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FACULTÉ DE ÉTUDES SUPÉRIEURES ET POSTDOCTORALES

FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

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Ph. D (Earth Sciences)

GRADE - DEGREE

Department of Earth Sciences

FACULTÉ, ÉCOLE, DÉPARTEMENT - FACULTY, SCHOOL, DEPARTMENT

TITRE DE LA THÈSE - TITLE OF THE THESIS

Sedimentology and Stratigraphy of an Ancient Progradational Terrigenous Clastic Shelf Margin, Missisauga Formation (Upper Jurassic-Lower Cretaceous), Offshore Nova Scotia, Canada

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DEAN OF THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

SEDIMENTOLOGY AND STRATIGRAPHY OF AN ANCIENT PROGRADATIONAL TERRIGENOUS CLASTIC SHELF MARGIN, MISSISAUGA FORMATION (UPPER JURASSIC-LOWER CRETACEOUS), OFFSHORE NOVA SCOTIA, CANADA

by

Donald I. Cummings

A thesis submitted to the School of Graduate Studies
in partial fulfillment of the requirements of the degree of Ph.D. in Earth Sciences

OTTAWA-CARLETON GEOSCIENCE CENTRE
UNIVERSITY OF OTTAWA
OTTAWA, ONTARIO CANADA

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ISBN: 0-494-01687-6
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ISBN: 0-494-01687-6

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ABSTRACT

Large-scale stratal architecture, structure, and commonly hydrocarbon distribution in the Missisauga Formation, Sable Subbasin, offshore Nova Scotia, can be satisfactorily explained by shelf margin progradation. Using an integrated subsurface dataset (2-D and 3-D seismic data, biostratigraphy, geophysical well logs, core), the physical characteristics and depositional history of the Missisauga Formation (Tithonian-Barremian) were studied on both local and regional scales. These data suggest that during deposition of the Missisauga, the shelf margin prograded southward from an initial position just basinward of the Venture Field (Tithonian) to a final position just basinward of the Glenelg and Alma fields (Barremian). Growth-faulted, storm-dominated deltaic sandstones deposited at or near the shelf margin during this process are interpreted to contain over half of the discovered in-place gas reserves offshore Nova Scotia. Because shelf-margin delta sand-bodies are typically shore-elongate, tend to occur in groups along a shelf margin and commonly correlate downdip to turbidite sand-bodies, recognition of the shelf-margin delta play-type will not only improve hydrocarbon exploitation strategies offshore Nova Scotia, but will provide an important framework to guide the identification of new exploration opportunities in genetically related parts of the stratigraphic section.

In the Venture Field, Tithonian shelf-margin delta lobes are stacked vertically, suggesting that growth-fault related subsidence at the shelf margin negated depositional topography and created topographic lows through which fluvio-deltaic systems preferentially flowed. Over several relative sea level cycles, the positive feedback between sediment supply and subsidence at the shelf margin potentially focused enough

sediment to have constructed slope turbidite systems downdip, which in turn represent new exploration targets.

In the Glenelg Field, Barremian shelf-margin deltas were initially tide-influenced (dominated?) and then changed to a storm-dominated state, possibly because the shoreline initially prograded into a tidally resonant topographic depression, which upon being filled was converted to a wave-dominated setting. Along depositional strike of the main hydrocarbon-bearing sandstones at Glenelg, Barremian sandstone reservoirs in the Alma Field are interpreted to be storm-dominated shelf-margin delta deposits. However, unlike Glenelg, incised valleys were not identified at Alma, suggesting that downdip depocenters were fed by sediment that bypassed Glenelg during the Barremian.

Transgression at the end of the Barremian deposited mudstone of the Naskapi Member throughout the Sable Subbasin, forming a regional seal. Sharp-based, bioturbated shallow marine sandstones deposited locally during this transgression are an important play type in the western Sable Subbasin (*e.g.*, Alma and Panuke fields).

RESUMÉ

L'architecture stratigraphique, les structures tectoniques, et souvent la distribution d'hydrocarbures dans la Formation Missisauga au large de la Nouvelle-Écosse peuvent être expliquées par la progradation de l'ancienne marge continentale. La sédimentologie et la stratigraphie de la Formation Missisauga (Tithonien-Barrémien) ont été étudiées dans le sous-bassin de Sable à l'aide d'une variété de données (diaphragies électrique, carottes de forage, données biostratigraphiques, sismique 2-D et 3-D). Ces données suggèrent que pendant la déposition de la Formation Missisauga la marge continentale a progradé vers le sud d'une position intiale près du champs Venture (Tithonien) jusqu'à une position finale au sud des champs Glenelg et Alma (Barrémien). Les deltas de marge continentale déposés grâce à ce processus contiennent vraissemblablement plus de la moitié du gaz naturel déjà découvert au large de la Nouvelle-Écosse. Parce que les corps sableux des deltas de marge continentale sont typiquement alongés de façon parallèle au rivage et agissent souvent comme entrepôt pour les sédiments livrés aux systèmes de turbidites sur la pente continentale, l'identification des deltas de marge continentale peut aider l'exploitation et l'exploration d'hydrocarbures au large de la Nouvelle-Écosse.

Dans le champs Venture, les lobes deltaïques Tithonien se juxtaposent à la verticale. Ceci suggère que la subsidence différentielle à la marge continentale peut créer des dépressions topographiques qui "attirent" les systèmes fluvio-deltaïques. Au cours de quelques cycles de niveaux relatifs de la mer, le "feedback" positif entre l'apport en sédiments et la subsidence de la marge continentale pourrait peut-être concentrer la livraison de sédiments aux systèmes de turbidites sur la pente continentale.

Dans le champs Glenelg, les deltas de marge continentale Barrémien ont premièrement été dominés par les marées, puis par les vagues. Adjacents à Glenelg, les réservoirs Barrémien dans le champs Alma sont interpretés comme des dépôts de deltas de marge continentale. Contrairement aux champs Glenelg, aucune vallée incisée n'a été identifiée à Alma.

La transgression marine à la fin du Barrémien a déposé de l'argile du Membre Naskapi dans toute la région du sous-bassin de Sable. Les corps sableux à bases érosives qui on été deposés localement pendant cette transgression forment des réservoirs de pétroles au coté ouest du sous-bassin de Sable (*e.g.*, les champs d'Alma et de Panuke).

ACKNOWLEDGEMENTS

This project was made possible thanks to financial support from Encana Energy, Norsk Hydro, Murphy Oil, and the Ontario Government. It was put together by Bill Arnott, Bruce Hart and John Hogg, three ex-Hamiltonians, two of whom were apparently born in a pub, wearing Speedos, and listening to bad '70s rock music (although, admittedly, Bruce has recently undergone a remarkable music-appreciation transformation). I owe a whole lot to all three of you, and especially Bill, for getting me a great project and supporting me throughout. Three lovely ladies, Mary Jean Verrall, Keri O'Kroneg and Nancy Williams, turned potentially dour summers in the Dartmouth core shack into a great experience. This thesis benefited from scientific discussions with Bill Arnott, Bruce Hart, Simone Dumas, Bob Dalrymple, Andrew MacRae, Dave Brown, Paul Harvey, Jack MacDonald, Gunilla Gard, Jason Crux, Sonia Dehler, John Schimeld, John Wade, Hazen Russell, Suzanne Leclair, Steven Goodbred, Bill Galloway, John Jaeger, Meade Allison, James MacEachern, Gisella Gerdes, Ron Steel, Shuji Yoshida, Kyungsik Choi, John Suter, Gela Crane, Rick Weirzbicki, and John Hogg. Thorough text editing by thesis committee members André Desrochers, Al Donaldson, Rob Rainbird and John Harper helped improve the final draft. Rob Fensome graciously analyzed palynology samples, Jim Fenton allowed me access to biostratigraphic data, and Paul Gammon helped identify skeletal fragments in thin section. Pat Allen provided much-needed technical support, and Hélene DeGouffe, the Earth Science Queen, made sure that I kept registered in school.

Mom and Dad, thanks for giving me the chance to even start this thesis. Diane, Margo, André, Sarah, Rob, Simon and Julie: thanks for helping out on the home front. Chris, Popo, Steve, Dave, Richard, John, and all members of the double-H express past and present (which covers just about everyone in town) are thanked for being great friends; I'm going to look back on all the late Ottawa nights with great fondness. Leo, I'd like to think that I did this thesis, in a large part, for you. And Simone, you were always there for me; I appreciate that more than anything.

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Chapter 1. Introduction

1.1 Rationale and objectives

Fluvial to continental slope sandstones of the Missisauga Formation contain ~75% of the original gas-in-place reserves discovered offshore Nova Scotia, Canada (Canada Nova Scotia Offshore Petroleum Board, 2000). Despite this, few studies have examined the sedimentology of the Missisauga in detail, and the formation has yet to be placed into a comprehensive sequence stratigraphic framework. The primary objective of this thesis, therefore, is to develop sequence stratigraphic-based depositional models for the Missisauga Formation at both local and regional scales in the hydrocarbon-rich Sable Subbasin, offshore Nova Scotia (Figure 1.1). Following a brief geological overview of the Sable Subbasin (Chapter 2), depositional models for selected parts of the Missisauga Formation are presented in a series of self-contained papers (Chapters 3, 4 and 5), followed by a short summary and conclusion (Chapter 6). Sedimentological logs are archived in appendices at the end of the thesis.

1.2 Statement of original contribution

All ideas, descriptions and interpretations presented in this thesis are my own, unless otherwise referenced. My supervisor and co-supervisor, Dr. R.W.C. Arnott (University of Ottawa) and Dr. B.S. Hart (McGill University), have contributed in minor but important ways, primarily during the text editing process.

1.3 Dataset

The results of this study are based on the analysis of geophysical well-log and cuttings data from 82 wells (Figure 1.2a), 2333 m of conventional core from 39 wells (Figure 1.2b), public and confidential biostratigraphic data (Figure 1.2c), ~1825 km of publicly available paper-format seismic data (Figure 1.2d) and an industry-donated digital 3-D seismic survey from the Panuke Field (96 km^2) cut off at 2.2 seconds (Figure 1.2d)[1]. Additionally, Rob Fensome (Geological Survey of Canada) analyzed seven palynology samples collected from conventional cores from the West Venture C-62 well (see Chapter 4).

1.4 Methodology

Cores were described in 2.5 cm resolution (see Appendix 1), noting lithology, sedimentary textures and structures, body fossils, trace fossils, macroscopic diagenetic features, and the nature of stratigraphic contacts. Depositional processes and depositional environments were interpreted using a standard "process-oriented" facies analysis approach (*e.g.*, Harms *et al.*, 1975; Scholle and Spearing, 1982; Walker and James, 1992; Reading, 1996; Pemberton *et al.*, 2002). Geophysical well logs were calibrated using core data, and were tied to seismic data using synthetic seismograms generated from sonic or sonic and density logs[2]. Seismic, well log, and core data were interpreted using standard seismic and sequence stratigraphic techniques and concepts (*e.g.*, Curray, 1964;

---

[1] Two additional industry-donated 3-D seismic surveys (Annapolis and Annapolis East) were also loaded and analyzed, but proved unusable because of poor resolution at depth.

[2] For digital seismic data, well ties were performed using a computer program (Landmark Geographix) at the McGill Seismic Research Lab. In the case of paper-copy seismic data, seismic and synthetic data were scanned into a computer program (Adobe Illustrator), and then the synthetics were adjusted (*i.e.* stretched) to "best fit" the seismic data. Where available, well ties were guided by checkshot data. The final well ties were checked against previously-reported well ties in MacLean and Wade (1993) and various unpublished reports (Sable Offshore Energy, 1996; Mobil 1997a,b,c, 1998a,b).

Vail *et al.*, 1977; Posamentier and Vail, 1988; Van Wagoner *et al.*, 1990; Emery and Myers, 1996; Posamentier and Allen, 1999).

Figure 1.1 Location of study area, Sable Subbasin, offshore Nova Scotia, Canada.

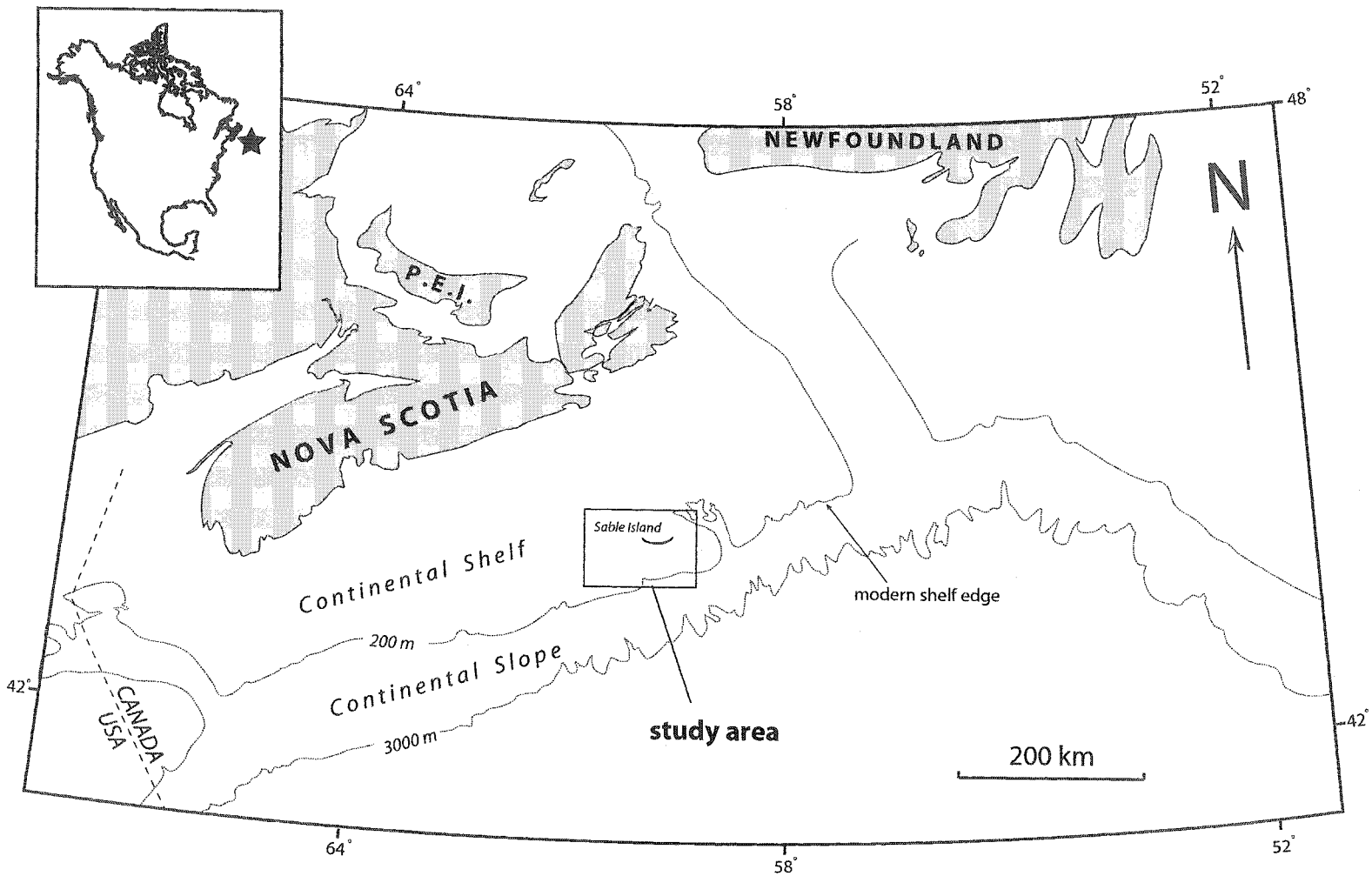

64°
58°
52°
48°
NEWFOUNDLAND
N
P.E.I.
NOVA SCOTIA
Sable Island
Continental Shelf
200 m
Continental Slope
3000 m
modern shelf edge
study area
200 km
42°
CANADA
USA
64°
58°
52°
42°

Figure 1.2a Location of oil and gas wells, Sable Subbasin, offshore Nova Scotia. A variety of geophysical well-log data (gamma ray, density, resistivity, dipmeter) were typically available for each well.

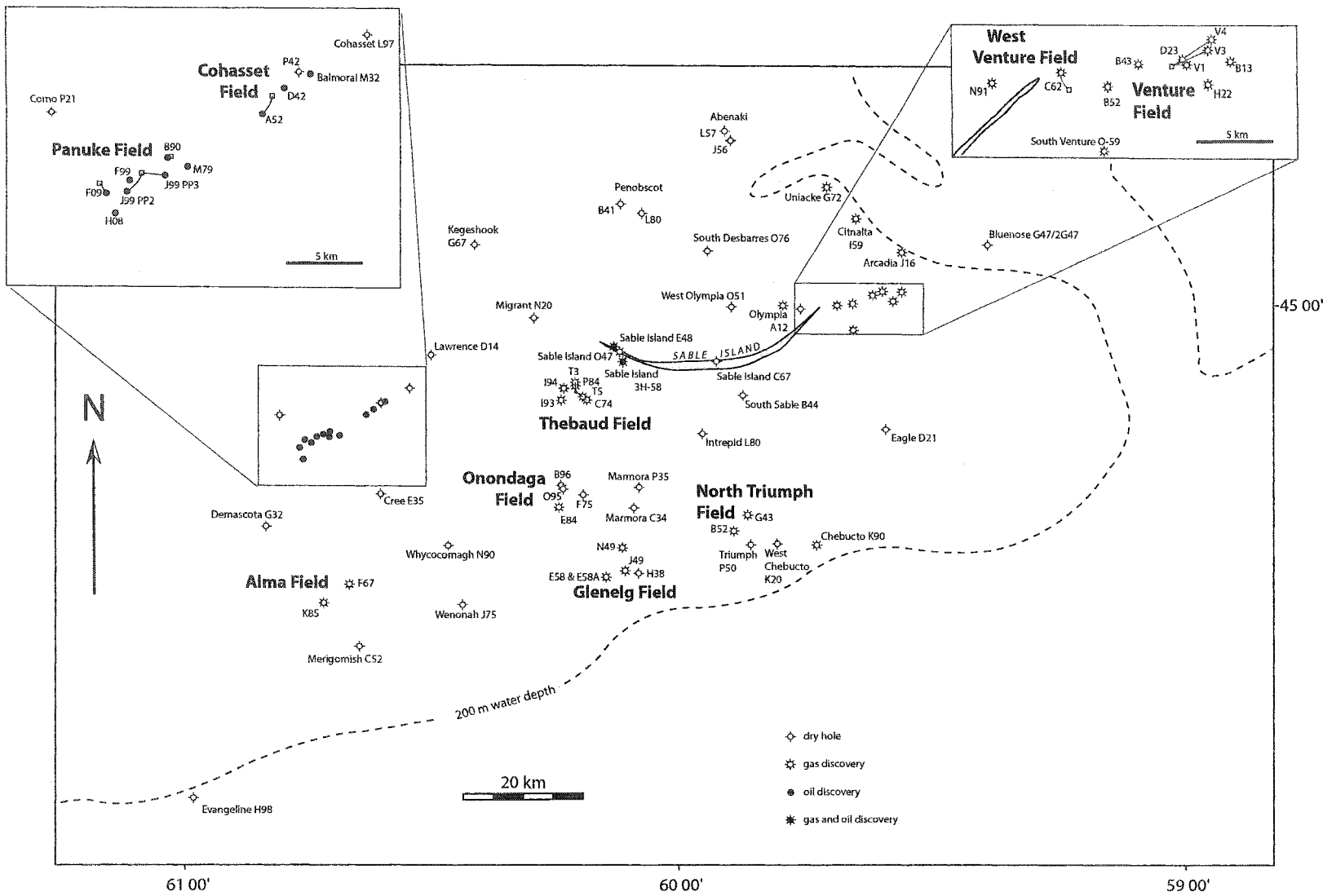

Cohasset L97
Cohasset Field
P42
Balmoral M32
D42
A52
Como P21
Panuke Field
B90
M79
F99
J99 PP3
F09
J99 PP2
H08
5 km
West Venture Field
V4
D23
V3
B43
V1
B13
N91
C62
B52
Venture Field
H22
South Venture O-59
5 km
Abenaki
L57
J56
Penobscot
B41
L80
Uniacke G72
Kegeshook G67
South Desbarres O76
Citnalta I59
Arcadia J16
Bluenose G47/2G47
West Olympia O51
Migrant N20
Olympia A12
Lawrence D14
Sable Island E48
Sable Island O47
SABLE ISLAND
T3
I94
P84
T5
I93
C74
Sable Island 3H-58
Sable Island C67
South Sable B44
Thebaud Field
Intrepid L80
Eagle D21
N
Onondaga Field
B96
O95
F75
E84
Marmora P35
Marmora C34
North Triumph Field
G43
B52
Chebucto K90
Triumph P50
West Chebucto K20
Cree E35
Demascota G32
Whycocomagh N90
N49
J49
E58 & E58A
H38
Glenelg Field
Alma Field
F67
K85
Wenonah J75
Merigomish C52
200 m water depth
dry hole
gas discovery
oil discovery
gas and oil discovery
20 km
Evangeline H98
45 00'
61 00'
60 00'
59 00'

Figure 1.2b Location of Missisauga Formation core used in this study, Sable Subbasin, offshore Nova Scotia. Cumulative core lengths for wells are given in meters.

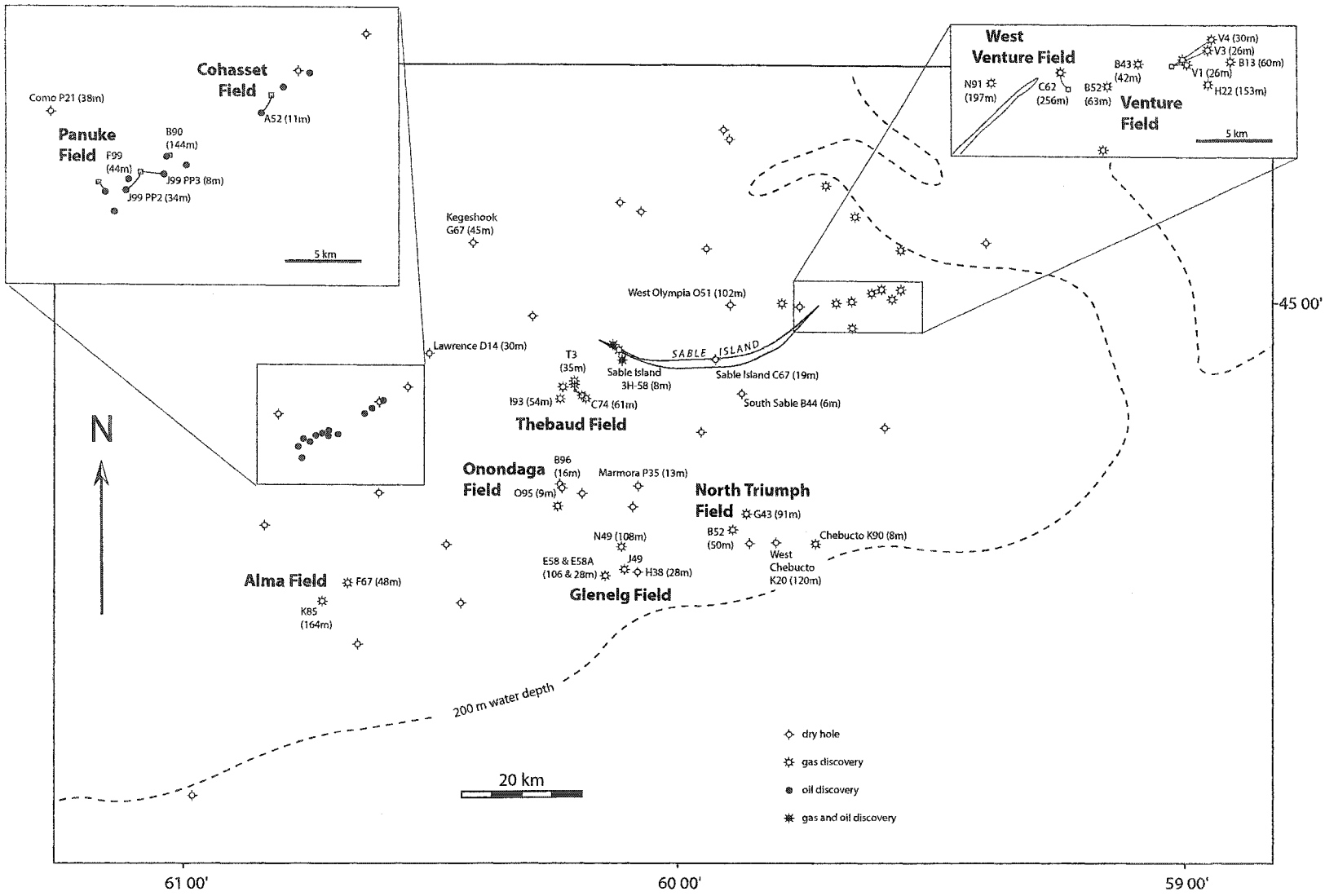

Cohasset Field
Como P21 (38m)
A52 (11m)
Panuke Field
B90 (144m)
F99 (44m)
J99 PP3 (8m)
J99 PP2 (34m)
5 km
West Venture Field
V4 (30m)
V3 (26m)
B13 (60m)
B43 (42m)
N91 (197m)
C62 (256m)
B52 (63m)
V1 (26m)
H22 (153m)
Venture Field
5 km
Kegeshook G67 (45m)
West Olympia O51 (102m)
Lawrence D14 (30m)
T3 (35m)
SABLE ISLAND
Sable Island 3H-58 (8m)
Sable Island C67 (19m)
I93 (54m)
C74 (61m)
South Sable B44 (6m)
Thebaud Field
N
Onondaga Field
B96 (16m)
O95 (9m)
Marmora P35 (13m)
North Triumph Field
G43 (91m)
B52 (50m)
Chebucto K90 (8m)
West Chebucto K20 (120m)
N49 (108m)
E58 & E58A (106 & 28m)
J49
H38 (28m)
Glenelg Field
Alma Field
F67 (48m)
K85 (164m)
200 m water depth
20 km
dry hole
gas discovery
oil discovery
gas and oil discovery
45 00'
61 00'
60 00'
59 00'

Figure 1.2c Location of biostratigraphic data used in this study, Sable Subbasin, offshore Nova Scotia.

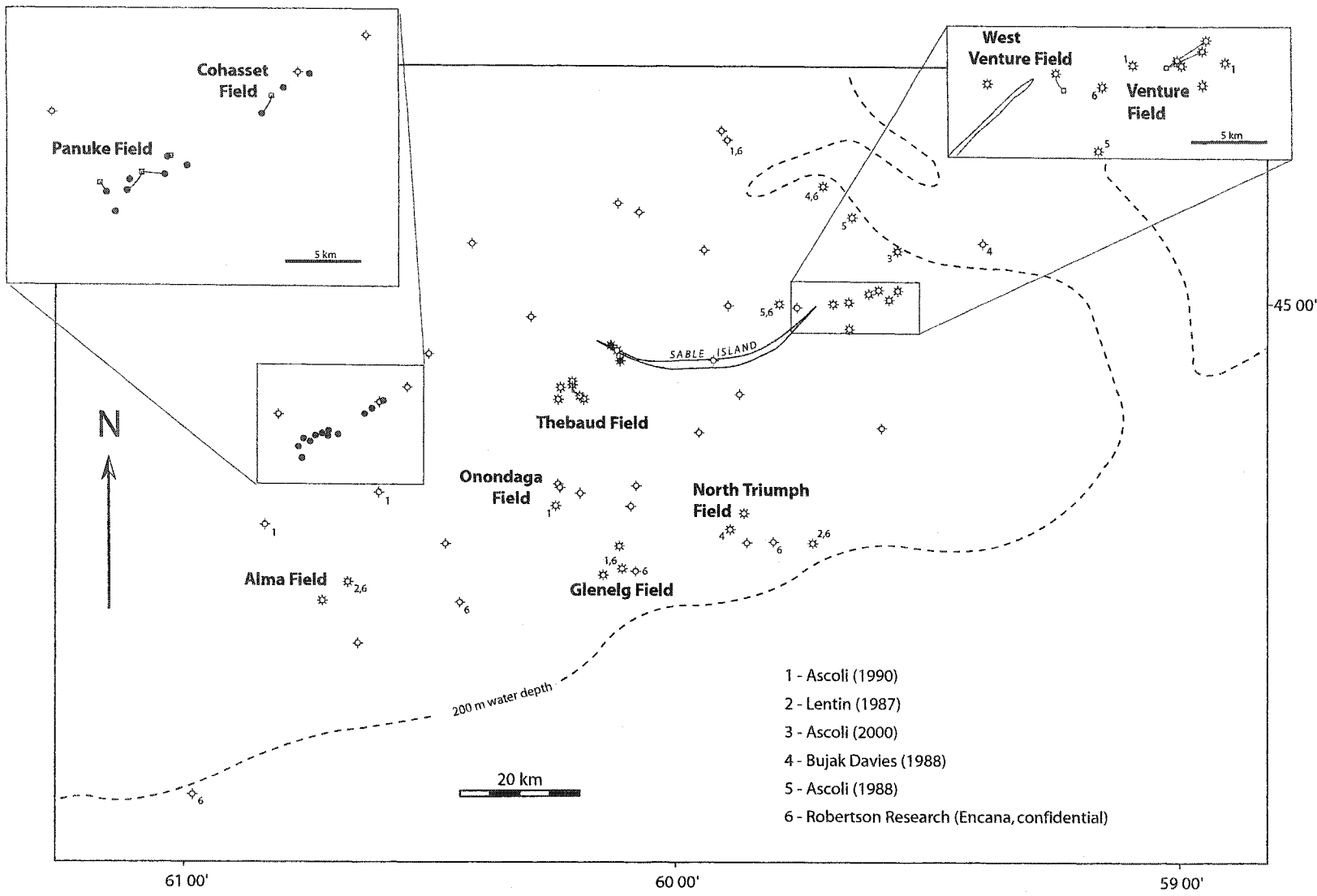
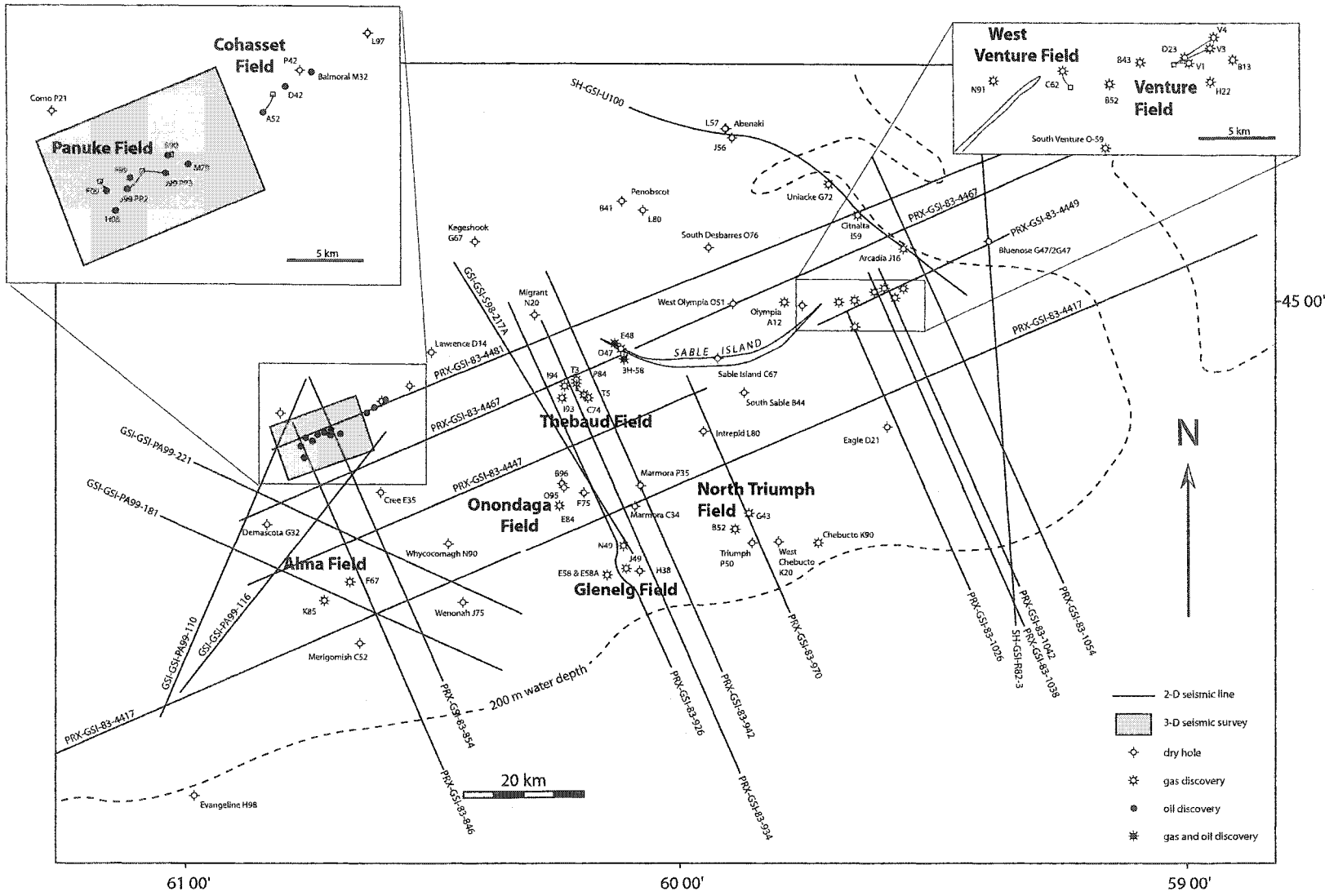

Cohasset Field
Panuke Field
5 km
West Venture Field
Venture Field
5 km
SABLE ISLAND
N
Thebaud Field
Onondaga Field
North Triumph Field
Alma Field
Glenelg Field
200 m water depth
20 km
45 00'
61 00'
60 00'
59 00'
1 - Ascoli (1990)
2 - Lentin (1987)
3 - Ascoli (2000)
4 - Bujak Davies (1988)
5 - Ascoli (1988)
6 - Robertson Research (Encana, confidential)

Figure 1.2d Location of seismic data used in this study, Sable Subbasin, offshore Nova Scotia.


Cohasset Field
Panuke Field
Como P21
L97
P42
Balmoral M32
D42
A52
5 km
West Venture Field
Venture Field
N91
C62
B52
B43
D23
V4
V3
V1
B13
H22
South Venture O-59
5 km
SH-GSI-U100
L57 Abenaki
J56
Penobscot
B41
L80
Uniacke G72
Kegeshook G67
South Desbarres O76
Citnalta I59
Arcadia J16
Bluenose G47/2G47
PRX-GSI-83-4467
PRX-GSI-83-4449
PRX-GSI-83-4417
GSI-GSI-598-217A
Migrant N20
West Olympia O51
Olympia A12
Lawrence D14
PRX-GSI-83-4481
E48
D47
3H-58
SABLE ISLAND
Sable Island C67
I94
T3
P84
T5
I93
C74
Thebaud Field
South Sable B44
Intrepid L80
Eagle D21
PRX-GSI-83-4447
B96
O95
F75
E84
Marmora P35
Marmora C34
Onondaga Field
North Triumph Field
G43
B52
Triumph P50
West Chebucto K20
Chebucto K90
Cree E35
Demascota G32
Whycocomagh N90
Alma Field
F67
K85
Wenonah J75
Merigomish C52
N49
J49
H38
E58 & E58A
Glenelg Field
GSI-GSI-PA99-221
GSI-GSI-PA99-181
GSI-GSI-PA99-110
GSI-GSI-PA99-116
PRX-GSI-83-4417
PRX-GSI-83-854
PRX-GSI-83-846
PRX-GSI-83-976
PRX-GSI-83-942
PRX-GSI-83-934
PRX-GSI-83-970
PRX-GSI-83-1025
SH-GSI-R82-3
PRX-GSI-83-1042
PRX-GSI-83-1038
PRX-GSI-83-1054
200 m water depth
Evangeline H98
20 km
N
45 00'
61 00'
60 00'
59 00'
2-D seismic line
3-D seismic survey
dry hole
gas discovery
oil discovery
gas and oil discovery

Chapter 2. Geological Overview

The Scotian Basin is one of a series of sedimentary basins along the eastern seaboard of North America that formed during the break up of Pangea and the subsequent opening of the Atlantic Ocean (Figure 2.1). Although its development was initiated during a period of tectonic activity that involved crustal extension and rifting, the Scotian Basin is commonly referred to as a *passive margin basin* because it straddles the continental-oceanic crust transition on the now tectonically quiescent trailing margin of the North American continental plate (*e.g.*, Allen and Allen, 1990; Busby and Ingersoll, 1995). Like most thick "Atlantic-type" passive margin basins, the Scotian Basin is characterized by 1) a distinct shelf-slope morphology, 2) basinward-increasing accommodation space for sediment accumulation[3], 3) a regional subsidence history driven by lithospheric cooling and sediment loading with zones of locally elevated subsidence related to salt withdrawal, 4) a rifted and "modified" continental crust basement[4], and 5) structural features (*e.g.*, salt diapirs, growth faults) that formed predominantly as a result of gravity instability (Figure 2.2). However, despite these similarities, the stratigraphy of the Scotian Basin is ultimately unique, and reflects the complex interplay of intra- and extra-basinal controls active during its development.

