	0.023	1061	8	0.178	0.001	1055	6	1.95
ADAS09-59	12.836	0.317	1144	49	2.080	0.052	1142	17	0.194	0.001	1141	5	0.28
ADAS09-60	12.401	0.227	1213	36	2.290	0.054	1209	17	0.206	0.003	1207	17	0.46
ADAS09-61	13.430	0.188	1054	28	1.745	0.086	1025	32	0.170	0.008	1012	44	4.00
ADAS09-62	12.607	0.201	1180	32	2.176	0.050	1174	16	0.199	0.003	1170	18	0.86
ADAS09-63	12.123	0.229	1257	37	2.405	0.057	1244	17	0.211	0.003	1237	16	1.62
ADAS09-64	13.074	0.332	1108	51	1.923	0.056	1089	19	0.182	0.003	1080	14	2.53
ADAS09-65	12.514	0.189	1195	30	2.226	0.037	1189	12	0.202	0.001	1186	7	0.73
ADAS09-66	12.536	0.180	1191	28	2.172	0.041	1172	13	0.198	0.002	1162	13	2.47
ADAS09-67	12.560	0.194	1188	31	2.230	0.044	1191	14	0.203	0.003	1192	14	0.00
ADAS09-68	12.668	0.231	1171	36	2.193	0.054	1179	17	0.202	0.003	1184	18	0.00
ADAS09-69	13.876	0.251	988	37	1.675	0.044	999	17	0.169	0.003	1004	18	0.00
ADAS09-70	10.396	0.361	1551	65	3.501	0.148	1527	33	0.264	0.006	1510	33	2.66
ADAS09-71	13.392	0.407	1060	61	1.912	0.061	1085	21	0.186	0.002	1098	10	0.00
ADAS09-72	10.940	0.288	1455	50	3.307	0.098	1483	23	0.262	0.004	1502	18	0.00
ADAS09-73	12.809	0.436	1149	68	2.138	0.086	1161	28	0.199	0.004	1168	23	0.00
ADAS09-74	12.697	0.206	1166	32	2.207	0.040	1183	13	0.203	0.002	1192	9	0.00
ADAS09-75	12.474	0.192	1201	30	2.286	0.038	1208	12	0.207	0.001	1212	7	0.00
ADAS09-76	12.623	0.201	1178	32	2.218	0.046	1187	15	0.203	0.003	1192	14	0.00

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
ADAS09-77	12.712	0.305	1164	48	2.195	0.059	1179	19	0.202	0.002	1188	13	0.00
ADAS09-78	13.181	0.328	1092	50	1.959	0.050	1102	17	0.187	0.001	1107	6	0.00
ADAS09-79	12.291	0.280	1230	45	2.434	0.056	1253	17	0.217	0.001	1266	4	0.00
ADAS09-80	13.159	0.459	1095	70	2.008	0.080	1118	27	0.192	0.004	1131	20	0.00
ADAS09-81	12.872	0.395	1139	61	2.126	0.069	1157	22	0.198	0.002	1167	11	0.00
ADAS09-82	12.741	0.386	1159	60	2.118	0.065	1155	21	0.196	0.001	1152	5	0.61
ADAS09-83	12.947	0.449	1127	69	2.070	0.073	1139	24	0.194	0.001	1145	7	0.00
ADAS09-84	12.456	0.267	1204	42	2.170	0.054	1172	17	0.196	0.002	1154	13	4.15
ADAS09-85	12.567	0.376	1186	59	2.265	0.096	1202	30	0.206	0.006	1210	33	0.00
ADAS09-86	12.611	0.301	1179	47	2.185	0.060	1176	19	0.200	0.003	1175	15	0.41
ADAS09-87	13.310	0.243	1072	37	1.885	0.074	1076	26	0.182	0.006	1078	34	0.00
ADAS09-88	12.726	0.336	1162	52	2.193	0.067	1179	21	0.202	0.003	1188	17	0.00
ADAS09-89	12.680	0.269	1169	42	2.155	0.055	1167	18	0.198	0.003	1165	15	0.28
ADAS09-90	12.718	0.378	1163	59	2.180	0.067	1175	21	0.201	0.002	1181	8	0.00
ADAS09-91	13.053	0.269	1111	41	2.003	0.042	1117	14	0.190	0.001	1119	4	0.00
ADAS09-92	13.161	0.245	1095	37	1.939	0.038	1095	13	0.185	0.001	1095	5	0.00
ADAS09-93	12.575	0.178	1185	28	2.184	0.034	1176	11	0.199	0.001	1171	7	1.20
ADAS09-94	12.430	0.246	1208	39	2.280	0.055	1206	17	0.206	0.003	1205	15	0.25
ADAS09-95	13.439	0.242	1053	36	1.832	0.034	1057	12	0.179	0.001	1059	5	0.00
ADAS09-96	12.814	0.165	1148	26	2.130	0.047	1159	15	0.198	0.004	1165	19	0.00
ADAS09-97	12.573	0.242	1186	38	2.237	0.057	1193	18	0.204	0.003	1197	19	0.00
ADAS09-98	12.656	0.185	1172	29	2.183	0.047	1176	15	0.200	0.003	1177	17	0.00
ADAS09-99	12.991	0.521	1121	80	2.072	0.093	1140	31	0.195	0.004	1150	21	0.00
ADAS09-100	13.053	0.342	1111	52	2.083	0.063	1143	21	0.197	0.003	1160	16	0.00
AS-2													
Output_1_1	13.316	0.461	1144	13	2.017	0.074	1142	7	0.1919	0.001	1138	7	2.83
Output_1_2	13.280	0.511	1067	15	1.903	0.073	1066	8	0.1795	0.001	1063	7	3.18
Output_1_3	16.129	3.382	1104	35	1.59	0.34	1075	14	0.1784	0.004	1072	14	5.76
Output_1_4	14.045	1.499	1166	16	1.95	0.22	1150	11	0.1922	0.003	1149	12	4.28

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.	
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±		
Output_1_5	12.531		1.068	1183	20	2.21	0.19	1151	12	0.1955	0.003	1151	12	4.51
Output_1_6	15.625		3.662	1086	35	1.74	0.45	1124	15	0.1888	0.004	1123	15	7.7
Output_1_7	13.699		2.439	1060	38	1.67	0.33	1006	13	0.1701	0.003	1009	13	7.22
Output_1_8	13.123		1.584	1158	26	1.99	0.25	1109	12	0.1863	0.003	1106	12	5.69
Output_1_9	12.500		1.125	1211	31	1.76	0.18	956	16	0.1595	0.003	947	16	6.5
Output_1_10	12.903		0.499	1184	16	2.051	0.087	1136	9	0.1915	0.002	1133	8	3.57
Output_1_11	10.661		0.182	1516	9	2.946	0.066	1338	19	0.2286	0.003	1318	18	5.01
Output_1_12	14.706		1.708	1213	26	1.82	0.22	1115	12	0.1867	0.003	1112	11	5.36
Output_1_13	12.048		1.452	1216	31	2.27	0.28	1119	12	0.1912	0.003	1119	12	5.81
Output_1_14	12.547		0.299	1176	12	2.188	0.057	1165	6	0.1976	0.001	1160	6	2.3
Output_1_15	13.661		1.232	1157	23	1.94	0.18	1101	10	0.1836	0.002	1097	9	5.06
Output_1_16	12.063		0.335	1233	12	2.281	0.069	1187	8	0.2017	0.001	1181	7	2.92
Output_1_17	15.103		0.205	965	9	0.802	0.015	545	7	0.0889	0.001	543	7	9.93
Output_1_18	15.385		3.314	1209	31	1.82	0.38	1129	14	0.1884	0.004	1128	15	6.74
Output_1_19	13.587		1.458	1176	23	2.06	0.22	1148	12	0.1955	0.003	1153	12	4.59
Output_1_20	13.850		1.765	1149	26	1.86	0.23	1097	15	0.1844	0.003	1095	14	5.37
Output_1_21	13.333		0.267	1119	10	1.215	0.024	705	5	0.1167	8E-04	703	5	9.71
Output_1_22	13.055		0.460	1119	17	1.472	0.054	859	12	0.1417	0.002	845	9	6.67
Output_1_23	13.605		0.185	1049	7	1.503	0.024	911	9	0.1481	0.002	888	9	3.65
Output_1_24	9.901		0.422	1663	15	3.91	0.18	1616	12	0.2833	0.003	1609	13	3.99
Output_1_25	13.459		0.380	1118	12	1.067	0.069	648	35	0.1055	0.006	636	34	10.28
Output_1_26	14.085		1.111	1189	21	1.94	0.16	1167	10	0.1955	0.002	1162	10	3.92
Output_1_27	12.953		0.436	1139	12	2.092	0.069	1147	8	0.1959	0.001	1155	7	3
Output_1_28	17.241		6.243	1187	39	1.5	0.55	1121	15	0.1886	0.006	1126	17	5.5
Output_1_29	12.500		0.734	1412	18	2.56	0.17	1352	10	0.2305	0.002	1344	10	4.33
Output_1_30	13.514		5.113	1183	54	2.53	0.79	1137	20	0.192	0.007	1135	20	10
Output_1_31	12.920		0.634	1167	16	2.12	0.1	1145	9	0.1947	0.002	1146	8	3.27
Output_1_32	13.210		0.576	1191	15	1.914	0.098	1096	13	0.1827	0.003	1089	15	3.67
Output_1_33	12.755		0.195	1161	9	2.132	0.033	1151	6	0.1968	0.001	1158	6	1.8

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_34	50.000	67.500	1189	34	0.79	0.63	1127	16	0.1834	0.006	1131	16	7.18
Output_1_35	18.182	7.273	1193	37	1.77	0.57	1100	15	0.1817	0.005	1099	16	8.07
Output_1_36	16.949	3.160	1182	29	1.69	0.31	1172	14	0.1955	0.003	1176	15	5.14
Output_1_37	15.625	2.686	1143	31	1.8	0.3	1131	13	0.19	0.003	1138	14	6.46
Output_1_38	13.298	0.531	1162	15	2.034	0.09	1168	7	0.198	0.002	1171	8	3.21
Output_1_39	47.619	63.492	1141	42	1	0.7	1150	20	0.1881	0.007	1148	21	9.8
Output_1_40	12.690	1.015	1453	19	2.38	0.22	1306	29	0.2202	0.006	1294	29	5.68
Output_1_41	12.658	2.403	1216	25	2.19	0.41	1154	13	0.1967	0.004	1154	14	5.71
Output_1_42	76.923	213.018	1222	39	1.04	0.88	1155	18	0.1878	0.008	1155	18	7.6
Output_1_43	31.250	18.555	1169	41	0.95	0.46	1142	17	0.1839	0.005	1146	19	8
Output_1_44	13.587	0.203	1083	10	1.169	0.02	701	6	0.1159	0.001	700	6	9.02
Output_1_45	13.441	0.361	1145	10	1.969	0.055	1131	8	0.1904	0.002	1131	10	2.78
Output_1_46	14.881	1.439	1152	15	1.56	0.15	993	15	0.1638	0.003	987	15	4.72
Output_1_47	13.423	0.234	1127	9	1.224	0.032	730	15	0.1206	0.002	726	14	9.24
Output_1_48	12.788	0.311	1171	11	2.135	0.055	1169	7	0.1985	0.001	1171	7	2.43
Output_1_49	13.477	0.436	1075	20	1.709	0.048	1010	11	0.1682	0.002	1002	11	2.71
Output_1_50	11.876	0.719	1400	20	2.77	0.18	1389	12	0.2407	0.003	1394	12	4.01
Output_1_51	16.393	6.181	1140	37	1.73	0.62	1073	15	0.1836	0.006	1079	16	8
Output_1_52	11.765	0.955	1131	24	2.16	0.18	1074	11	0.1835	0.003	1078	12	4.82
Output_1_53	12.987	0.388	1164	14	2.102	0.067	1172	8	0.1977	0.001	1167	7	2.9
Output_1_54	14.684	1.445	1138	26	1.86	0.19	1142	12	0.1915	0.002	1145	12	5.36
Output_1_55	13.550	0.312	1095	12	1.348	0.039	810	14	0.1331	0.002	797	12	6.66
Output_1_56	35.714	57.398	1232	53	2.1	1.1	1133	24	0.189	0.009	1132	25	11.4
Output_1_57	11.601	0.188	1395	12	2.066	0.032	1020	11	0.1731	0.002	1014	10	9.46
Output_1_58	15.385	3.314	1085	32	1.78	0.38	1113	14	0.1882	0.004	1118	14	5.12
Output_1_59	13.038	0.408	1143	12	1.992	0.065	1110	7	0.1872	0.001	1106	7	3.27
Output_1_60	12.837	0.346	1173	13	2.006	0.054	1111	7	0.1865	0.001	1101	7	2.64
Output_1_61	13.514	2.557	1080	34	1.91	0.43	1154	15	0.193	0.004	1148	16	7.59
Output_1_62	13.423	0.288	1079	12	1.773	0.043	1035	9	0.1734	0.001	1031	8	2.53

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_63	10.989	2.898	1201	38	2.86	0.72	1153	22	0.1988	0.007	1151	23	8.6
Output_1_64	11.574	0.308	1404	12	2.727	0.087	1329	16	0.2274	0.003	1324	16	3.48
Output_1_65	13.175	0.312	1158	10	1.72	0.042	999	14	0.1639	0.002	979	13	4.31
Output_1_66	13.695	0.171	1038	11	1.121	0.027	672	16	0.1103	0.002	666	15	8.52
Output_1_67	17.123	2.873	1138	23	1.56	0.28	1136	12	0.1876	0.003	1136	13	6.1
Output_1_68	15.521	0.217	917	12	0.6338	0.0088	438	4	0.0709	6E-04	437	4	11.03
Output_1_69	13.477	0.708	1203	19	1.99	0.11	1155	10	0.1946	0.002	1149	9	3.75
Output_1_70	13.210	0.890	1162	16	2.01	0.15	1141	9	0.1918	0.002	1138	9	3.8
Output_1_71	13.055	0.239	1058	8	1.827	0.038	1034	6	0.173	0.001	1027	5	1.9
Output_1_72	-62.500	152.344	1075	52	-0.35	0.9	1111	21	0.1705	0.008	1112	23	10.5
Output_1_73	12.788	0.409	1146	12	1.968	0.068	1081	11	0.1809	0.002	1073	11	3.55
Output_1_74	27.778	13.117	1162	31	0.94	0.41	1057	23	0.1676	0.005	1055	23	6.91
Output_1_75	11.891	0.792	1418	17	2.86	0.2	1398	13	0.242	0.003	1401	12	3.93
Output_1_76	13.212	0.131	1098	7	1.491	0.025	872	13	0.1433	0.002	856	11	5.9
Output_1_77	12.121	0.529	1215	15	2.14	0.1	1123	13	0.1904	0.002	1115	13	4.03
Output_1_78	12.674	0.337	1200	11	2.178	0.062	1175	8	0.1984	0.001	1168	7	2.73
Output_1_79	13.831	0.287	1116	9	1.117	0.037	680	16	0.1121	0.003	677	16	10.6
Output_1_80	12.755	0.537	1165	14	2.061	0.097	1127	9	0.1915	0.002	1127	10	2.97
Output_1_81	12.642	0.991	1176	19	2.16	0.18	1149	9	0.1951	0.002	1151	10	3.89
Output_1_82	13.106	0.429	1052	14	1.726	0.065	987	9	0.1639	0.002	975	8	2.76
Output_1_83	12.690	0.692	1145	18	2.16	0.13	1180	10	0.2006	0.002	1180	11	3.64
Output_1_84	13.986	1.232	1258	19	2.09	0.19	1224	11	0.2085	0.002	1228	12	4.55
Output_1_85	14.652	0.189	899	10	0.738	0.023	481	13	0.0785	0.002	480	13	9.74
Output_1_86	14.993	1.753	1254	39	1.65	0.21	1084	27	0.1794	0.005	1075	27	7
Output_1_87	13.158	1.731	1117	25	2.05	0.27	1096	12	0.185	0.003	1093	12	4.92
Output_1_88	13.106	0.378	1170	13	1.949	0.06	1094	9	0.1822	0.002	1078	9	3.28
Output_1_89	13.532	0.623	1173	12	1.97	0.1	1144	10	0.1918	0.002	1138	9	3.16
Output_1_90	13.495	0.182	1084	8	1.792	0.029	1053	7	0.1759	0.001	1045	6	2.23
Output_1_91	14.451	0.376	1111	10	0.863	0.026	552	6	0.09	0.001	550	6	13.22

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_92	13.158	0.606	1195	14	2.001	0.096	1129	11	0.1896	0.002	1123	11	3.32
Output_1_93	62.500	203.125	1124	82	1.1	1.3	1129	28	0.1838	0.009	1136	28	9.2
Output_1_94	13.514	2.009	1149	31	2.09	0.32	1146	14	0.1909	0.004	1139	14	6.31
Output_1_95	13.736	0.264	1106	11	1.066	0.023	646	6	0.1063	0.001	643	6	11.03
Output_1_96	12.788	0.196	1182	9	2.101	0.037	1151	8	0.1933	0.002	1141	9	2.22
Output_1_97	12.579	0.253	1171	10	1.875	0.052	1033	13	0.1716	0.002	1018	13	4.26
Output_1_98	13.038	0.204	1136	10	2.034	0.035	1127	7	0.19	0.001	1121	7	2.24
Output_1_99	13.532	0.385	1021	13	1.535	0.054	928	11	0.1526	0.002	913	12	3.53
Output_1_100	13.245	0.579	1168	15	1.916	0.093	1106	10	0.1833	0.002	1089	12	3.1
Output_1_101	13.680	0.337	1034	11	1.791	0.047	1053	7	0.1777	0.001	1058	7	2.46
Output_1_102	34.483	40.428	1085	46	0.93	0.85	1081	20	0.1739	0.008	1082	21	9.1
Output_1_103	10.091	0.122	1611	8	3.711	0.05	1569	9	0.2728	0.002	1554	9	2.42
AS-3													
Output_1_1	12.788	0.278	1169	26	2.154	0.069	1176	88	0.1996	0.007	1179	16	5.04
Output_1_2	12.285	0.181	1228	20	2.101	0.061	1170	49	0.1864	0.006	1104	11	4.77
Output_1_3	12.547	0.283	1196	24	2.162	0.07	1192	69	0.1936	0.007	1143	16	5.07
Output_1_4	12.531	0.314	1208	29	2.238	0.076	1120	120	0.2003	0.007	1167	22	6.27
Output_1_5	12.315	0.258	1222	21	1.935	0.055	1050	44	0.1726	0.007	1021	11	4.98
Output_1_6	12.469	0.326	1215	29	2.177	0.075	1170	100	0.1942	0.008	1149	17	4.25
Output_1_7	12.484	0.358	1227	33	2.125	0.078	830	150	0.1889	0.007	1075	21	6.4
Output_1_8	12.225	0.284	1226	30	2.239	0.07	1113	70	0.198	0.007	1146	12	4.1
Output_1_9	12.739	0.260	1141	24	2.139	0.062	1117	81	0.1967	0.007	1153	15	4.36
Output_1_10	12.706	0.274	1164	23	2.154	0.065	1141	69	0.1962	0.007	1155	13	4.51
Output_1_11	12.438	0.217	1202	22	2.164	0.067	1070	56	0.1942	0.007	1131	11	4.31
Output_1_12	12.674	0.241	1165	20	2.201	0.068	1109	58	0.1997	0.007	1157	14	4.44
Output_1_13	13.316	0.195	1061	18	1.861	0.054	1090	39	0.1785	0.006	1060	10	3.64
Output_1_14	12.407	0.570	1216	54	2.097	0.097	1470	170	0.1897	0.007	1052	50	10.2
Output_1_15	8.691	0.065	1874	8	5.174	0.14	1841	13	0.326	0.011	1816	11	2.56
Output_1_16	12.739	0.243	1179	17	2.11	0.065	1116	72	0.192	0.007	1131	14	4.54

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_17	12.469	0.342	1223	33	2.124	0.092	860	120	0.1924	0.008	1101	18	6.25
Output_1_18	12.788	0.196	1159	18	2.112	0.063	1066	62	0.1941	0.007	1133	12	3.75
Output_1_19	12.547	0.189	1194	19	2.154	0.064	1106	55	0.1946	0.007	1139	12	4
Output_1_20	12.970	0.555	1162	61	2.104	0.17	1170	190	0.1934	0.007	1151	36	7
Output_1_21	12.690	0.435	1185	32	2.023	0.068	930	140	0.1869	0.006	1078	25	5.3
Output_1_22	12.642	0.208	1178	18	2.096	0.064	1102	53	0.1929	0.007	1134	12	4.16
Output_1_23	12.674	0.257	1184	25	2.074	0.069	1131	76	0.1908	0.007	1120	15	5.03
Output_1_24	12.375	0.132	1216	12	2.04	0.055	1123	17	0.1864	0.006	1101	9	3.38
Output_1_25	12.887	0.349	1170	29	2.085	0.075	980	130	0.1937	0.007	1124	19	6.33
Output_1_26	12.092	0.175	1257	17	2.196	0.067	1086	67	0.1935	0.007	1130	12	4.11
Output_1_27	12.500	0.391	1174	35	2.1	0.078	970	170	0.1931	0.007	1116	26	6.23
Output_1_28	12.210	0.343	1248	28	2.177	0.073	1060	130	0.1941	0.007	1101	28	6.64
Output_1_29	12.547	0.252	1182	24	2.202	0.072	1168	75	0.2024	0.007	1185	15	4.71
Output_1_30	12.610	0.286	1184	22	2.16	0.068	1198	73	0.198	0.007	1174	14	5.2
Output_1_31	12.563	0.237	1195	25	2.111	0.078	1130	72	0.193	0.008	1133	13	4.27
Output_1_32	12.674	0.193	1178	16	2.103	0.062	1063	59	0.1935	0.007	1130	11	3.71
Output_1_33	12.594	0.222	1184	22	2.113	0.064	964	79	0.1928	0.007	1115	14	4.47
Output_1_34	12.453	0.357	1216	30	2.143	0.079	1020	120	0.1933	0.007	1122	20	6.14
Output_1_35	12.547	0.236	1177	24	2.135	0.07	1040	92	0.196	0.007	1140	16	3.59
Output_1_36	13.423	0.324	1048	30	1.812	0.06	1013	95	0.1772	0.006	1050	14	5.26
Output_1_37	12.755	0.277	1164	22	2.094	0.065	1149	90	0.1918	0.007	1142	16	4.59
Output_1_38	12.531	0.173	1185	16	2.056	0.059	1137	43	0.1873	0.007	1102	10	3.45
Output_1_39	12.788	0.278	1166	25	2.084	0.065	1025	73	0.1924	0.007	1121	13	4.78
Output_1_40	12.920	0.250	1141	23	2.016	0.084	1062	90	0.1879	0.009	1101	16	3.06
Output_1_41	12.804	0.295	1160	27	2.132	0.073	980	130	0.198	0.007	1133	18	5.52
Output_1_42	13.021	0.373	1112	32	2.065	0.079	1230	140	0.199	0.007	1184	23	6.75
Output_1_43	12.690	0.306	1159	28	2.123	0.072	1150	120	0.1971	0.007	1148	22	5.63
Output_1_44	12.788	0.262	1159	25	2.071	0.065	1165	82	0.1925	0.007	1133	16	4.91
Output_1_45	12.563	0.316	1198	26	2.153	0.074	1118	90	0.1975	0.007	1159	16	4.58

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_46	12.610	0.302	1167	29	2.085	0.074	1046	98	0.1931	0.007	1123	15	5.47
Output_1_47	12.788	0.311	1161	30	2.115	0.067	1142	79	0.1976	0.007	1148	18	5.09
Output_1_48	12.887	0.299	1155	22	2.11	0.071	1088	83	0.1961	0.007	1144	15	5.74
Output_1_49	12.569	0.126	1186	11	2.106	0.057	1161	17	0.195	0.007	1146	7	2.3
Output_1_50	11.947	0.514	1283	45	1.495	0.076	1350	160	0.1372	0.006	802	38	14
Output_1_51	12.453	0.326	1190	29	2.131	0.083	1192	97	0.1965	0.007	1163	19	5.9
Output_1_52	12.516	0.172	1196	14	2.133	0.06	1176	31	0.1966	0.007	1160	9	2.94
Output_1_53	12.516	0.329	1179	27	2.108	0.076	1080	130	0.1964	0.007	1138	22	6.33
Output_1_54	11.848	0.309	1314	29	2.272	0.078	940	140	0.1995	0.007	1124	18	5.78
Output_1_55	12.887	0.216	1142	18	2.082	0.066	1088	81	0.1999	0.007	1162	15	3.99
Output_1_56	12.531	0.424	1189	36	2.148	0.08	1190	130	0.2031	0.007	1183	30	7.2
Output_1_57	12.422	0.401	1224	33	2.205	0.079	1150	120	0.2007	0.007	1161	26	6.02
Output_1_58	12.180	0.252	1252	22	2.106	0.072	1030	100	0.1907	0.007	1116	18	4.75
Output_1_59	13.316	0.532	1095	54	1.866	0.081	1220	170	0.1819	0.007	1053	37	8.7
Output_1_60	12.516	0.235	1209	23	2.112	0.065	1031	88	0.1946	0.007	1126	15	4.35
Output_1_61	12.407	0.246	1218	28	2.221	0.071	1188	87	0.2013	0.007	1187	16	4.59
Output_1_62	11.905	0.482	1310	37	2.42	0.092	1370	160	0.2174	0.008	1255	35	6.2
Output_1_63	12.690	0.258	1167	24	2.113	0.067	982	78	0.1997	0.007	1152	15	4.63
Output_1_64	10.267	0.169	1575	19	1.464	0.044	648	96	0.1107	0.004	656	10	22.77
Output_1_65	12.674	0.209	1177	21	2.163	0.067	1054	76	0.2018	0.007	1172	16	4.06
Output_1_66	12.690	0.225	1187	21	2.148	0.068	1132	47	0.1994	0.007	1172	11	4.07
Output_1_67	12.755	0.260	1173	23	2.096	0.067	1153	91	0.1947	0.007	1158	16	5.03
Output_1_68	12.690	0.258	1155	24	2.109	0.068	1104	74	0.1965	0.007	1154	12	4.88
Output_1_69	12.690	0.322	1150	30	2.18	0.076	990	110	0.2041	0.007	1183	18	6.35
Output_1_70	12.195	0.327	1262	28	2.128	0.064	1100	76	0.1907	0.007	1115	16	5.25
Output_1_71	12.739	0.373	1181	29	1.193	0.072	839	86	0.1123	0.007	690	13	10.8
Output_1_72	12.547	0.139	1190	13	2.098	0.058	1125	28	0.1915	0.007	1126	8	2.93
Output_1_73	12.788	0.294	1157	26	2.084	0.068	1130	98	0.195	0.007	1150	17	4.99
Output_1_74	12.547	0.236	1189	23	2.123	0.065	1051	63	0.1949	0.007	1134	13	4.84

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
Output_1_75	12.610	0.254	1178	26	2.112	0.067	1068	73	0.1938	0.007	1128	12	4.73
Output_1_76	12.392	0.353	1222	29	2.171	0.081	1180	130	0.1957	0.007	1139	24	6.43
Output_1_77	12.594	0.174	1191	15	2.154	0.061	1097	37	0.1971	0.007	1152	10	3.17
Output_1_78	12.005	0.216	1276	17	1.771	0.053	956	43	0.1551	0.007	924	16	8.33
Output_1_79	12.300	0.439	1235	42	2.107	0.088	1130	170	0.1891	0.007	1087	35	8.5
Output_1_80	12.706	0.210	1175	17	2.142	0.066	1110	68	0.1975	0.007	1155	16	3.79
Output_1_81	4.965	0.071	2838	17	13.34	0.46	2700	36	0.481	0.018	2528	43	9.5
Output_1_82	12.710	0.107	1175	10	2.112	0.057	1165	17	0.1925	0.007	1134	8	2.34
Output_1_83	12.771	0.277	1175	29	2.137	0.071	1120	120	0.1979	0.007	1155	20	5.25
Output_1_84	12.658	0.240	1173	20	2.116	0.065	1164	57	0.1939	0.007	1142	13	5.01
Output_1_85	11.827	0.137	1299	13	1.838	0.056	922	44	0.1586	0.006	937	12	9.05
Output_1_86	12.937	0.368	1148	36	2.049	0.081	1230	130	0.1912	0.007	1151	25	6.89
Output_1_87	12.579	0.222	1185	20	2.155	0.065	1107	78	0.1947	0.007	1138	12	4.3
Output_1_88	12.755	0.195	1167	18	2.103	0.062	1153	45	0.1939	0.007	1139	10	3.52
Output_1_89	12.285	0.241	1240	21	1.616	0.05	886	55	0.1456	0.005	869	16	8.8
Output_1_90	12.544	0.156	1194	15	2.133	0.059	1145	29	0.1934	0.007	1137	9	3.12
Output_1_91	12.500	0.234	1191	21	2.088	0.065	1102	70	0.1903	0.007	1120	14	4.75
Output_1_92	12.821	0.312	1167	21	2.103	0.074	1253	97	0.1967	0.007	1171	18	5.68
Output_1_93	12.270	0.331	1229	36	2.191	0.083	1024	91	0.1965	0.007	1130	18	6.45
Output_1_94	11.905	0.269	1299	24	2.219	0.07	1009	80	0.192	0.007	1116	13	5.49
Output_1_95	12.594	0.254	1187	25	2.131	0.07	1216	87	0.1955	0.007	1153	16	5.16
Output_1_96	12.500	0.359	1205	30	2.145	0.076	1239	94	0.1934	0.007	1141	19	7.84
Output_1_97	12.610	0.175	1180	15	2.132	0.062	1103	57	0.1956	0.007	1144	11	3.76
Output_1_98	12.594	0.317	1194	29	2.191	0.073	1238	79	0.1981	0.007	1181	15	5.56
Output_1_99	12.658	0.304	1178	26	2.231	0.082	1153	86	0.2066	0.007	1201	19	5.11
Output_1_100	12.531	0.298	1200	27	2.186	0.12	1245	73	0.2009	0.007	1194	16	4.87
Output_1_101	12.755	0.325	1161	31	2.035	0.071	1074	91	0.1902	0.007	1116	15	6.16
Output_1_102	12.953	0.336	1184	33	2.118	0.073	1030	140	0.1971	0.007	1157	21	6.11
Output_1_103	12.547	0.268	1196	24	2.171	0.074	1104	88	0.1978	0.007	1160	15	4.81

