

**INTEGRATED HIGH-RESOLUTION CHEMOSTRATIGRAPHIC AND
CYCLOSTRATIGRAPHIC ANALYSIS OF THE PALEOTROPICAL
CARBONATES SPANNING THE ORDOVICIAN-SILURIAN BOUNDARY
AT THE WEST END OF ANTICOSTI ISLAND, EASTERN CANADA**

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Abstract

The carbonate storm-dominated sedimentary succession superbly exposed on Anticosti Island in Eastern Canada represents one of the most complete and well-preserved paleotropical stratigraphic records spanning the Ordovician-Silurian (O-S) boundary. We sampled the nearly continuous coastal outcrop exposed at low tide along the west coast of Anticosti Island for high-resolution $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ chemostratigraphy. These new isotopic curves comprise more than 500 data points spaced at ~ 0.6 m intervals; for a total of 320 m of strata across the O-S boundary. The $\delta^{13}\text{C}$ curve displays two distinctive positive excursions in the Hirnantian Ellis Bay Formation; a small lower excursion (+2.5‰) and an upper larger excursion (+4.5‰). These two positive isotopic carbon excursions provide a distinctive chemostratigraphic signature for regional and global correlations with other Hirnantian sections. The continuing descending $\delta^{13}\text{C}$ trend, at least 30 m above the currently interpreted O-S boundary, suggests a readjustment of that boundary on the Anticosti succession. The $\delta^{18}\text{O}$ curve, similarly to the Quaternary $\delta^{18}\text{O}$ marine curve, is tightly coupled with multi-order cyclic facies changes. Our tightly coupled lithological and oxygen isotopic data suggest that the Anticosti succession was influenced by glacio-eustatic fluctuations during the end-Ordovician. Furthermore, the estimated duration of these multi-order cycles supports an astronomical forcing. A primary isotopic signal record is also supported by the lack of significant covariance between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, by the excellent microfabric preservation of both macro and microfossils in petrographic, cathodoluminescence, and SEM microscopy, and by little or no diagenetic resetting as suggested by the trace element geochemistry, which is unusual in the deep geological time.

Résumé

La succession de carbonates sédimentaires, déposée sous l'influence de tempêtes et superbement exposée sur l'île d'Anticosti dans l'Est du Canada, représente l'une des coupes stratigraphiques paléotropicales des plus complètes et mieux préservées, chevauchant la limite Ordovicien-Silurien (O-S). Nous avons échantillonné l'affleurement côtier presque entièrement exposée à marée basse, le long de la côte ouest de l'île d'Anticosti pour des analyses chemostratigraphiques en $\delta^{13}\text{C}$ et $\delta^{18}\text{O}$. Ces nouvelles courbes isotopiques comprennent plus de 500 points de données espacées de ~ 0.6 m, pour un total de 320 m de strates traversant la frontière O-S. La courbe en $\delta^{13}\text{C}$ démontre deux excursions positives dans la Formation d'Ellis Bay d'âge Hirnantien; une petite excursion à sa base (+ 2,5 ‰) et une plus grande excursion à son sommet (+ 4,5 ‰). Ces deux excursions isotopiques positives ont fourni une signature distincte, pour reconnaître et établir une corrélation entre les coupes du même âge à l'échelle régionale ou mondiale. La tendance à la baisse en $\delta^{13}\text{C}$, au moins 30 m au-dessus de la limite O-S présentement établie, suggère un possible réajustement de cette limite dans la succession d'Anticosti. La courbe en $\delta^{18}\text{O}$, similaire à la courbe marine en $\delta^{18}\text{O}$ du Quaternaire, est étroitement couplée avec les changements cycliques de faciès à différentes échelles. Nos données lithologiques et $\delta^{18}\text{O}$ couplées suggèrent que la succession d'Anticosti a été influencée par les fluctuations glacio-eustatiques à la fin de l'Ordovicien. La durée de cette cyclicité de faciès multi-ordre supporte un forçage astronomique. Un enregistrement primaire du signal isotopique marin est également supporté par une absence de corrélation significative entre les valeurs en $\delta^{13}\text{C}$ et en $\delta^{18}\text{O}$, par l'excellente préservation des macro et microfossiles sous microscopie pétrographique, cathodoluminescente, ou MBE, et par une faible altération diagénétique démontrée par la géochimie des éléments traces, ce qui est inhabituel pour un temps géologique aussi lointain.

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Preface

Thesis Rationale

The sedimentary succession exposed on Anticosti Island has been subject to numerous sedimentological, geochemical, and paleontological studies over the years, due to its exceptional preservation and thickness. This Upper Ordovician-Lower Silurian (Katian to Telychian) succession spans a very important time interval in geological history; the End Ordovician Mass Extinction. The precise boundaries of the Hirnantian Stage, the final stage of the Ordovician, on Anticosti Island have been subject to some debate. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ chemostratigraphy is now routinely used to establish correlations at both regional and global scales. We propose here to examine the cyclic stratigraphic architecture coupled with a high-resolution $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ chemostratigraphy of the thick Hirnantian strata exposed at the west end of Anticosti Island. Such study could contribute to a better understanding of the dynamic linkages between the Earth systems during such important time interval.

Thesis objective and structure

This study aims to produce the highest resolution $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotope records ever executed on a succession spanning the O-S boundary, as well as to describe and interpret the cyclic carbonate-dominated facies exposed at the west end of Anticosti Island. Our integrated geochemical, sedimentological, and stratigraphic study comprises:

1. High-resolution geochemical sampling for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ stable isotope analyses along the continuous west coast of Anticosti Island where strata are superbly exposed at low tide. Sampling interval was equally spaced at every 0.5-0.7 m. GPS coordinates were used to

georeference all sample localities. Bulk rock sampling was used with preference given to the finest available and best preserved micritic material;

2. Field-based sedimentological observations supported by thin section petrography were used to identify and interpret the major depositional facies;
3. Field-based observations were also used to identify, measure and describe cyclic stratigraphic patterns in the studied succession. These observations were integrated with geochemical and sedimentological data.

This thesis is a compilation of three short articles describing the lithological, stratigraphic, and geochemical characteristics of the end-Ordovician succession exposed at the west end of Anticosti Island. The first chapter covers the $\delta^{13}\text{C}$ chemostratigraphy to establish an age constraint on the succession by comparing the data with previous Anticosti $\delta^{13}\text{C}$ studies as well as other age-equivalent sections in the world. Chapter 2 focuses on the sedimentological and stratigraphical characteristics of the succession in order to understand its sediment dynamics and to detect the possible influence of Earth's orbital parameters on its stratigraphic architecture. Chapter 3 combines the $\delta^{18}\text{O}$ record and stratigraphic architecture in order to decipher the end-Ordovician paleoclimate conditions.

Statement of contributions

Chapter 1 in large part, reproduces a manuscript recently published in the *Canadian Journal of Earth Sciences*:

Mauviel, A., and Desrochers, A. 2016. A high resolution, continuous $\delta^{13}\text{C}$ record spanning the O/S boundary on Anticosti Island, eastern Canada. *Canadian Journal of Earth Sciences*.

This paper is based on fieldwork carried out by Alain Mauviel with assistance in the field from Dr. André Desrochers, Pascale Daoust, Ariane Castagner, and Marili Vincent-Couture for general observations and sampling. All figures were conceived and created by Alain Mauviel, except where indicated. The initial manuscript was written by Alain Mauviel and later revised through discussions with Dr. Desrochers. The manuscript was submitted to the Canadian Journal of Earth Sciences on the 5th of January, 2016, accepted on the 15th of March, 2016, and published online on the 6th of June, 2016.

Chapters 2 and 3 are manuscripts in preparation for submission. These papers are based on fieldwork carried out by Alain Mauviel with assistance in the field from Dr. André Desrochers, Pascale Daoust, Ariane Castagner, and Marili Vincent-Couture for general observations and sampling. All figures were created by Alain Mauviel, unless indicated otherwise. The initial manuscript was written by Alain Mauviel and later revised through discussions with Dr. Desrochers.

Chapter 1: $\delta^{13}\text{C}$ chemostratigraphy

1.1 Introduction

Sedimentary proxies form the basis for the interpretation of cyclostratigraphic and sequence analysis, but geochemical proxies play an increasingly important role in tracking paleoenvironmental reconstructions and establishing stratigraphic correlations in the early Paleozoic (Munnecke et al. 2010). One of the key sedimentary records spanning the Ordovician-Silurian (O-S) boundary is well exposed on Anticosti Island, eastern Canada (Fig. 1.1). Several isotopic curves have been published over the past 30 years from the Anticosti O-S sections (Orth et al. 1986; Long 1993; Brenchley et al. 1994; Carden 1995; Underwood et al. 1997; Azmy et al. 1998; Bergström et al. 2006; Young 2008; Desrochers et al. 2010; Wickson 2010; Delabroye et al. 2011; Jones et al. 2011). Here, we present the first high-resolution $\delta^{13}\text{C}$ record study across the O-S boundary superbly exposed in continuous rocky tidal flat exposures at the west end of Anticosti Island. Our paper discusses the use of $\delta^{13}\text{C}$ stratigraphy for local, regional, and global correlations in the end Ordovician. The origin of positive carbon excursions reported here from our studied succession is, however, beyond the scope of the present study.

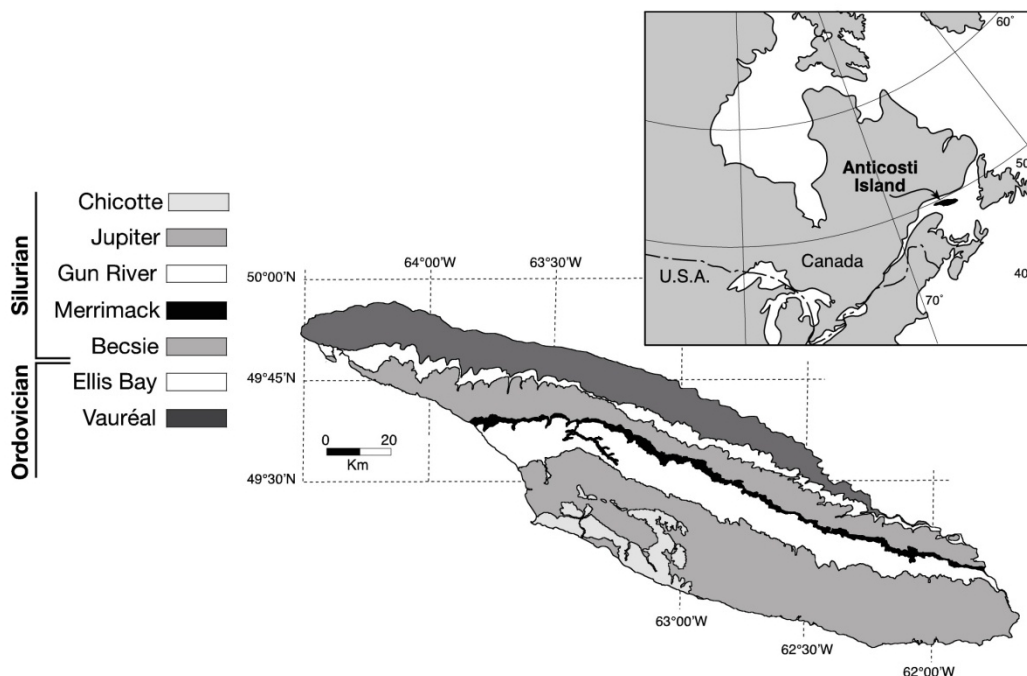


Figure 1.1. Location map (top right) of Anticosti Island (study area) and the distribution of formation outcrops on the island.

1.2 Geological Context

The tectonically undisturbed, fossiliferous Anticosti succession was deposited on a highly subsiding foreland basin along the eastern margin of Laurentia in the southern equatorial tropical hurricane belt (Jin et al. 2013). The upper 900 m of the >2 km thick Sandbian to Telychian succession (Fig. 1.1) constitutes a comprehensive late Ordovician to early Silurian record superbly exposed on Anticosti Island (Long, 2007). Coupled with a sustained sediment supply within a highly subsiding basin, the Anticosti succession is exceptionally thick (e.g. Sandbian to Katian= ~1600 m, Hirnantian= ~100 m, Rhuddanian to mid-Telychian= ~500 m), one or two orders thicker than those in age-equivalent carbonate sections deposited in other shallow epeiric or ramp settings (Ghienne et al. 2014).

1.3 Methods

Our study is the first one to sample strata exposed at low tide along the west coast of Anticosti Island (Fig. 1.2), thus providing a previously unexploited, exceptionally complete stratigraphic interval ranging from the upper Vauréal (late Katian), through Ellis Bay (Hirnantian), to lower Becscie (latest Hirnantian-Early Rhuddanian) formations. This stratigraphic interval includes two obvious stratigraphic hiatuses located at the top of the Ellis Bay Formation causing small offsets of the large positive carbon excursion seen in Fig. 1.3 (see also Fig. 4 in Ghienne et al. 2014). Apart from these two discontinuities, the coastal sections at the west end of Anticosti Island are mainly composed of storm-dominated mid to outer ramp carbonates with no obvious break in sedimentation (Desrochers et al. 2010). The stratigraphic elevation above our datum is shown at every 25 m interval as indicated by yellow dots in Fig. 1.2. We used a “bulk-rock” sampling in order to produce a high-resolution, continuous isotopic stratigraphic record that is not dependent on the distribution of brachiopods in the section. Bulk-rock geochemical samples equally spaced at every ~0.6 m were taken along the coastal sections. The Laframboise Member at the top of the Ellis Bay Formation was, however, sampled at a higher resolution (~0.1 m). In total, 512 samples were taken from the upper Vauréal (185 m), Ellis Bay (85 m), and lower Becscie (45 m) formations. A subset of these samples (n= 65) were thin-sectioned and stained (Dickson, 1966) and subsequently analyzed under transmitted light and cathodoluminescence (CL) microscopy for diagenetic screening. The finest available micritic (occasionally peloidal) material from each hand sample was microdrilled for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ geochemical analyses. Analyses were performed on a Gas Bench II interfaced with a Finnigan Mat Delta XL mass spectrometer at the G.G. Hatch Laboratory, University of Ottawa.

Data are reported here as $\delta^{13}\text{C}$ (equivalent to $\delta^{13}\text{C}_{\text{carb}}$) in permil (‰) with respect to the Vienna Pee Dee Belemnite, or VPDB standard. The analytical precision is $\pm 0.1\text{‰}$.

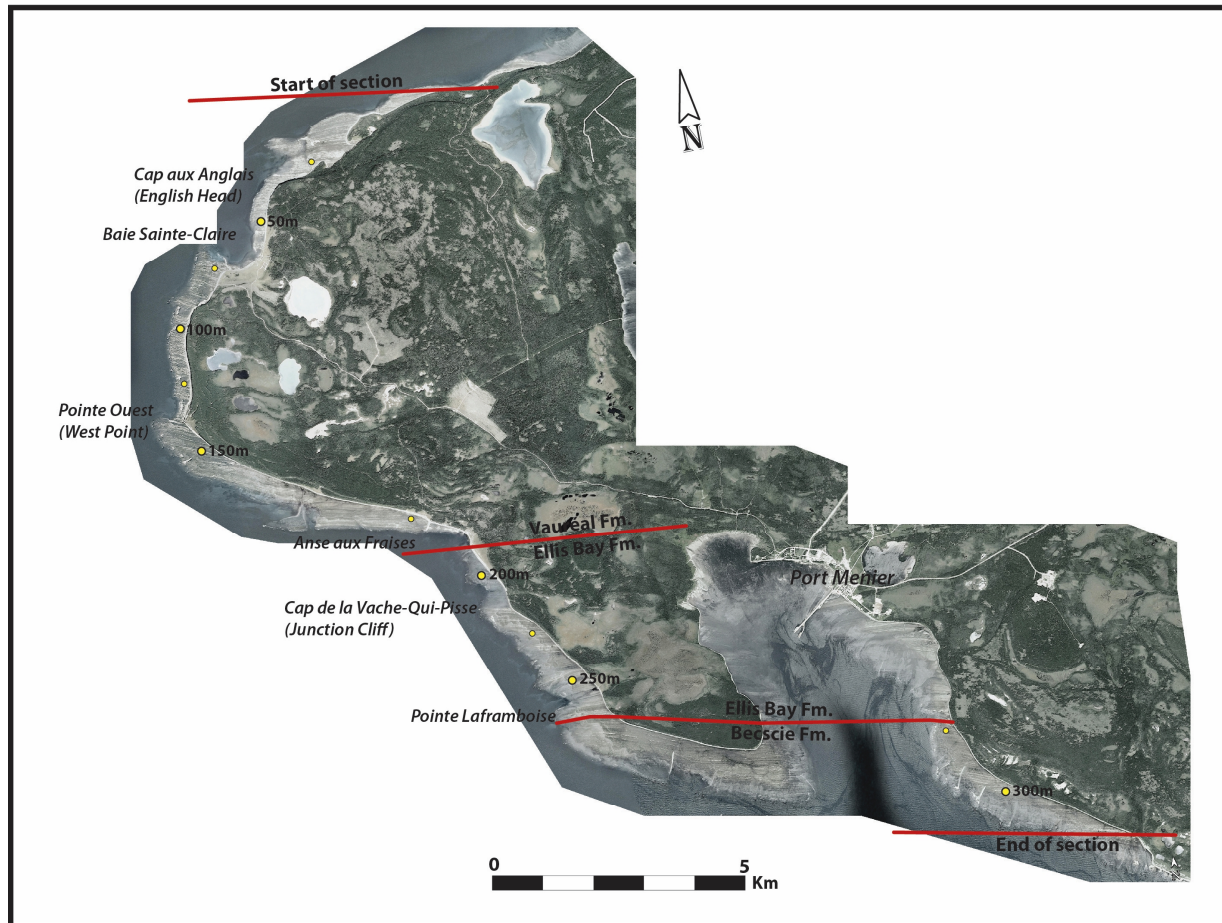


Figure 1.2. Satellite imagery showing the extensive development of rocky tidal flat exposures at the west end of Anticosti Island. The gently south-dipping strata exposed at low tide provide a continuous 315 m thick section that was sampled at every ~ 0.6 m. Yellow dots correspond to stratigraphic position in metres above the datum. Key lithostratigraphic contacts are also identified.

1.4 Results

Our continuous 315 m thick sequence of $\delta^{13}\text{C}$ data points spanning the O-S boundary at the west end of Anticosti island shows a broad positive excursion, with peak values of 2.5‰ centered at 200 m above our datum and a larger positive $\delta^{13}\text{C}$ excursion with peak values of 4.5‰ at the 265-275 m interval (Fig. 1.3). Pre- and post-excursion baseline values of $+0.5\text{‰}$ (McLaughlin & al. 2015) occur at ~ 45 -165 m and a few metres above the Ellis Bay-Becscie

contact respectively. In addition, several short-term $\delta^{13}\text{C}$ fluctuations with a magnitude of 0.25‰-0.5‰ and 0.5‰-1‰ are present in the Vauréal and Becscie formations and Ellis Bay Formation respectively (Fig. 1.3). Our high-resolution $\delta^{13}\text{C}$ curve is well constrained by late Katian to early Rhuddanian chitinozoan biozones in the upper Vauréal, Ellis Bay, and lower Becscie formations (Achab et al. 2011, 2013; Fig. 1.3). The chitinozoan biozones of the Ellis Bay Formation are all considered Hirnantian in age based on concordant paleontological evidence (Achab et al. 2011, 2013; see also the supplemental material of Ghienne et al. 2014). For an alternative view on the age of the lower Ellis Bay Formation, the reader is referred to Kaljo et al. (2008) or Bergström et al. (2011). Supplemental information includes *i*) a table compiling $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data with their stratigraphic position above the datum and global positioning system GPS localities (Appendix A), and *ii*) $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ cross-plots of studied units (Appendix B).

1.5 Preservation of the original $\delta^{13}\text{C}$ signal

Micrite-dominated matrix is the main component of studied Anticosti carbonates and the prime target for the bulk carbonate sampling. Confidence in the ability of those bulk carbonates to faithfully record pristine $\delta^{13}\text{C}$ signatures is based on the following arguments: *i*) the carbonate matrix is minimally dolomitized; *ii*) the carbonate matrix is composed of dense, aphanocrystalline calcite ($< 10\ \mu\text{m}$) and exhibits no aggrading neomorphic fabrics; *iii*) the carbonate matrix stains pink with Dickson solution (Dickson 1966) and shows no to weakly dull luminescence, indicating low Fe^{2+} and Mn^{2+} contents; *iv*) the original sedimentary fabrics and well-preserved paleontological material in the succession are independently known (Delabroye et al. 2011; Finnegan et al. 2011; Jones et al. 2011; among others); *v*) the conodont elements with

colour alteration indices are 1.0 and 1.5, suggesting that diagenetic stabilization occurred at relatively low burial temperatures and, hence, shallow depths mainly within the marine phreatic zone; *vi*) our micrite-based $\delta^{13}\text{C}$ curve (Fig. 1.3) yields comparable geochemical trends to previously published low-resolution brachiopod $\delta^{13}\text{C}$ curves (Long 1993; Brenchley et al. 1994, 2003; Bergström et al. 2006); *vii*) the positive carbon excursions in our succession are similar to those documented in a wide variety of end-Ordovician lithologies on several paleocontinents (Brenchley et al. 2003; Melchin et al. 2013; among others). Comparative brachiopod and bulk-rock geochemical data ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$, and trace-element contents in Sr, Mn, Fe, and Ca) collected along the same coastal sections and produced by other members of our research group (Wickson 2010; Kharodia 2015) were also taken into account to evaluate if a primary isotopic signal was present in our samples.

In addition, covariation of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values in marine carbonates is commonly regarded as evidence of diagenetic alteration (Lohmann 1988; Marshall 1992). Our data show no significant correlation between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ ($r^2 \leq 0.4$; appendix B) suggesting no or little diagenetic alteration of the studied successions. The only highly significant correlation between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ occurs in the Laframboise strata at the top of the Ellis Bay Formation where two regional discontinuity surfaces are present (Desrochers et al. 2010). Significantly depleted $\delta^{18}\text{O}$ values are present up to 1 m below these former subaerial surfaces, but the effects on $\delta^{13}\text{C}$ values are minimal (Fig. 1.3). In other words, they lack negative $\delta^{13}\text{C}$ anomalies, despite generally covariant $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ (also reported by Long 1993; Jones et al. 2011). This suggests that Laframboise $\delta^{13}\text{C}$ values were largely rock-buffered during meteoric diagenesis (Banner and Hanson 1990). Prior to the radiation of land plants in the Silurian and Devonian, the relative absence of terrestrially derived organic matter during meteoric diagenesis may have contributed

to the preservation of a near-pristine marine $\delta^{13}\text{C}$ record below such subaerial surfaces (Jones et al. 2015). In summary, our screening evaluation suggests that the $\delta^{13}\text{C}$ signatures of the investigated bulk carbonates are reliable and robust and can be utilized to reconstruct a high-resolution C-isotope profile spanning the O-S boundary on Anticosti Island.