2.1 Exploration history

Petroleum industry interest in offshore Nova Scotia was sparked in the 1950s by seismic refraction surveys that suggested the continental shelf and slope were underlain

[3] From a sedimentological point of view, the Atlantic Ocean is essentially unfilled accommodation space.
[4] Rifted continental crust that underlies the Scotian Basin may have been "modified" locally by rift-related magmatic underplating and is "modified" locally by rift-related basaltic volcanics (Keen *et al.*, 1994). The modified crust commonly has seismic velocities intermediate between those of continental and oceanic crust, and is commonly referred to as being "transitional" between continental and oceanic crust (Keen and Beaumont, 1990).

by a thick package of sedimentary rock similar to that of the U.S. Gulf Coast, a proven hydrocarbon province (*e.g.*, Officer and Ewing, 1954). The first offshore exploration license was issued to Mobil Oil in 1959, and the first offshore well, Sable Island C-67, was drilled in 1967 by Mobil from a platform on Sable Island. Although this well confirmed the presence of a thick (~4.5 km) succession of predominantly siliciclastic sedimentary rock, it did not encounter any significant hydrocarbon-bearing intervals. The first significant gas and oil discoveries were made in 1969 at Onondaga E-84 and in 1971 at Sable Island E-48, respectively (Bell and Campbell, 1990).

Although oil is present locally in economic quantities offshore Nova Scotia (*e.g.*, Cohasset and Panuke fields; LASMO, 1990), drilling results to date suggest that the Scotian Basin is largely gas-rich and oil-poor. In part, therefore, industry activity has been driven by the price of natural gas, not oil (Figure 2.3). The first wave of drilling activity, spurred on by the above mentioned discoveries, tailed off after 1973 when the Arab oil embargo forced western petroleum companies to shift exploration efforts to oil-rich basins (Paul Harvey, personal communication, 2002). Following a downturn in the late 1970s, a second wave of drilling was initiated when Mobil Oil discovered the giant Venture Field in 1978 under very favorable gas market conditions. This burst of activity was curtailed by a fall of gas prices in the mid-1980s. In the 1990s, a second wave of drilling activity started when several of the previously discovered oil and gas fields went into production under the Cohasset/Panuke and Sable Offshore Energy Projects (LASMO 1990; Sable Offshore Energy, 1996). Offshore Nova Scotia is currently experiencing a third wave of drilling activity as industry develops new fields and tests new shelf carbonate and siliciclastic slope turbidite plays (*e.g.*, Deep Panuke and Annapolis wells).

As of January 2002, 176 wells have been drilled, 377, 299 km of 2-D seismic have been shot, and 23, 944 km^2 of 3-D seismic have been collected (Canada-Nova Scotia Offshore Petroleum Board website).

2.2 Basin physiography

In plan view, the Scotian Basin has an elongate oval shape that extends parallel to the modern coast between a basement high offshore of the U.S.-Canada border (the Yarmouth Arch) and a Late Jurassic-Early Cretaceous uplifted region southeast of Newfoundland (the Avalon Uplift; Figure 2.4). In dip cross-section, basin fill thickens southeastward (*i.e.*, basinward) from a feather-edge to a zone of maximum thickness beneath the modern shelf margin, and then thins below the lower continental slope and merges with deposits of the Atlantic Ocean abyssal plain (Figure 2.5).

The Scotian Basin comprises several interconnected Mesozoic-Cenozoic depocenters or *subbasins* (Figure 2.4). Basin fill reaches an estimated maximum thickness of ~20 km in the Laurentian Subbasin (MacLean and Wade, 1992), the thickest sedimentary accumulation offshore Canada (Keen and Williams, 1990)[5]. Subbasins are located outboard of the *hinge zone*, a series of normal faults and flexures in basement rock across which substantial thickening of the sedimentary fill occurs (Figures 2.4 and 2.5). Landward of the hinge zone, basin fill is generally thin (<4 km).

Basement rock underlying the Scotian Basin subbasins has never been drilled and in general cannot be imaged seismically because of the substantial thickness of the sedimentary cover. Where wells have penetrated the thin basin fill landward of the hinge

[5] Other thick sedimentary accumulations, which likely exceed 14 km in thickness, include the Jean D'Arc Basin, offshore Newfoundland, and the Baffin Basin, offshore Baffin Island (Keen and Williams, 1990).

zone, basement consists of an offshore extension of continental igneous and metasedimentary rocks of the Cambrian-Ordovician Meguma Group (Pe-Piper and Loncarevic, 1989; Wade and MacLean, 1990). Basement seismic reflections in this region form a series of elongate, coast-parallel horst and grabens and half grabens interpreted to be Early Mesozoic rift basins (Welsink *et al.*, 1989; Wade and MacLean, 1990). Although basement cannot be imaged seismically below the thick subbasins, the presence of salt diapirs suggests that they too generally overlie rifted continental crust[6].

To date, efforts to find oil and natural gas offshore Nova Scotia have focused on the Sable Sabbasin, a thick (~18 km) and predominantly siliciclastic Mesozoic-Cenozoic depocenter located beneath Sable Island (Figure 2.4). As a result, the Sable Subbasin is the best understood of the Scotian Basin subbasins. The Sable Subbasin is separated to the north from the Abenaki Subbasin by a subtle basement high (the North Sable High; see Figure 2.5). To the northwest and west the hinge zone separates the Sable Subbasin from the Lahave Platform, a site of reduced subsidence and carbonate accumulation throughout much of the Mesozoic (Eliuk, 1978; Schalger, 1981). To the northeast, the Sable Subbasin thickens and becomes more carbonate rich before merging with the siliciclastic-rich Laurentian Subbasin (MacLean and Wade, 1992). The southeast boundary of the Sable Subbasin is the modern continental slope, a gently dipping (~1.4°) surface that separates basin fill from the Atlantic Ocean.

[6] The outermost, salt diapir-free region of the Scotian Basin likely overlies oceanic lithosphere (Wade and MacLean, 1990).

2.3 Tectonic evolution

During the Paleozoic, the eastern margin of North America was subjected to three convergent deformational events that accreted several allochtonous terranes onto the side of the continent, forming the Appalachian Mountains (Wilson, 1966). These deformational events, which occurred during the Ordovician, Silurian-Devonian, and Carboniferous-Permian, correspond to the Taconian, Acadian, and Alleghanian orogenies, respectively (Keen *et al.*, 1990). Pangea was amalgamated during the last of these when Laurasia and Gondwana collided and sutured about the Appalachian-Mauretinide fold and thrust belt.

Migrating northward, Pangea began to rift in the Permian when the compressional stress regime associated with the Alleghanian orogeny relaxed and was replaced by a tensional regime. Rift systems in the North Sea and Tethys regions propagated southward and westward respectively, intersecting one another in the North Atlantic region. Between the mid-Triassic and the early-Jurassic, a series of rift basins developed on the eastern side of North America parallel to the Appalachian Mountains (Figure 2.6). Commonly, rift basins formed by reactivation of older, compressional Appalachian structures (Withjack *et al.*, 1998). Graben and half-graben basins within the rift zone subsided and infilled with sediment as the continental crust thinned and underwent brittle extensional deformation. There is no current consensus as to whether rifting was active (*i.e.*, it was instigated by a buoyant mantle plume) or passive (*i.e.*, it was initiated by pre-existing horizontal tension in the lithosphere; Sonia Dehler, personal communication, 2004).

In the early- to mid-Jurassic, crust of central North America and West Africa separated when a linear seafloor-spreading ridge developed down the center of the rift system (Figure 2.6). This nascent spreading ridge was bracketed by transform faults south of Newfoundland and east of Florida (Withjack *et al.*, 1998). The central North American rift-drift transition was characterized by widespread basaltic volcanism (Pe-Piper and Piper, 1999), thermal uplift and erosion (Ziegler, 1989), and a brief transition from a tensional to a compressional stress regime (Withjack *et al.*, 1998). Following separation of central North America from West Africa, the spreading ridge "unzipped" and branched northward incrementally, with Newfoundland separating from Portugal in the Late Jurassic/Early Cretaceous, Labrador from Greenland in the early Paleocene, and Norway from Greenland in the mid to late Paleocene (Ziegler, 1989; Uchupi and Emery, 1991). Post-rift sediments began to accumulate on top of the rifted margin of North America, which appears to have started to subside during the early Jurassic as the lithosphere cooled and was loaded with sediment (Ryan and Zentilli, 1993)[7]. Through net progradation, these sediments eventually developed a large-scale (*i.e.*, several hundred to thousands of meters relief) "shelf-slope-rise" clinoform morphology (*e.g.*, Pirmez *et al.*, 1998).

2.4 Stratigraphic evolution

Stratigraphic frameworks published for the Scotian Basin all recognize the same general succession of lithostratigraphic units outlined originally by McIver (1972), and

[7] Thermal subsidence of the oceanic lithosphere is reflected in the increase in water depth from the modern (hot) mid-oceanic spreading ridge towards the (cooler) continental margin (Keen and Williams, 1990)

subdivide the stratigraphy into syn- and post-rift units (Figures 2.7 and 2.8)[8]. Unlike western Canada, our understanding of the post-Paleozoic history of eastern Canada comes largely from study of subsurface offshore datasets like that of the Scotian Basin because few Mesozoic or Cenozoic strata crop out on the adjacent continent (Duk-Rodkin and Hughes, 1994; White *et al.*, 2000; Stea and Pullen, 2001).

2.4.1 Syn-rift deposits

Halite and red-coloured continental deposits of the Argo and Eurydice formations were deposited in elongate half-graben and graben rift basins that formed between the Mid-Triassic and the Early Jurassic (Figure 2.9). Relatively little is known about these syn-rift deposits because they are deeply buried and are not traditional targets for petroleum exploration. The presence of thick (<2 km) syn-rift evaporites suggests that the climate was likely hot, arid and subtropical during rifting (Gradstein *et al.*, 1990; Rees *et al.*, 2000), and that rift basins were periodically connected with the Tethys Ocean to the east (Jansa *et al.*, 1980; Holser *et al.*, 1988). The Yarmouth Arch apparently limited southward extension of the main evaporite basin (Keen *et al.*, 1990).

2.4.2 Post-rift deposits

Post-rift "passive margin" deposition started offshore Nova Scotia in the Early Jurassic following the transition from rifting to "drifting" (*i.e.*, post-seafloor spreading). A prominent erosion surface, termed the break-up or post-rift unconformity, which

[8] Passive margin basins *sensu stricto* are "post-rift" features that develop following the transition from rifting to sea floor spreading (*e.g.*, Busby and Ingersoll, 1995). However, previous studies of the Scotian Basin typically include precursor "syn-rift" rift basin sediments as well as the "post-rift" passive margin sediments. This approach is followed here.

truncates syn-rift strata in proximal regions of the Scotian Basin, suggests that rift flank uplift occurred during the rift-drift transition (Wade and MacLean, 1990; Withjack *et al.*, 1998). The break-up unconformity is onlapped by either dolomite of the Iroquois Formation or by Mohican Formation siliciclastics. These Lower to Middle Jurassic deposits reach a combined thickness of 4 km locally, and complete the infill of rift basins and overlap basement highs (Wade and MacLean, 1990). $^{40}Ar/^{39}Ar$ radiogenic ages from the Mohican Formation are similar to those obtained from strata that crops out on the southern Nova Scotia mainland (*ca.* 250-350 Ma), suggesting that initial post-rift sediments were derived locally from uplifted rift flanks (Grist *et al.*, 1992). Neither the breakup unconformity nor the Iroquois or Mohican formations have been drilled or imaged seismically basinward of the hinge zone in the Sable Subbasin (Wade and MacLean, 1990).

Strata of the Western Bank Group were deposited on the Iroquois and Mohican formations following establishment of normal marine conditions across the Scotian Basin (McIver, 1972). The West Bank Group comprises the Abenaki, Mohawk, Mic Mac and Verrill Canyon formations (Figures 2.7 and 2.10). These lithostratigraphic units were deposited contemporaneously in different parts of the Scotian Basin between the Middle and Upper Jurassic (McIver, 1972; Eliuk, 1978). The deepest wells in the Sable Subbasin encounter but do not fully penetrate the West Bank Group (*e.g.*, Olympia A-12).

The Abenaki Formation consists of shallow-marine, oolite-rich limestone of the Scatarie and Baccaro members, lithistid sponge-rich limestone of the Artimon Member, and terrigenous shale of the Misaine Member (Eliuk, 1978; Eliuk and Levesque, 1989; Jansa *et al.*, 1989; PanCanadian Energy, 2002; Weirzbicki *et al.*, 2003, 2004). The

Abenaki Formation is best developed above the hinge zone along the western edge of the Sable Subbasin, where it locally reaches thicknesses of about 1.2 km. The top of the Abenaki Formation, which downlapped by Mesozoic siliciclastics and is locally karsted (Weirzbicki *et al.*, 2004), has been interpreted to be a drowning unconformity (Schlager, 1981). Abenaki shelf-margin carbonates grade basinward into deep-water mudstones of the Verrill Canyon Formation.

The Mic Mac Formation is a predominantly siliciclastic unit deposited coevally with and adjacent to the Abenaki Formation (Figures 2.10 and 2.11). The Late Jurassic shelf margin near Sable Island consisted of Abenaki Formation carbonates in the east where terrigenous sediment input was low, and Mic Mac Formation siliciclastics in the west where terrigenous sediment input was high (Figure 2.10). The Mic Mac has been encountered but not fully penetrated in deeper wells just east of Sable Island. In this region, the Mic Mac and overlying Lower Missisauga formations form large-scale (*i.e.*, about 1 second), southward-dipping seismic reflections that suggest shelf margin progradation occurred during Mic Mac deposition (Figure 2.12)[9].

The Nova Scotia Group, which comprises terrigenous clastics of the Missisauga and Logan Canyon formations, overlies the Western Bank Group in the Sable Subbasin (McIver, 1972). In seismic data, reflections associated with the Missisauga and Logan Canyon formations are generally parallel ("railroad track") and dip gently southwest; clinoform-shaped reflections and erosional truncation surfaces are typically absent,

[9] Because of their relief (*i.e.*, hundreds of meters), these clinoform-shaped reflections most likely record outbuilding of the entire continental slope during deposition of the Mic Mac and Missisauga formations. Although deltas are believed to be the primary sediment delivery system to the continental shelf edge, they typically have clinoforms that are an order of magnitude smaller than continental slope clinoforms, and unlike slope clinoforms, are rarely associated with substantial turbidite fans (Porebski and Steel, 2003; Donovan, 2003). As such, the use of the term "delta" when describing large-scale clinoform reflections in the Sable Subbasin (*e.g.*, "Sable Island delta" or "Sable Island delta complex") is somewhat misleading, and should be avoided.

although important exceptions exist (*e.g.*, Figures 2.12 and 2.15). Lack of obvious onlap-offlap lapout geometries complicates subdivision of the Nova Scotia Group using standard Vail-type seismic stratigraphic techniques (Cloetingh *et al.*, 1989).

The Missisauga Formation[10] (Portlandian-Aptian) consists of fluvial to slope siliciclastics with minor carbonates that reach an estimated maximum thickness of ~3.5 km below the modern shelf edge south of Sable Island (Figures 2.13 and 2.14). Net shelf-margin progradation during Missisauga deposition is inferred based on coarsening-upward grain size trends observed in well logs (*e.g.*, MacLean and Wade, 1993) and large-scale (*i.e.*, hundreds-of-meters plus relief) accretionary clinoform reflections observed in seismic data (*e.g.*, Figures 2.12 and 2.15). $^{40}Ar/^{39}Ar$ ages of K-feldspars from the Missisauga Formation suggest that sediment was derived from the Grenville Province of the Canadian Shield (Grist *et al.*, 1992). This in turn suggests that much of the terrigenous sediment was supplied to the basin via an ancestral version of the modern St. Lawrence River, which, during the Lower Cretaceous, was likely a large, continent-scale river system that drained much of the interior of eastern Canada (Wade and MacLean, 1990; Grist *et al.*, 1992).

Deposition of the Missisauga Formation in the Sable Subbasin is roughly coeval with break-up of Newfoundland from Europe, which uplifted offshore Newfoundland and proximal parts of the Laurentian Subbasin, generating the Avalon (angular) Unconformity (Jansa and Wade, 1975a,b; MacLean and Wade, 1992). In seismic data,

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[10] Key references on the Missisauga Formation include McIver (1972), Jansa and Wade (1975a,b), Given (1977), Schlager (1981), Grant *et al.*, (1986), Hutcheon (1986), Nantais (1986), Bujak Davies (1988), Lentin (1988), Cloetingh *et al.*, (1989), Mudford and Best (1989), Welsink *et al.*, (1989), Jansa and Noguera Urrea (1990), Wade and MacLean (1990), Ascoli (1990), LASMO (1990), East Coast Basin Atlas Series: Scotian Shelf (1991), MacLean and Wade (1992, 1993), Drummond (1992), Grist *et al.*, (1992), Mobil Oil Canada (1997a,b,c; 1998a,b), Sable Offshore Energy (1998; 2000a,b), Neil *et al.*, (1998), Kreisa *et al.*, (1998), Miller *et al.*, (1998), Hogg and DeLong (1998), Canada-Nova Scotia Offshore Petroleum Board (2000), Stea and Pullan (2001), Ingram (2002), Kidston *et al.*, (2002), MacRae (2003a), and Reimer (2003). Note that many of the unpublished reports listed above are available through the Canada-Nova Scotia Offshore Petroleum Board, the organization that regulates petroleum exploration offshore Nova Scotia.

the angularity of the discordance diminishes towards the southwest, and is no longer visible in lowermost Cretaceous strata in the Sable Subbasin (Wade and MacLean, 1990). Causal relationships between Newfoundland-Europe break-up and deposition of the Missisauga Formation in the Sable Subbasin, although hypothesized, have not been fully investigated. Answering this question, although important in understanding the origin of the Missisauga Formation offshore Nova Scotia, requires a basin-wide data base, and is therefore beyond the scope of this thesis.

In the central Sable Subbasin, the Missisauga overlies lithologically similar deposits of the Mic Mac Formation, whereas it downlaps a maximum flooding surface at the top of Abenaki carbonates along the western subbasin rim (Figure 2.15). Although the maximum flooding surface would be the most logical place to pick the base of the Missisauga, the maximum flooding surface is in fact difficult to correlate into the central subbasin using geophysical well logs or seismic data (*cf.* Welsink *et al.*, 1989; MacLean and Wade, 1993). As a consequence, the base of the Missisauga is typically picked at the top of the Abenaki Formation along the western subbasin rim, and at a Kimmeridgian limestone in the central Sable Subbasin (the Venture limestone 9; *e.g.*, MacLean and Wade, 1993). However, because the Venture limestone 9 does not generate a seismic reflection or well log marker outside of the Venture and West Venture gas fields, regional lithostratigraphic correlation of the base of the Missisauga is problematic. Attempts to identify an alternative base-Missisauga marker bed in this study have been unsuccessful.

The O Marker is the only prominent, regionally extensive reflection occurring in the Missisauga Formation (Figure 2.16). The O Marker reflection is generated by a mixed mudstone-sandstone-oolitic limestone unit at the base of the Upper Missisauga.

Although it is identifiable throughout the inner Sable Subbasin northwest of the Onondaga Field, the apparent absence of the O Marker in seismic and well data basinward (*i.e.*, southeast) of Onondaga has proven to be a major impediment to correlating inner to outer shelf strata and beyond (*cf.* Figure 18 in Welsink *et al.*, 1989; Wade, 1991a; MacLean and Wade, 1993).

Typically, the Missisauga Formation is subdivided into two or three members (Figure 2.7). The three-member framework, proposed by Wade and MacLean (1990) and elaborated upon by MacLean and Wade (1993), is similar to the two-member frameworks of Given (1977) and Welsink *et al.*, (1989), but recognizes a third, older member in the central Sable Subbasin that is coeval with the terminal phases of Abenaki carbonate deposition. Although offering potentially better stratigraphic resolution, regional correlation of the top of the lowermost member of Wade and MacLean (1990) in both seismic and well log data is equivocal (*cf.* Figure 9 in Wade, 1991a; MacLean and Wade, 1993), which makes the three-member framework difficult to apply in practice.

Fluvial to slope siliciclastics of the Logan Canyon Formation (Barremian to Cenomanian) overlie the Missisauga throughout the Sable Subbasin (Figure 2.17). The Logan Canyon consists of two mudstone-rich units (the Naskapi and Sable members) and two sandstone-rich units (the Cree and Marmora members; Wade, 1991b; MacLean and Wade, 1993). The formation displays a net upward-fining trend, and is generally interpreted to have been deposited during net long-term transgression that culminated in deposition of mudstone and chalk during the Late Cretaceous global sea level maximum (Grant *et al.*, 1986; see below). However, seismic data from the western Sable Subbasin suggest that shelf margin progradation occurred periodically during deposition of the

Logan Canyon Formation (*e.g.*, note that the sharp-based Cree Member in Figure 2.15 is associated with renewed shelf-margin progradation).

Although it does not generate a strong seismic reflection, the Missisauga-Logan Canyon contact is the most prominent and regionally extensive well-log marker associated with the Missisauga Formation. However, it has a variable expression in different regions of the Sable Subbasin (Figure 2.18). In proximal regions (*e.g.*, Panuke, Thebaud and Venture fields), Missisauga sandstone and mudstone with blocky to serrated gamma ray log profiles "grade" upward over several tens of meters into a monotonous succession of offshore mudstone (Naskapi Member)[11]. In more basinward regions of the subbasin (*e.g.*, Alma and Glenelg fields), however, the contact is generally relatively abrupt and easier to identify[12]. The "gradational" nature of the contact in proximal regions of the subbasin makes it difficult to assign a single surface to the contact across the Sable Subbasin.

The Gully Group (Cenomanian to Pliocene) overlies the Nova Scotia Group throughout the Sable Subbasin. Stratigraphically upward, the Gully Group consists of Dawson Canyon, Wyandot, and Banquereau formations.

The Dawson Canyon Formation (Cenomanian to Santonian) is generally considered to be a transgressive unit deposited in association with the aforementioned Late Cretaceous eustatic rise (Gradstein *et al.*, 1990). The Dawson Canyon Formation gradationally overlies the Logan Canyon Formation, and consists predominantly of mudstone. It is typically thin (~100 m) in the Sable Subbasin, and thickens

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[11] Although gradational in appearance, several fluvially incised unconformities (sequence boundaries) are inferred to exist within the transition – see later in this chapter, and also Chapter 3

[12] Locally, however, the Missisauga-Logan Canyon contact is difficult to identify without supporting biostratigraphic data, especially in the most distal wells that sample the Early Cretaceous paleoshelf-slope transition zone (*e.g.*, the Chebucto K-90 well).

northeastward to a maximum of ~500 m in the South Whale Subbasin (Wade and MacLean, 1990). One thin limestone unit within Dawson Canyon Formation, the Petrel Member, generates a strong seismic reflection throughout the Sable Subbasin.

The Wyandot Formation (Santonian-Paleocene) is a widespread coccolith-dominated limestone (chalk) deposited in association with Late Cretaceous maximum flooding. On average it is ~150 m thick in the Sable Subbasin, although it varies from 50 to 400 m in the Scotian Basin (Wade and MacLean, 1990; MacRae, 2001b). The Wyandot generates a strong regional seismic reflection, below which there is commonly a considerable decrease in the signal-to-noise ratio.

In contrast to sub-Wyandot deposits, which generally form "railroad track" seismic reflections, deposits above the Wyandot form large-scale (*i.e.*, hundreds of meters thick) clinoform-shaped reflections in seismic data that exhibit multiple cycles of onlap and offlap (Wade *et al.*, 1995; Kidston *et al.*, 2002). Despite this, pre-Quaternary deposits above the Wyandot are typically grouped into a single unit called the Banquereau Formation. The Banquereau Formation is composed predominantly of mudstone, although topset beds are locally sandstone-rich (MacRae, 2001b). It is typically ~1 km thick below the modern continental shelf, but thickens considerably below the continental slope.

2.5 Petroleum geology

Although minor amounts of gas are trapped locally within the Wyandot, Dawson Canyon and Abenaki formations (*e.g.*, Primrose, West Sable and Deep Panuke wells) and in slope sandstones of the Missisauga Formation (*e.g.*, Annapolis well), the most

important hydrocarbon reservoirs in the Scotian Basin are fluvial to shelf-margin Upper Jurassic-Lower Cretaceous sandstones of the Mic Mac, Missisauga, and Logan Canyon formations, which contain >95% of all discovered gas offshore Nova Scotia (Grant *et al.*, 1986; Canada-Nova Scotia Offshore Petroleum Board, 2000). Of these, the Missisauga Formation contains most of the currently discovered gas reserves (~192 x 10^6 m^3, or ~75%; Canada-Nova Scotia Offshore Petroleum Board, 2000). Hydrocarbons were likely generated from Type III kerogen disseminated in marine shale of the Verrill Canyon Formation[13], (Powell, 1982; Grant *et al.*, 1986; Bell and Campbell, 1990), which may explain the apparent gas-rich/oil-poor nature of the Scotian Basin. Marine shales form the top seal for all currently discovered commercial hydrocarbon accumulations. Of note are mudstones of the Naskapi Member of the Logan Canyon Formation, which seal gas-rich Upper Missisauga sandstone reservoirs in the Alma, Panuke, North Triumph, and Glenelg fields. The most important traps are rollover "anticlines" (domes) formed in association with "down-to-the-basin" listric growth-faults (*e.g.*, Thebaud, Venture, Glenelg, Alma fields). Other important trap types include compactional drapes over antecedant topography (*e.g.*, Panuke, Cohasset fields) and salt-diapir related traps (*e.g.*, West Sable, Slope Diapir Province; Wade *et al.*, 1989; Kidston *et al.*, 2002; Shimeld, 2004).

[13] Core data suggest that marine condensed sections associated with maximum flooding surfaces are commonly rich in disseminated organic matter (*e.g.*, in the Alma Field)

Figure 2.1 Mesozoic-Cenozoic passive margin basins offshore eastern North America (modified from Hutchinson and Klitgord, 1988). These basins formed during the breakup of Pangea and the subsequent opening of the Atlantic Ocean.

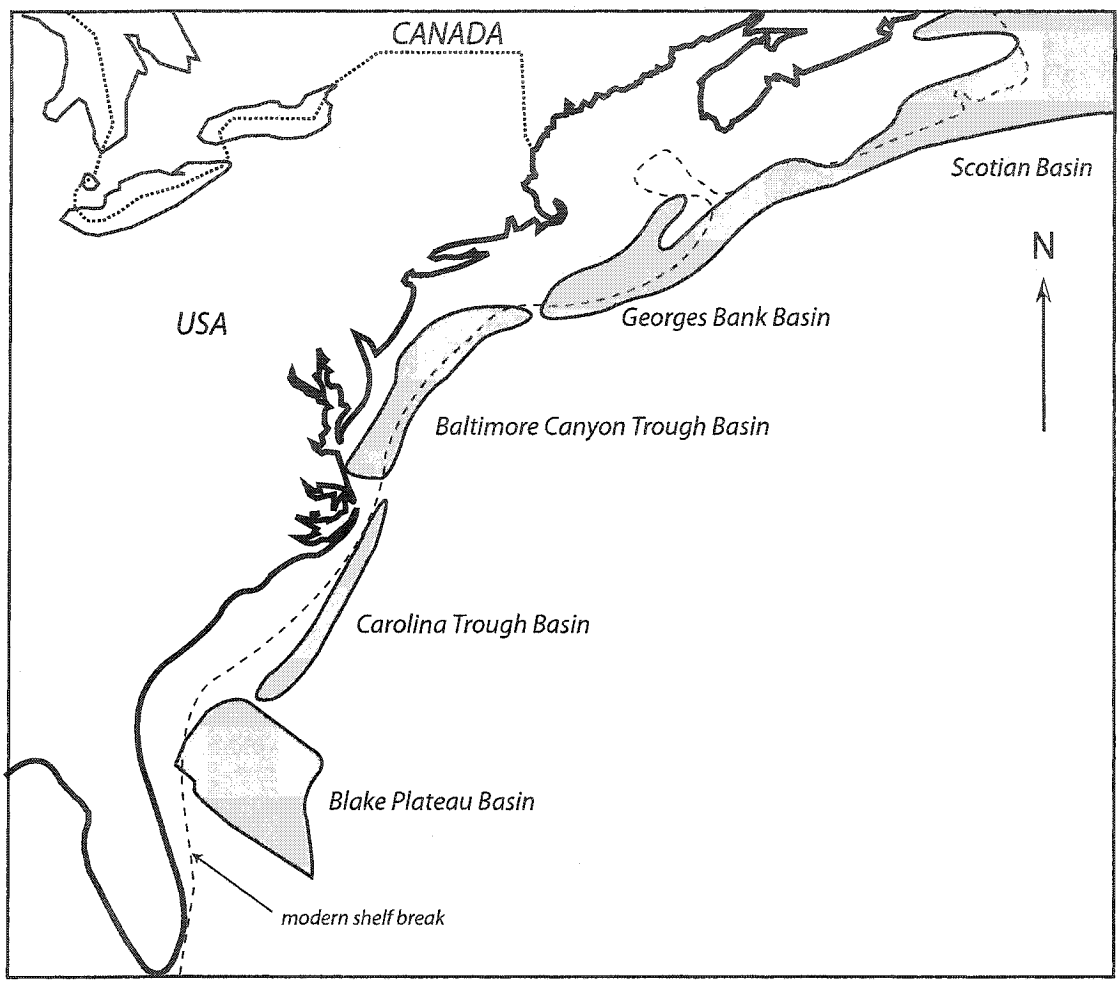

CANADA
Scotian Basin
N
USA
Georges Bank Basin
Baltimore Canyon Trough Basin
Carolina Trough Basin
Blake Plateau Basin
modern shelf break

Figure 2.2 Schematic diagram showing the key features of the Scotian Basin, the passive margin basin offshore Nova Scotia.

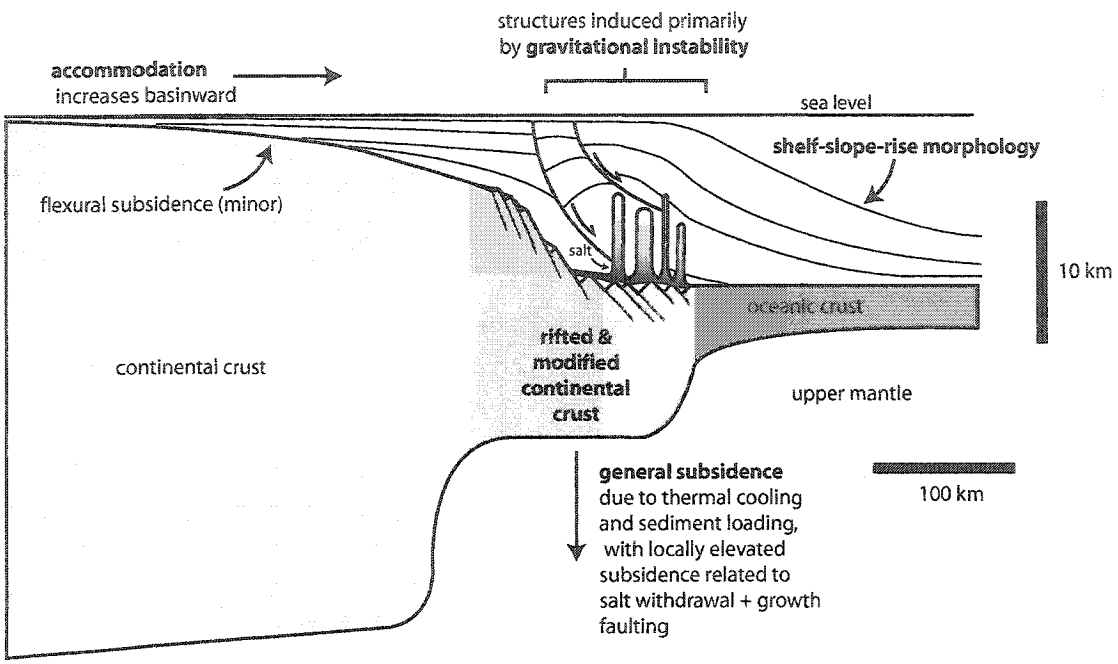

structures induced primarily
by gravitational instability
accommodation
increases basinward
sea level
shelf-slope-rise morphology
flexural subsidence (minor)
salt
10 km
oceanic crust
rifted &
modified
continental
crust
continental crust
upper mantle
general subsidence
due to thermal cooling
and sediment loading,
with locally elevated
subsidence related to
salt withdrawal + growth
faulting
100 km

Figure 2.3 Exploration history offshore Nova Scotia (in part from Mary Jean Verrall, personal communication and Paul Harvey, personal communication). Because the Scotian Basin, to date, has proven to be gas-rich and oil-poor, petroleum exploration offshore Nova Scotia has been driven, at least in part, by the price of natural gas.

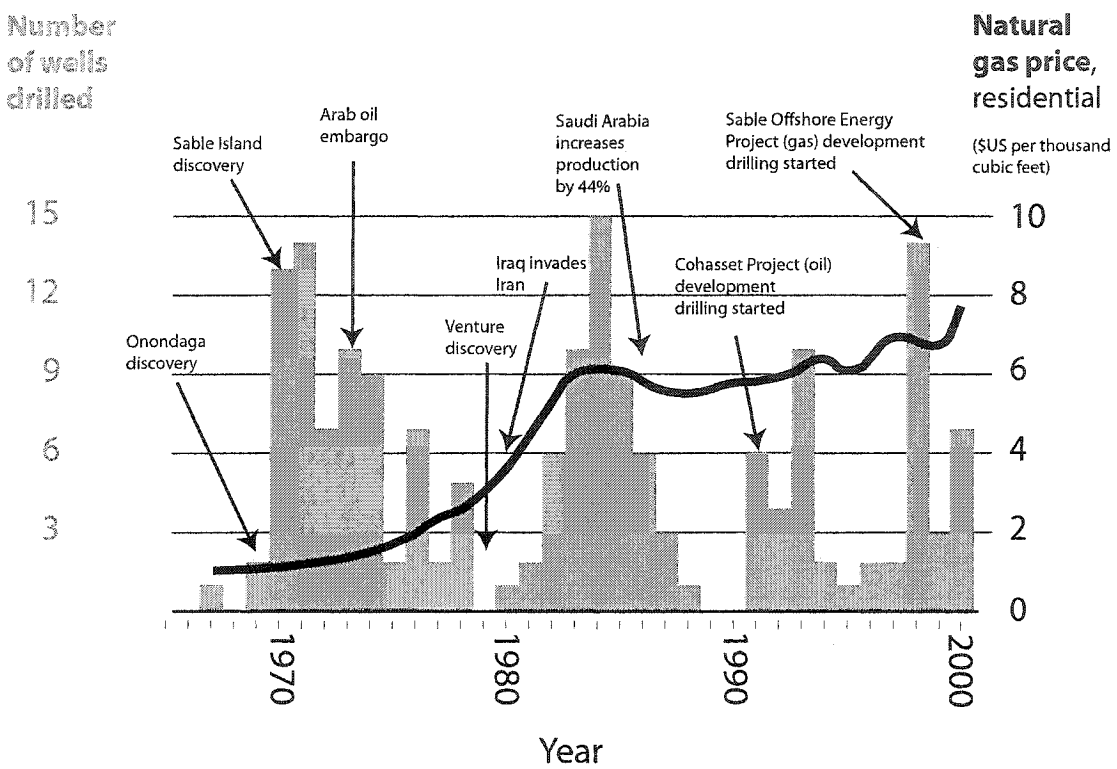

Number of wells drilled
Natural gas price, residential
($US per thousand cubic feet)
Sable Island discovery
Arab oil embargo
Saudi Arabia increases production by 44%
Sable Offshore Energy Project (gas) development drilling started
Iraq invades Iran
Cohasset Project (oil) development drilling started
Venture discovery
Onondaga discovery
15
12
9
6
3
10
8
6
4
2
0
1970
1980
1990
2000
Year

Figure 2.4 Isopach map, Scotian Basin (in part estimated). Contours are in kilometers (modified from MacLean and Wade, 1992).