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_104	12.706	0.307	1160	26	2.102	0.071	1159	74	0.1956	0.007	1153	12	5.93
Output_1_105	12.594	0.270	1179	26	2.14	0.069	961	86	0.1958	0.007	1134	14	5.3
AS-4													
Output_1_47	12.788	0.327	1172	31	2.116	0.064	1157	19	0.1957	0.003	1152	12	6.38
Output_1_1	4.619	0.045	2958	9	17.28	0.28	2949	10	0.5788	0.008	2945	18	3.55
Output_1_2	5.701	0.033	2615	6	9.73	0.17	2409	11	0.4023	0.006	2179	18	13.41
Output_1_3	12.970	0.387	1129	32	2.105	0.059	1152	20	0.1974	0.003	1161	13	5.7
Output_1_4	7.918	0.088	2050	11	6.13	0.11	1994	11	0.3502	0.006	1935	17	4.37
Output_1_5	12.424	0.114	1205	11	2.229	0.037	1189	7	0.2009	0.003	1180	7	2.41
Output_1_6	13.369	0.268	1067	25	1.904	0.043	1080	12	0.185	0.003	1095	12	4.85
Output_1_7	12.453	0.264	1201	25	2.257	0.056	1198	14	0.205	0.003	1202	13	4.97
Output_1_8	8.808	0.052	1856	7	5.091	0.074	1834	6	0.3239	0.004	1809	7	2.09
Output_1_9	12.594	0.365	1205	33	2.217	0.056	1183	20	0.1986	0.003	1167	16	5.38
Output_1_10	12.837	0.198	1153	16	2.153	0.045	1166	11	0.1993	0.003	1171	10	3.81
Output_1_11	12.791	0.139	1152	13	2.17	0.036	1171	8	0.2003	0.003	1177	7	2.42
Output_1_12	12.590	0.119	1183	11	2.195	0.037	1179	8	0.2003	0.003	1177	8	2.25
Output_1_13	12.407	0.416	1234	36	2.209	0.067	1179	20	0.1971	0.004	1159	17	7.3
Output_1_14	12.005	0.389	1263	42	2.22	0.078	1190	22	0.1946	0.004	1147	15	8.1
Output_1_15	13.495	0.455	1077	41	1.857	0.063	1067	21	0.1797	0.004	1065	15	7.4
Output_1_16	12.330	0.198	1213	23	2.144	0.042	1163	11	0.191	0.003	1127	10	4.22
Output_1_17	11.249	0.253	1399	40	2.322	0.062	1215	16	0.1867	0.003	1103	9	8.3
Output_1_18	12.579	0.316	1189	30	2.181	0.058	1175	16	0.1979	0.003	1165	12	5.98
Output_1_19	12.241	0.145	1242	14	2.283	0.039	1206	8	0.2025	0.003	1189	7	2.92
Output_1_20	6.845	0.056	2298	9	6.199	0.13	2003	12	0.3055	0.005	1718	17	17.68
Output_1_21	12.361	0.168	1208	13	2.152	0.037	1165	9	0.192	0.003	1132	9	3.43
Output_1_22	12.048	0.189	1271	16	2.45	0.042	1259	11	0.2155	0.004	1258	12	3.05
Output_1_23	10.156	0.083	1593	9	3.777	0.059	1587	7	0.2773	0.004	1579	8	2.25
Output_1_24	12.453	0.279	1193	27	2.22	0.054	1189	15	0.2015	0.003	1183	12	4.92
Output_1_25	12.633	0.123	1184	14	2.157	0.087	1167	7	0.1965	0.003	1156	7	1.96

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
Output_1_26	12.446	0.088	1205	7	2.03	0.031	1125	6	0.1828	0.003	1082	7	3.21
Output_1_27	12.652	0.101	1165	10	2.159	0.036	1167	7	0.1987	0.003	1168	8	2.15
Output_1_28	12.610	0.137	1187	12	2.191	0.038	1180	8	0.2002	0.003	1176	8	2.76
Output_1_29	9.960	0.119	1630	14	3.995	0.069	1632	9	0.2866	0.004	1626	10	3.13
Output_1_30	9.355	0.123	1743	13	4.342	0.078	1700	10	0.2938	0.004	1660	12	3.89
Output_1_31	12.723	0.308	1178	25	2.132	0.055	1158	16	0.1956	0.003	1151	13	5.45
Output_1_32	12.821	0.247	1158	21	2.153	0.051	1165	14	0.2005	0.003	1178	9	4.86
Output_1_33	12.473	0.115	1204	10	2.199	0.034	1180	6	0.1989	0.003	1169	7	2.53
Output_1_34	12.019	0.318	1273	36	2.237	0.058	1188	20	0.1934	0.004	1140	14	6.3
Output_1_35	12.770	0.160	1172	14	2.168	0.038	1171	9	0.2004	0.003	1177	8	2.75
Output_1_36	12.804	0.180	1153	18	2.149	0.038	1163	10	0.1992	0.003	1171	7	3.03
Output_1_37	12.607	0.153	1181	12	2.164	0.036	1170	8	0.1983	0.003	1166	8	3.07
Output_1_38	12.601	0.154	1188	13	2.15	0.038	1164	8	0.1967	0.003	1158	8	3.24
Output_1_39	10.834	0.176	1474	20	1.797	0.04	1044	14	0.1411	0.004	851	16	16.2
Output_1_40	12.547	0.315	1198	30	2.16	0.06	1170	17	0.198	0.004	1164	14	6.13
Output_1_41	12.516	0.204	1194	21	2.217	0.047	1186	12	0.2012	0.003	1181	10	3.88
Output_1_42	9.960	0.149	1632	18	3.853	0.074	1605	11	0.2781	0.004	1581	13	3.91
Output_1_43	12.531	0.220	1203	24	2.153	0.099	1165	12	0.1946	0.005	1146	11	2.75
Output_1_44	12.219	0.128	1246	14	2.209	0.036	1184	7	0.1953	0.003	1151	7	3.24
Output_1_45	12.658	0.288	1189	28	2.142	0.059	1158	17	0.1961	0.004	1154	14	5.71
Output_1_46	12.642	0.192	1178	13	2.163	0.04	1171	11	0.1988	0.003	1169	11	2.93
Output_1_48	13.158	0.225	1126	20	2.052	0.044	1131	11	0.1953	0.003	1150	9	3.72
Output_1_49	12.737	0.157	1167	14	2.142	0.038	1162	8	0.197	0.003	1159	8	2.97
Output_1_50	12.470	0.148	1201	13	2.201	0.039	1180	9	0.2003	0.003	1178	7	2.97
Output_1_51	9.174	0.093	1787	11	4.441	0.087	1719	9	0.2944	0.005	1663	10	3.78
Output_1_52	12.649	0.152	1165	16	2.15	0.038	1164	8	0.1979	0.003	1164	7	3.17
Output_1_53	12.674	0.109	1165	10	2.17	0.035	1172	7	0.1998	0.003	1174	7	2.24
Output_1_54	12.723	0.324	1163	26	2.109	0.049	1155	16	0.197	0.003	1159	12	5.51
Output_1_55	13.459	0.326	1045	28	1.822	0.051	1053	16	0.1786	0.003	1059	10	5.87

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_56	13.263	0.211	1077	21	1.93	0.043	1093	12	0.1856	0.003	1097	11	4
Output_1_57	12.520	0.136	1191	13	2.145	0.038	1163	8	0.1943	0.003	1145	8	3.14
Output_1_58	12.750	0.153	1160	16	2.127	0.042	1158	10	0.1989	0.003	1169	10	3.04
Output_1_59	13.193	0.383	1100	35	1.839	0.056	1056	18	0.1758	0.003	1044	14	7.67
Output_1_60	12.361	0.229	1208	20	2.178	0.049	1173	13	0.1962	0.003	1155	10	4.81
Output_1_61	12.231	0.114	1228	10	2.139	0.037	1161	8	0.1911	0.003	1127	9	3.71
Output_1_62	12.577	0.120	1186	10	2.195	0.035	1179	6	0.2003	0.003	1177	7	2.55
Output_1_63	12.642	0.192	1180	16	2.085	0.041	1145	10	0.1921	0.003	1132	9	3.91
Output_1_64	12.658	0.192	1170	17	2.125	0.043	1155	11	0.1937	0.003	1142	8	3.93
Output_1_65	12.599	0.140	1183	12	2.174	0.039	1172	9	0.1987	0.003	1169	7	2.64
Output_1_66	12.531	0.361	1206	36	2.174	0.069	1174	20	0.1979	0.004	1164	15	7.61
Output_1_67	12.723	0.421	1191	37	2.149	0.074	1164	24	0.1966	0.003	1157	12	7.05
Output_1_68	12.261	0.123	1244	14	2.186	0.036	1177	7	0.1932	0.003	1138	9	3.45
Output_1_69	12.422	0.262	1208	26	2.177	0.052	1178	14	0.1962	0.003	1155	12	5.5
Output_1_70	9.355	0.080	1750	9	4.46	0.07	1724	7	0.3019	0.004	1700	10	2.64
Output_1_71	13.123	0.379	1102	31	1.873	0.059	1069	18	0.1798	0.003	1068	11	6.58
Output_1_72	12.484	0.203	1209	19	2.231	0.046	1191	11	0.2016	0.003	1183	10	3.72
Output_1_73	9.823	0.164	1664	17	4.085	0.13	1657	16	0.295	0.008	1665	27	3.83
Output_1_74	12.658	0.176	1169	18	2.201	0.043	1182	10	0.2009	0.003	1180	8	3.51
Output_1_75	12.778	0.072	1155	8	1.389	0.034	882	12	0.129	0.003	782	13	9.24
Output_1_76	12.658	0.256	1171	24	2.132	0.051	1159	14	0.1962	0.003	1155	10	4.51
Output_1_77	12.789	0.160	1147	15	2.132	0.039	1158	9	0.1984	0.003	1167	7	3.1
Output_1_78	8.787	0.100	1855	13	5.158	0.11	1847	14	0.3318	0.005	1847	15	3.12
Output_1_79	12.626	0.239	1164	21	2.166	0.051	1172	13	0.1989	0.003	1169	11	4.89
Output_1_80	12.571	0.081	1189	8	2.146	0.033	1163	6	0.1952	0.003	1150	7	1.85
Output_1_81	12.650	0.086	1180	7	1.742	0.029	1024	7	0.1594	0.002	953	8	5.37
Output_1_82	12.563	0.347	1190	34	2.164	0.068	1164	20	0.1962	0.004	1154	16	7
Output_1_83	13.210	0.419	1095	33	1.891	0.062	1078	20	0.1799	0.003	1066	14	7.44
Output_1_84	12.539	0.108	1189	10	2.16	0.034	1170	6	0.1972	0.003	1160	8	2.32

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_85	12.690	0.193	1171	17	2.121	0.043	1156	11	0.1962	0.003	1155	9	3.87
Output_1_86	12.755	0.358	1159	32	2.14	0.062	1169	17	0.1978	0.003	1163	12	6.79
Output_1_87	12.547	0.173	1197	17	2.196	0.042	1181	10	0.1989	0.003	1169	9	3.54
Output_1_88	12.609	0.148	1184	12	2.144	0.037	1162	8	0.1954	0.003	1150	7	2.85
Output_1_89	13.123	0.207	1095	21	1.896	0.041	1081	11	0.1793	0.003	1063	8	3.74
Output_1_90	12.453	0.574	1242	52	2.14	0.11	1161	33	0.1938	0.005	1141	21	12
Output_1_91	12.755	0.537	1169	43	2.092	0.071	1139	27	0.193	0.003	1137	17	8.7
Output_1_92	12.626	0.255	1184	24	2.163	0.051	1172	14	0.1987	0.003	1168	10	4.9
Output_1_93	12.484	0.234	1215	19	2.197	0.047	1178	12	0.1985	0.003	1167	11	4.67
Output_1_94	12.804	0.295	1181	26	2.177	0.063	1176	17	0.2017	0.003	1184	12	5.35
Output_1_95	12.987	0.439	1115	44	1.903	0.068	1080	21	0.1765	0.004	1047	15	8.2
Output_1_96	12.594	0.286	1190	25	2.143	0.051	1161	14	0.1958	0.003	1153	12	5.69
Output_1_97	12.639	0.131	1181	12	2.224	0.036	1190	7	0.2035	0.003	1194	8	2.49
Output_1_98	12.516	0.235	1194	21	2.155	0.048	1164	13	0.1959	0.003	1153	10	4.49
Output_1_99	12.563	0.331	1203	33	2.143	0.059	1162	17	0.1957	0.003	1152	13	6.14
Output_1_100	13.141	0.190	1087	16	1.844	0.037	1060	10	0.1755	0.003	1042	8	3.75
Output_1_101	12.920	0.401	1135	34	2.109	0.064	1149	21	0.198	0.004	1164	14	6.75
Output_1_102	12.771	0.163	1160	15	2.175	0.04	1173	9	0.2005	0.003	1178	9	3.2
AS-5													
Output_1_2	13.346	0.134	1066	11	1.843	0.016	1061	6	0.1778	0.001	1055	6	2.59
Output_1_3	12.788	0.311	1172	28	2.163	0.049	1169	16	0.1986	0.002	1168	11	5.52
Output_1_4	13.514	0.237	1068	22	1.875	0.033	1070	12	0.1818	0.002	1077	8	4.19
Output_1_5	12.538	0.154	1196	12	2.171	0.026	1172	8	0.197	0.001	1159	7	3.44
Output_1_6	10.121	0.164	1604	16	3.891	0.06	1610	12	0.2846	0.002	1614	10	4.05
Output_1_7	9.443	0.196	1747	21	4.538	0.093	1739	17	0.3071	0.003	1729	14	5.33
Output_1_8	5.552	0.052	2655	10	11.29	0.15	2546	13	0.4549	0.006	2416	25	7.78
Output_1_9	11.050	0.122	1434	13	3.049	0.036	1420	9	0.2425	0.002	1401	8	3.07
Output_1_10	10.834	0.141	1466	15	3.185	0.037	1452	9	0.2491	0.002	1433	11	3.94
Output_1_11	12.739	0.276	1143	22	2.096	0.041	1149	13	0.195	0.002	1148	10	5.09

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_12	13.132	0.122	1097	11	1.91	0.021	1084	7	0.1809	1E-03	1072	5	2.47
Output_1_13	11.364	0.220	1377	20	2.8	0.051	1359	14	0.2312	0.002	1343	13	5.12
Output_1_14	11.507	0.146	1348	14	2.669	0.034	1321	10	0.2226	0.002	1297	12	3.58
Output_1_15	10.799	0.222	1484	20	3.137	0.064	1442	16	0.2435	0.002	1404	12	5.49
Output_1_16	10.870	0.130	1472	13	3.144	0.038	1442	9	0.246	0.002	1418	9	3.31
Output_1_17	10.695	0.149	1515	17	3.312	0.043	1482	10	0.2554	0.002	1467	10	3.92
Output_1_18	13.387	0.233	1069	19	1.884	0.031	1076	11	0.1818	0.002	1077	8	4.4
Output_1_19	12.631	0.120	1165	12	2.226	0.023	1188	7	0.203	0.001	1192	6	2.63
Output_1_20	13.141	0.190	1092	19	1.916	0.032	1086	11	0.1826	0.001	1081	8	3.74
Output_1_21	12.674	0.193	1176	18	2.185	0.035	1175	11	0.1992	0.002	1171	9	4.06
Output_1_22	12.970	0.303	1140	32	2.114	0.048	1155	15	0.1955	0.002	1151	12	6.45
Output_1_23	12.195	0.178	1248	19	2.433	0.034	1252	10	0.2128	0.002	1244	10	3.73
Output_1_24	12.610	0.223	1191	18	2.18	0.039	1174	12	0.1985	0.002	1167	9	4.69
Output_1_25	12.376	0.460	1199	47	1.942	0.07	1103	23	0.1749	0.002	1038	13	9.9
Output_1_26	12.610	0.302	1167	26	2.123	0.046	1155	15	0.1938	0.002	1142	13	5.88
Output_1_27	9.966	0.094	1631	10	4.009	0.045	1638	9	0.2898	0.003	1640	15	3.24
Output_1_28	13.106	0.361	1111	32	1.945	0.057	1095	20	0.1839	0.003	1089	14	6.37
Output_1_29	12.723	0.162	1172	16	2.14	0.027	1161	9	0.196	0.001	1154	7	3.41
Output_1_30	10.823	0.293	1480	32	3.096	0.078	1434	20	0.2446	0.003	1410	17	6.03
Output_1_31	9.718	0.113	1671	12	4.024	0.046	1640	9	0.2816	0.002	1599	11	3.98
Output_1_32	5.624	0.060	2630	10	12.31	0.15	2627	11	0.4974	0.004	2602	16	4.03
Output_1_33	13.298	0.566	1105	54	1.883	0.08	1074	28	0.1766	0.003	1048	16	9.3
Output_1_34	12.300	0.303	1234	28	2.338	0.058	1222	18	0.2059	0.002	1206	13	5.79
Output_1_35	13.028	0.166	1119	16	1.893	0.025	1078	9	0.1761	0.002	1045	9	3.44
Output_1_36	12.500	0.281	1197	26	2.148	0.043	1163	14	0.1931	0.002	1138	11	5.58
Output_1_37	11.554	0.101	1344	14	1.601	0.053	967	20	0.132	0.004	802	21	14.5
Output_1_38	10.941	0.539	1502	51	2.98	0.14	1396	36	0.2325	0.004	1347	23	10.1
Output_1_39	13.459	0.308	1058	29	1.821	0.042	1053	15	0.1778	0.002	1055	11	5.77
Output_1_40	11.236	0.215	1422	24	2.895	0.052	1380	14	0.2364	0.003	1368	14	5.22

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_41	11.737	0.455	1347	49	2.72	0.11	1337	29	0.2301	0.004	1334	22	8.7
Output_1_42	13.055	0.528	1149	48	2.241	0.085	1185	27	0.2083	0.003	1219	18	9.3
Output_1_43	12.422	0.201	1217	18	2.27	0.04	1203	12	0.2022	0.002	1187	9	3.66
Output_1_44	12.346	0.244	1220	25	2.321	0.046	1220	13	0.2092	0.002	1226	10	5.35
Output_1_45	10.885	0.091	1464	9	3.209	0.026	1459	6	0.252	0.001	1449	7	2.63
Output_1_46	12.837	0.297	1138	28	1.911	0.039	1084	13	0.178	0.002	1056	10	5.3
Output_1_47	8.977	0.089	1823	10	4.857	0.054	1795	9	0.3136	0.002	1758	11	2.97
Output_1_48	12.407	0.292	1230	28	2.305	0.052	1218	16	0.2049	0.002	1201	13	5.77
Output_1_49	13.158	0.260	1099	20	1.937	0.035	1095	12	0.1836	0.002	1087	9	4.36
Output_1_50	12.690	0.338	1185	34	2.152	0.052	1162	17	0.195	0.002	1148	13	6.66
Output_1_52	11.534	0.239	1358	23	2.79	0.057	1354	15	0.233	0.002	1350	12	5.1
Output_1_53	11.416	0.261	1383	27	2.776	0.058	1347	16	0.2275	0.002	1321	11	5.76
Output_1_54	12.438	0.217	1206	23	2.252	0.038	1197	12	0.2009	0.002	1180	10	4.08
Output_1_55	9.681	0.169	1689	17	4.174	0.071	1666	14	0.2907	0.003	1645	15	4.58
Output_1_56	12.514	0.094	1190	7	1.964	0.025	1102	9	0.1783	0.002	1057	10	3.71
Output_1_57	10.846	0.247	1485	26	3.129	0.074	1437	18	0.2426	0.003	1400	15	5.75
Output_1_58	11.025	0.146	1439	13	3.141	0.039	1446	9	0.249	0.002	1433	8	3.38
Output_1_59	13.038	0.391	1177	34	2.111	0.067	1148	22	0.194	0.002	1144	12	7.22
Output_1_60	13.106	0.601	1120	57	1.882	0.082	1068	29	0.1774	0.004	1052	21	10.2
Output_1_61	13.123	0.362	1113	33	1.91	0.048	1086	17	0.1806	0.002	1070	11	6.11
Output_1_62	12.765	0.134	1162	12	1.915	0.019	1086	7	0.1752	0.001	1040	7	3.94
Output_1_63	10.741	0.288	1496	28	3.134	0.079	1438	20	0.2415	0.003	1394	17	7.49
Output_1_64	13.210	0.436	1098	36	1.895	0.059	1079	21	0.1816	0.002	1076	13	7.73
Output_1_65	13.228	0.402	1107	35	1.908	0.054	1081	19	0.1814	0.002	1074	12	6.9
Output_1_66	12.690	0.338	1177	32	2.147	0.056	1164	18	0.1953	0.002	1150	11	6.4
Output_1_67	11.198	0.226	1423	23	2.903	0.057	1383	15	0.2356	0.003	1364	14	5.25
Output_1_68	12.195	0.461	1251	46	2.448	0.09	1247	27	0.2161	0.004	1260	21	9.6
Output_1_69	11.834	0.210	1309	21	2.531	0.048	1281	14	0.2172	0.002	1267	11	4.88
Output_1_70	11.862	0.225	1320	20	2.596	0.045	1300	13	0.2228	0.002	1297	9	4.69

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
Output_1_71	11.429	0.274	1403	26	2.777	0.07	1346	19	0.2259	0.003	1312	15	6.44
Output_1_72	12.870	0.232	1144	20	2.071	0.035	1140	12	0.192	0.002	1132	9	4.54
Output_1_73	10.460	0.109	1548	12	3.392	0.037	1504	8	0.2561	0.002	1470	9	3.31
Output_1_74	12.469	0.280	1221	23	2.255	0.053	1196	16	0.203	0.002	1191	12	5.34
Output_1_75	12.438	0.665	1253	63	1.93	0.1	1093	34	0.1762	0.004	1050	22	13.1
Output_1_76	12.853	0.297	1161	28	2.027	0.043	1123	14	0.1884	0.002	1114	11	5.8
Output_1_77	10.964	0.115	1451	12	3.135	0.031	1441	8	0.2492	0.002	1434	8	2.76
Output_1_78	11.312	0.294	1376	33	2.72	0.07	1335	20	0.2226	0.003	1297	15	6.77
Output_1_80	12.706	0.355	1170	33	2.069	0.053	1137	18	0.1896	0.002	1119	11	5.18
Output_1_81	13.569	0.258	1041	19	1.789	0.031	1040	11	0.1746	0.001	1037	8	4.5
Output_1_82	12.612	0.100	1178	10	2.192	0.02	1180	6	0.2011	0.001	1181	6	2.24
Output_1_83	10.860	0.106	1465	10	3.227	0.03	1464	7	0.2557	0.001	1468	7	2.76
Output_1_84	11.765	0.194	1321	23	2.693	0.044	1326	12	0.23	0.002	1334	10	4.51
Output_1_85	11.025	0.292	1427	25	2.914	0.08	1384	21	0.2337	0.003	1353	17	6.36
Output_1_86	12.642	0.224	1188	17	2.206	0.036	1181	12	0.2006	0.002	1179	9	4.69
Output_1_87	10.834	0.176	1476	20	3.211	0.063	1458	15	0.2534	0.002	1457	13	4.18
Output_1_89	5.302	0.084	2733	15	13.14	0.21	2688	15	0.5034	0.005	2628	21	4.97
Output_1_90	12.674	0.161	1175	15	2.179	0.028	1175	9	0.2002	0.001	1176	7	3.02
Output_1_91	13.263	0.299	1084	21	1.843	0.04	1060	14	0.1758	0.002	1044	10	4.95
Output_1_92	13.193	0.348	1114	30	2.096	0.057	1143	19	0.1983	0.002	1166	12	5.63
Output_1_93	12.658	0.320	1165	28	2.193	0.053	1180	16	0.2009	0.002	1180	12	6.18
Output_1_94	13.245	0.175	1068	16	1.905	0.027	1082	9	0.183	0.001	1083	6	3.17
Output_1_95	13.193	0.383	1084	37	1.921	0.051	1090	17	0.1861	0.003	1100	14	6.74
Output_1_96	11.038	0.231	1449	23	2.725	0.071	1334	20	0.219	0.005	1275	26	6.66
Output_1_97	12.063	0.378	1292	36	2.363	0.066	1238	18	0.2078	0.003	1217	15	7.13
Output_1_98	11.001	0.266	1471	25	2.999	0.067	1409	18	0.2389	0.002	1382	13	6.28
Output_1_99	9.940	0.109	1637	12	3.849	0.04	1603	9	0.2753	0.002	1567	12	3.65
Output_1_100	10.989	0.326	1456	27	3.056	0.085	1424	21	0.2427	0.003	1404	15	7.17
Output_1_101	10.929	0.382	1470	37	3.15	0.11	1441	26	0.2471	0.004	1423	19	8.4

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_102	11.099	0.259	1465	25	3.185	0.066	1452	16	0.2531	0.003	1457	16	6.11
Output_1_103	10.823	0.316	1474	34	3.184	0.073	1462	17	0.2506	0.004	1441	20	7.39
Output_1_104	10.903	0.118	1457	12	3.323	0.036	1487	9	0.2622	0.002	1501	9	3.32
Output_1_105	13.004	0.490	1140	38	2.096	0.081	1142	27	0.1939	0.003	1142	17	8.7
Output_1_106	12.853	0.198	1143	18	1.697	0.04	1009	16	0.1582	0.004	946	23	5.55
Output_1_107	14.108	0.167	945	17	0.3805	0.0043	327	3	0.0385	3E-04	244	2	16.76
Output_1_108	12.674	0.369	1170	33	2.153	0.063	1167	21	0.1999	0.003	1176	15	7.09
Output_1_109	9.501	0.084	1721	7	4.09	0.037	1652	7	0.2813	0.002	1599	11	3.97
Output_1_110	13.333	0.320	1080	27	1.897	0.043	1079	15	0.1828	0.002	1082	10	5.3
Output_1_111	12.069	0.131	1267	10	2.471	0.029	1264	9	0.2157	0.002	1259	11	3.08
Output_1_112	11.198	0.201	1419	17	3.072	0.049	1428	12	0.2475	0.002	1425	11	4.66
Output_1_113	11.614	0.162	1340	17	2.714	0.04	1332	11	0.2287	0.002	1328	9	3.77
Output_1_114	12.674	0.466	1182	40	2.267	0.077	1198	24	0.2057	0.003	1205	18	7.4
Output_1_115	12.048	0.203	1294	19	2.482	0.037	1268	11	0.2145	0.002	1253	11	3.95
Output_1_116	10.965	0.180	1448	21	3.416	0.059	1509	14	0.2689	0.002	1535	12	4.31
Output_1_117	13.021	0.559	1133	42	2.038	0.086	1126	29	0.1951	0.003	1150	19	9.6
Output_1_118	13.387	0.502	1078	45	1.831	0.071	1057	26	0.1783	0.003	1058	14	8.8
Output_1_119	10.010	0.180	1627	17	3.8	0.069	1594	15	0.2717	0.004	1549	20	4.34
Output_1_120	13.089	0.463	1102	46	2.06	0.069	1137	23	0.1941	0.003	1143	15	7.7
Output_1_121	13.441	0.361	1071	28	1.806	0.041	1051	15	0.1767	0.003	1048	14	6.27
Output_1_122	13.351	0.178	1056	14	1.876	0.025	1073	9	0.1792	0.001	1063	7	3.12
Output_1_123	12.853	0.198	1135	20	2.046	0.037	1133	12	0.1899	0.002	1120	10	3.68
Output_1_124	11.834	0.196	1307	18	2.453	0.045	1256	13	0.2097	0.002	1227	12	4.32
Output_1_125	10.834	0.211	1498	22	3.194	0.06	1460	15	0.2504	0.003	1440	13	5.32
Output_1_126	11.737	0.138	1312	14	2.521	0.033	1279	10	0.2169	0.001	1265	6	3.3
Output_1_127	6.061	0.114	2500	18	9.07	0.18	2343	18	0.3958	0.004	2149	20	11.1
Output_1_128	12.107	0.249	1251	19	2.498	0.053	1269	15	0.219	0.002	1276	12	4.14
Output_1_129	12.180	0.267	1251	24	2.246	0.048	1193	15	0.1938	0.002	1143	12	4.81
Output_1_130	12.210	0.164	1252	16	2.132	0.042	1158	14	0.1873	0.002	1106	12	4.05

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
Output_1_131	12.034	0.174	1268	21	2.562	0.05	1288	14	0.2212	0.003	1288	14	2.99
Output_1_132	9.579	0.275	1716	31	4.21	0.12	1677	23	0.2916	0.004	1649	20	7.7
Output_1_133	13.072	0.906	1146	65	2	0.13	1122	42	0.1882	0.005	1113	25	15.5
Output_1_51	17.765	0.120	463	8	0.444	0.0036	373	3	0.0568	5E-04	356	3	2.87
Output_1_79	12.970	0.185	1123	19	1.962	0.028	1103	9	0.184	0.001	1089	8	3.35
HF-1													
AD3-1	12.631	0.211	1176	33	2.129	0.052	1158	17	0.195	0.004	1149	19	2.35
AD3-2	12.400	0.229	1213	36	2.309	0.087	1215	27	0.208	0.007	1216	36	0.00
AD3-3	12.523	0.243	1193	38	2.217	0.081	1186	26	0.201	0.006	1183	33	0.89
AD3-4	12.213	0.226	1243	36	2.436	0.087	1253	26	0.216	0.007	1260	35	0.00
AD3-5	12.998	0.246	1120	38	2.045	0.068	1130	23	0.193	0.005	1136	29	0.00
AD3-6	9.396	0.148	1739	29	4.593	0.088	1748	16	0.313	0.003	1755	17	0.00
AD3-7	10.599	0.103	1515	18	3.432	0.105	1512	24	0.264	0.008	1509	39	0.38
AD3-8	10.728	0.212	1492	37	3.138	0.086	1442	21	0.244	0.005	1408	24	5.63
AD3-9	13.423	0.192	1055	29	1.800	0.059	1045	21	0.175	0.005	1041	28	1.35
AD3-10	12.272	0.191	1233	31	2.315	0.099	1217	30	0.206	0.008	1208	44	2.08
AD3-11	12.512	0.179	1195	28	2.208	0.054	1184	17	0.200	0.004	1177	22	1.47
AD3-12	12.589	0.197	1183	31	2.103	0.042	1150	14	0.192	0.002	1132	12	4.31
AD3-13	12.930	0.211	1130	32	2.037	0.040	1128	14	0.191	0.002	1127	12	0.28
AD3-14	12.757	0.225	1157	35	2.118	0.045	1155	15	0.196	0.002	1153	12	0.28
AD3-15	12.704	0.235	1165	37	2.067	0.042	1138	14	0.190	0.002	1124	9	3.53
AD3-16	11.797	0.249	1310	41	2.473	0.055	1264	16	0.212	0.001	1237	7	5.56
AD3-17	13.620	0.304	1026	45	1.802	0.057	1046	21	0.178	0.004	1056	22	0.00
AD3-18	13.022	0.385	1116	59	2.020	0.078	1122	26	0.191	0.005	1126	25	0.00
AD3-19	13.201	0.536	1089	81	1.981	0.082	1109	28	0.190	0.001	1119	8	0.00
AD3-21	12.534	0.270	1192	42	2.162	0.061	1169	20	0.197	0.004	1157	19	2.92
AD3-22	12.776	0.226	1154	35	2.165	0.041	1170	13	0.201	0.001	1179	7	0.00
AD3-23	13.034	0.299	1114	46	2.049	0.064	1132	21	0.194	0.004	1141	22	0.00
AD3-24	12.561	0.376	1187	59	2.157	0.076	1167	25	0.197	0.004	1157	20	2.58