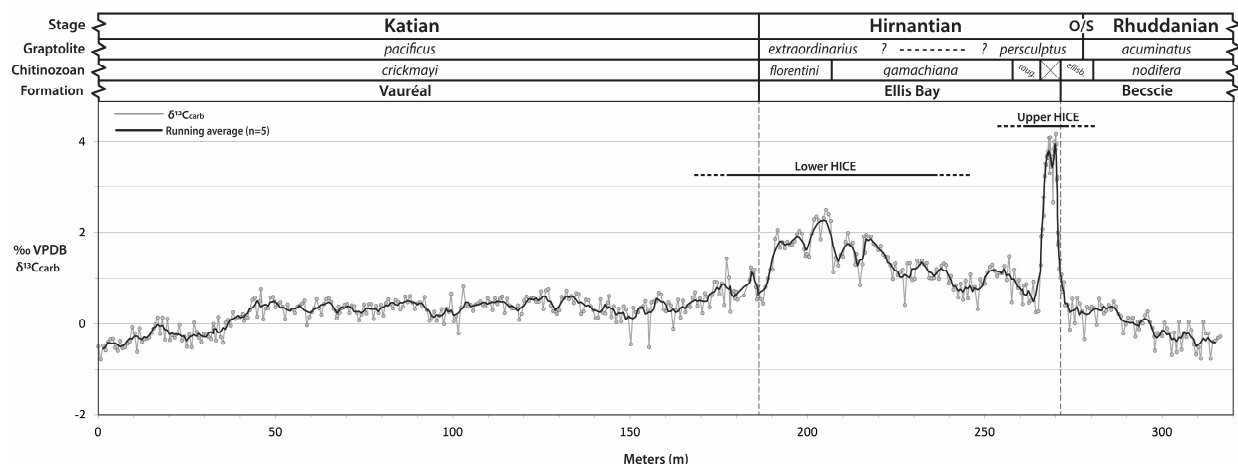


Figure 1.3. Biostratigraphic framework (Desrochers et al. 2010; Achab et al. 2013) and $\delta^{13}\text{C}$ chemostratigraphic profile of the upper Vauréal, Ellis Bay and Becscie formations exposed at the west end of Anticosti Island. *taug.*, = *taugourdeau*; *ellisb.*, = *ellisbayensis*

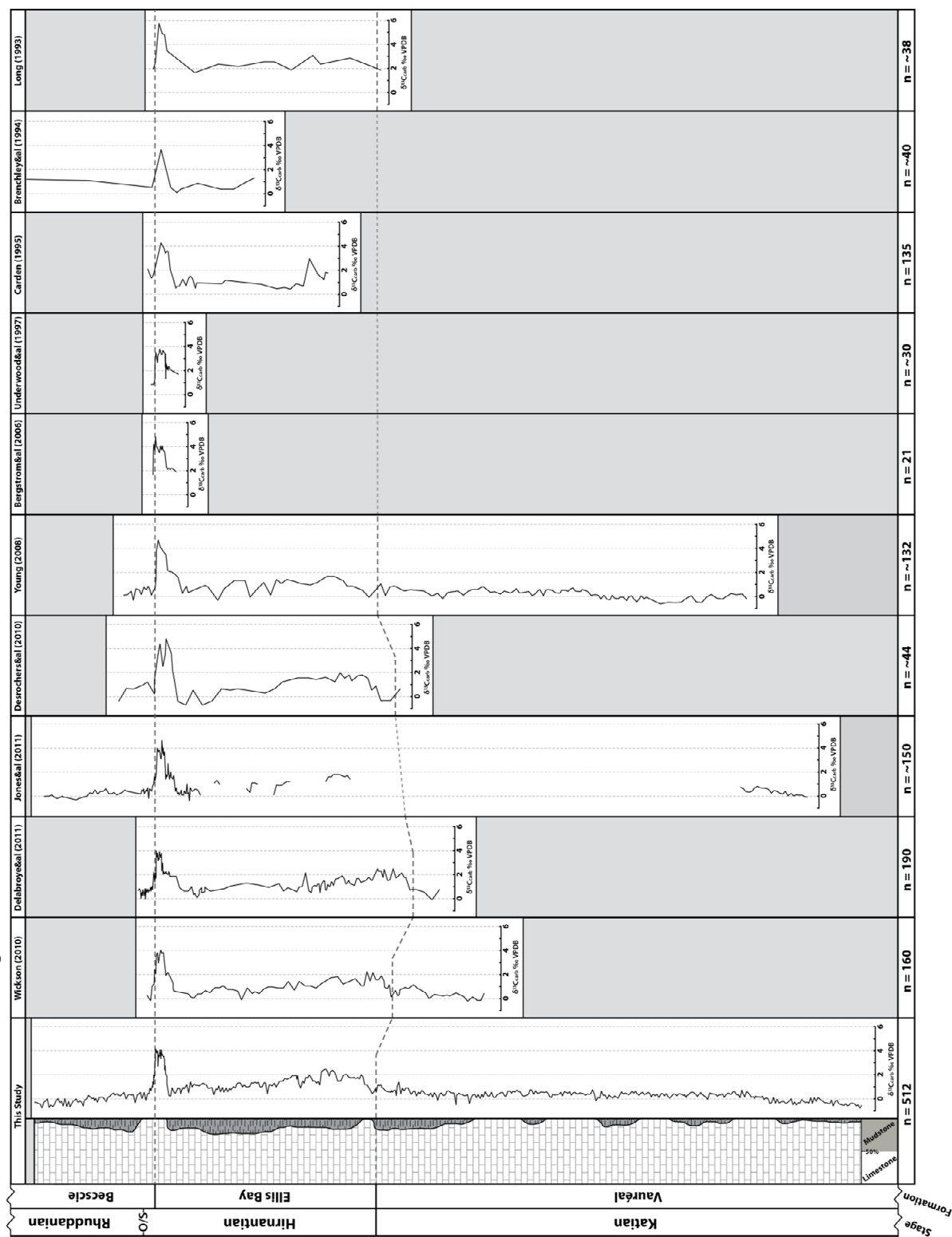
1.6 Discussion

In the following section, we briefly discuss the significance of our new high-resolution $\delta^{13}\text{C}$ curve as a tool for local, regional, and global stratigraphic correlations at the O-S boundary. Previously published $\delta^{13}\text{C}$ curves (Fig. 1.4) spanning the O-S boundary at the west end of Anticosti Island contain several pitfalls that are important to flag because they are often used for global stratigraphic correlations and compared with $\delta^{13}\text{C}$ curves from other paleocontinents (Brenchley et al. 2003; Kaljo et al. 2008; Bergström et al. 2011). Several of the first published Anticosti $\delta^{13}\text{C}$ curves either covered a limited stratigraphic interval close to the O-S boundary (Orth et al. 1986; Underwood et al. 1997; Bergström et al. 2006) or sampled the section at a low resolution unable to capture short- and long-term $\delta^{13}\text{C}$ variations (Long 1993; Brenchley et al.

1994; Carden 1995; Desrochers et al. 2010). More recently published $\delta^{13}\text{C}$ curves expanded their stratigraphic coverage to the entire Ellis Bay Formation and adjacent units (Young 2008; Desrochers et al. 2010; Jones et al. 2011; Delabroye et al. 2011). These more recent curves were sampled at several coastal bluff exposures separated by more or less important stratigraphic gaps, thus resulting in $\delta^{13}\text{C}$ curves with data points collected at inconsistent sampling intervals. This is well illustrated in our Fig. 1.4 by the Jones's $\delta^{13}\text{C}$ curve, which appears highly segmented when compared with our new high-resolution $\delta^{13}\text{C}$ curve. Wickson (2010; see also supplementary material in Ghienne et al. 2014) provided the first $\delta^{13}\text{C}$ curve to continuously sample the O-S units from the rocky tidal flat outcrops exposed at low tide along the west end of Anticosti Island. Wickson's $\delta^{13}\text{C}$ curve also had some pitfalls including an inadequate sampling resolution to decipher short-term from longer-term $\delta^{13}\text{C}$ variations and a limited stratigraphic sampling to capture $\delta^{13}\text{C}$ baseline values. Our new high-resolution $\delta^{13}\text{C}$ curve was able to solve these pitfalls (see the text below).

Although the absolute values and the amplitudes may vary from section to section, a global Upper Ordovician carbon chemostratigraphy with distinct positive excursions has been proposed for regional and global correlations of late Katian and Hirnantian strata (Bergström et al. 2009; Melchin et al. 2013). Our new high-resolution Anticosti $\delta^{13}\text{C}$ curve displays a lower and an upper positive carbon excursion or Hirnantian Isotope Carbon Excursions (HICEs) in the Hirnantian Ellis Bay Formation. The first major positive excursion has been referred to as, the late Katian, Elkhorn excursion (*sensu* Bergström et al. 2009). Paleontological evidence (Achab et al. 2011, 2013), however, suggests that this excursion (referred here as lower HICE) is early Hirnantian in age (*sensu* Melchin et al. 2013). The ascending limb of the lower HICE corresponds to the upper 20 m of the late Katian Vauréal Formation, but peak values occur in the

Figure 1.4. Our $\delta^{13}\text{C}$ chemostratigraphic profile versus previously published $\delta^{13}\text{C}$ curves (from left to right Wickson 2010; Delabroye et al. 2011; Jones et al. 2011; Desrochers et al. 2010; Young 2008; Bergström et al. 2006; Underwood et al. 1997; Carden 1995; Brenchley et al. 1994; Long 1993) of the upper Vauréal, Ellis Bay and Becschie formations at the west end of Anticosti Island. The Ellis Bay-Becschie contact was used as a datum for comparison between the curves. *n*, number of data points.



lower part of the Hirnantian Ellis Bay Formation (Fig. 1.3). In spite of a $\delta^{13}\text{C}$ record segmented by a few stratigraphic hiatuses, the upper HICE is well registered in the upper part of the Ellis Bay Formation (Fig. 1.3). When compared to sections from around the globe, our $\delta^{13}\text{C}$ curve displays a distinct long-term trend with a long sustained lower HICE (165-245 m in Fig. 1.3) followed by the large upper HICE (265-275 m in Fig. 1.3) and a continued descending trend well into the Becscie Formation (>50 m).

Applied to the late Katian-Hirnantian glacial context (Ghienne et al. 2014), a representative $\delta^{13}\text{C}$ stratigraphic sampling in a shallow epeiric or ramp setting is only possible if either subsidence rates were high or initial water depth was significant. The Anticosti stratigraphy was under active subsidence combined with moderate initial water depths (~100 m) prior to the Hirnantian (Long, 2007; Desrochers et al. 2010); thus allowing the deposition of a thick sedimentary succession with a few hiatuses and preserving a comprehensive $\delta^{13}\text{C}$ record. Without subsidence and no or modest initial water depth, the outcome would have been a thin succession with a low stratigraphic sampling and multiple amalgamated hiatuses.

In every well-dated graptolitic succession, the return to $\delta^{13}\text{C}$ baseline values after the positive HICE peak occurs in the upper part of the *Metabolograptus persculptus* graptolite Zone (e.g., Mirny Creek, Dob's Linn, Vinini Creek sections in Melchin et al. 2013). The return to Katian $\delta^{13}\text{C}$ baseline values of +0.5‰ in our curve (Fig. 1.3) occurs a few metres above the Ellis Bay/Becscie formations contact, but the descending isotopic trend continues well into the Becscie Formation (>50 m). This raises questions about the possibility of an adjustment of the O-S boundary well above the present base of the Becscie Formation. It is interesting to note that earlier stratigraphic studies (Twenhofel 1928; Bolton 1961) have also placed the Ellis Bay-Becscie contact at a comparable stratigraphic level. A high-resolution $\delta^{13}\text{C}$ curve for the

Rhuddanian strata of Anticosti Island is, however, required to reevaluate the position of the O-S boundary on Anticosti Island.

1.7 Conclusions

- 1) This is the first study to sample strata superbly exposed at low tide along the west coast of Anticosti Island; thus providing a previously unexploited, nearly complete stratigraphic interval spanning the O-S boundary for $\delta^{13}\text{C}$ chemostratigraphy.
- 2) We are able to recognize a lower and an upper positive HICE within peak values of +2.5‰ and +4.5‰ respectively rising above late Katian and early Rhuddanian baseline values of +0.5‰. The upper larger HICE abruptly interrupted the descending limb of the lower HICE. As seen in well-dated graptolitic successions around the globe, the return to $\delta^{13}\text{C}$ baseline values following the upper HICE suggests that the O-S boundary at the west end of Anticosti may be stratigraphically located higher above the base of the Becscie Formation than currently identified.
- 3) Our new high-resolution $\delta^{13}\text{C}$ curve with more than 500 data points derived from well-preserved micritic samples and spaced at every ~0.6m rectifies important pitfalls (i.e. low sampling resolution, variable sampling intervals, stratigraphic gaps) of previously published $\delta^{13}\text{C}$ curves at the west end of Anticosti Island.

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Chapter 2: Stratigraphic architecture

2.1 Introduction

Cyclostratigraphy has improved our understanding of astronomical forcing on global paleoclimate systems, and has become an useful global time scale calibration tool (Hinnov 2013). The astronomical time scale is well defined for the Cenozoic and much of the Mesozoic (Hilgen et al. 2014). It is less well constrained in the Paleozoic due to a combination of factors: no high-precision geochronology, incomplete biostratigraphy, no magnetic reversal stratigraphy, and lack of confidence in models of the astronomical parameters (Hinnov 2013). Orbital signals, however, have been recently reported for the middle and late Paleozoic (Heckel 1986; Anderson 2011; Davydov et al. 2010; Martin et al. 2012; De Vleeschouwer et al. 2012, 2013; Wu et al. 2013; Severson et al. 2015). The exceptionally well exposed succession composed of numerous repetitive facies on a metre-scale at the west end of Anticosti Island represents a target of choice to test the presence of a Milankovitch signal in the early Paleozoic (Fig. 2.1). Although a full treatment statistical analysis is beyond the scope of the present study (Currently performed by Matthias Sinnesael at Vrije Universiteit Brussel), the objective of our study is to examine potential linkages between lithological changes, multi-order stratigraphic cycles and the Earth's orbital parameters.

2.2 Geological context

Anticosti Island displays an impressive undeformed gently south-west dipping sedimentary section, largely composed of storm-influenced carbonate sediments spanning the Ordovician-Silurian boundary (Long 2007; Desrochers et al. 2010; Ghienne et al. 2014a).

Sustained sediment supply and high subsidence rates contributed to the deposition of the exceptionally thick Anticosti succession (e.g. Sandbian to Katian= ~1600 m, Hirnantian= ~100 m, Rhuddanian to mid Telychian= ~500 m), which is one or two orders thicker than in age equivalent carbonate sections deposited in similar shallow epeiric or ramp settings (Long 2007; Ghienne et al. 2014b). The Upper Ordovician - Lower Silurian portion of the succession was deposited on the distal portion of a Taconic-Acadian foreland located at southern paleolatitudes of 15-20° along the eastern margin of Laurentia (Fig. 2.2). The Anticosti Basin developed following the fragmentation of Rodinia in the Neoproterozoic - Early Cambrian and the subsequent development of passive margins around Laurentia during the early Paleozoic (Allen et al. 2009). In the late Early Ordovician, a shift from a passive to active margin allowed the formation of a tectonically active foreland basin with high subsidence rates along the eastern margin of Laurentia. The gently dipping strata exposed on Anticosti Island indicate that they only experienced minor far-field deformation, even during the most active phase of the foreland basin development (Bordet et al. 2010). Subsidence rates driving the long-term accommodation space in the basin, however, were at their highest during the tectonically active foreland basin. Subsidence rates peaked at 17.9 cm/ka during the deposition of the early part of the Upper Ordovician (Katian) Vauréal Formation (Long 2007). A marked decline in basin subsidence at ~1 cm/ka, beginning in the Hirnantian (Ellis Bay Fm.) and continuing in the early Silurian (Becscie Fm.), likely reflects the decoupling of thrust loads to the south (Malo 2004). A modern stratigraphic framework was recently proposed for the Ellis Bay and Becscie formations (Desrochers et al. 2010, Copper et al. 2013, Copper and Jin 2014), but is pending for the Vauréal Formation (Long and Copper 1987). Age control of the studied succession is documented by

chitinozoans (Achab et al. 2011; 2013) and conodonts (Nowlan and Barnes, 1981; McCracken and Barnes, 1981).

2.3 Methods

Our study is the first to sample the gently dipping strata exposed at low tide along the west coast of Anticosti Island (Fig. 2.3), thus providing a previously unexploited, exceptionally complete stratigraphic interval spanning the O-S boundary and including from base to top: 185 m of the upper part of the Katian Vauréal Formation, 85 m of the whole Hirnantian Ellis Bay Formation, and 45 m of the lower part of the Rhuddanian Becscie Formation. The lithostratigraphic contacts between these formations and the stratigraphic elevation above our zero datum is shown at every 25 m interval in Fig. 2.3. Six depositional facies were recognized in outcrop on the basis of their composition, depositional textures and fabrics, sedimentary structures, and levels of bioturbation. Representative samples (n= 65) of these facies were thin-sectioned, stained with a mixture of Alizarin red S and potassium ferricyanide (Dickson 1966), and subsequently examined under transmitted light microscopy for a thorough examination of their sedimentological and paleontological characteristics. The studied succession was subdivided into metre-scale Transgressive/Regressive (TR) cycles (*sensu* Embry, 2009) using various erosion and deposition surfaces or zones present in the field (Fig. 2.4). The metre-scale TR cycles locally display more important facies shifts that can be used to delimit longer-term TR cycles at the decametre scale

2.4 Results

A facies analysis of the studied Vauréal-Ellis Bay-Becsie succession at the west end of Anticosti Island is presented below. First, all major depositional facies are briefly described and interpreted. Second, the complex, but repetitive nature of these facies is examined to decipher their stratigraphic architecture at both metre- and decametre-scales.

2.4.1 Facies description and interpretation

Numerous portions of the coastal cliff sections exposed at the west end of Anticosti Island have been previously described (Sami and Desrochers, 1992; Long, 2007; Farley, 2008; Desrochers et al. 2010, Jones et al., 2011; Copper et al. 2013; Copper and Jin 2014; Ghienne et al., 2014). We revisited the facies description of these previous studies, made additional observations, and more importantly included the gently dipping strata exposed at low tide along the west coast of Anticosti Island in our study. A summary of our facies description and environmental interpretation is provided in table 2.1. We identified in total six depositional facies representing sediments that were deposited under the influence of episodic storm events mainly below the fairweather wave base on a mid to outer carbonate ramp depositional system (Aigner, 1985). Fig. 2.5 illustrates the relative abundance of these facies in a stratigraphic log covering the entire studied section.

Episodic storm deposition is evidenced by the calcisiltite/calcarenite beds with abundant hummocky and swaley cross-stratification (HCS, SCS) with sharp, locally scoured, basal contact. HCS and SCS form under oscillatory-dominated combined flow during storms (Dumas and Arnott, 2006). The storm beds, called here tempestites, are typically lenticular and interbedded with muddy, bioturbated fairweather deposits (Fig. 2.6a,b,c). Transgressive oncolitic

calcirudites (Fig. 2.7e,f) locally overlain metazoan-calcimicrobial bioherms (Fig. 2.7g,h) in the Laframboise member at the top of the Ellis Bay Formation are, however, shallower inner ramp facies deposited above the fairweather wave base. Two regional discontinuities are present below and above the oncolitic and reefal Laframboise limestones (Desrochers et al. 2010). The mid-ramp Vauréal and Becscie facies are relatively coarse grained while the Ellis Bay ones are muddier. The "coarser" mid ramp facies are thin- to medium-bedded calcisiltite/calcarenite in which highly abraded bioclasts are overlain by abundant peloids (Fig. 2.6c,d,e). The "muddy" mid ramp environment is largely composed of pure lime mud with a very thin bioclastic/peloid basal layer. The biotic assemblage present in all six facies is diverse and dominated by open marine stenohaline taxa (Fig. 2.6f,g; Fig. 2.7a,b,g,h) including brachiopods, molluscs, bryozoans, corals, stromatoporoids, and crinoids.

2.4.2 Stratigraphic architecture

Various stratigraphic tools were used to track relative sea level changes in the Vauréal-Ellis Bay-Becscie succession at the west end of Anticosti Island including: variations in grain size of the sediments, changes in bed thickness, gradual versus abrupt facies shifts and multi-scale tempestite proximality trends (Sami and Desrochers 1992). Two superimposed orders of sedimentary cycles, formed by a repetitive succession of facies, are present in the 320 m thick studied succession. More than 80 metre-scale cycles are present with their thickness averaging 4.8 m (SD= 1.6), 2.3m (SD= 1.1), and 3.4m (SD= 1.3) in the upper Vauréal, Ellis Bay and lower Becscie formations respectively (Fig. 2.8). These metre-scale cycles are bundled into 22 decametre-scale cycles (Fig. 2.8). The metre-scale cycles correspond to small-scale, transgressive regressive units (*sensu* Embry, 2009). The metre-scale cycles display two system

tracts; a deepening-upward transgressive system tract (TST) bounded by a maximum regressive surface (MRS) below and the maximum flooding surface or zone (MFZ) above and a shallowing upward regressive system tract (RST) bounded by the MFZ below and the MRS above. Their proximal and distal expressions along a storm-dominated carbonate ramp profile are schematically illustrated in Fig. 2.9. The proximal metre-scale cycles comprise mainly inner- to mid ramp, storm-influenced facies (i.e. facies 2 and 3) while the more distal cycles are mainly composed of mid to outer ramp bioturbated muddy facies (i.e. facies 1). In both cases, the MRSs coincide with the amalgamated thick tempestite beds with their distinctive HSC/SWS whereas the MFZs occur in heavily bioturbated, mud rich thinner beds. The precise location of MFZs in the thicker homogeneous bioturbated mud rich cycles, however, remains difficult to pinpoint. On the other hand, the repeated occurrence of near *in situ* large colonial skeletons (e.g. tabulate coral, *Aulacerid* stromatoporoids...) coincides with numerous MRZs or marks the earliest portion of TRSs. In general, cycles are relatively thinner in distal ramp settings (1-5m) than in more proximal shallower ramp settings (2-6m). The tempestites deposits are relatively coarse grained with peloids and bioclasts in the Vauréal and Becscie cycles, but are mud rich in those of the Ellis Bay Formation (Fig. 2.10; see discussion below). Another distinctive feature among metre-scale cycles is the presence of abrupt facies shifts or facies offsets recorded within some RSTs (Fig. 2.4c, Fig. 2.10) of the studied succession. These facies offsets represent forced regression surfaces and are more common in the Ellis Bay Formation (Fig. 2.8).

The large decametre-scale TR cycles comprise 3-5 metre-scale TR cycles and range from 8 to 30 m in thickness. These larger TR cycles display an asymmetrical shape with 1-2 metre-scale cycles defining a major TRS overlain by 2-4 stacked metre-scale cycles recording a RST capped by a major MRS (Fig. 2.8). In general, the stacking of the large decametre-scale cycles is

thinning upward from the upper Katian Vauréal Formation toward the lowermost Rhuddanian Becscie Formation. A cycle thickening above the O/S boundary is apparently present, but remains speculative until the rest of the overlying Rhuddanian Becscie strata is included into a more complete cyclostratigraphic study (P. Daoust, MSc thesis in progress at uOttawa).

2.5 Discussion

This section investigates the presence of a Milankovitch signal in our studied succession at the west end of Anticosti Island using the expected thickness of metre- and decametre-scale cycles if they were driven by astronomical forces and second by a preliminary time-series analysis of our stable isotope data. Accumulation rates (not considering compaction) are based on known stratigraphic thickness and biostratigraphic age control (Long 2007; Cooper et al. 2012; Mauviel and Desrochers 2016; McLaughlin et al. 2016) of the studied Anticosti succession, and were calculated into corresponding cycle thicknesses for each astronomical parameter per time stage (table 2.2). This approach provides us with an approximate order of thickness characterizing each parameter. A critical issue, however, remains the absolute age control on the individual segments and completeness of the studied Anticosti succession. The entire >1000 m thick Vauréal Formation is assigned to the Ka4 time slice (McLaughlin et al. 2016). The presence of unconformities of unknown duration, however, is suspected in the subsurface for the Vauréal Formation; thus underestimating the number of metre-scale TR cycle present. A similar situation prevails in the Ellis Bay Formation, which contains two regional discontinuities of unknown duration. Furthermore, a recent proposal (Mauviel and Desrochers 2016) suggest that the Ordovician-Silurian boundary could be located stratigraphically higher

(>30 m) than currently interpreted; consequently the overall Hirnantian time interval could contain more metre-scale TR cycles.