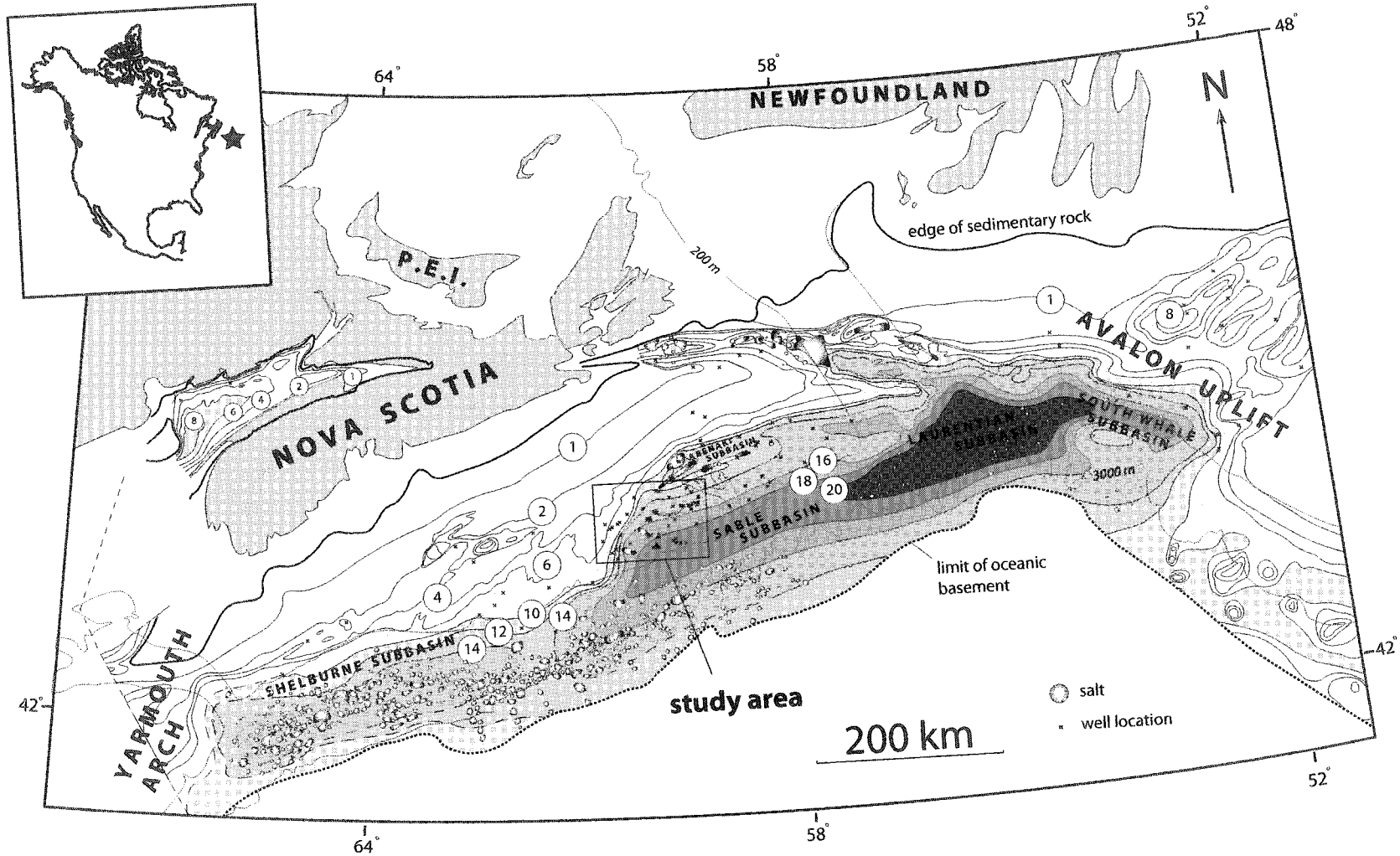
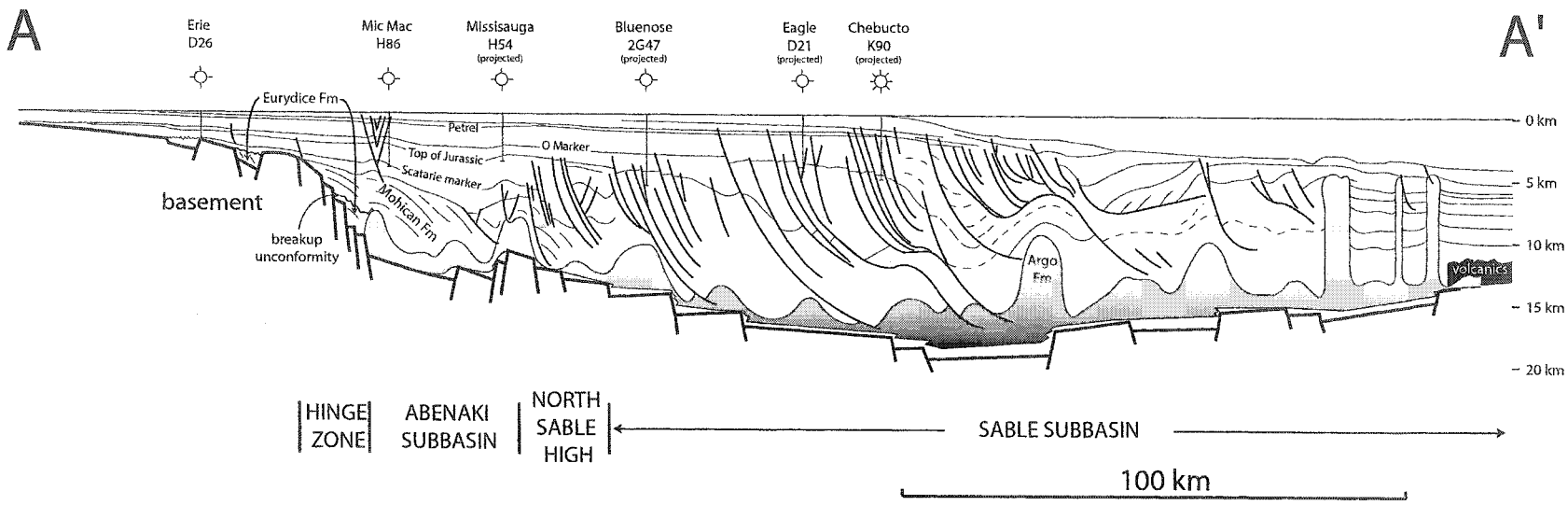

NEWFOUNDLAND
N
edge of sedimentary rock
200 m
P.E.I.
NOVA SCOTIA
AVALON UPLIFT
LAURENTIAN SUBBASIN
SOUTH WHALE SUBBASIN
3000 m
SABLE SUBBASIN
limit of oceanic basement
SHELBURNE SUBBASIN
YARMOUTH ARCH
study area
salt
well location
200 km
64°
58°
52°
48°
42°

Figure 2.5 Interpreted seismic dip cross section, Sable Subbasin, offshore Nova Scotia (modified from Wade and MacLean, 1990).


A
A'
Erie
D26
Mic Mac
H86
Mississauga
H54
(projected)
Bluenose
2G47
(projected)
Eagle
D21
(projected)
Chebucto
K90
(projected)
Eurydice Fm
Petrel
O Marker
Top of Jurassic
Scatarie marker
Mohican Fm
basement
breakup
unconformity
Argo
Fm
volcanics
0 km
5 km
10 km
15 km
20 km
HINGE
ZONE
ABENAKI
SUBBASIN
NORTH
SABLE
HIGH
SABLE SUBBASIN
100 km

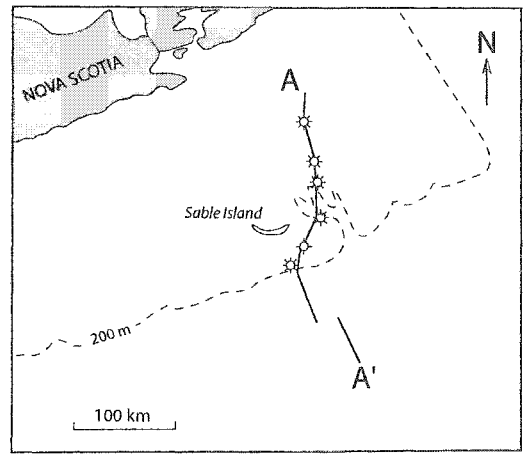
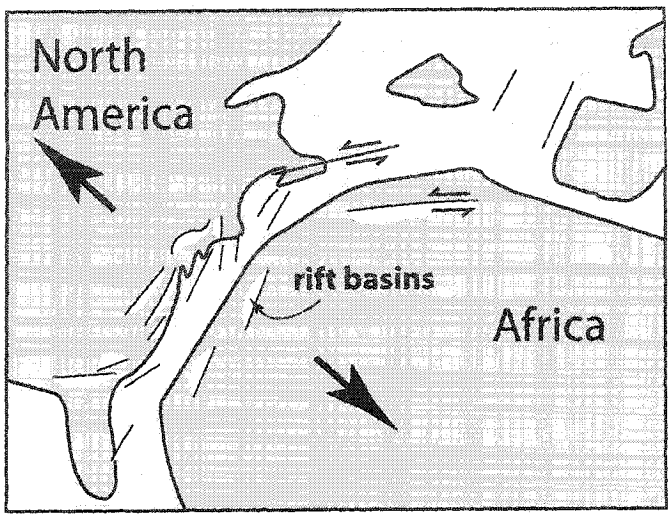
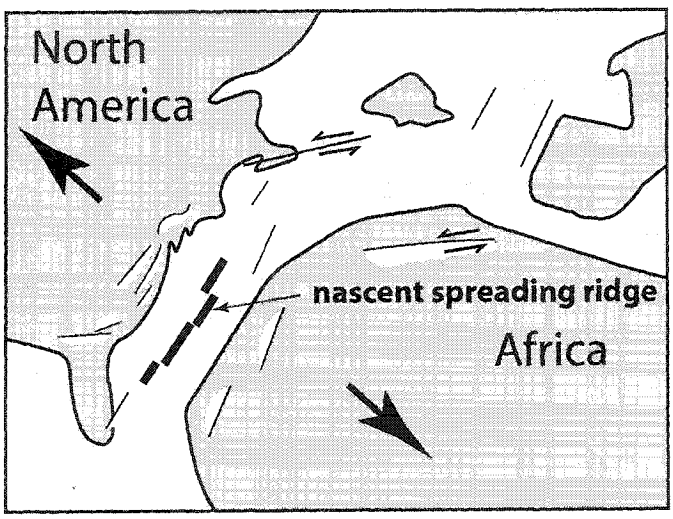

NOVA SCOTIA
N
A
Sable Island
200 m
A'
100 km

Figure 2.6 Schematic diagram depicting the rifting and breakup of Pangea and subsequent opening of the Atlantic Ocean (modified from Withjack *et al.*, 1998).

Middle Triassic



Lower Jurassic



Lower Cretaceous

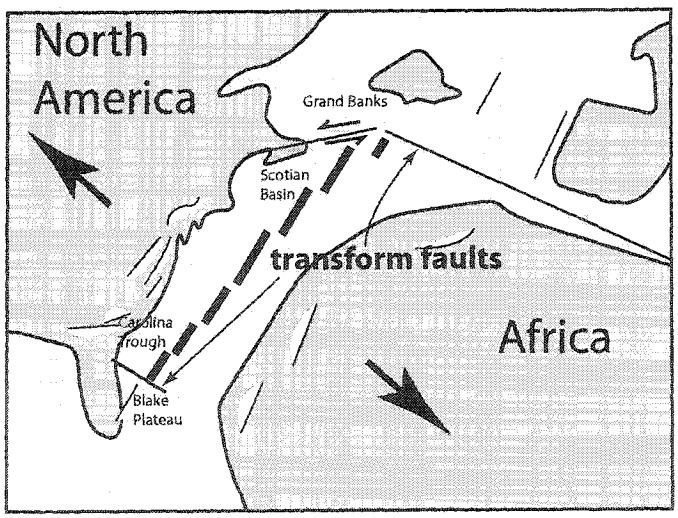


Figure 2.7 Lithostratigraphic frameworks published for the Sable Subbasin, offshore Nova Scotia. Note that the original framework by McIver (1972) is not included because, at the time, lithostratigraphic data were constrained by relatively few biostratigraphic data.

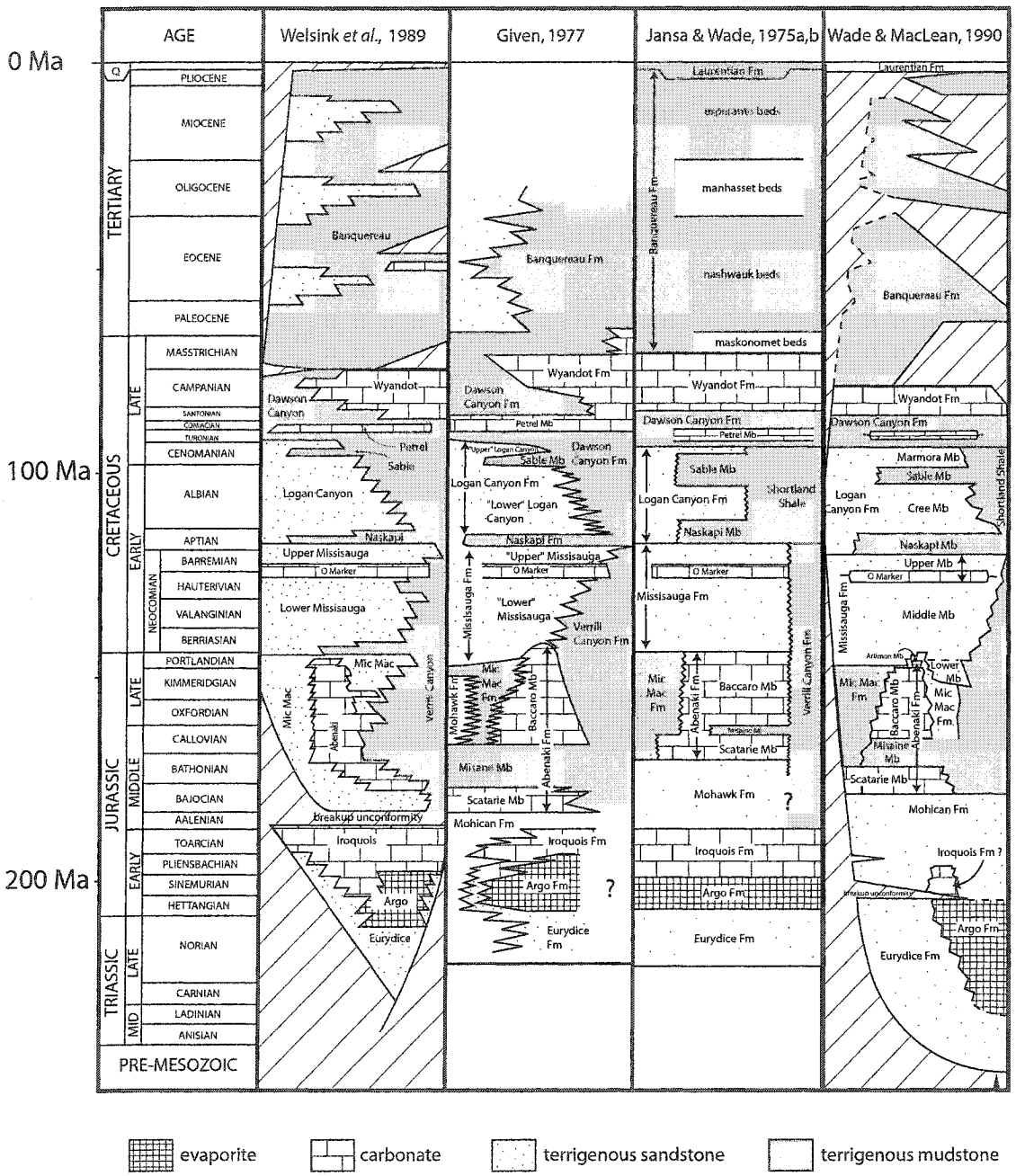

AGE
Welsink et al., 1989
Given, 1977
Jansa & Wade, 1975a,b
Wade & MacLean, 1990
0 Ma
100 Ma
200 Ma
TERTIARY
CRETACEOUS
JURASSIC
TRIASSIC
PRE-MESOZOIC
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
MASSTRICHIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
PORTLANDIAN
KIMMERIDGIAN
OXFORDIAN
CALLOVIAN
BATHONIAN
BAJOCIAN
AALENIAN
TOARCIAN
PLIENSBACHIAN
SINEMURIAN
HETTANGIAN
NORIAN
CARNIAN
LADINIAN
ANISIAN
Banquereau
Wyandot
Dawson Canyon
Petrel
Sable
Logan Canyon
Naskapi
Upper Missisauga
O Marker
Lower Missisauga
Mic Mac
Verrill Canyon
Abenaki
Breakup unconformity
Iroquois
Argo
Eurydice
Banquereau Fm
Wyandot Fm
Dawson Canyon Fm
Petrel Mb
Sable Mb
Logan Canyon Fm
"Lower" Logan Canyon
Naskapi Fm
"Upper" Missisauga
"Lower" Missisauga
Missisauga Fm
Verrill Canyon Fm
Mic Mac Fm
Mohawk Fm
Baccaro Mb
Abenaki Fm
Misaine Mb
Scatarie Mb
Mohican Fm
Iroquois Fm
Argo Fm
Eurydice Fm
?
Laurentian Fm
esplanade beds
manhasset beds
nashwauk beds
maskonomet beds
Shortland Shale
Mohawk Fm
?
Marmora Mb
Cree Mb
Upper Mb
Middle Mb
Lower Mb
Artinskia Mb
Iroquois Fm ?
evaporite
carbonate
terrigenous sandstone
terrigenous mudstone

Figure 2.8 Schematic section across the Sable Subbasin showing major stratigraphic and structural relationships. Vertical exaggeration 10:1 (modified from Grant *et al.*, 1986).

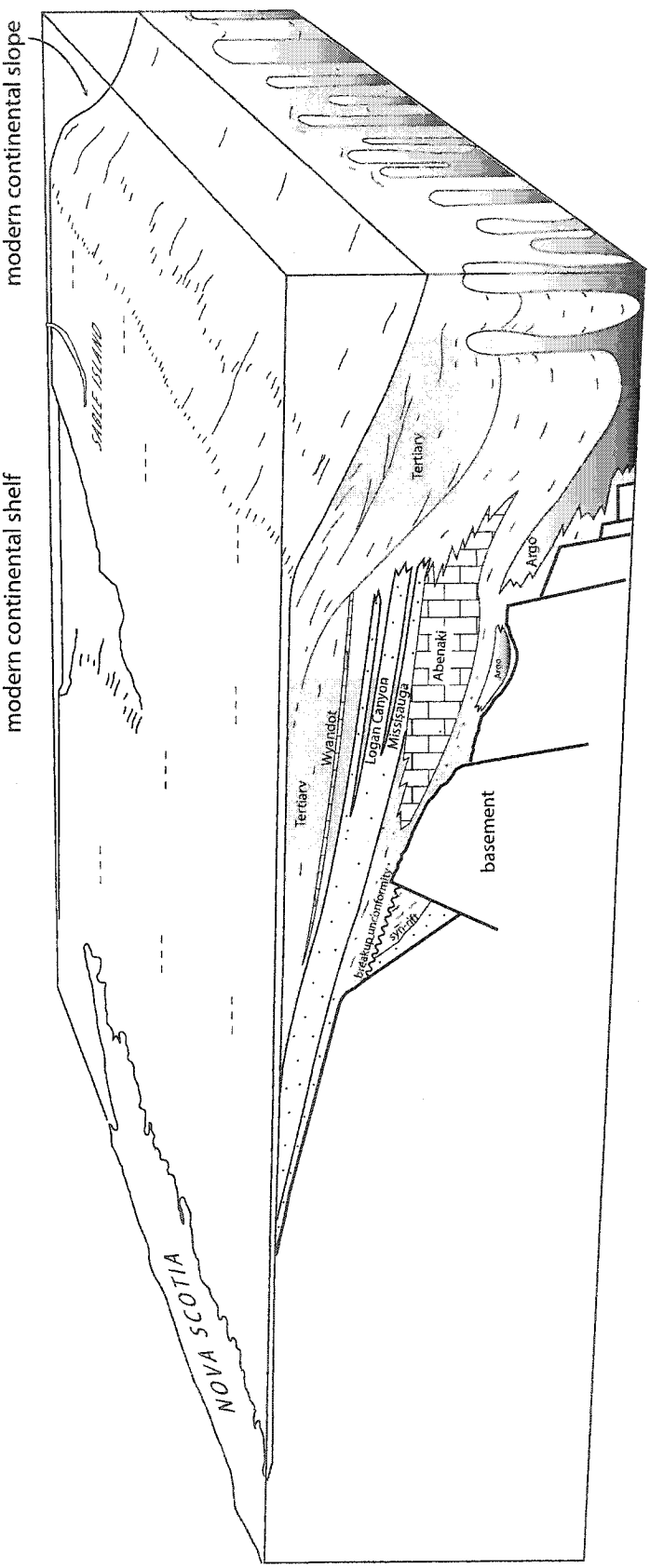

modern continental slope
modern continental shelf
SABLE ISLAND
NOVA SCOTIA
Tertiary
Wyandot
Logan Canyon
Missisauga
Abenaki
Argo
Tertiary
Argo
basement
Mississauga unconformity
Jurassic

Figure 2.9 Distribution of Late Triassic to Early Jurassic syn-rift salt in relation to Triassic paleogeography (modified from Holser *et al.*, 1988).

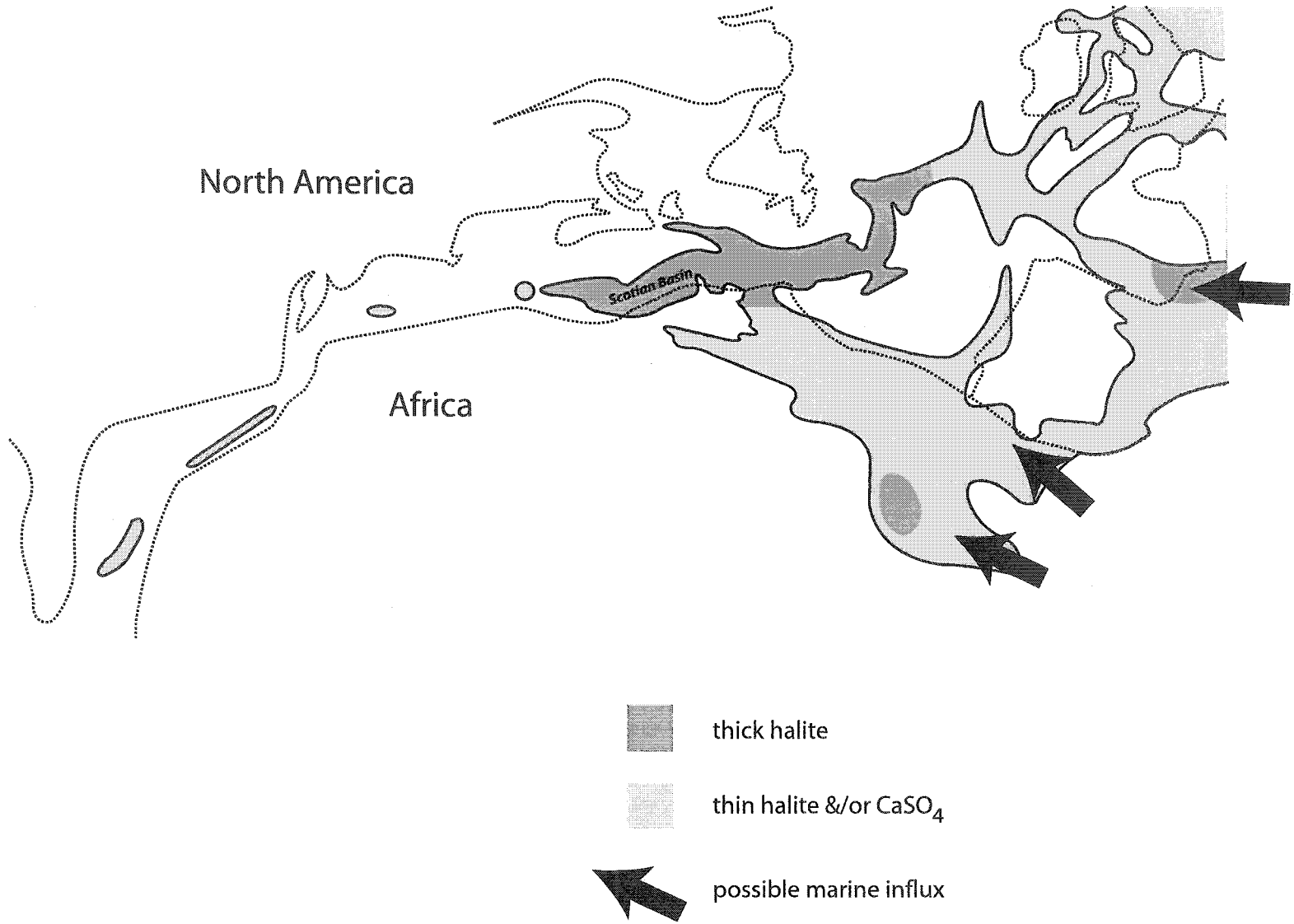

North America
Africa
Scotian Basin
thick halite
thin halite &/or $CaSO_4$
possible marine influx

Figure 2.10 Late Jurassic paleogeography, Sable Subbasin (modified from Wade and MacLean, 1990). Note that the shelf edge during this time was defined by terrigenous siliciclastics near Sable Island, and by carbonates west of Sable Island.

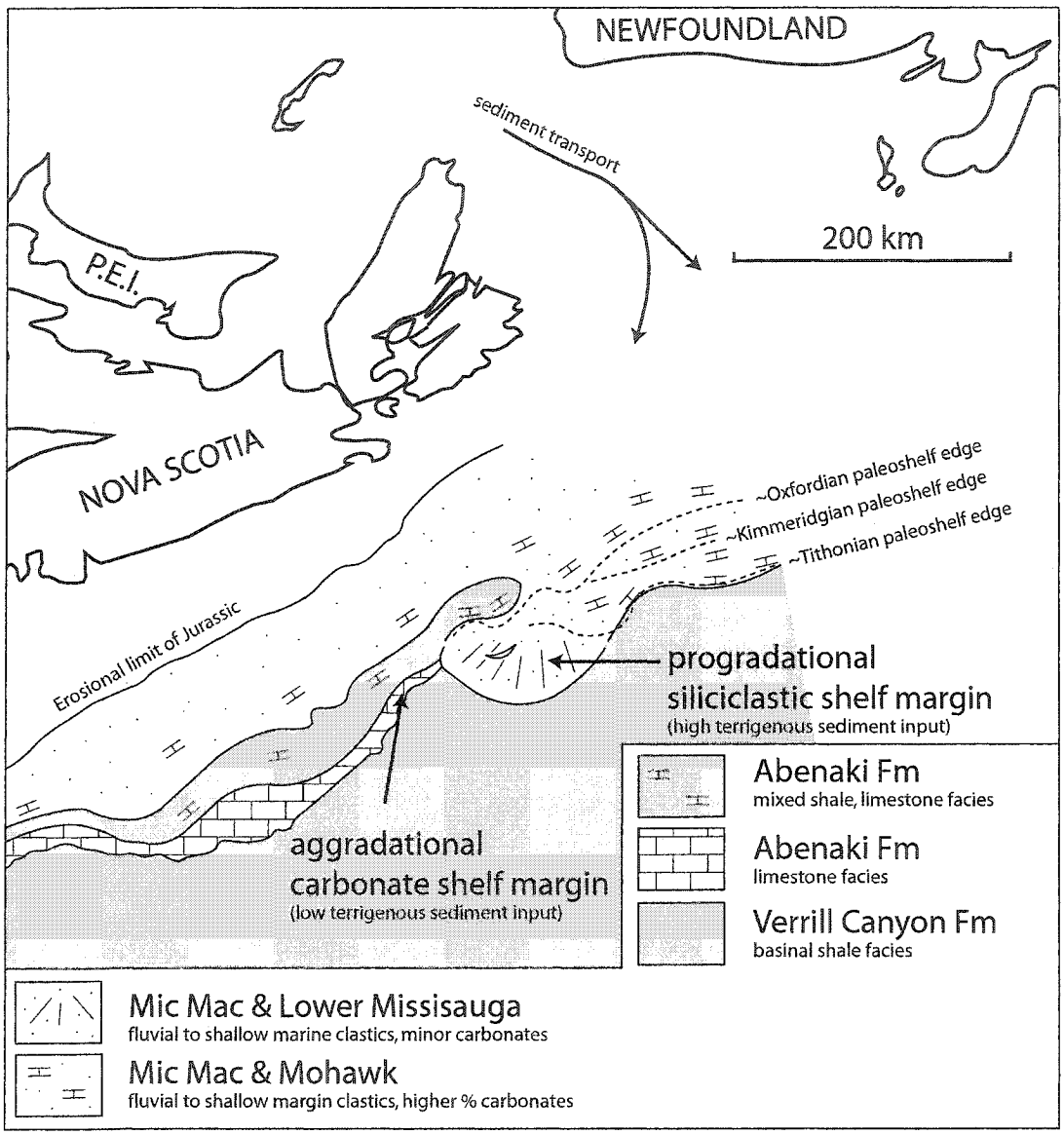

NEWFOUNDLAND
sediment transport
200 km
P.E.I.
NOVA SCOTIA
~Oxfordian paleoshelf edge
~Kimmeridgian paleoshelf edge
~Tithonian paleoshelf edge
Erosional limit of Jurassic
progradational
siliciclastic shelf margin
(high terrigenous sediment input)
aggradational
carbonate shelf margin
(low terrigenous sediment input)
Abenaki Fm
mixed shale, limestone facies
Abenaki Fm
limestone facies
Verrill Canyon Fm
basinal shale facies
Mic Mac & Lower Missisauga
fluvial to shallow marine clastics, minor carbonates
Mic Mac & Mohawk
fluvial to shallow margin clastics, higher % carbonates

Figure 2.11 Schematic diagram illustrating interfingering of Upper Jurassic siliciclastic and carbonate rocks near Sable Island (modified from Wade and MacLean, 1990).

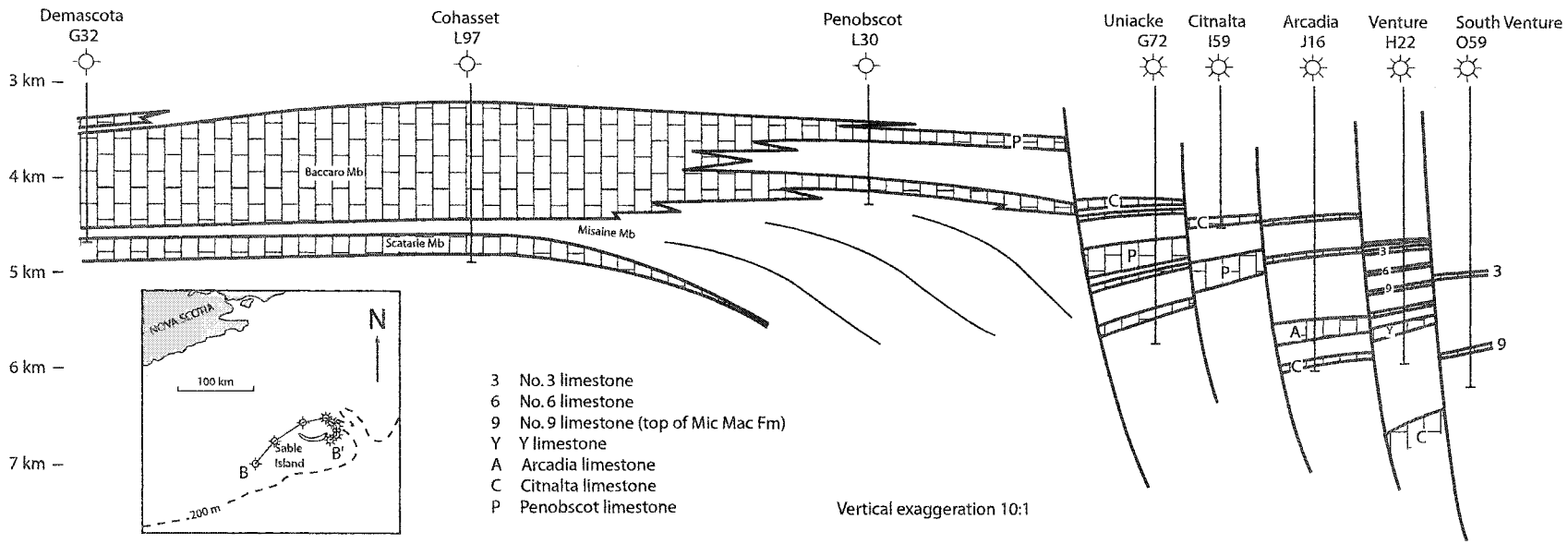

Demascota
G32
Cohasset
L97
Penobscot
L30
Uniacke
G72
Citnalta
I59
Arcadia
J16
Venture
H22
South Venture
O59
3 km
4 km
5 km
6 km
7 km
Baccaro Mb
Scatarie Mb
Misaine Mb
P
C
A
Y
3
6
9
N
NOVA SCOTIA
100 km
Sable
Island
B
B'
200 m
3 No. 3 limestone
6 No. 6 limestone
9 No. 9 limestone (top of Mic Mac Fm)
Y Y limestone
A Arcadia limestone
C Citnalta limestone
P Penobscot limestone
Vertical exaggeration 10:1

Figure 2.12 Uninterpreted and interpreted dip-oriented seismic cross-sections, Sable Subbasin (PRX-GSI-83-1042 seismic line). Note accretionary Mic Mac and Lower Missisauga slope clinoforms. Well-to-seismic ties are the same as those outlined in MacLean and Wade (1993) and Mobil Oil Canada (1997b).