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
AD3-25	12.779	0.232	1153	36	2.154	0.050	1166	16	0.200	0.003	1173	15	0.00
AD3-26	12.512	0.190	1195	30	2.235	0.037	1192	12	0.203	0.001	1191	7	0.37
AD3-27	12.848	0.281	1143	43	2.071	0.050	1139	17	0.193	0.002	1138	11	0.45
AD3-28	13.074	0.573	1108	88	2.047	0.091	1131	30	0.194	0.001	1144	8	0.00
AD3-29	12.448	0.143	1205	23	2.266	0.031	1202	10	0.205	0.001	1200	8	0.41
AD3-30	12.680	0.382	1169	60	2.145	0.066	1163	21	0.197	0.001	1160	7	0.71
AD3-31	12.839	0.627	1144	97	1.624	0.125	979	48	0.151	0.009	908	50	20.66
AD3-32	11.771	0.584	1314	96	2.613	0.137	1304	38	0.223	0.004	1298	19	1.24
AD3-33	13.216	0.251	1086	38	1.875	0.044	1072	16	0.180	0.003	1065	14	1.92
AD3-35	12.752	0.299	1157	46	2.180	0.076	1175	24	0.202	0.005	1184	28	0.00
AD3-36	12.864	0.382	1140	59	2.167	0.076	1170	25	0.202	0.004	1187	21	0.00
AD3-37	12.588	0.258	1183	41	2.217	0.059	1187	18	0.202	0.003	1188	18	0.00
AD3-38	12.660	0.246	1172	38	2.234	0.044	1192	14	0.205	0.001	1203	4	0.00
AD3-39	12.668	0.373	1171	58	2.244	0.069	1195	22	0.206	0.002	1208	9	0.00
AD3-40	5.224	0.156	2755	49	14.315	0.523	2771	35	0.542	0.011	2793	48	0.00
AD3-41	12.915	0.228	1132	35	2.115	0.046	1154	15	0.198	0.003	1165	14	0.00
AD3-42	12.404	0.296	1212	47	2.247	0.068	1196	21	0.202	0.004	1187	20	2.09
AD3-43	12.566	0.219	1187	34	2.024	0.048	1124	16	0.184	0.003	1091	16	8.02
AD3-44	12.958	0.312	1126	48	2.070	0.058	1139	19	0.195	0.003	1146	15	0.00
AD3-45	12.754	0.431	1157	67	2.214	0.078	1185	25	0.205	0.002	1201	12	0.00
AD3-46	12.824	0.252	1146	39	2.101	0.064	1149	21	0.195	0.005	1151	25	0.00
AD3-47	12.265	0.233	1234	37	2.354	0.053	1229	16	0.209	0.003	1226	14	0.69
AD3-48	12.605	0.154	1180	24	2.186	0.045	1177	14	0.200	0.003	1175	18	0.50
AD3-49	12.758	0.360	1157	56	2.157	0.067	1167	22	0.200	0.003	1173	14	0.00
AD3-50	12.792	0.253	1151	39	2.150	0.049	1165	16	0.200	0.002	1173	12	0.00
AD3-51	12.342	0.343	1222	55	2.427	0.079	1251	24	0.217	0.004	1267	20	0.00
AD3-52	12.736	0.241	1160	38	2.207	0.054	1183	17	0.204	0.003	1196	17	0.00
AD3-53	12.683	0.162	1168	25	2.186	0.035	1177	11	0.201	0.002	1181	10	0.00
AD3-54	12.447	0.258	1205	41	2.165	0.055	1170	18	0.195	0.003	1151	16	4.52

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
AD3-55	12.679	0.087	1169	14	2.139	0.017	1162	6	0.197	0.001	1158	5	0.96
AD3-56	13.439	0.230	1053	34	1.784	0.035	1040	13	0.174	0.002	1033	10	1.83
AD3-57	12.649	0.139	1174	22	2.185	0.026	1176	8	0.200	0.001	1178	5	0.00
AD3-58	12.504	0.088	1196	14	2.215	0.025	1186	8	0.201	0.002	1180	9	1.37
AD3-59	12.747	0.115	1158	18	2.090	0.025	1146	8	0.193	0.001	1139	8	1.68
AD3-60	12.035	0.153	1271	25	2.468	0.037	1263	11	0.215	0.002	1258	9	1.07
AD3-61	12.674	0.101	1170	16	2.128	0.021	1158	7	0.196	0.001	1152	6	1.53
AD3-62	12.690	0.138	1167	22	2.140	0.032	1162	10	0.197	0.002	1159	11	0.72
AD3-63	12.679	0.161	1169	25	2.180	0.032	1175	10	0.200	0.001	1178	8	0.00
AD3-64	13.466	0.190	1049	28	1.798	0.029	1045	11	0.176	0.001	1043	8	0.55
AD3-65	12.564	0.546	1187	86	2.150	0.095	1165	31	0.196	0.002	1153	10	2.82
AD3-66	13.090	0.356	1105	54	1.999	0.056	1115	19	0.190	0.001	1120	7	0.00
AD3-67	12.608	0.153	1180	24	2.172	0.039	1172	12	0.199	0.003	1168	14	1.02
AD3-68	11.489	0.130	1361	22	2.697	0.032	1328	9	0.225	0.001	1307	5	4.00
AD3-69	13.201	0.173	1088	26	1.852	0.031	1064	11	0.177	0.002	1052	10	3.32
AD3-70	12.916	0.198	1132	30	2.070	0.035	1139	12	0.194	0.001	1143	7	0.00
AD3-71	12.815	0.172	1148	27	2.058	0.035	1135	12	0.191	0.002	1128	11	1.69
AD3-72	13.194	0.227	1090	34	1.866	0.036	1069	13	0.179	0.002	1059	9	2.80
AD3-73	12.624	0.220	1178	34	2.166	0.044	1170	14	0.198	0.002	1166	11	0.98
AD3-74	12.817	0.225	1147	35	2.071	0.040	1139	13	0.193	0.002	1135	9	1.07
AD3-75	11.628	0.116	1338	19	2.652	0.029	1315	8	0.224	0.001	1301	6	2.75
AD3-76	12.600	0.495	1181	78	2.268	0.090	1202	28	0.207	0.001	1214	8	0.00
AD3-77	12.927	0.273	1130	42	2.061	0.050	1136	16	0.193	0.002	1139	12	0.00
AD3-78	12.788	0.133	1152	21	2.025	0.028	1124	9	0.188	0.002	1110	9	3.67
AD3-79	10.259	0.435	1576	79	3.736	0.170	1579	36	0.278	0.005	1581	23	0.00
AD3-80	12.623	0.158	1178	25	2.070	0.036	1139	12	0.189	0.002	1119	12	5.02
AD3-81	12.446	0.125	1206	20	2.251	0.030	1197	10	0.203	0.002	1193	10	1.07
AD3-82	12.626	0.150	1177	24	2.142	0.030	1163	10	0.196	0.001	1155	8	1.91
AD3-83	12.619	0.150	1178	24	2.150	0.028	1165	9	0.197	0.001	1158	6	1.72

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
AD3-84	12.628	0.224	1177	35	2.179	0.043	1174	14	0.200	0.002	1173	9	0.34
AD3-86	13.472	0.411	1048	61	1.767	0.055	1033	20	0.173	0.001	1026	6	2.03
AD3-87	12.458	0.301	1204	48	2.320	0.093	1219	28	0.210	0.007	1227	36	0.00
AD3-88	12.561	0.212	1187	33	2.164	0.053	1169	17	0.197	0.003	1160	19	2.31
AD3-89	13.387	0.173	1060	26	1.804	0.039	1047	14	0.175	0.003	1040	17	1.90
AD3-90	13.055	0.312	1111	48	2.031	0.053	1126	18	0.192	0.002	1134	11	0.00
AD3-91	12.844	0.151	1143	23	2.087	0.032	1145	11	0.194	0.002	1145	11	0.00
AD3-92	12.626	0.249	1177	39	2.145	0.051	1164	17	0.196	0.003	1156	15	1.78
AD3-93	13.406	0.319	1058	48	1.855	0.051	1065	18	0.180	0.003	1069	14	0.00
AD3-94	12.632	0.284	1176	45	2.196	0.050	1180	16	0.201	0.001	1182	5	0.00
AD3-95	13.020	0.643	1116	99	2.100	0.105	1149	35	0.198	0.002	1166	10	0.00
AD3-96	11.475	0.230	1364	39	2.819	0.060	1361	16	0.235	0.002	1359	9	0.38
AD3-97	12.548	0.182	1189	29	2.238	0.035	1193	11	0.204	0.001	1195	7	0.00
AD3-98	12.772	0.244	1154	38	2.087	0.049	1145	16	0.193	0.003	1140	15	1.28
AD3-99	12.831	0.314	1145	49	2.147	0.055	1164	18	0.200	0.001	1174	7	0.00
AD3-100	13.596	0.291	1029	43	1.825	0.043	1055	15	0.180	0.002	1067	10	0.00
HF-2													
Output_1_1	13.587	0.185	1023	14	1.826	0.045	1056	9	0.1829	0.005	1083	7	3.43
Output_1_2	11.261	0.355	1409	31	2.927	0.11	1384	23	0.2368	0.007	1369	18	8.1
Output_1_3	12.563	0.410	1168	40	2.245	0.076	1192	22	0.2064	0.006	1209	16	6.82
Output_1_4	11.211	0.176	1413	18	2.969	0.076	1399	12	0.2436	0.006	1405	13	4.37
Output_1_5	12.723	0.259	1165	23	2.185	0.063	1176	15	0.2024	0.005	1188	11	5.05
Output_1_6	13.459	0.254	1044	19	1.847	0.049	1063	12	0.1825	0.005	1081	10	4.37
Output_1_7	10.953	0.300	1432	29	3.143	0.086	1440	21	0.2501	0.007	1439	17	5.11
Output_1_8	11.161	0.212	1427	19	3.009	0.086	1411	15	0.2434	0.006	1404	14	4.75
Output_1_9	12.674	0.305	1205	22	2.171	0.062	1169	17	0.1992	0.005	1171	13	4.72
Output_1_10	11.416	0.339	1368	40	2.808	0.084	1356	20	0.2314	0.006	1341	16	6.27
Output_1_11	13.072	0.513	1152	46	1.933	0.082	1094	26	0.1812	0.005	1073	16	8.6
Output_1_12	11.261	0.190	1390	20	2.901	0.075	1381	12	0.2378	0.006	1375	9	4.2

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_13	5.580	0.078	2644	10	12.21	0.3	2621	13	0.4987	0.013	2609	22	4.97
Output_1_14	13.362	0.123	1054	10	1.849	0.042	1062	7	0.1799	0.004	1066	6	2.29
Output_1_15	13.277	0.134	1085	14	1.501	0.034	930	6	0.1432	0.004	863	6	5.35
Output_1_16	10.989	0.242	1449	25	3.229	0.092	1467	16	0.2564	0.007	1471	13	5.2
Output_1_17	13.755	0.322	1013	26	1.781	0.055	1037	15	0.1752	0.005	1041	9	5.33
Output_1_18	12.903	0.350	1134	35	2.132	0.072	1162	19	0.1995	0.005	1172	12	6.71
Output_1_19	11.299	0.166	1386	17	2.852	0.073	1369	12	0.2331	0.006	1350	11	4.13
Output_1_20	12.500	0.188	1202	18	2.206	0.054	1182	10	0.2001	0.005	1176	8	3.89
Output_1_21	12.788	0.213	1169	20	2.162	0.058	1167	12	0.1994	0.005	1172	11	4.24
Output_1_22	10.091	0.214	1623	25	3.67	0.12	1569	19	0.2693	0.007	1536	18	6
Output_1_23	12.136	0.339	1258	30	2.409	0.085	1241	21	0.2088	0.006	1223	14	6.92
Output_1_24	10.870	0.213	1464	20	3.166	0.093	1450	17	0.2515	0.007	1447	14	4.65
Output_1_25	12.937	0.218	1125	21	1.997	0.054	1113	12	0.1862	0.005	1101	8	4.07
Output_1_26	10.060	0.132	1620	15	3.71	0.09	1574	10	0.2688	0.007	1534	11	4.05
Output_1_27	13.298	0.318	1059	25	1.792	0.054	1045	14	0.1733	0.004	1030	10	5.86
Output_1_28	13.333	0.409	1064	34	1.859	0.066	1068	19	0.1804	0.005	1069	14	7.65
Output_1_29	12.285	0.407	1248	40	2.354	0.095	1227	27	0.2063	0.006	1209	15	7.56
Output_1_30	12.563	0.144	1188	15	2.221	0.052	1188	9	0.201	0.005	1180	7	2.87
Output_1_31	13.263	0.369	1061	34	1.91	0.062	1086	17	0.1824	0.005	1080	13	6.73
Output_1_32	11.299	0.166	1400	20	2.791	0.071	1352	12	0.2274	0.006	1321	12	3.48
Output_1_33	13.333	0.178	1077	15	1.918	0.047	1087	9	0.1855	0.005	1097	7	3.23
Output_1_34	9.901	0.176	1661	18	4.033	0.12	1642	17	0.2849	0.008	1615	17	4.76
Output_1_35	12.270	0.256	1245	25	2.309	0.065	1215	15	0.2052	0.005	1203	10	4.79
Output_1_36	10.309	0.138	1566	15	3.334	0.087	1487	13	0.2485	0.006	1431	13	4.56
Output_1_37	12.392	0.184	1223	15	2.307	0.055	1213	10	0.2048	0.005	1201	8	3.4
Output_1_38	10.823	0.164	1470	16	3.288	0.083	1477	12	0.2561	0.006	1470	10	4.13
Output_1_39	12.610	0.132	1175	13	2.131	0.049	1160	8	0.1936	0.005	1141	6	2.86
Output_1_40	11.468	0.171	1370	17	2.88	0.071	1376	11	0.237	0.006	1372	12	4.02
Output_1_41	5.708	0.098	2612	18	12.31	0.43	2621	26	0.501	0.017	2620	55	7.3

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_42	11.198	0.138	1415	15	3.081	0.073	1431	10	0.248	0.006	1429	9	3.32
Output_1_43	12.689	0.127	1172	14	2.218	0.051	1187	8	0.2022	0.005	1187	8	2.88
Output_1_44	12.503	0.084	1195	7	2.144	0.047	1163	6	0.193	0.005	1137	7	2.35
Output_1_45	12.642	0.336	1161	33	2.157	0.075	1166	19	0.198	0.005	1166	12	6.46
Output_1_46	11.099	0.283	1432	28	3.15	0.095	1445	19	0.2529	0.007	1453	17	6.23
Output_1_47	12.690	0.258	1182	23	2.216	0.059	1185	12	0.2014	0.005	1183	11	5.08
Output_1_48	11.377	0.272	1384	30	2.833	0.089	1363	18	0.2333	0.006	1351	12	5.8
Output_1_49	13.011	0.103	1124	9	0.84	0.024	618	10	0.0794	0.003	492	11	15.3
Output_1_50	13.316	0.355	1094	32	1.848	0.061	1064	17	0.178	0.005	1057	12	6.4
Output_1_51	11.494	0.172	1358	18	2.768	0.068	1345	11	0.2305	0.006	1337	10	4.14
Output_1_52	13.123	0.224	1085	21	1.894	0.051	1078	12	0.1788	0.005	1061	9	4.23
Output_1_53	11.325	0.141	1383	15	2.902	0.071	1383	10	0.2403	0.006	1389	10	3.16
Output_1_54	10.893	0.261	1451	27	3.16	0.1	1442	19	0.2513	0.007	1446	18	6.53
Output_1_55	5.394	0.049	2700	9	12.91	0.29	2672	9	0.5031	0.012	2628	16	3.81
Output_1_56	10.823	0.117	1472	12	3.201	0.074	1457	9	0.2515	0.006	1446	9	3.02
Output_1_57	12.579	0.237	1178	22	2.191	0.057	1176	13	0.1986	0.005	1169	11	4.15
Output_1_58	11.404	0.121	1374	11	2.768	0.064	1346	8	0.2294	0.006	1331	7	2.81
Output_1_59	11.013	0.182	1449	21	3.293	0.086	1480	13	0.2645	0.007	1512	12	3.71
Output_1_60	14.124	0.339	978	31	1.765	0.055	1033	16	0.1807	0.005	1071	10	6.04
Output_1_61	11.050	0.101	1442	9	2.979	0.067	1401	7	0.2392	0.006	1383	8	2.76
Output_1_62	12.920	0.250	1153	22	2.155	0.059	1170	13	0.2027	0.005	1189	10	4.89
Output_1_63	12.579	0.222	1181	19	2.186	0.059	1175	12	0.2008	0.005	1179	9	4.31
Output_1_64	10.991	0.109	1453	10	3.119	0.071	1437	8	0.2497	0.006	1437	10	2.93
Output_1_65	11.351	0.142	1389	12	2.846	0.068	1367	10	0.2337	0.006	1354	8	3.3
Output_1_66	5.447	0.056	2688	11	13.15	0.29	2689	9	0.519	0.013	2694	21	3.72
Output_1_67	11.820	0.154	1292	14	2.574	0.062	1293	9	0.2204	0.005	1284	8	3.41
Output_1_68	11.038	0.146	1429	17	3.069	0.075	1426	11	0.246	0.006	1417	11	3.41
Output_1_69	10.881	0.201	1460	20	3.221	0.088	1462	14	0.2555	0.007	1468	12	4.56
Output_1_70	12.579	0.206	1185	20	2.218	0.059	1186	12	0.2028	0.005	1190	9	4.02

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
Output_1_71	11.062	0.184	1445	19	3.125	0.081	1436	13	0.2503	0.006	1440	13	4.31
Output_1_72	13.441	0.434	1070	42	1.782	0.07	1039	23	0.1726	0.005	1026	14	7.7
Output_1_73	12.469	0.264	1184	26	2.228	0.067	1191	15	0.2019	0.005	1185	13	5.19
Output_1_74	13.387	0.197	1066	19	1.838	0.047	1061	10	0.1778	0.004	1055	7	3.51
Output_1_75	12.240	0.345	1249	31	2.367	0.077	1230	18	0.2112	0.006	1235	14	6.85
Output_1_76	12.563	0.237	1185	19	2.294	0.063	1209	13	0.2067	0.005	1211	10	3.34
Output_1_77	12.240	0.195	1243	18	2.381	0.061	1235	11	0.2124	0.005	1242	10	4.05
Output_1_78	10.320	0.138	1576	15	3.603	0.087	1551	11	0.2688	0.007	1534	10	3.52
Output_1_79	11.050	0.159	1424	18	3.093	0.075	1429	10	0.2485	0.006	1432	9	3.62
Output_1_80	11.669	0.381	1334	38	2.681	0.096	1326	23	0.2284	0.006	1325	18	7.6
Output_1_81	13.021	0.390	1118	34	2.173	0.063	1171	21	0.2039	0.005	1196	13	5.35
Output_1_82	9.717	0.092	1674	11	3.934	0.13	1622	20	0.2765	0.009	1571	31	4.38
Output_1_83	13.004	0.169	1123	16	2.065	0.05	1137	9	0.1943	0.005	1144	9	3.34
Output_1_84	12.739	0.682	1171	58	2.242	0.58	1190	30	0.2057	0.009	1206	23	8.4
Output_1_85	12.063	0.233	1259	21	2.462	0.067	1261	14	0.2153	0.006	1259	11	5.12
Output_1_86	11.507	0.212	1356	21	2.716	0.076	1330	14	0.2254	0.006	1310	15	4.81
Output_1_87	13.275	0.145	1069	13	1.925	0.045	1090	8	0.1865	0.005	1103	7	2.51
Output_1_88	11.050	0.171	1441	17	3.083	0.079	1429	12	0.2477	0.006	1426	12	4.14
Output_1_89	13.106	0.309	1086	25	1.931	0.059	1092	15	0.1832	0.005	1084	12	5.77
Output_1_90	13.004	0.287	1116	26	1.962	0.058	1101	14	0.1838	0.005	1087	11	5.52
Output_1_91	13.141	0.743	1147	52	1.877	0.11	1062	35	0.1802	0.006	1069	20	13.8
Output_1_92	13.643	0.175	1014	15	1.774	0.043	1037	8	0.1753	0.004	1042	6	3.05
Output_1_93	11.765	0.194	1319	21	2.697	0.072	1325	13	0.2311	0.006	1340	12	4.2
KV-1													
AD2A-1	13.774	0.342	1003	50	1.752	0.044	1028	16	0.175	0.001	1040	5	0.00
AD2A-3	13.434	0.431	1053	65	1.820	0.061	1053	22	0.177	0.002	1052	9	0.11
AD2A-4	12.384	0.284	1215	45	2.196	0.052	1180	17	0.197	0.001	1161	7	4.50
AD2A-5	12.505	0.604	1196	95	2.155	0.105	1167	34	0.195	0.001	1151	5	3.79
AD2A-6	5.181	0.097	2768	31	14.218	0.415	2764	28	0.534	0.012	2759	50	0.32

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
AD2A-8	13.593	0.616	1030	92	1.726	0.079	1018	29	0.170	0.001	1013	6	1.62
AD2A-9	11.772	0.473	1314	78	2.621	0.113	1307	32	0.224	0.004	1302	19	0.96
AD2A-10	12.596	0.547	1182	86	2.147	0.095	1164	31	0.196	0.002	1155	8	2.29
AD2A-11	11.224	0.378	1406	64	3.063	0.119	1423	30	0.249	0.005	1435	25	0.00
AD2A-12	11.309	0.334	1392	57	2.853	0.084	1370	22	0.234	0.000	1355	2	2.62
AD2A-13	12.771	0.629	1155	98	2.165	0.107	1170	34	0.201	0.001	1178	4	0.00
AD2A-14	13.049	0.415	1112	64	1.833	0.062	1058	22	0.174	0.002	1031	11	7.22
AD2A-15	12.278	0.511	1232	82	2.302	0.096	1213	30	0.205	0.001	1202	3	2.43
AD2A-16	11.435	0.284	1370	48	2.777	0.070	1349	19	0.230	0.001	1336	4	2.51
AD2A-18	12.233	0.517	1239	83	1.853	0.081	1064	29	0.164	0.002	981	10	20.85
AD2A-19	12.323	0.268	1225	43	1.873	0.054	1072	19	0.167	0.003	998	17	18.56
AD2A-20	12.927	0.483	1130	74	2.062	0.078	1136	26	0.193	0.001	1139	5	0.00
AD2A-21	12.780	0.346	1153	54	2.154	0.059	1166	19	0.200	0.001	1173	4	0.00
AD2A-22	9.725	0.222	1676	42	4.183	0.096	1671	19	0.295	0.001	1667	3	0.55
AD2A-23	12.648	0.192	1174	30	2.138	0.035	1161	11	0.196	0.001	1155	6	1.63
AD2A-25	12.583	0.217	1184	34	1.900	0.038	1081	13	0.173	0.002	1031	10	12.93
AD2A-24	12.903	0.434	1134	67	2.042	0.070	1130	23	0.191	0.001	1127	6	0.60
AD2A-26	8.728	0.103	1873	21	5.175	0.063	1849	10	0.328	0.001	1827	5	2.48
AD2A-27	13.686	0.159	1016	24	1.713	0.020	1014	8	0.170	0.000	1013	2	0.33
AD2A-28	12.783	0.211	1153	33	2.125	0.035	1157	12	0.197	0.000	1159	2	0.00
AD2A-29	13.607	0.209	1027	31	1.748	0.034	1027	12	0.173	0.002	1026	11	0.13
AD2A-30	13.851	0.294	992	43	1.708	0.039	1012	15	0.172	0.001	1021	8	0.00
AD2A-31	13.814	0.235	997	35	1.709	0.036	1012	13	0.171	0.002	1019	12	0.00
AD2A-32	11.621	1.549	1339	259	2.404	0.325	1244	97	0.203	0.005	1189	24	11.20
AD2A-33	12.874	0.267	1139	41	2.094	0.043	1147	14	0.195	0.000	1151	2	0.00
AD2A-34	13.644	0.357	1022	53	1.830	0.051	1056	18	0.181	0.002	1073	10	0.00
AD2A-35	12.605	0.255	1180	40	2.111	0.046	1152	15	0.193	0.002	1138	9	3.64
AD2A-36	13.809	0.383	998	56	1.666	0.048	996	18	0.167	0.001	995	7	0.28
AD2A-37	5.376	0.154	2707	47	12.604	0.374	2650	28	0.491	0.004	2577	16	4.81

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
AD2A-38	12.111	0.293	1259	47	2.535	0.067	1282	19	0.223	0.002	1296	13	0.00
AD2A-39	7.057	0.262	2248	64	7.791	0.289	2207	33	0.399	0.001	2163	3	3.76
AD2A-40	11.903	0.244	1293	40	2.556	0.055	1288	16	0.221	0.001	1285	8	0.60
AD2A-41	12.269	0.310	1234	50	2.215	0.074	1186	24	0.197	0.004	1160	23	5.99
AD2A-42	9.763	0.188	1669	36	3.975	0.087	1629	18	0.281	0.003	1599	15	4.18
AD2A-43	13.802	0.243	999	36	1.711	0.031	1013	12	0.171	0.001	1019	4	0.00
AD2A-44	13.396	0.595	1059	89	1.850	0.083	1063	29	0.180	0.001	1065	5	0.00
AD2A-45	12.431	0.768	1208	122	2.236	0.249	1192	78	0.202	0.019	1184	100	1.99
AD2A-46	5.374	0.101	2708	31	12.865	0.304	2670	22	0.501	0.007	2620	31	3.24
AD2A-47	12.998	0.656	1120	101	2.086	0.105	1144	35	0.197	0.001	1157	3	0.00
AD2A-48	12.644	0.344	1174	54	2.277	0.066	1205	21	0.209	0.002	1222	12	0.00
AD2A-49	13.740	0.298	1008	44	1.734	0.038	1021	14	0.173	0.000	1028	2	0.00
AD2A-50	12.591	0.275	1183	43	2.162	0.047	1169	15	0.197	0.001	1161	3	1.80
AD2A-51	10.809	0.135	1478	24	3.238	0.057	1466	14	0.254	0.003	1458	16	1.35
AD2A-52	12.548	0.134	1189	21	2.230	0.030	1191	9	0.203	0.002	1191	8	0.00
AD2A-53	10.415	0.123	1548	22	3.489	0.049	1525	11	0.264	0.002	1508	10	2.58
AD2A-54	12.402	0.275	1213	44	2.234	0.053	1192	17	0.201	0.002	1180	9	2.64
AD2A-55	13.734	0.167	1009	25	1.730	0.034	1020	13	0.172	0.003	1025	14	0.00
AD2A-56	10.971	0.143	1450	25	3.217	0.048	1461	12	0.256	0.002	1469	10	0.00
AD2A-57	13.375	0.191	1062	29	1.870	0.029	1071	10	0.181	0.001	1075	6	0.00
AD2A-58	13.180	0.568	1092	86	1.847	0.080	1062	29	0.177	0.001	1048	5	4.00
AD2A-59	12.532	0.106	1192	17	2.209	0.031	1184	10	0.201	0.002	1179	12	1.05
AD2A-60	12.579	0.288	1185	45	2.236	0.053	1192	17	0.204	0.001	1197	6	0.00
AD2A-61	10.108	0.230	1604	42	3.851	0.106	1604	22	0.282	0.004	1603	22	0.06
AD2A-62	12.148	0.214	1253	34	2.499	0.052	1272	15	0.220	0.002	1283	13	0.00
AD2A-63	12.610	0.108	1180	17	2.160	0.033	1168	11	0.198	0.002	1162	13	1.48
AD2A-64	12.885	0.114	1137	18	2.078	0.021	1142	7	0.194	0.001	1144	5	0.00
AD2A-65	12.549	0.203	1189	32	2.201	0.043	1181	14	0.200	0.002	1177	12	1.04
AD2A-66	10.783	0.122	1482	21	3.279	0.048	1476	11	0.256	0.002	1472	12	0.73

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
AD2A-67	13.462	0.240	1049	36	1.814	0.042	1051	15	0.177	0.003	1051	14	0.00
AD2A-68	12.767	0.199	1155	31	2.149	0.037	1165	12	0.199	0.001	1170	7	0.00
AD2A-69	13.384	0.097	1061	15	1.850	0.025	1064	9	0.180	0.002	1065	11	0.00
AD2A-70	12.956	0.217	1126	33	2.095	0.038	1147	13	0.197	0.001	1159	8	0.00
AD2A-72	12.766	0.188	1155	29	2.089	0.051	1145	17	0.193	0.004	1140	20	1.32
AD2A-73	13.772	0.215	1003	32	1.632	0.027	983	10	0.163	0.001	973	4	2.96
AD2A-74	12.961	0.252	1125	39	1.430	0.031	901	13	0.134	0.001	813	8	27.76
AD2A-75	13.132	0.282	1099	43	1.954	0.046	1100	16	0.186	0.002	1100	9	0.00
AD2A-77	13.076	0.315	1108	48	1.964	0.051	1103	18	0.186	0.002	1101	10	0.59
AD2A-78	14.032	0.263	965	38	1.641	0.047	986	18	0.167	0.004	995	20	0.00
AD2A-79	12.581	0.142	1184	22	2.137	0.031	1161	10	0.195	0.002	1148	10	3.04
AD2A-80	11.745	0.143	1319	24	2.569	0.038	1292	11	0.219	0.002	1276	9	3.28
AD2A-81	11.836	0.492	1304	81	2.346	0.105	1226	32	0.201	0.003	1183	18	9.29
AD2A-82	12.656	0.223	1173	35	2.150	0.043	1165	14	0.197	0.002	1161	10	0.97
AD2A-83	10.891	0.207	1464	36	2.861	0.085	1372	22	0.226	0.005	1314	27	10.25
AD2A-84	12.582	0.195	1184	31	2.181	0.054	1175	17	0.199	0.004	1170	21	1.18
AD2A-85	13.021	0.230	1116	35	1.998	0.038	1115	13	0.189	0.001	1114	7	0.15
AD2A-86	13.379	0.219	1062	33	1.745	0.035	1025	13	0.169	0.002	1008	11	5.03
AD2A-87	8.613	0.129	1897	27	5.251	0.119	1861	19	0.328	0.006	1829	27	3.61
AD2A-88	12.678	0.309	1169	48	2.088	0.054	1145	18	0.192	0.002	1132	9	3.16
AD2A-89	11.658	0.203	1333	34	2.617	0.054	1305	15	0.221	0.002	1289	13	3.35
AD2A-90	12.800	0.232	1150	36	2.030	0.040	1126	13	0.188	0.001	1113	7	3.20
AD2A-91	11.974	0.185	1281	30	2.480	0.042	1266	12	0.215	0.002	1257	8	1.87
AD2A-92	13.532	0.318	1039	47	1.742	0.046	1024	17	0.171	0.002	1017	11	2.06
AD2A-93	12.224	0.408	1241	65	2.291	0.079	1210	25	0.203	0.002	1192	10	3.93
AD2A-94	13.474	0.247	1047	37	1.743	0.041	1025	15	0.170	0.002	1014	14	3.18
AD2A-95	11.507	0.212	1358	35	2.681	0.060	1323	17	0.224	0.003	1302	15	4.15
AD2A-96	10.930	0.164	1457	29	3.140	0.051	1443	12	0.249	0.001	1433	7	1.65
AD2A-97	13.908	0.257	983	38	1.688	0.032	1004	12	0.170	0.001	1014	5	0.00

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
AD2A-98	13.870	0.310	989	45	1.693	0.041	1006	16	0.170	0.002	1014	9	0.00
AD2A-99	13.989	0.283	971	41	1.643	0.045	987	17	0.167	0.003	994	17	0.00
AD2A-100	12.296	0.557	1229	89	2.532	0.115	1281	33	0.226	0.001	1312	5	0.00
KV-2													
Output_1_3	5.565	0.040	2650	6	12.445	0.095	2638	7	0.5045	0.003	2633	12	2.72
Output_1_4	13.532	0.178	1034	17	1.803	0.022	1047	8	0.1779	0.001	1056	6	3.18
Output_1_5	13.633	0.171	1027	16	1.752	0.022	1028	8	0.1736	0.001	1032	6	3.01
Output_1_6	13.885	0.177	983	15	1.738	0.02	1022	7	0.1752	1E-03	1041	5	3.34
Output_1_7	13.141	0.483	1144	42	1.934	0.073	1092	25	0.1822	0.003	1079	14	7.8
Output_1_8	13.521	0.128	1042	11	1.818	0.016	1052	6	0.178	1E-03	1056	5	2.27
Output_1_9	13.245	0.544	1091	51	2.001	0.077	1112	27	0.1918	0.003	1130	17	8.2
Output_1_10	13.624	0.241	1020	18	1.754	0.028	1028	10	0.1749	0.001	1040	7	3.93
Output_1_11	12.837	0.445	1179	38	2.028	0.062	1135	21	0.1915	0.003	1129	16	8.5
Output_1_12	12.987	0.202	1130	18	2.078	0.032	1141	11	0.1955	0.001	1151	7	3.68
Output_1_13	11.123	0.297	1430	31	2.875	0.073	1376	19	0.2318	0.003	1344	15	5.83
Output_1_14	11.136	0.149	1424	14	3.111	0.041	1434	10	0.2523	0.002	1450	9	3.17
Output_1_15	12.840	0.106	1141	10	2.123	0.018	1156	6	0.1981	0.001	1165	6	2.03
Output_1_16	12.658	0.288	1167	25	2.215	0.047	1185	15	0.2036	0.002	1195	12	4.97
Output_1_17	13.512	0.122	1050	11	1.831	0.017	1058	6	0.1796	9E-04	1065	5	2.2
Output_1_18	13.569	0.221	1026	19	1.782	0.032	1040	11	0.1751	0.001	1040	7	3.8
Output_1_19	12.706	0.291	1169	28	2.101	0.049	1147	16	0.1932	0.002	1138	11	5.11
Output_1_20	13.736	0.226	1019	21	1.803	0.026	1048	10	0.1785	0.002	1059	8	4.01
Output_1_21	12.136	0.427	1247	40	2.431	0.079	1252	24	0.2149	0.003	1254	17	8.1
Output_1_22	12.568	0.131	1175	11	2.232	0.023	1190	7	0.2037	0.001	1195	6	2.54
Output_1_23	12.579	0.348	1219	32	2.251	0.055	1197	17	0.2049	0.003	1201	14	6.62
Output_1_24	13.628	0.137	1026	12	1.796	0.019	1044	7	0.177	0.001	1051	6	2.53
Output_1_25	13.569	0.276	1048	22	1.74	0.035	1024	13	0.1717	0.001	1022	7	4.72
Output_1_26	12.771	0.587	1138	49	2.089	0.089	1157	31	0.1948	0.004	1146	21	11
Output_1_27	13.416	0.146	1051	12	1.891	0.02	1078	7	0.1836	1E-03	1087	5	2.62