The Vauréal metre- and decametre-scale TR cycles are in general accordance with the expected ~5-6 m thick precession and ~30 m thick, eccentricity signals respectively (Table 2.2). As suggested by the reduced rates in basement subsidence during the Hirnantian and Rhuddanian (Long 2007), the metre-scale cycles of the Ellis Bay and Becscie are thinner, but are in line with the expected ~1 m thick precession signal (Table 2.2). The Hirnantian Ellis Bay Formation also displays thinner cycles at the decametre-scale averaging around 8-10 metres in thickness. However, decametre-scale cycles identified within this formation contain a few areas of uncertainty, namely where metre-scale cycles are likely to miss because high-frequency oscillations of sea-level within highstands potentially produced hidden cycles within the deepest ramp argillaceous facies. Cycles in the Becscie Formation are difficult to interpret at the decametre-scale because our studied interval is limited to its lowest 45 m portion. In spite of reduced rates of tectonic subsidence in the Anticosti Basin (Long 2007), a significant cycle thickening at the decametre scale is present above the Ellis Bay/Becscie formations contact. These thicker cycles could also support a 400 ka eccentricity signal (~20 m in table 2.2).

Despite all uncertainties, we cautiously interpret the decameter-scale cyclicity in the studied succession as a 100 ka eccentricity stratigraphic signal. They typically contain 3-5 high-frequency meter-scale cycles, likely corresponding to a mix of the obliquity and precession signals. The asymmetrical nature of our 100 ka cycles (rapid deepening followed by a step-wise shallowing) bears a striking resemblance to those seen in the late Pleistocene (Lisiecki and Raymo, 2005) as 100 ka eccentricity cycles characterized rapid deglaciation followed by several

glacial pulses. This further reinforces the interpretation of a Cenozoic-style glaciation at the end of the Ordovician (Ghienne et al., 2014).

A second set of interpretations is based on a preliminary time-series analysis of our $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ stable isotope data (Sinnesael et al. 2016). The data shows an unambiguous link between stratigraphic cyclicity (and sea level variations) and isotopic record; thus suggesting the presence of a glacio-eustatic signal. The time-series analysis suggests a strong astronomical imprint of the precession, obliquity and eccentricity in the Vauréal isotopic datasets as well as the metre- and decametre-scale cycles present in the Vauréal Formation. The time series analysis in the Ellis Bay and Becscie formations also show evidence of astronomical imprint but are more difficult to match with their metre- and decametre-scale TR cycles. A full time-series analysis is in progress but beyond the scope of the present thesis.

2.6 Conclusions

- 1) This study is the first one to include an integrated facies description and cyclostratigraphic and chemostratigraphic analysis of the nearly complete stratigraphic interval spanning the O-S boundary, superbly exposed at low tide, along the west end of Anticosti Island.
- 2) Six major depositional facies are present in the upper Vauréal - Ellis Bay - lower Becscie succession representing mainly mid- to outer carbonate ramp sediment deposited under the influence of episodic storm events below the fairweather wave base. Shallow, inner-ramp facies are, however, present in the uppermost Ellis Bay Formation.
- 3) More than 80 metre-scale T-R cycles of various thicknesses have been identified within the upper Vauréal, entire Ellis Bay, and lowermost Becscie formations. These metre-scale cycles bundle to form 22 larger decametre-scale TR cycles.

- 4) Based on a cyclostratigraphic and a preliminary time-series analyses, we cautiously interpret the decametre-scale TR cycles as recording a 100 ka eccentricity signal, while the metre-scale cycles represent a mix of precession and obliquity forcing.
- 5) Finally, a multi-cyclic stratigraphic architecture, similar to the one seen in the late Pleistocene record, suggests a glacio-eustatic influence on the deposition of the studied succession.

2.7 References

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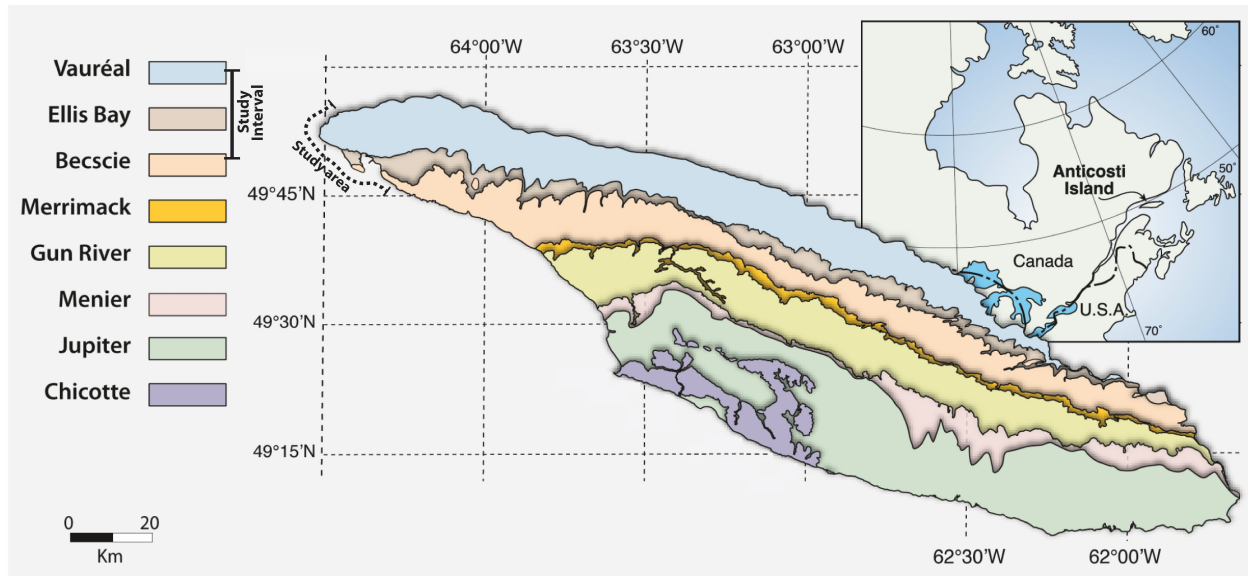


Figure 2.1. Location map (top right) of Anticosti Island (study area) and the bedrock geology. Studied stratigraphic interval and area are also outlined.

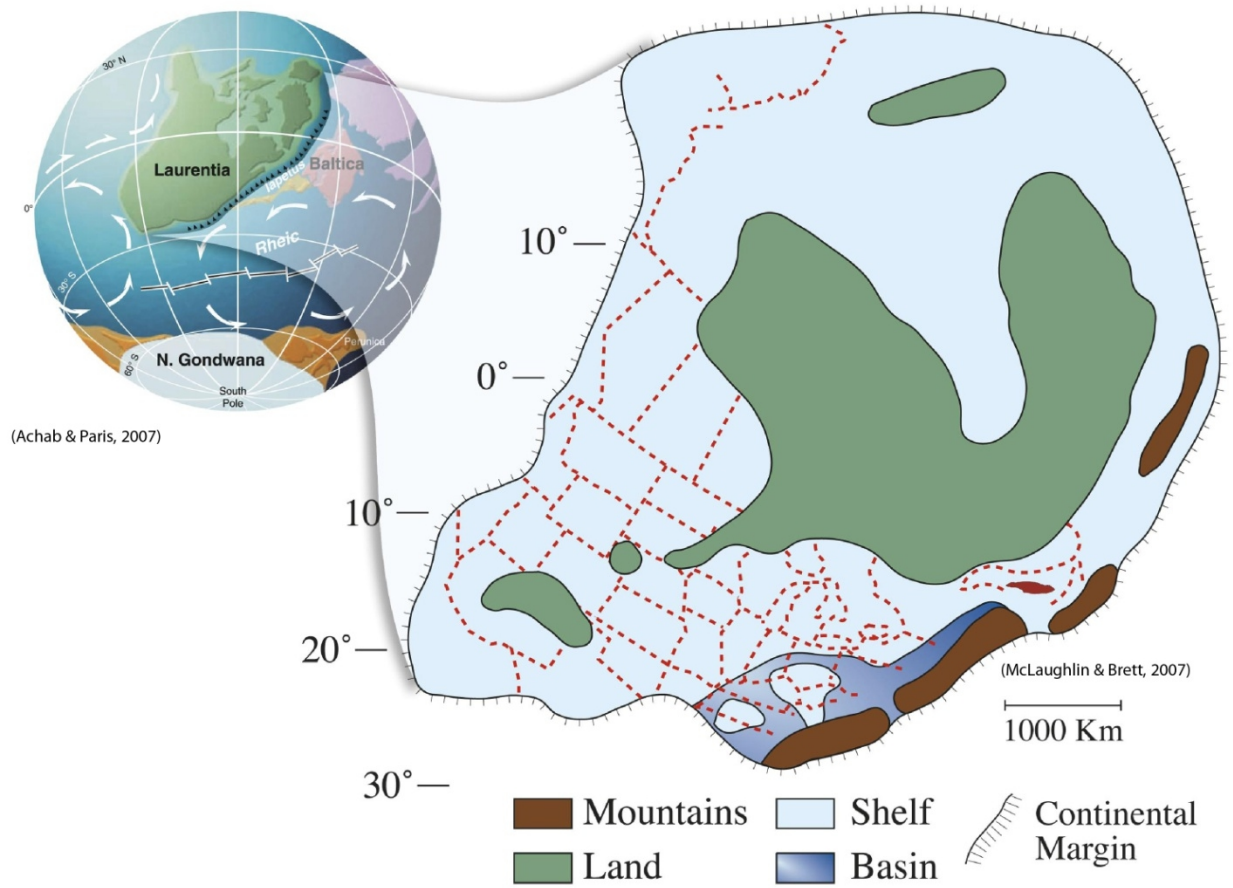


Figure 2.2. Regional and worldwide paleogeographic maps of showing the location of Anticosti Island during the end Ordovician (modified from Achab and Paris 2007, McLaughlin and Brett 2007).

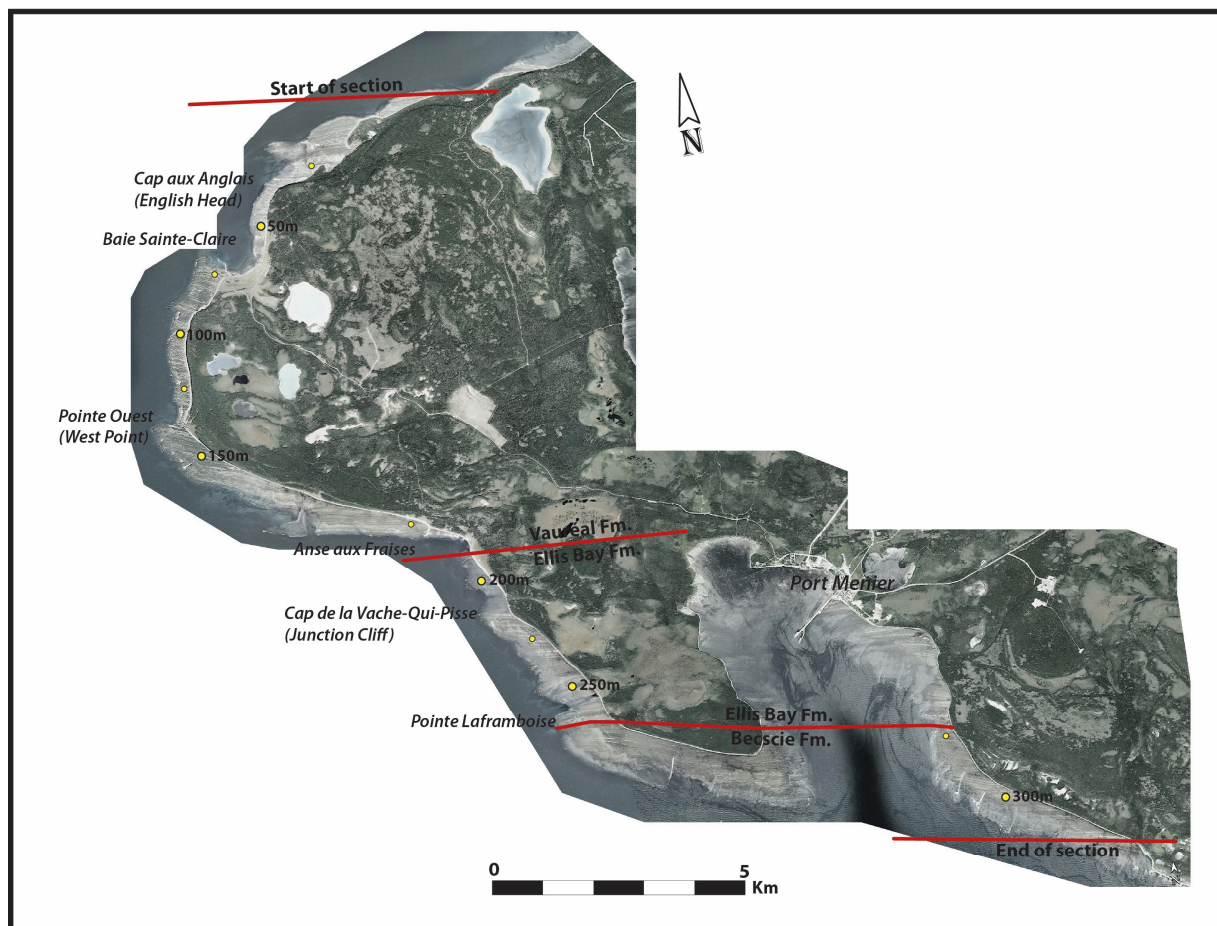


Figure 2.3. Satellite imagery showing the extensive development of rocky tidal flat exposures at the west end of Anticosti Island. The gently south dipping strata exposed at low tide provide a continuous 315 m thick section that was sampled at every ~0.6m. Yellow dots correspond to stratigraphic position in metres above the datum. Key lithostratigraphic contacts are also identified.

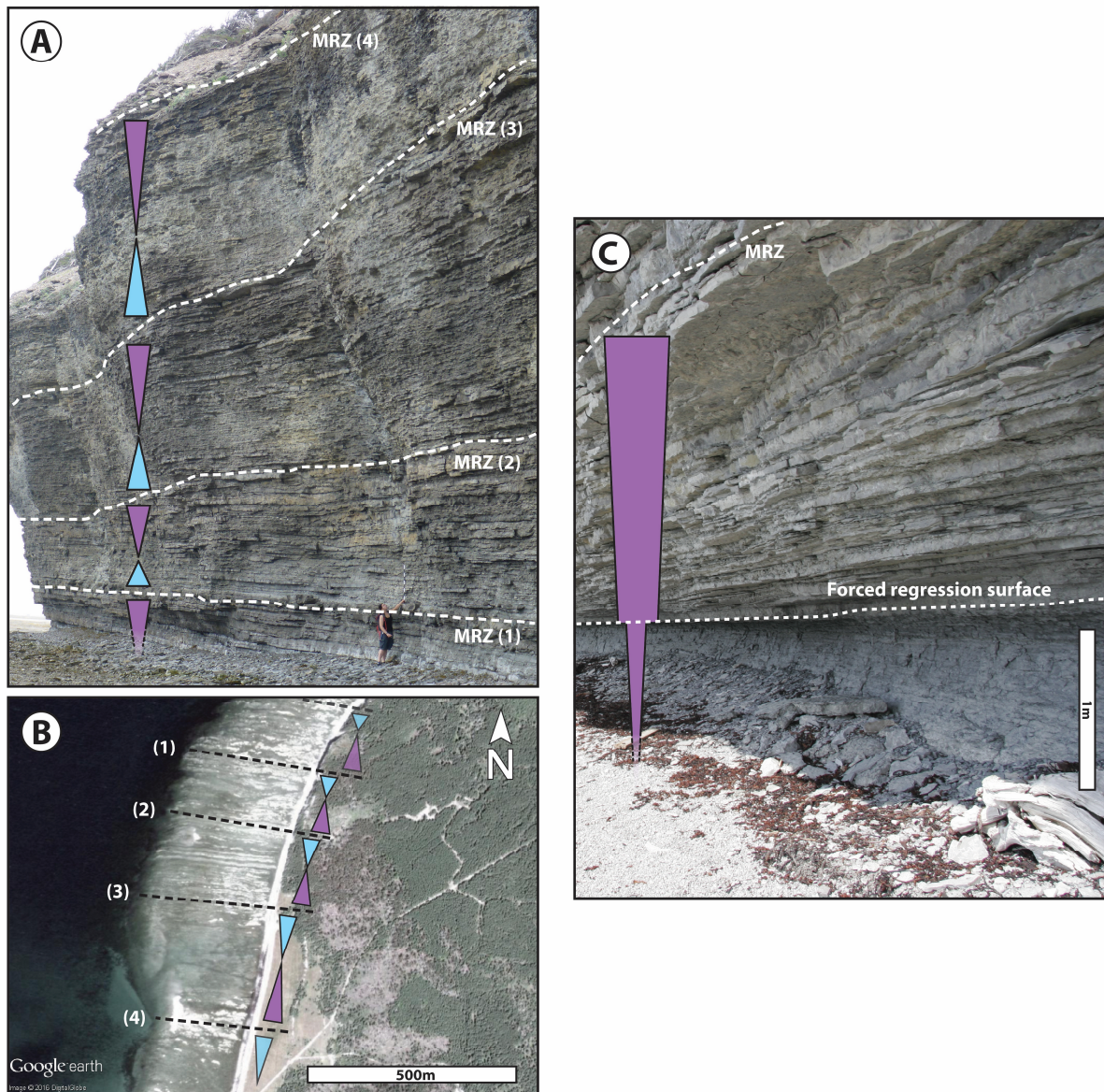


Figure 2.4. Coastal cliff exposure at Cap aux Anglais/ English Head (A) displaying several metre-scale TR cycles (TST in blue, RST in purple). Dotted line indicates MRZ. (B) Satellite imagery showing the the metre-scale TR cycles identified in (A) along the rocky tidal flat exposed at low tide. Note the preferential weathering of recessive units on coastal outcrop, accentuating the TR cycles. C) Coastal cliff exposure at Cap de la Vache-qui-Pisse/Junction Cliff displaying an abrupt facies offset within a TR cycle, which is identified as a forced regression surface.

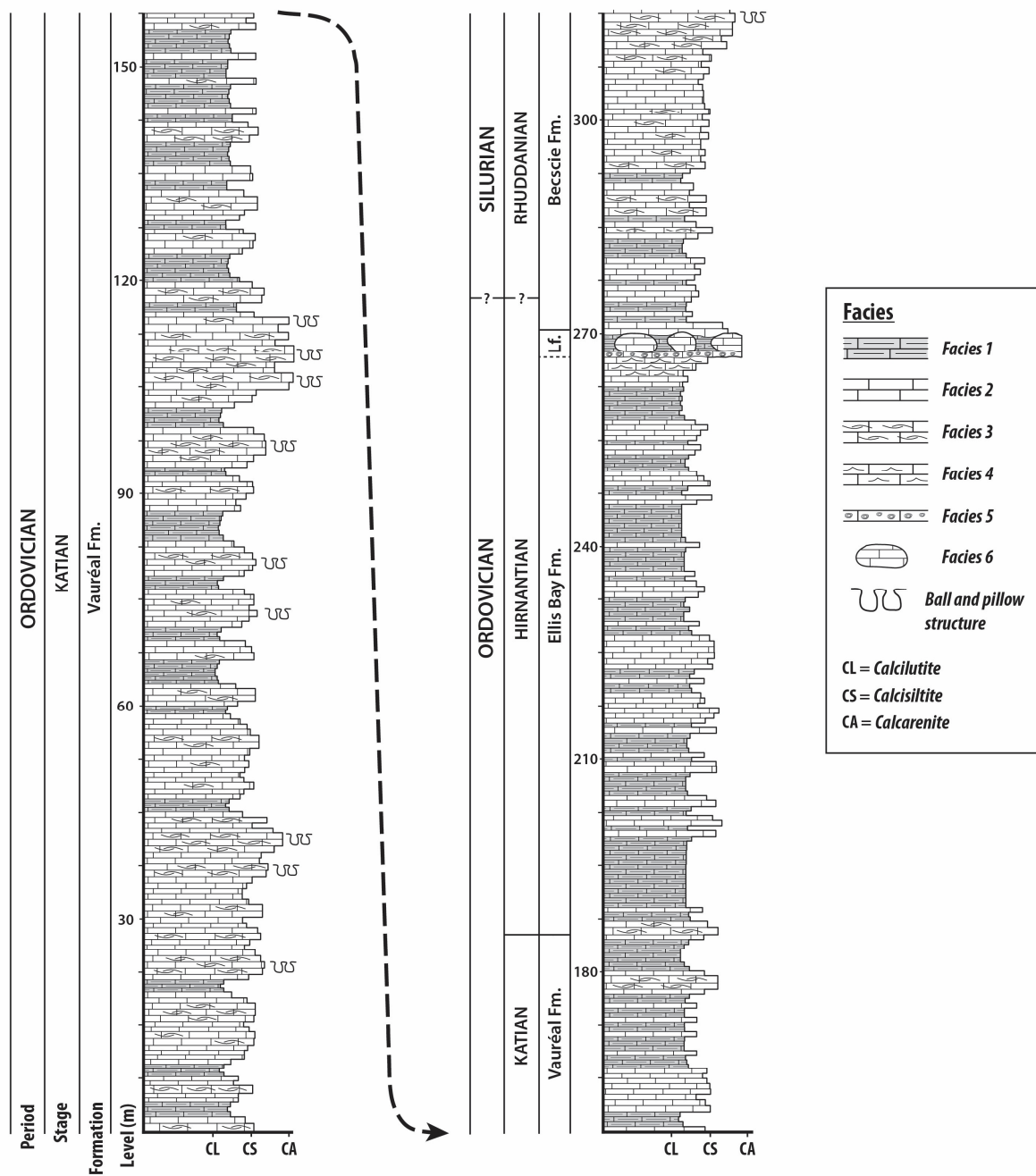


Figure 2.5. Stratigraphic log outlining the entire section (315 m). The section covers the Late Katian upper Vauréal, entire Hirnantian Ellis Bay, and lowermost Hirnantian/Rhuddanian Becscie formations. Facies descriptions are summarized in table 2.1.

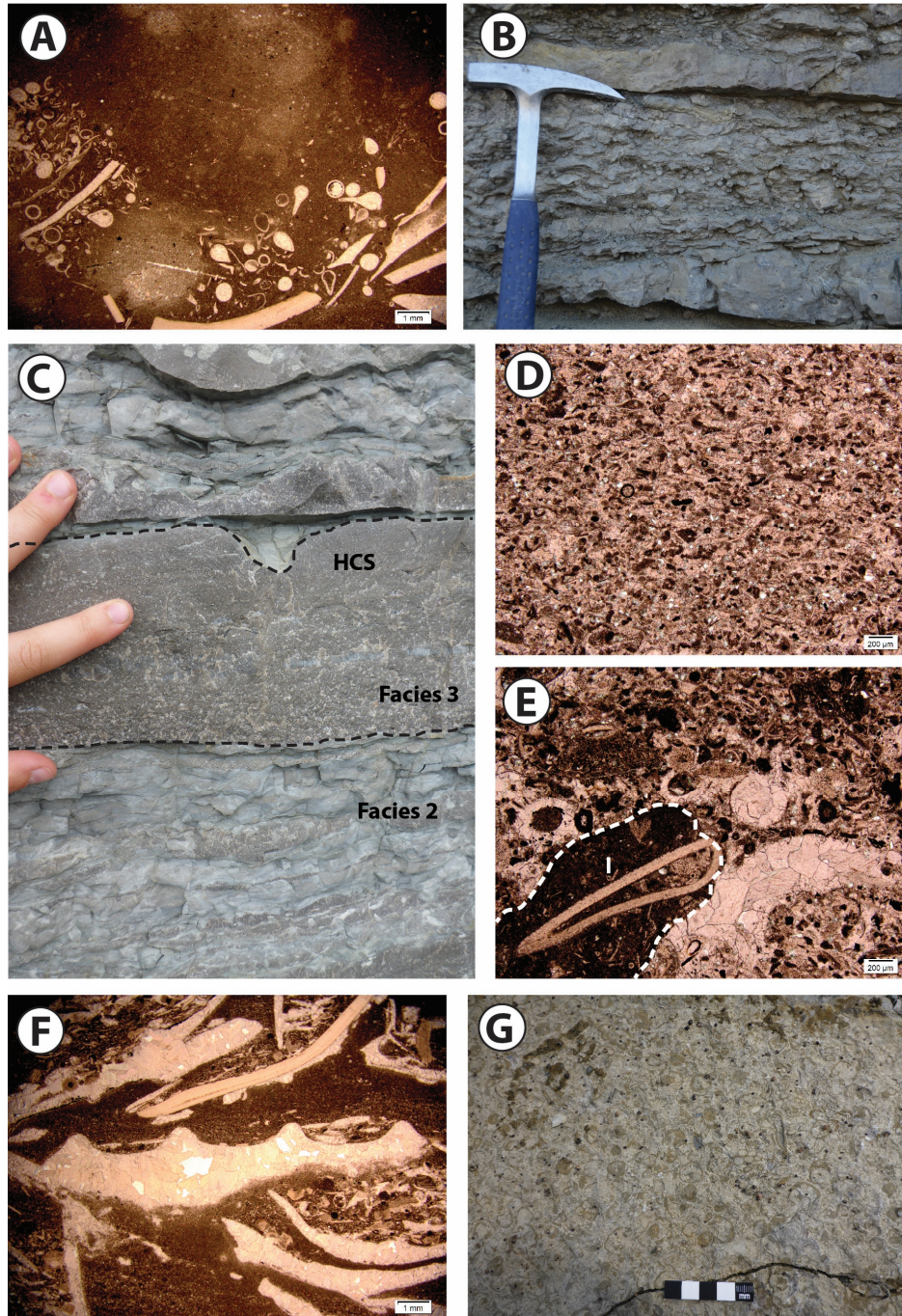


Figure 2.6. Field photos and photomicrographs of stained (30 um) thin sections under regular transmitted light, illustrating several facies described in table 2.1. (A) Facies 1 in photomicrography displaying, bioturbated calcareous mudstone/shale. (B) Facies 1 in outcrop seen in cross section. (C) Outcrop photo displaying in cross section both facies 2 (bottom) and facies 3 (middle) grading into HCS at top of bed. (D) Photomicrograph of HCS portion of the peloid rich facies 3. (E) Basal bed with an intraclast lag in facies 3. (F) Facies 2 in photomicrograph displaying a low diversity, bivalve rich assemblage. (G) Outcrop picture of a bedding plane showing the bivalve rich facies 2.