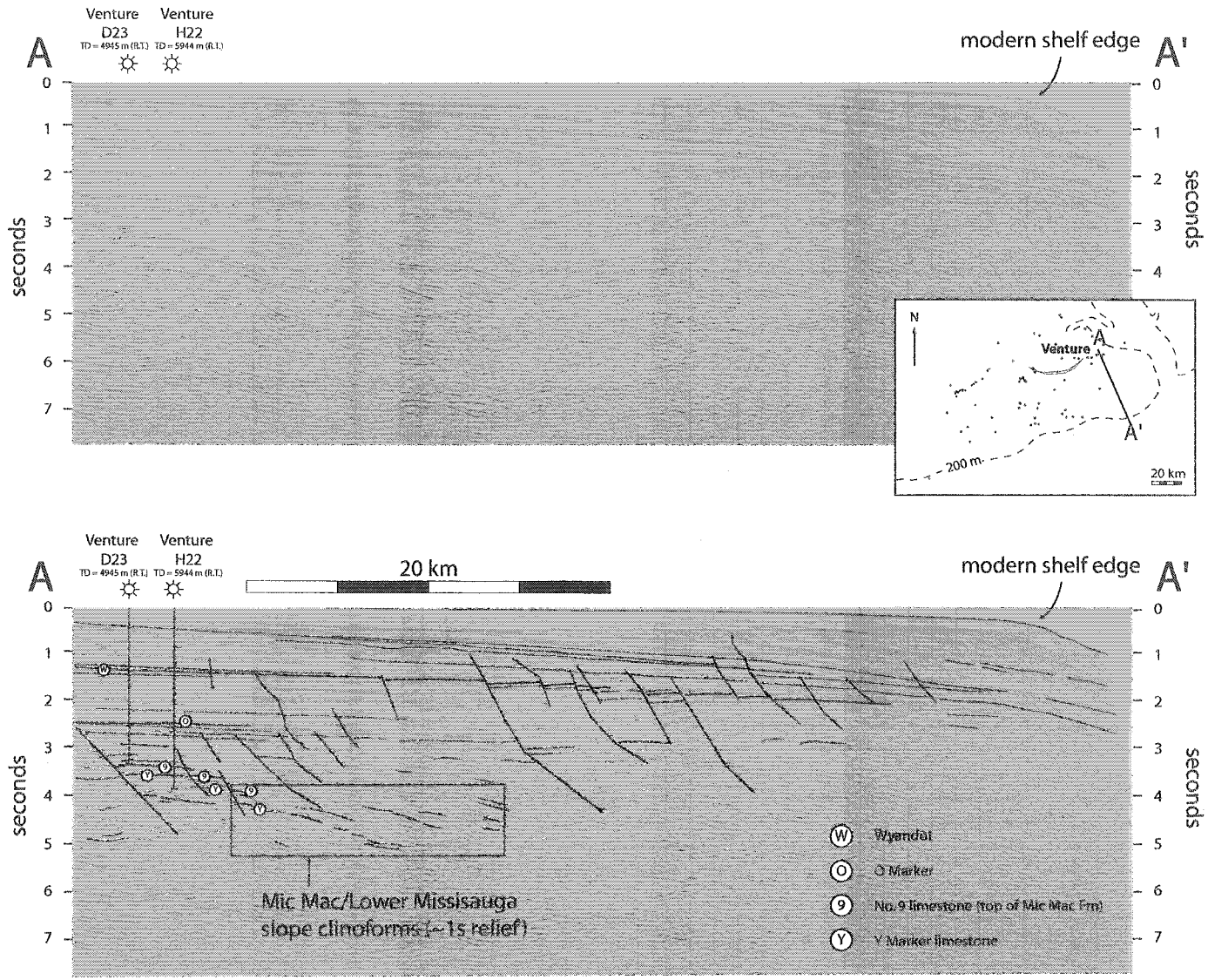

Venture D23
TD = 4945 m (R.T.)
Venture H22
TD = 5944 m (R.T.)
A
A'
modern shelf edge
seconds
0
1
2
3
4
5
6
7
N
Venture
A
A'
200 m
20 km
20 km
W Wyandot
O O Marker
9 No. 9 limestone (top of Mic Mac Fm)
Y Y Marker limestone
Mic Mac/Lower Missisauga
slope clinoforms (~1s relief)

Figure 2.13 Isopach map, Missisauga Formation, offshore Nova Scotia (modified from Wade, 1991a).

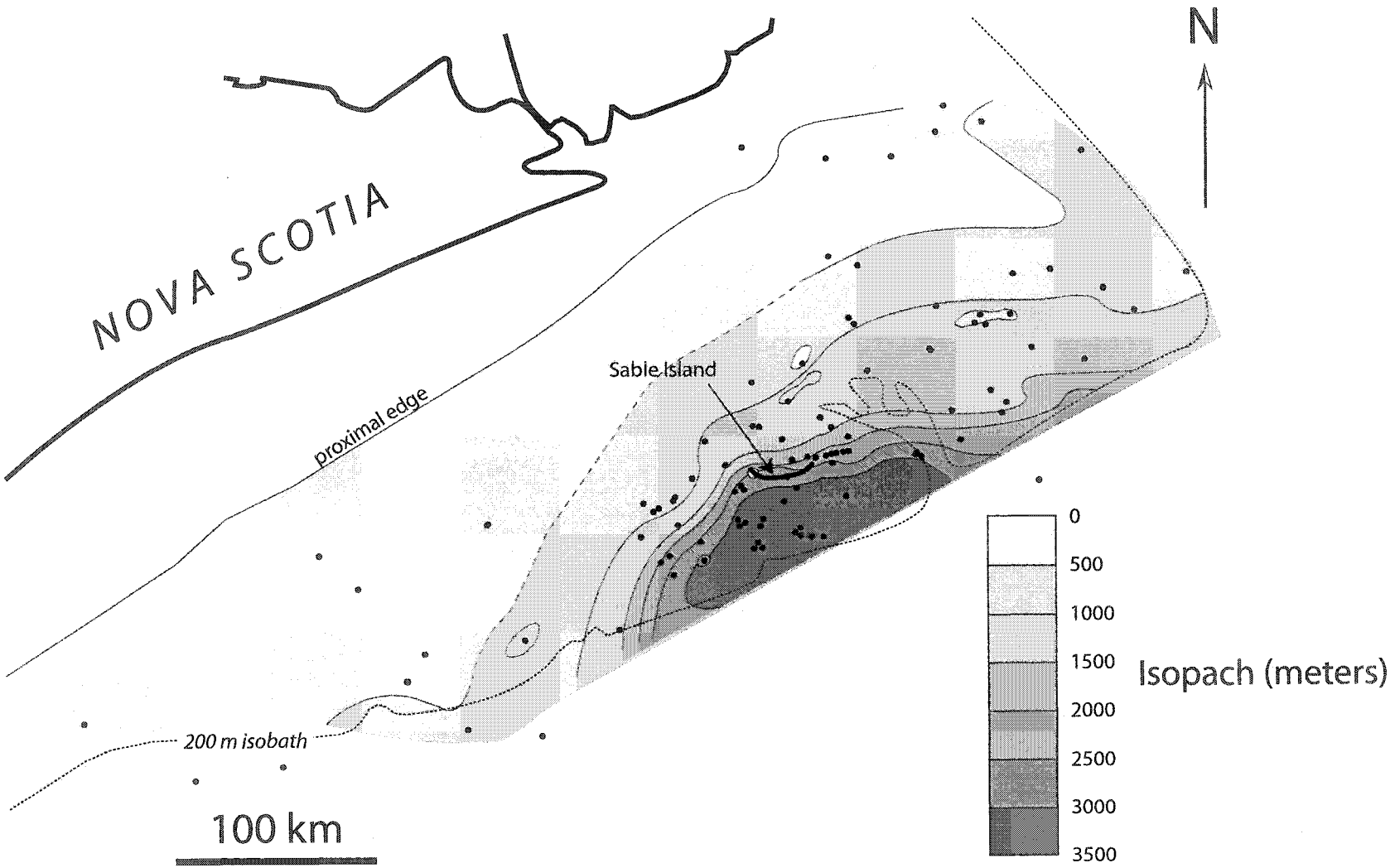

NOVA SCOTIA
N
Sable Island
proximal edge
200 m isobath
100 km
0
500
1000
1500
2000
2500
3000
3500
Isopach (meters)

Figure 2.14 Percentage of sandstone and siltstone, Missisauga Formation, offshore Nova Scotia (modified from Wade, 1991a).

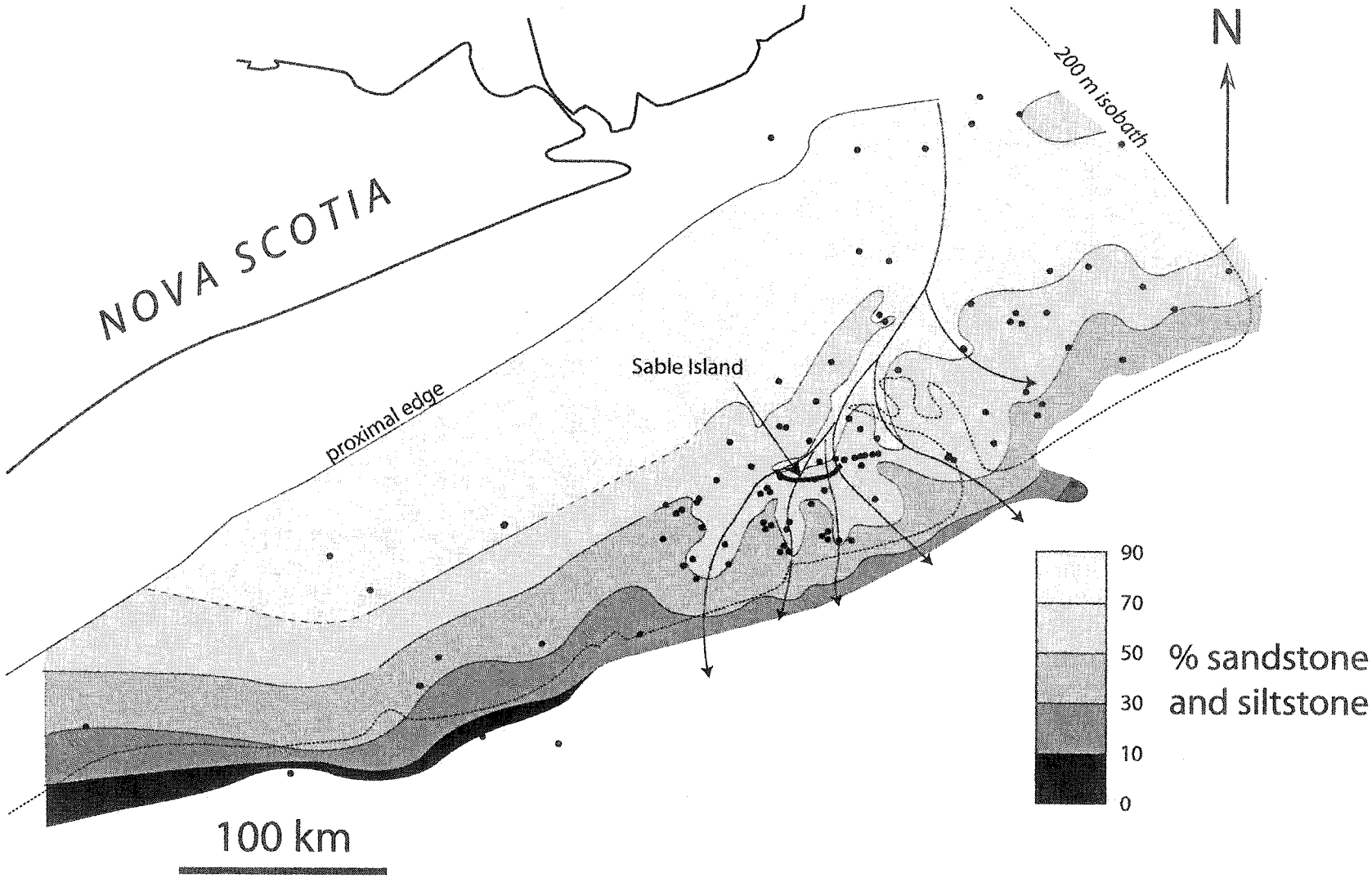
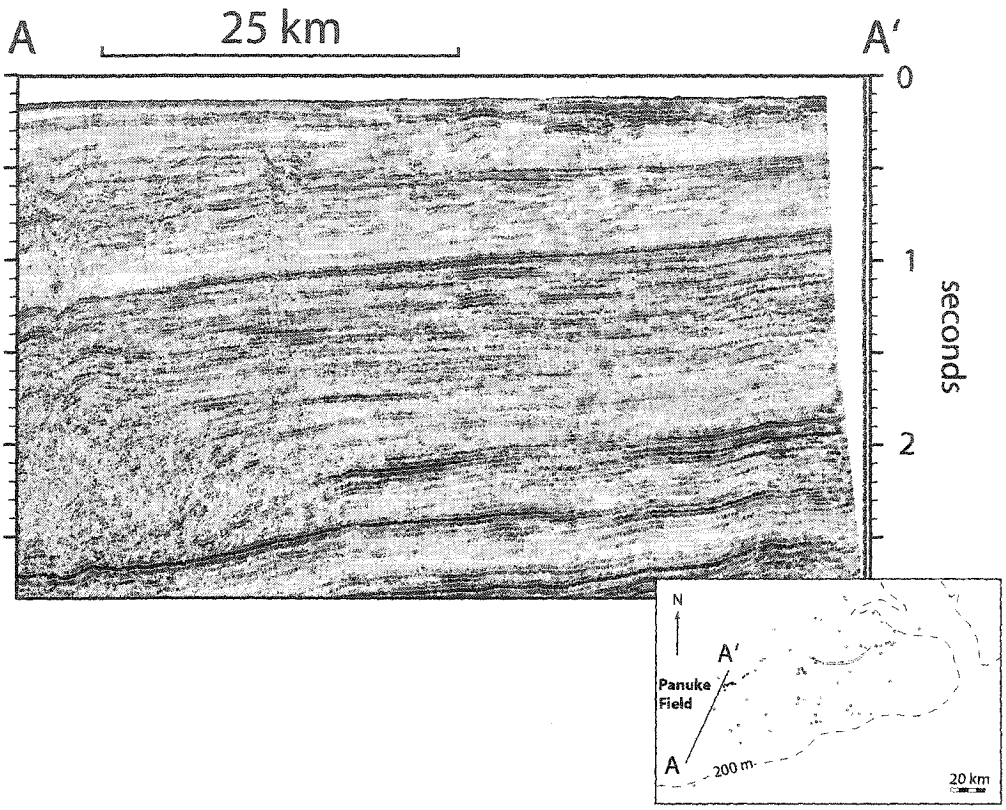

NOVA SCOTIA
200 m isobath
N
proximal edge
Sable Island
90
70
50
30
10
0
% sandstone
and siltstone
100 km

Figure 2.15 Uninterpreted and interpreted dip-oriented seismic cross-sections from the western rim of the Sable Subbasin that clearly show the progradational nature (upward and basinward shelf-margin trajectory) of the Missisauga Formation. Relief from the clinoform break-point to toe is approximately 400 m.


A
25 km
A'
0
1
2
seconds
N
A'
Panuke
Field
A
200 m
20 km

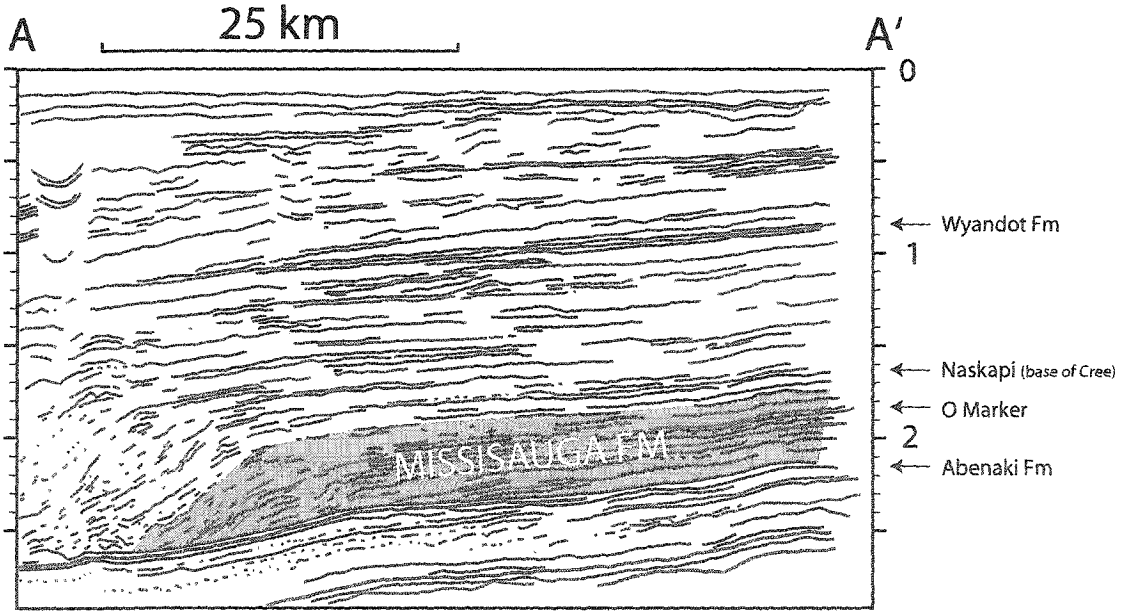

A
25 km
A'
0
1
2
Wyandot Fm
Naskapi (base of Cree)
O Marker
Abenaki Fm
MISSISAUGA FM

Figure 2.16 O Marker structure (time), Sable Subbasin, reconstructed from 2-D seismic data (see Figure 1.2d for location of seismic lines). Note how the O Marker dips and becomes increasingly hard to identify toward the southeast.

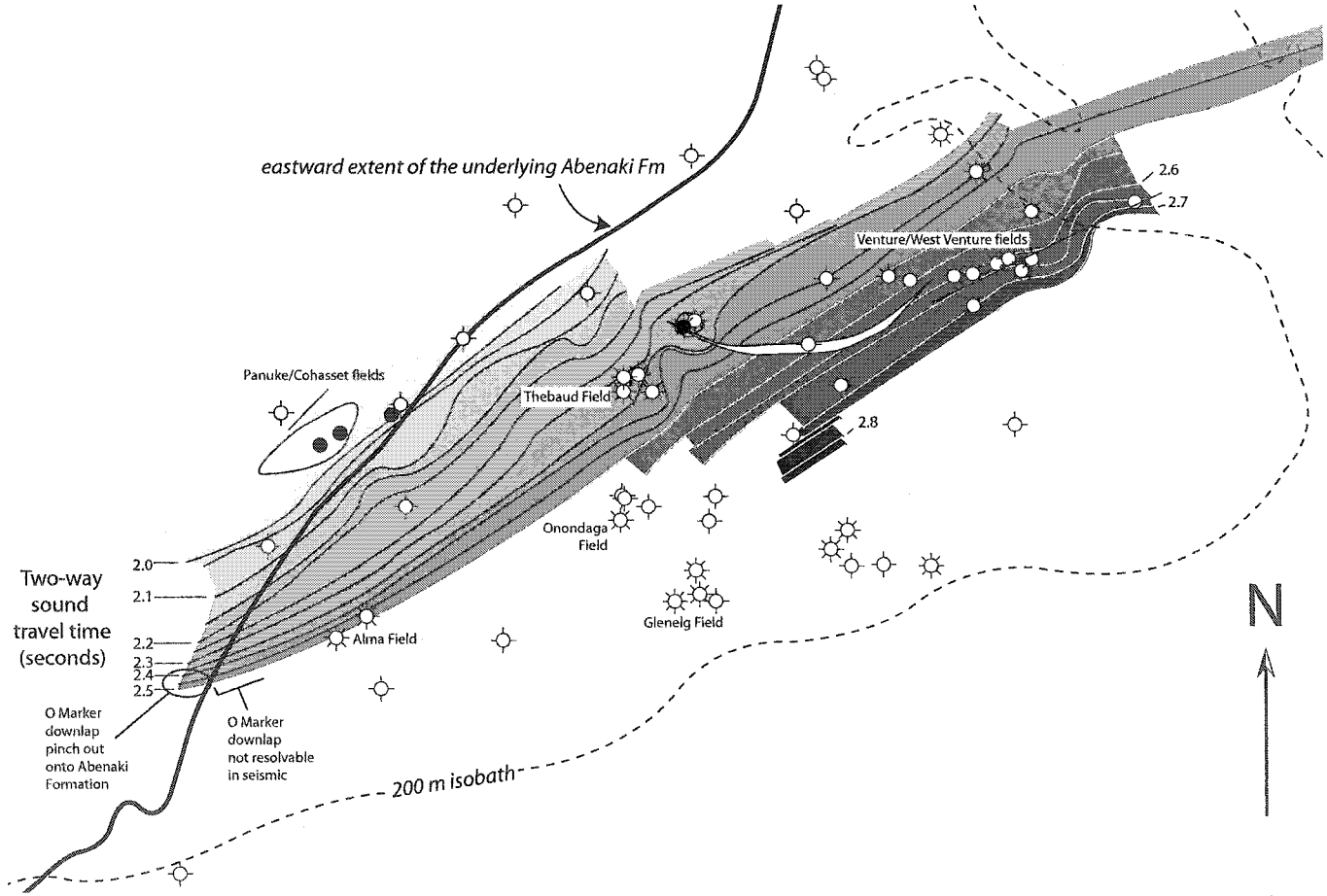

eastward extent of the underlying Abenaki Fm
Panuke/Cohasset fields
Thebaud Field
Venture/West Venture fields
2.6
2.7
2.8
Onondaga Field
Glenelg Field
Alma Field
Two-way sound travel time (seconds)
2.0
2.1
2.2
2.3
2.4
2.5
O Marker downlap pinch out onto Abenaki Formation
O Marker downlap not resolvable in seismic
200 m isobath
N

Figure 2.17 Isopach map, Logan Canyon Formation, offshore Nova Scotia (modified from Wade, 1991b).

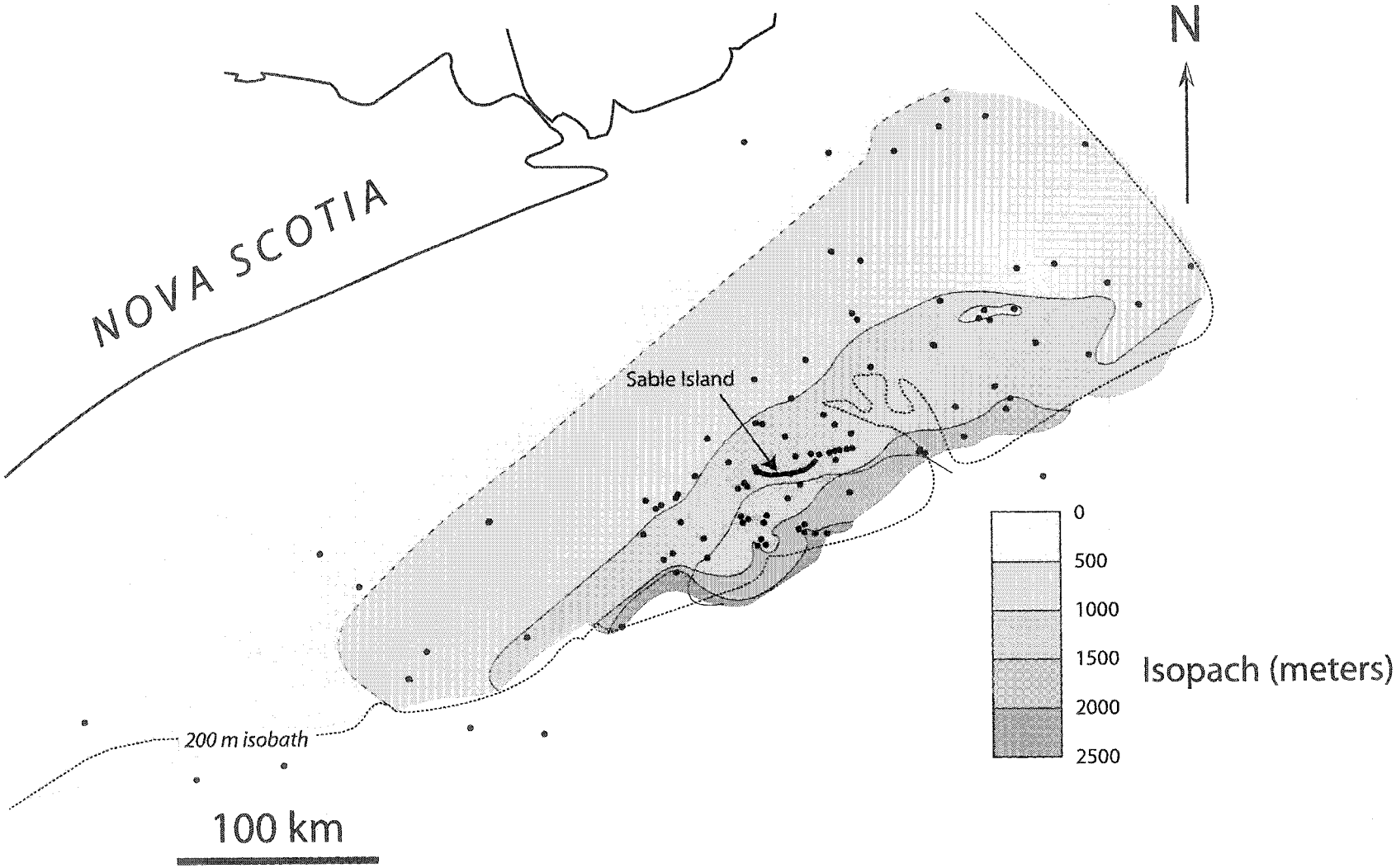
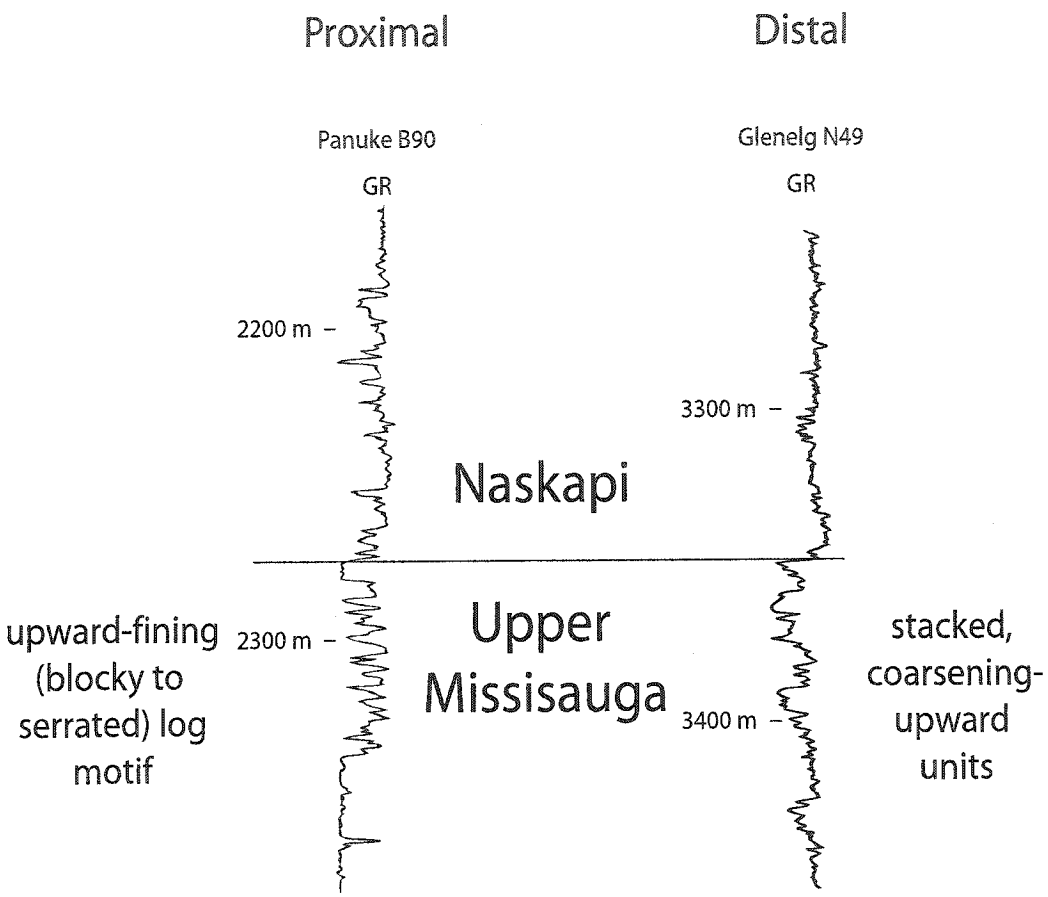

N
NOVA SCOTIA
Sable Island
0
500
1000
1500
2000
2500
Isopach (meters)
200 m isobath
100 km

Figure 2.18 Comparison of the Missisauga-Naskapi contact in proximal versus distal wells, Sable Subbasin. Note how the contact appears gradational and has an upward-fining motif in proximal wells, whereas it is typically sharp and underlain by stacked, upward-coarsening units in distal wells.


Proximal
Distal
Panuke B90
GR
Glenelg N49
GR
2200 m
3300 m
Naskapi
Upper
Missisauga
2300 m
3400 m
upward-fining (blocky to serrated) log motif
stacked, coarsening-upward units

Chapter 3. Sedimentology, 3-D seismic geomorphology, and sequence stratigraphy of a thick and laterally extensive fluvial-marine transition (Hauterivian-Aptian), Missisauga Formation, offshore Nova Scotia, Canada

3.1 Introduction

Stratigraphic successions that pass upward from fluvial into marine deposits, here called fluvial-marine transitions, form during transgression following an episode of forced or normal regression. Over the past half-century, they have been the subject of much geological research (Fisk, 1944; Suter and Berryhill, 1985; Posamentier and Vail, 1988; Penland *et al.*, 1988; Dalrymple *et al.*, 1992; Muto and Steel, 1992; Wood *et al.*, 1993; Dalrymple *et al.*, 1994; Leeder and Stewart, 1996; Blum and Törnqvist, 2000; Swenson *et al.*, 2000: Posamentier, 2001; Heller *et al.*, 2001; Cattaneo and Steel, 2002), not only because they commonly host economic quantities of oil and natural gas, but because they can be used to estimate long-term rates of coastal land loss (*e.g.*, Milliman and Haq, 1996), reconstruct paleogeography, and unravel the history of eustatic, tectonic, and climate change. With the recent attention on offshore hydrocarbon exploration in deep-water areas basinward of the shelf edge (*e.g.*, Weimer *et al.*, 2000), fluvial-marine transitions have come under increased scrutiny because, when incised, they commonly correlate downdip with sand-bodies on the shelf edge, slope and basin-floor. As such, geologists are currently striving to understand how the sedimentologic and stratigraphic characteristics of incised fluvial-marine transitions on the shelf can be used to better predict sand-body distribution at the shelf edge and basinward (*e.g.*, Reading and Richards, 1994; Porebski and Steel, 2003).

Sheet-like fluvial-marine transitions have seldom been reported on continental shelves (Olsen *et al.*, 1995; Holbrook, 1996; Pulham *et al.*, 1997; Posamentier, 2001), and as a result, how (and if) they feed sediment downdip to the shelf edge, slope and basin-floor is not well understood. Using core and well log data from the western edge of the Sable Subbasin, offshore Nova Scotia, coupled with a 3-D seismic survey from the Panuke Field, this study identifies and describes a thick, laterally extensive fluvial-marine transition in the Lower Cretaceous Missisauga Formation, and uses regional 2-D seismic lines to correlate it downdip to the undrilled shelf-edge and slope. Implications for reservoir distribution within the Panuke Field are discussed, and the potential of the fluvial system as a deep-water feeder system is evaluated.

3.2 Geological setting

The Sable Subbasin is one of several interconnected Mesozoic-Cenozoic depocenters that make up the Scotia Basin, offshore Nova Scotia (Figure 3.1). The center of the subbasin is underlain by unstable syn-rift salt, and contains numerous growth faults and salt diapirs (Figure 3.2). In contrast, the western edge of the subbasin, where the Panuke Field is situated, is underlain by stable Jurassic carbonate rocks and lacks such features. Siliciclastic strata of the Missisauga Formation thin significantly when correlated onto the western edge of the subbasin (MacLean and Wade, 1993), suggesting that the western subbasin edge was relatively low accommodation setting during Missisauga deposition. Terrigenous clastic sediments are interpreted to have been fed southward into the subbasin by the paleo-St. Lawrence River, a sediment-charged, continent-scale fluvial system that drained much of Eastern Canada (Wade and MacLean,

1990; Grist *et al.*, 1992). During deposition of the Missisauga, Nova Scotia was located approximately 30°N of the equator (Irving *et al.*, 1993), the receiving basin (*i.e.*, the Atlantic Ocean) was ~1000 km wide (Ziegler, 1989), and climate was warm and temperate, having become colder, wetter, and less seasonal following Pangean rifting in the Early Mesozoic (Rees *et al.*, 2000).

3.3 Lithostratigraphy

In the Sable Subbasin, the Missisauga Formation forms a southeastward-thickening wedge of fluvial and shallow-marine siliciclastic rocks with minor carbonate rocks. It reaches a maximum drilled thickness of ~2100 m in the central Sable Subbasin, and thins to ~950 m in the Panuke Field (MacLean and Wade, 1993). The Missisauga is underlain by the lithologically similar Mic Mac Formation, except along the western subbasin edge where it is underlain by Jurassic carbonates of the Abenaki Formation (Figure 3.3). The Missisauga Formation is overlain throughout the Sable Subbasin by offshore marine shale of the Naskapi Member of the Logan Canyon Formation.

Internally, the Missisauga is divided into Upper, Middle and Lower members (Wade and MacLean, 1990; MacLean and Wade, 1993) or alternatively Upper and Lower members (Welsink *et al.*, 1989). The Upper and Lower members (*sensu* Welsink *et al.*, 1989) are separated by the O Marker, a mixed carbonate-siliciclastic unit that generates a strong seismic reflection in the proximal subbasin (*e.g.*, northwest of the Onondaga Field). In the distal Sable Subbasin (*i.e.*, southeast of Onondaga), the O Marker becomes difficult to identify in both seismic and well log data (*cf.* Welsink *et al.*, 1989) due to

growth faults, poor quality seismic data below the modern shelf margin, and facies change and/or erosion.

3.4 Panuke Field history and reservoir stratigraphy

The Panuke Field discovery well, Panuke B-90, was drilled in 1986 to test for the presence of hydrocarbons in a drape structure formed by differential compaction of Lower Cretaceous clastics over underlying Abenaki carbonates (LASMO, 1990; Canada-Nova Scotia Offshore Petroleum Board, 2000). The B-90 well penetrated five condensate-bearing sandstones in the top ~40 m of the Upper Missisauga (Figure 3.4). The field was subsequently delineated in 1987 with a second vertical well, Panuke F99, and four directionally drilled development wells, Panuke J-99 PP1 to PP4, were drilled between 1991 and 1992. Original oil in place was estimated to be 6.676 m^3 x 10^6 (Canada Nova Scotia Offshore Petroleum Board, 2000). Production began in 1992, and proceeded in two separate phases. During phase one, the two main reservoirs, the P2 and P3 sandstones, were perforated and produced as a co-mingled zone under natural flow. Pressure data collected during this phase suggested that 75% of the hydrocarbons were coming from the P2 sandstone and the remaining 25% from the P3 sandstone (Encana, unpublished data, 2002). Primary production was suspended in 1995. In 1997, a water-flood program was started. During this phase, the P2 and P3 sandstones, along with the P4 sandstone and the C9 sandstone (C9 is the basal sandstone in the Cree Member of the Logan Canyon Formation; LASMO, 1990), were perforated and produced as a co-mingled zone under pump flow. However, production ceased in 1999 because of high

water production and low hydrocarbon volumes. In total, 38.5% of the original oil in place, or 2.2568 m^3 x 10^6 (16.155 MMbls), was recovered from the Panuke Field.

3.5 Dataset and methodology

This study integrates 8 cores (~320 m) and geophysical well log data from 20 wells in the western Sable Subbasin with a 3-D seismic survey shot over the Panuke Field and regional 2-D seismic lines (Figure 3.2). Cores were described in 2.5 cm detail, noting sedimentary textures, physical and biogenic sedimentary structures, macrofossils, and macroscopic diagenetic features. These data were used to calibrate well logs, which were then tied to the 3-D seismic data using synthetic traces generated from sonic logs, or a combination of sonic and density logs when both were available (Figure 3.5). Subsurface geomorphology, which is the description and interpretation of depositional features observed in 3-D seismic plan view, was performed using 3-D seismic horizon slices flattened to the O Marker. A flooding surface near the base of the Naskapi Formation was used as a stratigraphic datum for well log cross-sections. Lithostratigraphic and seismic stratigraphic picks used in this study are the same as MacLean and Wade (1993) and LASMO (1990), except for the top of the Missisauga, which, for convenience, was picked at an easily correlatable surface at the top of the main reservoir, the P2 sandstone (Figure 3.4).