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_28	12.610	0.223	1184	21	2.199	0.04	1179	13	0.2003	0.002	1177	10	4.46
Output_1_30	12.531	0.330	1183	30	2.169	0.062	1171	20	0.1981	0.003	1166	17	5.81
Output_1_31	13.643	0.104	1023	12	1.168	0.025	782	10	0.1158	0.003	706	14	7.01
Output_1_32	12.658	0.320	1179	26	2.17	0.057	1171	18	0.1976	0.002	1162	13	5.95
Output_1_33	12.063	0.349	1276	26	2.433	0.068	1249	21	0.2114	0.003	1236	14	7.08
Output_1_34	12.706	0.274	1183	25	2.106	0.045	1151	15	0.1937	0.002	1142	10	5.1
Output_1_35	12.788	0.294	1156	33	2.104	0.05	1152	16	0.1956	0.002	1151	13	5.73
Output_1_36	13.483	0.131	1042	11	1.816	0.017	1051	6	0.1779	8E-04	1055	5	2.39
Output_1_37	9.569	0.137	1714	15	4.381	0.06	1707	11	0.3034	0.002	1708	10	3.9
Output_1_38	9.488	0.126	1730	15	4.385	0.065	1710	12	0.3027	0.003	1704	14	3.59
Output_1_39	11.050	0.354	1443	35	3.082	0.096	1423	24	0.2477	0.003	1426	17	7.47
Output_1_40	11.050	0.244	1438	25	3.287	0.078	1474	19	0.2626	0.003	1505	15	4.92
Output_1_41	12.698	0.155	1168	14	2.163	0.027	1169	9	0.2	0.001	1175	7	2.86
Output_1_42	5.531	0.046	2663	8	12.81	0.11	2668	8	0.5141	0.003	2674	11	2.68
Output_1_43	12.920	0.250	1157	19	2.074	0.038	1138	13	0.1941	0.002	1143	8	4.43
Output_1_44	13.072	0.239	1103	20	2.003	0.035	1115	12	0.1903	0.002	1124	9	4.45
Output_1_45	11.751	0.193	1311	20	2.68	0.047	1324	12	0.2273	0.002	1320	11	4
Output_1_46	12.853	0.198	1163	16	2.145	0.029	1164	10	0.1986	0.001	1168	7	3.62
Output_1_47	11.099	0.148	1432	13	3.127	0.043	1439	11	0.2517	0.002	1447	9	3.57
Output_1_48	12.987	0.270	1135	27	2.052	0.04	1132	14	0.1914	0.002	1129	10	5.07
Output_1_49	12.469	0.451	1175	39	2.143	0.079	1165	26	0.1951	0.003	1148	16	8
Output_1_50	12.626	0.239	1161	17	2.21	0.041	1182	13	0.2032	0.002	1192	9	4.28
Output_1_51	12.438	0.387	1244	34	2.235	0.066	1191	21	0.2013	0.003	1182	16	6.92
Output_1_52	12.804	0.574	1165	46	2.161	0.094	1174	30	0.1958	0.004	1152	20	10.5
Output_1_53	12.594	0.206	1189	21	2.167	0.037	1171	12	0.1969	0.002	1160	9	3.64
Output_1_54	13.699	0.600	1034	50	1.842	0.078	1057	28	0.1831	0.003	1083	17	9.7
Output_1_55	12.970	0.437	1139	41	2.074	0.069	1139	22	0.1956	0.003	1151	16	8.4
Output_1_56	12.531	0.298	1218	25	2.193	0.047	1177	15	0.1972	0.002	1162	13	5.73
Output_1_57	11.013	0.267	1434	24	2.932	0.067	1390	17	0.2338	0.002	1354	12	6.04

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_58	12.594	0.286	1187	23	2.171	0.047	1169	15	0.1972	0.002	1161	9	4.57
Output_1_59	13.605	0.740	1066	61	1.815	0.09	1049	34	0.1812	0.004	1075	23	12.6
Output_1_60	5.302	0.070	2725	12	13.46	0.19	2711	13	0.5184	0.005	2694	21	4.34
Output_1_61	12.547	0.118	1193	12	2.196	0.024	1179	8	0.1995	0.001	1172	7	1.86
Output_1_62	13.717	0.489	1017	41	2.023	0.067	1120	23	0.2013	0.004	1182	19	8.5
Output_1_63	12.811	0.144	1154	11	2.143	0.023	1164	8	0.1982	0.001	1165	6	2.57
Output_1_64	12.658	0.176	1169	16	2.126	0.03	1157	10	0.196	0.002	1154	8	3.56
Output_1_65	12.788	0.196	1146	19	2.102	0.036	1150	12	0.1954	0.002	1151	8	3.74
Output_1_66	12.550	0.124	1192	12	2.216	0.024	1186	8	0.2014	0.002	1183	9	2.62
Output_1_67	12.937	0.485	1164	43	2.096	0.069	1143	23	0.1968	0.003	1159	17	9.6
Output_1_68	11.123	0.136	1424	17	1.299	0.037	843	17	0.104	0.004	637	20	20.31
Output_1_69	12.615	0.153	1167	15	2.146	0.026	1164	8	0.1967	0.001	1157	6	3.01
Output_1_70	12.563	0.284	1201	26	2.125	0.047	1156	15	0.1938	0.002	1142	12	5.37
Output_1_71	12.469	0.342	1206	31	2.177	0.063	1173	21	0.1967	0.002	1158	13	6.64
Output_1_72	12.484	0.234	1197	20	2.229	0.038	1192	13	0.201	0.002	1180	10	4.55
Output_1_73	9.804	0.250	1676	26	4.03	0.1	1643	20	0.2816	0.005	1602	24	5.87
Output_1_74	12.771	0.196	1156	16	2.118	0.03	1154	10	0.1959	0.001	1153	7	3.58
Output_1_75	12.422	0.432	1198	40	2.193	0.074	1173	24	0.1974	0.003	1161	14	6.9
Output_1_76	13.405	0.323	1048	30	1.877	0.041	1071	15	0.1821	0.002	1078	11	4.89
Output_1_77	12.745	0.135	1167	12	2.176	0.022	1174	7	0.2009	0.001	1180	6	2.41
Output_1_79	12.920	0.501	1136	42	2.08	0.079	1144	26	0.1987	0.004	1168	19	8.1
Output_1_81	11.050	0.269	1452	24	3.074	0.07	1427	18	0.2443	0.003	1412	16	5.21
Output_1_82	11.601	0.269	1342	24	2.701	0.061	1331	17	0.2268	0.002	1318	13	5.25
Output_1_83	10.941	0.156	1456	16	3.222	0.049	1462	12	0.2547	0.002	1462	12	3.05
Output_1_84	13.514	0.126	1041	10	1.765	0.017	1034	6	0.1727	9E-04	1028	5	2.11
Output_1_85	11.249	0.111	1401	10	3.064	0.031	1423	8	0.2496	0.002	1436	9	2.2
Output_1_86	13.495	0.382	1033	30	1.783	0.051	1037	19	0.1737	0.002	1034	12	5.81
Output_1_87	12.594	0.444	1208	49	2.098	0.072	1155	23	0.1916	0.002	1130	11	7.2
Output_1_88	12.666	0.116	1175	9	2.15	0.019	1165	6	0.1968	9E-04	1158	5	2.24

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_89	12.469	0.373	1213	26	2.226	0.067	1191	20	0.2011	0.003	1183	14	5.51
Output_1_90	12.739	0.260	1156	21	2.115	0.04	1154	13	0.1954	0.002	1150	10	4.83
Output_1_91	12.837	0.181	1139	16	2.004	0.027	1117	9	0.1874	0.001	1108	7	3.4
Output_1_92	12.837	0.395	1172	32	2.119	0.056	1157	18	0.1967	0.003	1157	13	7
Output_1_93	12.077	0.190	1264	18	2.371	0.04	1237	12	0.2073	0.002	1214	8	3.87
Output_1_94	11.287	0.166	1401	15	2.765	0.043	1349	12	0.2238	0.002	1302	10	3.95
Output_1_95	12.255	0.706	1261	54	2.21	0.12	1189	37	0.1983	0.003	1166	18	12.8
Output_1_96	12.453	0.202	1201	17	2.115	0.035	1153	11	0.1913	0.002	1129	8	4.4
Output_1_97	10.989	0.555	1449	52	3	0.14	1408	35	0.237	0.005	1370	26	10.5
Output_1_98	12.953	0.570	1169	55	2.156	0.091	1164	29	0.2001	0.004	1175	19	9.4
Output_1_99	13.089	0.531	1110	54	2.135	0.096	1163	29	0.2006	0.004	1178	21	8.5
Output_1_100	13.387	0.197	1056	17	1.816	0.025	1050	9	0.1759	0.001	1045	6	3.51
Output_1_101	10.870	0.295	1457	29	3.254	0.079	1472	19	0.2559	0.003	1470	18	6.7
Output_1_102	11.468	0.210	1367	23	2.805	0.049	1355	13	0.2315	0.002	1342	11	4.38
Output_1_103	12.723	0.615	1208	47	2.08	0.089	1152	30	0.191	0.004	1128	19	10.7
Output_1_104	13.464	0.129	1049	11	1.765	0.017	1032	6	0.1727	9E-04	1027	5	2.09
Output_1_105	11.338	0.334	1379	35	2.819	0.079	1360	21	0.2307	0.003	1339	14	6.51
Output_1_106	12.315	0.288	1234	28	2.225	0.054	1189	17	0.1972	0.003	1160	14	5.37
Output_1_108	12.500	0.203	1192	19	2.153	0.033	1167	11	0.1951	0.001	1149	7	4.16
Output_1_109	13.158	0.433	1098	40	1.818	0.047	1053	17	0.1719	0.003	1022	14	7.9
Output_1_110	13.569	0.221	1038	20	1.821	0.028	1054	10	0.178	0.001	1056	7	3.47
Output_1_111	12.888	0.164	1143	16	2.115	0.025	1154	8	0.1966	0.002	1157	8	3.27
Output_1_112	13.423	0.396	1075	31	1.769	0.049	1032	18	0.1709	0.003	1016	14	7.11
Output_1_113	12.690	0.499	1174	43	2.143	0.085	1157	28	0.193	0.003	1137	16	7.9
Output_1_114	12.607	0.122	1190	12	2.141	0.02	1162	6	0.1943	0.001	1145	7	2.21
Output_1_115	13.351	0.250	1056	26	1.77	0.034	1033	12	0.1714	0.002	1021	8	4.03
Output_1_116	13.387	0.197	1055	15	1.793	0.028	1044	10	0.1733	0.001	1031	7	3.26
Output_1_117	13.038	0.221	1106	20	1.972	0.032	1104	11	0.1863	0.001	1101	6	3.89
Output_1_118	12.136	0.368	1235	39	2.056	0.06	1135	20	0.1826	0.003	1081	18	7.7

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_119	13.351	0.178	1071	15	1.825	0.023	1055	8	0.1766	0.002	1048	9	3.74
Output_1_120	12.225	0.553	1239	49	2.227	0.097	1186	30	0.1981	0.004	1164	20	10
Output_1_121	13.141	0.242	1108	22	1.923	0.033	1089	12	0.1814	0.002	1074	10	4.65
Z_91500_11	13.228	0.315	1098	31	1.854	0.042	1062	15	0.1768	0.002	1050	10	5.99
Output_1_2	13.184	0.163	1089	16	1.947	0.023	1097	8	0.1875	0.001	1108	6	3.01
Output_1_29	13.266	0.151	1077	15	1.913	0.02	1085	7	0.1835	0.001	1086	6	2.73
Output_1_80	12.979	0.152	1122	13	1.964	0.023	1103	8	0.185	0.001	1094	6	2.71
Output_1_107	13.423	0.252	1074	24	1.938	0.03	1094	10	0.1871	0.002	1106	8	3.54
Output_1_122	13.038	0.127	1115	10	1.981	0.018	1109	6	0.1866	8E-04	1103	4	2.43
KV-3													
AD1-1	13.089	0.507	1106	78	2.049	0.106	1132	35	0.195	0.007	1146	36	0.00
AD1-2	13.356	0.520	1065	78	1.854	0.078	1065	28	0.180	0.003	1065	15	0.05
AD1-3	11.058	0.561	1435	97	3.084	0.160	1429	40	0.247	0.003	1425	14	0.68
AD1-4	11.148	0.586	1419	101	3.179	0.168	1452	41	0.257	0.001	1475	4	0.00
AD1-5	5.253	0.244	2745	77	14.137	0.664	2759	45	0.539	0.003	2777	14	0.00
AD1-7	13.688	1.071	1016	159	1.791	0.143	1042	52	0.178	0.003	1055	15	0.00
AD1-8	12.722	0.774	1162	121	2.129	0.137	1158	44	0.196	0.004	1156	22	0.48
AD1-9	12.606	0.587	1180	92	2.257	0.112	1199	35	0.206	0.003	1210	19	0.00
AD1-11	13.085	0.704	1106	108	2.099	0.115	1149	38	0.199	0.002	1171	12	0.00
AD1-12	5.348	0.171	2716	53	13.805	0.444	2736	30	0.535	0.002	2764	8	0.00
AD1-13	13.323	0.368	1070	56	1.918	0.056	1087	20	0.185	0.002	1096	10	0.00
AD1-14	10.959	0.363	1452	63	3.279	0.111	1476	26	0.261	0.002	1493	10	0.00
AD1-15	12.914	0.779	1132	120	2.205	0.137	1183	44	0.207	0.003	1210	17	0.00
AD1-17	12.063	0.524	1267	85	2.553	0.117	1287	33	0.223	0.003	1300	17	0.00
AD1-19	13.825	0.451	995	66	1.739	0.058	1023	22	0.174	0.001	1036	7	0.00
AD1-20	13.731	0.568	1009	84	1.791	0.075	1042	27	0.178	0.001	1058	7	0.00
AD1-22	13.451	0.456	1051	68	1.886	0.065	1076	23	0.184	0.001	1089	5	0.00
AD1-23	6.170	0.511	2477	140	9.834	0.818	2419	77	0.440	0.003	2351	13	5.11
AD1-24	11.786	0.508	1312	84	2.775	0.120	1349	32	0.237	0.001	1372	4	0.00

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
AD1-25	13.776	0.772	1002	114	1.787	0.104	1041	38	0.179	0.003	1059	16	0.00
AD1-26	11.054	0.383	1435	66	3.033	0.127	1416	32	0.243	0.006	1403	30	2.26
AD1-27	12.387	0.692	1215	110	2.197	0.123	1180	39	0.197	0.001	1161	6	4.40
AD1-28	12.544	0.679	1190	107	2.087	0.117	1144	38	0.190	0.003	1120	15	5.85
AD1-29	14.053	1.002	962	146	1.698	0.124	1008	47	0.173	0.003	1029	16	0.00
AD1-30	10.787	0.441	1482	78	3.181	0.136	1452	33	0.249	0.003	1433	15	3.33
AD1-31	13.579	0.433	1032	65	1.789	0.060	1042	22	0.176	0.002	1046	9	0.00
AD1-32	13.201	0.536	1088	81	1.875	0.078	1072	27	0.180	0.001	1064	8	2.22
AD1-33	13.970	0.614	974	90	1.718	0.076	1015	29	0.174	0.001	1034	7	0.00
AD1-34	13.481	0.303	1046	45	1.838	0.045	1059	16	0.180	0.002	1065	9	0.00
AD1-35	13.556	0.649	1035	97	1.821	0.092	1053	33	0.179	0.003	1062	15	0.00
AD1-36	13.332	0.625	1069	94	1.894	0.091	1079	32	0.183	0.002	1084	9	0.00
AD1-37	13.352	0.472	1066	71	1.904	0.071	1082	25	0.184	0.002	1091	12	0.00
AD1-39	11.560	0.872	1350	146	2.598	0.206	1300	58	0.218	0.005	1270	28	5.88
AD1-41	11.591	0.422	1344	70	2.895	0.142	1381	37	0.243	0.008	1404	42	0.00
AD1-43	8.528	0.681	1915	144	5.521	0.445	1904	69	0.341	0.003	1894	16	1.11
AD1-44	11.616	0.634	1340	105	2.746	0.152	1341	41	0.231	0.002	1342	12	0.00
AD1-45	12.306	0.519	1228	83	2.481	0.108	1267	31	0.221	0.002	1290	12	0.00
AD1-46	12.513	0.896	1195	141	2.374	0.171	1235	51	0.215	0.001	1258	8	0.00
AD1-47	12.059	0.559	1267	91	2.466	0.129	1262	38	0.216	0.005	1259	28	0.67
AD1-48	11.417	0.345	1373	58	2.667	0.094	1319	26	0.221	0.004	1286	21	6.33
AD1-49	13.703	0.744	1013	110	1.731	0.099	1020	37	0.172	0.003	1023	17	0.00
AD1-51	11.288	1.039	1395	177	2.673	0.248	1321	69	0.219	0.003	1276	14	8.58
AD1-52	13.947	0.505	977	74	1.713	0.064	1014	24	0.173	0.002	1030	8	0.00
AD1-53	13.143	0.825	1097	126	2.089	0.135	1145	44	0.199	0.003	1170	16	0.00
AD1-54	13.108	0.395	1103	60	1.958	0.075	1101	26	0.186	0.004	1100	24	0.20
AD1-56	13.243	0.648	1082	98	1.862	0.092	1068	33	0.179	0.001	1061	7	1.98
AD1-57	13.408	0.478	1057	72	1.900	0.071	1081	25	0.185	0.002	1093	11	0.00
AD1-58	13.862	0.699	990	103	1.768	0.094	1034	34	0.178	0.003	1055	15	0.00

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
AD1-59	13.522	0.790	1040	118	1.759	0.119	1030	44	0.172	0.006	1026	33	1.38
AD1-60	13.360	0.534	1064	80	1.905	0.079	1083	28	0.185	0.002	1092	11	0.00
AD1-61	11.542	0.197	1352	33	2.853	0.061	1369	16	0.239	0.003	1380	16	0.00
AD1-62	13.345	0.434	1067	65	1.966	0.068	1104	23	0.190	0.002	1123	12	0.00
AD1-63	11.715	0.123	1324	20	2.672	0.043	1321	12	0.227	0.003	1319	14	0.36
AD1-64	12.640	0.267	1175	42	2.224	0.062	1189	20	0.204	0.004	1196	20	0.00
AD1-65	9.770	0.217	1667	41	4.266	0.145	1687	28	0.302	0.008	1702	38	0.00
AD1-66	12.401	0.289	1213	46	2.193	0.072	1179	23	0.197	0.005	1161	24	4.29
AD1-67	12.842	0.243	1144	38	2.102	0.066	1150	22	0.196	0.005	1153	27	0.00
AD1-68	11.405	0.160	1375	27	2.688	0.066	1325	18	0.222	0.004	1294	23	5.90
AD1-69	13.688	0.273	1015	40	1.720	0.057	1016	21	0.171	0.005	1016	25	0.00
AD1-70	13.209	0.178	1087	27	1.818	0.054	1052	19	0.174	0.005	1035	25	4.80
AD1-71	13.504	0.346	1043	52	1.756	0.047	1030	17	0.172	0.001	1023	8	1.88
AD1-72	12.880	0.168	1138	26	2.059	0.033	1135	11	0.192	0.002	1134	10	0.33
AD1-73	12.615	0.368	1179	58	2.102	0.067	1149	22	0.192	0.003	1134	14	3.83
AD1-74	13.909	0.274	983	40	1.668	0.038	996	15	0.168	0.002	1003	11	0.00
AD1-75	13.530	0.483	1039	72	1.710	0.061	1012	23	0.168	0.001	1000	4	3.74
AD1-76	10.538	0.239	1526	43	3.216	0.076	1461	18	0.246	0.002	1417	9	7.16
AD1-77	13.813	0.300	997	44	1.703	0.042	1010	16	0.171	0.002	1015	11	0.00
AD1-78	13.246	0.316	1082	48	1.880	0.046	1074	16	0.181	0.001	1070	6	1.03
AD1-79	11.715	0.260	1324	43	2.596	0.061	1299	17	0.221	0.002	1285	9	2.94
AD1-80	13.869	0.416	989	61	1.699	0.055	1008	21	0.171	0.002	1017	11	0.00
AD1-81	8.899	0.263	1838	53	5.153	0.153	1845	25	0.333	0.001	1851	6	0.00
AD1-82	12.822	0.317	1147	49	2.087	0.056	1145	18	0.194	0.002	1143	10	0.29
AD1-83	12.476	0.276	1201	44	2.286	0.054	1208	17	0.207	0.002	1212	9	0.00
AD1-84	13.812	0.485	997	71	1.780	0.064	1038	23	0.178	0.001	1058	7	0.00
AD1-85	11.725	0.301	1322	50	2.669	0.074	1320	20	0.227	0.002	1319	12	0.27
AD1-86	11.076	0.226	1432	39	3.146	0.068	1444	17	0.253	0.002	1452	10	0.00
AD1-87	13.508	0.283	1042	42	1.833	0.046	1057	16	0.180	0.002	1065	13	0.00

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
AD1-88	11.969	0.359	1282	58	2.496	0.077	1271	22	0.217	0.002	1264	9	1.38
AD1-89	12.812	0.484	1148	75	2.137	0.083	1161	27	0.199	0.002	1168	9	0.00
AD1-90	12.659	0.261	1172	41	2.199	0.053	1181	17	0.202	0.002	1185	13	0.00
AD1-92	11.958	0.392	1284	64	2.665	0.089	1319	25	0.231	0.001	1340	7	0.00
AD1-93	10.178	0.184	1591	34	3.740	0.071	1580	15	0.276	0.002	1572	8	1.23
AD1-94	13.598	0.506	1029	75	1.809	0.069	1049	25	0.178	0.001	1058	7	0.00
AD1-95	11.578	0.355	1347	59	2.813	0.090	1359	24	0.236	0.002	1367	10	0.00
AD1-96	13.855	0.509	991	75	1.714	0.067	1014	25	0.172	0.002	1024	13	0.00
AD1-97	11.812	0.389	1308	64	2.574	0.090	1293	25	0.221	0.002	1285	13	1.76
AD1-99	12.423	0.617	1209	98	2.159	0.116	1168	37	0.194	0.004	1146	21	5.26
AD1-100	13.522	0.336	1040	50	1.836	0.051	1058	18	0.180	0.002	1067	12	0.00
AD1-101	12.789	0.393	1152	61	2.168	0.069	1171	22	0.201	0.002	1181	8	0.00
AD1-102	12.043	0.362	1270	59	2.573	0.080	1293	23	0.225	0.002	1307	10	0.00
AD1-103	10.987	0.276	1447	48	3.179	0.082	1452	20	0.253	0.001	1456	7	0.00
KV-4													
Output_1_1	14.025	0.669	992	68	1.653	0.69	989	33	0.1694	0.009	1009	14	3.9
Output_1_2	11.519	0.104	1360	10	2.862	0.06	1372	8	0.2406	0.007	1390	9	2.64
Output_1_3	13.477	0.381	1068	31	1.859	0.058	1067	17	0.1815	0.005	1075	12	6.7
Output_1_4	12.285	0.272	1231	26	2.149	0.06	1163	15	0.1932	0.006	1141	13	5.73
Output_1_5	11.813	0.106	1313	10	1.823	0.057	1055	7	0.1567	0.006	938	8	9.01
Output_1_6	5.546	0.077	2655	12	11.26	0.3	2543	14	0.4548	0.013	2418	21	6.67
Output_1_7	12.610	0.334	1158	31	2.145	0.066	1163	17	0.2004	0.006	1177	14	6.48
Output_1_8	12.469	0.187	1196	18	2.243	0.051	1194	10	0.2055	0.006	1205	8	3.74
Output_1_9	13.423	0.306	1061	26	1.914	0.054	1083	15	0.1886	0.005	1113	10	5.33
Output_1_10	12.329	0.103	1231	10	2.383	0.057	1237	11	0.2133	0.006	1248	14	2.22
Output_1_11	12.598	0.141	1179	13	2.198	0.047	1182	8	0.2029	0.005	1191	7	2.84
Output_1_12	10.880	0.111	1465	11	3.224	0.069	1464	9	0.2557	0.007	1467	9	2.42
Output_1_13	13.532	0.458	1067	49	1.751	0.068	1025	22	0.1712	0.005	1018	15	7.43
Output_1_14	13.569	0.313	1023	28	1.801	0.058	1043	17	0.1763	0.005	1046	11	5.44

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_15	9.008	0.076	1815	8	5.06	0.1	1829	8	0.3297	0.009	1838	11	2.58
Output_1_16	13.263	0.369	1077	31	1.907	0.062	1081	18	0.1818	0.005	1076	13	6.56
Output_1_17	12.690	0.258	1165	26	2.212	0.059	1184	14	0.2021	0.006	1186	12	5.25
Output_1_18	12.642	0.304	1180	29	2.128	0.061	1161	16	0.1961	0.006	1154	11	5.67
Output_1_19	13.316	0.426	1042	34	1.745	0.06	1026	19	0.1689	0.005	1006	15	8.4
Output_1_20	12.516	0.219	1181	18	2.169	0.054	1172	12	0.1969	0.006	1158	11	4.76
Output_1_21	11.891	0.198	1287	18	2.57	0.066	1291	13	0.2199	0.006	1281	11	3.88
Output_1_22	11.455	0.236	1342	29	2.732	0.076	1337	15	0.2253	0.006	1312	12	5.47
Output_1_23	12.392	0.276	1232	23	2.389	0.068	1236	16	0.2105	0.006	1231	12	5.54
Output_1_24	11.820	0.168	1299	16	2.577	0.061	1293	11	0.2195	0.006	1279	11	3.73
Output_1_25	13.717	0.245	1010	22	1.757	0.045	1029	12	0.1735	0.005	1031	7	3.8
Output_1_26	11.494	0.211	1370	22	2.93	0.075	1389	14	0.2417	0.007	1395	11	4.56
Output_1_27	12.903	0.366	1145	34	2.129	0.066	1162	18	0.2005	0.006	1178	12	7.05
Output_1_28	13.106	0.223	1114	23	1.936	0.049	1094	12	0.184	0.005	1090	9	4.15
Output_1_29	13.569	0.239	1033	19	1.729	0.043	1020	11	0.1695	0.005	1010	9	4.19
Output_1_30	13.717	0.301	1021	29	1.731	0.047	1021	14	0.1736	0.005	1032	10	4.95
Output_1_31	12.180	0.356	1243	33	2.263	0.072	1198	20	0.199	0.006	1170	14	6.11
Output_1_32	11.805	0.135	1305	13	1.621	0.064	973	23	0.1408	0.006	847	30	11.3
Output_1_33	13.569	0.423	1054	36	1.764	0.059	1031	18	0.1745	0.005	1036	12	7.57
Output_1_34	11.751	0.262	1327	26	2.495	0.07	1267	16	0.2151	0.006	1256	14	5.68
Output_1_35	13.514	0.237	1044	24	1.747	0.043	1024	11	0.1723	0.005	1025	8	4
Output_1_36	11.148	0.174	1414	15	2.765	0.065	1346	11	0.2274	0.006	1322	11	3.93
Output_1_37	13.477	0.327	1048	30	1.747	0.052	1026	16	0.1721	0.005	1024	9	5.87
Output_1_38	12.563	0.237	1191	18	2.223	0.048	1187	14	0.2027	0.006	1190	13	2.26
Output_1_39	13.280	0.282	1074	28	1.876	0.051	1071	13	0.1837	0.005	1087	8	4.79
Output_1_40	13.831	0.287	999	23	1.697	0.041	1009	13	0.1718	0.005	1022	10	3.59
Output_1_41	11.933	0.214	1274	21	2.146	0.066	1165	12	0.1874	0.007	1107	10	4.52
Output_1_42	10.870	0.130	1464	13	3.149	0.066	1447	8	0.2499	0.007	1438	11	3.31
Output_1_43	12.853	0.231	1147	23	2.165	0.054	1168	12	0.2013	0.006	1182	12	4.97

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_44	5.488	0.057	2675	13	12.83	0.26	2667	10	0.5133	0.014	2670	22	4.51
Output_1_45	9.285	0.103	1759	12	4.648	0.094	1757	10	0.3149	0.008	1765	10	2.33
Output_1_46	12.804	0.279	1169	25	2.109	0.069	1155	18	0.1959	0.006	1152	18	4.97
Output_1_47	12.594	0.174	1195	15	2.235	0.053	1192	11	0.2038	0.006	1196	8	3.72
Output_1_48	12.300	0.318	1243	28	2.352	0.069	1228	16	0.2098	0.006	1227	14	6.59
Output_1_49	6.920	0.110	2284	17	7.29	0.19	2146	16	0.3645	0.01	2003	20	7.83
Output_1_50	13.089	0.308	1114	33	2.108	0.06	1150	16	0.1995	0.006	1172	12	5.79
Output_1_51	12.804	0.410	1135	33	2.099	0.076	1146	21	0.1944	0.006	1145	13	7.56
Output_1_52	12.706	0.339	1176	30	2.142	2	1160	19	0.1978	0.011	1163	12	5.85
Output_1_53	11.792	0.278	1314	27	2.584	0.079	1297	18	0.2207	0.006	1285	14	5.74
Output_1_54	12.469	0.264	1187	26	2.162	0.061	1167	15	0.1955	0.006	1151	12	5.37
Output_1_55	12.853	0.264	1155	23	2.163	0.057	1167	14	0.2011	0.006	1181	10	5.06
Output_1_56	13.158	0.502	1102	46	1.884	0.077	1067	24	0.1814	0.006	1074	17	9.5
Output_1_57	13.624	0.204	1027	18	1.784	0.042	1040	10	0.175	0.005	1040	9	3.8
Output_1_58	13.477	0.454	1048	35	1.728	0.063	1017	21	0.1714	0.005	1019	15	8.4
Output_1_59	13.624	0.297	1022	22	1.748	0.05	1025	14	0.1727	0.005	1027	9	4.98
Output_1_60	12.753	0.156	1160	14	2.139	0.049	1160	10	0.1972	0.005	1160	9	3.09
Output_1_61	11.905	0.241	1302	24	2.525	0.068	1280	15	0.2182	0.006	1274	14	4.41
Output_1_62	13.532	0.458	1063	39	1.734	0.062	1020	19	0.1687	0.005	1005	16	8.2
Output_1_63	12.300	0.408	1225	35	2.181	0.072	1175	23	0.1926	0.006	1137	18	7.5
Output_1_64	12.107	0.381	1236	36	2.237	0.08	1193	22	0.1971	0.006	1161	15	6.8
Output_1_65	12.594	0.254	1176	27	2.157	0.058	1165	14	0.197	0.006	1159	12	5.45
Output_1_66	12.755	0.423	1173	38	2.074	0.076	1146	22	0.1923	0.006	1133	15	8
Output_1_67	12.625	0.142	1184	11	2.172	0.046	1171	8	0.1992	0.005	1171	8	2.95
Output_1_68	11.494	0.198	1376	18	2.894	0.068	1381	11	0.2394	0.007	1383	12	4.3
Output_1_69	13.055	0.273	1122	25	2.044	0.058	1129	15	0.1929	0.005	1137	10	5.09
Output_1_70	12.610	0.334	1186	29	2.136	0.065	1158	17	0.194	0.006	1143	12	6.47
Output_1_71	12.642	0.416	1189	34	2.158	0.077	1167	22	0.1964	0.006	1159	14	7.74
Output_1_72	6.618	0.066	2362	9	7.343	0.21	2155	10	0.3503	0.01	1936	15	12.84