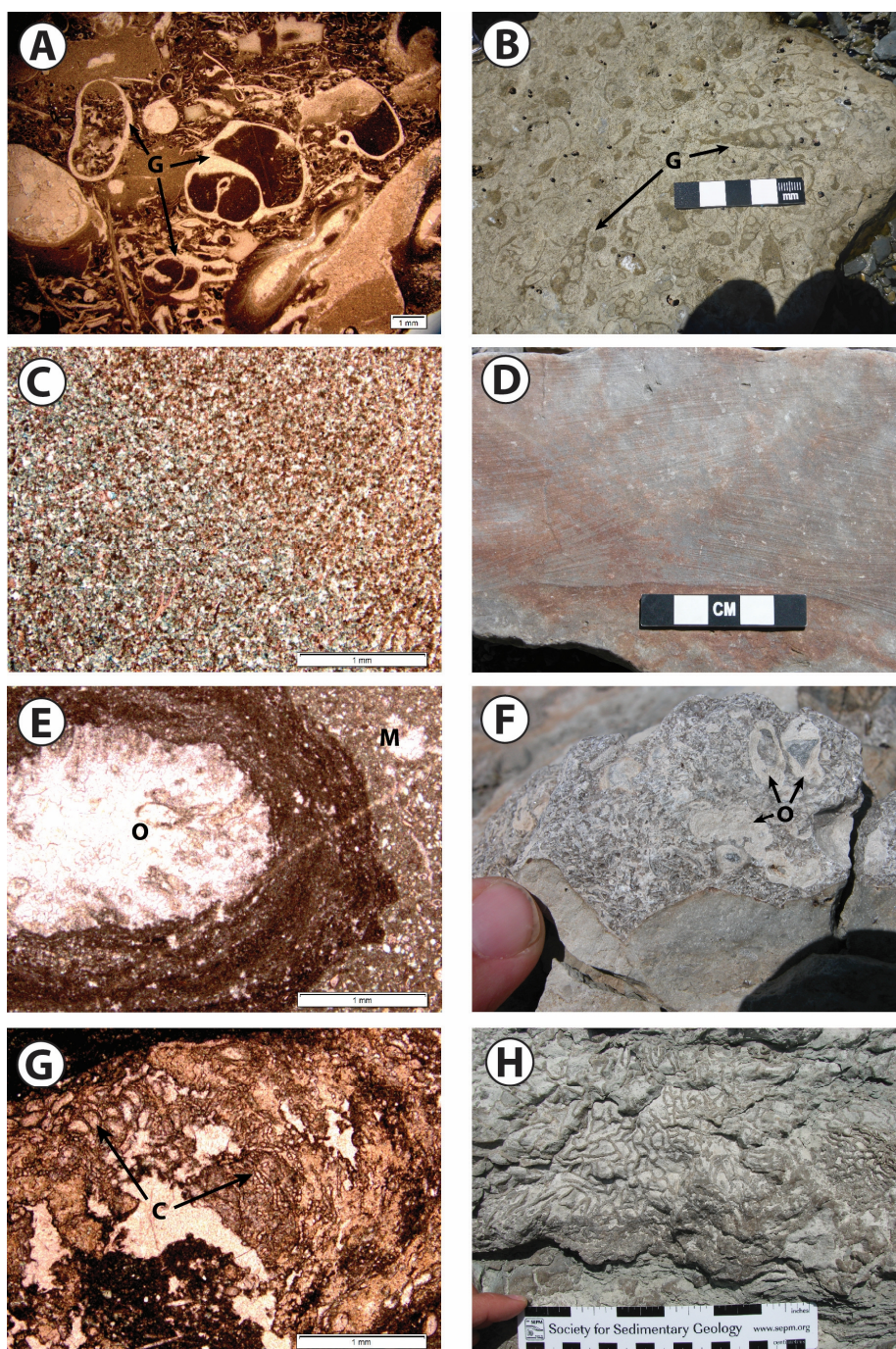


Figure 2.7. Field photos and photomicrographs of stained (30 um) thin sections under regular transmitted light, illustrating several facies described in table 2.1. (A) Photomicrograph showing facies 2 with a low diversity, gastropod (indicated with G) rich assemblage. (B) Field photo of a typical gastropod rich facies 2 in bedding plane view. (C) Photomicrograph of facies 4 displaying partially dolomitized (blue), quartz-rich peloidal sand in wave rippled calcarenite. (D) Outcrop picture of facies 4 displaying wave-ripple cross-stratification in cross section view. (E) Photomicrography of facies 5 showing a large microbial oncoïd (indicated with O) in a calcisiltite matrix. (F) Outcrop picture of facies 5 displaying cm-scale oncoïds in cross section view. Note the erosional contact with the underlying facies 4 at the base of the Laframboise Member near the top of the Ellis Bay Formation. (G) Photomicrograph of facies 6 displaying calcimicrobes (indicated with C) rich in a bioherm core. (H) Outcrop picture of facies 6 displaying common chain corals (*Halysites*) above a dense calcimicrobial crust in a bioherm core seen in cross section view

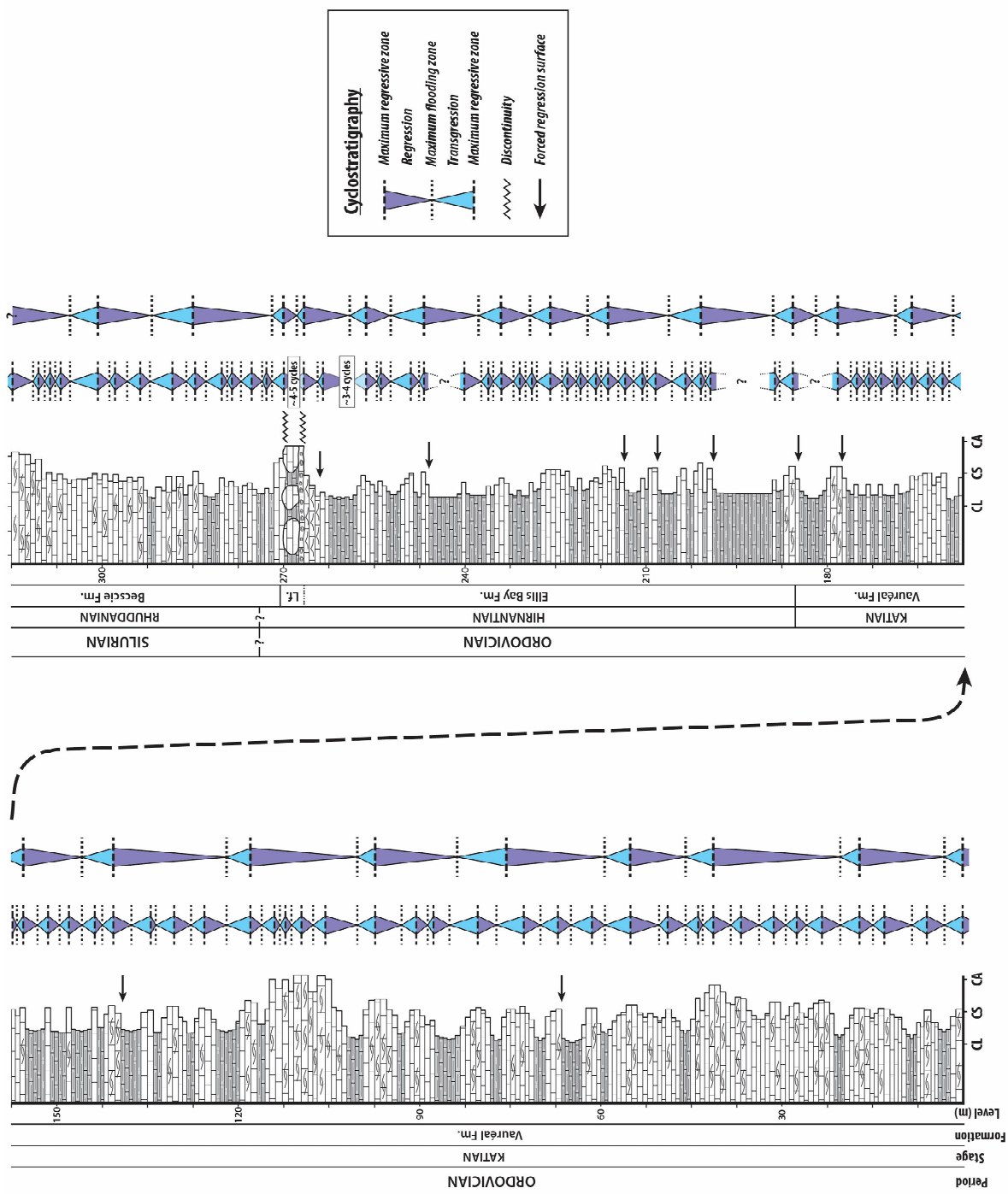


Figure 2.8. Stratigraphic logs (Fig. 2.5) coupled with metre-scale (left) and decametre-scale (right) Transgressive (blue) - Regressive (purple) cycles. Also included are important forced regression surfaces and discontinuities.

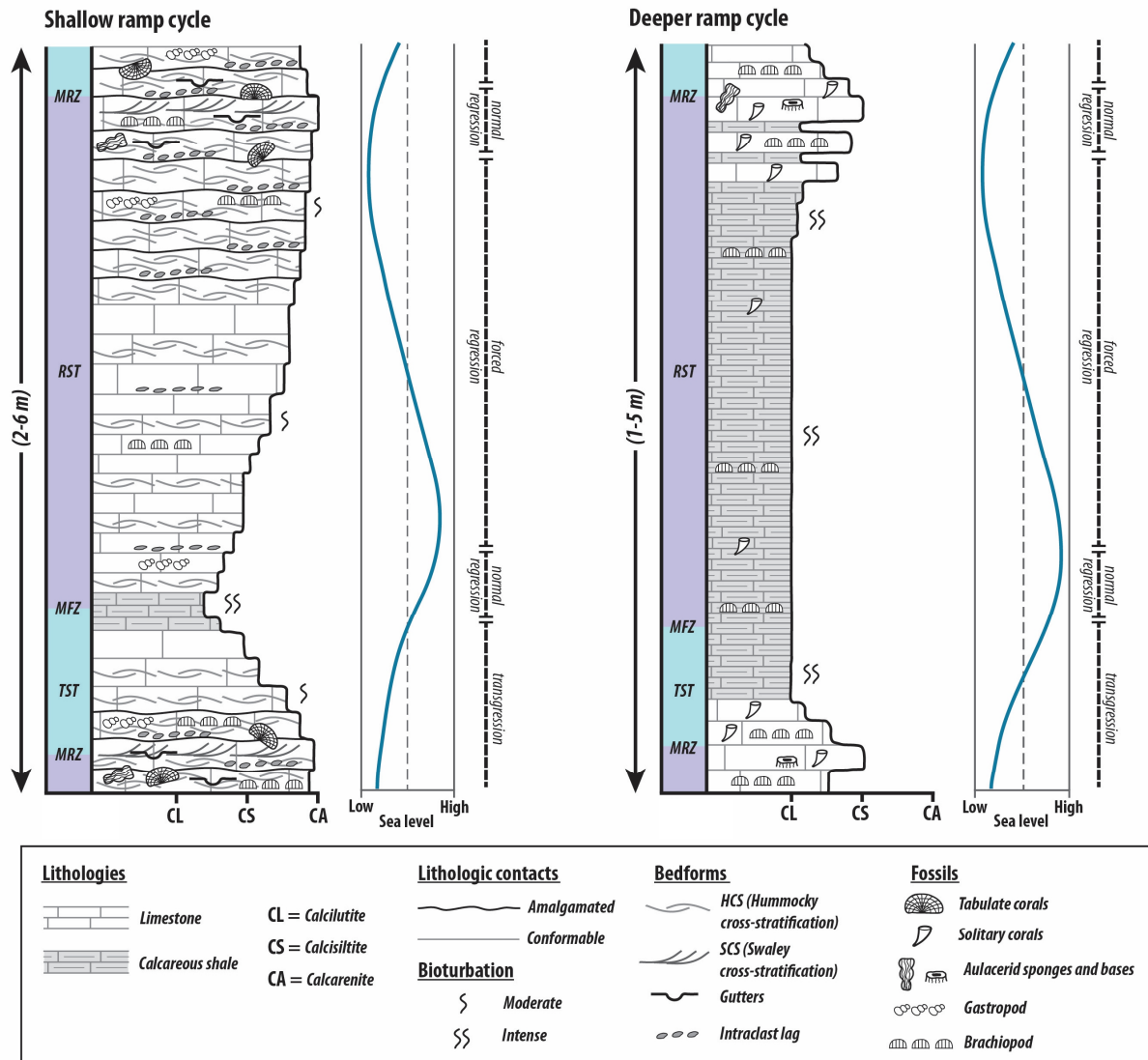


Figure 2.9. Schematic diagram showing the internal facies organization within metre-scale TR cycles along an idealized depositional ramp gradient. Key stratigraphic terms on the left-hand side of both proximal and distal metre-scale TR cycles include the following: Transgressive System Tract (TST), Maximum Flooding Zone (MFZ), Regressive System Tract (RST) and Maximum Regressive Zone (MRZ). The relative sea level curves on the right-hand side of both proximal and distal cycles are based on our facies interpretation. Note that the distal metre-scale TR cycles are generally thinner than the proximal ones.

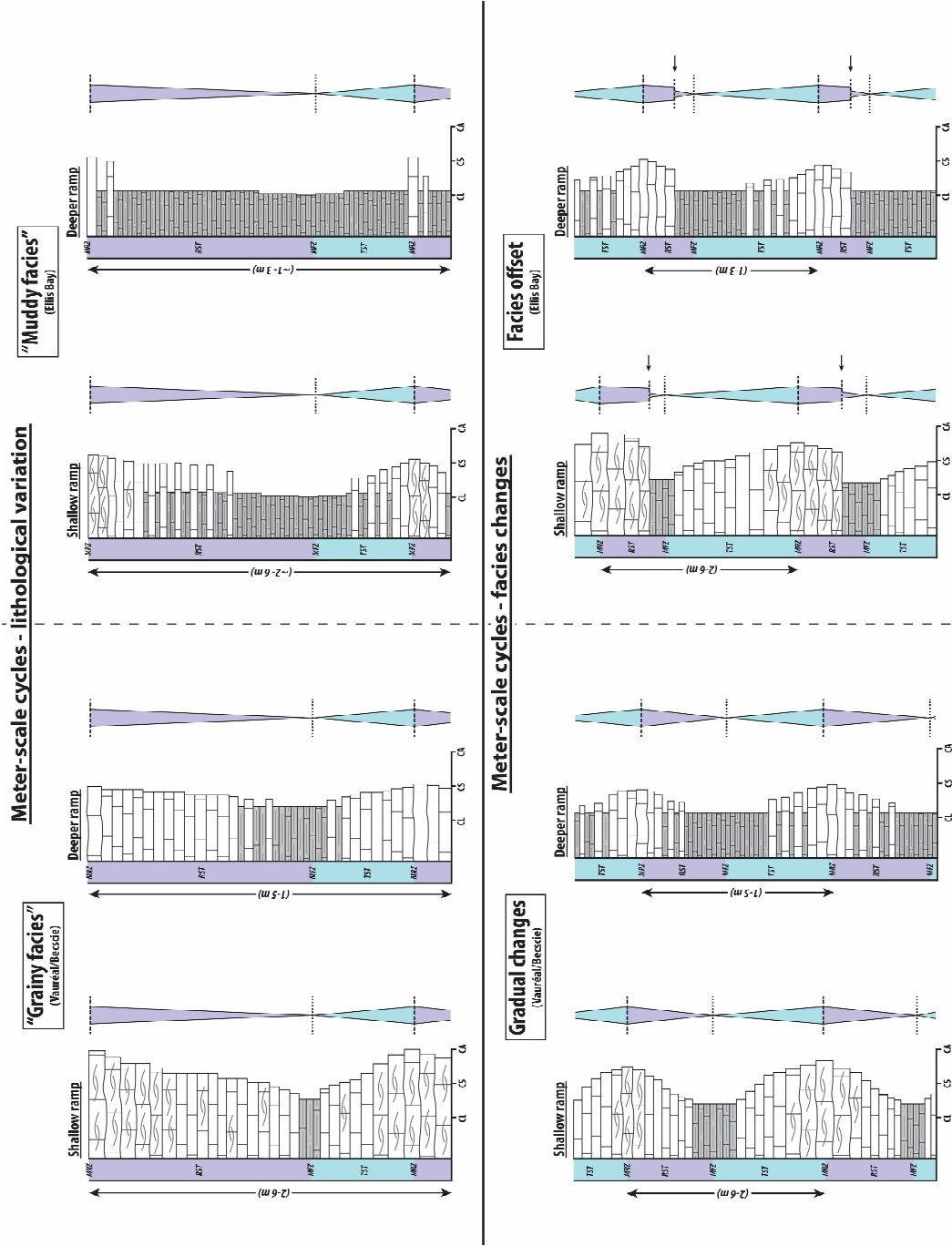


Figure 2.10. Schematic illustration showing variations in the metre-scale TR cycles. The upper panel displays lithological variations in the "grainy" (Vauréal and Becsiec formations) and more "muddy" (Ellis Bay Formation) metre-scale TR cycles. These cycle types represent sediments produced by two distinct carbonate factories. The lower panel shows variations in the possible vertical facies changes within a given metre-scale TR cycle. Metre-scale TR cycles display either gradual (lower left) or offset facies change (lower right). Some metre-scale TR cycles show a major facies offset in their RSTs where deeper muddy ramp facies are abruptly overlain by shallower clean ramp facies. These abrupt facies changes correspond to forced regression surfaces driven by a rapid sea level drop. See Figs. 2.8 or 2.9 for a symbol legend.

Facies		Description	Interpretation
1-Bioturbated calcareous shale		Massive to fissile, thin nodular bedding, dark grey calcareous shale, locally mixed with quartz silt particles, variously bioturbated; poorly fossiliferous. Interbedded with facies 2 and 3.	Fair weather deposition between storm events on the mid- to outer ramp setting (between SWB and FWWB; occasionally below SWB).
2-Graded calcilutite/calcarenites		Thin- to medium bedded, fine-grained calcilutite/calcarenites with a thin basal graded bioclastic calcarenite interbedded with facies 1; Basal calcarenite layer locally contains crinoidal material of siliclastic silt-sized grains. Both in situ and reworked shells; monotypic to very low diversity shell assemblage including large, thick-shelled, inarticulate brachiopods, bivalves or gastropods in a matrix of peloid/fine bioclast to coarse micrite.	Inner- to mid ramp setting (between SWB and FWWB); Episodic storm event.
3-HCS/SCS calcilutite/fine calcarenite		Medium- to thick-bedded calcilutite to fine calcarenite interbedded with facies 1; a abundant well sorted peloids and highly abraded bioclasts; Basal intraclast lag when present grading upwards into HCS/SCS; Scoured base locally with shale rip-up clasts, HCS with 3-8 m wavelength; HCS beds are locally amalgamated; locally slumped beds expressed as ball and pillow structures.	Inner- to mid ramp setting (between SWB and FWWB); Episodic storm event. Slumped bed likely a result of seismic events.
4-Wave ripple/small-scale HCS calcarenite		Medium- to thick bedded, wave ripple to amalgamated HCS calcarenite with sub-meter wavelength; Abundant peloids and highly abraded bioclasts; Scoured base overlain by a thin, but coarser, bioclastic lag; Minor dolomitization; Only present in the Upper Lousy Cove member of the Ellis Bay Formation and capped by a regional discontinuity.	Inner ramp to shoreface setting; Constantly agitated environment by wave and storm deposition.
5-Oncolitic calcirudite		Poorly-bedded, massive unit (10-100 cm thick) resting on an erosion surface of regional extent with an intraclast lag deposit; Abundant calcimicrobial oncolites; Common fine-grained fabric ranging from calcirudite to fine calcarenite, cross-bedded to wave ripple cross-lamination locally present; Associated large, highly abraded mega-fossils (solitary rugose corals, tabulate corals, stromatoporoids, bryozoans); Only present at the base of the Laframboise member of the Ellis Bay Formation.	Beach to shoreface sands and gravels deposited in a highly agitated setting above FWWB; Basal transgressive deposits.
6-Calcimicrobial-coral bioherm		Up to 5.0 m thick, stratigraphic reef cores interfingering with thin-bedded, mud-supported bioclastic limestone and shale; 10-30 cm thick amalgamated boundstone layers separated by shale partings with, in order of importance: calcimicrobes, tabulate corals, bryozoans, and stromatoporoids; Bioherms capped by an erosional surface of regional extent exhuming resistant cores and removing partially to totally inter-reef facies; Paleorelief up to 1.5 m draped by basal Beccles strata; Overlying facies 5 in the Laframboise member of the Ellis Bay Formation.	Inner mid-ramp patch reefs.

Table 2.1. Facies descriptions and interpretations of the studied succession

Stage	Thickness (m)	Time (ka)	Eccentricity		Obliquity		Precession	
			m/400 ka	m/100 ka	m/30 546 a	m/37 222 a	m/ 16 399 a	m/19 297 a
Rhuddanian	155	3000	20.67	5.17	1.58	1.92	0.85	1.00
Hirnantian	90	1400	25.71	6.43	1.96	2.39	1.05	1.24
Katian (KA4)	1020	3300	123.64	30.91	9.44	11.50	5.07	5.96

Table 2.2. Expected TR cycle thicknesses in an astronomical context in metres/thousand years (ka) and year (a). Only the relevant time stages are represented in this table. The thicknesses of Katian (Ka4), Hirnantian and Rhuddanian strata in the Anticosti Basin are based on McLaughlin et al. (2016), Mauviel and Desrochers (2016), and Long (2007) respectively. The stage duration is based on Cooper and Sadler (2012) and Melchin et al. (2012).