3.6 Facies

The ten facies identified in core data (Table 3.1) are described below.

Facies 1: Upward-fining, high-angle (>15°) cross-stratified coarse to medium sandstone

Facies 1 is composed of moderately well to well-sorted, brown sandstone (Figure 3.6). This sandstone is usually coarse to medium grained, although a few beds of very fine sandstone are present. Beds are typically thick (10-100 cm thick) and are high-angle (>15°) cross-stratified or planar laminated. Beds are organized into sharp-based, upward-fining units that are several meters thick (maximum ~8 m). Mud intraclasts and coal fragments are common at the base of the upward-fining units. No trace fossils or shells were observed. Mudstone interbeds are rare and unbioturbated.

Interpretation: Braided fluvial channel fills

Facies 1 is interpreted to be a fluvial channel-fill deposit. Large-scale high-angle cross-stratification likely formed by the downstream migration and aggradation of dunes under unidirectional flow (Southard and Boguchwal, 1990; Ashley, 1990; Leclair and Bridge, 2001). Planar-laminated sandstone beds are interpreted to have formed by aggradation of millimeter-high, low-relief bed waves under upper-flow-regime plane bed conditions (Jopling, 1964; Bridge and Best, 1988; Paola *et al.*, 1989; Best and Bridge, 1992). Based on the thickness of cross-beds and fining-upward units, flow depths were likely on the order of 7-10 m deep (see Leclair and Bridge, 2001; Bridge and Tye, 2000). A braided channel pattern is inferred based on the predominant medium to coarse sandstone sediment caliber, general lack of cohesive bank mudstone, and the presence of a braid-bar feature interpreted from 3-D seismic plan view (see below). The sharp-based, upward-fining units indicate decreasing depositional energy upwards, and are interpreted to have formed by downstream building of braid bars into channel confluences, or

alternatively, if the braided fluvial system was slightly sinuous, by the building of point bars into downstream bends (Shelton and Noble, 1974; Bridge, 2003).

Table 3.1 Facies descriptions and interpretations, Panuke Field region

Facies	Texture	Physical sedimentary structures	Biogenic features	Diagenetic features	Gamma ray log character	Interpretation
1	very fine to coarse sandstone	dune cross-stratification (max=1m); planar lamination; mud rip-ups	coal chunks common; no bioturbation or shells	rare dm-scale patches of carbonate cement	sharp-based and blocky to upward-fining	braided fluvial channel deposits
2	same as Facies 1	same as Facies 1; also wispy mud laminae on dune foresets; rare double mud drapes	Rare *Skolithos* and escape traces; coal chunks common	same as Facies 1	blocky to slightly upward-fining; always grades up from Facies 1	tidally-influenced braided fluvial channel deposits
3	mudstone with thin siltstone beds and laminae	siltstone beds are typically normally graded, and are commonly small-scale wave ripple cross-stratified, wavy parallel laminated, or flat parallel laminated	bioturbation is typically absent, but locally intense; trace fossils include small *Planolites*, *Teichichnus*, *Asterosoma*, *Zoophycos*, *?Cylindrichnus* and *Rosselia*.	thin siderite bands and nodules are common	exhibits both coarsening and fining upward trends	lagoon deposits
4	mudstone with thin fine sandstone beds and laminae	sandstone laminae are lenticular, wavy or pinstripe shaped; internally, they are planar laminated or high-angle (>15 degrees) current and small wave ripple cross-laminated; rare small rotational slumps and microfaults; rare dm-scale rhythmic "overprint"; rare synaeresis cracks	bioturbation is typically absent or low, but locally intense. Trace fossils include small *Planolites*, *Arenicolites*, *Teichichnus*, *Chondrites*, *Diplocraterion*, *?Skolithos*, *?Thalassinoides*, and *?Rosselia*; rare oyster shells		serrated	tidal flat deposits
5	very fine to fine sandstone	current ripple cross-stratification; dune cross-stratification (max=10cm); planar lamination; rare bipolar cross-stratification; mud wisps to thin layers common	rare roots; rare *Ophiomorpha* and *Skolithos* burrows, small *Planolites* burrows (in mudstone laminae), and escape traces		sharp based and blocky to upward-fining	small tidal channel deposits
6	very fine to fine sandstone	current ripple, small wave ripple, and dune cross-stratification; mud rip-ups present	disseminated mm-scale organic flecks abundant; rare *Ophiomorpha* in sandstone and small *Planolites* in mudstone laminae; rare oyster shells	rare dm-scale patches of carbonate cement	gradationally based, coarsening upwards	bayhead delta barform deposits

7	poorly sorted sandstone with many isolated, white quartz sand grains and granules ("paint-speckles")	obliterated by bioturbation	intensely bioturbated; unlined *Thalassinoides* burrows (and rarely large *?Teichichnus* burrows) subtend from lower contact; trace fossils include *Ophiomorpha*, *Palaeophycus*, *?Cylindrichnus*, *Teichichnus*, and *Chondrites*; oyster shell fragments very abundant; other shell fragments (gastropod, scaphopod) common	cm-scale siderite patches common pervasive carbonate cementation; pebbles occasionally have 'diagenetic' rings and are rarely coated with carbonate; occasionally glauconite rich	sharp based, thin blocky units; <2 m thick; commonly overlies a firmground-burrowed surface	wave ravinement lag deposits
8	very fine to medium sandstone	typically hard to see, but includes small-scale wave ripple cross-stratification, high-angle, decimeter-scale cross-stratification and hummocky cross-stratification	moderately to intensely bioturbated; trace fossils include *Ophiomorpha*, *Cylindrichnus*, *?Rosselia*, *Chondrites* (in the *Rosselia*), *?Teichichnus*	cm-scale patches of siderite cement; m-scale patches of carbonate cement; trace fossil linings often oxidized	sharp based and blocky to coarsening upward	transgressive shallow marine sandstone sheet
9	mudstone with thin siltstone and very fine sandstone beds and laminae	hummocky cross-stratification; small- to medium-scale wave ripple cross-stratification	low to moderately bioturbated; trace fossils include *Planolites*, *Teichichnus*, *Palaeophycus*, *Terebellina*, *Chondrites*, *Cylindrichnus*, *?Asterosoma*, *Ophiomorpha*, *?Rosselia*	rare small siderite nodules	coarsening-upwards	offshore storm-dominated shelf deposits close to base of storm weather wave base
10	very fine sandstone; some mudstone interbeds	amalgamated hummocky cross-stratification; small- to medium-scale wave ripple cross-stratification	rare *Ophiomorpha* burrows		coarsening-upwards	storm-dominated lower shoreface deposits

Facies 2: Upward-fining, high-angle (>15°) cross-stratified coarse to medium sandstone with mud drapes

Facies 2 is similar to Facies 1 in terms of texture and sedimentary structures. However, double mud-drapes and rare *Skolithos* and escape traces are present, and millimeter-thick wispy mudstone veneers on cross-beds are common (Figure 3.7). Facies 2 always gradationally overlies Facies 1.

Interpretation: Tidally influenced braided fluvial deposits

Because it gradationally overlies braided fluvial deposits with similar characteristics (Facies 1), Facies 2 is also interpreted to be braided fluvial channel fill. However, the presence of double mud-drapes and *Skolithos* burrows suggests that the depositional environment was both tidally influenced and brackish during deposition (*cf.* Nio and Yang, 1991; Pemberton *et al.*, 2002). As such, Facies 2 is interpreted to have been deposited in brackish, tidally influenced braided fluvial channels.

Facies 3: Mudstone with thin siltstone laminae and oyster shells

Facies 3 comprises mudstone with common thin (<5 cm) siltstone beds and laminae (Figures 3.8a to 3.8c). Sandstone interbeds thicker than several centimeters are generally absent. Siltstone beds are either normally graded, wavy to planar laminated and normally graded, or low-angle (<10°) cross-stratified (Figures 3.8a and 3.8b). Commonly, siltstone laminae pinch and swell across the core and have slightly loaded basal contacts. Oyster shells are locally abundant (Figure 3.8c), as are swelling clays and siderite nodules and bands. Bioturbation is generally absent, but is locally intense. Trace fossils include small *Planolites*, *Teichichnus*, *Asterosoma*, *Zoophycos*, *?Cylindrichnus* and *Rosselia*. Facies 3 commonly grades upwards into Facies 4 or 6, or is erosionally overlain by Facies 7.

Interpretation: Lagoonal deposits

Facies 3 is interpreted to be a lagoonal deposit. Normally graded siltstone laminae are interpreted to have been deposited from suspension, possibly during storm-

related barrier-washover and bottom agitation, or, alternatively, during flood-related fluvial inflow into the lagoon (*e.g.*, Nemec, 1995). Episodic, intense bioturbation suggests that the environment was periodically less ecologically stressed, as would be expected in a lagoonal environment subject to temporal and spatial variations in salinity, turbidity, temperature, nutrient supply, etc. (*e.g.*, Ward and Ashley, 1989).

Apparently inconsistent with a lagoonal interpretation is the presence of rare *Asterosoma*, *Zoophycos* and *Rosselia* burrows. Although previously reported in lagoon-type deposits (*e.g.*, Murakoshi and Masuda, 1991; Pemberton *et al.*, 2002), these traces are more commonly associated with fully marine deposits (Pemberton *et al.*, 2002). However, it seems unlikely that Facies 3 is an open marine deposit, given the abundance of oyster shells (oysters are generally most prolific in ecologically stressed lagoon-type depositional environments; see Merill *et al.*, 1965; Donaldson *et al.*, 1970; Isreal *et al.*, 1987; van Heerdon and Roberts, 1988; Pemberton *et al.*, 2002). Also, the general absence of cross-stratification formed by large waves (hummocky cross-stratificaton; see Southard *et al.*, 1990; Arnott and Southard, 1990; Dumas, 2004) and the common upward gradation into lenticular-bedded mudstone interpreted to be tidal flat deposits (Facies 4) differentiate Facies 3 from mudstone interpreted to have been deposited in a storm-dominated, open marine environment (Facies 9). The presence of *Asterosoma*, *Zoophycos* and *Rosselia* burrows in Facies 3, therefore, suggests a relatively open connection between the lagoon and open marine basin during deposition as opposed to the existence of unrestricted, fully marine conditions.

Facies 4: Mudstone with pinstripe, lenticular and wavy sandstone laminae

Facies 4 is composed of mudstone with thin fine sandstone beds and laminae (Figures 3.9a to 3.9d). Sandstone laminae (<1 cm thick) are lenticular (pod-shaped), wavy (undulating top and bottom contacts), or pinstripe shaped (mm-thick, flat, and discontinuous across the core; Figure 3.9a). Internally, sandstone laminae are either flat-parallel laminated, wavy-parallel laminated, or are high-angle (>15°) cross-stratified. In cross-section parallel to maximum foreset dip (*i.e.*, parallel to flow), high-angle cross-sets either have scoop-shaped bases and are laterally discontinuous over several centimeters, or have flat bases and are laterally continuous across the core. Synaeresis cracks (Figure 3.9d), small-scale concave-up normal faults (Figure 3.9c), and microfaults are present locally. Decimeter-thick, rhythmically interstratified mudstone and fine sandstone also occur rarely (Figure 3.9b). Coal fragments and flakes are common. Bioturbation is generally low, but locally intense. Trace fossils include small *Planolites*, *Arenicolites, Teichichnus, Chondrites*, *Diplocraterion*, *?Skolithos, ?Thalassinoides,* and *?Rosselia.* Facies 4 commonly overlies Facies 3, 7, or 6.

Interpretation: Tidal flat deposits

Strata of Facies 4 are interpreted to be tidal flat deposits. Small-scale, scoop-based and flat-based cross-sets are interpreted to have been deposited by wave- and current-formed ripples, respectively (*e.g.*, Boersma, 1970; de Raaf, 1977). The occurrence of 1) a low diversity of trace fossils, 2) the admixture of vertical and horizontal burrows (a mixed *Cruziana/Skolithos* assemblage), 3) diminutive burrows (*e.g.*, *Planolites*), and 4) synaeresis cracks suggest that the environment was most likely

brackish during deposition (Pemberton *et al.*, 2002; Plummer and Gostin, 1981). Abundant coal fragments and carbonaceous flakes suggest deposition close to a terrestrial organic source. The heterolithic nature of Facies 4 indicates that episodes of mud deposition from suspension alternated with sand bedload transport by small waves and/or weak unidirectional flows, as would be expected to occur on sheltered tidal flats in a back-barrier environment (Postma, 1961; Reineck and Wunderlich, 1968; Amos and Collins, 1978; Dingler and Clifton, 1984). Furthermore, the lenticular, wavy, and pinstriped sandstone laminae, although not unique to tidal flats (*e.g.*, Coleman and Gagliano, 1965), are commonly observed in tidal flat deposits (Evans, 1965; Reineck and Wunderlich, 1968; Weimer *et al.*, 1982; Ginsburg, 1975; Klein, 1976; Amos, 1995; Gingras *et al.*, 1999).

Facies 5: Upward-fining, high-angle (>15°) cross-stratified fine sandstone

Facies 5 consists of planar laminated and small- (<5 cm) to large-scale (5-20 cm) high-angle (>15°) cross-stratified fine to very fine sandstone (Figures 3.10a and 3.10b). Bidirectional cross-stratification is present, but rare. Millimeter-thick mudstone laminae are common, as are mudstone veneers on cross-strata. Trace fossils are rare, and include *Skolithos*, *Ophiomorpha*, small *Planolites* and escape traces. Beds are organized into sharp-based, upward-fining to ungraded units that are several tens to a maximum of 300 cm thick (Figure 3.10a). Unlined, passively filled *Thalassinoides* burrows commonly subtend from the base of the units (Figure 3.10b). Roots, carbonaceous mudstone, and a thin cm-thick coal bed occur at the top of one of the sharp-based units (Figure 3.10a). Facies 5 typically erosively overlies Facies 3, and less commonly, Facies 4.

Interpretation: Tidal channel deposits

Facies 5 is interpreted to be tidal channel deposits. Small- and large-scale, high-angle cross-sets are interpreted to have formed by migrating current ripples and dunes under unidirectional flow conditions (Southard and Boguchwal, 1990). The thinness of dune cross-sets (maximum ~20 cm) and upward-fining units (maximum ~3 m) suggests that flows were at most several meters deep (*cf.* Leclair and Bridge, 2001; Bridge and Tye, 2000). Roots at the top of one of the Facies 5 sand-bodies indicate subaerial exposure. On the other hand, unlined *Thalassinoides* burrows that subtend from the base of the upward-fining units suggest exhumation of firm mud by subaqueous tidal-channel scour (*e.g.*, Pemberton *et al.*, 1985; Gingras *et al.*, 2000). Double mud-drapes and bidirectional cross-strata suggest deposition from reversing tidal currents (*cf.* Nio and Yang, 1991). Furthermore, the low-diversity, *Skolithos*-type trace fossil assemblage suggests that the depositional environment was marine-influenced (*cf.* Pemberton *et al.*, 2002). Together, these observations are consistent with a shallow tidal channel interpretation. Lateral building of tidal channel point-bars into channel thalwegs is known to form sharp-based, upward-fining sand-bodies that contain *Skolithos*-type trace fossil assemblages and overlie burrowed, muddy firmground surfaces (van Straaten, 1952; Barwis, 1978; Pemberton and Frey, 1985; Fenies and Faugères, 1998; Gingras *et al.*, 1999; Gingras *et al.*, 2000).

Facies 6: Coarsening-upward high-angle(>15°) cross-stratified sandstone

Facies 6 is composed of well-sorted, fine to very fine sandstone (Figures 3.11a and 3.11b). Beds are either planar laminated or small- (<5 cm) to large-scale (5-10 cm)

high-angle (>15°) cross-stratified (Figure 3.11a). Small-scale (<5 cm), high-angle cross-sets are typically flat-based and laterally-continuous, but small-scale (<5 cm) laterally discontinuous, scoop-based cross-sets are present locally. Millimeter-sized disseminated organic flecks are abundant, and commonly highlight ripple and dune cross-strata. In general, bioturbation is absent, but small *Planolites* burrows occur in thin mudstone interbeds, and rare *Ophiomorpha* burrows occur in sandstone. Sub-angular to round mudstone clasts are common (Figure 3.11a). Shell material is generally absent. Beds are organized into upward-coarsening units (maximum ~5 m thick) that gradationally overlie Facies 3 (Figure 3.11b). In some upward-coarsening units, small-scale (<2 cm thick) high-angle cross-stratified and planar-laminated beds grade upward into large-scale (5-10 cm thick) cross-stratified beds.

Interpretation: Bayhead delta deposits

Facies 6 is interpreted to have been deposited by small bayhead delta lobes that prograded into low-energy lagoons. The gradational contact with underlying lagoonal mudstone (Facies 2) and upward-coarsening nature of Facies 6 suggests a progressive increase in flow energy during deposition, most likely related to upward shallowing during progradation. The thinness of the upward-coarsening units (maximum 5 m), diminutive size of some burrows (*e.g.*, *Planolites*), low-diversity trace fossil assemblage, and lack of hummocky cross-stratification suggests that the receiving basin was likely shallow, sheltered, and brackish. Small-scale, flat- and scoop-based high-angle cross-sets are interpreted to have been deposited by current and small wave-ripples, respectively, whereas large-scale, high-angle cross-sets are interpreted to have been deposited by

subaqueous dunes (Boersma, 1970; de Raaf *et al.*, 1977; Southard and Boguchwal, 1990; Ashley, 1990), as might be expected in a fluvially dominated bayhead delta influenced by small waves. Although landward progradation of flood-tidal deltas into backbarrier lagoons can also generate upward-coarsening sand-bodies (*e.g.*, Roy *et al.*, 1980; Heron *et al.*, 1984; Barwis and Hayes, 1985; Hennessy and Zarillo, 1987; Isreal *et al.*, 1987; Murakoshi and Masuda, 1991), the low diversity trace fossil assemblage, lack of evidence of storm washover deposits (*e.g.*, climbing ripples, sand volcanoes, plane bed and/or antidune cross-stratificaton), presence of mud clasts and high organic content in Facies 6 are more consistent with deposition in a bayhead delta as opposed to a flood-tidal delta (*e.g.*, Donaldson *et al.*, 1970; van Heerdon and Roberts, 1988; Nichol *et al.*, 1997).

Facies 7: Sharp-based, poorly-sorted muddy sandstone

Facies 7 is composed of poorly sorted muddy sandstone (Figure 3.12). Units are typically less than 2 m thick. Bioturbation is typically intense and includes *Ophiomorpha*, *Palaeophycus*, *?Cylindrichnus*, *Teichichnus*, and *Chondrites*. Burrows are commonly robust and thick-walled (Figures 3.12a and 3.12c). Shell fragments (oyster, gastropod, scaphopod), isolated white quartz sand grains and granules ("paint-speckles"), and patches of siderite cement are common. Facies 7 commonly reacts strongly with hydrochloric acid, and rarely contains glauconite and carbonate-coated granules and sandstone pebbles. Physical sedimentary structures are obliterated by bioturbation. Lower contacts are sharp, and typically have subtending, unlined

Thalassinoides burrows (Figure 3.12b). Facies 7 erosively overlies either Facies 3, 4 or 8, and grades upward into Facies 8 or 9.

Interpretation: Wave ravinement lag deposits

Facies 7 is interpreted to be a lag deposit formed by wave ravinement during shoreface retreat. The high-diversity *Skolithos*-type trace fossil assemblage with common robust, thick-walled burrows suggests that the environment was most likely fully marine during deposition (*e.g.,* Pemberton *et al.*, 2002). This interpretation is supported by the common upward gradation into well-sorted, shallow marine sandstone (Facies 8). Burrowed mud firmground surfaces, which typically occur at the base of Facies 7, are interpreted to be transgressive wave ravinement surfaces formed by the landward passage of the high-energy shoreface over the coastal plain during shoreface retreat. Transgressive ravinement commonly erodes thick successions of previously deposited sediment (*e.g.*, 10-20 m), exhumes mud firmgrounds, and then abruptly superimposes shallow marine sandstone on coastal plain deposits (Fischer, 1961; Suter and Berryhill, 1985; Demarest and Kraft, 1987; Bhattacharya, 1993; Abbott, 1998; Snedden and Dalrymple, 1999; Hwang and Heller, 2002; Pemberton *et al.*, 2002; Rodriguez *et al.*, 2001; Cattaneo and Steel, 2002).

Facies 8: Well-sorted, bioturbated sandstone with high and low angle cross-stratification

Facies 8 is composed of well sorted very fine to medium sandstone (Figure 3.13). Bioturbation is typically moderate to intense. The trace fossil assemblage is dominated by *Ophiomorpha* (Figure 3.13b), with less common *Cylindrichnus*, *Skolithos*, *?Rosselia*,

and *Chondrites* (in the *?Rosselia*). Dispersed, white-coloured quartz sand grains and granules ("paint-speckles") are common. Shells and decimeter-scale patches of pore-filling carbonate cement are present locally. Bed contacts and physical sedimentary structures are typically not identifiable. However, where visible, both high-angle (around 15°) and low-angle (<10°) cross-stratification were observed. Facies 8 always gradationally overlies poorly sorted lag deposits (Facies 7), and forms meter-scale units that are either upward-coarsening or ungraded (Figure 3.13c). Facies 8 is overlain either by Facies 9, 3 or 7.

Interpretation: Transgressive shallow marine sandstone sheet

Facies 8 is interpreted to have been deposited in a shallow marine shoreface environment during transgression and shoreface retreat. The high-diversity *Skolithos*-type trace fossil suggests deposition in an unstressed, fully marine setting (*e.g.*, Pemberton *et al.*, 2002). The stratigraphic position of Facies 8 above sharp-based lag deposits (Facies 7) that in turn overlie burrowed lagoonal mud firmground surfaces suggests deposition during shoreface retreat associated with relative sea level rise (*e.g.*, Fischer, 1961). Carbonate cementation, shell fragments, and a mix of high- and low-angle cross-stratified beds are features common to transgressive shelf sand-bodies (*e.g.*, Penland *et al.*, 1988; Snedden and Dalrymple, 1999; Molgat and Arnott, 2001; Posamentier, 2002).

Facies 9: Mudstone with thin siltstone and sandstone interbeds

Strata consist of mudstone with common thin (<5 cm) siltstone and rare thin (<5 cm) very fine sandstone beds and laminae. Siltstone and sandstone beds are commonly low-angle (<10°) cross-stratified, with rare concave low-angle truncations. Sandstone beds are rarely capped by small-scale, scoop-based wave ripple cross-sets. One ammonite shell was observed on a bedding plane surface. Oyster shells were not observed in Facies 9. Bioturbation is typically low but diverse and includes *Planolites, Teichichnus, Palaeophycus, Terebellina, Chondrites, Ophiomorpha, Cylindrichnus, ?Asterosoma,* and *?Rosselia.* Facies 9 commonly overlies poorly sorted lag deposits (Facies 7) and coarsens upwards into well-sorted, low-angle cross-stratified sandstone (Facies 10).

Interpretation: Offshore mudstone

Facies 9 is interpreted to have been deposited near storm wave-base in a fully marine inner shelf/lower shoreface environment. Low-angle cross-stratification in sandstone interbeds is interpreted to be hummocky cross-stratification. Hummocky cross-stratification has been interpreted to form under the influence of large, long-period waves (*i.e.*, wave period > 8 seconds; *cf.* Southard *et al.*, 1990; Arnott and Southard, 1990; Dumas, 2004), suggesting deposition occurred in a large, unrestricted basin (Barnett and Wilkerson, 1967). This interpretation is supported by the presence of an ammonite shell and high-diversity trace fossil assemblage, both suggestive of a fully marine depositional environment.

Facies 10: Low-angle (<10°) laminated sandstone with mudstone interbeds

Facies 10 is composed of well-sorted, very fine to fine sandstone with rare to common mudstone interbeds (Figure 3.14). Sandstone beds are commonly amalgamated, form bedsets up to several meters thick, and are commonly low-angle (<10°) cross-stratified. Low-angle cross-strata are rarely gently curved either concave- or convex-up. Rare, concave, low-angle truncations are onlapped asymptotically by laminae that decrease in dip upwards (Figure 3.14). Small-scale (<2 cm) scoop-based high-angle (>15°) cross-sets commonly cap sandstone beds. Sandstones are sparsely bioturbated with rare *Ophiomorpha* burrows. Mudstone interbeds are also sparsely bioturbated, and contain *Planolites*, *Teichichnus, Palaeophycus, Terebellina, Chondrites, Ophiomorpha, Cylindrichnus, ?Asterosoma,* and *?Rosselia* burrows. Facies 10 gradationally overlies marine mudstone (Facies 9), and together form upward-coarsening units that are capped by poorly sorted lag deposits (Facies 7).

Interpretation: Storm-dominated lower shoreface deposits

Facies 10 is interpreted to have been deposited at the base of an open marine shoreface subjected to large, long-period waves. Low-angle, gently curved cross-strata (both convex- and concave-up), low-angle internal truncation surfaces, and small-scale, scoop-based cross-sets that cap beds (small wave ripple cross-sets) are features commonly associated with hummocky cross-stratification (Campbell, 1967; Harms *et al.*, 1975). The occurrence of hummocky cross-stratification suggests that the basin was relatively large (see discussion above), and the high-diversity trace fossil assemblage suggests that fully marine conditions existed during deposition.

3.7 Facies Associations

Based on observations from core, three facies associations were identified (Table 3.2). Stratigraphically upwards, these are interpreted to be 1) braided fluvial, 2) coastal plain, and 3) offshore marine/shoreface deposits (Figures 3.15 and 3.16a).

Table 3.2 Facies Associations, Panuke Field region

Facies Association	**Constituent facies**	**Nature of lower contact**	**Geomorphological features observed in 3-D seismic data (see Fig. 3.16)**	**Gamma log response**	**3-D distribution in the Panuke field region**
Facies Association 1: Braided fluvial deposits	Predominantly Facies 1 and 2 (>95%); minor amounts of Facies 3?	erosive, overlies undifferentiated shallow marine deposits	a NE-SW oriented braid-bar like feature in 3-D seismic plan view	blocky	~50 m thick sheet
Facies Association 2: Coastal plain deposits	Facies 3,4, 5, 6,7,8	sharp (as observed in core) or gradational (inferred from logs); no lag	several curvilinear channel like features in 3-D seismic plan view	serrated	~50 m thick sheet
Facies Association 3: Storm-dominated offshore/ shoreface	Facies 7,9,10	intertongued with coastal plain deposits; contact picked at highest transgressive lag deposit over which all deposits are marine (top of the P2 sandstone)	featureless in 3-D seismic plan view, save for one thin, deep channel that subtends from a surface near the lower contact	muddy, stacked coarsening-upward units	~150 m thick sheet

Facies Association 1: Braided fluvial deposits

Facies Association 1, which is composed predominantly of braided fluvial and tidally influenced braided fluvial deposits (Facies 1 and 2) with minor lagoonal mudstone (Facies 3), is interpreted to be a multi-storied braided-fluvial deposit. Facies Association 1 has a blocky gamma ray signature (Figure 3.15), and erosively overlies undifferentiated shallow marine deposits (Figure 3.17). In the low-accommodation western edge of the Sable Subbasin near Panuke, log data suggests that it forms a ~50 m thick sheet that

overlies a low-relief erosion surface (Figure 3.15). When correlated southeast into the high-accommodation central Sable Subbasin, Facies Association 1 doubles in thickness to a maximum of ~100 m (Figure 3.15b). However, because of complications related to intervening growth faults and facies change and/or erosion (*e.g.*, the O Marker is not identifiable in the distal subbasin), Facies Association 1 cannot be correlated into the distal part of the Sable Subbasin (*i.e.*, southeast of the Onondaga Field).

Facies Association 2: Coastal plain deposits

Strata of Facies Association 2 are interpreted to be coastal plain deposit. Facies Association 2 forms a ~50 m thick sheet throughout the Panuke/Cohasset region (Figures 3.15a and 3.15b). Where cored (Panuke B-90 well only), the lower contact is sharp and lacks lag (Facies 2), although log data from adjacent wells suggests that the contact is locally gradational. In comparison to underlying braided fluvial deposits (Facies Association 1), Facies Association 2 is markedly heterolithic, and is characterized by a serrated gamma ray log profile (Figure 3.15). It is dominated by tidal flat and lagoonal mudstone (Facies 3 and 4), with subordinate tidal channel and bayhead delta sandstone bodies (Facies 5 and 6) that are difficult to correlate laterally for more than several kilometers. The upward transition from mudstone to sharp-based sandstone at the top of Facies Association 2 (the P3 and P2 sandstones) represents intertonguing of marine and coastal plain deposits (see discussion below; Figure 3.20).

Facies Association 3: Storm-dominated offshore marine/shoreface deposits

Facies Association 3 is interpreted to have been deposited in a storm-dominated shelf to shoreface environment. It forms a ~150 m thick, areally extensive sheet in the Panuke region (Figure 3.15). Facies Association 3 consists primarily of offshore mudstone and lower shoreface sandstone (Facies 9 and 10) organized into upward-coarsening units (max. ~20 m thick) that are capped by thin (<2 m), erosionally based lags (Facies 7). Because of the complicated nature of the contact between underlying coastal plain deposits and Facies Association 3, the base of the latter is placed at the base of a prominent, thin (<2 m) lag that mantles the top of the P2 sandstone, the main Panuke reservoir. This boundary corresponds to the Upper Missisauga-Naskapi contact as defined in this paper (Figure 3.4).

3.8 3-D seismic data

When the Panuke 3-D seismic data are flattened to the O Marker, four seismic features interpreted to be depositional or erosional in origin are observed in plan view between the O Marker and the Naskapi Member (Figure 3.16). Stratigraphically-upward, these features are described and interpreted below.

Seismic feature 1: Large E-W trending channel (1.928 to 1.936 ms)

A 1.5 to 3 km wide channel that erodes directly into the top of the O Marker is visible in seismic plan and cross-section view (Figure 3.16a and 3.16b). All Panuke wells penetrate this uncored feature, except for Panuke M-79 and H-08, which lie to the south of it. Log data suggest the channel is filled with mudstone, sandstone and

carbonate. The channel is 0.008 ms thick, which corresponds to an approximate thickness of 12 m[14]. Furthermore, the channel is gently curved, broadens upward, and trends roughly E-W. Paleoflow direction is inferred to be westward because the shelf margin is located to the southwest of the Panuke Field (see below). The channel overlies the crest of a drape structure formed by differential compaction above the edge of the underlying Abenaki carbonate bank. It runs slightly oblique to the reef margin and also slightly oblique to normal faults along the reef margin. Fault control on channel position is therefore equivocal.

Seismic feature 2: Diamond-shaped feature (1.896 to 1.900 ms)

Near the top of the braided-fluvial deposits (Facies Association 1), a diamond-shaped feature is visible in seismic plan view (Figure 3.16a). It is 1.5 km wide, 2.5 km long, ~6 m thick, and is elongate in a NE-SW direction. Channel-like features on either side of the diamond-shaped feature are ~250 m wide, and curve around it in a general NE-SW direction. Based on its similarity with bars in large modern braided fluvial systems (*e.g.*, the Brahmaputra River; Best *et al.*, 2003), and similarity in thickness with upward-fining fluvial units (Facies 1), the diamond-shaped feature is interpreted to be a braid bar. Although Panuke F-09 and Panuke F-99 penetrate this feature no core was cut and because of its thinness, it is below resolution of the data in seismic cross-section (Figure 3.16c).

[14] Although a rough approximation, the vertical dimension of a seismic feature is not equal to the thickness of the associated stratigraphic body (*e.g.* channel, barform etc) because seismic response can extend both above and below a stratigraphic body. This can make correlation of seismic features to stratigraphic surfaces problematic.

Seismic Feature 3: Thin, NE-SW oriented channel (1.872 to 1.900 ms)

A channel is visible in seismic plan view within the coastal plain deposits (Facies Association 2; Figure 3.16a and 3.16b). It has a crude oval shape in cross-section, is 350 to 700 m wide, and is about 40 m thick (0.028 ms). No wells penetrate the feature.

Seismic Feature 4: Thin, deep channel (1.852 to 1.892 ms)

Marine deposits (Facies Association 3) that overlie coastal plain deposits (Facies Association 2) are featureless in seismic plan view. However, a thin (~175 m), deep (0.040 ms, or ~60 m) channel subtends from a surface near the contact between Facies Association 3 and Facies Association 2 (Figure 3.16a and 3.16c). No wells penetrate this feature.

3.9 Regional seismic stratigraphy

The Upper Member of the Missisauga Formation in the Panuke Field correlates to progradational/aggradational clinoform-shaped reflections basinward to the southwest (Figure 3.18). Because there are no seismically distinct regional reflections within the Upper Missisauga in the Panuke Field region, the Upper Missisauga is correlated here as a single package of reflections. At present, no wells penetrate the clinoform-shaped reflections. Relief from clinoform brink-point to toe is of the order of 400 m, suggesting that the clinoforms are shelf margin and slope deposits that downlap onto Jurassic carbonates of the Abenaki Formation (*e.g.*, Porebski and Steel, 2003; Donovan, 2003). The top of this package is onlapped by a landward-thinning group of reflections that has the stratigraphic character of a healing-phase wedge. Shoreface/offshore marine deposits

at the base of the Naskapi Member (Facies Association 3) drape the top of the healing-phase wedge. The base of the blocky Cree Member truncates the offshore/shoreface deposits (Facies Association 3) of the Naskapi Member (Figure 3.15), and is associated with renewed shelf margin progradation/aggradation (Figure 3.18).

When correlated across depositional strike from the Panuke Field into the central Sable Subbasin, the Upper Missisauga fluvial-marine succession thickens from ~100 m to ~250 m (Figure 3.19). Internally, the fluvial-marine transition cannot be differentiated seismically. Most of the thickening occurs across a narrow zone (~10 km wide) that overlies the Abenaki carbonate reef margin.

3.10 Depositional model

Two major, unconformity-bounded sequences are interpreted to occur between the O Marker and the base of the Cree Member in the western Sable Subbasin (Figure 3.16). Biostratigraphic data places the Upper Missisauga and Naskapi between the Hauterivian and Albian (Wade and MacLean, 1990), suggesting that these sequences were associated with low-frequency (1-10 m.y.) 3rd order relative sea-level fluctuations. The lowermost sequence, Sequence 1, lies between the channelized top of the O Marker and the low-relief base of the braided fluvial sheet (Facies Association 1). Sequence 1 is not cored in the Panuke Field region, and is interpreted based on 3-D seismic and limited log data. The second sequence, Sequence 2, lies between the base of the braided fluvial facies association and the base of the Cree. Core data locally sample Sequence 2, including its lower boundary.

Sequence 1

The wide channel eroded into the O Marker identified in 3-D seismic data is interpreted to be an incised valley formed during forced regression (*i.e.*, falling relative sea-level) and lowstand (*i.e.* low but rising relative sea-level and normal regression; Figure 3.16). This interpretation is consistent with correlative progradational reflections at the coeval shelf-margin to the southwest that suggest sediment largely bypassed the channel and supplied the shelf margin (Figure 3.18)[15]. Although uncored, log data suggests that the valley is filled with a heterolithic assemblage of sandstone, mudstone, and carbonate. The presence of several meter-thick carbonate layers within the incised valley fill may be due to low fluvial sediment input during transgression, which led to underfilling of the incised valley (*e.g.*, the Late Pleistocene Hudson Valley, offshore New York; see Posamentier, 2001).