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_73	11.377	0.246	1382	27	2.702	0.071	1329	15	0.2237	0.006	1301	12	5.37
Output_1_74	12.853	0.231	1132	22	2.069	0.056	1136	14	0.1933	0.005	1139	10	3.92
Output_1_75	12.937	0.201	1121	19	2.051	0.051	1131	12	0.1932	0.005	1138	10	3.86
Output_1_76	13.908	0.387	990	31	1.72	0.056	1015	17	0.1731	0.005	1030	13	6.62
Output_1_77	13.459	0.308	1058	28	1.787	0.045	1040	14	0.1731	0.005	1029	11	5.32
Output_1_78	12.563	0.316	1163	29	2.248	0.062	1199	16	0.2067	0.006	1211	12	5.9
Output_1_79	12.626	0.223	1185	19	2.188	0.05	1176	12	0.199	0.005	1170	10	3.93
Output_1_80	12.270	0.211	1234	19	2.14	0.066	1161	13	0.1909	0.006	1126	11	4.75
Output_1_81	11.356	0.086	1384	9	2.886	0.058	1378	7	0.2364	0.006	1368	8	2.34
Output_1_82	12.121	0.294	1252	26	2.18	0.063	1173	16	0.1922	0.005	1133	11	6.94
Output_1_83	13.812	0.515	1005	49	1.697	0.063	1008	21	0.1695	0.005	1009	14	9.1
Output_1_84	13.736	0.340	1012	27	1.704	0.049	1012	14	0.1705	0.005	1015	11	6.12
Output_1_85	11.390	0.130	1385	14	2.908	0.062	1386	9	0.238	0.007	1376	11	3.02
Output_1_86	11.628	0.270	1350	25	2.712	0.068	1331	15	0.2292	0.007	1332	15	5.27
Output_1_87	12.453	0.155	1199	14	2.252	0.049	1196	8	0.2025	0.006	1188	8	3.17
Output_1_88	13.624	0.538	1020	51	1.717	0.073	1018	23	0.1702	0.005	1013	14	8.7
Output_1_89	12.547	0.268	1169	24	2.151	0.06	1162	15	0.1973	0.006	1160	10	5
Output_1_90	12.804	0.295	1144	27	2.095	0.06	1143	16	0.1944	0.006	1145	11	5.57
Output_1_91	13.245	0.439	1087	36	1.859	0.073	1064	22	0.1786	0.005	1059	15	7.7
Output_1_92	13.908	0.542	1014	38	1.694	0.064	1000	24	0.1709	0.005	1017	12	8.4
Output_1_93	13.405	0.323	1066	23	1.836	0.056	1058	16	0.1795	0.005	1064	11	5.33
Output_1_94	12.330	0.456	1228	40	2.244	0.088	1188	25	0.2003	0.006	1176	17	9.4
Output_1_95	13.333	0.338	1066	33	1.879	0.056	1072	16	0.1792	0.005	1062	10	5.9
Output_1_96	12.771	0.587	1183	53	2.074	0.091	1137	28	0.1954	0.006	1149	22	10.9
Output_1_97	12.376	0.291	1222	26	2.233	0.064	1197	15	0.2014	0.006	1182	13	5.77
Output_1_98	12.674	0.241	1162	22	2.103	0.051	1148	11	0.1936	0.006	1141	11	5
Output_1_99	13.158	0.173	1097	16	1.866	0.043	1068	9	0.1783	0.005	1058	6	3.16
Output_1_100	13.736	0.302	1018	25	1.833	0.049	1058	13	0.1841	0.005	1090	9	5.06
Output_1_101	12.821	0.394	1129	35	1.876	0.06	1070	19	0.1781	0.005	1056	14	7.5

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_102	13.850	0.441	999	38	1.723	0.059	1021	20	0.1742	0.005	1035	11	7.55
Output_1_103	12.937	0.251	1141	21	2.04	0.053	1128	13	0.1918	0.005	1132	12	4.58
Output_1_104	12.531	0.143	1197	12	2.214	0.046	1186	7	0.2015	0.005	1183	7	2.96
KV-5													
Output_1_61	13.021	0.373	1113	29	1.966	0.065	1103	18	0.1854	0.003	1096	11	5.8
Output_1_47	12.392	0.215	1218	20	2.251	0.058	1197	11	0.2017	0.003	1184	8	4.27
Output_1_72	12.376	0.429	1224	39	2.096	0.082	1143	23	0.1888	0.004	1114	15	8.8
Output_1_45	12.610	0.318	1177	26	2.146	0.064	1162	15	0.1959	0.003	1153	10	5.97
Output_1_14	11.455	0.499	1373	43	2.76	0.12	1339	28	0.2286	0.005	1327	18	9.1
Output_1_107	11.751	0.221	1328	22	2.591	0.066	1298	11	0.2214	0.003	1290	11	5.11
Output_1_32	10.799	0.245	1483	23	3.088	0.09	1428	16	0.2441	0.004	1408	14	6.25
Output_1_5	12.579	0.332	1178	33	2.104	0.065	1148	16	0.1937	0.003	1141	10	6.5
Output_1_6	10.718	0.184	1490	18	3.25	0.084	1468	12	0.2539	0.004	1459	9	3.67
Output_1_113	12.739	0.746	1223	59	2.16	0.12	1168	36	0.1982	0.005	1165	23	13.7
Output_1_96	13.351	0.196	1069	15	1.866	0.044	1068	8	0.1808	0.003	1072	7	3.56
Output_1_69	12.723	0.421	1175	37	2.156	0.078	1167	20	0.1989	0.004	1169	15	7.9
Output_1_126	13.387	0.269	1079	25	1.866	0.051	1067	12	0.1808	0.003	1072	10	5.21
Output_1_27	10.953	0.168	1446	16	3.009	0.074	1408	11	0.2401	0.004	1387	9	4.21
Output_1_31	12.970	0.219	1120	19	1.985	0.048	1109	9	0.1868	0.003	1104	8	4.05
Output_1_49	10.917	0.346	1474	36	3.188	0.11	1450	22	0.2536	0.005	1456	18	8
Output_1_125	12.594	0.301	1201	30	2.114	0.064	1152	15	0.1938	0.003	1142	10	5.92
Output_1_21	12.547	0.268	1188	24	2.284	0.065	1208	14	0.2095	0.003	1226	10	4.04
Output_1_77	13.141	0.673	1055	59	1.879	0.1	1064	33	0.1788	0.004	1060	21	9.7
Output_1_62	13.351	0.303	1072	24	1.805	0.053	1046	14	0.1738	0.003	1033	8	5.14
Output_1_124	12.626	0.430	1204	37	2.123	0.081	1162	23	0.1978	0.004	1163	15	8.7
Output_1_18	12.531	0.220	1192	21	2.217	0.058	1187	12	0.2016	0.003	1185	9	4.42
Output_1_120	11.086	0.246	1431	27	2.924	0.084	1390	15	0.2364	0.004	1369	13	5.3
Output_1_50	12.642	0.320	1169	29	2.143	0.067	1159	17	0.1959	0.003	1153	10	5.49
Output_1_83	13.210	0.297	1100	22	1.905	0.056	1080	14	0.182	0.003	1079	10	4.77

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
Output_1_23	13.072	0.393	1082	38	1.902	0.065	1079	19	0.182	0.003	1078	13	7.25
Output_1_104	11.025	0.292	1452	36	3.071	0.1	1427	20	0.2436	0.004	1407	16	6.59
Output_1_100	12.346	0.274	1228	29	2.185	0.065	1176	15	0.1946	0.003	1147	12	5.75
Output_1_40	13.423	0.288	1059	28	1.722	0.05	1017	13	0.1689	0.003	1006	9	5.59
Output_1_93	11.779	0.721	1318	65	2.59	0.15	1287	41	0.2184	0.006	1273	28	10.8
Output_1_84	12.953	0.369	1136	34	1.967	0.063	1100	17	0.185	0.003	1094	10	6.3
Output_1_8	12.920	0.300	1149	30	1.931	0.057	1092	14	0.1815	0.003	1075	9	5.57
Output_1_64	11.601	0.283	1352	26	2.63	0.079	1310	17	0.2217	0.004	1292	14	6.18
Output_1_116	13.175	0.312	1119	26	1.878	0.056	1075	14	0.1801	0.003	1067	10	5.89
Output_1_65	12.255	0.225	1231	18	2.203	0.058	1181	12	0.1955	0.003	1152	9	4.81
Output_1_80	13.158	0.502	1122	40	1.923	0.076	1087	23	0.1832	0.004	1085	16	8.7
Output_1_66	13.175	0.226	1087	19	1.865	0.048	1067	11	0.1788	0.003	1060	7	3.62
Output_1_97	12.610	0.334	1200	32	2.146	0.07	1163	18	0.1952	0.003	1149	12	6.02
Output_1_15	12.500	0.234	1186	19	2.1	0.056	1149	11	0.1912	0.003	1128	9	4.56
Output_1_43	12.547	0.331	1195	30	2.227	0.074	1194	18	0.2035	0.004	1194	13	6.18
Output_1_25	12.626	0.351	1183	36	2.105	0.073	1147	19	0.1922	0.004	1133	15	5.98
Output_1_19	12.579	0.380	1193	33	2.156	0.079	1163	21	0.1966	0.004	1157	13	7.09
Output_1_35	9.891	0.127	1639	13	4.011	0.094	1637	10	0.2879	0.004	1631	11	3.63
Output_1_79	12.500	0.281	1208	24	2.152	0.062	1164	15	0.196	0.003	1154	10	5.37
Output_1_57	12.034	0.145	1272	12	2.392	0.055	1239	8	0.2103	0.003	1230	6	3.15
Output_1_85	13.514	0.237	1047	21	1.721	0.045	1018	11	0.1691	0.003	1007	7	3.32
Output_1_9	13.423	0.378	1048	32	1.845	0.06	1059	17	0.1786	0.003	1059	13	6.69
Output_1_117	12.610	0.350	1178	32	2.156	0.069	1166	18	0.1979	0.004	1163	14	6.82
Output_1_114	11.001	0.375	1462	38	3.025	0.12	1410	24	0.2419	0.005	1396	18	8.4
Output_1_123	12.853	0.330	1160	30	1.945	0.061	1096	16	0.1806	0.003	1070	13	5.32
Output_1_119	11.099	0.172	1441	17	2.971	0.075	1399	11	0.2379	0.004	1376	10	4.09
Output_1_10	12.642	0.272	1164	27	2.174	0.065	1175	15	0.2004	0.003	1177	10	4.61
Output_1_118	12.315	0.273	1220	26	2.159	0.064	1166	15	0.1941	0.003	1143	12	5.75
Output_1_38	10.941	0.180	1456	16	3.04	0.077	1416	12	0.2435	0.004	1405	10	4.23

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_33	10.989	0.157	1451	17	3.007	0.072	1410	10	0.2409	0.004	1391	10	3.91
Output_1_59	11.587	0.161	1334	15	2.593	0.061	1298	9	0.2187	0.003	1275	7	3.5
Output_1_92	13.298	0.813	1110	64	1.75	0.11	1035	38	0.1711	0.005	1017	23	15
Output_1_112	13.387	0.287	1055	25	1.751	0.05	1028	13	0.1719	0.003	1023	8	4.29
Output_1_30	10.741	0.196	1502	23	3.284	0.086	1478	13	0.2539	0.004	1458	12	3.05
Output_1_17	12.300	0.363	1233	34	2.199	0.076	1175	19	0.1962	0.004	1156	14	7.18
Output_1_48	11.198	0.263	1432	28	2.877	0.085	1375	17	0.2333	0.004	1352	13	5.31
Output_1_121	10.799	0.140	1488	14	3.173	0.076	1449	10	0.2489	0.004	1432	9	3.5
Output_1_99	12.195	0.580	1289	58	2.37	0.13	1233	35	0.2053	0.005	1205	22	11
Output_1_12	11.062	0.147	1437	19	2.942	0.073	1393	11	0.2349	0.003	1360	9	3.67
Output_1_58	9.588	0.165	1710	21	4.066	0.1	1648	13	0.2827	0.004	1605	12	4.31
Output_1_56	12.610	0.207	1190	18	2.177	0.054	1174	11	0.1987	0.003	1168	8	3.97
Output_1_34	11.074	0.135	1432	13	2.884	0.068	1378	9	0.2312	0.003	1341	7	3.4
Output_1_39	11.038	0.219	1443	26	2.909	0.079	1382	14	0.2333	0.004	1352	12	5.2
Output_1_81	13.245	0.246	1094	21	1.882	0.052	1072	13	0.1803	0.003	1069	9	4.07
Output_1_55	12.633	0.128	1173	12	2.091	0.047	1146	7	0.1922	0.003	1133	6	2.17
Output_1_73	10.173	0.124	1589	13	3.668	0.085	1564	9	0.2733	0.004	1557	10	3.54
Output_1_87	13.191	0.130	1104	11	1.891	0.042	1077	6	0.1811	0.003	1074	6	2.43
Output_1_101	12.579	0.316	1220	33	2.2	0.072	1180	18	0.2006	0.003	1178	11	5.78
Output_1_63	12.804	0.328	1150	28	1.962	0.062	1102	16	0.1834	0.003	1085	11	6.32
Output_1_7	12.788	0.262	1150	23	2.196	0.065	1180	15	0.2042	0.003	1198	11	4.37
Output_1_127	11.905	0.269	1285	26	2.283	0.069	1207	16	0.1975	0.003	1161	11	5.78
Output_1_110	11.136	0.211	1415	20	2.887	0.081	1380	15	0.2337	0.004	1354	12	4.66
Output_1_42	11.198	0.276	1434	30	2.825	0.091	1364	19	0.2269	0.004	1318	14	4.8
Output_1_90	12.136	0.339	1250	28	2.262	0.079	1199	20	0.2003	0.004	1176	15	7.28
Output_1_2	13.316	0.195	1070	16	1.797	0.045	1044	10	0.1741	0.002	1035	6	3.29
Output_1_94	10.881	0.142	1462	12	3.097	0.074	1431	10	0.2431	0.004	1403	9	3.47
Output_1_89	11.834	0.322	1304	31	2.492	0.089	1264	21	0.2159	0.004	1260	13	5.69
Output_1_122	12.361	0.168	1214	17	2.231	0.054	1190	10	0.2005	0.003	1178	7	3.6

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_29	10.905	0.392	1479	41	3.11	0.13	1435	28	0.2451	0.005	1412	21	7.3
Output_1_44	12.837	0.214	1147	20	1.897	0.049	1079	11	0.1784	0.003	1058	9	4.04
Output_1_109	10.811	0.175	1480	18	3.158	0.083	1444	13	0.2475	0.004	1425	11	4.1
Output_1_54	13.038	0.306	1114	29	1.966	0.057	1103	14	0.1862	0.004	1100	14	3.79
Output_1_88	13.028	0.161	1120	15	1.919	0.046	1088	9	0.1815	0.003	1075	8	2.9
Output_1_86	12.136	0.221	1259	19	2.314	0.064	1217	14	0.2051	0.003	1203	9	4.71
Output_1_70	12.063	0.175	1273	15	2.461	0.059	1260	9	0.2143	0.003	1252	8	3.7
Output_1_41	11.473	0.129	1376	13	2.73	0.064	1337	9	0.2259	0.003	1314	8	2.46
Output_1_22	11.962	0.444	1277	39	2.343	0.1	1230	28	0.2044	0.004	1198	15	7.7
Output_1_52	10.953	0.168	1461	18	3.154	0.08	1445	12	0.2493	0.004	1436	11	3.89
Output_1_91	9.681	0.197	1690	22	4.169	0.12	1665	17	0.2926	0.005	1654	15	4.3
Output_1_74	11.587	0.175	1342	18	2.622	0.065	1307	11	0.2207	0.003	1285	9	3.41
Output_1_98	11.779	0.236	1312	24	2.719	0.079	1331	16	0.2314	0.004	1342	12	4.23
Output_1_78	13.291	0.136	1084	10	1.886	0.043	1076	7	0.1819	0.003	1077	5	2.3
Output_1_11	10.893	0.392	1473	39	3.24	0.14	1460	29	0.2575	0.005	1476	21	8.8
Output_1_76	10.893	0.225	1477	21	3.002	0.088	1404	16	0.2384	0.004	1378	15	5.56
Output_1_28	11.099	0.197	1428	18	2.995	0.082	1407	14	0.2435	0.004	1404	12	4.23
Output_1_3	13.158	0.242	1105	24	1.893	0.052	1079	12	0.1797	0.003	1065	10	3.61
Output_1_106	10.953	0.180	1451	17	3.1	0.081	1434	12	0.2485	0.004	1430	11	4.02
Output_1_115	12.531	0.188	1195	16	2.151	0.054	1165	10	0.1959	0.003	1153	10	2.69
Output_1_13	5.453	0.068	2677	12	12.9	0.3	2673	12	0.5116	0.008	2663	20	4.21
Output_1_128	12.626	0.287	1188	22	2.086	0.066	1142	17	0.1918	0.003	1131	12	5.27
Output_1_95	12.303	0.144	1236	13	2.231	0.054	1190	9	0.199	0.003	1170	8	2.94
Output_1_20	12.469	0.311	1200	26	2.193	0.069	1177	17	0.2017	0.003	1184	12	3.58
Output_1_67	5.495	0.063	2675	11	12.51	0.29	2642	11	0.4986	0.007	2607	17	4.13
Output_1_82	10.799	0.198	1471	22	3.148	0.088	1449	15	0.2504	0.004	1440	11	4.27
Output_1_26	12.361	0.183	1209	16	2.202	0.055	1180	10	0.1974	0.003	1161	9	3.63
Output_1_105	12.470	0.138	1201	15	2.258	0.053	1199	9	0.2044	0.003	1199	7	1.88
Output_1_24	5.176	0.072	2771	13	14.02	0.36	2752	14	0.5256	0.009	2721	27	5.7

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_36	5.450	0.045	2682	8	12.25	0.27	2625	9	0.4838	0.007	2544	13	4.02
Output_1_75	11.442	0.183	1367	18	2.889	0.077	1380	13	0.2415	0.004	1394	12	3.54
Output_1_102	5.397	0.050	2701	9	12.67	0.29	2658	10	0.4972	0.007	2601	14	3.83
Output_1_103	5.665	0.029	2620	5	11.016	0.23	2525	6	0.4536	0.006	2411	12	5.99
Output_1_60	13.038	0.442	1116	37	1.757	0.069	1032	22	0.1685	0.003	1004	14	7.6
Output_1_16	11.792	0.348	1277	35	2.239	0.081	1189	21	0.1937	0.004	1142	15	8.2
Output_1_46	12.034	0.275	1278	28	2.215	0.065	1183	15	0.193	0.003	1137	12	6.41
Output_1_111	11.737	0.331	1310	34	2.294	0.082	1212	21	0.1964	0.004	1157	16	7.1
Output_1_51	12.804	0.393	1164	34	1.842	0.063	1061	18	0.1704	0.003	1014	12	7.6
Output_1_4	11.990	0.158	1275	17	2.127	0.054	1158	11	0.1857	0.003	1098	8	4.41
Output_1_71	11.587	0.363	1328	41	2.293	0.083	1207	21	0.1929	0.004	1137	14	6.5
Output_1_53	7.215	0.094	2214	21	2.651	0.065	1314	10	0.1388	0.002	838	5	40.21
Output_1_68	5.731	0.108	2592	31	3.285	0.074	1477	8	0.1358	0.003	820	11	55.1
Output_1_37	12.907	0.115	1135	10	1.979	0.043	1108	5	0.1864	0.003	1102	7	1.79
Output_1_108	12.920	0.184	1132	17	1.984	0.049	1109	9	0.1859	0.003	1099	7	2.7
Output_1_1	12.997	0.103	1115	10	1.982	0.043	1110	5	0.1872	0.003	1107	5	1.37
KV-6													
Output_1_1	12.837	0.231	1142	20	2.096	0.039	1147	12	0.1962	0.002	1156	9	4.2
Output_1_2	11.011	0.086	1447	9	3.226	0.034	1463	8	0.2583	0.002	1481	10	2.2
Output_1_3	5.824	0.047	2573	9	11.17	0.12	2538	10	0.4712	0.005	2490	22	3.63
Output_1_4	5.650	0.048	2616	9	11.31	0.12	2549	10	0.4647	0.004	2459	18	5.11
Output_1_5	13.141	0.207	1090	19	1.928	0.032	1091	11	0.1847	0.002	1092	9	4.02
Output_1_6	12.249	0.144	1237	13	2.356	0.026	1229	8	0.2102	0.001	1230	8	3.1
Output_1_7	10.571	0.324	1494	33	3.24	0.11	1478	26	0.2526	0.004	1451	20	7.35
Output_1_8	11.455	0.197	1355	22	2.84	0.049	1368	13	0.2368	0.002	1370	11	4.56
Output_1_9	12.508	0.124	1195	11	2.236	0.023	1193	7	0.2036	0.001	1195	7	2.51
Output_1_10	12.788	0.311	1163	30	2.218	0.048	1188	15	0.2058	0.002	1206	11	5.76
Output_1_11	11.086	0.209	1431	21	3.052	0.057	1421	14	0.2445	0.003	1410	13	5.22
Output_1_12	5.685	0.036	2614	6	11.863	0.093	2594	7	0.4897	0.004	2570	15	3.1

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_13	12.690	0.435	1150	35	2.169	0.069	1166	22	0.1992	0.003	1170	15	8.3
Output_1_14	10.989	0.169	1455	16	3.149	0.048	1444	12	0.2497	0.003	1436	13	3.69
Output_1_15	13.441	0.199	1045	16	1.451	0.016	910	7	0.1413	0.002	852	10	4.8
Output_1_16	13.235	0.121	1081	13	1.905	0.017	1082	6	0.1829	0.001	1083	7	2.51
Output_1_17	5.531	0.058	2655	10	12.66	0.16	2653	12	0.5081	0.005	2654	22	4.01
Output_1_18	12.674	0.119	1166	11	2.187	0.021	1178	7	0.2015	0.001	1183	7	2.4
Output_1_19	13.493	0.104	1046	9	1.814	0.013	1051	5	0.1768	9E-04	1050	5	2.04
Output_1_20	10.684	0.217	1500	19	2.915	0.058	1385	15	0.2248	0.002	1309	11	5.3
Output_1_21	11.261	0.203	1398	20	3.043	0.052	1416	13	0.2466	0.003	1421	14	4.75
Output_1_22	12.500	0.172	1205	16	1.743	0.028	1025	10	0.1586	0.002	948	11	6.53
Output_1_23	9.328	0.165	1762	19	4.474	0.076	1723	14	0.3024	0.003	1703	15	5.44
Output_1_24	12.771	0.179	1142	16	2.158	0.035	1168	11	0.1995	0.001	1173	7	3.53
Output_1_25	12.837	0.297	1155	29	2.161	0.047	1170	15	0.1999	0.002	1174	12	5.79
Output_1_26	13.344	0.139	1064	13	1.879	0.022	1074	8	0.1819	0.002	1078	8	2.71
Output_1_27	13.284	0.088	1076	8	0.73	0.018	555	10	0.07	0.002	436	10	15.15
Output_1_28	11.614	0.175	1354	17	2.731	0.043	1337	11	0.2295	0.002	1332	12	4.08
Output_1_29	11.236	0.139	1413	14	3.103	0.047	1433	11	0.2519	0.003	1448	15	3.23
Output_1_30	13.141	0.294	1099	26	1.686	0.039	1004	15	0.1605	0.001	960	8	4.51
Output_1_31	12.484	0.281	1206	25	2.08	0.051	1146	17	0.1879	0.002	1111	11	5.7
Output_1_32	13.587	0.111	1033	9	1.837	0.015	1059	6	0.1808	1E-03	1071	5	2.05
Output_1_33	12.953	0.218	1126	20	2.082	0.037	1142	12	0.1955	0.002	1151	8	3.92
Output_1_34	11.429	0.144	1362	14	2.903	0.041	1382	11	0.2405	0.002	1389	11	3.15
Output_1_35	10.983	0.104	1448	10	3.089	0.035	1429	9	0.2458	0.002	1416	10	2.13
Output_1_36	13.495	0.255	1044	23	1.809	0.03	1047	11	0.178	0.002	1056	9	4.12
Output_1_37	10.983	0.089	1445	10	3.27	0.027	1473	6	0.2602	0.002	1491	9	2.59
Output_1_38	9.681	0.094	1683	11	4.22	0.052	1677	10	0.2961	0.003	1672	13	3.06
Output_1_39	12.563	0.379	1186	39	2.155	0.064	1164	20	0.1954	0.003	1150	17	5.8
Output_1_40	12.392	0.445	1227	36	2.154	0.079	1163	27	0.195	0.003	1148	16	8.8
Output_1_41	5.516	0.067	2665	11	12.03	0.16	2606	13	0.4798	0.004	2526	18	5.33

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_42	10.277	0.148	1580	15	3.579	0.061	1544	13	0.2685	0.004	1533	20	2.46
Output_1_43	9.579	0.119	1709	13	4.191	0.051	1674	10	0.29	0.003	1642	14	4.1
Output_1_44	13.514	0.201	1035	19	1.834	0.024	1057	9	0.1791	0.002	1062	8	3.81
Output_1_45	11.299	0.332	1402	30	2.961	0.088	1395	22	0.2401	0.003	1391	17	6.09
Output_1_46	12.747	0.141	1166	12	2.157	0.024	1167	8	0.1995	0.001	1173	6	2.71
Output_1_47	11.186	0.125	1420	12	3.009	0.032	1411	8	0.2432	0.002	1403	9	3.13
Output_1_48	13.459	0.235	1046	21	1.842	0.036	1058	13	0.1792	0.002	1063	8	4.32
Output_1_49	12.970	0.269	1129	25	1.994	0.04	1113	13	0.1878	0.002	1110	11	4.76
Output_1_50	12.920	0.250	1137	22	2.044	0.037	1128	12	0.1913	0.002	1128	11	5.12
Output_1_51	12.903	0.233	1161	20	2.106	0.042	1148	14	0.1959	0.002	1153	9	4.22
Output_1_52	12.580	0.152	1182	15	2.226	0.029	1189	9	0.2025	0.002	1189	8	3.02
Output_1_53	12.594	0.222	1190	19	2.189	0.038	1177	12	0.1994	0.002	1172	10	4.25
Output_1_54	13.374	0.120	1058	11	1.872	0.018	1071	6	0.1811	0.001	1073	6	2.26
Output_1_55	11.669	0.340	1344	32	2.652	0.071	1313	20	0.2233	0.004	1299	20	3.76
Output_1_56	11.120	0.120	1419	10	2.405	0.043	1245	13	0.1944	0.003	1145	16	7.22
Output_1_57	13.378	0.166	1069	13	1.82	0.024	1053	8	0.1768	0.001	1049	7	3.2
Output_1_58	13.300	0.170	1082	16	1.896	0.022	1079	8	0.1837	0.001	1087	6	3.14
Output_1_59	12.788	0.196	1154	18	2.163	0.034	1169	11	0.2013	0.002	1182	9	3.65
Output_1_60	12.788	0.150	1159	15	2.143	0.024	1162	8	0.1987	0.001	1169	8	2.97
Output_1_61	5.814	0.051	2576	10	10.54	0.1	2486	9	0.4446	0.003	2371	14	6.28
Output_1_62	12.453	0.341	1209	29	2.157	0.057	1167	18	0.1952	0.003	1149	13	6.98
Output_1_63	10.730	0.161	1489	13	3.396	0.044	1504	10	0.2635	0.002	1509	11	3.03
Output_1_64	12.837	0.346	1129	27	2.059	0.053	1138	18	0.1928	0.003	1136	14	7.04
Output_1_65	12.744	0.123	1156	11	2.169	0.021	1170	7	0.2001	0.001	1176	6	2.55
Output_1_66	13.390	0.109	1054	9	1.834	0.015	1058	6	0.1784	0.001	1058	6	1.98
Output_1_67	5.862	0.069	2571	10	9.71	0.13	2406	12	0.4111	0.005	2222	22	10.35
Output_1_68	11.137	0.114	1426	12	3.078	0.034	1428	9	0.25	0.002	1438	9	2.71
Output_1_69	11.521	0.252	1367	26	2.654	0.054	1314	15	0.223	0.002	1298	11	5.65
Output_1_70	13.175	0.243	1108	22	1.92	0.034	1088	12	0.1821	0.001	1078	8	4.47

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_71	13.369	0.197	1054	18	1.849	0.027	1062	10	0.18	0.002	1068	8	3.78
Output_1_72	12.837	0.214	1147	21	2.147	0.033	1165	10	0.1998	0.002	1174	9	4.1
Output_1_73	12.811	0.089	1152	7	2.127	0.019	1157	6	0.198	0.001	1164	7	1.72
Output_1_74	12.802	0.131	1156	10	2.17	0.024	1171	8	0.2031	0.002	1192	8	2.57
Output_1_75	11.368	0.089	1386	10	1.779	0.026	1037	10	0.1459	0.002	878	10	12.88
Output_1_76	12.739	0.211	1162	17	2.089	0.034	1144	11	0.1928	0.002	1136	9	3.86
Output_1_77	12.392	0.491	1210	51	2.19	0.085	1177	27	0.1989	0.004	1169	19	9.4
Output_1_78	11.136	0.161	1417	15	3.441	0.051	1512	12	0.2747	0.002	1564	12	4.69
Output_1_79	12.970	0.185	1128	17	2.091	0.03	1145	10	0.1959	0.001	1154	7	3.37
Output_1_80	12.903	0.216	1135	20	2.144	0.033	1165	11	0.2013	0.002	1182	9	4.35
Output_1_81	12.361	0.336	1196	32	2.36	0.062	1232	19	0.2113	0.002	1236	12	6.32
Output_1_82	11.737	0.358	1332	30	2.534	0.073	1278	21	0.2141	0.003	1250	14	7.4
Output_1_83	5.631	0.032	2626	5	12.044	0.086	2607	7	0.4931	0.003	2584	12	2.72
Output_1_84	11.075	0.120	1424	13	3.137	0.034	1441	8	0.2513	0.002	1445	8	2.86
Output_1_85	12.500	0.156	1193	14	2.151	0.027	1165	9	0.1953	0.002	1150	8	3.22
Output_1_86	12.626	0.255	1187	20	2.192	0.045	1179	14	0.1998	0.002	1174	12	4.95
Output_1_87	12.945	0.163	1126	14	2.086	0.029	1144	10	0.1952	0.001	1150	7	3.17
Output_1_88	11.086	0.197	1430	21	2.978	0.051	1404	13	0.2398	0.002	1387	13	4.85
Output_1_89	12.771	0.179	1152	17	2.116	0.03	1156	10	0.1963	0.001	1155	8	3.31
Output_1_90	11.223	0.189	1426	21	3.008	0.057	1411	14	0.2422	0.002	1398	11	4.04
Output_1_91	12.594	0.222	1163	21	2.127	0.04	1155	13	0.195	0.002	1149	13	5.06
Output_1_92	12.855	0.139	1140	14	2.091	0.023	1146	8	0.1951	0.001	1149	6	2.7
Output_1_93	13.961	0.127	979	11	1.677	0.016	999	6	0.1696	0.001	1010	6	2.3
Output_1_94	13.526	0.161	1040	13	1.773	0.02	1037	7	0.1747	0.001	1038	6	2.89
Output_1_95	8.636	0.082	1889	11	5.03	0.067	1823	11	0.3139	0.003	1759	13	3.96
Output_1_96	12.755	0.228	1169	22	2.156	0.037	1165	12	0.1981	0.002	1165	9	4.15
Output_1_97	11.025	0.170	1438	18	3.152	0.048	1445	12	0.2527	0.002	1452	10	4.16
Output_1_98	13.376	0.127	1057	12	1.821	0.018	1053	6	0.1776	0.001	1054	6	2.34
Output_1_99	11.547	0.253	1355	21	2.88	0.061	1375	16	0.2402	0.003	1387	14	5.58