Chapter 3: $\delta^{18}\text{O}$ chemostratigraphy

3.1 Introduction

Oxygen isotope chemostratigraphy has greatly improved our understanding of Earth's paleoclimate systems and has enabled paleoreconstructions of the chemistry of Phanerozoic oceans (Grossman 2012). Strata exposed on Anticosti Island in Eastern Canada represent one of the key sedimentary records spanning the Ordovician-Silurian (O-S) boundary, and have been subject to numerous chemostratigraphic studies over the past 30 years (Orth et al. 1986; Long 1993; Brenchley et al. 1994; Carden 1995; Underwood et al. 1997; Azmy et al. 1998; Bergström et al. 2006; Young 2008; Desrochers et al. 2010; Jones et al. 2011; Delabroye et al. 2011; Wickson 2010). These studies focused largely on the carbon isotopic signature of the Anticosti succession but also presented their associated $\delta^{18}\text{O}$ values (Orth et al. 1986; Long 1993; Brenchley et al. 1994; Carden 1995; Azmy et al. 1998; Young 2008; Jones et al. 2011). They have, however, several pitfalls (i.e. limited stratigraphic intervals, low sample resolution, significant stratigraphic gaps, diagenetic resetting...) which encumber the interpretation of the geochemical signal. In this study, we present the first high-resolution $\delta^{18}\text{O}$ record coupled with cyclostratigraphic data obtained from the continuous rocky tidal outcrop spanning the O-S boundary at the west end of Anticosti Island and discuss the possible preservation of the original $\delta^{18}\text{O}$ signal in the deep geological time.

3.2 Geological Context

The well-preserved, fossiliferous Anticosti succession was deposited on the southern equatorial belt along the eastern margin of Laurentia in a highly subsidizing foreland basin (Bordet et al. 2010). This exceptionally thick and tectonically undisturbed succession totals more than 2 km of Sandbian to Telychian stratigraphy (Ghienne et al. 2014; McLaughlin et al. 2016). The upper 900 m, exposed on Anticosti Island, constitutes a comprehensive late Ordovician to early Silurian stratigraphic record (Long 2007). The Anticosti succession is one or two orders thicker than age equivalent carbonate sections deposited in similar epeiric or ramp settings (e.g. Sandbian to Katian= ~1600 m, Hirnantian= ~100 m, Rhuddanian to mid Telychian= ~500 m) and enabled by a sustained sediment supply and high subsidence rates (Ghienne et al. 2014).

3.3 Methods

Our study is the first to sample the previously unexploited, complete stratigraphic interval, exposed on the rocky tidal flats at low tide, along the west coast of Anticosti Island. This studied interval covers the upper Vauréal (late Katian), Ellis Bay (Hirnantian), and lower Becscie (latest Hirnantian/early Rhuddanian) formations. The western Anticosti strata are predominately composed of mid to outer ramp storm-deposited carbonates with no obvious break in sedimentation, except at the base and top of the reefal Laframboise member of the Ellis Bay Formation (Desrochers et al. 2010). The chosen sample type is bulk rock, which is not dependent on the sporadic distribution of brachiopods and allows to sample a continuous, high-resolution isotopic stratigraphic record. The studied section covers a 315 m stratigraphic interval (e.g. 185 m of Vauréal, 85 m of Ellis Bay and 45 m of Becscie formations). A total of

512 geochemical samples, equally spaced at every ~0.6 m were taken along the coastal section. A subset of samples were taken at a higher (~0.15 m) resolution in the Laframboise member of the uppermost Ellis Bay Formation. 65 samples were thin-sectioned and stained (Dickson 1966) and analyzed under transmitted light and cathodoluminescence (CL) microscopy for diagenetic screening. Another subset of the geochemical samples (55 equally spaced samples) was further analyzed for trace elements. The finest available micritic (occasionally peloidal) material from each hand sample was microdrilled for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, and trace element geochemical analyses. Stable isotope analyses were performed on a Gas Bench II interfaced with a Finnigan Mat Delta XL mass spectrometer at the G.G. Hatch Laboratory, University of Ottawa. Data are reported here as $\delta^{18}\text{O}$ in permil (‰) with respect to the Vienna Pee Dee Belemnite, or VPDB standard. The analytical precision is $\pm 0.1\text{‰}$. Trace element geochemistry was performed on a Varian (Agilent) Vista-Pro Inductively Coupled Plasma Emission Spectrometer (ICP-ES) equipped with a CCD detector at the Geochemistry Geosciences Laboratory, University of Ottawa. Data are reported in parts per million (ppm) with an Mn and Sr detection limit of 0.016 ppm and 0.034 ppm respectively.

3.4 Results

Our continuous 315 m thick sequence of $\delta^{18}\text{O}$ data points (Fig. 3.1) spanning the O-S boundary at the west end of Anticosti Island shows a long-term $\delta^{18}\text{O}$ single broad cycle, spanning the upper Vauréal to lower Becscie interval, with maximum $\delta^{18}\text{O}$ values in the Hirnantian Ellis Bay Formation (on average ~0.5‰ higher values than those in the Vauréal and Becscie formations). Three smaller $\delta^{18}\text{O}$ changes are superimposed on this long-term trend including: i) in the late Katian (0-150 m level in Fig. 3.1), ii) in the latest Katian to early

Hirnantian (150-260 m level in Fig. 3.1), and iii) in the latest Hirnantian continuing into the Early Rhuddanian or Silurian (260 and above? in Fig. 3.1). The Vauréal $\delta^{18}\text{O}$ metre- and decametre-scale variations are typically 0.5-1‰ in magnitude while those in the Ellis Bay Formation (excluding the large positive excursions) are 0.25-0.5‰. The only stratigraphic level that contains more negative values occur near the Laframboise Member in the uppermost Ellis Bay Formation (~265-270 m level in Fig. 3.1). These negative values coincide with two sub-aerially exposed surfaces (i.e. discontinuities at base and top of Laframboise Member) below which $\delta^{18}\text{O}$ depleted meteoric waters alter the original marine isotopic oxygen signal. Our $\delta^{18}\text{O}$ curve is well constrained by late Katian to early Rhuddanian chitinozoan biozones in the upper Vauréal, Ellis Bay, and lower Becscie formations (Achab et al. 2011, 2013). Concordant paleontological evidence supports that the entire Ellis Bay Formation is of Hirnantian age (Achab et al. 2011, 2013; see also the supplemental material of Ghienne et al. 2014). For an alternative view on the age of the lower Ellis Bay Formation, the reader is referred to Kaljo et al. (2008) or Bergström et al. (2011). Supplemental information accompanying this paper includes *i*) a table compiling $\delta^{13}\text{C}/\delta^{18}\text{O}$ and Sr/Mn trace element data with their stratigraphic position above the datum and GPS localities (Appendix A), and *ii*) $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ cross-plots of studied stratigraphic units (Appendix B).

3.5 Preservation of $\delta^{18}\text{O}$ signal

The micrite-dominated matrix was the target for bulk carbonate sampling. Confidence in retention of a near-primary $\delta^{18}\text{O}$ signal is based on numerous visual and geochemical evidences. The carbonate matrix is composed of dense, aphanocrystalline calcite (<10 μm) and exhibits neither aggrading neomorphic fabric nor minimal dolomitization as evidenced by the pink

staining of all thin-sections with Dickson solution (Dickson 1966). In CL, micrite matrix reveals no to weakly dull luminescence indicating low Fe^{2+} and Mn^{2+} contents. The conodont elements with colour alteration indices are 1.0 and 1.5 suggesting that any diagenetic stabilization occurred at relatively low burial temperatures (Nowlan and Barnes 1981).

In terms of geochemical data, covariation of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values in marine carbonates is commonly regarded as evidence for diagenetic alteration (Lohmann 1988; Marshall 1992). Our data show no significant correlation between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ ($r^2 \leq 0.4$; appendix B) with the exception of the Laframboise member of the Ellis Bay Formation ($r^2 = 0.7$), where two regional discontinuities are present. Significantly depleted $\delta^{18}\text{O}$ values resulting from meteoric alteration can be found immediately below these subaerial surfaces.

The content in Mn of our sampled micrites is similar to those found in well-preserved brachiopod shells from the Ellis Bay Formation (Shields et al. 2003) and modern brachiopod shells. The content in Sr is only slightly depleted when compared to the same brachiopod datasets (Fig. 3.2). Any covariance between Mn and Sr values should be attributed to a diagenetic trend. In addition, there is a notable lack of correlation between Mn and Sr ($r^2 = 0.005$) as well as for the Mn/Sr and $\delta^{13}\text{C}/\delta^{18}\text{O}$ ($r^2 = 0.036$, $r^2 = 0.049$ respectively). In a previously published study (Al-Aasm and Veizer 1982), trace element geochemistry of some lower Ellis Bay carbonates shows Mn and Sr values for bulk rock samples that are heavily depleted and enriched respectively in comparison to brachiopods present within the same sample. Our trace element data shows similar results for the Lower Ellis Bay strata near the Cap de la Vache-Quei-Pisse/Junction Cliff. These depleted Sr and enriched Mn values, however, are not representative of the rest of the formation; thus are treated here as outliers.

Despite the known complications with the bulk rock $\delta^{18}\text{O}$ analyses, we feel that the petrographic and geochemical evidences presented above support, a near-primary preservation of the $\delta^{18}\text{O}$ signal, reflecting values in equilibrium with their paleoenvironmental conditions.

3.6 Discussion

In the following section, we decipher short and long-term $\delta^{18}\text{O}$ variations in association with both metre- and decametre-scale TR cycles (see chapter 2).

Our new complete and continuous $\delta^{18}\text{O}$ curve spanning the Ordovician-Silurian boundary rectifies the problems of previously published curves within parts of the same succession. One study covered a limited stratigraphic interval (Orth et al. 1986), while several studies display low sampling resolution (Long 1993; Brenchley et al. 1994; Carden 1995) and significant stratigraphic gaps in sampling exclusively cliff exposures (Young 2008; Jones et al. 2011).

Calcitic lime mud was the primary inorganic marine calcium carbonate precipitate at the time of the deposition; a time of calcite sea (Stanley and Hardie 1998). Changes in $\delta^{18}\text{O}$ values from well-preserved micrite samples are, however, not easy to interpret since they usually indicate a combination of changes in temperature, salinity, and ice volume (Elrick et al., 2013). During time of glaciation, isotopic values within a given cycle are expected to be at their lowest at, or near, the deeper water facies while their highest values are at, or near, the shallowest water facies, caused by preferential evaporation and stocking of the lighter ^{16}O in growing ice sheets at higher latitudes. The long-term $\delta^{18}\text{O}$ changes of the entire succession (Fig. 3.2) support a protracted glaciation event peaking during the Hirnantian. The superimposed three higher frequency variations in $\delta^{18}\text{O}$ and values suggest three distinct glacial-interglacial episodes during the latest Ordovician time as recently reported by Ghienne et al. (2014). The highly positive

values in the Laframboise member are interpreted to represent the peak of this protracted glaciation; thus the time with the lowest sea level and highest ice volume trapped on high latitude paleocontinents.

Fig. 3.3 illustrates the metre-scale TR cycles with high frequency $\delta^{18}\text{O}$ fluctuations. The relationship is far from perfect; some cycles correspond well with the oxygen curve while others do not. The nature of the signal is chaotic to make significant correlations and the sample resolution is too small to properly capture the thinnest TR cycles (e.g. Ellis Bay Formation). The distal deeper facies in the lower Ellis Bay strata show apparent $\delta^{18}\text{O}$ variations without significant lithological changes. These "missing beats" likely reflect the largest depositional water depth gradient recorded by these distal facies in comparison to the more proximal facies. Local environmental factors could also contribute to the background noise of our data, complicating interpretation at that level. $\delta^{18}\text{O}$ variations in metre-scale TR cycles are typically around 0.5‰–1‰ within the Vauréal Formation and 0.25–0.5‰ within the Ellis Bay and Becscie formations. The only exception is found in the Laframboise member of the Ellis Bay Formation, where $\delta^{18}\text{O}$ values are more negative, but could be attributed to some meteoric diagenetic alteration occurring below ancient subaerial exposure surfaces.

The $\delta^{18}\text{O}$ variations in decametre-scale TR cycles, however, appear to correlate better than those at the metre-scale (Fig. 3.4). The resolution of our dataset is, here, sufficient to capture the coupling trends between the facies changes within a given decametre-scale TR cycles and the $\delta^{18}\text{O}$ variations. Within most of our decametre-scale TR cycles, $\delta^{18}\text{O}$ values are rapidly decreasing in their thinner TST portions while the $\delta^{18}\text{O}$ values are slowly increasing in their thickest RST portions. $\delta^{18}\text{O}$ variations in decametre-scale cycles are similar in scale to those present in the metre-scale cycles (i.e. 0.5‰–1‰ in the Vauréal Formation and 0.25–0.5‰ in the

Ellis Bay and Becscie formations). Thus, the frequency and amplitude $\delta^{18}\text{O}$ variations within the metre- and decametre-scale cycles show a striking similitude with those seen in astronomically tuned, glacioeustatic influenced $\delta^{18}\text{O}$ curves during the Pleistocene (Lisiecki and Raymo, 2005).

In summary, our $\delta^{18}\text{O}$ data are in accordance with sea-level reconstructions based on our sedimentological and stratigraphic interpretation and support our hypothesis that glacioeustasy was the dominant control on water-depth changes during the time interval spanning the O-S boundary. A prime control by changes in ice volume is also suggested by the $\delta^{18}\text{O}$ values from well-preserved conodont apatite (Elrick et al., 2013) recently reported in some metre-scale TR cycles of the Vauréal Formation in the central part of Anticosti Island.

3.7 Conclusions

- 1) Our new complete and continuous $\delta^{18}\text{O}$ curve spanning the Ordovician-Silurian boundary at the west end of Anticosti Island rectifies the problems of previously published curves.
- 2) Sedimentological and geochemical evidence supports, a near-primary preservation of the $\delta^{18}\text{O}$ signal which is unusual for bulk rock (micrite) samples in the deep geological time.
- 3) The long-term $\delta^{18}\text{O}$ changes of the entire succession support a protracted glaciation event peaking during the Hirnantian, in particular in the Laframboise member. Three superimposed higher frequency variations in the $\delta^{18}\text{O}$ values suggest the presence of three distinct glacial-interglacial episodes during the latest Ordovician time.
- 4) Unlike the metre-scale TR cycles, the 22 decametre-scale TR cycles in the studied succession correlate well with their associated $\delta^{18}\text{O}$ variations; thus supporting a Cenozoic-style glacial-interglacial scenario and controlling the development of a multi-order cyclic stratigraphic architecture coupled with distinct $\delta^{18}\text{O}$ variations during the late Ordovician-early Silurian.

3.8 References

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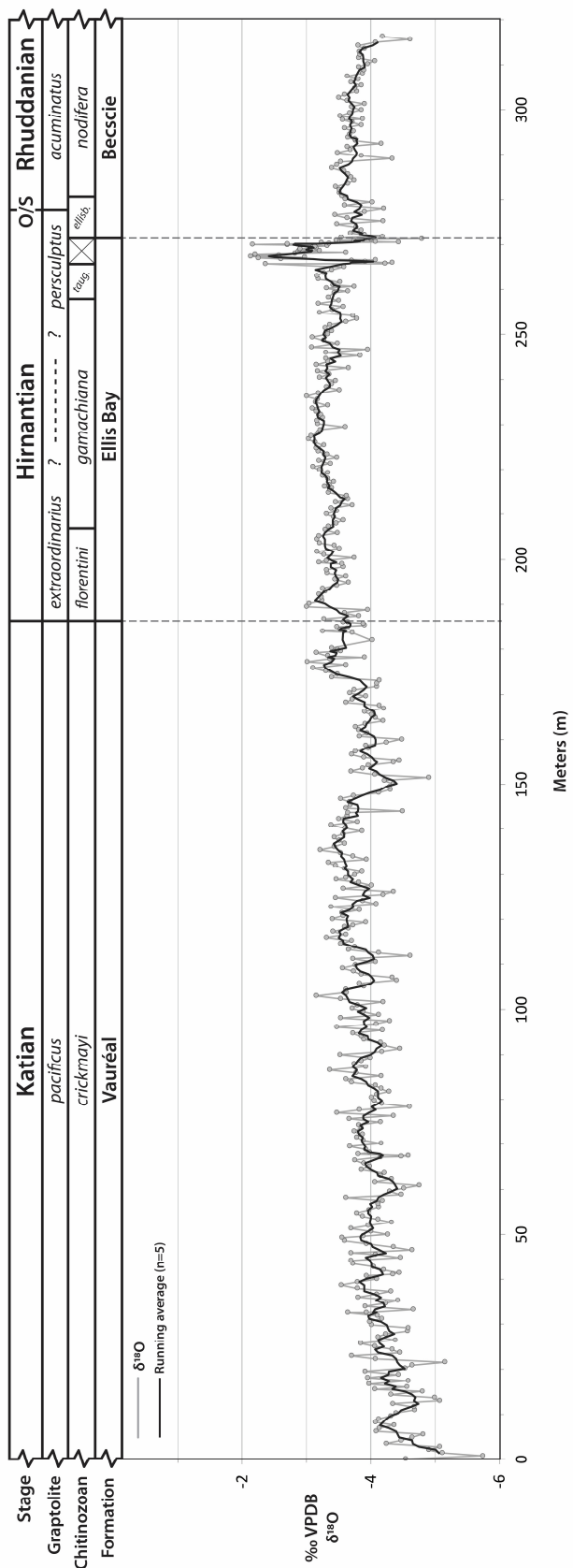


Figure 3.1. Biostratigraphic framework (Ahab et al. 2013; Desrochers et al. 2010) and $\delta^{18}\text{O}$ chemostratigraphic profile of the upper Vauréal, Ellis Bay and Beccie formations exposed at the west end of Anticosti Island.

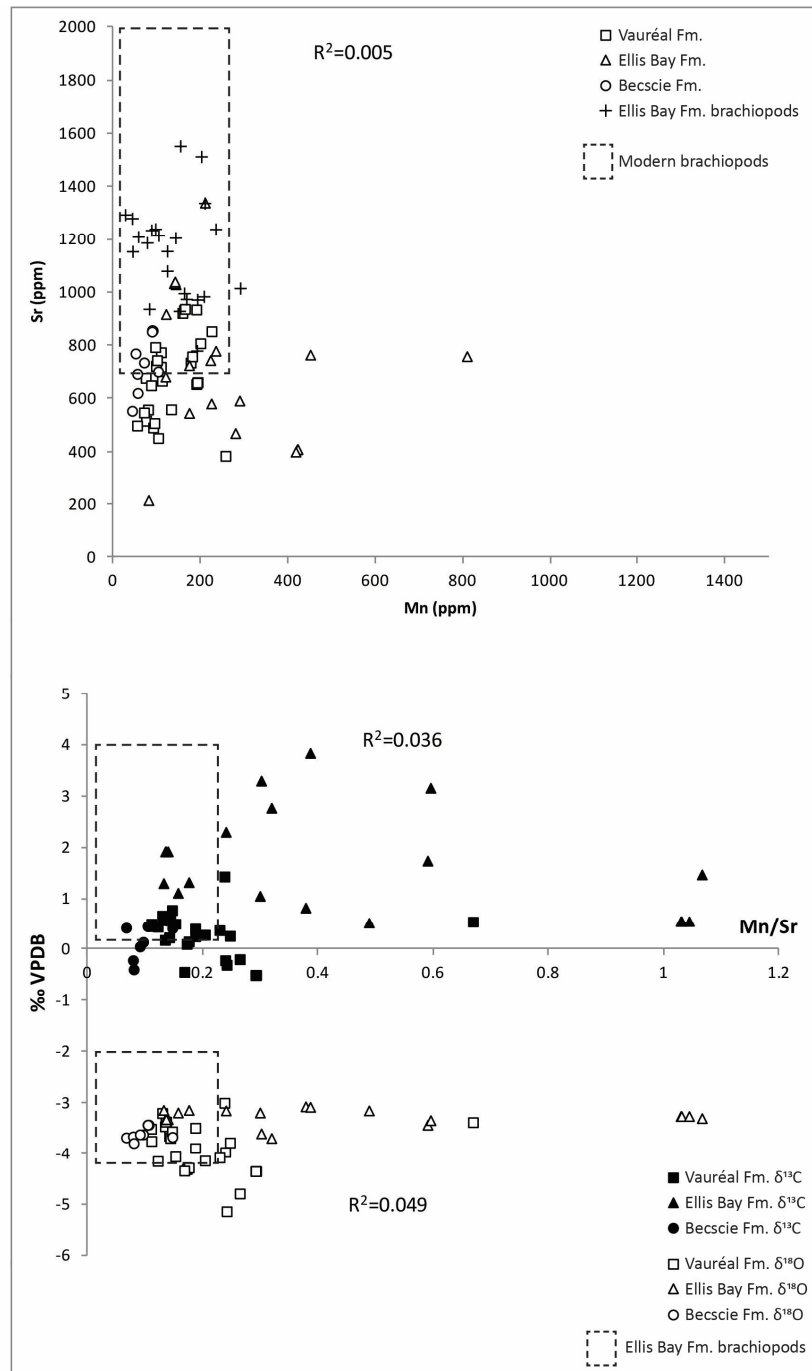


Figure 3.2. (Upper part) Scatter diagram of Mn/Sr (ppm) ratios for bulk rock micrite data by formations. The Ellis Bay Formation brachiopod values are from Shields et al. (2003). The box represents trace element ranges for Holocene brachiopods. (Lower Part) Scatter diagram of Mn/Sr (ppm) ratios vs $\delta^{18}O/\delta^{13}C$ (%VPDB). The boxes represent similar ratios for the Ellis Bay brachiopod shells from Shields et al. (2003).

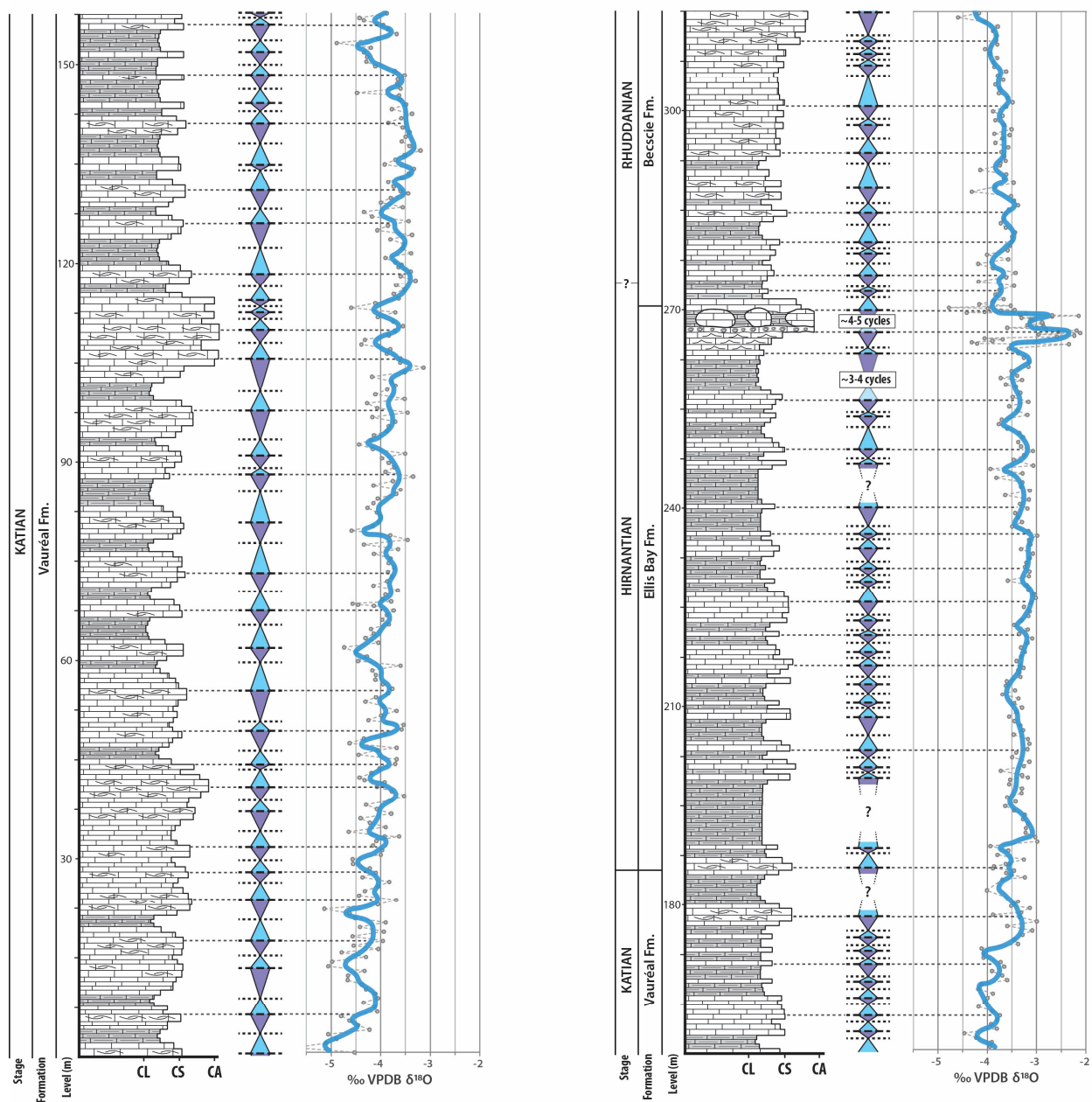


Figure 3.3. Stratigraphic log showing metre-scale TR cycles and $\delta^{18}\text{O}$ data (blue line represents smoothed running average, $n=5$). Dotted lines represent the MRZs of individual meter-scale TR cycles where higher $\delta^{18}\text{O}$ values are matching with glacial sea level lowstands. See chapter 2 (Fig. 2.5 and 2.8) for symbols.