Sequence 2

Thick (~50 m) braided fluvial deposits (Facies Association 1) are separated from underlying undifferentiated shallow marine deposits of Sequence 1 by an erosion surface over an area of at least ~20 km perpendicular and ~60 km parallel to interpreted paleoflow in the western Sable Subbasin (paleoflow based on braid bar orientation; see Figures 3.15 to 3.17). The erosion surface has little geomorphological expression in both log cross-sections and 3-D seismic data (Figures 3.15 and 3.16). The braided fluvial sheet is interpreted to occur in a wide, flat-based incised valley formed during forced

[15] 3-D seismic data suggests that the O Marker is locally incised at the shelf edge in the Sable Subbasin (Gela Crane, personal communication, 2004).

regression and lowstand. This interpretation is based on the absence of underlying delta front facies in the Panuke Field (Figure 3.17), and the observation that sediment was fed to the shelf margin during deposition of the braided fluvial sheet (Figure 3.18). Because incised valleys typically require time to widen following initial flow-parallel incision (*e.g.*, Zaitlin *et al.*, 1994; Leeder and Stewart, 1996; Heller *et al.*, 2001), the substantial width and low relief of the incised valley base perpendicular to interpreted paleoflow (>20 km) suggests that relative sea-level fall and lowstand was prolonged.

Although minor amounts of fluvial sediment may have been deposited during relative sea-level fall (*cf.* Blum and Törnquist, 2000), significant fluvial aggradation probably did not start until after sea level reached its lowest level and began to rise. The rate of accommodation increase associated with the relative sea-level rise was likely low compared to avulsion rate, which allowed for a sheet-like fluvial deposit to form over the sequence boundary (*e.g.*, Blakey and Gubitosa, 1984; Holbrook, 1996; Arnott *et al.*, 2001). The significant thickness of the braided fluvial sheet (~50 m in the Panuke field) suggests that sediment supply remained high in the face of net base level rise (*cf.* Curray, 1964). No unequivocal upward change in channel style (*i.e.*, braided to meandering or anastomosing) or density of the channel stacking pattern is observed in either 3-D seismic or well log data.

The contact between braided fluvial (Facies Association 1) and coastal plain deposits (Facies Associaton 2) is gradational to sharp, does not have an associated lag, and is preceded by marine- and tidally-influenced braided fluvial deposits (Facies 2). These data suggest that the contact is conformable, and formed during progressive aggradational backstepping of the tidally- and marine-influenced coastal plain over the

alluvial plain (*cf.* Shanley *et al.*, 1992). Given the considerable thickness of the coastal plain deposits (~50 m in the Panuke field), sediment supply likely remained high during transgression (*cf.* Curray, 1964).

The contact between the coastal plain and overlying offshore-marine facies associations is characterized by intertonguing of sharp-based shallow marine sandstone sheets (the P2 and P3 sandstones) and coastal plain mudstone (Figure 3.20). The sharp-based lower contacts, presence of basal lags, marine trace fossil assemblages, and well-sorted nature of the P2 and P3 sandstones suggest that they were emplaced on a shallow seafloor following episodes of transgressive wave ravinement (Figure 3.21). The basal contacts of both P2 and P3 sandstones are possible amalgamated sequence boundary/transgressive ravinement (SB/TR) surfaces formed during higher-frequency (4^{th} or 5^{th} order) fluctuations of relative sea-level. The top of the P2 sandstone, which is mantled by a sharp-based lag (Facies 7), is also a possible amalgamated high-order SB/TR surface because lags generally occur at the base of transgressively emplaced sandstone bodies (*e.g.*, Posamentier, 2002). Thick sandbodies immediately below the top of the Upper Missisauga in wells adjacent to the Panuke Field (*e.g.*, Cree E-35 well; Figure 3.15a) as well as the narrow (<1 km), deep (40-60 m) channels observed in 3-D seismic data (Figure 3.16; Seismic features 3 and 4) may be incised valleys that extend down from these higher-order amalgamated SB/TR surfaces. The occurrence of these amalgamated SB/TR surfaces suggests that the 3^{rd} order relative sea-level rise associated with the Upper Missisauga/Naskapi boundary was punctuated by higher-frequency (4^{th} and 5^{th} order) relative sea-level fluctuations, and as a consequence complicated the stratigraphy.

Parasequences within the offshore marine deposits of the Naskapi (Facies Association 3) are aggradationally stacked in the Panuke Field region (Figure 3.15). The absence of either a turnaround to progradational parasequence stacking or an obvious seismic downlap within the Naskapi in the Panuke region may suggest that the maximum flooding surface of Sequence 2 was truncated in the Panuke region during relative sea-level fall and deposition of the Cree Member. The sharp contact between Cree and Naskapi members is interpreted to be the upper boundary of Sequence 2 (Figures 3.15 and 3.16). This surface is associated with renewed shelf-margin progradation to the southwest of Panuke (Figure 3.18).

3.11 Shelf margin accretion during transgression?

2-D seismic data (Figure 3.18) suggest that the shelf margin continued to be supplied with sediment until the *end* of coastal plain deposition in the Panuke Field, which corresponds to the Upper Missisauga/Naskapi boundary. This observation is *apparently* in contradiction with sequence stratigraphic models that suggest shelf-margin accretion typically stops as a result of relative sea-level rise overcoming fluvial sediment supply to the lowstand shelf-edge (*e.g.*, Posamentier and Vail, 1988; Porebski and Steel, 2003). However, if the transgression is punctuated by higher-frequency episodes of relative sea-level fall and rise and fluvial sediment supply varies temporally, as is likely the norm for longer-period relative sea-level cycles (*e.g.* 1st, 2nd, or 3rd order), sediment has the potential to episodically bypass the shelf and prograde the shelf margin, even during net transgression. As such, sediment bypass across one or several of the 4th or 5th order amalgamated SB/TR surfaces present near the top of the coastal plain deposits

(Facies Association 2) could have temporarily supplied the shelf edge with sediment and caused continued shelf margin progradation.

3.12 Exploration significance

This paper suggests that transgressively emplaced shallow-marine sand-bodies can constitute a significant stratigraphic play type in the western Sable Subbasin (Figures 3.20 and 3.21). These sand-bodies are sheet-like over tens of kilometers, are commonly several meters thick (maximum 9 m), and consist predominantly of well-sorted sandstone with good reservoir quality (permeability is commonly between 100-500 mD and reaches a maximum of about 2000 mD; Table 3.3; Figure 3.20). Although unresolvable in Panuke 3-D seismic data because of their thinness, the sheet-like sand-bodies may thicken close to local sources of sand such as tidal channels or incised valleys, as observed in late Pleistocene analogs (Snedden and Dalrymple, 1999), which may make them more easily identifiable in 3-D seismic data.

Table 3.3 P2 and P3 Sandstones: Sedimentology and Reservoir Quality

Reservoir	Lower Contact	Underlain by...	Overlain by...	Facies (in stratigraphic order)	Permeability			
					F-99	J-99 PP2	B-90	Potential flow barriers
P2 sandstone	erosive, with unlined *Thalassinoides* burrows subtending from contact	lagoonal mudstone (Facies 3)	offshore mudstone (Facies 9)	poorly sorted glauconite-rich sandstone (Facies 7)	0 to 667	0 to 0.2	0	carbonate cement throughout
				well sorted bioturbated fine sandstone (Facies 8)	58 to 1050	49 to 165	9 to 422	meter-scale carbonate cemented intervals
				poorly sorted, bioturbated sandstone (Facies 7)	0 to 127	0 to 0.3	not sampled	commonly very muddy; siderite cement
				tidal channel (Facies 5)	not developed	not developed	185 to 408	laterally confined by lagoonal facies
P3 sandstone	erosive, with unlined *Thalassinoides* burrows subtending from contact	lagoonal mudstone (Facies 3)	lagoonal mudstone (Facies 3)	well sorted, bioturbated fine sandstone (Facies 8)	35 to 1980	3 to 941	6 to 203	
				transgressive lag (Facies 7)	.01 to 5	0.1 to 0.75	0 to 0.88	very muddy

As shelf-margin progradation is interpreted to have occurred during lowstand and fluvial sediment bypass at the base of both Sequence 1 and 2 (Figure 3.18), fluvial systems at the base of both sequences potentially supplied coarse clastic sediment to down-dip slope and basin-floor turbidite systems. Regional mapping of these fluvial systems using a combination of available data (especially 3-D seismic data flattened to the O Marker) may therefore help identify down-dip shelf margin and slope exploration targets in the Sable Subbasin.

3.13 Conclusions

A thick (~100 m), areally extensive (>20 km wide) fluvial-marine transition has been identified between the Upper Missisauga and Naskapi in the western Sable Subbasin. The thickness of the fluvial-marine transition suggests that sediment supply remained high during base level rise. Furthermore, the areal extent of the fluvial-marine transition suggests that the fluvial system was relatively unrestricted, which allowed it to avulse laterally and erode a flat basal contact. Delta front deposits are absent below fluvial deposits, and the shelf margin accreted during its deposition, suggesting that the base of the fluvial deposits is a sequence boundary formed at the base of a wide incised valley. Continued shelf margin progradation until the end of coastal plain deposition was apparently facilitated by episodes of high-frequency (4^{th} and 5^{th} order; *i.e.*, <1 million year duration) relative sea-level rise and fall that caused sediment to episodically bypass the shelf and feed the shelf margin.

The two main Panuke reservoirs (P2 and P3 sandstones) are sharp-based sandstone sheets that intertongue with coastal plain mudstone just below the Upper

Missisauga/Naskapi boundary. They are commonly several meters thick in the western Sable Subbasin, and several tens of kilometers in area. They are interpreted to be shallow marine sand-bodies deposited above transgressive ravinement surfaces during shoreface retreat. Given their good reservoir quality and areally extensive geometry, transgressive sandstone sheets may represent an important reservoir play-type in the western Sable Subbasin.

Figure 3.1 Isopach map (in part estimated), Scotian Basin. Contours are in kilometers. Modified from MacLean and Wade (1992).

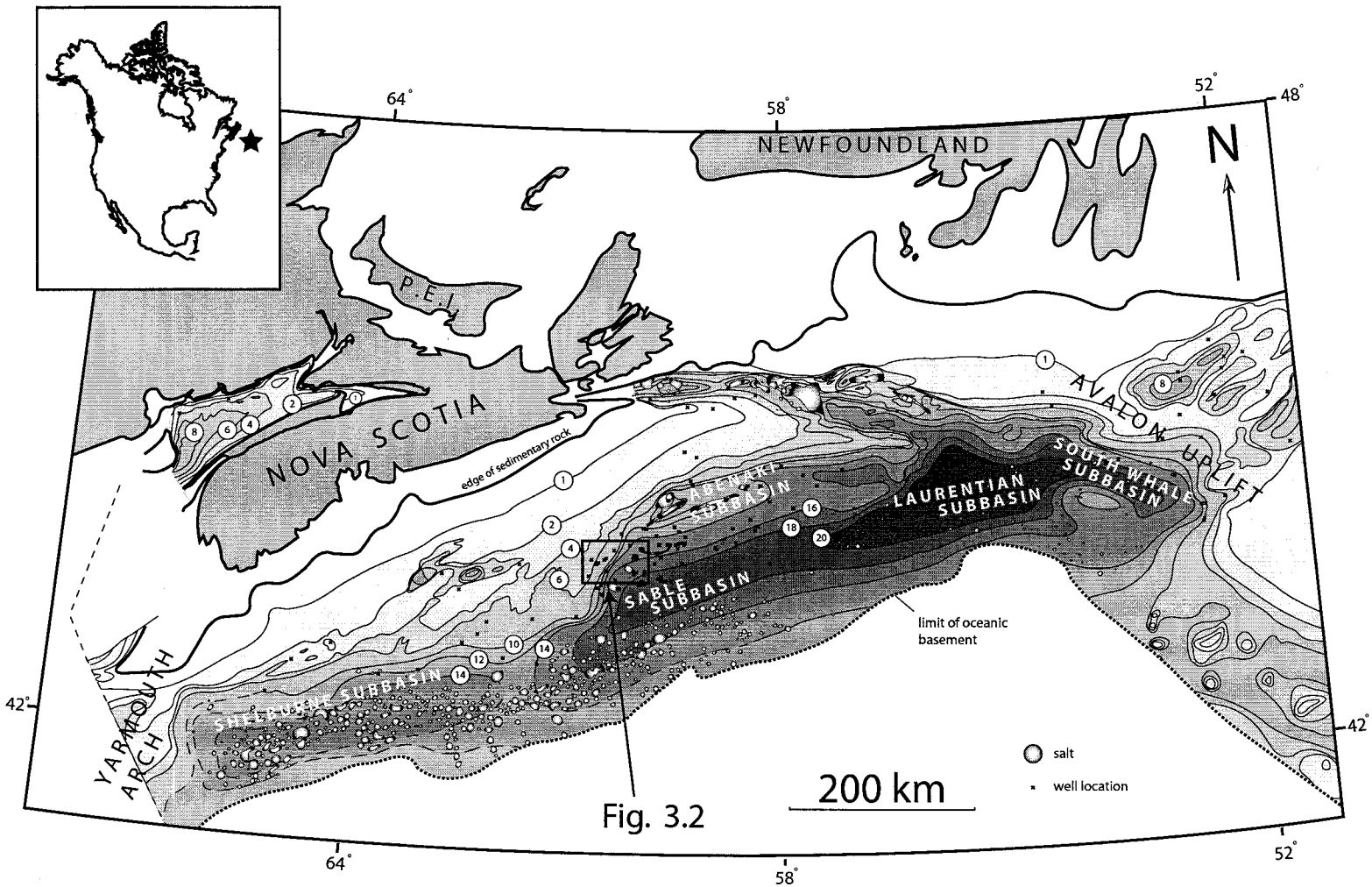

64°
58°
52°
48°
42°
NEWFOUNDLAND
N
P.E.I.
NOVA SCOTIA
edge of sedimentary rock
AVALON UPLIFT
ABENAKI SUBBASIN
LAURENTIAN SUBBASIN
SOUTH WHALE SUBBASIN
SABLE SUBBASIN
limit of oceanic basement
SHELBURNE SUBBASIN
YARMOUTH ARCH
salt
well location
200 km
Fig. 3.2

Figure 3.2 Location of the Panuke Field, western edge of the Sable Subbasin, offshore Nova Scotia (modified after Welsink *et al.*, 1989; Canada Nova Scotia Offshore Petroleum Board, 2000). Solid black dots designate cored wells.

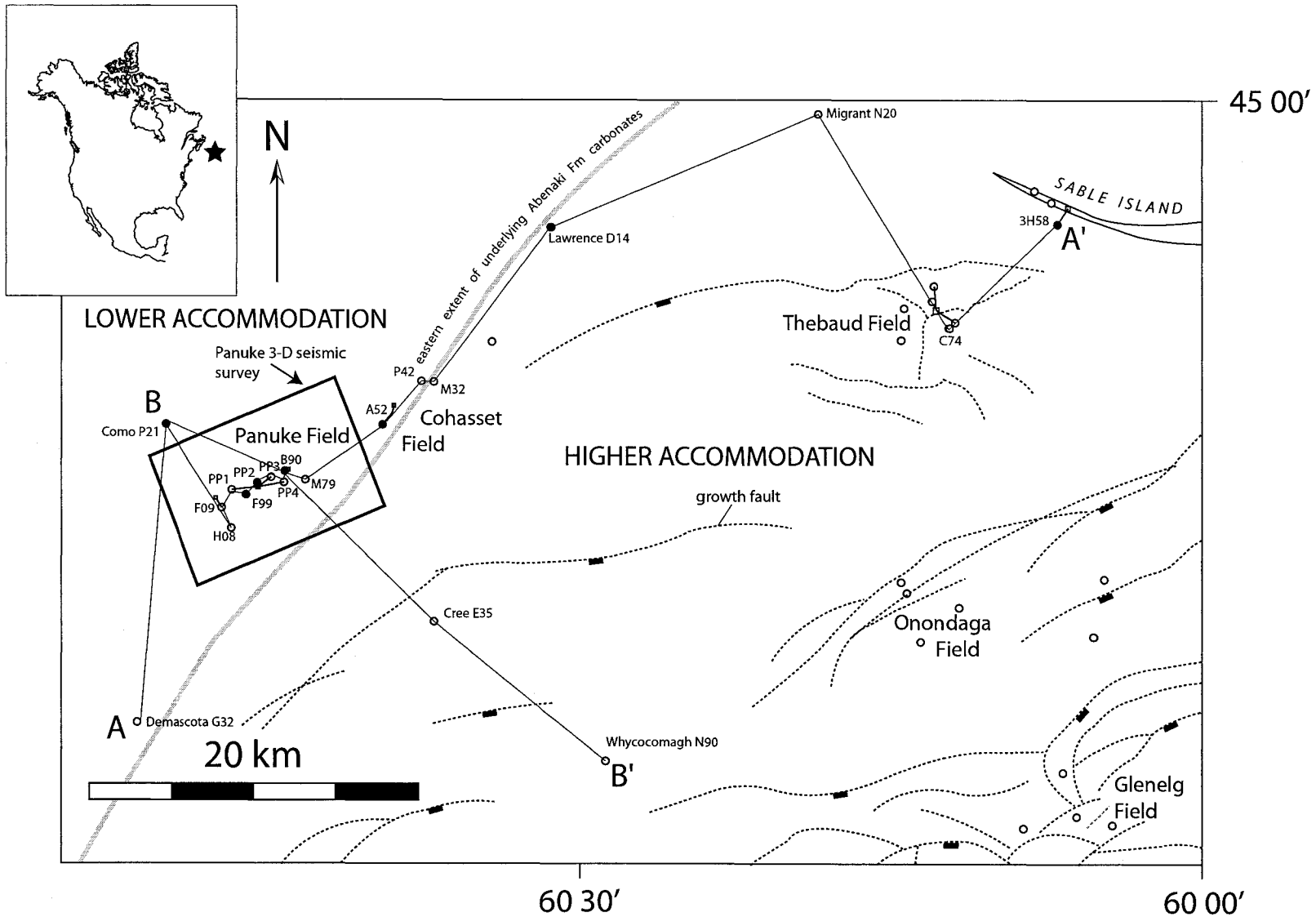

N
45 00′
60 30′
60 00′
LOWER ACCOMMODATION
HIGHER ACCOMMODATION
Panuke 3-D seismic survey
Panuke Field
Cohasset Field
Thebaud Field
Onondaga Field
Glenelg Field
SABLE ISLAND
eastern extent of underlying Abenaki Fm carbonates
growth fault
Migrant N20
Lawrence D14
3H58
A'
C74
P42
M32
A52
B
Como P21
B90
PP1
PP2
PP3
PP4
M79
F09
F99
H08
Cree E35
A
Demascota G32
B'
Whycocomagh N90
20 km

Figure 3.3 Stratigraphic framework of Upper Jurassic/Lower Cretaceous strata in the Sable Subbasin of the Scotian Basin, offshore Nova Scotia (after Welsink *et al.*, 1989 and Wade and MacLean *et al.*, 1990)

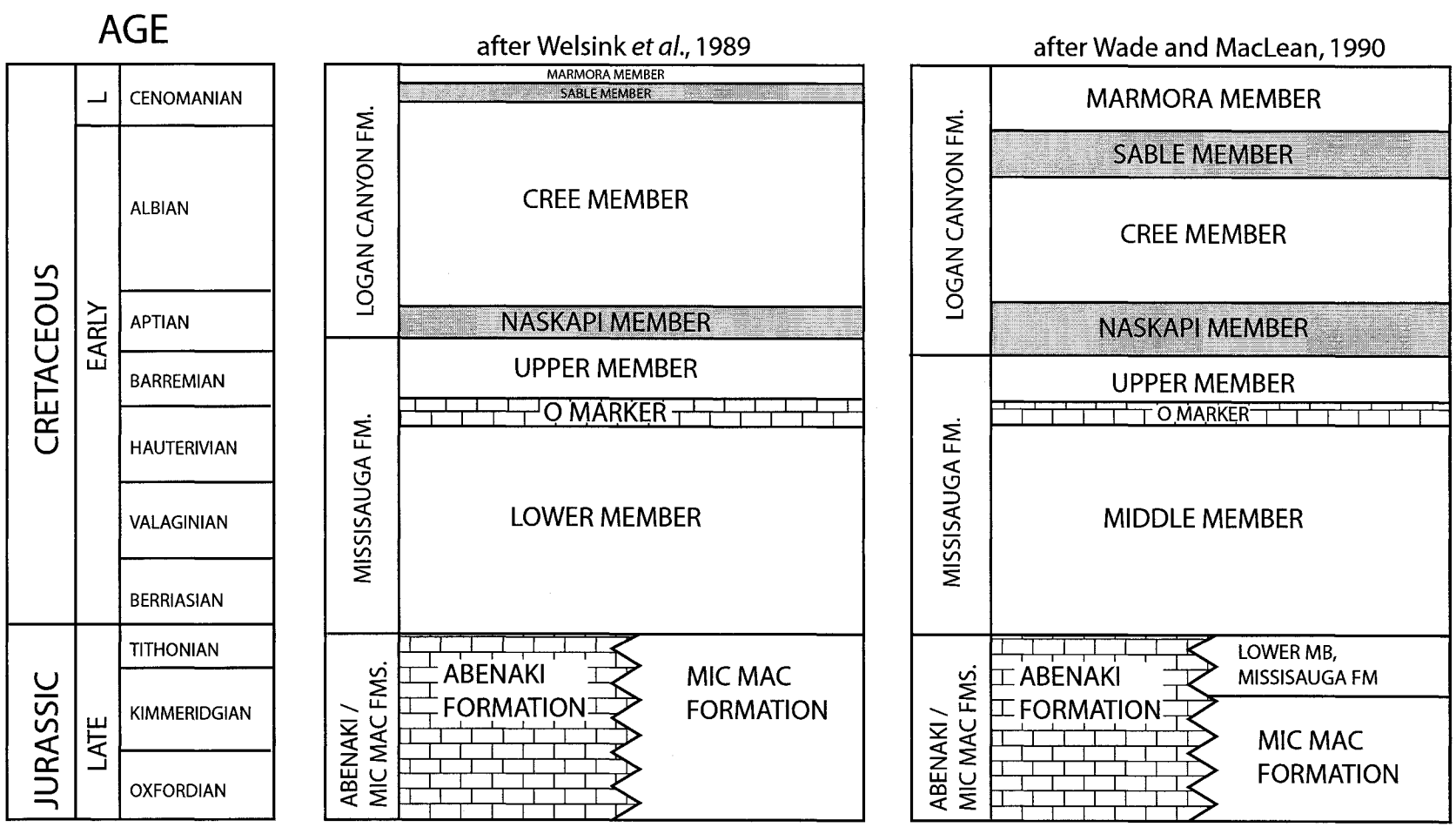

AGE
CRETACEOUS
JURASSIC
L
EARLY
LATE
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALAGINIAN
BERRIASIAN
TITHONIAN
KIMMERIDGIAN
OXFORDIAN
after Welsink et al., 1989
LOGAN CANYON FM.
MISSISAUGA FM.
ABENAKI / MIC MAC FMS.
MARMORA MEMBER
SABLE MEMBER
CREE MEMBER
NASKAPI MEMBER
UPPER MEMBER
O MARKER
LOWER MEMBER
ABENAKI FORMATION
MIC MAC FORMATION
after Wade and MacLean, 1990
LOGAN CANYON FM.
MISSISAUGA FM.
ABENAKI / MIC MAC FMS.
MARMORA MEMBER
SABLE MEMBER
CREE MEMBER
NASKAPI MEMBER
UPPER MEMBER
O MARKER
MIDDLE MEMBER
LOWER MB, MISSISAUGA FM
ABENAKI FORMATION
MIC MAC FORMATION

Figure 3.4 Panuke sandstone reservoirs (P1 to P5 sandstones), Upper Missisauga-Naskapi transition, Panuke B-90 well. Lithostratigraphic picks are after MacLean and Wade (1993) and LASMO (1990). Reservoir picks are after LASMO (1990) and in-house data (Encana, unpublished). Note that for convenience, the Upper Missisauga is picked so that it coincides with the top of the main reservoir (the P2 sandstone).

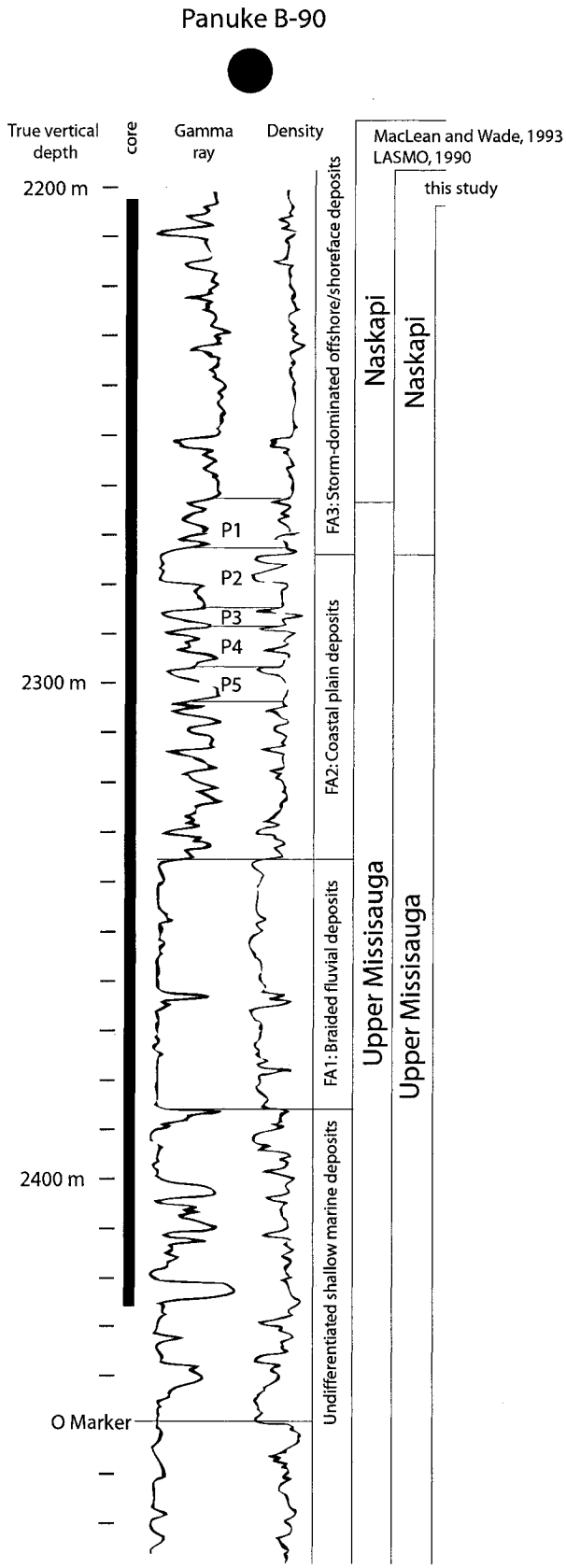

Panuke B-90
True vertical depth
core
Gamma ray
Density
MacLean and Wade, 1993
LASMO, 1990
this study
2200 m
2300 m
2400 m
P1
P2
P3
P4
P5
O Marker
FA3: Storm-dominated offshore/shoreface deposits
FA2: Coastal plain deposits
FA1: Braided fluvial deposits
Undifferentiated shallow marine deposits
Naskapi
Naskapi
Upper Missisauga
Upper Missisauga

Figure 3.5 Well-to-seismic tie used for the Panuke 3-D seismic survey. Well log and seismic picks, except for the top of the Missisauga Formation (see Figure 3.3), are the same as those in MacLean and Wade (1993).

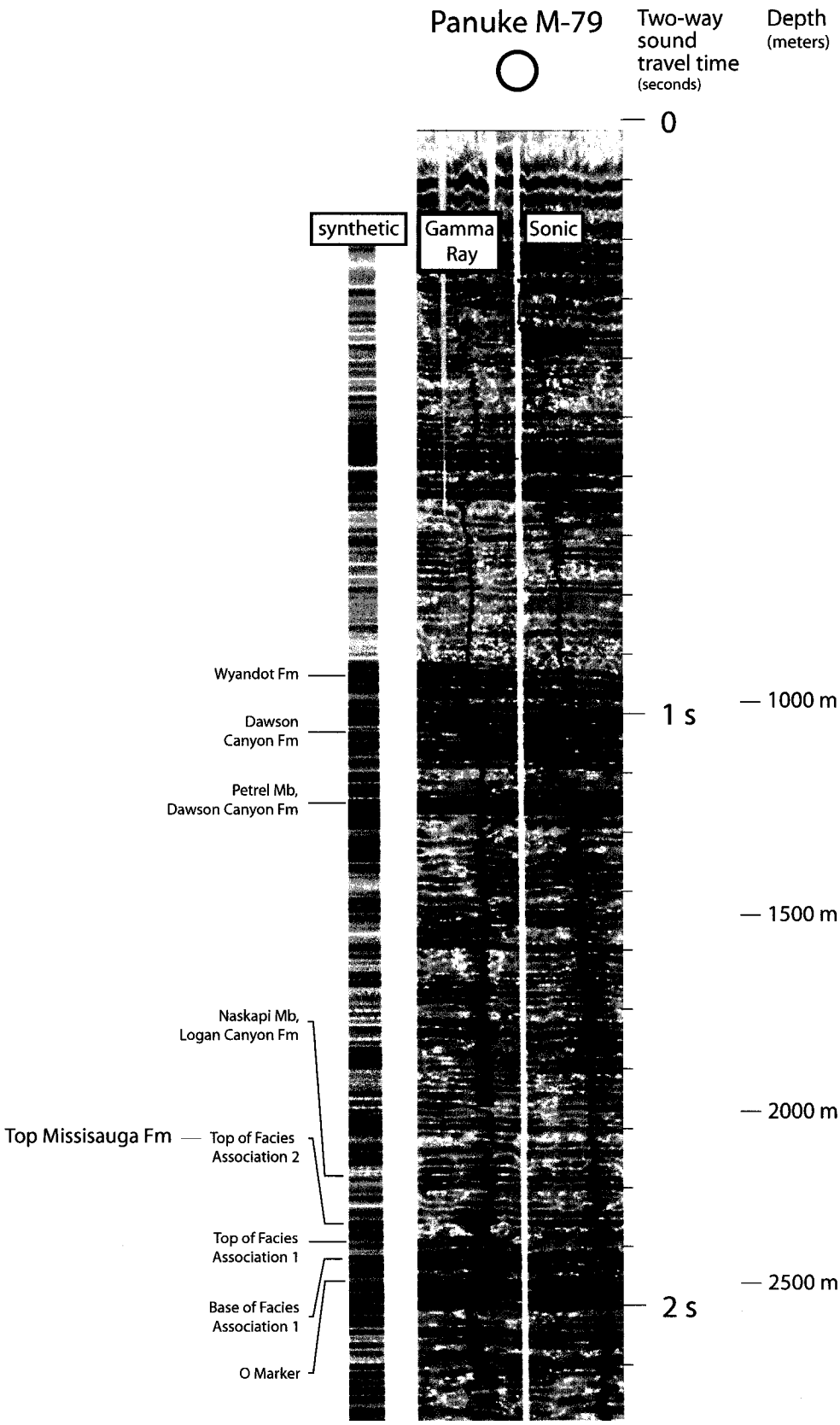

Panuke M-79
Two-way sound travel time (seconds)
Depth (meters)
0
synthetic
Gamma Ray
Sonic
Wyandot Fm
Dawson Canyon Fm
Petrel Mb, Dawson Canyon Fm
1 s
1000 m
1500 m
Naskapi Mb, Logan Canyon Fm
Top Missisauga Fm
Top of Facies Association 2
2000 m
Top of Facies Association 1
Base of Facies Association 1
2500 m
2 s
O Marker

Figure 3.6 Facies 1 (interpretation - braided fluvial channel fill deposits). Note high-angle (dune) cross-stratification. Photo taken from Panuke B-90 well, core 11.


2.5 cm

Figure 3.7 Facies 2 (interpretation – tidally influenced braided fluvial channel fill deposits). Note high-angle (dune) cross-stratification, with *Skolithos* burrow (top arrow) and double mud-drape (bottom arrow). Photo taken from Panuke B-90 well, core 9, box 19, 2354.91 m (measured depth).

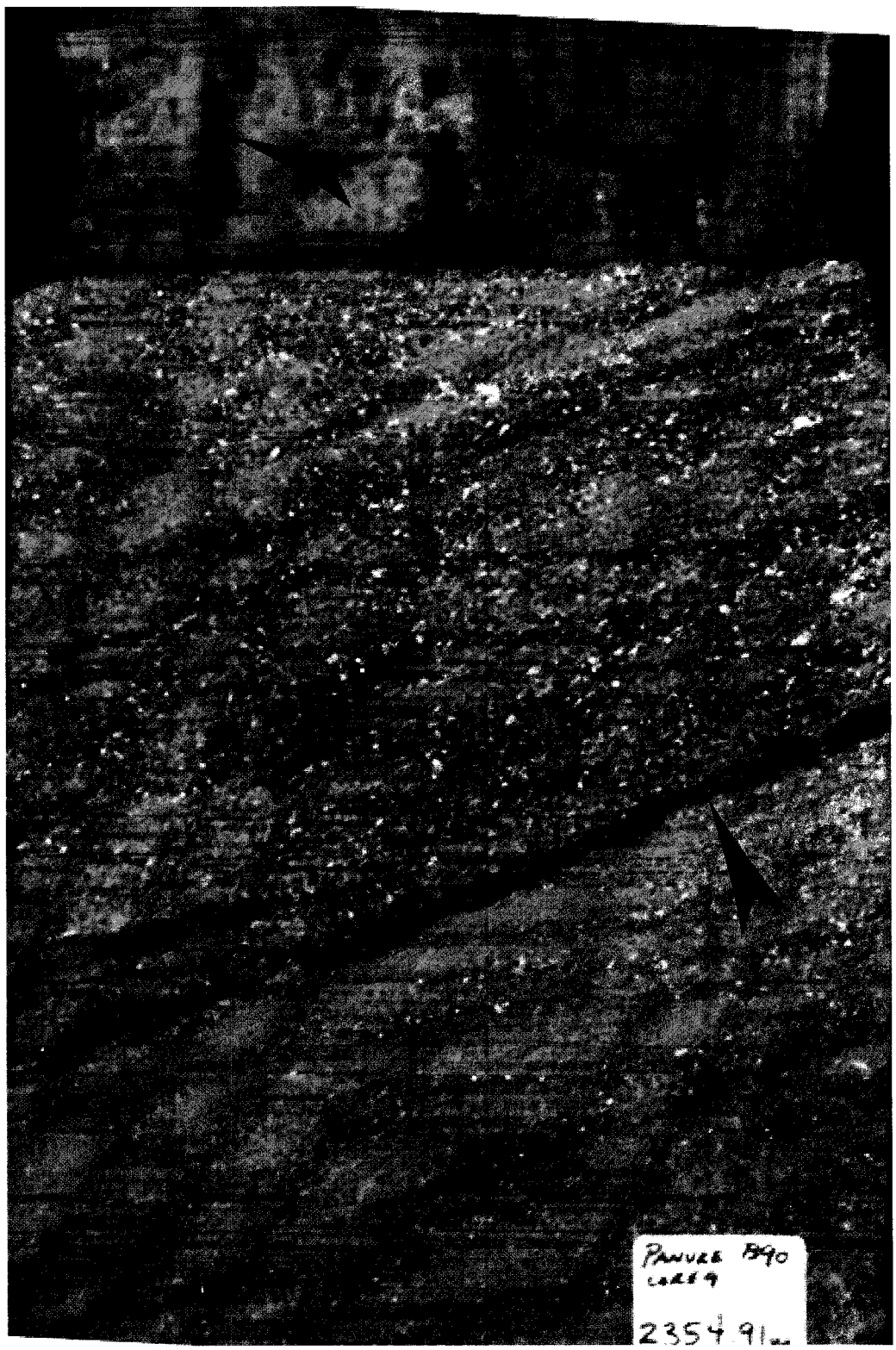
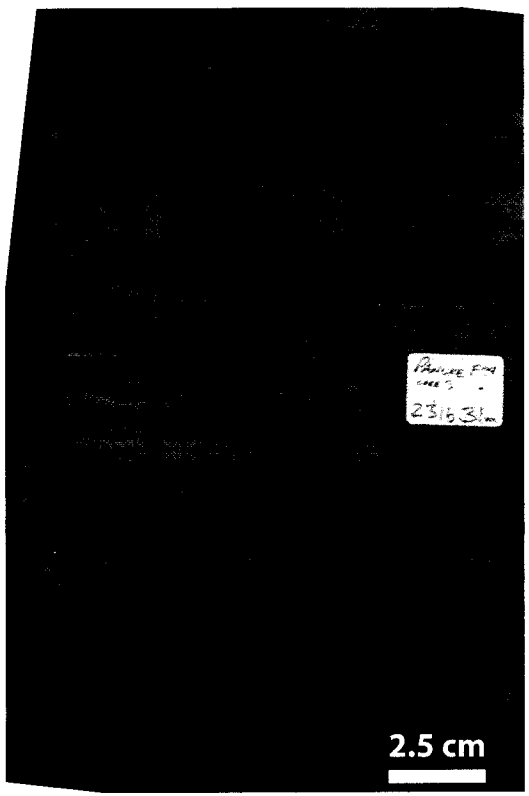
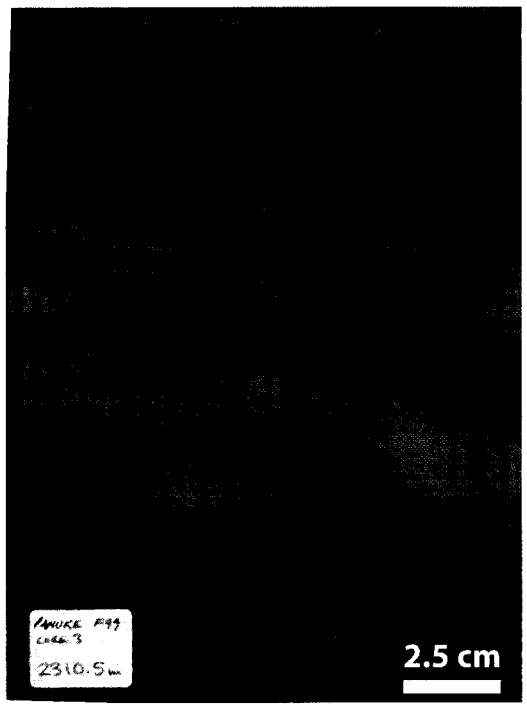

2.5 cm

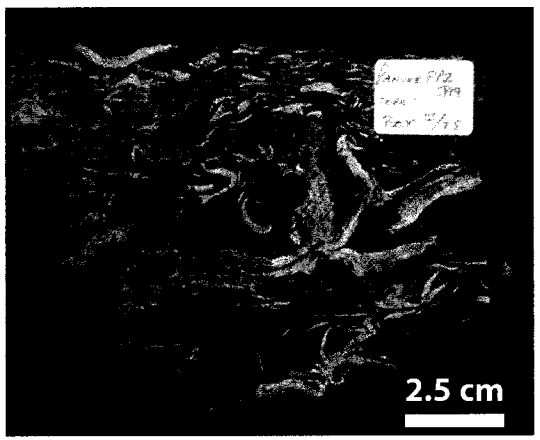
Figure 3.8 Facies 3 (interpretation – lagoonal mudstone). (**a**) Mudstone with normally graded siltstone laminae (Panuke F-99, core 3, box 24, 2316.31 m (measured depth)), (**b**) small-scale wave ripple cross-stratification (Panuke F-99, core 3, box 15, 2310.5 m (measured depth)), (**c**) oyster shells (Panuke J-99 PP2, core 1, box 12, 2305.8 m (measured depth)).