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_100	12.531	0.267	1199	22	2.175	0.045	1173	14	0.1977	0.002	1163	9	5.03
KV-7													
Output_1_3	9.066	0.082	1807	10	5.007	0.046	1822	7	0.3291	0.002	1834	10	2.6
Output_1_4	13.333	0.693	1057	57	1.778	0.096	1035	36	0.1722	0.004	1023	21	10.5
Output_1_5	12.034	0.333	1277	30	2.419	0.066	1248	19	0.2097	0.003	1227	16	6.36
Output_1_6	13.316	0.266	1073	21	1.846	0.035	1065	12	0.1794	0.002	1063	9	4.7
Output_1_7	13.308	0.161	1065	14	1.865	0.025	1071	9	0.1803	0.001	1068	8	2.93
Output_1_8	11.123	0.198	1430	20	2.973	0.052	1398	13	0.2404	0.002	1388	12	4.31
Output_1_9	13.106	0.309	1123	27	2.066	0.048	1136	16	0.1957	0.002	1152	11	5.41
Output_1_10	4.998	0.037	2829	7	15.42	0.13	2842	8	0.5599	0.004	2866	15	3.38
Output_1_11	12.870	0.265	1133	28	1.943	0.04	1095	13	0.1834	0.002	1085	10	5.32
Output_1_12	13.193	0.278	1108	26	1.957	0.043	1099	15	0.1885	0.002	1113	12	3.99
Output_1_13	11.737	0.179	1316	18	2.661	0.046	1321	13	0.2277	0.002	1322	11	3.29
Output_1_14	12.361	0.321	1225	31	2.164	0.055	1170	18	0.1938	0.003	1141	13	6.59
Output_1_15	12.723	0.178	1161	17	2.118	0.031	1154	10	0.1953	0.002	1150	8	3.25
Output_1_16	13.569	0.387	1043	32	1.725	0.051	1024	20	0.1734	0.002	1031	13	6.87
Output_1_17	13.514	0.475	1065	42	1.776	0.059	1038	21	0.175	0.002	1039	13	8.08
Output_1_18	13.459	0.326	1040	26	1.801	0.042	1045	15	0.1766	0.002	1048	11	5.45
Output_1_19	13.477	0.363	1043	30	1.903	0.048	1087	15	0.1886	0.002	1114	11	4.96
Output_1_20	13.405	0.305	1053	21	1.803	0.039	1045	14	0.1752	0.002	1041	9	5.3
Output_1_21	13.351	0.303	1080	23	1.875	0.042	1073	15	0.181	0.002	1072	10	4.82
Output_1_22	13.369	0.322	1077	28	1.773	0.041	1036	15	0.1749	0.002	1039	11	5.79
Output_1_23	13.193	0.244	1081	26	1.876	0.035	1070	12	0.1811	0.002	1073	9	4.55
Output_1_24	13.495	0.455	1047	43	1.804	0.06	1045	23	0.1762	0.003	1045	15	8
Output_1_25	11.447	0.106	1367	10	2.678	0.055	1321	15	0.2244	0.004	1304	22	3.61
Output_1_26	13.441	0.289	1059	21	1.882	0.044	1073	15	0.1837	0.002	1087	12	3.57
Output_1_27	13.245	0.509	1052	41	1.776	0.062	1039	22	0.1721	0.002	1024	11	8.1
Output_1_28	10.917	0.179	1455	19	3.102	0.054	1433	14	0.248	0.002	1429	11	3.82
Output_1_29	13.175	0.295	1081	24	1.916	0.043	1086	15	0.1846	0.002	1092	11	5.33

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_30	11.468	0.145	1373	14	2.943	0.037	1392	10	0.2433	0.002	1404	10	2.7
Output_1_31	13.106	0.344	1138	27	1.881	0.046	1073	17	0.179	0.002	1063	11	5.44
Output_1_32	11.919	0.227	1286	23	2.57	0.045	1292	13	0.2238	0.002	1302	12	4.62
Output_1_33	13.280	0.265	1088	24	1.905	0.038	1082	14	0.1848	0.002	1093	10	4.34
Output_1_34	12.165	0.829	1306	84	2.7	0.19	1340	54	0.2392	0.008	1385	39	13.1
Output_1_35	13.298	0.265	1060	30	1.891	0.041	1077	15	0.1837	0.002	1088	11	4.52
Output_1_36	11.325	0.154	1392	14	2.806	0.038	1358	10	0.2328	0.002	1349	9	3.38
Output_1_37	11.236	0.353	1421	31	2.88	0.084	1373	22	0.2309	0.003	1338	18	7.16
Output_1_38	12.739	0.438	1170	40	1.957	0.061	1099	22	0.1812	0.002	1073	11	8.5
Output_1_39	13.643	0.335	1004	31	1.709	0.037	1014	14	0.1723	0.002	1024	10	5.48
Output_1_40	13.072	0.256	1125	23	2.017	0.04	1120	13	0.1906	0.002	1125	8	4.45
Output_1_41	13.459	0.471	1033	43	1.822	0.06	1052	22	0.1801	0.003	1069	14	8.29
Output_1_42	11.507	0.278	1363	23	2.696	0.067	1322	18	0.2269	0.002	1318	13	5.49
Output_1_43	13.369	0.393	1071	34	1.874	0.06	1075	21	0.1812	0.003	1073	15	6.8
Output_1_44	12.392	0.353	1211	29	2.183	0.058	1176	19	0.197	0.003	1159	15	6.8
Output_1_45	11.696	0.178	1346	17	2.716	0.041	1332	11	0.2307	0.002	1338	9	3.52
Output_1_46	13.605	0.296	1031	26	1.834	0.042	1055	15	0.1804	0.002	1069	10	4.97
Output_1_47	13.123	0.241	1106	20	1.918	0.03	1088	10	0.1828	0.002	1082	8	4.17
Output_1_48	13.587	0.185	1037	17	1.785	0.023	1039	9	0.1759	0.001	1045	7	3.38
Output_1_49	12.210	0.358	1253	33	2.312	0.064	1213	19	0.2053	0.003	1203	14	6.7
Output_1_50	5.379	0.043	2705	8	13.34	0.12	2705	9	0.5228	0.004	2711	15	2.87
Output_1_51	8.681	0.090	1886	11	5.366	0.056	1880	9	0.3384	0.002	1879	9	2.71
Output_1_52	13.831	0.497	1007	47	1.671	0.058	1002	23	0.1689	0.002	1006	13	8.6
Output_1_53	13.459	0.670	1043	50	1.734	0.08	1025	30	0.1699	0.003	1011	16	10
Output_1_54	12.953	0.873	1156	75	1.97	0.12	1096	43	0.1792	0.004	1061	24	15.3
Output_1_55	11.074	0.233	1418	23	3.092	0.069	1428	17	0.2487	0.002	1431	12	4.78
Output_1_56	11.962	0.200	1306	18	2.51	0.041	1273	12	0.2181	0.002	1271	12	3.95
Output_1_57	10.194	0.166	1588	18	3.82	0.063	1595	13	0.2814	0.003	1598	13	4.22
Output_1_58	9.804	0.125	1655	16	3.892	0.055	1613	12	0.2791	0.002	1587	9	3.64

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_59	12.755	0.260	1163	26	1.994	0.04	1114	14	0.1839	0.002	1088	9	4.59
Output_1_60	11.338	0.141	1391	14	2.868	0.036	1373	10	0.2349	0.002	1360	9	3.34
Output_1_61	11.377	0.259	1371	25	2.768	0.057	1344	15	0.2289	0.003	1330	14	5.68
Output_1_62	13.550	0.294	1046	24	1.749	0.041	1025	15	0.1716	0.002	1021	10	5.04
Output_1_63	13.141	0.345	1099	29	1.93	0.047	1091	16	0.184	0.002	1090	11	5.61
Output_1_64	13.175	0.434	1110	39	1.823	0.054	1051	19	0.1754	0.003	1041	14	8.1
Output_1_65	13.387	0.627	1051	53	1.96	0.082	1102	28	0.1872	0.004	1105	21	10.3
Output_1_66	13.405	0.377	1051	34	1.849	0.05	1063	18	0.1801	0.002	1067	11	6.44
Output_1_67	10.917	0.238	1433	24	2.994	0.07	1404	18	0.2392	0.003	1382	13	5.85
Output_1_68	13.021	0.559	1099	45	1.873	0.07	1073	25	0.1791	0.003	1061	16	9.7
Output_1_69	5.426	0.059	2688	12	13.68	0.15	2727	10	0.5389	0.005	2778	20	4.55
Output_1_70	13.089	0.240	1092	23	1.917	0.036	1087	12	0.1834	0.002	1085	9	4.42
Output_1_71	12.361	0.397	1224	41	2.378	0.075	1234	23	0.2134	0.002	1247	13	7.31
Output_1_72	13.387	0.932	1127	65	1.83	0.13	1058	46	0.1752	0.004	1042	21	15.5
Output_1_73	13.210	0.209	1081	19	1.83	0.03	1056	10	0.1759	0.001	1044	7	3.63
Output_1_74	8.751	0.072	1872	8	5.251	0.052	1860	9	0.3332	0.002	1854	11	2.25
Output_1_75	12.804	0.197	1152	18	2.042	0.03	1130	10	0.1891	0.002	1118	10	3.78
Output_1_76	11.561	0.267	1351	26	2.729	0.071	1332	19	0.2273	0.003	1320	13	5.27
Output_1_77	13.643	0.372	1014	34	1.866	0.052	1071	19	0.1848	0.002	1093	11	5.94
Output_1_78	13.495	0.291	1045	23	1.736	0.038	1024	14	0.1697	0.002	1010	8	4.71
Output_1_79	13.106	0.326	1082	29	1.898	0.046	1079	16	0.1825	0.002	1080	10	5.42
Output_1_80	8.673	0.075	1886	8	5.366	0.044	1879	7	0.3365	0.002	1869	11	2.63
Output_1_81	13.210	0.227	1085	23	1.933	0.031	1093	11	0.1849	0.002	1094	9	3.47
Output_1_82	12.970	0.286	1110	26	1.868	0.042	1068	15	0.1769	0.002	1050	11	5.06
Output_1_83	10.718	0.115	1490	14	3.322	0.044	1486	10	0.2581	0.002	1480	10	2.9
Output_1_84	9.794	0.153	1662	17	4.151	0.074	1667	14	0.295	0.003	1666	14	3.91
Output_1_85	13.141	0.276	1081	25	1.631	0.035	986	13	0.1602	0.003	957	16	4.68
Output_1_87	11.792	0.236	1323	23	2.541	0.049	1283	14	0.2188	0.002	1276	10	4.49
Output_1_88	13.889	0.849	1038	76	1.91	0.11	1085	37	0.1893	0.005	1116	28	13

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
Output_1_89	13.333	0.249	1073	27	1.915	0.035	1085	12	0.1863	0.002	1102	10	3.94
Output_1_90	13.228	0.245	1070	23	1.929	0.034	1091	12	0.1847	0.002	1092	9	4.29
Output_1_91	13.038	0.306	1112	31	1.879	0.048	1076	17	0.1777	0.002	1054	11	5
Output_1_93	9.355	0.184	1732	23	4.531	0.086	1740	16	0.3122	0.003	1751	15	5.67
Output_1_94	13.643	0.931	1059	78	1.82	0.13	1047	47	0.1784	0.005	1057	28	12.8
Output_1_95	5.411	0.047	2693	8	13.27	0.12	2699	9	0.521	0.003	2703	15	3.24
Output_1_96	12.953	0.470	1141	48	1.998	0.07	1117	24	0.1866	0.003	1106	15	8.2
Output_1_97	12.970	0.269	1127	22	1.987	0.04	1113	14	0.1862	0.002	1101	10	4.85
Output_1_98	13.123	1.119	1143	90	1.77	0.15	1045	55	0.1743	0.006	1034	33	17.4
Output_1_99	13.473	0.169	1057	15	1.857	0.023	1066	8	0.1814	0.001	1075	6	2.93
Output_1_100	5.760	0.086	2598	13	12.03	0.19	2605	14	0.4987	0.005	2607	22	5.16
Output_1_101	12.563	0.253	1196	20	2.163	0.04	1169	13	0.1971	0.002	1160	9	4.68
Output_1_102	13.387	0.305	1079	25	1.856	0.041	1064	15	0.1795	0.002	1064	11	5.42
Output_1_103	13.175	0.694	1147	65	1.852	0.091	1065	33	0.1794	0.004	1063	22	11.9
Output_1_104	12.987	0.287	1136	26	2.062	0.045	1139	14	0.1934	0.002	1140	12	4.63
Output_1_105	11.919	0.199	1288	19	2.541	0.043	1283	13	0.2186	0.002	1274	10	4.18
Output_1_106	13.158	0.260	1077	23	1.893	0.034	1077	12	0.1827	0.002	1082	9	4.69
Output_1_107	13.477	0.200	1045	17	1.858	0.027	1065	10	0.1813	0.001	1074	7	3.42
Output_1_108	12.681	0.153	1162	13	2.156	0.025	1167	8	0.1985	0.001	1167	7	2.98
Output_1_109	13.245	0.351	1089	30	1.847	0.049	1060	17	0.1782	0.002	1057	11	5.7
Output_1_110	13.477	0.654	1109	51	1.859	0.082	1072	30	0.1822	0.004	1078	21	11.3
Output_1_111	11.779	0.291	1317	27	2.485	0.057	1270	16	0.2131	0.003	1246	14	6.12
Output_1_112	12.706	0.387	1154	41	2.08	0.067	1144	22	0.1937	0.003	1142	14	6.97
Output_1_113	11.547	0.200	1358	23	2.688	0.046	1327	13	0.2259	0.002	1312	12	4.22
Output_1_114	12.658	0.385	1172	37	2.104	0.058	1148	19	0.1953	0.002	1150	13	6.74
Output_1_115	13.193	0.174	1096	16	1.901	0.026	1081	9	0.182	0.001	1078	6	3.39
Output_1_116	13.038	0.561	1141	60	1.926	0.089	1085	31	0.1778	0.003	1054	18	9.6
Output_1_117	12.642	0.368	1178	37	2.064	0.055	1137	18	0.1898	0.003	1122	14	7.18
Output_1_118	13.605	0.222	1036	19	1.876	0.032	1071	11	0.1857	0.002	1099	8	3.64

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
Output_1_119	12.438	0.340	1210	32	2.389	0.069	1234	20	0.2132	0.003	1247	13	6.69
Output_1_120	12.953	0.352	1136	28	1.93	0.049	1089	17	0.1823	0.002	1079	11	6.32
Output_1_121	5.325	0.037	2720	6	13.86	0.099	2740	7	0.5324	0.003	2751	14	2.46
Output_1_122	5.408	0.059	2702	10	13.53	0.13	2716	9	0.5295	0.004	2740	17	3.82
Output_1_123	13.116	0.139	1100	12	1.901	0.018	1082	6	0.1823	0.001	1080	6	2.63
Output_1_124	12.821	0.362	1164	34	2.024	0.058	1123	19	0.1857	0.002	1098	12	6.32
Output_1_125	12.853	0.314	1140	25	1.948	0.048	1096	17	0.1819	0.002	1077	12	5.34
Output_1_126	9.901	0.167	1648	16	3.972	0.067	1628	13	0.2834	0.003	1608	13	3.95
Output_1_127	13.387	0.466	1108	44	1.848	0.062	1061	22	0.1804	0.002	1069	13	7.9
Output_1_128	5.627	0.048	2627	8	12.09	0.1	2611	8	0.4906	0.003	2573	11	3.02
Output_1_129	13.245	0.228	1083	18	1.876	0.028	1076	10	0.1804	0.001	1070	7	3.84
Output_1_130	13.387	0.233	1064	18	1.874	0.031	1072	11	0.1819	0.001	1077	7	3.23
Output_1_131	5.453	0.054	2690	8	13.68	0.15	2727	10	0.5383	0.005	2775	19	4.64
Output_1_132	12.870	0.447	1127	35	2.07	0.078	1134	25	0.195	0.004	1147	23	7.4
Output_1_2	13.135	0.148	1098	13	1.964	0.022	1103	7	0.1875	0.001	1108	6	2.69
Output_1_92	13.120	0.108	1104	10	1.95	0.019	1098	6	0.1865	0.001	1102	6	2.12
KV-8													
ADN109-1	13.582	0.267	1031	40	1.813	0.047	1050	17	0.179	0.003	1059	17	0.00
ADN109-2	11.814	0.297	1307	49	2.683	0.071	1324	20	0.230	0.002	1334	10	0.00
ADN109-3	13.596	0.939	1029	140	1.750	0.123	1027	46	0.173	0.002	1026	13	0.27
ADN109-4	13.616	0.639	1026	95	1.873	0.089	1072	31	0.185	0.001	1094	6	0.00
ADN109-5	13.155	0.234	1095	36	1.997	0.044	1114	15	0.191	0.002	1124	13	0.00
ADN109-6	5.612	0.083	2636	25	11.916	0.513	2598	40	0.485	0.020	2549	85	3.29
ADN109-7	11.538	0.194	1353	32	2.752	0.079	1343	21	0.230	0.005	1336	28	1.28
ADN109-8	12.415	0.242	1210	38	2.367	0.077	1233	23	0.213	0.006	1245	30	0.00
ADN109-9	13.452	0.409	1051	61	1.928	0.074	1091	26	0.188	0.004	1111	24	0.00
ADN109-10	13.193	0.152	1090	23	1.919	0.045	1088	16	0.184	0.004	1087	21	0.29
ADN109-11	13.564	0.431	1034	64	1.888	0.113	1077	40	0.186	0.009	1098	51	0.00
ADN109-12	12.529	0.247	1192	39	2.263	0.052	1201	16	0.206	0.003	1206	13	0.00

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
ADN109-13	12.682	0.143	1168	22	2.197	0.038	1180	12	0.202	0.003	1187	14	0.00
ADN109-14	13.173	0.300	1093	46	2.040	0.052	1129	18	0.195	0.002	1148	13	0.00
ADN109-15	12.600	0.179	1181	28	2.250	0.050	1197	15	0.206	0.003	1206	18	0.00
ADN109-16	13.594	0.378	1030	56	1.817	0.067	1052	24	0.179	0.004	1062	24	0.00
ADN109-17	11.441	0.268	1369	45	2.820	0.103	1361	27	0.234	0.007	1356	34	1.01
ADN109-18	12.528	0.104	1193	16	2.225	0.065	1189	20	0.202	0.006	1187	30	0.47
ADN109-19	12.703	0.131	1165	20	2.173	0.056	1172	18	0.200	0.005	1176	25	0.00
ADN109-20	13.621	0.265	1025	39	1.807	0.056	1048	20	0.179	0.004	1059	23	0.00
ADN109-21	13.551	0.360	1036	54	1.858	0.052	1066	18	0.183	0.002	1081	9	0.00
ADN109-22	12.564	0.309	1187	49	2.279	0.062	1206	19	0.208	0.002	1217	13	0.00
ADN109-23	13.051	0.340	1111	52	2.075	0.057	1140	19	0.196	0.002	1156	9	0.00
ADN109-24	5.042	0.067	2812	22	14.941	0.319	2811	20	0.546	0.009	2810	38	0.09
ADN109-25	13.586	0.441	1031	66	1.855	0.067	1065	24	0.183	0.003	1082	16	0.00
ADN109-26	13.237	0.221	1083	33	1.949	0.034	1098	12	0.187	0.001	1105	5	0.00
ADN109-27	12.575	0.170	1185	27	2.244	0.043	1195	13	0.205	0.003	1200	15	0.00
ADN109-28	11.391	0.224	1378	38	2.792	0.085	1353	23	0.231	0.005	1338	28	2.90
ADN109-29	12.544	0.235	1190	37	2.240	0.046	1194	14	0.204	0.002	1196	9	0.00
ADN109-30	13.002	0.334	1119	51	2.056	0.056	1134	19	0.194	0.002	1142	10	0.00
ADN109-31	10.969	0.409	1450	71	2.822	0.130	1361	34	0.225	0.006	1306	32	9.95
ADN109-32	12.429	0.381	1208	60	2.288	0.074	1208	23	0.206	0.002	1209	12	0.00
ADN109-33	13.165	0.249	1094	38	1.948	0.040	1098	14	0.186	0.002	1100	8	0.00
ADN109-34	12.795	0.184	1151	29	2.118	0.035	1155	11	0.197	0.002	1157	8	0.00
ADN109-35	5.155	0.051	2776	16	14.244	0.198	2766	13	0.533	0.005	2752	22	0.88
ADN109-36	11.463	0.169	1366	28	2.679	0.123	1323	34	0.223	0.010	1296	51	5.08
ADN109-37	5.249	0.070	2747	22	13.826	0.423	2738	29	0.526	0.014	2726	61	0.76
ADN109-38	13.055	0.132	1111	20	1.966	0.025	1104	9	0.186	0.001	1101	8	0.91
ADN109-39	12.664	0.135	1171	21	2.152	0.055	1166	18	0.198	0.005	1163	25	0.73
ADN109-40	12.840	0.285	1144	44	2.108	0.062	1152	20	0.196	0.004	1156	21	0.00
ADN109-41	13.651	0.453	1021	67	1.807	0.065	1048	24	0.179	0.003	1061	14	0.00

Analysis	$^{206}\text{Pb}/^{207}\text{Pb}$				$^{207}\text{Pb}/^{235}\text{U}$				$^{206}\text{Pb}/^{238}\text{U}$				%Disc.
	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	Ratio 2 σ	$\pm$	Age 2 σ	$\pm$	
ADN109-42	11.853	0.225	1301	37	2.596	0.083	1300	24	0.223	0.006	1299	30	0.18
ADN109-43	13.226	0.220	1085	33	1.884	0.037	1075	13	0.181	0.002	1071	11	1.30
ADN109-44	13.191	0.298	1090	45	1.964	0.052	1103	18	0.188	0.003	1110	14	0.00
ADN109-45	10.803	0.253	1479	44	3.293	0.083	1479	20	0.258	0.002	1479	12	0.00
ADN109-46	6.035	0.103	2515	29	10.704	0.228	2498	20	0.469	0.006	2477	26	1.50
ADN109-47	12.494	0.240	1198	38	2.224	0.057	1188	18	0.201	0.003	1183	18	1.23
ADN109-48	13.618	0.349	1026	52	1.754	0.057	1029	21	0.173	0.003	1030	19	0.00
ADN109-49	13.255	0.170	1080	26	1.864	0.041	1068	15	0.179	0.003	1062	18	1.66
ADN109-50	13.090	0.180	1105	27	1.928	0.036	1091	12	0.183	0.002	1084	12	1.97
ADN10-51	13.511	0.297	1042	44	1.836	0.057	1058	20	0.180	0.004	1067	22	0.00
ADN10-52	13.346	0.464	1067	70	1.775	0.078	1036	29	0.172	0.005	1022	26	4.16
ADN10-53	11.184	0.460	1413	79	2.528	0.115	1280	33	0.205	0.004	1202	22	14.92
ADN10-54	13.150	0.417	1096	64	1.952	0.098	1099	34	0.186	0.007	1101	40	0.00
ADN10-55	12.859	0.381	1141	59	2.139	0.066	1162	21	0.200	0.002	1173	10	0.00
ADN10-56	11.626	0.240	1338	40	2.775	0.075	1349	20	0.234	0.004	1355	22	0.00
ADN10-57	13.229	0.219	1084	33	1.921	0.075	1088	26	0.184	0.006	1090	35	0.00
ADN10-58	11.828	0.569	1305	94	2.631	0.134	1309	38	0.226	0.004	1312	20	0.00
ADN10-59	13.223	0.136	1085	21	1.847	0.057	1062	20	0.177	0.005	1051	28	3.15
ADN10-60	10.956	0.296	1452	51	3.214	0.145	1461	35	0.255	0.009	1466	48	0.00
ADN10-61	11.094	0.134	1429	23	3.050	0.078	1420	19	0.245	0.005	1415	28	0.98
ADN10-62	13.203	0.348	1088	53	1.974	0.086	1107	29	0.189	0.007	1116	36	0.00
ADN10-63	10.846	0.156	1471	27	3.312	0.113	1484	27	0.261	0.008	1492	41	0.00
ADN10-64	13.653	0.580	1021	86	1.837	0.098	1059	35	0.182	0.006	1077	32	0.00
ADN10-65	13.455	0.256	1050	38	1.840	0.091	1060	33	0.180	0.008	1065	45	0.00
ADN10-66	5.783	0.075	2586	22	11.878	0.380	2595	30	0.498	0.015	2606	63	0.00
ADN10-67	13.491	0.361	1045	54	1.878	0.053	1073	19	0.184	0.002	1087	9	0.00
ADN10-68	12.877	0.277	1138	43	2.086	0.046	1144	15	0.195	0.001	1148	5	0.00
ADN10-69	11.996	0.382	1278	62	2.532	0.087	1281	25	0.220	0.003	1283	15	0.00
ADN10-70	10.836	0.299	1473	52	3.387	0.121	1501	28	0.266	0.006	1521	31	0.00

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	
ADN10-71	12.417	0.297	1210	47	2.312	0.057	1216	18	0.208	0.001	1219	8	0.00
ADN10-72	11.702	0.302	1326	50	2.712	0.093	1332	25	0.230	0.005	1335	27	0.00
ADN10-73	12.895	0.195	1135	30	2.050	0.039	1132	13	0.192	0.002	1131	12	0.42
ADN10-74	14.001	0.605	969	88	1.682	0.083	1002	31	0.171	0.004	1016	22	0.00
ADN10-75	12.482	0.202	1200	32	2.306	0.050	1214	15	0.209	0.003	1222	16	0.00
ADN10-76	11.926	0.217	1289	35	2.469	0.047	1263	14	0.214	0.001	1248	7	3.21
ADN10-77	9.611	0.132	1698	25	4.317	0.081	1697	15	0.301	0.004	1696	19	0.11
ADN10-78	13.334	0.120	1068	18	1.828	0.020	1056	7	0.177	0.001	1049	6	1.77
ADN10-79	13.654	0.387	1021	57	1.776	0.075	1037	27	0.176	0.005	1045	30	0.00
ADN10-80	13.039	0.186	1113	28	1.993	0.041	1113	14	0.188	0.003	1113	15	0.01
ADN10-81	13.422	0.510	1055	77	1.970	0.076	1105	26	0.192	0.001	1131	7	0.00
ADN10-82	13.600	0.277	1029	41	1.773	0.042	1036	15	0.175	0.002	1039	12	0.00
ADN10-83	12.318	0.260	1226	41	2.352	0.050	1228	15	0.210	0.001	1229	3	0.00
ADN10-84	5.242	0.129	2749	41	14.187	0.375	2762	25	0.539	0.005	2781	21	0.00
ADN10-85	13.481	0.308	1046	46	1.843	0.043	1061	15	0.180	0.001	1068	5	0.00
ADN10-86	13.938	0.658	979	96	1.759	0.085	1030	31	0.178	0.002	1055	9	0.00
ADN10-87	13.457	0.181	1050	27	1.856	0.027	1066	9	0.181	0.001	1073	5	0.00
ADN10-88	5.234	0.075	2751	24	14.078	0.227	2755	15	0.534	0.004	2760	16	0.00
ADN10-89	11.016	0.099	1442	17	3.087	0.038	1430	9	0.247	0.002	1421	11	1.44
ADN10-90	13.594	0.210	1029	31	1.788	0.030	1041	11	0.176	0.001	1047	6	0.00
ADN10-91	12.836	0.148	1144	23	2.106	0.032	1151	11	0.196	0.002	1154	11	0.00
ADN10-92	13.751	0.239	1006	35	1.757	0.034	1030	13	0.175	0.002	1041	9	0.00
ADN10-93	13.292	0.420	1075	63	1.946	0.064	1097	22	0.188	0.002	1108	8	0.00
ADN10-94	13.361	0.177	1064	27	1.834	0.030	1058	11	0.178	0.002	1055	9	0.90
ADN10-95	13.005	0.202	1118	31	2.050	0.034	1132	11	0.193	0.001	1139	6	0.00
ADN10-96	12.296	0.130	1229	21	2.316	0.037	1217	11	0.206	0.002	1210	13	1.57
ADN10-97	13.467	0.108	1048	16	1.816	0.024	1051	9	0.177	0.002	1052	10	0.00
ADN10-98	13.269	0.191	1078	29	1.896	0.035	1080	12	0.182	0.002	1080	11	0.00
ADN10-99	12.732	0.119	1161	19	2.129	0.033	1158	11	0.197	0.002	1157	13	0.31

Analysis	²⁰⁶ Pb/ ²⁰⁷ Pb				²⁰⁷ Pb/ ²³⁵ U				²⁰⁶ Pb/ ²³⁸ U				%Disc.	
	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±	Ratio 2σ	±	Age 2σ	±		
ADN10-100	13.606		0.263	1028	39	1.731	0.043	1020	16	0.171	0.003	1016	15	1.10

Appendix E: Paleoflow data

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
1	Keeseville	A3	FA4	Subaq. dune x-bed	210
1	Keeseville	A3	FA4	Subaq. dune x-bed	235
1	Keeseville	A3	FA4	Subaq. dune x-bed	250
3	Keeseville	A3	FA4	Aeolian dune	275
3	Keeseville	A3	FA4	Subaq. dune x-bed	130
3	Keeseville	A3	FA4	Subaq. dune x-bed	165
5	Keeseville	A3	FA4	Subaq. dune x-bed	220
7	Keeseville	A3	FA4	Subaq. dune x-bed	210
7	Keeseville	A3	FA4	Subaq. dune x-bed	212
7	Keeseville	A3	FA4	Subaq. dune x-bed	194
7	Keeseville	A3	FA4	Subaq. dune x-bed	223
7	Keeseville	A3	FA4	Subaq. dune x-bed	215
7	Keeseville	A3	FA4	Subaq. dune x-bed	202
7	Keeseville	A3	FA4	C. Rip	200
7	Keeseville	A3	FA4	Adhesion ripples	270
7	Keeseville	A3	FA4	C. Rip	220
7	Keeseville	A3	FA4	Subaq. dune x-bed	220
7	Keeseville	A3	FA4	Subaq. dune x-bed	75
8	Keeseville	A3	FA5	Subaq. dune x-bed	230
8	Keeseville	A3	FA5	Subaq. dune x-bed	220
8	Keeseville	A3	FA5	Subaq. dune x-bed	210
8	Keeseville	A3	FA5	Subaq. dune x-bed	190
8	Keeseville	A3	FA5	Subaq. dune x-bed	215
8	Keeseville	A3	FA5	Subaq. dune x-bed	180
8	Keeseville	A3	FA5	Subaq. dune x-bed	170
8	Keeseville	A3	FA5	Subaq. dune x-bed	150
8	Keeseville	A3	FA5	Subaq. dune x-bed	115
8	Keeseville	A3	FA5	Subaq. dune x-bed	125
9	Keeseville	A3	FA5	Subaq. dune x-bed	145
9	Keeseville	A3	FA5	Subaq. dune x-bed	230
9	Keeseville	A3	FA5	Subaq. dune x-bed	220
9	Keeseville	A3	FA5	Subaq. dune x-bed	210
9	Keeseville	A3	FA5	Subaq. dune x-bed	190
9	Keeseville	A3	FA5	Subaq. dune x-bed	215
9	Keeseville	A3	FA5	Subaq. dune x-bed	180
9	Keeseville	A3	FA5	Subaq. dune x-bed	170
9	Keeseville	A3	FA5	Subaq. dune x-bed	150
11	Keeseville	A3	FA5	Subaq. dune x-bed	235
11	Theresa			Subaq. dune x-bed	250