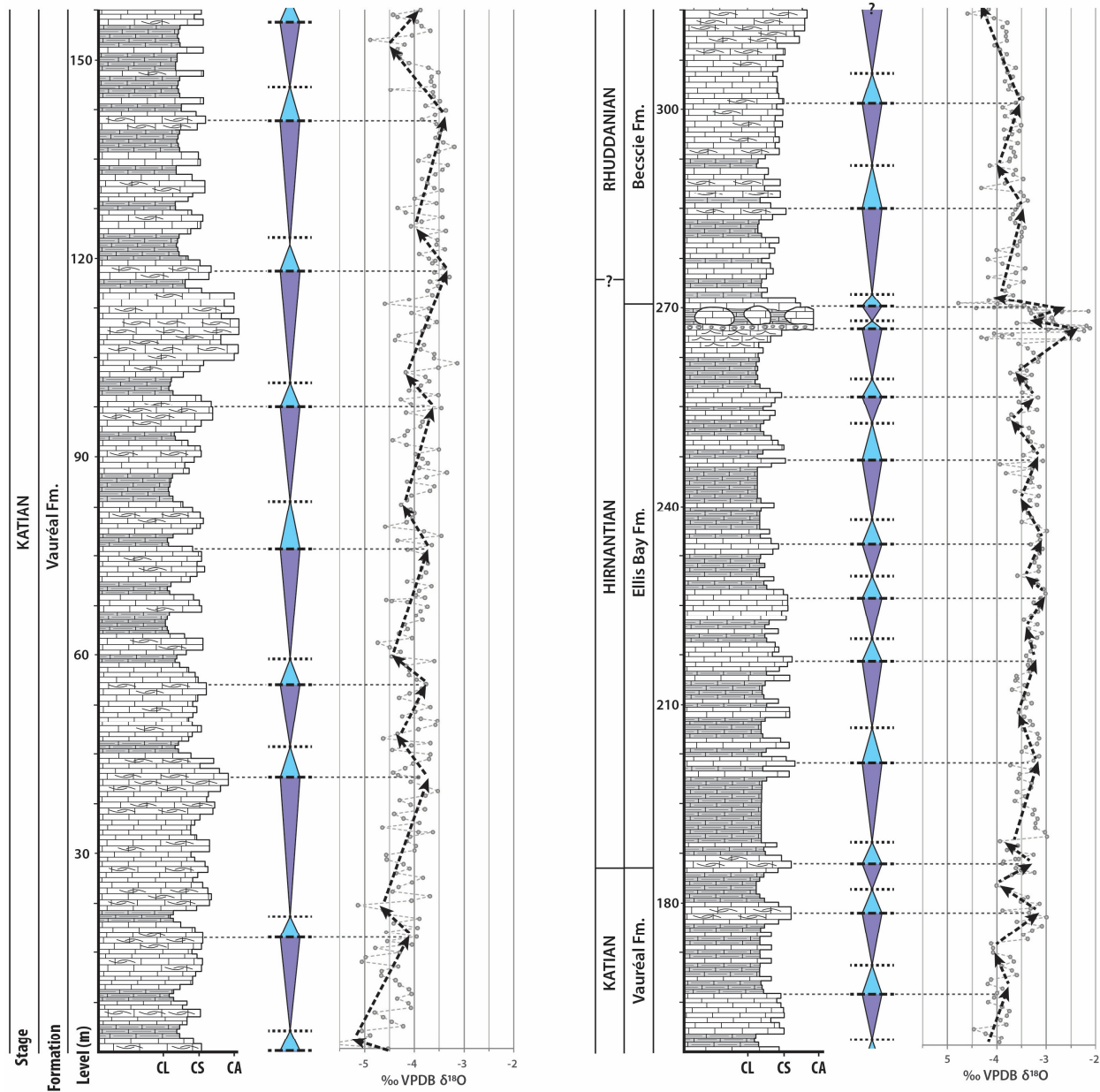


Figure 3.4. Stratigraphic log showing the decametre-scale TR cycles and $\delta^{18}\text{O}$ data (dotted arrows represent overall isotopic trends). Dotted lines represent the MRZs of individual decametre-scale TR cycles where higher $\delta^{18}\text{O}$ values are well matched by interpreted glacial sea level lowstands. See chapter 2 (Fig. 2.5 and 2.8) for symbols.

General Conclusions

Summary of conclusions

This is the first study to sample strata superbly exposed at low tide along the west coast of Anticosti Island; thus providing a previously unexploited, nearly complete stratigraphic interval spanning the O-S boundary. This study is also the first to include an integrated facies description and cyclostratigraphic and chemostratigraphic analysis. Six major depositional facies are present in the upper Vauréal - Ellis Bay - lower Becscie succession representing mainly mid- to outer carbonate ramp sediment deposited under the influence of episodic storm events below the fairweather wave base. Shallow, inner-ramp facies are, however, present in the uppermost Ellis Bay Formation. More than 80 metre-scale TR cycles of various thicknesses have been identified within the studied succession. These metre-scale TR cycles bundle to form 22 larger decametre-scale TR cycles.

Our new high-resolution $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ curves with more than 500 data points derived from well-preserved micritic samples and spaced at every $\sim 0.6\text{m}$ rectifies important pitfalls (i.e. low sampling resolution, variable sampling intervals, stratigraphic gaps) of previously published $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ curves at the west end of Anticosti Island. The $\delta^{13}\text{C}$ curve displays a lower and an upper positive HICE within peak values of $+2.5\text{‰}$ and $+4.5\text{‰}$ respectively rising above late Katian and early Rhuddanian baseline values of $+0.5\text{‰}$. The upper larger HICE abruptly interrupted the descending limb of the lower HICE. As seen in well-dated graptolitic successions around the globe, the return to $\delta^{13}\text{C}$ baseline values following the upper HICE suggests that the O-S boundary at the west end of Anticosti is stratigraphically located higher above the base of the Becscie Formation than currently identified. The long-term $\delta^{18}\text{O}$ changes of the entire

succession support a protracted glaciation event peaking during the Hirnantian, specifically in the Laframboise member time. The superimposed three higher frequency variations in $\delta^{18}\text{O}$ and values suggest three distinct glacial-interglacial episodes during the latest Ordovician time.

Metre-scale TR cycles and $\delta^{18}\text{O}$ variations are difficult to interpret because the sample resolution is lacking at that scale. The decametre-scale TR cycles and $\delta^{18}\text{O}$ correlate better, and the nature of the variations support that the glacioeustasy was the dominant control on water-depth changes. We cautiously interpret the decametre-scale TR cycles as recording a 100 ka eccentricity signal, while the metre-scale TR cycles represent a mix of precession and obliquity forcing. Multi-cyclic stratigraphic architecture and $\delta^{18}\text{O}$ tendencies, similar to the one seen in the late Pleistocene record, further suggests a glacio-eustatic influence on the deposition of the studied succession.

Contributions

The strata superbly exposed along the rocky tidal flats at the west end of Anticosti Island represents one of the thickest and most complete stratigraphic intervals spanning the late Katian to early Rhuddanian. The Hirnantian stage itself is ~100 m thick, which is an order or two of magnitude thicker than age-equivalent sections elsewhere around the world, generating a particular interest in this succession. This study contributes:

- New $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ stable isotope records, representing the most complete and highest resolution curves ever produced from a succession of this age, providing a more accurate age constraint for worldwide correlating purposes;

- Evidence supporting the good preservation of the $\delta^{18}\text{O}$ signal, substantiating the potential usefulness of this geochemical proxy after appropriate screening, even in the deep geological time;

This study has generated $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, lithological and stratigraphic data at a scale adequate for time-series analyses.

Areas of future research

General

- This study focuses on integrating lithological, cyclostratigraphic and chemostratigraphic ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) data for interpretive purposes. Time-series data treatment was beyond the scope of this study but our high-resolution datasets could benefit from such analyses.

Chapter 1

- Further work in the overlying Becscie Formation is required to locate more precisely the stratigraphic position of the O-S boundary on Anticosti Island.

Chapter 2

- A more detailed study of the facies and their depositional environments could be useful to explore the possibility of isotope variability related to facies changes.
- The Becscie cycles are difficult to interpret on a time-series basis without more data. A study covering the entire Becscie Formation is required in order to determine how the upper Becscie strata are related to our studied succession.

Chapter 3

- To properly interpret the oxygen isotopes at the metre scale, a higher resolution sampling is required. We suggest performing a more detailed $\delta^{18}\text{O}$ study with a smaller sampling

interval on different segments of our studied succession. A $\delta^{18}\text{O}$ study based on lithological sampling could also be considered in future work.

Appendix A: $\delta^{13}\text{C}/\delta^{18}\text{O}$ and Sr/Mn trace elements data with their stratigraphic position above the datum and GPS localities

Sample #	$\delta^{18}\text{O}$ (‰)	$\delta^{13}\text{C}$ (‰)	Mn (ppm)	Sr (ppm)	Stratigraphic level (m)	Lithology	GPS Data		
							UTM	X	Y
----- Vauréal Formation -----									
V1	-4.53	-0.5			0	calcilutite	20U	395825	5530349
V2	-5.73	-0.77			0.684	calcisiltite			
V3	-5.1	-0.48			1.368	calcilutite	20U	395824	5530319
V4	-4.89	-0.57			2.052	calcilutite			
V5	-5.06	-0.4			2.736	calcisiltite			
V6	-4.23	-0.34			3.42	calcisiltite	20U	395823	5530214
V7	-4.46	-0.33			4.104	calcilutite			
V8	-4.63	-0.52			4.788	calcilutite	20U	395784	5530144
V9	-4.8	-0.58			5.472	calcisiltite			
V10	-4.07	-0.38			6.156	calcisiltite	20U	395542	5530092
V12	-4.12	-0.53			6.84	calcisiltite			
V13	-4.35	-0.51	192.56	659.09	7.524	calcilutite			
V14	-4.06	-0.44			8.208	calcisiltite	20U	394398	5529976
V15	-4.11	-0.39			8.892	calcilutite			
V16	-4.3	-0.07			9.576	calcisiltite			
V17	-4.38	-0.21			10.26	calcilutite	20U	394352	5529934
V18	-4.67	-0.6			10.944	calcilutite			
V19	-4.66	-0.1			11.628	calcilutite			
V20	-4.33	-0.4			12.312	calcilutite	20U	394393	5529839
V21	-5.06	-0.34			12.996	calcisiltite			
V22	-4.98	-0.33			13.68	calcisiltite			
V23	-4.3	-0.3			14.364	calcilutite	20U	394355	5529741
V24	-4.79	-0.2	225.55	852.80	15.048	calcisiltite			
V25	-4.05	-0.11			15.561	calcisiltite			
V26	-4.55	-0.01			16.074	calcilutite	20U	394390	5529601
V28	-3.96	0.14			16.758	calcisiltite			
V29	-4.57	-0.22			17.442	calcilutite			
V30	-3.94	0.14			18.126	calcisiltite			
V31	-4.42	-0.35			18.81	calcilutite			
V32	-3.9	0.11			19.494	calcisiltite	20U	393866	5529499
V33	-4.52	-0.36			20.178	calcisiltite			
V34	-4.63	-0.25			20.862	calcisiltite	20U	393824	5529404
V36	-5.14	-0.31	177.66	734.87	21.546	calcilutite			
V37	-4.06	-0.22			22.23	calcisiltite	20U	393835	5529346
V38	-3.69	-0.02			22.914	calcisiltite			
V39	-4.44	-0.37			23.598	calcisiltite	20U	393839	5529299
V40	-4.32	-0.28			24.282	calcilutite	20U	393838	5529263
V41	-4.05	-0.5			24.966	calcilutite	20U	393832	5529235
V42	-3.83	-0.23			25.65	calcilutite	20U	393828	5529198
V43	-4.37	-0.51			26.334	calcisiltite			
V44	-4.1	0.03			27.018	calcilutite			
V46	-4.22	-0.18			27.702	calcisiltite	20U	393387	5529192
V47	-4.56	-0.31			28.386	calcilutite			
V48	-4.57	-0.4			29.07	calcilutite			
V49	-4	-0.22			29.754	calcilutite	20U	393379	5529109
V50	-3.97	-0.22	181.36	758.14	30.438	calcisiltite			
V51	-4.16	-0.29			31.122	calcisiltite			
V52	-4.09	-0.34			31.806	calcisiltite			
V53	-3.63	0			32.49	calcisiltite	20U	393329	5528976
V54	-3.92	-0.08			32.49	calcisiltite	20U	393068	5529033
V57	-4.65	-0.37			33.174	calcilutite			
V58	-3.9	0.15			33.858	calcisiltite			
V59	-4.22	-0.29			34.542	calcisiltite			
V60	-4.41	-0.42			35.226	calcilutite	20U	393030	5528922
V61	-3.79	0.03			35.91	calcisiltite			
V62	-4.08	0.09			36.594	calcisiltite			

V63	-4.3	-0.04			37.278	calcisiltite			
V64	-3.78	0.26	199.86	807.63	37.962	calcilutite	20U	392923	5528827
V65	-3.53	0.11			38.646	calcisiltite	20U	392917	5528791
V66	-3.78	0.15			39.33	calcilutite			
V67	-4.08	0.15			40.014	calcisiltite			
V68	-3.92	0.22			40.698	calcisiltite			
V69	-4.33	0.07			41.04	calcisiltite	20U	392864	5528692
V70	-4.43	0.15			41.382	calcisiltite			
V71	-4.19	0.14			42.066	calcisiltite			
V72	-4.03	0.31			42.75	calcilutite	20U	392830	5528630
V73	-3.71	0.54			43.434	calcisiltite			
V74	-3.68	0.58			44.118	calcisiltite	20U	392809	5528549
V76	-4.45	0.16			44.802	calcilutite			
V77	-4.06	0.5	109.79	719.08	45.486	calcilutite			
V79	-3.68	0.77			45.828	calcisiltite	20U	392780	5528482
V81	-4.63	0.1			46.512	calcisiltite			
V82	-4.34	0.34			47.196	calcisiltite			
V83	-3.92	0.35			47.88	calcisiltite			
V84	-3.58	0.59			48.564	calcisiltite			
V85	-3.54	0.6			49.248	calcisiltite			
V86	-3.87	0.5			49.59	calcisiltite	20U	392734	5528308
V87	-4.25	0.37			49.932	calcilutite			
V88	-3.99	0.44			50.616	calcilutite			
V89	-3.68	0.48			51.3	calcilutite	20U	392695	5528218
V90	-3.95	0.38			51.984	calcisiltite			
V91	-4.31	0.1	158.92	921.56	52.668	calcilutite			
V92	-4.1	0.43			53.352	calcilutite			
V93	-3.86	0.32			54.036	calcisiltite			
V94	-3.77	0.32			54.72	calcisiltite	20U	392669	5528071
V95	-3.96	0.24			55.404	calcisiltite			
V96	-4.11	0.38			56.088	calcisiltite			
V97	-4.1	0.41			56.772	calcilutite			
V98	-4.17	0.45			57.456	calcilutite			
V99	-3.6	0.52			58.14	calcisiltite	20U	392550	5527940
V100	-4.46	-0.03			58.824	calcisiltite			
V101	-4.28	0.15	164.80	936.94	59.508	calcilutite			
V102	-4.5	0.26			60.192	calcisiltite			
V103	-4.74	0.35			60.876	calcisiltite	20U	392555	5527827
V104	-4.05	0.55			61.56	calcisiltite/calcarenite			
V105	-4.31	0.35			62.244	calcisiltite			
V106	-4.14	0.2			62.928	calcilutite			
V107	-4.2	0.44			63.612	calcilutite			
V108	-3.84	0.55			64.296	calcilutite			
V109	-3.97	0.57			64.98	calcilutite			
V110	-3.88	0.49			65.664	calcilutite	20U	392456	5527632
V111	-3.74	0.33			66.348	calcilutite			
V112	-4.14	0.28	190.62	934.40	67.032	calcilutite			
V113	-4.46	0.12			67.203	calcilutite			
V114	-4.57	0.18			67.374	calcisiltite	20U	392461	5527564
V124	-3.79	0.38			67.716	calcisiltite			
V125	-3.97	0.25			68.058	calcisiltite			
V126	-3.91	0.35			68.742	calcisiltite			
V127	-3.66	0.42			69.426	calcilutite	20U	391430	5527740
V128	-4.15	0.44			70.11	calcilutite			
V129	-3.87	0.24			70.794	calcisiltite			
V130	-3.77	0.41			71.478	calcisiltite			
V131	-3.86	0.39			72.162	calcisiltite	20U	391403	5527648
V132	-3.73	0.25			72.846	calcisiltite			
V133	-3.84	0.08			73.53	calcilutite			

V134	-3.8	0.21			74.214	calcilutite			
V135	-4.14	0.43			74.898	calcilutite			
V136	-3.65	0.23	109.86	773.58	75.582	calcilutite			
V137	-4.34	0.44			76.266	calcilutite			
V138	-3.46	0.44			76.95	calcilutite/calcsiltite	20U	391365	5527432
V139	-3.81	0.11			77.634	calcsiltite			
V140	-4.59	0.4			78.318	calcilutite			
V141	-4.16	0.24			79.002	calcilutite			
V142	-4.04	0.42			79.686	calcilutite			
V143	-4	0.18			80.37	calcilutite/calcsiltite			
V144	-4.08	0.46			81.054	calcilutite	20U	391285	5527222
V145	-4.27	0.55			81.738	calcilutite			
V146	-4.15	0.44	96.85	793.23	82.422	calcilutite			
V147	-4.06	0.34			83.106	calcilutite			
V148	-3.69	0.53			83.79	calcsiltite			
V149	-3.6	0.49			84.474	calcilutite	20U	391131	5527101
V150	-4.15	0.32			85.158	calcilutite	20U	391106	5527038
V151	-3.76	0.38			85.842	calcilutite			
V152	-3.35	0.61			86.526	calcsiltite	20U	391070	5526993
V153	-3.91	0.48			87.21	calcilutite			
V154	-3.73	0.62			87.894	calcilutite			
V155	-3.84	0.47			88.578	calcilutite			
V156	-3.98	0.33			89.262	calcilutite			
V157	-3.51	0.45	74.98	677.64	89.946	calcsiltite			
V158	-4.16	0.48			90.63	calcsiltite			
V159	-4.44	0.41			91.314	calcsiltite	20U	390979	5526816
V160	-4.2	0.6			91.998	calcilutite/calcsiltite			
V161	-4.14	0.31			92.682	calcsiltite			
V162	-3.88	0.07			93.366	calcilutite			
V163	-3.84	0.15			94.05	calcsiltite	20U	390908	5526731
V164	-3.71	0.27			94.734	calcsiltite			
V165	-4.17	0.07			95.418	calcilutite			
V166	-3.46	0.18	87.49	649.91	96.102	calcsiltite			
V167	-4.07	0.33			96.786	calcsiltite			
V168	-4.28	0			97.47	calcsiltite			
V169	-3.52	0.34			98.154	calcilutite			
V170	-4.11	0.27			98.838	calcilutite	20U	390848	5526541
V171	-3.87	0.67			99.522	calcsiltite			
V172	-3.7	0.06			100.206	calcsiltite			
V173	-3.78	0.17			100.89	calcilutite	20U	390803	5526432
V174	-4.18	-0.21			101.574	calcilutite/calcsiltite			
V175	-3.52	0.36			102.258	calcsiltite			
V176	-3.14	0.83			102.942	calcilutite	20U	390800	5526342
V177	-3.61	0.41			103.626	calcilutite			
V178	-3.6	0.38			104.31	calcsiltite			
V179	-3.88	0.42			104.994	calcilutite			
V180	-3.81	0.29			105.678	calcsiltite	20U	390771	5526219
V181	-4.39	0.43			106.362	calcsiltite			
V182	-4.32	0.45			107.046	calcsiltite			
V183	-3.84	0.5			107.73	calcilutite	20U	390750	5526125
V184	-3.72	0.42			108.414	calcsiltite			
V185	-3.55	0.39			109.098	calcsiltite	20U	390736	5526072
V186	-3.75	0.57			109.782	calcsiltite			
V188	-4.06	0.48			110.466	calcilutite			
V189	-3.71	0.31			111.15	calcsiltite			
V190	-4.6	0.57			111.834	calcsiltite			
V191	-4.11	0.44			112.518	calcsiltite	20U	390719	5525904
V193	-3.64	0.56			113.202	calcilutite	20U	390715	5525878
V194	-3.74	0.61			113.886	calcilutite			

V195	-3.52	0.24			114.57	calcisiltite	20U	390698	5525816
V196	-3.69	0.56	80.31	558.63	115.254	calcilutite			
V197	-3.3	0.41			115.938	calcisiltite/calcarenite			
V198	-3.6	0.34			116.622	calcilutite	20U	390689	5525726
V199	-3.4	0.34			117.306	calcisiltite			
V200	-3.64	0.34			117.99	calcisiltite			
V201	-3.58	0.41			118.332	calcisiltite	20U	390678	5525652
V202	-3.71	0.09			118.674	calcisiltite			
V203	-3.91	0.22			119.358	calcisiltite			
V204	-3.39	0.52			120.042	calcisiltite			
V205	-3.56	0.61			120.726	calcilutite			
V206	-3.54	0.51			121.41	calcisiltite			
V207	-3.81	0.57			122.094	calcilutite	20U	390656	5525480
V208	-3.37	0.57	99.38	729.93	122.778	calcilutite			
V209	-4.07	0.49			123.462	calcisiltite			
V210	-3.86	0.49			124.146	calcilutite			
V211	-3.44	0.72			124.83	calcilutite			
V212	-4.18	0.33			125.514	calcisiltite	20U	390624	5525338
V213	-4.34	0.74			126.198	calcisiltite			
V214	-3.56	0.77	75.83	516.33	126.882	calcilutite			
V215	-4	0.41			127.566	calcilutite			
V216	-3.8	0.28			128.25	calcilutite			
V217	-3.45	0.27			128.934	calcisiltite			
V218	-3.6	0.22			129.276	calcisiltite	20U	390585	5525173
V219	-3.74	0.3			129.96	calcilutite			
V220	-3.85	0.6			130.644	calcisiltite			
V221	-3.58	0.58			131.328	calcilutite			
V222	-3.44	0.73			132.012	calcilutite	20U	390540	5525061
V223	-3.33	0.55			132.696	calcisiltite			
V224	-3.92	0.62			133.38	calcisiltite	20U	390516	5524979
V225	-3.71	0.46			134.064	calcisiltite			
V226	-3.52	0.68			134.748	calcilutite			
V227	-3.2	0.66	71.13	547.63	135.432	calcilutite			
V228	-3.42	0.22			136.116	calcilutite			
V229	-3.58	0.28			136.8	calcisiltite	20U	390448	5524819
V230	-3.5	0.54			137.484	calcilutite			
V231	-3.42	0.53			138.168	calcilutite			
V232	-3.56	0.39			138.852	calcisiltite			
V233	-3.85	0.31			139.536	calcisiltite			
V234	-3.59	0.12			140.22	calcisiltite	20U	390479	5524661
V235	-3.37	0.14			140.904	calcilutite/calcisiltite			
V236	-3.78	0.55			141.588	calcilutite			
V237	-3.49	0.25	91.88	490.95	142.272	calcilutite	20U	390451	5524563
V238	-3.62	0.23			142.956	calcilutite			
V239	-3.63	0.47			143.64	calcilutite			
V240	-4.48	0.62			143.982	calcisiltite	20U	390434	5524496
V241	-3.6	0.15			144.666	calcisiltite			
V242	-3.67	0.39			145.35	calcilutite			
V243	-3.66	0.04			146.034	calcisiltite			
V244	-3.52	0.34			146.718	calcisiltite			
V245	-3.72	0.06			147.402	calcisiltite	20U	390566	5524235
V246	-4.11	0.39			148.086	calcilutite/calcisiltite			
V247	-4.29	0.32			148.77	calcilutite	20U	390562	5524190
V248	-4.28	0.15			149.454	calcisiltite			
V249	-4.34	-0.45	112.24	666.94	150.138	calcilutite			
V250	-4.2	0.36			150.822	calcisiltite			
V251	-4.89	0.26			151.506	calcilutite	20U	390541	5524072
V252	-4.05	0.26			152.19	calcilutite			
V253	-3.68	0.36			152.874	calcilutite/calcisiltite	20U	391000	5523791