(a)



(b)



(c)

Figure 3.9 Facies 3 (interpretation – tidal flat deposits). (**a**) pinstripe- and lenticular-laminated sandstone (Panuke B-90, core 3, box 23, 2333.15 m (measured depth)), (**b**) rhythmic stratification (neap-spring cycles?; Panuke B-90, core 7, box 12, 2298.3 m (measured depth)), (**c**) small-scale slump (Panuke B-90, core 8, box 21, 2331.95 m (measured depth)), (**d**) synaeresis cracks (Panuke B-90, core 8, box 27, 2336.11 m (measured depth)).

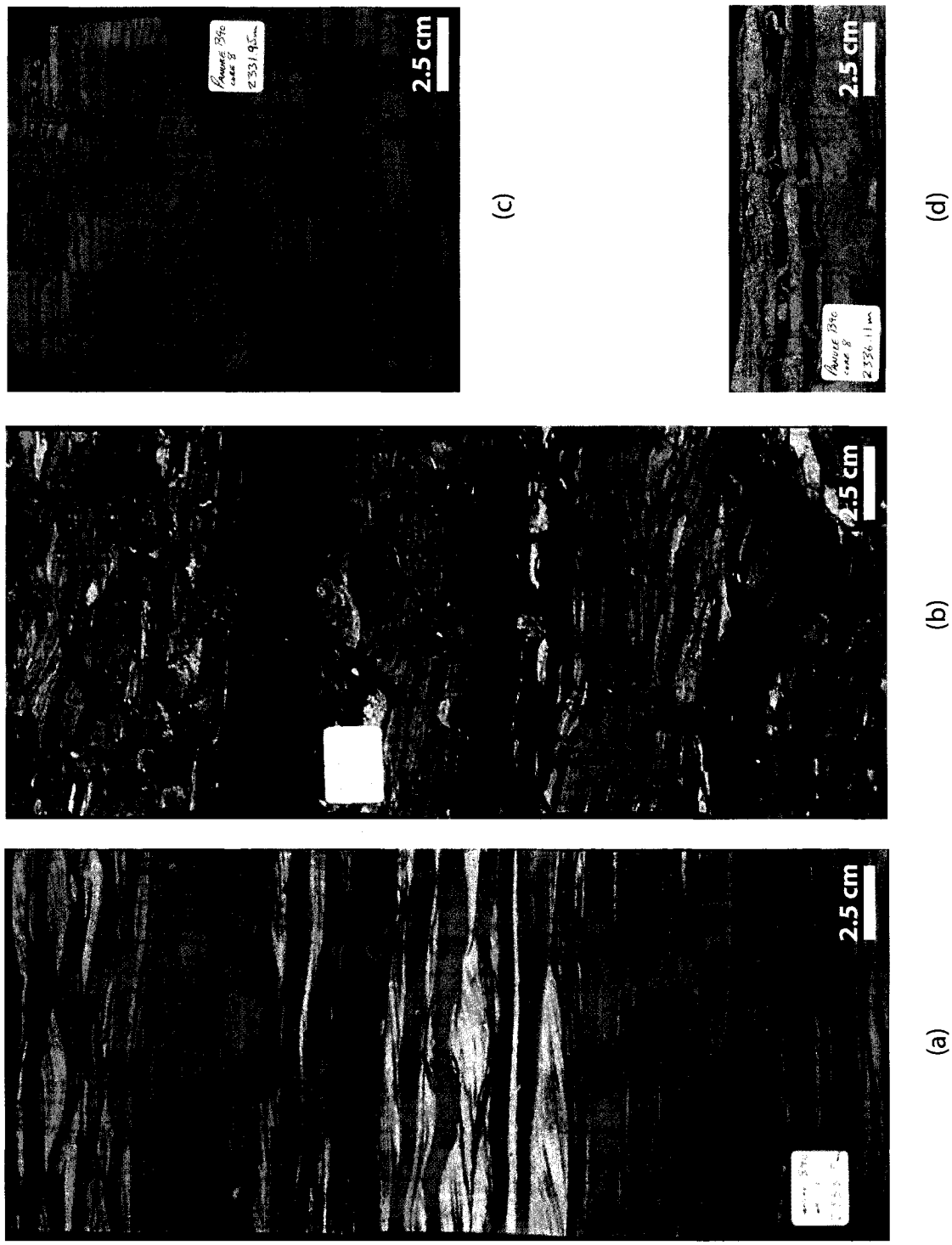
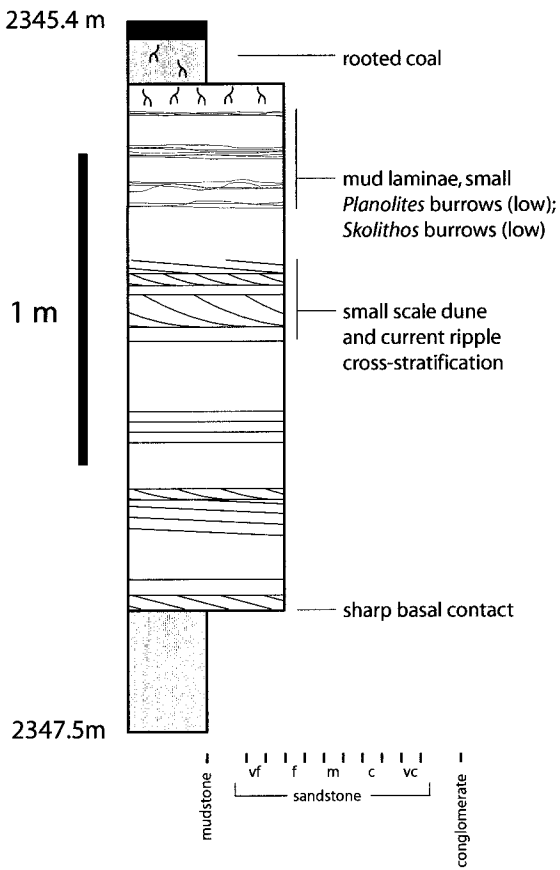

2.5 cm
(a)
2.5 cm
(b)
2.5 cm
(c)
2.5 cm
(d)

Figure 3.10 Facies 5 (interpretation – tidal channel deposits). (**a**) sharp-based Facies 5 unit with rooted top contact (Panuke B-90, core 9, boxes 5 to 3, 2347.5-2345.4 m (measured depth)), (**b**) unlined *Thalassinoides* burrows subtending from the basal contact of Facies 5 unit (Lawrence D-14, core 2, box 11, 2280 m (measured depth)).

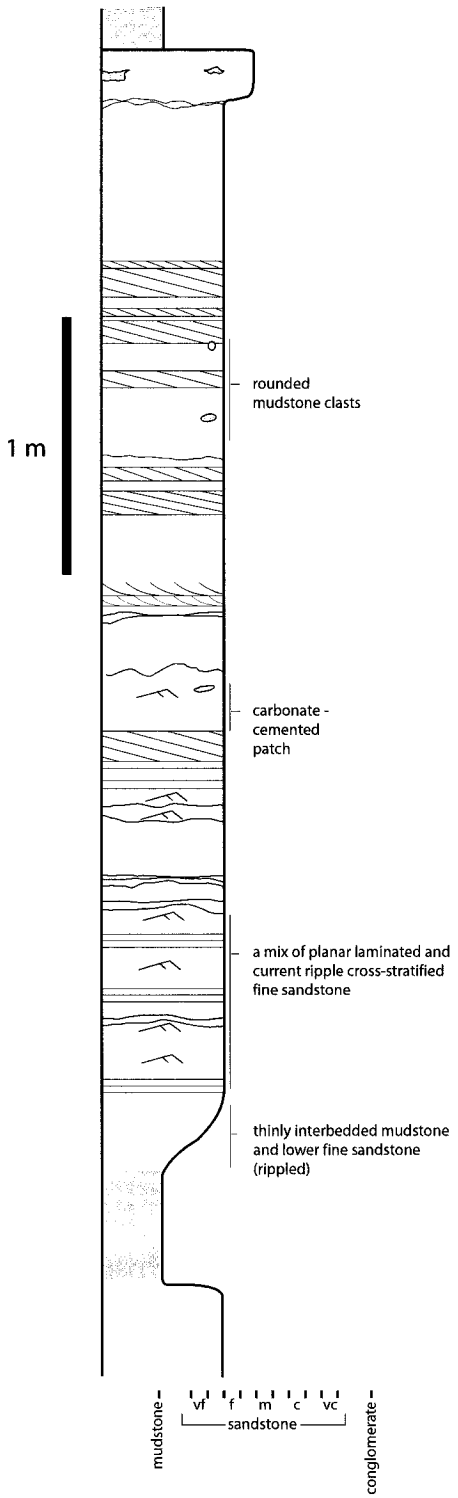

2345.4 m
rooted coal
mud laminae, small
Planolites burrows (low);
Skolithos burrows (low)
1 m
small scale dune
and current ripple
cross-stratification
sharp basal contact
2347.5m
mudstone
vf
f
m
c
vc
sandstone
conglomerate

(a)

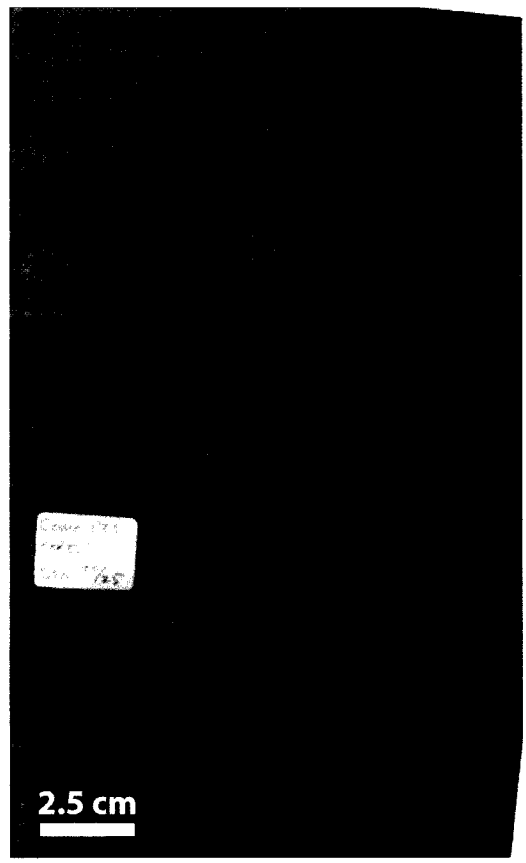

2.5 cm

(b)

Figure 3.11 Facies 6 (interpretation – bayhead delta deposit). (**a**) Gradationally based, coarsening-upward unit (Como P-21, core 1, boxes 25 to 18, 2205.75-2200.9 m (measured depth)), (**b**) dune cross-stratification, with rounded mudstone clast (Como P-21, core 1, box 20, 2202.3 m (measured depth)).


1 m
rounded mudstone clasts
carbonate - cemented patch
a mix of planar laminated and current ripple cross-stratified fine sandstone
thinly interbedded mudstone and lower fine sandstone (rippled)
mudstone
vf
f
m
c
vc
sandstone
conglomerate

(a)


2.5 cm

(b)

Figure 3.12 Facies 7 (interpretation – wave ravinement lag). (**a**) Thick-walled, robust *Ophiomorpha* burrow. Note ubiquitous white "paint-speckle" quartz sand grains and granules (Panuke F-99, core 2, box 15, 2294.25 m (measured depth)), (**b**) unlined *Thalassinoides* burrows subtending from the base of a Facies 7 bed (Panuke J-99 PP2, core 1, box 24, 2314.0 m (measured depth)), (**c**) sandstone pebbles (peb) and *Ophiomorpha* (Oph) burrows in Facies 7 (Panuke F-99, core 2, box 12, 2292 m (measured depth)).



(c)



(b)

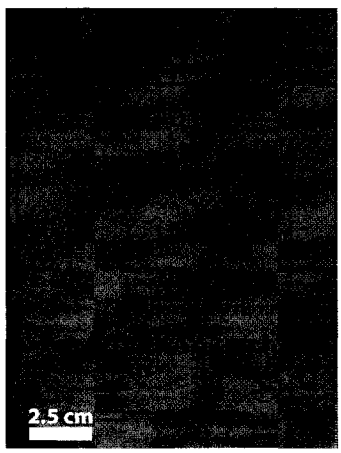


(a)

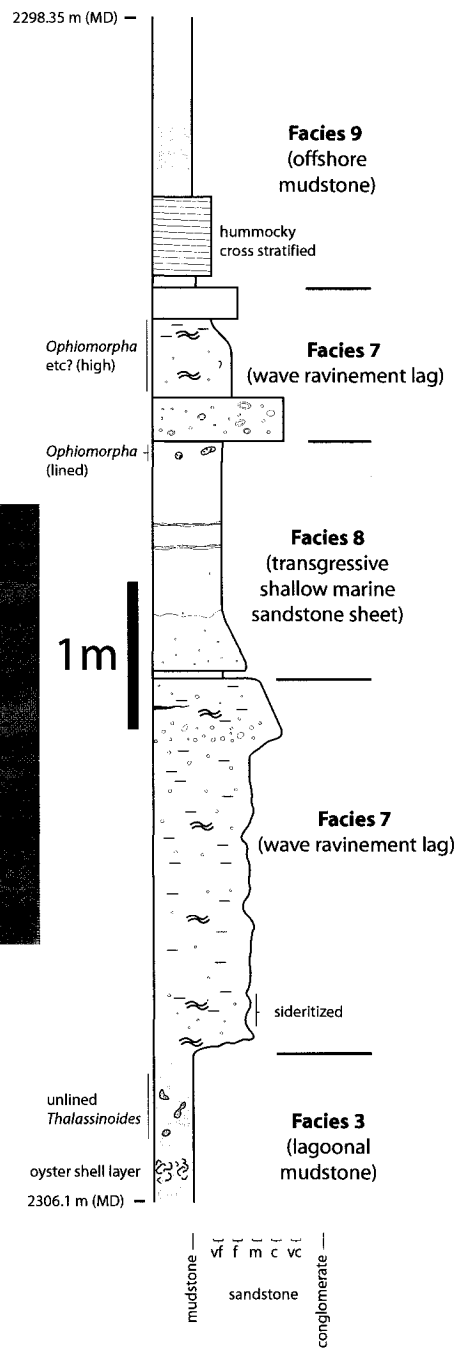
Figure 3.13 Facies 8 (interpretation – transgressively emplaced shallow-marine deposits). (**a**) Bioturbated sandstone (Panuke F-99, core 2, box 13, 2292.8 m (measured depth)), (**b**) *Cylindrichnus* (Cy) and *Ophiomorpha* (Oph) burrows (Panuke F-99, core 2, box 13, 2292.5 m (measured depth)) (**c**) graphic log showing stratigraphic position of Facies 8, P2 sandstone (Panuke J-99 PP2, core 1, boxes 12 to 2, 2306.1-2298.35 m (measured depth)).


2.5 cm

(a)


2.5 cm

(b)


2298.35 m (MD)
Facies 9
(offshore
mudstone)
hummocky
cross stratified
Ophiomorpha
etc? (high)
Facies 7
(wave ravinement lag)
Ophiomorpha
(lined)
Facies 8
(transgressive
shallow marine
sandstone sheet)
1m
Facies 7
(wave ravinement lag)
sideritized
unlined
Thalassinoides
Facies 3
(lagoonal
mudstone)
oyster shell layer
2306.1 m (MD)
mudstone
vf f m c vc
sandstone
conglomerate

(c)

Figure 3.14 Facies 10 (interpretation – storm-dominated lower shoreface deposits). Note low-angle truncation surface (arrow) with onlapping laminae whose dip shallows up core (interpretation – hummocky cross-stratification; Lawrence D-14, core 2, box 3, 2272.8 m (measured depth)).

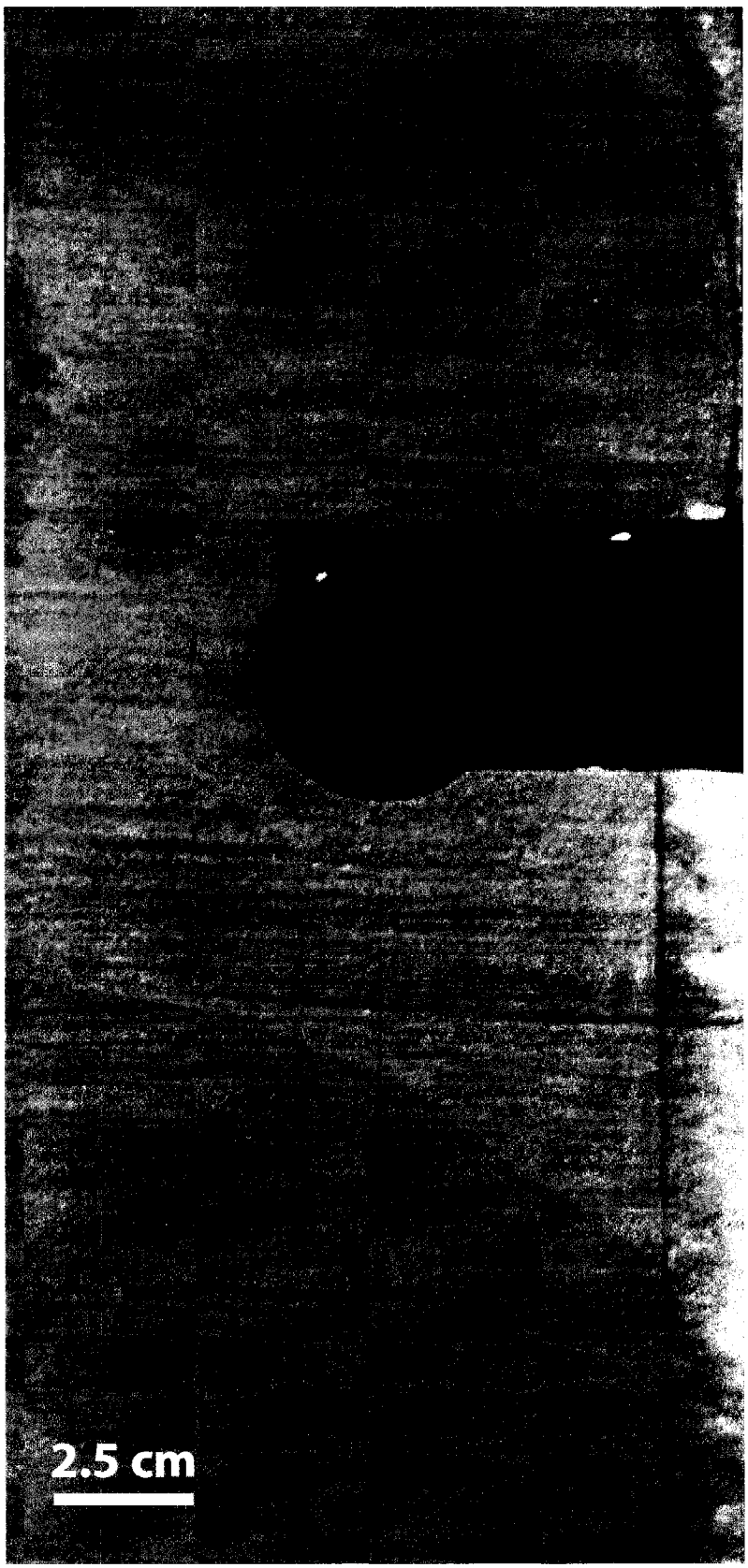

2.5 cm

Figure 3.15 Well log cross-sections (**a**) perpendicular and (**b**) parallel to interpreted paleoflow (paleoflow direction based on braid-bar orientation interpreted from 3-D seismic data). Shown also are synthetic traces generated from sonic logs used to tie well data to regional 2-D seismic data (note strong peak generated by the O Marker). See Figure 3.2 for cross-section locations.

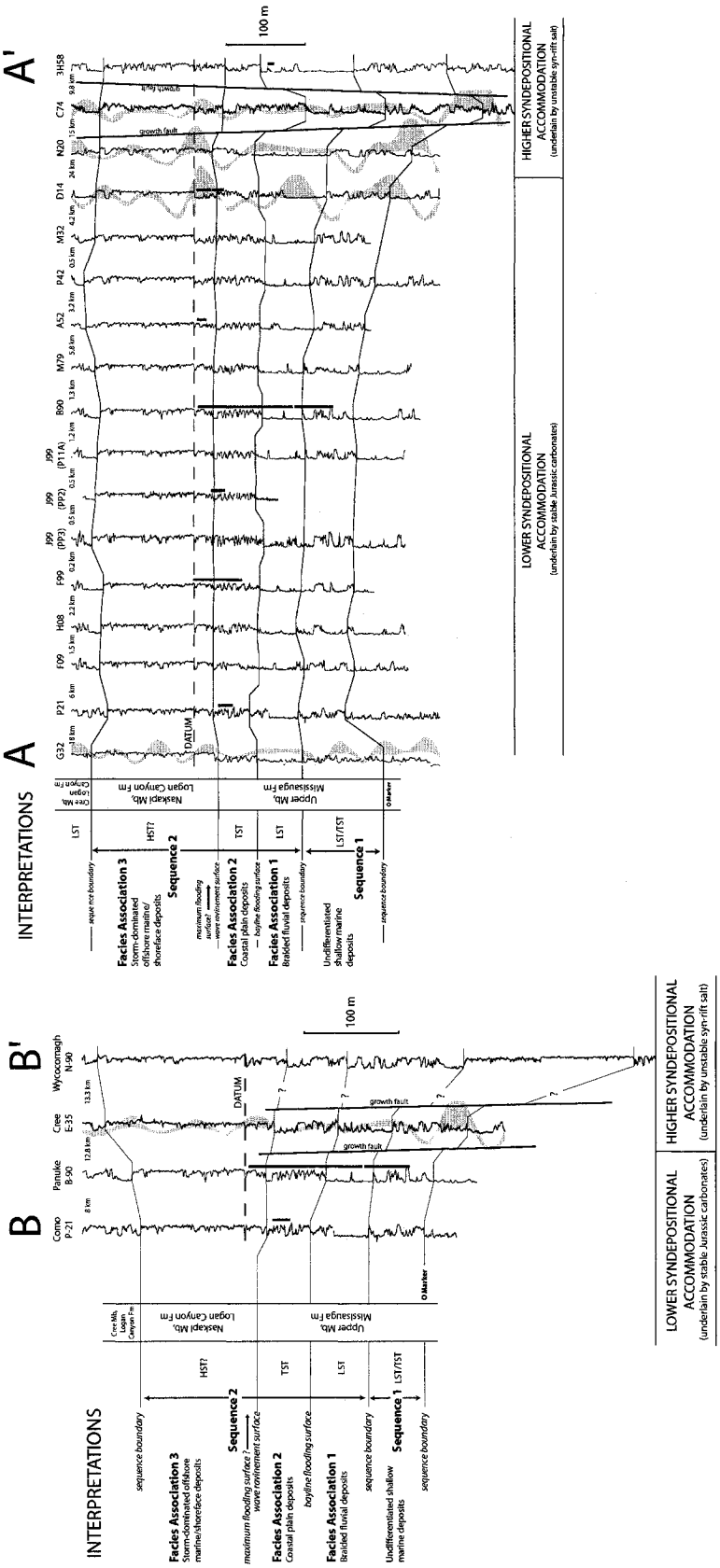

A
A'
INTERPRETATIONS
G32
P21
f09
H08
f99
J99 (PP3)
J99 (PP2)
J99 (P11A)
B90
M79
A52
P42
M32
D14
N20
C74
3H58
DATUM
100 m
growth fault
Oldman
Naskapi Mb, Logan Canyon Fm
Upper Mb, Missisauga Fm
LST
HST?
TST
LST/TST
Sequence 3
Sequence 2
Sequence 1
Facies Association 3
Storm-dominated offshore/ marine/shoreface deposits
Facies Association 2
Coastal plain deposits
Facies Association 1
Braided fluvial deposits
Undifferentiated shallow marine deposits
sequence boundary
maximum flooding surface ?
wave ravinement surface
baylline flooding surface
LOWER SYNDEPOSITIONAL ACCOMMODATION
(underlain by stable Jurassic carbonates)
HIGHER SYNDEPOSITIONAL ACCOMMODATION
(underlain by unstable syn-rift salt)
(a)
B
B'
Como P-21
Panuke B-90
Cree E-35
Wyccomagh N-90
DATUM
100 m
growth fault
?
INTERPRETATIONS
Naskapi Mb, Logan Canyon Fm
Upper Mb, Missisauga Fm
HST?
TST
LST
LST/TST
Sequence 2
Sequence 1
Facies Association 3
Storm-dominated offshore/ marine/shoreface deposits
Facies Association 2
Coastal plain deposits
Facies Association 1
Braided fluvial deposits
Undifferentiated shallow marine deposits
sequence boundary
maximum flooding surface ?
wave ravinement surface
baylline flooding surface
LOWER SYNDEPOSITIONAL ACCOMMODATION
(underlain by stable Jurassic carbonates)
HIGHER SYNDEPOSITIONAL ACCOMMODATION
(underlain by unstable syn-rift salt)
(b)

Figure 3.16a Facies associations and 3-D seismic geomorphology across the Upper Missisauga-Naskapi transition, Panuke Field. Two major (3^{rd}-order) sequences are interpreted to occur in between the O Marker and the base of the Cree Member in the western Sable Subbasin. Several higher-order sequences (4^{th}- and 5^{th}-order) are interpreted to be "nested" within these lower-order sequences (*e.g.*, candidate amalgamated sequence boundaries/ravinement surfaces at the base of the P2 and P3 sandstones).

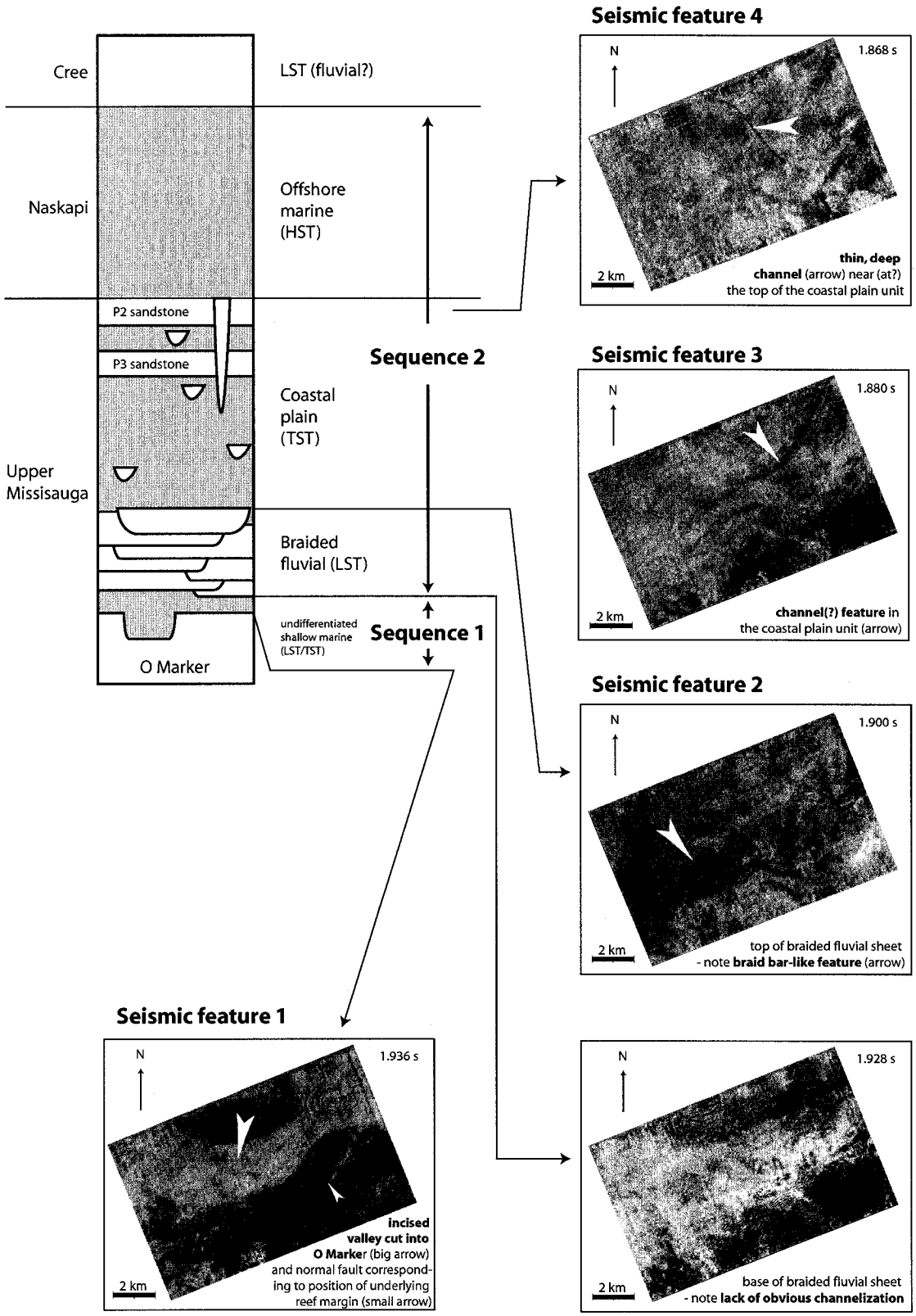

Cree
LST (fluvial?)
Naskapi
Offshore marine (HST)
P2 sandstone
P3 sandstone
Sequence 2
Coastal plain (TST)
Upper Missisauga
Braided fluvial (LST)
undifferentiated shallow marine (LST/TST)
Sequence 1
O Marker
Seismic feature 4
N
1.868 s
2 km
thin, deep channel (arrow) near (at?) the top of the coastal plain unit
Seismic feature 3
N
1.880 s
2 km
channel(?) feature in the coastal plain unit (arrow)
Seismic feature 2
N
1.900 s
2 km
top of braided fluvial sheet - note braid bar-like feature (arrow)
Seismic feature 1
N
1.936 s
2 km
incised valley cut into O Marker (big arrow) and normal fault corresponding to position of underlying reef margin (small arrow)
N
1.928 s
2 km
base of braided fluvial sheet - note lack of obvious channelization

Figure 3.16b Cross-sectional view of seismic features 1 and 3, Panuke Field. Red lines in the seismic data are troughs, blue lines are peaks. Seismic feature 1 is interpreted to be a fluvial channel eroded into the O Marker. Seismic feature 3 is a channel-like feature in coastal plain deposits (Facies Association 2) just below the Missisauga-Naskapi boundary.