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
12	Ausable	A1	FA1	imbrication	31
12	Ausable	A1	FA1	imbrication	166
12	Ausable	A1	FA1	imbrication	255
12	Ausable	A1	FA1	imbrication	195
12	Ausable	A1	FA1	imbrication	210
12	Ausable	A1	FA1	imbrication	245
12	Ausable	A1	FA1	unit bar	5
12	Ausable	A1	FA1	imbrication	250
12	Ausable	A1	FA1	imbrication	215
12	Ausable	A1	FA1	imbrication	190
12	Ausable	A1	FA1	Subaq. dune x-bed	150
16	Keeseville	A2	FA1	Subaq. dune x-bed	170
16	Keeseville	A2	FA1	Subaq. dune x-bed	160
16	Keeseville	A2	FA1	Subaq. dune x-bed	195
16	Keeseville	A2	FA1	Subaq. dune x-bed	325
16	Keeseville	A2	FA1	Subaq. dune x-bed	175
16	Keeseville	A2	FA1	imbrication	170
16	Keeseville	A2	FA1	imbrication	170
16	Keeseville	A2	FA1	imbrication	150
16	Keeseville	A2	FA1	imbrication	160
16	Keeseville	A2	FA1	imbrication	150
16	Keeseville	A3	FA5	Subaq. dune x-bed	95
16	Keeseville	A3	FA5	Subaq. dune x-bed	95
16	Keeseville	A3	FA5	Subaq. dune x-bed	145
16	Keeseville	A3	FA5	Subaq. dune x-bed	130
16	Keeseville	A3	FA5	Subaq. dune x-bed	100
16	Keeseville	A3	FA5	Subaq. dune x-bed	160
16	Keeseville	A3	FA5	Subaq. dune x-bed	155
16	Keeseville	A3	FA5	Subaq. dune x-bed	95
16	Keeseville	A3	FA5	Subaq. dune x-bed	60
16	Keeseville	A3	FA5	Subaq. dune x-bed	180
16	Keeseville	A3	FA5	Subaq. dune x-bed	165
18	Keeseville	A2	FA1	Subaq. dune x-bed	195
18	Keeseville	A2	FA1	Subaq. dune x-bed	210
18	Keeseville	A2	FA1	Subaq. dune x-bed	175
18	Keeseville	A2	FA1	Subaq. dune x-bed	190
18	Keeseville	A2	FA1	Subaq. dune x-bed	195
18	Keeseville	A2	FA1	Subaq. dune x-bed	200
18	Keeseville	A2	FA1	Subaq. dune x-bed	165
18	Keeseville	A2	FA5	Subaq. dune x-bed	170
18	Keeseville	A2	FA5	Subaq. dune x-bed	210
18	Keeseville	A2	FA5	Subaq. dune x-bed	215
18	Keeseville	A3	FA1	Subaq. dune x-bed	180
18	Keeseville	A3	FA1	Subaq. dune x-bed	215

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
18	Keeseville	A3	FA1	Subaq. dune x-bed	220
18	Keeseville	A3	FA1	Subaq. dune x-bed	130
18	Keeseville	A3	FA1	Subaq. dune x-bed	90
18	Keeseville	A3	FA1	Subaq. dune x-bed	60
18	Keeseville	A3	FA1	Subaq. dune x-bed	225
18	Keeseville	A3	FA1	Subaq. dune x-bed	230
18	Keeseville	A3	FA1	Subaq. dune x-bed	108
20	Keeseville	A3	FA2/FA4	Subaq. dune x-bed	325
20	Keeseville	A3	FA2/FA4	Subaq. dune x-bed	290
20	Keeseville	A3	FA2/FA4	C. Rip	0
20	Keeseville	A3	FA2/FA4	Subaq. dune x-bed	130
20	Keeseville	A3	FA2/FA4	Subaq. dune x-bed	260
20	Keeseville	A3	FA2/FA4	Subaq. dune x-bed	120
20	Keeseville	A3	FA5	C. Rip	245
20	Keeseville	A3	FA5	C. Rip	280
22	Keeseville	A2	FA1	Subaq. dune x-bed	290
22	Keeseville	A2	FA1	Subaq. dune x-bed	285
22	Keeseville	A2	FA1	Subaq. dune x-bed	345
22	Keeseville	A2	FA1	Subaq. dune x-bed	295
22	Keeseville	A2	FA1	Subaq. dune x-bed	280
22	Keeseville	A2	FA1	Subaq. dune x-bed	340
22	Keeseville	A2	FA1	Subaq. dune x-bed	270
22	Keeseville	A2	FA1	Subaq. dune x-bed	285
22	Keeseville	A2	FA1	Subaq. dune x-bed	350
22	Keeseville	A2	FA1	Subaq. dune x-bed	300
22	Keeseville	A2	FA1	Subaq. dune x-bed	270
22	Keeseville	A2	FA1	Subaq. dune x-bed	325
22	Keeseville	A2	FA2	C. Rip	315
22	Keeseville	A2	FA2	C. Rip	285
26	Hannawa Falls	A1	FA3	Aeolian dune	205
26	Hannawa Falls	A1	FA3	Aeolian dune	225
27	Hannawa Falls	A1	FA3	Aeolian dune	130
27	Keeseville	A2	FA2	C. Rip	205
27	Keeseville	A2	FA2	C. Rip	215
27	Hannawa Falls	A1	FA3	Aeolian dune	130
27	Keeseville	A3	FA5	Subaq. dune x-bed	215
27	Hannawa Falls	A1	FA3	Aeolian dune	130
28	Hannawa Falls	A1	FA2	C. Rip	265
28	Hannawa Falls	A1	FA2	C. Rip	285
28	Hannawa Falls	A1	FA2	C. Rip	265
28	Keeseville	A2	FA2	imbrication	45
28	Keeseville	A2	FA2	imbrication	33
28	Keeseville	A2	FA2	imbrication	36
28	Keeseville	A2	FA2	imbrication	70

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
28	Keeseville	A2	FA2	imbrication	10
28	Hannawa Falls	A1	FA2	Subaq. dune x-bed	130
28	Hannawa Falls	A1	FA2	Subaq. dune x-bed	150
28	Hannawa Falls	A1	FA3	Aeolian dune	190
28	Hannawa Falls	A1	FA3	Aeolian dune	130
29	Hannawa Falls	A1	FA3	Aeolian dune	240
31	Keeseville	A3	FA5	Subaq. dune x-bed	120
31	Keeseville	A3	FA5	Subaq. dune x-bed	310
31	Keeseville	A3	FA5	Subaq. dune x-bed	280
34	Keeseville	A2	FA1/FA2?	Subaq. dune x-bed	180
34	Keeseville	A2	FA1/FA2?	Subaq. dune x-bed	190
34	Keeseville	A2	FA1/FA2?	Subaq. dune x-bed	185
34	Keeseville	A2	FA1/FA2?	Subaq. dune x-bed	165
34	Keeseville	A3	FA5	Subaq. dune x-bed	160
34	Keeseville	A3	FA5	Subaq. dune x-bed	180
34	Keeseville	A3	FA5	Subaq. dune x-bed	155
34	Keeseville	A3	FA5	Subaq. dune x-bed	145
34	Keeseville	A3	FA5	Subaq. dune x-bed	145
34	Keeseville	A3	FA5	Subaq. dune x-bed	180
36	Keeseville	A2	FA1	Subaq. dune x-bed	200
36	Keeseville	A3	FA5	Subaq. dune x-bed	140
36	Keeseville	A3	FA5	Subaq. dune x-bed	155
36	Keeseville	A3	FA5	Subaq. dune x-bed	180
37	Keeseville	A3	FA5	Subaq. dune x-bed	120
37	Keeseville	A3	FA5	Subaq. dune x-bed	60
37	Keeseville	A3	FA5	Subaq. dune x-bed	60
37	Keeseville	A3	FA5	C. Rip	200
41	Hannawa Falls	A1	FA2	Aeolian dune	285
41	Hannawa Falls	A1	FA2	Aeolian dune	255
41	Hannawa Falls	A1	FA2	Aeolian dune	275
40	Keeseville	A3	FA5	C. Rip	250
42	Keeseville	A3	FA5	C. Rip	145
42	Keeseville	A3	FA5	C. Rip	120
42	Keeseville	A3	FA5	Subaq. dune x-bed	130
42	Keeseville	A3	FA5	Subaq. dune x-bed	140
42	Keeseville	A3	FA5	Subaq. dune x-bed	150
44	Keeseville	A3	FA4	C. Rip	125
44	Keeseville	A3	FA4	C. Rip	160
44	Keeseville	A3	FA4	C. Rip	125
44	Keeseville	A3	FA4	Subaq. dune x-bed	110
44	Keeseville	A3	FA4	Subaq. dune x-bed	30
44	Keeseville	A3	FA4	Subaq. dune x-bed	180
44	Keeseville	A3	FA4	Subaq. dune x-bed	65
44	Keeseville	A3	FA4	Subaq. dune x-bed	10

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
44	Keeseville	A3	FA4	Subaq. dune x-bed	190
53	Hannawa Falls	A1	FA2	Aeolian dune	155
51	Keeseville	A3	FA5	Subaq. dune x-bed	205
51	Keeseville	A3	FA5	Subaq. dune x-bed	120
54	Keeseville	A2	FA1	imbrication	125
54	Keeseville	A2	FA1	imbrication	175
54	Keeseville	A2	FA1	imbrication	185
54	Keeseville	A2	FA1	imbrication	200
54	Keeseville	A2	FA1	Subaq. dune x-bed	285
54	Keeseville	A2	FA1	imbrication	165
54	Keeseville	A2	FA1	imbrication	155
54	Keeseville	A2	FA1	imbrication	160
54	Keeseville	A2	FA1	imbrication	165
54	Keeseville	A2	FA1	imbrication	215
54	Keeseville	A2	FA1	imbrication	215
54	Keeseville	A2	FA1	Subaq. dune x-bed	210
55	Keeseville	A2	FA1	imbrication	210
55	Keeseville	A2	FA1	imbrication	235
55	Keeseville	A2	FA1	imbrication	175
55	Keeseville	A2	FA1	imbrication	255
55	Keeseville	A2	FA1	imbrication	230
55	Keeseville	A2	FA1	imbrication	230
55	Keeseville	A2	FA1	imbrication	150
55	Keeseville	A2	FA1	imbrication	225
55	Keeseville	A2	FA1	imbrication	145
55	Keeseville	A2	FA1	imbrication	190
55	Keeseville	A2	FA1	imbrication	185
55	Keeseville	A2	FA1	Subaq. dune x-bed	110
55	Keeseville	A2	FA1	imbrication	200
55	Keeseville	A2	FA1	Subaq. dune x-bed	180
55	Keeseville	A2	FA1	imbrication	140
55	Keeseville	A2	FA1	imbrication	175
55	Keeseville	A2	FA1	imbrication	160
57	Keeseville	A2	FA1	imbrication	185
57	Keeseville	A2	FA1	imbrication	165
57	Keeseville	A2	FA1	imbrication	170
57	Keeseville	A2	FA1	imbrication	170
57	Keeseville	A2	FA1	imbrication	150
57	Keeseville	A2	FA1	imbrication	170
57	Keeseville	A2	FA1	Subaq. dune x-bed	230
57	Keeseville	A2	FA1	Subaq. dune x-bed	210
57	Keeseville	A2	FA1	Subaq. dune x-bed	205
57	Keeseville	A2	FA1	Subaq. dune x-bed	205
58	Keeseville	A2	FA1	Subaq. dune x-bed	100

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
58	Keeseville	A2	FA1	imbrication	205
58	Keeseville	A2	FA1	imbrication	205
58	Keeseville	A2	FA1	imbrication	195
58	Keeseville	A2	FA1	imbrication	195
58	Keeseville	A2	FA1	imbrication	185
58	Keeseville	A2	FA1	Subaq. dune x-bed	215
59	Keeseville	A2	FA1	Subaq. dune x-bed	225
59	Keeseville	A2	FA1	Subaq. dune x-bed	230
61	Keeseville	A3	FA5	Subaq. dune x-bed	155
61	Keeseville	A3	FA5	Subaq. dune x-bed	90
61	Keeseville	A3	FA5	Subaq. dune x-bed	100
61	Keeseville	A3	FA5	Subaq. dune x-bed	183
61	Keeseville	A3	FA5	Subaq. dune x-bed	5 or 185(?)
62	Keeseville	A3	FA5	Subaq. dune x-bed	135
63	Keeseville	A3	FA5	Subaq. dune x-bed	5
63	Keeseville	A3	FA5	Subaq. dune x-bed	280
63	Keeseville	A3	FA5	Subaq. dune x-bed	340
63	Keeseville	A3	FA5	Subaq. dune x-bed	275
63	Keeseville	A3	FA5	Subaq. dune x-bed	135
64	Keeseville	A3	FA5	Subaq. dune x-bed	135
70	Keeseville	A3	FA5	Subaq. dune x-bed	190
70	Keeseville	A3	FA5	Subaq. dune x-bed	175
70	Keeseville	A3	FA5	Subaq. dune x-bed	205
70	Keeseville	A3	FA5	Subaq. dune x-bed	185
70	Keeseville	A3	FA5	Subaq. dune x-bed	205
70	Keeseville	A3	FA5	Subaq. dune x-bed	190
70	Keeseville	A3	FA5	Subaq. dune x-bed	300
74	Keeseville	A3	FA5	Subaq. dune x-bed	115
75	Hannawa Falls	A1	FA2	Aeolian dune	180
76	Keeseville	A2	FA2	C. Rip	150
76	Keeseville	A2	FA2	C. Rip	190
81	Keeseville	A2	FA2	Supercrit. xstrat	220
85	Keeseville	A2	FA2	Subaq. dune x-bed	20
85	Keeseville	A2	FA2	Subaq. dune x-bed	35
85	Keeseville	A2	FA2	Subaq. dune x-bed	15
85	Keeseville	A2	FA2	Supercrit. xstrat	200
85	Keeseville	A2	FA2	Subaq. dune x-bed	50
85	Keeseville	A2	FA2	Subaq. dune x-bed	320
85	Keeseville	A2	FA2	Subaq. dune x-bed	40
85	Keeseville	A2	FA2	Supercrit. xstrat	180
85	Keeseville	A2	FA2	Supercrit. xstrat	205
85	Keeseville	A2	FA2	Supercrit. xstrat	200
85	Keeseville	A2	FA2	Supercrit. xstrat	180
85	Keeseville	A2	FA2	Supercrit. xstrat	145

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
85	Keeseville	A2	FA2	Supercrit. xstrat	180
85	Keeseville	A2	FA1	Confluence scour	320
85	Keeseville	A2	FA1	Subaq. dune x-bed	345
85	Keeseville	A2	FA1	Subaq. dune x-bed	315
85	Keeseville	A2	FA1	Subaq. dune x-bed	20
85	Keeseville	A2	FA1	Subaq. dune x-bed	35
85	Keeseville	A2	FA1	Subaq. dune x-bed	15
87	Keeseville	A2	FA2	Supercrit. xstrat	230
87	Keeseville	A2	FA2	Supercrit. xstrat	210
87	Keeseville	A2	FA2	Supercrit. xstrat	190
87	Keeseville	A3	FA5	Subaq. dune x-bed	230
87	Keeseville	A3	FA5	C. Rip	90 to 40
87	Keeseville	A3	FA5	C. Rip	135
87	Keeseville	A3	FA5	Subaq. dune x-bed	NE to N
88	Keeseville	A3	FA5	Subaq. dune x-bed	320
88	Keeseville	A3	FA5	Subaq. dune x-bed	120
95	Keeseville	A2	FA2	Supercrit. xstrat	240
95	Keeseville	A2	FA2	Subaq. dune x-bed	0
95	Keeseville	A2	FA2	Subaq. dune x-bed	355
96	Keeseville	A2	FA2	Supercrit. xstrat	220
96	Keeseville	A2	FA2	Supercrit. xstrat	245
96	Keeseville	A2	FA2	Supercrit. xstrat	210
100	Keeseville	A2	FA2	Supercrit. xstrat	230
100	Keeseville	A2	FA2	Supercrit. xstrat	225
100	Keeseville	A2	FA2	Supercrit. xstrat	170
100	Keeseville	A2	FA2	Supercrit. xstrat	210
100	Keeseville	A2	FA2	Supercrit. xstrat	235
100	Keeseville	A2	FA1	Subaq. dune x-bed	25
100	Keeseville	A2	FA1	Subaq. dune x-bed	15
100	Keeseville	A2	FA1	Subaq. dune x-bed	355
100	Keeseville	A2	FA1	Subaq. dune x-bed	22
100	Keeseville	A2	FA1	Subaq. dune x-bed	335
100	Keeseville	A2	FA1	Subaq. dune x-bed	45
102	Keeseville	A2	FA2	Supercrit. xstrat	130
102	Keeseville	A2	FA2	Supercrit. xstrat	145
102	Keeseville	A2	FA2	Subaq. dune x-bed	230
102	Keeseville	A2	FA2	imbrication	285
102	Keeseville	A2	FA2	Subaq. dune x-bed	310
102	Keeseville	A2	FA2	Subaq. dune x-bed	240
102	Keeseville	A2	FA2	Subaq. dune x-bed	340
102	Keeseville	A2	FA2	Subaq. dune x-bed	280
104	Keeseville	A2	FA2	C. Rip	230
104	Keeseville	A2	FA2	C. Rip	245
104	Keeseville	A2	FA2	Subaq. dune x-bed	245

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
104	Keeseville	A2	FA2	Subaq. dune x-bed	40
104	Keeseville	A3	FA5	Subaq. dune x-bed	235
104	Keeseville	A3	FA5	Subaq. dune x-bed	240
108	Keeseville	A2	FA2	Subaq. dune x-bed	325
108	Keeseville	A2	FA2	Subaq. dune x-bed	315
108	Keeseville	A2	FA2	Subaq. dune x-bed	330
108	Keeseville	A2	FA2	Subaq. dune x-bed	335
109	Keeseville	A2	FA2	Subaq. dune x-bed	290
109	Keeseville	A2	FA2	Subaq. dune x-bed	295
109	Keeseville	A2	FA2	Subaq. dune x-bed	310
110	Keeseville	A2	FA2	Subaq. dune x-bed	215
110	Keeseville	A2	FA2	Supercrit. xstrat	125
115	Keeseville	A2	FA1	Subaq. dune x-bed	240
115	Keeseville	A2	FA1	Subaq. dune x-bed	255
115	Keeseville	A2	FA1	Subaq. dune x-bed	185
115	Keeseville	A2	FA1	Subaq. dune x-bed	250
115	Keeseville	A2	FA1	Subaq. dune x-bed	210
115	Keeseville	A2	FA1	Subaq. dune x-bed	160
115	Keeseville	A2	FA1	Subaq. dune x-bed	255
115	Keeseville	A2	FA1	Subaq. dune x-bed	200
115	Keeseville	A2	FA2	Supercrit. xstrat	135
115	Keeseville	A2	FA2	Supercrit. xstrat	185
115	Keeseville	A2	FA1	Subaq. dune x-bed	230
115	Keeseville	A2	FA1	Subaq. dune x-bed	220
115	Keeseville	A2	FA1	Subaq. dune x-bed	175
115	Keeseville	A2	FA1	Subaq. dune x-bed	245
115	Keeseville	A2	FA1	Subaq. dune x-bed	280
115	Keeseville	A2	FA1	Subaq. dune x-bed	255
115	Keeseville	A2	FA1	Subaq. dune x-bed	260
115	Keeseville	A2	FA1	Subaq. dune x-bed	265
117	Keeseville	A2	FA1	imbrication	265
117	Keeseville	A2	FA1	imbrication	295
117	Keeseville	A2	FA1	imbrication	270
117	Keeseville	A2	FA1	imbrication	265
117	Keeseville	A2	FA1	imbrication	290
117	Keeseville	A2	FA1	imbrication	255
117	Keeseville	A2	FA1	imbrication	285
117	Keeseville	A2	FA1	imbrication	300
117	Keeseville	A2	FA1	imbrication	340
117	Keeseville	A2	FA1	imbrication	270
117	Keeseville	A2	FA1	Unit Bar	340
117	Keeseville	A2	FA1	Unit Bar	355
117	Keeseville	A2	FA1	imbrication	295
117	Keeseville	A2	FA1	imbrication	295

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
117	Keeseville	A3	FA5	C. Rip	80
118	Keeseville	A2	FA1	Subaq. dune x-bed	255
118	Keeseville	A2	FA1	Subaq. dune x-bed	265
118	Keeseville	A2	FA1	Subaq. dune x-bed	275
118	Keeseville	A2	FA1	Subaq. dune x-bed	290
118	Keeseville	A2	FA1	Subaq. dune x-bed	290
118	Keeseville	A2	FA1	Subaq. dune x-bed	280
118	Keeseville	A2	FA1	Subaq. dune x-bed	285
118	Keeseville	A2	FA1	Subaq. dune x-bed	345
118	Keeseville	A2	FA1	Subaq. dune x-bed	275
118	Keeseville	A2	FA1	Subaq. dune x-bed	285
118	Keeseville	A2	FA1	Subaq. dune x-bed	280
118	Keeseville	A2	FA1	Subaq. dune x-bed	300
118	Keeseville	A2	FA1	Subaq. dune x-bed	340
118	Keeseville	A2	FA1	Subaq. dune x-bed	335
118	Keeseville	A2	FA1	Subaq. dune x-bed	5
118	Keeseville	A2	FA1	Subaq. dune x-bed	270
118	Keeseville	A2	FA1	Subaq. dune x-bed	345
124	Keeseville	A2	FA2	Supercrit. xstrat	110
127	Keeseville	A2	FA1	Subaq. dune x-bed	315
137	Keeseville	A2/A3?	FA2	Supercrit. xstrat	25
137	Keeseville	A2/A3?	FA2	Supercrit. xstrat	20
139	Ausable	A1	FA1	Subaq. dune x-bed	50
139	Ausable	A1	FA1	Subaq. dune x-bed	95
139	Ausable	A1	FA1	Subaq. dune x-bed	80
139	Ausable	A1	FA1	Subaq. dune x-bed	85
139	Ausable	A1	FA1	Subaq. dune x-bed	75
139	Ausable	A1	FA1	Subaq. dune x-bed	85
139	Ausable	A1	FA1	Subaq. dune x-bed	80
139	Ausable	A1	FA1	Subaq. dune x-bed	140
139	Ausable	A1	FA1	Subaq. dune x-bed	135
144	Ausable	A1	FA1	Subaq. dune x-bed	110
144	Ausable	A1	FA1	Subaq. dune x-bed	102
144	Ausable	A1	FA1	Subaq. dune x-bed	83
144	Ausable	A1	FA1	Subaq. dune x-bed	94
144	Ausable	A1	FA1	Subaq. dune x-bed	130
144	Ausable	A1	FA1	Subaq. dune x-bed	165
144	Ausable	A1	FA1	Subaq. dune x-bed	155
144	Ausable	A1	FA1	Subaq. dune x-bed	135
144	Ausable	A1	FA1	Subaq. dune x-bed	145
144	Ausable	A1	FA1	Subaq. dune x-bed	150
145	Keeseville	A2	FA1	Subaq. dune x-bed	140
145	Keeseville	A2	FA1	Subaq. dune x-bed	125
145	Keeseville	A2	FA1	Subaq. dune x-bed	143

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
145	Keeseville	A2	FA1	Subaq. dune x-bed	140
145	Keeseville	A2	FA1	Subaq. dune x-bed	105
145	Keeseville	A2	FA1	Subaq. dune x-bed	110
145	Keeseville	A2	FA1	Subaq. dune x-bed	123
145	Keeseville	A2	FA1	Subaq. dune x-bed	119
145	Keeseville	A2	FA1	Subaq. dune x-bed	~SW
145	Keeseville	A2	FA1	Subaq. dune x-bed	120
145	Keeseville	A2	FA1	Subaq. dune x-bed	120
145	Keeseville	A2	FA1	Subaq. dune x-bed	115
145	Keeseville	A2	FA1	Subaq. dune x-bed	140
146	Keeseville	A3	FA2	Subaq. dune x-bed	110
146	Keeseville	A3	FA2	Subaq. dune x-bed	90
146	Keeseville	A3	FA2	Subaq. dune x-bed	100
146	Keeseville	A3	FA2	Wave rip. crest	20-200
146	Keeseville	A3	FA2	Wave rip. crest	20-200
148	Keeseville	A3	FA2	Supercrit. xstrat	35
148	Keeseville	A3	FA2	Supercrit. xstrat	65
148	Keeseville	A3	FA2	Supercrit. xstrat	15
152	Keeseville	A3	FA2	Wave rip. crest	5-185
152	Keeseville	A3	FA2	Subaq. dune x-bed	165
152	Keeseville	A3	FA2	Subaq. dune x-bed	195
152	Keeseville	A3	FA2	Subaq. dune x-bed	170
152	Keeseville	A3	FA2	Wave rip. crest	5-185
152	Keeseville	A3	FA2	Supercrit. xstrat	355
152	Keeseville	A3	FA2	Supercrit. xstrat	323
152	Keeseville	A3	FA2	Supercrit. xstrat	15
152	Keeseville	A3	FA2	Supercrit. xstrat	27
152	Keeseville	A3	FA2	C. Rip	188
152	Keeseville	A3	FA2	Subaq. dune x-bed	123
152	Keeseville	A3	FA2	Subaq. dune x-bed	172
152	Keeseville	A3	FA2	Subaq. dune x-bed	190
152	Keeseville	A3	FA2	C. Rip	150
152	Keeseville	A3	FA2	Supercrit. xstrat	335
153	Keeseville	A2	FA1	Subaq. dune x-bed	10
153	Keeseville	A2	FA1	Subaq. dune x-bed	12
153	Keeseville	A2	FA1	Subaq. dune x-bed	25
153	Keeseville	A2	FA1	Subaq. dune x-bed	7
153	Keeseville	A2	FA1	Subaq. dune x-bed	6
153	Keeseville	A2	FA1	Subaq. dune x-bed	4
153	Keeseville	A2	FA1	Subaq. dune x-bed	5
154	Ausable	A1	FA1	Subaq. dune x-bed	121
154	Ausable	A1	FA1	Subaq. dune x-bed	125
154	Ausable	A1	FA1	Subaq. dune x-bed	115
154	Ausable	A1	FA1	Subaq. dune x-bed	160

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
154	Ausable	A1	FA1	Subaq. dune x-bed	135
154	Ausable	A1	FA1	Subaq. dune x-bed	55
154	Ausable	A1	FA1	Subaq. dune x-bed	115
154	Ausable	A1	FA1	Subaq. dune x-bed	117
154	Ausable	A1	FA1	Subaq. dune x-bed	125
154	Ausable	A1	FA1	Subaq. dune x-bed	145
154	Ausable	A1	FA1	Subaq. dune x-bed	140
154	Ausable	A1	FA1	Subaq. dune x-bed	115
154	Ausable	A1	FA1	Subaq. dune x-bed	150
154	Ausable	A1	FA1	Subaq. dune x-bed	125
154	Ausable	A1	FA1	Subaq. dune x-bed	120
154	Ausable	A1	FA1	Subaq. dune x-bed	145
154	Ausable	A1	FA1	Subaq. dune x-bed	125
154	Ausable	A1	FA1	Subaq. dune x-bed	150
155	Keeseville	A2	FA1	Subaq. dune x-bed	40
155	Keeseville	A2	FA1	Subaq. dune x-bed	55
155	Keeseville	A2	FA1	Subaq. dune x-bed	35
157	Keeseville	A3	FA2	Subaq. dune x-bed	220
157	Keeseville	A3	FA2	Subaq. dune x-bed	200
158	Ausable	A1	FA1	Subaq. dune x-bed	~E
159	Keeseville	A2/A3?	FA2	Subaq. dune x-bed	~E
160	Keeseville	A3	FA2	Subaq. dune x-bed	150
160	Keeseville	A3	FA2	Subaq. dune x-bed	150
160	Keeseville	A3	FA4	Subaq. dune x-bed	160
160	Keeseville	A3	FA4	Subaq. dune x-bed	175
162	Keeseville	A2	FA1	Subaq. dune x-bed	~SE
163	Keeseville	A2	FA1	Subaq. dune x-bed	~N
164	Keeseville	A2/A3?	FA2	Subaq. dune x-bed	165
164	Keeseville	A2/A3?	FA2	C. Rip	120
167	Keeseville	A2/A3?	FA2	Supercrit. xstrat	345
167	Keeseville	A2/A3?	FA2	Subaq. dune x-bed	230
167	Keeseville	A2/A3?	FA2	Wave rip. crest	N-S
167	Keeseville	A2/A3?	FA2	Wave rip. crest	E-W
168	Keeseville	A2	FA1	Subaq. dune x-bed	325-355
168	Keeseville	A2	FA1	Subaq. dune x-bed	350
168	Keeseville	A2	FA1	Subaq. dune x-bed	260
168	Keeseville	A2	FA1	Subaq. dune x-bed	5
168	Keeseville	A2	FA1	Subaq. dune x-bed	10
168	Keeseville	A2	FA1	Subaq. dune x-bed	340
168	Keeseville	A2	FA1	Subaq. dune x-bed	295
168	Keeseville	A2	FA1	Subaq. dune x-bed	320
168	Keeseville	A2	FA2	Supercrit. xstrat	100
168	Keeseville	A2	FA2	Supercrit. xstrat	115
168	Keeseville	A2	FA2	Supercrit. xstrat	170

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
168	Keeseville	A2	FA2	Supercrit. xstrat	190
168	Keeseville	A2	FA2	Supercrit. xstrat	330
168	Keeseville	A2	FA2	Supercrit. xstrat	180
168	Keeseville	A2	FA2	Supercrit. xstrat	135
176	Keeseville	A2	FA1	Subaq. dune x-bed	75
176	Ausable	A1	FA1	Subaq. dune x-bed	50
176	Ausable	A1	FA1	Subaq. dune x-bed	80
176	Ausable	A1	FA1	Subaq. dune x-bed	40
176	Ausable	A1	FA1	Subaq. dune x-bed	55
176	Ausable	A1	FA1	Subaq. dune x-bed	35
176	Ausable	A1	FA1	Subaq. dune x-bed	80
176	Ausable	A1	FA1	Subaq. dune x-bed	85
176	Ausable	A1	FA1	Subaq. dune x-bed	70
176	Ausable	A1	FA1	Subaq. dune x-bed	100
176	Ausable	A1	FA1	Subaq. dune x-bed	55
176	Ausable	A1	FA1	Subaq. dune x-bed	100
176	Ausable	A1	FA1	Subaq. dune x-bed	60
176	Ausable	A1	FA1	Subaq. dune x-bed	70
176	Ausable	A1	FA1	Subaq. dune x-bed	45
176	Ausable	A1	FA1	Subaq. dune x-bed	55
176	Ausable	A1	FA1	Subaq. dune x-bed	75
176	Ausable	A1	FA1	Subaq. dune x-bed	190
176	Ausable	A1	FA1	Subaq. dune x-bed	125
176	Ausable	A1	FA1	Subaq. dune x-bed	100
176	Ausable	A1	FA1	Subaq. dune x-bed	105
176	Ausable	A1	FA1	Subaq. dune x-bed	105
176	Ausable	A1	FA1	Subaq. dune x-bed	115
176	Ausable	A1	FA1	Subaq. dune x-bed	100
176	Ausable	A1	FA1	Subaq. dune x-bed	110
176	Ausable	A1	FA1	Subaq. dune x-bed	90
176	Ausable	A1	FA1	Subaq. dune x-bed	20
176	Ausable	A1	FA1	Subaq. dune x-bed	80
176	Ausable	A1	FA1	Subaq. dune x-bed	60
176	Ausable	A1	FA1	Subaq. dune x-bed	40
176	Ausable	A1	FA1	Subaq. dune x-bed	100
176	Ausable	A1	FA1	Subaq. dune x-bed	80
176	Ausable	A1	FA1	Subaq. dune x-bed	85
176	Ausable	A1	FA1	Subaq. dune x-bed	60
176	Ausable	A1	FA1	Subaq. dune x-bed	70
176	Ausable	A1	FA1	Subaq. dune x-bed	65
176	Ausable	A1	FA1	Subaq. dune x-bed	80
176	Ausable	A1	FA1	Subaq. dune x-bed	60
176	Ausable	A1	FA1	Subaq. dune x-bed	85
176	Ausable	A1	FA1	Subaq. dune x-bed	95