V254	-3.86	0.39			153.558	calcilutite			
V255	-3.95	0.51			154.242	calcilutite			
V256	-4.34	0.31			154.926	calcilutite			
V257	-4.43	-0.51			155.268	calcisiltite	20U	390997	5523710
V258	-3.88	0.48			155.952	calcilutite	20U	391536	5523519
V259	-3.69	0.5			156.636	calcisiltite			
V260	-3.75	0.5	55.42	498.61	157.32	calcilutite/calcisiltite	20U	391524	5523480
V261	-3.95	0.69			158.004	calcilutite			
V262	-3.91	0.65			158.688	calcilutite			
V263	-4.23	0.32			159.372	calcilutite/calcisiltite	20U	392211	5523061
V264	-4.47	0.28			160.056	calcilutite			
V265	-3.81	0.48			160.74	calcilutite/calcisiltite	20U	392200	5522998
V266	-3.93	0.41			161.424	calcilutite			
V267	-3.8	-0.11			162.108	calcilutite			
V268	-3.75	0.3			162.792	calcisiltite			
V269	-3.9	0.54			163.476	calcilutite/calcisiltite			
V270	-4.18	0.14			164.16	calcilutite/calcisiltite	20U	392221	5522842
V271	-4.06	0.52			164.844	calcilutite			
V272	-4	0.26			165.528	calcilutite			
V273	-3.89	0.4	94.93	507.72	166.212	calcilutite			
V274	-4.19	0.37			166.896	calcilutite	20U	392191	5522739
V276	-4.12	0.58			167.58	calcilutite			
V277	-3.6	0.7			168.264	calcilutite			
V278	-3.7	0.4			168.948	calcilutite			
V279	-3.91	0.57			169.632	calcilutite			
V280	-3.66	0.24			170.316	calcilutite			
V281	-3.73	0.68			171	calcilutite			
V282	-4.08	0.6			171.684	calcilutite			
V283	-4.08	0.37	103.52	451.43	172.368	calcilutite			
V284	-4.12	0.64			173.052	calcilutite			
V285	-3.38	0.93			173.736	calcilutite			
V286	-3.47	0.92			174.42	calcilutite			
V287	-3.29	0.66			175.104	calcilutite			
V288	-3.09	0.89			175.788	calcilutite			
V289	-3.6	0.42			176.472	calcilutite/calcisiltite			
V290	-3	1.43	133.12	559.66	177.156	calcisiltite			
V291	-3.35	1.02			177.84	calcisiltite			
V292	-3.89	0.27			178.182	calcisiltite	20U	393522	5522049
V293	-3.32	0.7			178.524	calcilutite	20U	393520	5522029
V294	-3.14	0.73			179.208	calcilutite			
V295	-3.52	0.56			179.55	calcilutite	20U	393512	5521998
VAF2	-3.47	0.71			179.892	calcilutite			
VAF3	-3.38	0.54	257.27	384.52	180.234	calcilutite			
VAFX	-4.01	0.63			182	calcilutite	20U	395636	5521447
VAF13	-3.7	0.97			183.654	calcilutite			
VAF14	-3.24	1.23			183.996	calcilutite			
VAF15	-3.51	1.11			184.338	calcilutite			
VAF16	-3.62	1.12			184.68	calcilutite			
VAF17	-3.46	1.18			185.022	calcilutite			
VAF18	-3.89	0.82			185.364	calcilutite			
VAF19	-3.87	0.54			185.706	calcilutite			
VAF20	-3.56	0.84			186.048	calcilutite			
Ellis Bay Formation									
E296	-3.63	0.86			186.048	calcisiltite	20U	395655	5521275
E297	-3.26	0.55	420.41	406.36	186.732	calcisiltite			
E298	-3.8	0.45			187.416	calcisiltite			
E299	-3.58	0.82			188.1	calcilutite/calcisiltite			
E300	-3.94	1			188.784	calcilutite/calcisiltite			
E301	-2.99	1.18			189.468	calcisiltite			

E302	-3.03	1.18			190.152	calcilutite			
E303	-3.23	1.86			190.836	calcilutite, argillaceous			
E304	-3.22	2.06			191.52	calcilutite			
E305	-3.18	1.67			192.204	calcilutite, argillaceous			
E306	-3.28	1.79			192.888	calcilutite			
E307	-3.24	1.66			193.572	calcilutite			
E308	-3.46	1.8			194.256	calcilutite			
E309	-3.64	1.73			194.94	calcilutite			
E310	-3.43	1.74	451.28	764.63	195.624	calcilutite, argillaceous			
E311	-3.6	1.81			196.308	calcilutite/calcisiltite			
E312	-3.31	1.97			196.992	calcilutite			
E313	-3.3	2.04			197.676	calcilutite			
E314	-3.56	1.98			198.36	calcilutite			
E315	-3.54	1.64			199.044	calcilutite, argillaceous			
E316	-3.18	1.49			199.386	calcilutite/calcisiltite	20U	395718	5520723
E317	-3.3	1.53			199.728	calcilutite/calcisiltite			
E318	-3.73	1.47			200.412	calcilutite/calcisiltite	20U	395721	5520682
E319	-3.26	1.97			201.096	calcilutite			
E320	-3.15	2.3	174.19	725.12	201.78	calcilutite			
E321	-3.5	2.36			202.464	calcilutite			
E322	-3.42	2.28			203.148	calcilutite			
E323	-3.19	1.85			203.661	calcilutite	20U	395952	5520514
E324	-3.15	2.33			204.516	calcilutite			
E325	-3.18	2.51			205.2	calcilutite, bioturbated			
E326	-3.47	2.41			205.884	calcilutite, bioturbated			
E327	-3.28	2.27			206.568	calcilutite, bioturbated			
E328	-3.33	1.13			207.252	calcilutite, argillaceous	20U	395976	5520336
E329	-3.45	1.45			207.936	calcilutite, argillaceous			
E330	-3.56	1.27			208.62	calcilutite, argillaceous			
E331	-3.41	1.51			209.304	calcisiltite/calcarenite	20U	395982	5520277
E333	-3.3	1.47	809.38	759.18	209.988	calcilutite, argillaceous	20U	395987	5520227
E334	-3.46	1.8			210.672	calcilutite, argillaceous			
E335	-3.37	2			211.356	calcilutite, argillaceous			
E336	-3.7	1.73			212.04	calcilutite/calcisiltite			
E337	-3.44	1.78			212.724	calcilutite, argillaceous			
E338	-3.63	1.29			213.408	calcilutite			
E339	-3.59	1.53			213.75	calcilutite	20U	395980	5520077
E340	-3.61	1.35			214.092	calcilutite, argillaceous			
E341	-3.33	0.86			214.776	calcilutite, argillaceous			
E342	-3.35	1.3			215.46	calcilutite			
E343	-3.38	1.92			215.802	calcisiltite			
E344	-3.27	1.56			216.144	calcilutite			
E345	-3.34	1.96			216.486	calcilutite	20U	395989	5519956
E346	-3.41	1.92			217.17	calcilutite			
E347	-3.32	1.92	141.66	1034.06	217.854	calcilutite	20U	396146	5519880
E348	-3.24	1.76			218.538	calcilutite			
E349	-3.32	1.71			219.222	calcilutite			
E350	-3.19	1.62			219.906	calcilutite			
E351	-3.09	1.71			220.59	calcilutite			
E352	-3.36	1.52			221.274	calcilutite			
E353	-3.18	1.47			221.958	calcilutite			
E354	-3.46	1.46			222.642	calcilutite, bioturbated			
E355	-3.31	1.28			223.326	calcilutite, bioturbated			
E356	-3.17	0.99			224.01	calcilutite, bioturbated	20U	396173	5519612
E357	-3.14	1.32	120.08	682.36	224.694	calcilutite			
E358	-3.26	1.07			225.378	calcilutite			
E359	-3.12	1.13			226.062	calcilutite	20U	396576	5519422
E360	-3.02	1.18			226.746	calcilutite			
E361	-3.06	0.42			227.43	calcilutite			

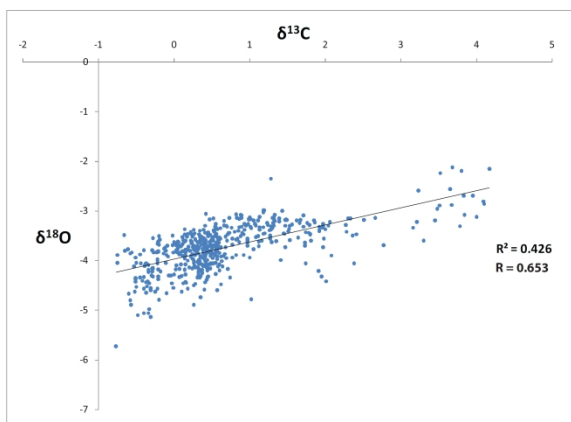
E362	-3.17	1.32			228.114	calcilutite			
E363	-3.2	1.33			228.798	calcilutite			
E364	-3.59	0.97			229.482	calcilutite, argillaceous	20U	396589	5519251
E365	-3.16	0.99			230.166	calcilutite, bioturbated			
E366	-3.15	1.39			230.85	calcilutite, bioturbated			
E367	-3.24	1.31			231.534	calcilutite			
E368	-3.21	1.39			232.218	calcilutite			
E369	-3.14	1.3	121.19	917.66	232.902	calcilutite	20U	396630	5519117
E370	-3.08	1.33			233.586	calcilutite			
E371	-3.32	1.01			234.27	calcilutite			
E372	-3.13	1			234.954	calcilutite, bioturbated			
E373	-3.16	1.01			235.638	calcilutite			
E374	-2.99	1.19			236.322	calcilutite	20U	396969	5518938
E375	-3.17	0.99			237.006	calcilutite, bioturbated			
E376	-3.5	1.27			237.69	calcilutite			
E377	-3.3	1.32			238.374	calcilutite			
E378	-3.38	1.28			239.058	calcilutite			
E379	-3.44	0.9			239.742	calcilutite			
E380	-3.19	1.05	222.79	744.20	240.426	calcilutite	20U	397013	5518751
E381	-3.34	0.76			241.11	calcilutite			
E382	-3.16	0.86			241.794	calcilutite, argillaceous			
E383	-3.64	0.59			242.478	calcilutite, bioturbated			
E384	-3.14	0.89			243.162	calcilutite, argillaceous	20U	397040	5518621
E385	-3.32	0.54			243.846	calcilutite, argillaceous			
E386	-3.29	0.95			244.53	calcilutite			
E387	-3.82	0.57			245.214	calcilutite, argillaceous			
E388	-3.29	1.08			245.898	calcilutite, argil., bioturb.			
E389	-3.94	0.77			246.582	calcilutite, argil., bioturb.			
E390	-3.07	0.82	81.39	214.99	247.095	calcilutite/calcsiltite	20U	397082	5518468
E391	-3.47	0.33			247.95	calcilutite			
E392	-3.26	0.98			248.634	calcilutite	20U	397320	5518467
E393	-3.08	0.88			249.318	calcilutite			
E394	-3.32	0.89			250.002	calcilutite			
E395	-3.38	1.13			250.686	calcilutite			
E396	-3.28	1.24			251.37	calcilutite, argillaceous	20U	397357	5518355
E397	-3.35	1.29			252.054	calcilutite, argillaceous			
E398	-3.6	1.16			252.738	calcilutite			
E399	-3.77	1.05			253.422	calcilutite	20U	397378	5518267
E400	-3.71	1.12			254.106	calcilutite			
E401	-3.19	1.11	210.48	1339.23	254.79	calcilutite	20U	397385	5518212
E402	-3.39	1.26			255.474	calcilutite			
E403	-3.56	0.97			256.158	calcilutite			
E404	-3.17	1.48			256.842	calcilutite, bioturbated			
E405	-3.49	0.48			257.526	calcilutite, bioturbated	20U	397436	5518102
E406	-3.33	1.18			258.21	calcilutite, argillaceous			
E407	-3.42	0.8			259.236	calcilutite	20U	397536	5518048
E408	-3.63	0.97			259.578	calcilutite			
E409	-3.3	0.69			260.262	calcilutite, argillaceous			
E410	-3.73	0.44			260.604	calcilutite, argillaceous	20U	397549	5517978
E411	-3.4	0.85			260.946	calcilutite, argillaceous			
E412	-3.51	0.88			261.63	calcilutite, argillaceous			
E413	-3.17	0.47			262.314	calcilutite, argillaceous			
E414	-3.15	0.52	289.50	592.62	262.998	calcilutite, argillaceous			
E415	-3.26	0.93			263.682	calcilutite, argillaceous			
E416	-3.38	0.26			264.366	calcilutite, argillaceous	20U	397577	5517812
E417	-3.57	0.28			265.05	calcilutite, argillaceous			
E418	-2.35	1.28			265.734	calcilutite, argillaceous			
L2	-4.21	1.91			265.818	calcsiltite			
L3	-4.32	1.95			266.018	calcsiltite			

L4	-3.9	2.08			266.218	calcisiltite			
L5	-3.69	2.77	174.27	545.78	266.468	calcisiltite (Oncolite)			
L6	-4.06	2.38			266.618	calcisiltite			
L7	-2.59	3.23			266.818	calcilutite			
L8	-2.24	3.52			267.018	calcisiltite			
L9	-2.96	3.48			267.218	calcisiltite			
L10	-2.12	3.68			267.418	calcilutite			
L11	-2.56	3.65			267.618	calcilutite			
L12	-2.19	3.8			267.818	calcilutite			
L13	-2.81	4.09			268.018	calcisiltite			
L14	-3.6	3.3	235.03	779.40	268.218	calcisiltite			
L15	-2.86	4.1			268.418	calcisiltite			
L16	-3.19	3.45			268.618	calcisiltite			
L17	-2.88	3.67			268.818	calcisiltite			
L18	-2.89	3.51			269.018	calcilutite			
L19	-3.14	2.66			269.218	calcilutite			
L20	-3.08	3.84	224.82	581.52	269.318	calcilutite			
L21	-3.12	4			269.518	Reef			
L22	-3.31	3.78			269.718	Reef			
L23	-2.69	3.83			269.918	Reef			
L24	-2.15	4.17			270.018	Reef			
L25	-2.69	3.95			270.118	Reef			
L26	-3.34	3.16	279.89	470.13	270.218	Reef			
L27	-3.22	3.21			270.418	Reef			
Beccie Formation									
L28	-4.42	2.01			270.518	calcarenite			
L29	-4.06	1.74			270.618	calcilutite			
L30	-3.48	1.8			270.718	calcilutite			
L31	-3.73	1.97			270.818	calcarenite			
L32	-3.45	1.2			270.918	calcilutite			
L33	-3.99	1.41			271.168	calcilutite			
L34	-4.78	1.02			271.268	calcilutite			
L35	-3.53	1.08			271.568	calcilutite			
L36	-4.17	0.71			271.818	calcisiltite			
L37	-3.89	0.92			272.268	calcisiltite			
B443	-3.67	0.41	103.40	701.28	272.57	calcilutite	20U	404252	5516359
B444	-3.84	0.43			273.254	calcilutite			
B445	-3.76	-0.13			273.938	calcilutite, bioturbated			
B446	-3.46	0.56			274.622	calcilutite			
B447	-4.18	0.02			275.306	calcilutite			
B448	-3.62	0.58			275.99	calcilutite			
B449	-3.43	0.45	89.94	854.68	276.674	calcilutite			
B450	-3.89	0.28			277.358	calcilutite			
B451	-4.19	-0.34			278.042	calcilutite			
B452	-3.58	0.38			278.726	calcilutite	20U	404272	5516080
B453	-4.01	0.34			279.41	calcilutite, bioturbated			
B454	-3.59	0.38			280.094	calcilutite			
B455	-3.54	0.35			280.778	calcisiltite	20U	404276	5516006
B456	-3.5	-0.02			281.462	calcilutite			
B457	-3.5	0.56			282.146	calcilutite			
B458	-3.44	0.41			282.83	calcilutite			
B459	-3.63	0.23			283.514	calcilutite			
B460	-3.73	0.29			284.198	calcilutite			
B461	-3.68	0.42	51.77	769.34	284.882	calcisiltite	20U	404268	5515837
B462	-3.63	0.31			285.566	calcilutite			
B463	-3.57	0.5			286.25	calcisiltite			
B464	-3.38	0.39			286.934	calcilutite, bioturbated			
B465	-3.46	0.22			287.618	calcilutite/calcisiltite			
B466	-3.52	0.17			288.302	calcilutite			

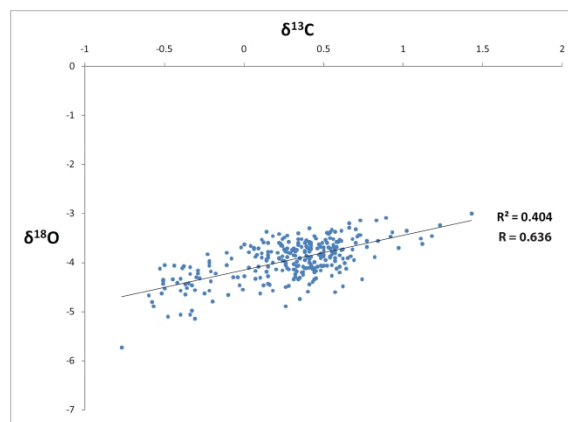
B467	-4.32	-0.21			288.986	calcisiltite	20U	404222	5515658
B468	-3.84	-0.01			289.67	calcisiltite			
B469	-3.47	0.14			290.354	calcisiltite			
B470	-3.67	0.11			291.038	calcilutite			
B471	-3.62	0.14	71.18	735.22	291.722	calcilutite	20U	404672	5515387
B472	-4.15	-0.28			292.406	calcilutite			
B473	-3.75	0.05			293.09	calcilutite			
B474	-3.74	-0.12			293.432	calcisiltite	20U	404663	5515315
B475	-3.63	0.06			293.774	calcilutite			
B476	-3.66	0.01			294.458	calcilutite/calcisiltite			
B477	-3.72	0.19			295.142	calcilutite			
B478	-3.58	0.28			295.826	calcilutite			
B479	-3.84	0.04			296.51	calcilutite, bioturbated			
B480	-3.7	-0.09			297.194	calcilutite			
B481	-3.55	-0.28			297.707	calcisiltite	20U	404619	5515115
B482	-3.86	-0.58			297.878	calcilutite			
B483	-3.51	-0.2			298.562	calcisiltite			
B484	-3.66	-0.22	43.84	553.73	299.246	calcisiltite			
B485	-3.84	-0.27			299.93	calcisiltite			
B486	-3.69	0.03			300.614	calcisiltite	20U	405390	5514765
B487	-3.89	-0.1			301.298	calcisiltite			
B488	-3.62	-0.21			301.982	calcilutite			
B489	-3.49	-0.66			302.666	calcilutite/calcisiltite			
B490	-3.58	-0.19			303.35	calcilutite/calcisiltite			
B491	-3.77	-0.61			304.034	calcilutite/calcisiltite			
B492	-3.74	0.05			304.718	calcilutite	20U	406014	5514397
B493	-3.84	-0.56			305.402	calcilutite			
B494	-3.68	-0.2			306.086	calcilutite			
B495	-3.79	-0.29			306.77	calcisiltite			
B496	-3.62	0.05	56.58	620.94	307.454	calcisiltite	20U	406299	5514219
B497	-3.86	-0.14			308.138	calcilutite/calcisiltite			
B498	-3.88	-0.45			308.822	calcisiltite	20U	406302	5514160
B499	-3.8	-0.65			309.506	calcilutite/calcisiltite			
B500	-3.94	-0.51			310.19	calcisiltite			
B501	-4.05	-0.75			310.874	calcilutite	20U	406454	5514034
B502	-3.8	0.04			311.558	calcilutite/calcisiltite			
B503	-3.82	-0.21			312.242	calcilutite/calcisiltite			
B504	-3.81	-0.21			312.926	calcilutite			
B505	-3.89	-0.75			313.61	calcilutite/calcisiltite			
B506	-3.79	-0.4	55.67	692.61	314.294	calcilutite/calcisiltite			
B507	-4.06	-0.37			314.978	calcisiltite	20U	406436	5513849
B508	-4.6	-0.31			315.662	calcisiltite			
B509	-4.17	-0.28			316.346	calcisiltite			

Appendix B: $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ cross-plots of the studied units

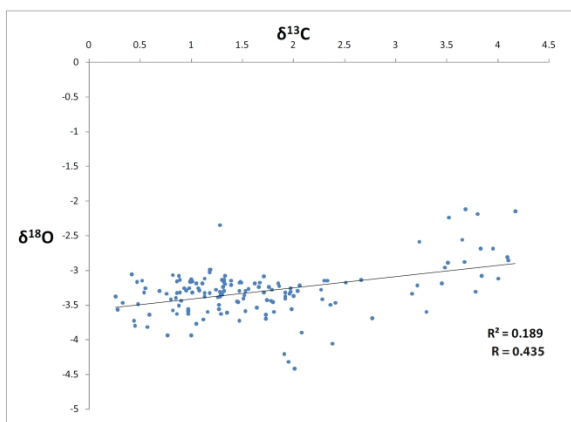
Complete Data



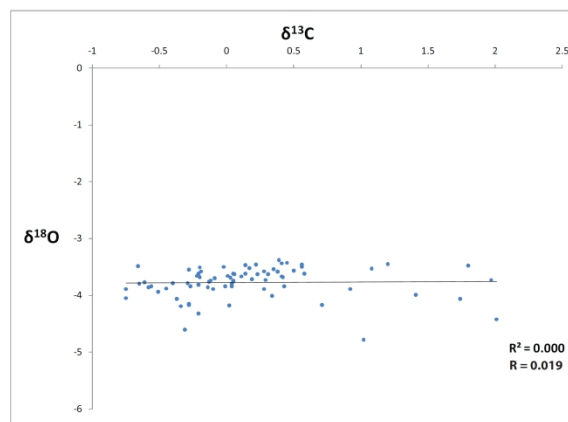
Vauréal Formation Data



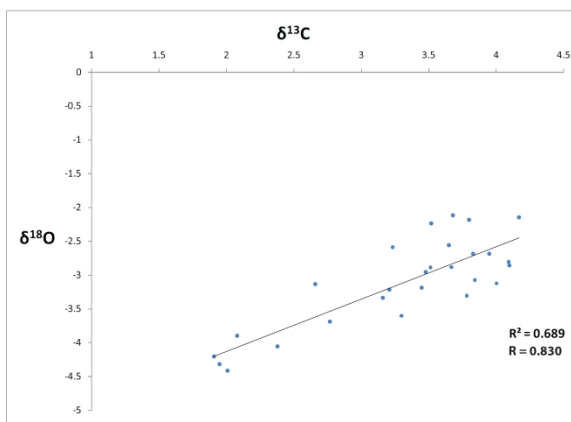
Ellis Bay Formation Data



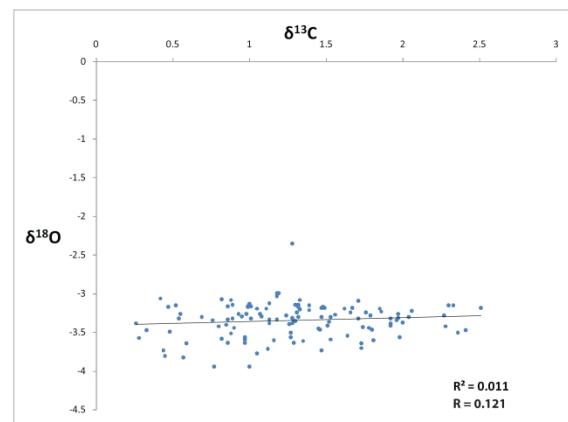
Beccsie Formation Data



Laframboise Member Data

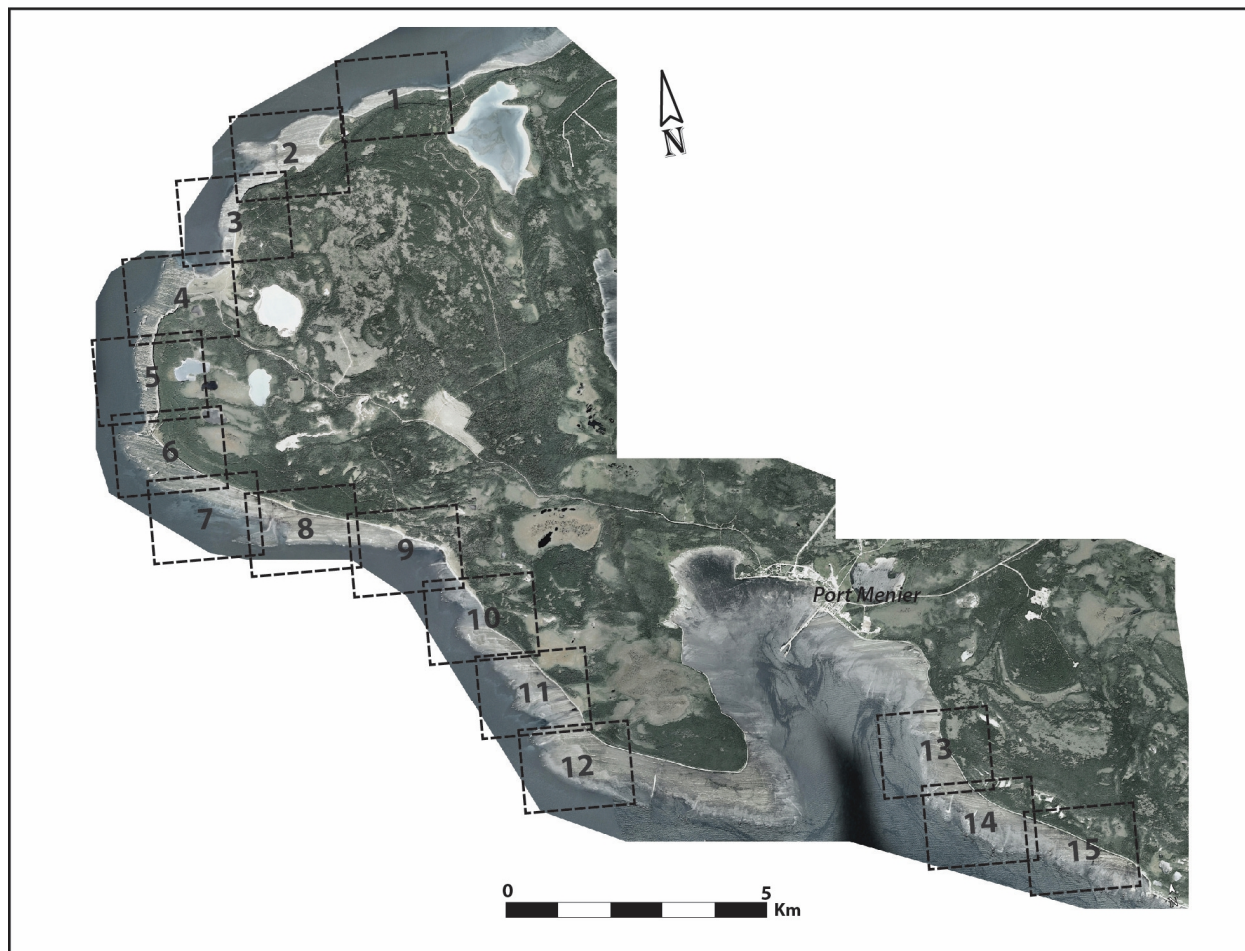


Ellis Bay Formation Data (w/o Laframboise Member data)



Appendix C: Satellite images of study area showing the location of key stratigraphic surfaces of the metre-scale TR cycles (MRZ, MFZ) at the west end of Anticosti Island expressed in metre above the datum.

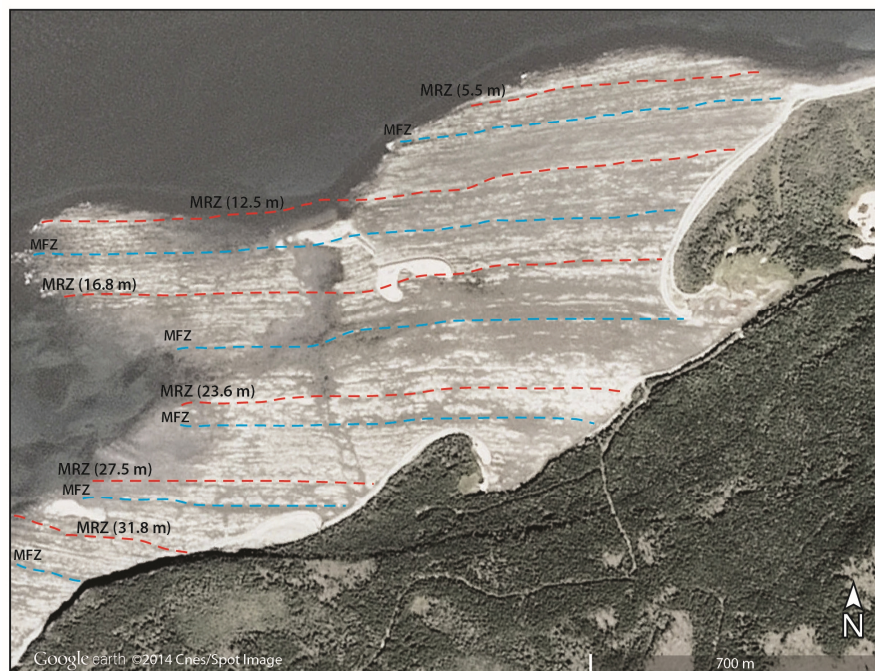
Complete Section



1



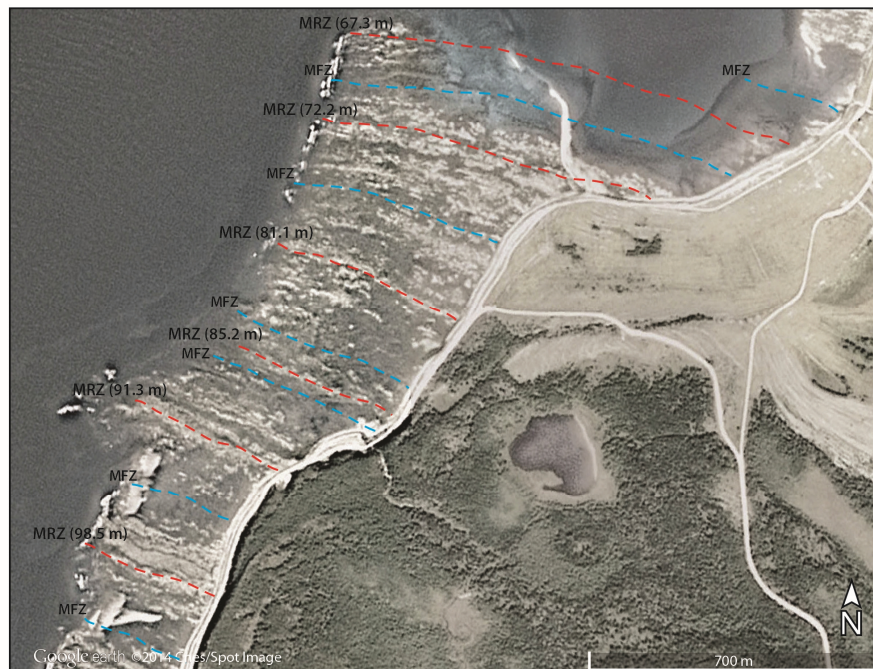
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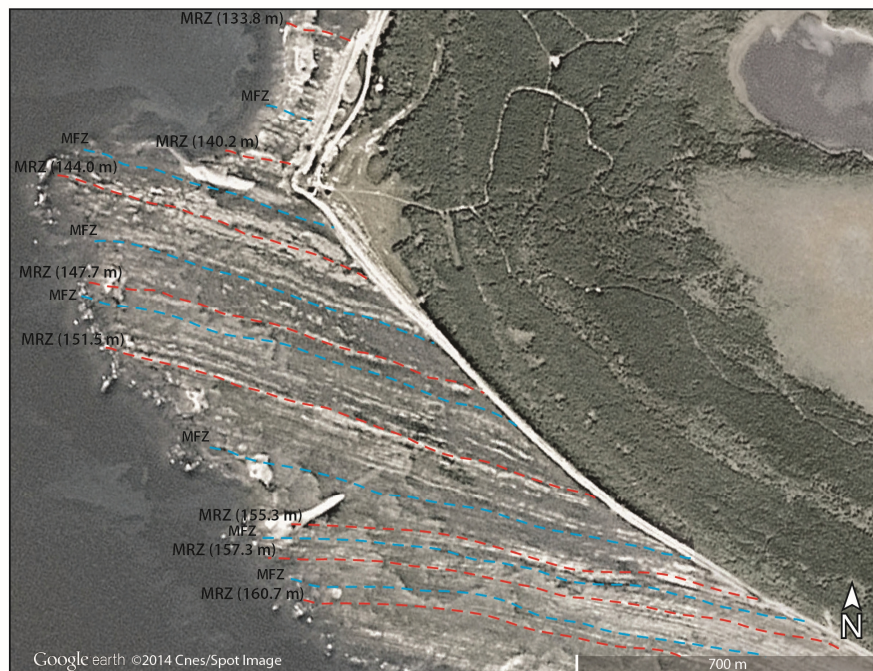
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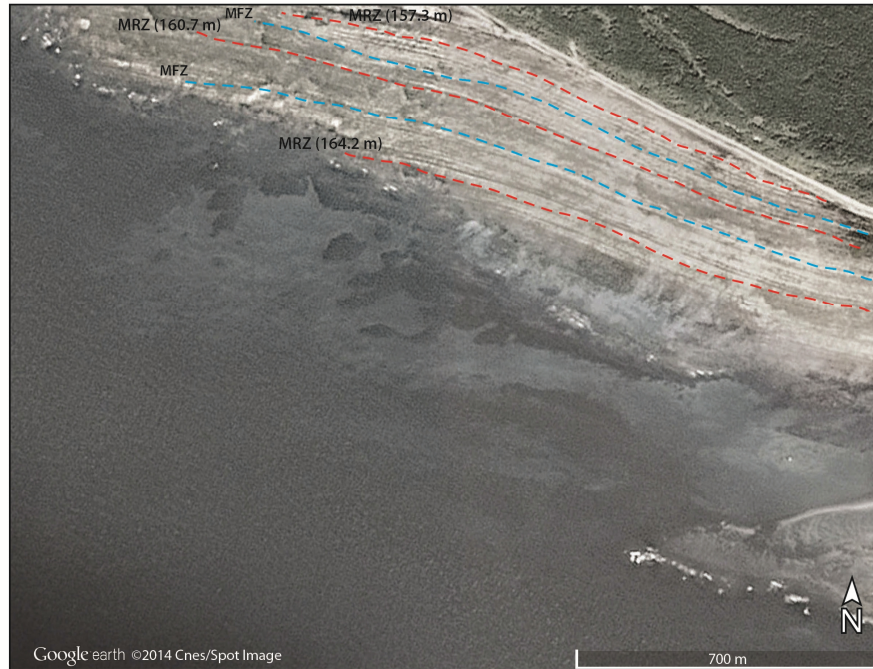
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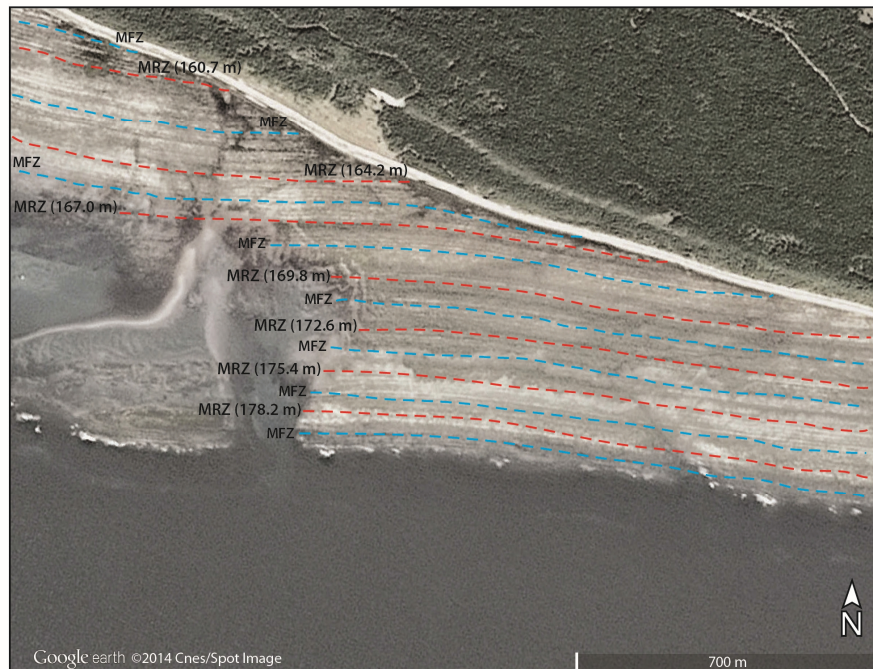
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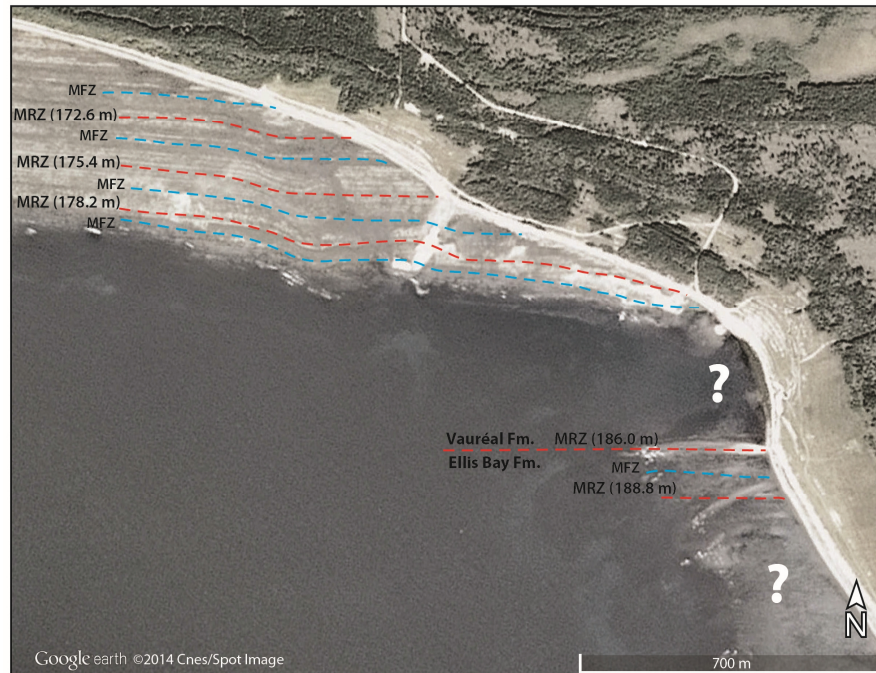
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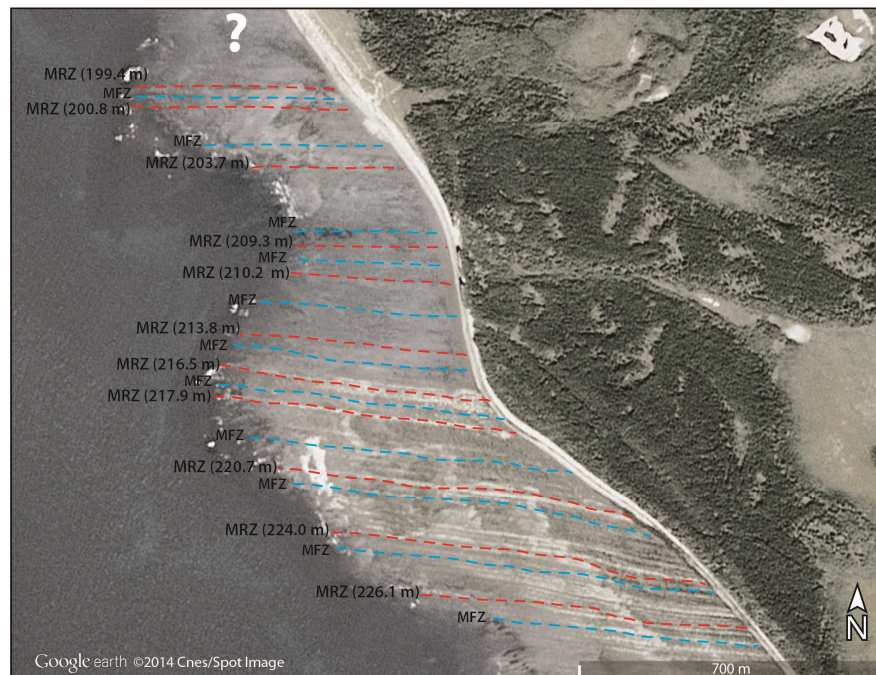
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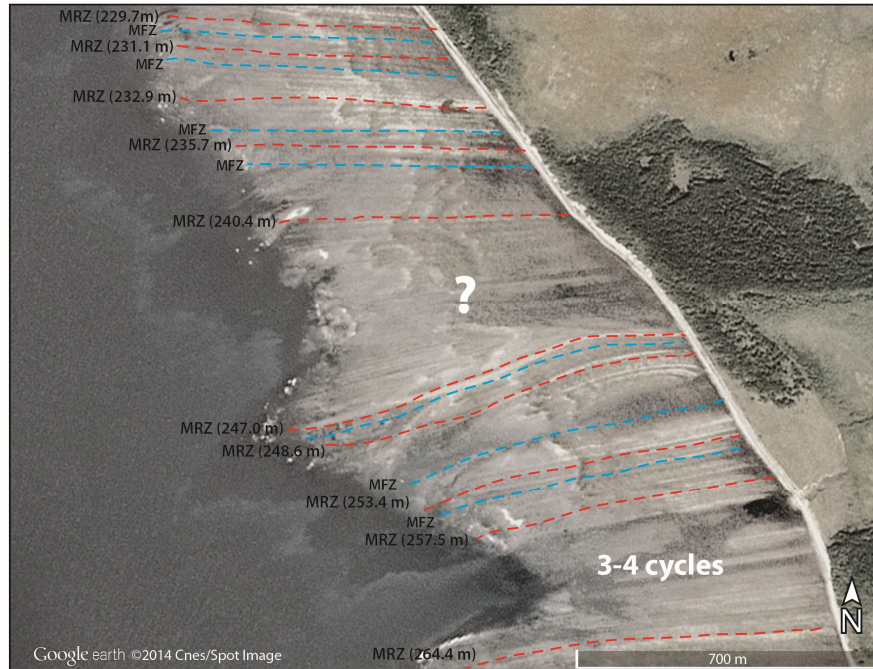
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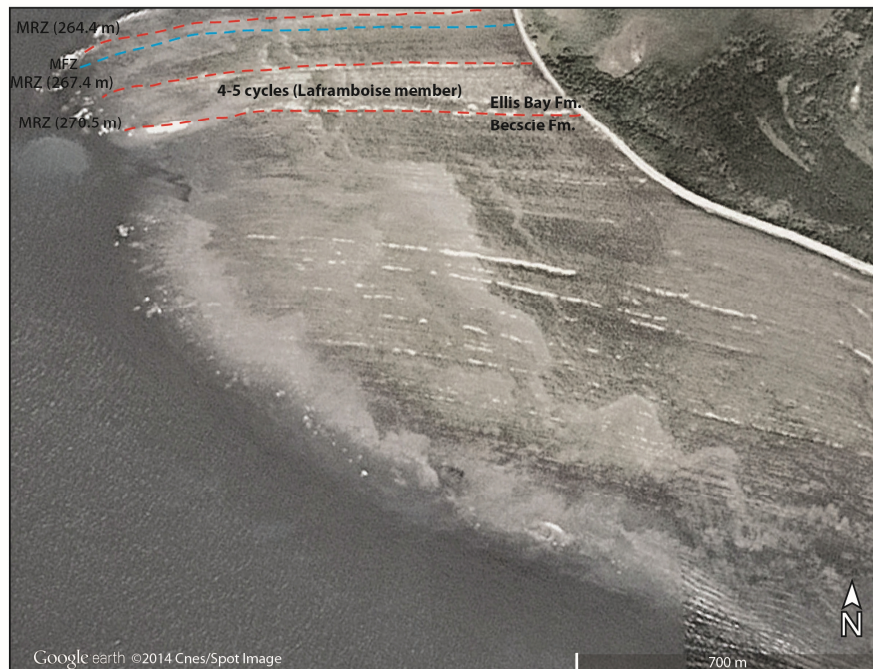
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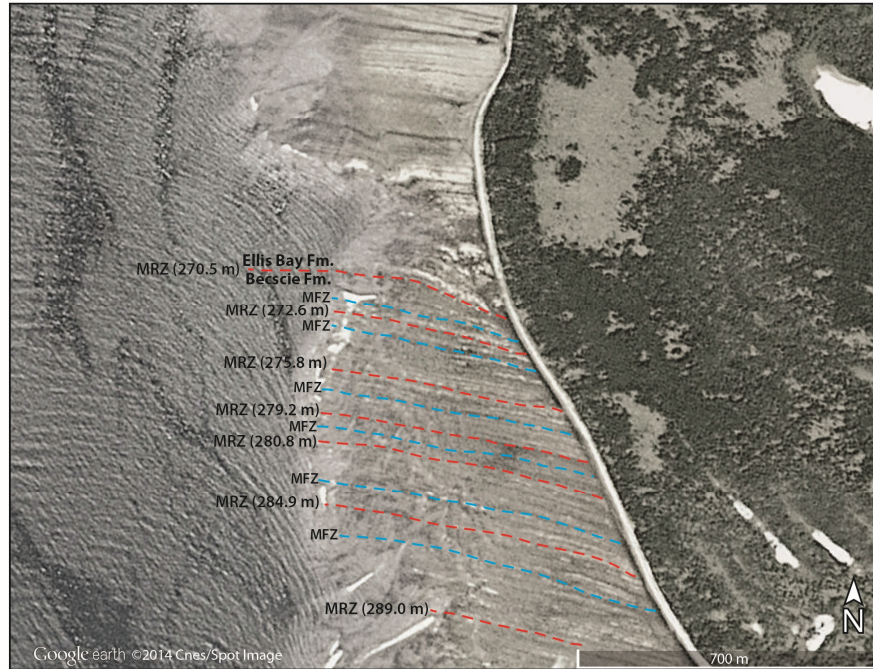
11



12



13



14