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
176	Ausable	A1	FA1	Subaq. dune x-bed	100
176	Ausable	A1	FA1	Subaq. dune x-bed	110
176	Ausable	A1	FA1	Subaq. dune x-bed	130
176	Ausable	A1	FA1	Subaq. dune x-bed	120
176	Ausable	A1	FA1	Subaq. dune x-bed	90
176	Ausable	A1	FA1	Subaq. dune x-bed	80
176	Ausable	A1	FA1	Subaq. dune x-bed	140
176	Ausable	A1	FA1	Subaq. dune x-bed	140
176	Ausable	A1	FA1	Subaq. dune x-bed	105
176	Ausable	A1	FA1	Subaq. dune x-bed	135
176	Ausable	A1	FA1	Subaq. dune x-bed	130
176	Ausable	A1	FA1	Subaq. dune x-bed	125
176	Ausable	A1	FA1	Subaq. dune x-bed	S-SW
176	Ausable	A1	FA1	Subaq. dune x-bed	64
176	Ausable	A1	FA1	Subaq. dune x-bed	75
176	Ausable	A1	FA1	Subaq. dune x-bed	68
176	Ausable	A1	FA1	Subaq. dune x-bed	63
176	Keeseville	A2	FA1	Unit bar	75
176	Keeseville	A2	FA1	Unit bar	80
176	Keeseville	A2	FA1	Subaq. dune x-bed	65
176	Keeseville	A2	FA1	Subaq. dune x-bed	80
176	Keeseville	A2	FA1	Subaq. dune x-bed	55
176	Keeseville	A2	FA1	Subaq. dune x-bed	70
176	Keeseville	A2	FA1	Subaq. dune x-bed	72
176	Keeseville	A2	FA1	Subaq. dune x-bed	80
176	Keeseville	A2	FA1	Subaq. dune x-bed	85
176	Keeseville	A2	FA1	Subaq. dune x-bed	45
176	Keeseville	A2	FA1	Subaq. dune x-bed	50
176	Keeseville	A2	FA1	Subaq. dune x-bed	40
177	Keeseville	A2	FA1	Subaq. dune x-bed	155
177	Keeseville	A2	FA1	Subaq. dune x-bed	145
177	Keeseville	A2	FA1	Subaq. dune x-bed	145
177	Keeseville	A2	FA1	Subaq. dune x-bed	155
177	Keeseville	A2	FA1	Subaq. dune x-bed	135
177	Keeseville	A2	FA1	Subaq. dune x-bed	135
179	Ausable	A1	FA1	Subaq. dune x-bed	65
179	Ausable	A1	FA1	Subaq. dune x-bed	95
179	Ausable	A1	FA1	Subaq. dune x-bed	40
179	Ausable	A1	FA1	Subaq. dune x-bed	60
179	Ausable	A1	FA1	Subaq. dune x-bed	60
179	Ausable	A1	FA1	Subaq. dune x-bed	55
179	Ausable	A1	FA1	Subaq. dune x-bed	55
179	Ausable	A1	FA1	Subaq. dune x-bed	55
183	Ausable	A1	FA1	Subaq. dune x-bed	130

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
183	Ausable	A1	FA1	Subaq. dune x-bed	210
183	Ausable	A1	FA1	Subaq. dune x-bed	145
183	Ausable	A1	FA1	Subaq. dune x-bed	210
183	Ausable	A1	FA1	Subaq. dune x-bed	350
183	Ausable	A1	FA1	Subaq. dune x-bed	175
183	Ausable	A1	FA1	Subaq. dune x-bed	50
183	Ausable	A1	FA1	Subaq. dune x-bed	25
183	Ausable	A1	FA1	Subaq. dune x-bed	325
183	Ausable	A1	FA1	Subaq. dune x-bed	215
183	Ausable	A1	FA1	Subaq. dune x-bed	215
183	Ausable	A1	FA1	Subaq. dune x-bed	135
183	Ausable	A1	FA1	Subaq. dune x-bed	130
183	Ausable	A1	FA1	Subaq. dune x-bed	125
183	Ausable	A1	FA1	Subaq. dune x-bed	30
183	Ausable	A1	FA1	Subaq. dune x-bed	220
187	Keeseville	A3	FA2	Wave rip. crest	80-260
187	Keeseville	A3	FA2	Wave rip. crest	50-230
187	Keeseville	A3	FA2	Wave rip. crest	140-320
187	Keeseville	A3	FA2	Supercrit. xstrat	20
187	Keeseville	A3	FA2	Supercrit. xstrat	350
187	Keeseville	A3	FA2	Subaq. dune x-bed	275
187	Keeseville	A3	FA2	Supercrit. xstrat	350
187	Keeseville	A3	FA2	Supercrit. xstrat	30
187	Keeseville	A3	FA2	Supercrit. xstrat	350
187	Keeseville	A3	FA2	Supercrit. xstrat	350
187	Keeseville	A3	FA2	Supercrit. xstrat	330
187	Keeseville	A3	FA2	Supercrit. xstrat	320
187	Keeseville	A3	FA2	Supercrit. xstrat	60
187	Keeseville	A3	FA2	Supercrit. xstrat	20
187	Keeseville	A3	FA2	Supercrit. xstrat	50
187	Keeseville	A3	FA2	Supercrit. xstrat	20
187	Keeseville	A3	FA2	C. Rip	200
187	Keeseville	A3	FA2	Supercrit. xstrat	355
187	Keeseville	A3	FA2	Supercrit. xstrat	340
187	Keeseville	A3	FA2	Supercrit. xstrat	350
187	Keeseville	A3	FA2	Supercrit. xstrat	20
188	Keeseville	A3	FA3	Aeolian dune	340
188	Keeseville	A3	FA3	Aeolian dune	350
189	Keeseville	A2	FA1	Subaq. dune x-bed	145
189	Keeseville	A2	FA1	Subaq. dune x-bed	150
189	Keeseville	A2	FA1	Subaq. dune x-bed	135
189	Keeseville	A2	FA1	Subaq. dune x-bed	140
189	Keeseville	A2	FA1	Subaq. dune x-bed	60
192	Hannawa Falls	A1	FA2	Aeolian dune	245

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
193	Keeseville	A3	FA4	Subaq. dune x-bed	290
193	Keeseville	A3	FA4	Subaq. dune x-bed	280
193	Keeseville	A3	FA4	Subaq. dune x-bed	165
193	Keeseville	A3	FA4	Subaq. dune x-bed	125
193	Keeseville	A3	FA4	Subaq. dune x-bed	5
193	Keeseville	A3	FA4	Subaq. dune x-bed	30
193	Keeseville	A3	FA4	C. Rip	15
193	Keeseville	A3	FA4	Subaq. dune x-bed	125
194	Ausable	A1	FA1	Subaq. dune x-bed	30
194	Ausable	A1	FA1	Subaq. dune x-bed	70
194	Ausable	A1	FA1	Subaq. dune x-bed	55
194	Ausable	A1	FA1	Subaq. dune x-bed	90
194	Ausable	A1	FA1	Subaq. dune x-bed	40
194	Ausable	A1	FA1	Subaq. dune x-bed	75
194	Ausable	A1	FA1	Subaq. dune x-bed	80
194	Ausable	A1	FA1	Subaq. dune x-bed	105
194	Ausable	A1	FA1	Subaq. dune x-bed	40
194	Ausable	A1	FA1	Subaq. dune x-bed	85
194	Ausable	A1	FA1	Subaq. dune x-bed	76
194	Ausable	A1	FA1	Subaq. dune x-bed	59
194	Ausable	A1	FA1	Subaq. dune x-bed	80
194	Ausable	A1	FA1	Subaq. dune x-bed	70
194	Ausable	A1	FA1	Subaq. dune x-bed	95
194	Ausable	A1	FA1	Subaq. dune x-bed	100
194	Ausable	A1	FA1	Subaq. dune x-bed	115
194	Ausable	A1	FA1	Subaq. dune x-bed	355
194	Ausable	A1	FA1	Subaq. dune x-bed	65
194	Ausable	A1	FA1	Subaq. dune x-bed	69
194	Ausable	A1	FA1	Subaq. dune x-bed	70
194	Ausable	A1	FA1	Subaq. dune x-bed	30
195	Keeseville	A3	FA5	Subaq. dune x-bed	225
195	Keeseville	A3	FA5	Subaq. dune x-bed	175
200	Keeseville	A3	FA2	C. Rip	ENE
201	Keeseville	A3	FA2	Subaq. dune x-bed	205
201	Keeseville	A3	FA4	Subaq. dune x-bed	210
201	Keeseville	A3	FA4	Subaq. dune x-bed	225
201	Keeseville	A3	FA4	C. Rip	195
201	Keeseville	A3	FA5	Subaq. dune x-bed	190
201	Keeseville	A3	FA5	C. Rip	145
201	Keeseville	A3	FA5	Subaq. dune x-bed	135
201	Keeseville	A3	FA5	Subaq. dune x-bed	25
202	Keeseville	A3	FA2	Subaq. dune x-bed	270
202	Keeseville	A3	FA2	Supercrit. xstrat	50
202	Keeseville	A3	FA2	Subaq. dune x-bed	155

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
202	Keeseville	A3	FA2	Subaq. dune x-bed	165
202	Keeseville	A3	FA2	Subaq. dune x-bed	149
202	Keeseville	A3	FA2	C. Rip	95
202	Keeseville	A3	FA2	Subaq. dune x-bed	115
202	Keeseville	A3	FA2	Supercrit. xstrat	45
202	Keeseville	A3	FA2	Subaq. dune x-bed	130
202	Keeseville	A3	FA2	Supercrit. xstrat	30
202	Keeseville	A3	FA2	Subaq. dune x-bed	105
202	Keeseville	A3	FA2	Subaq. dune x-bed	85
202	Keeseville	A3	FA2	Subaq. dune x-bed	95
202	Keeseville	A3	FA2	C. Rip	215
202	Keeseville	A3	FA2	Subaq. dune x-bed	115
203	Keeseville	A2	FA2	Subaq. dune x-bed	110
203	Keeseville	A2	FA2	Subaq. dune x-bed	100
203	Keeseville	A2	FA2	Subaq. dune x-bed	115
203	Keeseville	A2	FA2	Subaq. dune x-bed	112
203	Keeseville	A2	FA2	Subaq. dune x-bed	114
203	Keeseville	A2	FA2	Subaq. dune x-bed	117
203	Keeseville	A2	FA2	Subaq. dune x-bed	110
203	Keeseville	A2	FA2	Subaq. dune x-bed	114
203	Keeseville	A2	FA2	Supercrit. xstrat	45
203	Keeseville	A2	FA2	Subaq. dune x-bed	115
203	Keeseville	A2	FA2	Subaq. dune x-bed	112
203	Keeseville	A2	FA2	Subaq. dune x-bed	120
203	Keeseville	A2	FA2	Supercrit. xstrat	310
203	Keeseville	A2	FA2	Supercrit. xstrat	315
203	Keeseville	A2	FA2	Supercrit. xstrat	326
203	Keeseville	A2	FA2	Supercrit. xstrat	355
203	Keeseville	A2	FA2	Supercrit. xstrat	334
203	Keeseville	A2	FA2	Parting lineations	135-315
203	Keeseville	A2	FA2	Subaq. dune x-bed	114
203	Keeseville	A2	FA2	Subaq. dune x-bed	126
203	Keeseville	A2	FA2	Subaq. dune x-bed	120
203	Keeseville	A2	FA2	Subaq. dune x-bed	144
203	Keeseville	A2	FA2	Subaq. dune x-bed	125
203	Keeseville	A2	FA2	Adhesion ripples	320
203	Keeseville	A2	FA2	Adhesion ripples	15
203	Keeseville	A2	FA2	Subaq. dune x-bed	150
203	Keeseville	A2	FA2	Subaq. dune x-bed	145
203	Keeseville	A2	FA2	Subaq. dune x-bed	320
203	Keeseville	A2	FA2	Subaq. dune x-bed	138
203	Keeseville	A2	FA2	Subaq. dune x-bed	146
203	Keeseville	A2	FA2	Subaq. dune x-bed	130
203	Keeseville	A2	FA2	Subaq. dune x-bed	117

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
203	Keeseville	A2	FA2	Subaq. dune x-bed	104
203	Keeseville	A2	FA2	Subaq. dune x-bed	124
203	Keeseville	A2	FA2	Subaq. dune x-bed	134
203	Keeseville	A2	FA2	Supercrit. xstrat	55
203	Keeseville	A2	FA1	Subaq. dune x-bed	165
203	Keeseville	A2	FA1	Subaq. dune x-bed	150
203	Keeseville	A2	FA1	Subaq. dune x-bed	155
203	Keeseville	A2	FA1	Subaq. dune x-bed	160
203	Keeseville	A2	FA1	Subaq. dune x-bed	168
203	Keeseville	A2	FA1	Subaq. dune x-bed	165
203	Keeseville	A2	FA1	Subaq. dune x-bed	155
203	Keeseville	A2	FA1	Subaq. dune x-bed	165
204	Keeseville	A2	FA1	Subaq. dune x-bed	70
204	Keeseville	A2	FA1	Subaq. dune x-bed	110
204	Keeseville	A2	FA1	Subaq. dune x-bed	80
204	Keeseville	A2	FA1	Subaq. dune x-bed	300
204	Keeseville	A2	FA1	Subaq. dune x-bed	135
207	Keeseville	A3	FA4	Subaq. dune x-bed	330
207	Keeseville	A3	FA4	Subaq. dune x-bed	115
207	Keeseville	A3	FA4	Subaq. dune x-bed	335
210	Keeseville	A3	FA2	Supercrit. xstrat	65
210	Keeseville	A3	FA2	Subaq. dune x-bed	100
210	Keeseville	A3	FA2	Subaq. dune x-bed	120
210	Keeseville	A3	FA4	Subaq. dune x-bed	85
210	Keeseville	A3	FA4	Subaq. dune x-bed	115
210	Keeseville	A3	FA4	Subaq. dune x-bed	115
210	Keeseville	A3	FA4	C. Rip	130
211	Keeseville	A2	FA1	Subaq. dune x-bed	245
211	Keeseville	A2	FA1	Subaq. dune x-bed	225
211	Keeseville	A2	FA1	Subaq. dune x-bed	265
211	Keeseville	A3	FA5	Subaq. dune x-bed	45
211	Keeseville	A3	FA5	Subaq. dune x-bed	30
211	Keeseville	A3	FA5	Subaq. dune x-bed	40
214	Keeseville	A2	FA2	Subaq. dune x-bed	305
215	Keeseville	A2	FA2	Subaq. dune x-bed	225
215	Keeseville	A3	FA4	Subaq. dune x-bed	270
217	Keeseville	A2	FA1	Subaq. dune x-bed	320
219	Keeseville	A2	FA1	Subaq. dune x-bed	325
222	Keeseville	A3	FA4	Subaq. dune x-bed	50
222	Keeseville	A3	FA4	Subaq. dune x-bed	200
222	Keeseville	A3	FA4	C. Rip	170
222	Keeseville	A3	FA4	Subaq. dune x-bed	180
222	Keeseville	A3	FA4	Subaq. dune x-bed	110
222	Keeseville	A3	FA4	Subaq. dune x-bed	175

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
222	Keeseville	A3	FA4	Subaq. dune x-bed	140
222	Keeseville	A3	FA4	Subaq. dune x-bed	185
222	Keeseville	A3	FA4	C. Rip	180
222	Keeseville	A3	FA4	Subaq. dune x-bed	170
222	Keeseville	A3	FA4	Subaq. dune x-bed	205
222	Keeseville	A3	FA4	Subaq. dune x-bed	305
222	Keeseville	A3	FA4	C. Rip	15
222	Keeseville	A3	FA4	Subaq. dune x-bed	195
223	Keeseville	A3	FA5	Subaq. dune x-bed	50
223	Keeseville	A3	FA5	C. Rip	60
223	Keeseville	A3	FA5	Subaq. dune x-bed	85
223	Keeseville	A3	FA5	Subaq. dune x-bed	55
223	Keeseville	A3	FA5	Subaq. dune x-bed	20
223	Keeseville	A3	FA5	Subaq. dune x-bed	230
223	Keeseville	A3	FA5	C. Rip	215
223	Keeseville	A3	FA5	Subaq. dune x-bed	200
224	Keeseville	A3	FA5	Subaq. dune x-bed	112
224	Keeseville	A3	FA5	Subaq. dune x-bed	124
224	Keeseville	A3	FA5	Subaq. dune x-bed	175
224	Keeseville	A3	FA5	Subaq. dune x-bed	165
224	Keeseville	A3	FA5	C. Rip	150
224	Keeseville	A3	FA5	C. Rip	15
228	Ausable	A1	FA1	Subaq. dune x-bed	150
228	Ausable	A1	FA1	Unit bar	165
228	Ausable	A1	FA1	Subaq. dune x-bed	135
228	Ausable	A1	FA1	Subaq. dune x-bed	135
228	Ausable	A1	FA1	Subaq. dune x-bed	150
228	Ausable	A1	FA1	Unit bar	150
228	Ausable	A1	FA1	Subaq. dune x-bed	155
228	Ausable	A1	FA1	Subaq. dune x-bed	130
228	Ausable	A1	FA1	Subaq. dune x-bed	208
228	Ausable	A1	FA1	Subaq. dune x-bed	75
228	Ausable	A1	FA1	Subaq. dune x-bed	140
228	Ausable	A1	FA1	Subaq. dune x-bed	45
228	Ausable	A1	FA1	Subaq. dune x-bed	150
229	Ausable	A1	FA1	Subaq. dune x-bed	145
229	Ausable	A1	FA1	Subaq. dune x-bed	155
229	Ausable	A1	FA1	Subaq. dune x-bed	25
228	Ausable	A1	FA1	Subaq. dune x-bed	50
228	Ausable	A1	FA1	Subaq. dune x-bed	90
228	Ausable	A1	FA1	Subaq. dune x-bed	95
229	Ausable	A1	FA1	Subaq. dune x-bed	118
229	Ausable	A1	FA1	Subaq. dune x-bed	95
229	Ausable	A1	FA1	Subaq. dune x-bed	100

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
229	Ausable	A1	FA1	Subaq. dune x-bed	130
229	Ausable	A1	FA1	Subaq. dune x-bed	98
230	Ausable	A1	FA1	Subaq. dune x-bed	95
230	Ausable	A1	FA1	Subaq. dune x-bed	115
230	Ausable	A1	FA1	Subaq. dune x-bed	130
230	Ausable	A1	FA1	Subaq. dune x-bed	70
230	Ausable	A1	FA1	Subaq. dune x-bed	117
230	Ausable	A1	FA1	Subaq. dune x-bed	50
230	Ausable	A1	FA1	Subaq. dune x-bed	112
235	Keeseville	A2	FA1	Subaq. dune x-bed	330
235	Keeseville	A2	FA1	Subaq. dune x-bed	150
236	Keeseville	A2	FA1	Subaq. dune x-bed	255
236	Keeseville	A2	FA1	Subaq. dune x-bed	325
236	Keeseville	A2	FA1	Confluence scour	330
236	Keeseville	A2	FA1	Subaq. dune x-bed	275
236	Keeseville	A2	FA1	Subaq. dune x-bed	260
236	Keeseville	A2	FA1	Subaq. dune x-bed	312
236	Keeseville	A2	FA1	Subaq. dune x-bed	295
236	Keeseville	A2	FA1	Subaq. dune x-bed	300
236	Keeseville	A2	FA1	Subaq. dune x-bed	310
236	Keeseville	A2	FA1	Subaq. dune x-bed	305
236	Keeseville	A2	FA1	imbrication	315
236	Keeseville	A2	FA1	imbrication	295
236	Keeseville	A3	FA5	imbrication	260
236	Keeseville	A3	FA5	Subaq. dune x-bed	5
236	Keeseville	A3	FA5	Subaq. dune x-bed	15
236	Keeseville	A3	FA5	Subaq. dune x-bed	355
238	Keeseville	A3	FA4	Subaq. dune x-bed	195
238	Keeseville	A3	FA4	Subaq. dune x-bed	185
238	Keeseville	A3	FA4	Subaq. dune x-bed	180
244	Keeseville	A2	FA4	Subaq. dune x-bed	10
244	Keeseville	A2	FA4	Subaq. dune x-bed	112
244	Keeseville	A2	FA4	Subaq. dune x-bed	124
244	Keeseville	A2	FA4	Subaq. dune x-bed	225
244	Keeseville	A2	FA4	Subaq. dune x-bed	200
244	Keeseville	A2	FA4	Wave rip. crest	95-265
244	Keeseville	A2	FA4	Wave rip. crest	109-289
244	Keeseville	A2	FA4	Wave rip. crest	310-130
244	Keeseville	A2	FA4	Wave rip. crest	125-305
244	Keeseville	A2	FA4	Adhesion ripples	345
245	Ausable	A1	FA1	Subaq. dune x-bed	155
245	Ausable	A1	FA1	Subaq. dune x-bed	150
245	Ausable	A1	FA1	Subaq. dune x-bed	150
245	Ausable	A1	FA1	Subaq. dune x-bed	145

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
245	Ausable	A1	FA1	Subaq. dune x-bed	120
245	Ausable	A1	FA1	Subaq. dune x-bed	135
245	Ausable	A1	FA1	Subaq. dune x-bed	130
245	Ausable	A1	FA1	Subaq. dune x-bed	135
245	Ausable	A1	FA1	Subaq. dune x-bed	140
245	Ausable	A1	FA1	Subaq. dune x-bed	150
245	Ausable	A1	FA1	Subaq. dune x-bed	130
245	Ausable	A1	FA1	Subaq. dune x-bed	120
245	Ausable	A1	FA1	Subaq. dune x-bed	135
245	Ausable	A1	FA1	Subaq. dune x-bed	145
245	Ausable	A1	FA1	Subaq. dune x-bed	135
245	Ausable	A1	FA1	Subaq. dune x-bed	150
245	Ausable	A1	FA1	Subaq. dune x-bed	80
245	Ausable	A1	FA1	Subaq. dune x-bed	75
245	Ausable	A1	FA1	Subaq. dune x-bed	160
245	Ausable	A1	FA1	Subaq. dune x-bed	270
245	Ausable	A1	FA1	Subaq. dune x-bed	100
245	Ausable	A1	FA1	Subaq. dune x-bed	126
245	Ausable	A1	FA1	Subaq. dune x-bed	105
245	Ausable	A1	FA1	Subaq. dune x-bed	345
245	Ausable	A1	FA1	Subaq. dune x-bed	145
245	Ausable	A1	FA1	Subaq. dune x-bed	195
246	Ausable	A1	FA1	Subaq. dune x-bed	350
246	Ausable	A1	FA1	Subaq. dune x-bed	20
246	Ausable	A1	FA1	Subaq. dune x-bed	15
246	Ausable	A1	FA1	Subaq. dune x-bed	23
250	Keeseville	A2	FA1	Subaq. dune x-bed	170
250	Keeseville	A2	FA1	Subaq. dune x-bed	240
252	Ausable	A1	FA1	Subaq. dune x-bed	140
252	Ausable	A1	FA1	Subaq. dune x-bed	130
252	Ausable	A1	FA1	Subaq. dune x-bed	115
252	Ausable	A1	FA1	Subaq. dune x-bed	144
252	Ausable	A1	FA1	Subaq. dune x-bed	123
252	Ausable	A1	FA1	Subaq. dune x-bed	108
252	Ausable	A1	FA1	Subaq. dune x-bed	135
252	Ausable	A1	FA1	Subaq. dune x-bed	95
252	Ausable	A1	FA1	Subaq. dune x-bed	90
253	Ausable	A1	FA1	Subaq. dune x-bed	150
253	Ausable	A1	FA1	Subaq. dune x-bed	118
253	Ausable	A1	FA1	Subaq. dune x-bed	116
253	Ausable	A1	FA1	Subaq. dune x-bed	120
253	Ausable	A1	FA1	Subaq. dune x-bed	55
253	Ausable	A1	FA1	Subaq. dune x-bed	57
253	Ausable	A1	FA1	Subaq. dune x-bed	112

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
253	Ausable	A1	FA1	Subaq. dune x-bed	108
253	Ausable	A1	FA1	Subaq. dune x-bed	110
253	Ausable	A1	FA1	Subaq. dune x-bed	175
253	Ausable	A1	FA1	Subaq. dune x-bed	155
253	Ausable	A1	FA1	Subaq. dune x-bed	84
253	Ausable	A1	FA1	Subaq. dune x-bed	144
253	Ausable	A1	FA1	Subaq. dune x-bed	130
253	Ausable	A1	FA1	Subaq. dune x-bed	154
253	Ausable	A1	FA1	Subaq. dune x-bed	133
253	Ausable	A1	FA1	Subaq. dune x-bed	127
253	Ausable	A1	FA1	Subaq. dune x-bed	152
253	Ausable	A1	FA1	Subaq. dune x-bed	135
253	Ausable	A1	FA1	Subaq. dune x-bed	166
253	Ausable	A1	FA1	Subaq. dune x-bed	117
253	Ausable	A1	FA1	Subaq. dune x-bed	85
253	Ausable	A1	FA1	Subaq. dune x-bed	101
253	Ausable	A1	FA1	Subaq. dune x-bed	145
254	Ausable	A1	FA1	Subaq. dune x-bed	135
254	Ausable	A1	FA1	Subaq. dune x-bed	115
254	Ausable	A1	FA1	Subaq. dune x-bed	140
254	Ausable	A1	FA1	Subaq. dune x-bed	125
259	Ausable	A1	FA1	Subaq. dune x-bed	125
259	Ausable	A1	FA1	Subaq. dune x-bed	115
259	Ausable	A1	FA1	Subaq. dune x-bed	108
259	Ausable	A1	FA1	Subaq. dune x-bed	105
261	Keeseville	A2	FA2	Subaq. dune x-bed	320
263	Keeseville	A2	FA1	Subaq. dune x-bed	95
263	Keeseville	A2	FA1	Subaq. dune x-bed	125
265	Ausable	A1	FA1	Subaq. dune x-bed	140
265	Ausable	A1	FA1	Subaq. dune x-bed	130
265	Ausable	A1	FA1	Subaq. dune x-bed	155
268	Keeseville	A2	FA2	Subaq. dune x-bed	20
268	Keeseville	A2	FA2	C. Rip	5
268	Keeseville	A2	FA2	Subaq. dune x-bed	355
268	Keeseville	A2	FA2	Subaq. dune x-bed	10
268	Keeseville	A2	FA2	C. Rip	350
268	Keeseville	A2	FA2	Subaq. dune x-bed	320
270	Ausable	A1	FA1	Subaq. dune x-bed	110
270	Ausable	A1	FA1	Subaq. dune x-bed	105
270	Ausable	A1	FA1	Subaq. dune x-bed	45
270	Ausable	A1	FA1	Subaq. dune x-bed	30
270	Ausable	A1	FA1	Subaq. dune x-bed	40
270	Ausable	A1	FA1	Subaq. dune x-bed	60
270	Ausable	A1	FA1	Subaq. dune x-bed	104

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
270	Ausable	A1	FA1	Subaq. dune x-bed	95
270	Ausable	A1	FA1	Subaq. dune x-bed	89
270	Ausable	A1	FA1	Subaq. dune x-bed	100
270	Ausable	A1	FA1	Subaq. dune x-bed	74
270	Ausable	A1	FA1	Subaq. dune x-bed	85
271	Ausable	A1	FA1	Subaq. dune x-bed	89
271	Ausable	A1	FA1	Subaq. dune x-bed	106
271	Ausable	A1	FA1	Subaq. dune x-bed	83
271	Ausable	A1	FA1	Subaq. dune x-bed	70
271	Ausable	A1	FA1	Subaq. dune x-bed	130
271	Ausable	A1	FA1	Subaq. dune x-bed	100
271	Ausable	A1	FA1	Subaq. dune x-bed	98
271	Ausable	A1	FA1	Subaq. dune x-bed	85
272	Keeseville	A3	FA2	Subaq. dune x-bed	100
272	Keeseville	A3	FA2	Subaq. dune x-bed	85
272	Keeseville	A3	FA2	Subaq. dune x-bed	80
272	Keeseville	A3	FA2	Subaq. dune x-bed	78
272	Keeseville	A3	FA2	Subaq. dune x-bed	98
272	Keeseville	A3	FA2	Supercrit. xstrat	220
272	Keeseville	A3	FA2	Subaq. dune x-bed	90
272	Keeseville	A3	FA2	Subaq. dune x-bed	85
272	Keeseville	A3	FA2	Subaq. dune x-bed	90
272	Keeseville	A3	FA2	C. Rip	75
272	Keeseville	A3	FA2	Subaq. dune x-bed	80
272	Keeseville	A3	FA4	Subaq. dune x-bed	75
272	Keeseville	A3	FA4	Subaq. dune x-bed	80
272	Keeseville	A3	FA4	Subaq. dune x-bed	90
272	Keeseville	A3	FA4	C. Rip	75
273	Keeseville	A2	FA4	C. Rip	345
273	Keeseville	A2	FA2	Supercrit. xstrat	28
273	Keeseville	A2	FA2	Supercrit. xstrat	30
273	Keeseville	A2	FA2	Subaq. dune x-bed	105
273	Keeseville	A2	FA2	Subaq. dune x-bed	95
273	Keeseville	A2	FA2	C. Rip	120
273	Keeseville	A2	FA2	Wave rip. crest	150-330
273	Keeseville	A2	FA2	Wave rip. crest	100-280
273	Keeseville	A2	FA2	Wave rip. crest	50-240
273	Keeseville	A2	FA2	Wave rip. crest	65-235
273	Keeseville	A2	FA2	Wave rip. crest	20-280
273	Keeseville	A2	FA2	Wave rip. crest	150-330
273	Keeseville	A2	FA2	Subaq. dune x-bed	115
273	Keeseville	A2	FA2	Subaq. dune x-bed	120
273	Keeseville	A2	FA2	Subaq. dune x-bed	120
273	Keeseville	A2	FA2	Subaq. dune x-bed	110

Station	Formation	Allounit	Facies Association	Measurement Type	Azimuth
273	Keeseville	A2	FA2	C. Rip	70
273	Keeseville	A2	FA2	Subaq. dune x-bed	65
273	Keeseville	A2	FA2	Subaq. dune x-bed	80
273	Keeseville	A2	FA2	Subaq. dune x-bed	80
293	Keeseville	A3	FA5	Subaq. dune x-bed	120
293	Keeseville	A3	FA5	Subaq. dune x-bed	130
293	Keeseville	A3	FA5	Subaq. dune x-bed	125
293	Keeseville	A3	FA5	Subaq. dune x-bed	125
293	Keeseville	A3	FA5	Subaq. dune x-bed	143
293	Keeseville	A3	FA5	Subaq. dune x-bed	140
294	Keeseville	A3	FA5	Subaq. dune x-bed	143
294	Keeseville	A3	FA5	Subaq. dune x-bed	120
294	Keeseville	A3	FA5	Subaq. dune x-bed	130