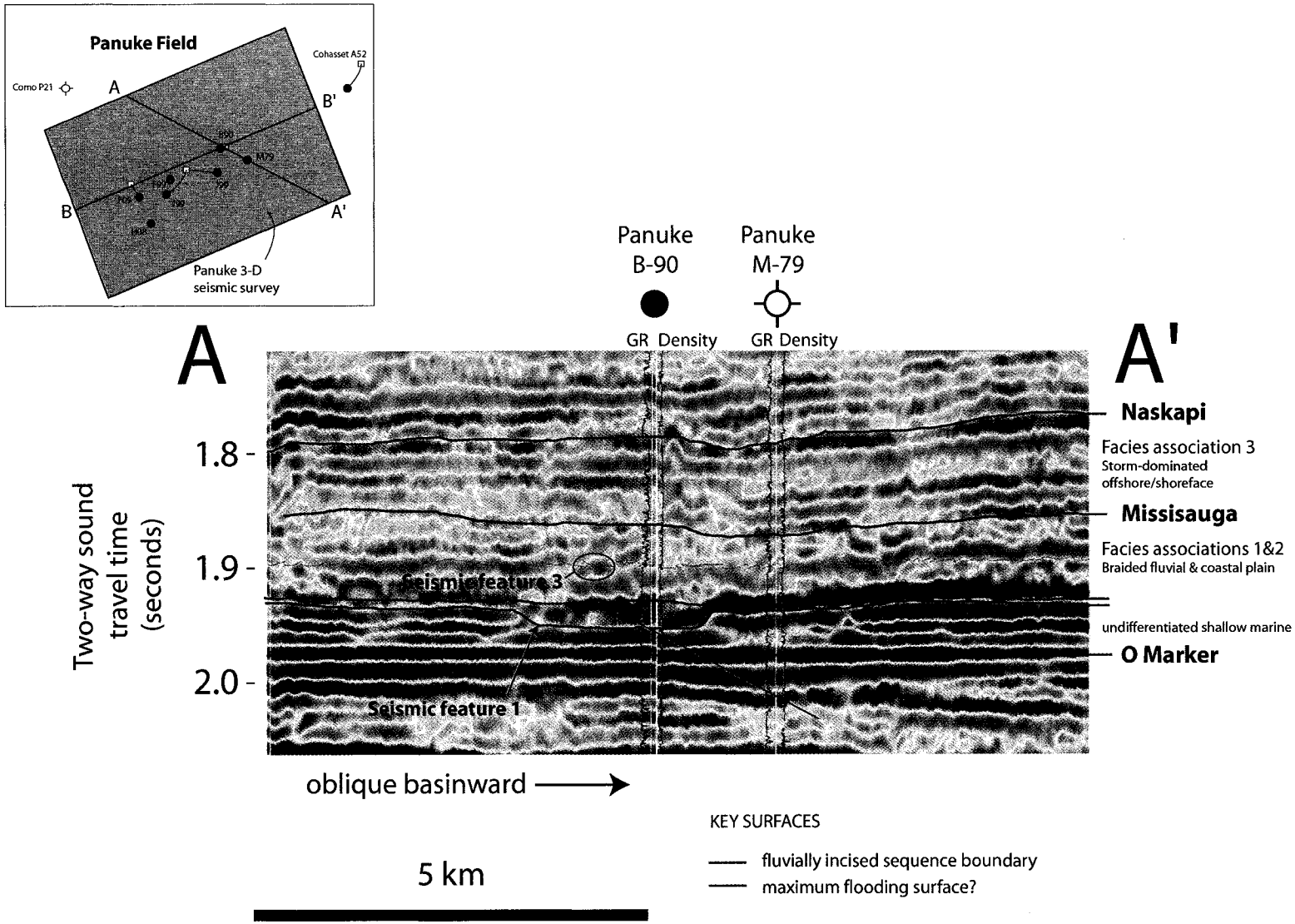

Panuke Field
Cohasset A52
Como P21
A
B'
B
A'
Panuke 3-D
seismic survey
Panuke
B-90
Panuke
M-79
GR Density
GR Density
A
A'
1.8 -
1.9 -
2.0 -
Two-way sound
travel time
(seconds)
Seismic feature 3
Seismic feature 1
Naskapi
Facies association 3
Storm-dominated
offshore/shoreface
Missisauga
Facies associations 1&2
Braided fluvial & coastal plain
undifferentiated shallow marine
O Marker
oblique basinward
5 km
KEY SURFACES
fluvially incised sequence boundary
maximum flooding surface?

Figure 3.16c Cross-sectional view of Seismic features 2 and 4, Panuke Field. Red lines in the seismic data are troughs, blue lines are peaks. Seismic feature 2, which is located near the top of the fluvial sandstone unit (Facies Association 1), is interpreted to be a braid-bar. Seismic feature 4 is interpreted to be a channel located very close to (at?) the top of the coastal plain unit (Facies Association 2).

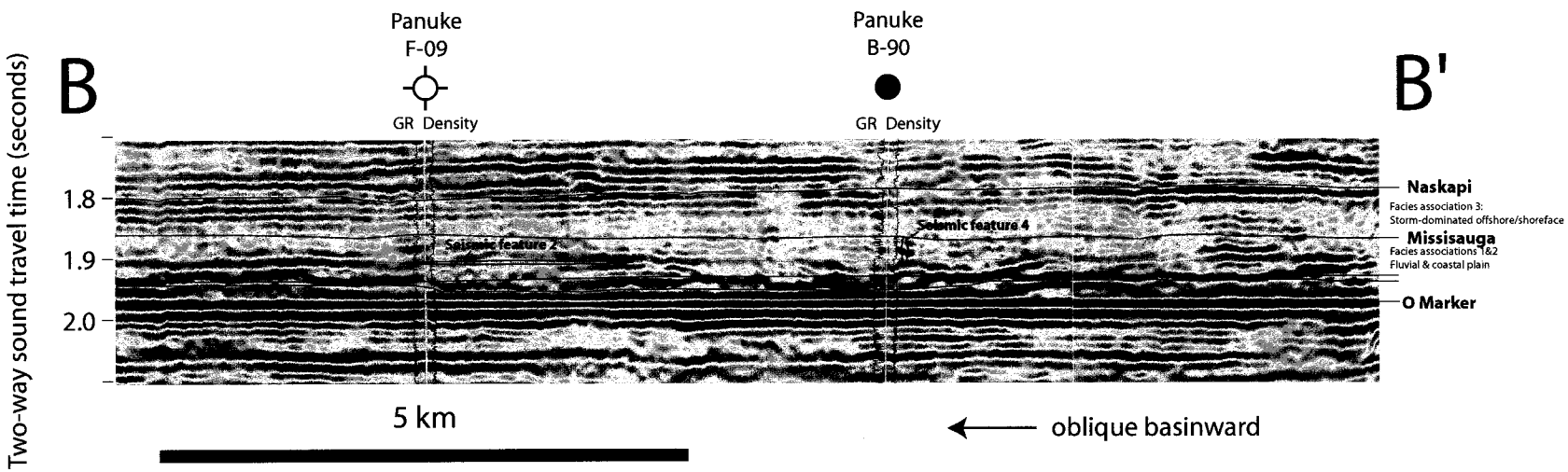

Panuke
F-09
Panuke
B-90
B
B'
GR Density
GR Density
Two-way sound travel time (seconds)
1.8
1.9
2.0
Seismic feature 2
Seismic feature 4
Naskapi
Facies association 3:
Storm-dominated offshore/shoreface
Missisauga
Facies associations 1&2
Fluvial & coastal plain
O Marker
5 km
oblique basinward
KEY SURFACES
fluvially incised sequence boundary
maximum flooding surface?
Panuke Field
Como P21
Cohasset A52
A
A'
B
B'
Panuke 3-D
seismic survey

Figure 3.17 Lower contact of Facies Association 1 (braided fluvial deposits), Panuke B-90 well. Note lack of underlying delta front deposits below the fluvial sandstone.

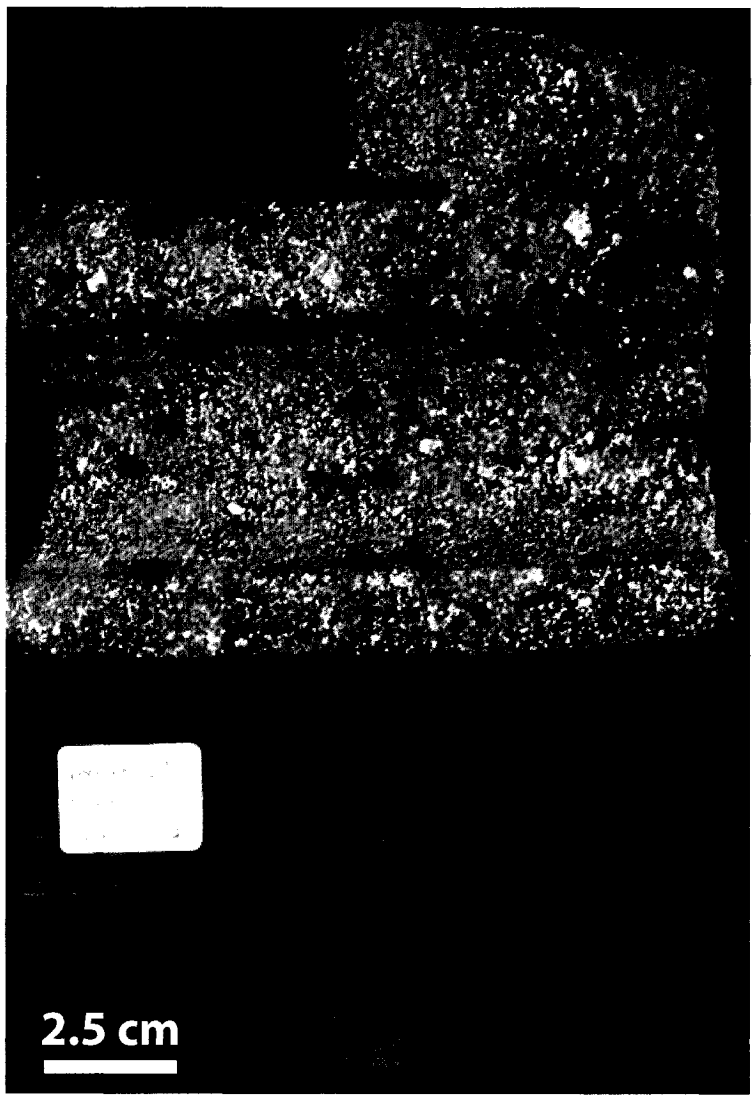
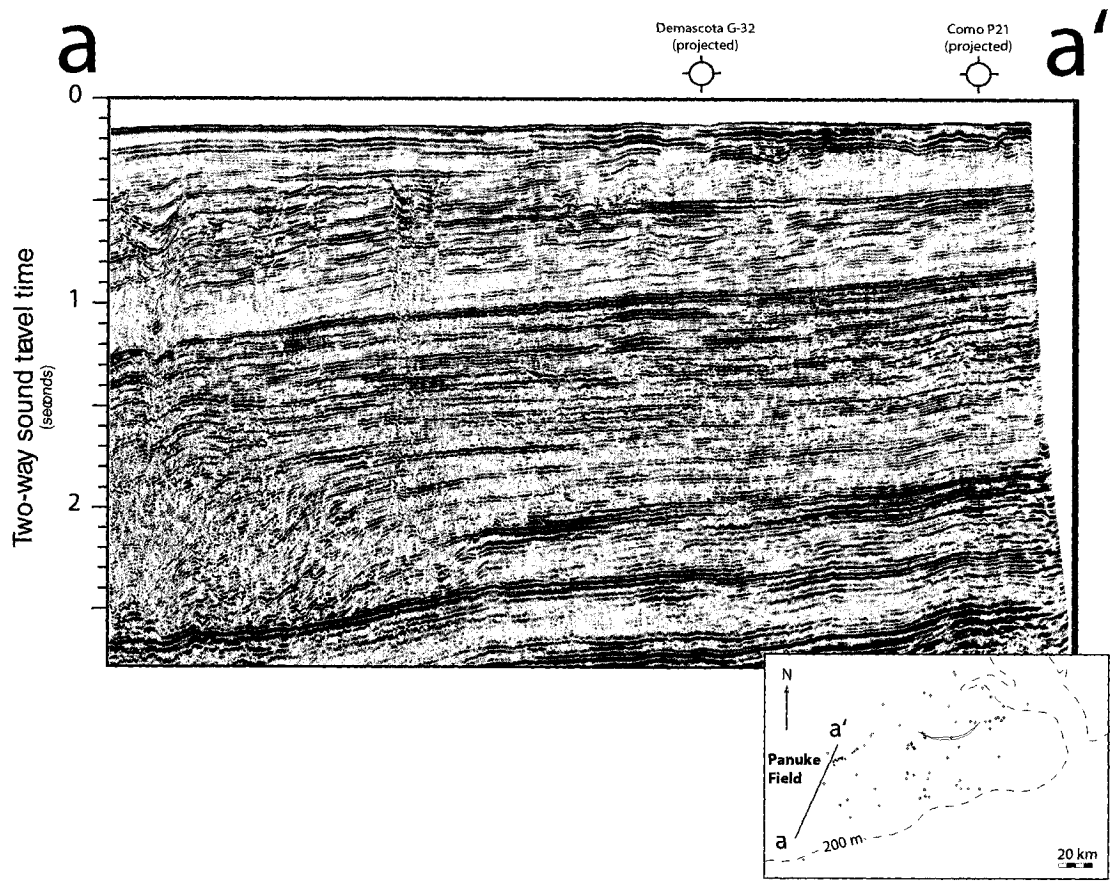

2.5 cm

Figure 3.18 Uninterpreted and interpreted dip-oriented seismic cross-section, western Sable Subbasin (GSI-GSI-PA99-110). Note the decrease of clinoform dip angle at the Upper Missisauga-Naskapi contact. Subsequently, however, clinoform dip increases above the Naskapi-Cree contact, and is interpreted to indicate renewed progradation of the shelf margin. Red lines in the seismic data are troughs, blue lines are peaks. Well logs were tied to the seismic data by stretching them linearly between reflections associated with the Wyandot and the O Marker. See Figure 3.2 for location of the 2-D seismic line.


a
a'
Demascota G-32
(projected)
Como P21
(projected)
0
1
2
Two-way sound tavel time
(seconds)
N
a'
Panuke
Field
a
200 m
20 km

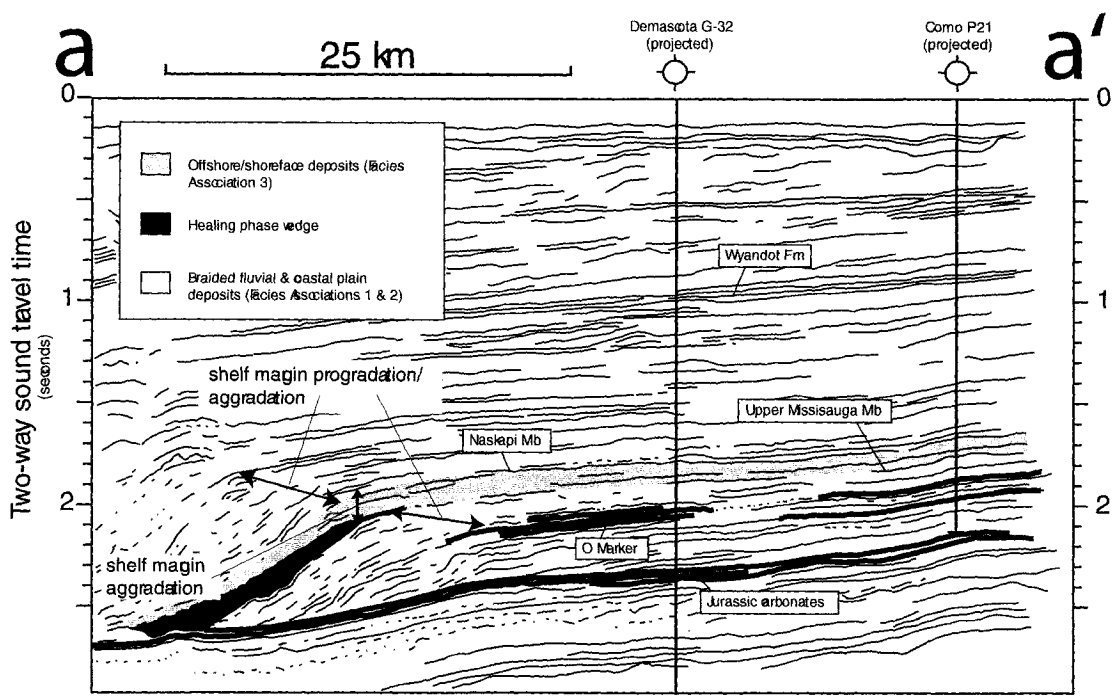

a
a'
25 km
Demascota G-32
(projected)
Como P21
(projected)
0
1
2
Two-way sound tavel time
(seconds)
Offshore/shoreface deposits (facies Association 3)
Healing phase wedge
Braided fluvial & coastal plain deposits (facies Associations 1 & 2)
Wyandot Fm
shelf magin progradation/
aggradation
Upper Missisauga Mb
Naskapi Mb
O Marker
shelf magin
aggradation
Jurassic carbonates

Figure 3.19 Uninterpreted and interpreted strike-oblique form line tracing of a seismic section, central Sable Subbasin (PRX-GSI-83-4481). Red lines in the seismic data are troughs, blue lines are peaks. Well logs were tied to the seismic data by stretching them linearly between reflections associated with the Wyandot and the O Marker. See Figure 3.2 for location of 2-D seismic line.

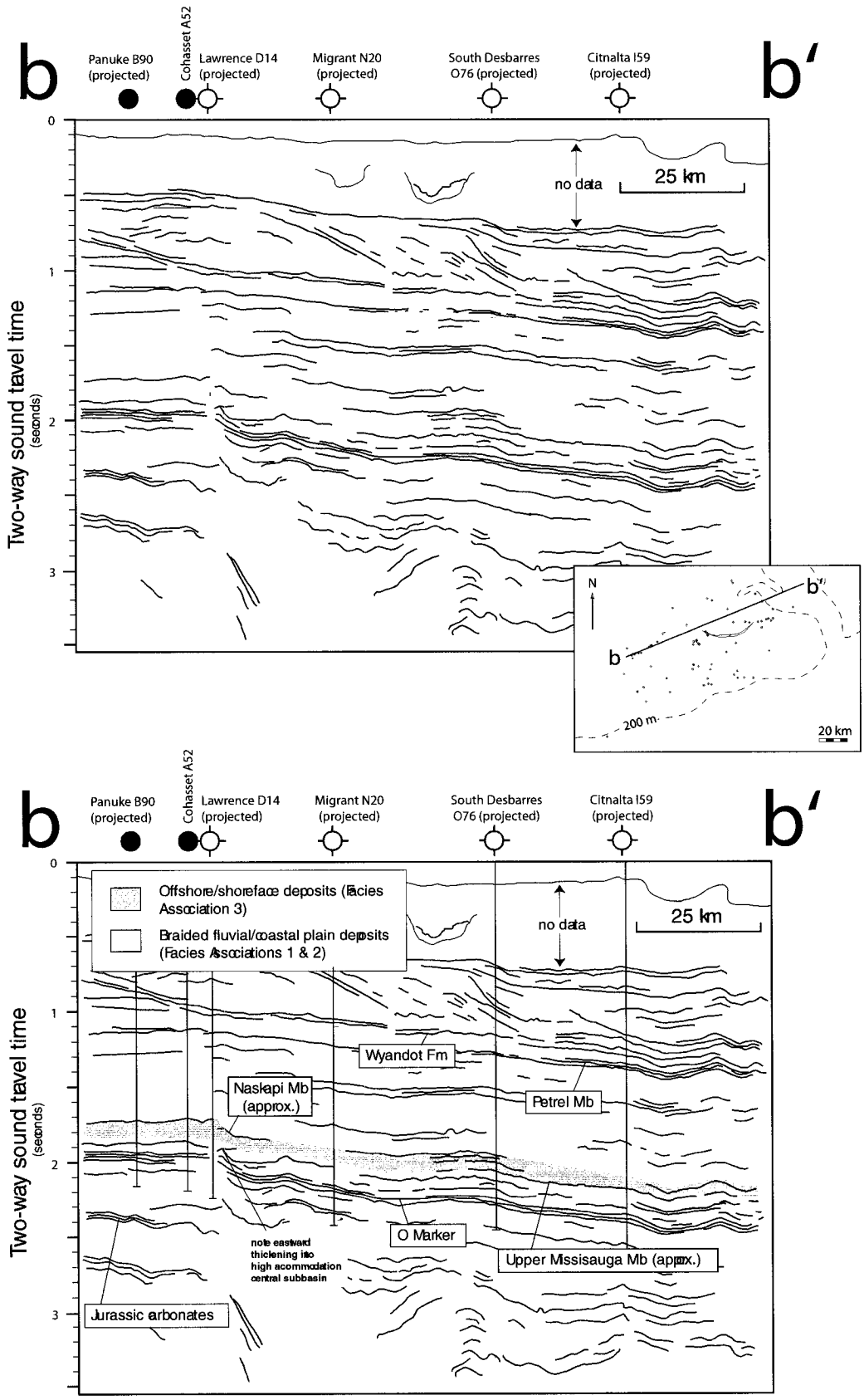

b
b′
Panuke B90 (projected)
Cohasset A52
Lawrence D14 (projected)
Migrant N20 (projected)
South Desbarres O76 (projected)
Citnalta I59 (projected)
Two-way sound travel time (seconds)
0
1
2
3
no data
25 km
N
b
b′
200 m
20 km
Offshore/shoreface deposits (facies Association 3)
Braided fluvial/coastal plain deposits (Facies Associations 1 & 2)
Wyandot Fm
Naskapi Mb (approx.)
Petrel Mb
O Marker
Upper Mississauga Mb (approx.)
Jurassic carbonates
note eastward thickening into high accommodation central subbasin

Figure 3.20 P2 and P3 sandstones, showing constituent facies, permeability variation, and sequence stratigraphic interpretation. Dashed lines along facies boundaries indicate gradational contacts; solid lines indicate sharp contacts. See text for facies details.

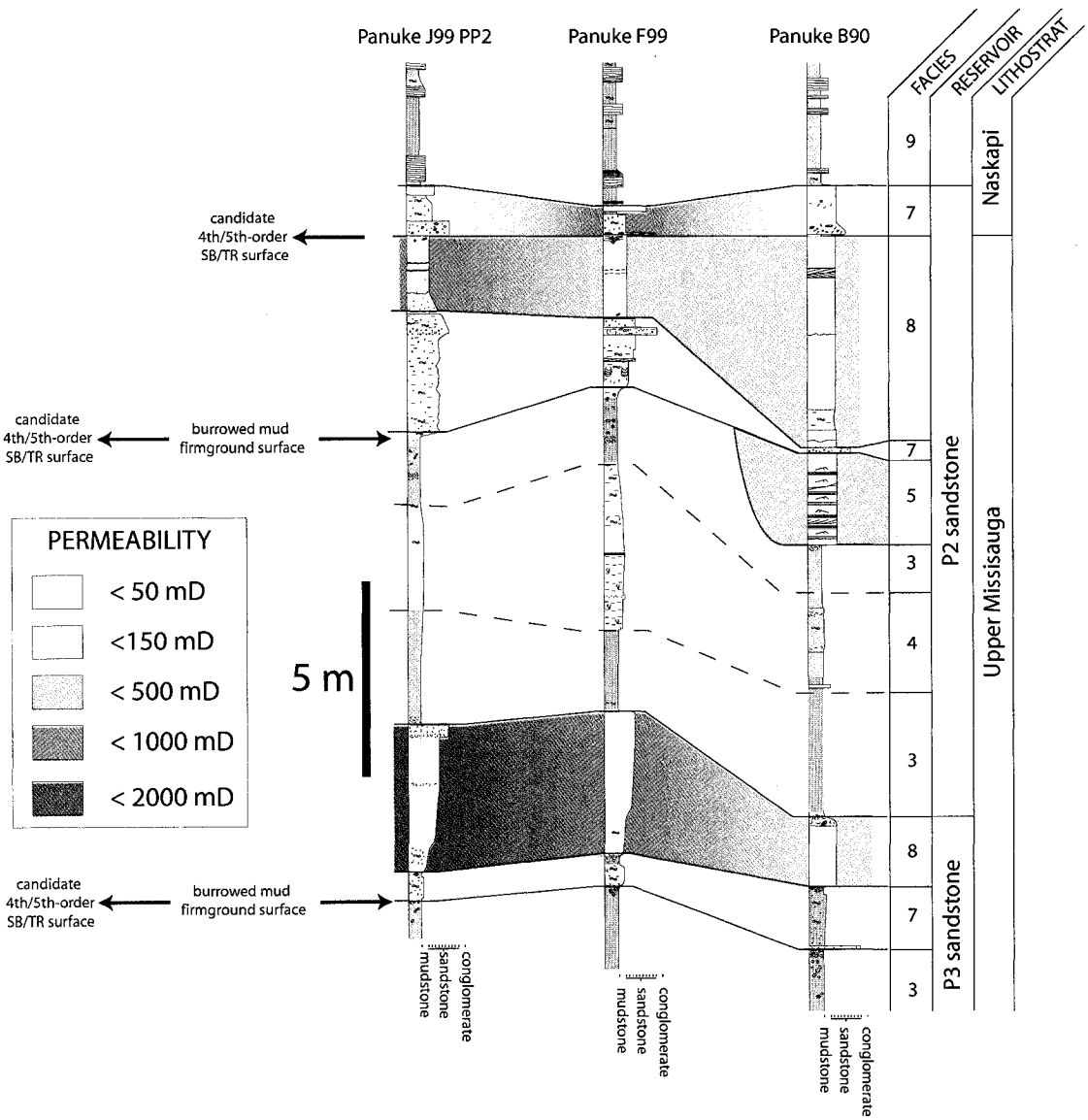
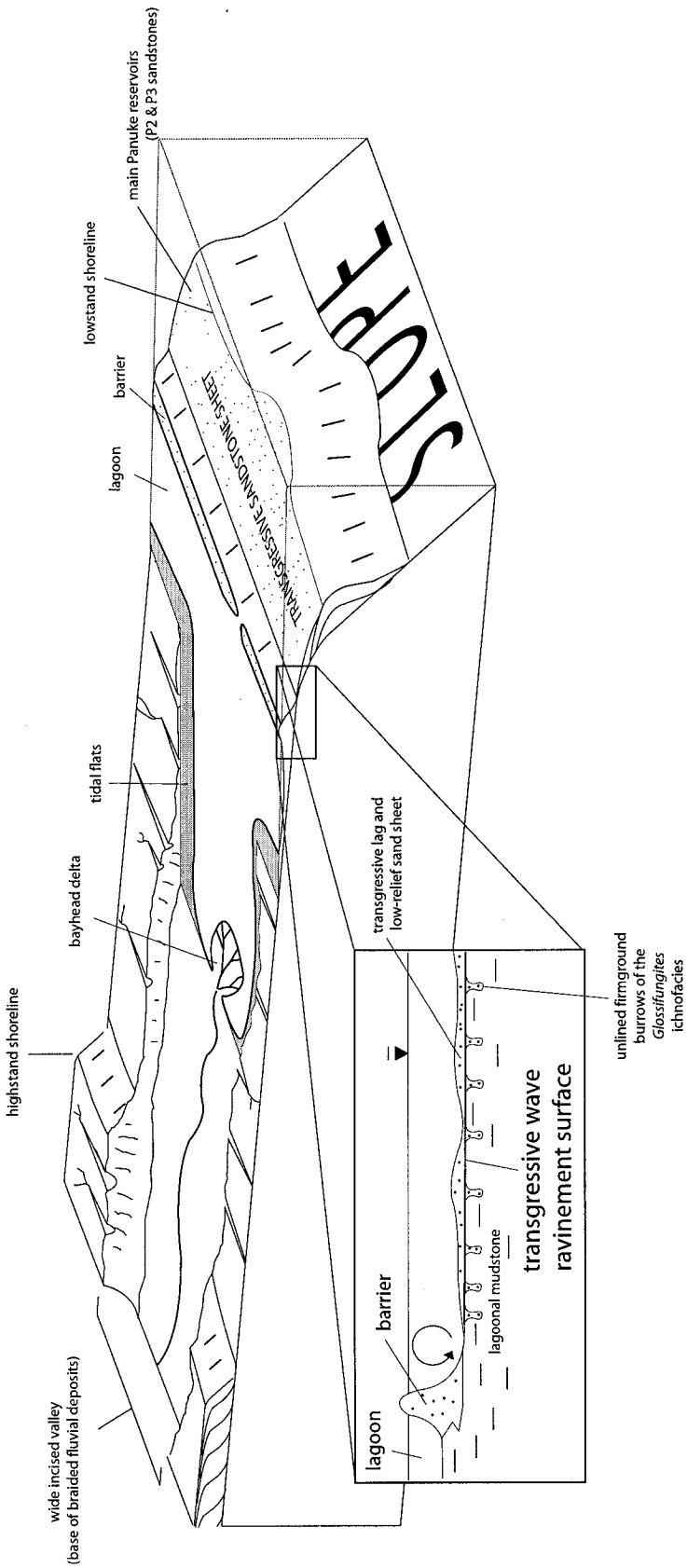

Panuke J99 PP2
Panuke F99
Panuke B90
FACIES
RESERVOIR
LITHOSTRAT
candidate 4th/5th-order SB/TR surface
candidate 4th/5th-order SB/TR surface
burrowed mud firmground surface
candidate 4th/5th-order SB/TR surface
burrowed mud firmground surface
PERMEABILITY
< 50 mD
<150 mD
< 500 mD
< 1000 mD
< 2000 mD
5 m
9
7
8
7
5
3
4
3
8
7
3
P2 sandstone
P3 sandstone
Naskapi
Upper Missisauga
conglomerate
sandstone
mudstone

Figure 3.21 General depositional model for hydrocarbon-bearing sheet-like sandstones near the top of the Upper Missisauga (*e.g.*, P2 sandstone), western Sable Subbasin.


SLOPE
TRANSGRESSIVE SANDSTONE SHEET
main Panuke reservoirs
(P2 & P3 sandstones)
lowstand shoreline
barrier
lagoon
tidal flats
bayhead delta
highstand shoreline
wide incised valley
(base of braided fluvial deposits)
transgressive lag and
low-relief sand sheet
unlined firmground
burrows of the
Glossifungites
ichnofacies
transgressive wave
ravinement surface
lagoon
barrier
lagoonal mudstone

Chapter 4. Abrupt wave-tidal facies transitions in the Missisauga Formation, Venture Field region, offshore Nova Scotia, Canada

4.1 Introduction

Deltas have long been recognized as sensitive to changes in relative sea-level (*e.g.*, Fisk 1944; Boyd *et al.*, 1992). In passive margin basins, for example, deltas are commonly observed to become increasingly wave-influenced during regression, and then switch to a tidally influenced state during transgression (*e.g.*, Fisher and McGowen, 1967; Ookmens, 1974; Demarest and Kraft, 1987; Morton and Suter, 1996; Suter, 2001). Theoretically, this happens because tidal prism volume and shelf width, and, accordingly, wave attenuation and tidal range, tend to decrease during regression and then increase during transgression, often in association with the transgressive drowning of tidally resonant incised river valleys (Yoshida *et al.*, 2003). This relationship, which forms one of the theoretical underpinnings of the incised valley facies model (*e.g.*, Dalrymple *et al.*, 1992; Zaitlin *et al.*, 1994), offers an elegant explanation for the erosive superposition of tide-influenced over wave-influenced deposits in the stratigraphic record (*e.g.*, Mellere and Steel 1995; Marjanac and Steel 1997; Willis, 2000; Martinius *et al.*, 2001).

However, it is theoretically possible to form abrupt wave-tidal transitions without regressive-to-transgressive shoreline turnaround (Figure 4.1; Table 4.1). For example, abrupt wave-tide transitions can form during normal regression of 'mixed energy' deltas, where tidally influenced deltaic distributaries prograde over and erode into wave-influenced delta front deposits (*e.g.*, Oomkens, 1974). Also, although seldom documented, abrupt wave-tidal transitions can theoretically be produced during falling

Table 4.1 Characteristics of different types of abrupt wave-tidal transitions

Process	Basal contact of tidally-influenced deposits	Geometry of contact	Associated pedogenesis	Architecture of tidally-influenced deposits	Evidence of marine influence in tidal deposits
Regressive-to-transgressive shoreline turnaround and incised valley fill[1,2,9]	sequence boundary	channel-form (incised valley); typically narrow (<10 km)[1] and relatively deep (max. ~100 m)[2]; tributaries are incised[10]	pedogenesis of interfluve surfaces likely, pedogenesis of valley floor may also occur[14]	back stepping (low fluvial input) to forward stepping (high fluvial input)[15]; restricted laterally by the incised valley	increases stratigraphically upward
"Mixed energy" delta progradation[11,12,13]	channel diastem	channel-form; channels likely to be shallower (usually <15 m?; max. ~30 m)[3] and narrower (<1 km?); also likely less extensive downdip due to autoretreat[6,7]	pedogensis of inter-channel surfaces possible, but soils likely less well developed	forward stepping; likely channel-form	decreases stratigraphically upward
Switch from wave- to tide-dominated sedimentation during regression due to heightened tidal resonance[5,8,9,11]	regressive tidal scour surface	less likely channel-form, more likely areally-extensive (up to 300 km wide?)[4,5]	no pedogensis of contact	forward stepping, possibly aggradational; restricted laterally by the resonant antecedent topographic depression	Decreases stratigraphically upward

1) Posamentier and Vail (1988), 2) Zaitlin *et al.*, (1994), 3) Best and Ashworth (1997), 4) Berné *et al.*, (2002), 5) Willis and Gabel (2001), 6) Muto and Steel (1992), 7) Swenson *et al.*, (2000), 8) Martinsen (2001), 9) Yoshida *et al.* (2003), 10) Posamentier (2000), 11) Ta *et al.*, (2002), 12) Galloway (1976), 13) Allen (1970), 14) Marjanac and Steel, 1997, 15) Dalrymple *et al.*, 1992

relative sea level when a wave-dominated shoreline is forced into a fetch-limited, tidally resonant topographic constriction (Willis and Gabel, 2001, 2003; Yoshida *et al.*, 2003). Because proper identification of the mechanism responsible for producing a given wave-tide transition can significantly shift the focus of a hydrocarbon exploration or development strategy, care must be taken and multiple criteria must be used in their interpretation (*e.g.*, Dalrymple *et al.*, 1994; Zaitlin *et al.*, 1994).

This paper describes several abrupt wave-tidal transitions in the Venture Field (Venture sandstones 8 to 5), offshore Nova Scotia, and interprets them to be incised

valleys formed on the outer shelf several kilometers updip of the shelf margin. The implications of the interpretations presented are discussed with respect to reservoir distribution on both a local and regional scale.

4.2 Geological setting and lithostratigraphy

The Venture Field is several kilometers east of Sable Island near the center of the Sable Subbasin, one of several interconnected Mesozoic-Cenozoic depocenters that make up the passive margin basin offshore Nova Scotia (Figures 4.2 and 4.3). During the Mesozoic, clastic sediments were likely fed into the subbasin by an ancestral St. Lawrence River, a large, continental-scale river system that drained much of eastern Canada (Wade and MacLean, 1990; Grist *et al.*, 1992). Sediment loaded underlying syn-rift salt and caused salt displacement and growth fault tectonism (Figure 4.3). At the time of deposition of the Venture sandstone reservoirs (Kimmeridgian to Berriasian-Valanginian), Nova Scotia was approximately 30°N of the equator (Irving *et al.*, 1993), the receiving basin (*i.e.,* the Atlantic Ocean) was ~1000 km wide (Ziegler, 1989), and climate was warm and temperate (Rees *et al.*, 2000).

The Venture sandstone reservoirs occur partly in the Lower Member of the Missisauga Formation and partly in the underlying Mic Mac Formation (Figure 4.4). Correlating the Missisauga/Mic Mac contact throughout the Sable Subbasin is problematic because the two units are lithologically similar and their contact has no distinctive regional marker bed or seismic reflection. Following MacLean and Wade (1993), therefore, the base of the Missisauga in the Venture Field is picked at a locally-prominant Kimmeridgian-aged limestone unit (the Venture limestone 9).

The Lower Missisauga shelf edge is interpreted to be situated just south of the Venture Field (Figure 4.5; *cf.* Figure 5.31 in Wade and MacLean, 1990). Seismic reflections in the Venture Field, the strongest of which are associated with limestone units, are parallel and roughly horizontal. When traced basinward to the south, these reflections downdrop across a series of growth faults and appear to correlate roughly to a package of large-scale (*i.e.,* >1 km relief) southward-dipping reflections located between 5 and 20 km south of the Venture Field. Although confident correlation of specific reflections across the growth faults is not possible, the relief and general stratigraphic and geographic position of the southward-dipping reflections suggests that they are Mic Mac and Lower Missisauga slope clinoforms (*cf.* Wade and MacLean, 1990).

4.3 Venture Field history and reservoir stratigraphy

The Venture Field contains an estimated 66 million cubic meters of original gas in place (Sable Offshore Energy, 1996), which is about 25% of the gas discovered to date offshore Nova Scotia (Canada Nova Scotia Offshore Petroleum Board, 2000). The discovery well, Venture D-23, was drilled in 1979 to test for hydrocarbons in a rollover anticline formed in the hanging wall of an east-west trending normal growth fault (Figure 4.5). Subsequently, five vertical delineation wells were drilled in the early 1980s, and four deviated development wells were drilled in the mid-1990s. A total of ten wells have now been drilled in the field.

In the Venture Field, gas is trapped in sandstone units within a succession of interstratified shale, sandstone, and limestone (Figure 4.4; Drummond, 1992). The upper two sandstone reservoirs, Venture sandstones 1 and 2, are hydropressured. Underlying

sandstones (below ~4.5 km) are overpressured and have anomalously high porosity, possibly because 1) early grain-coating chlorite inhibited silica cementation (Hutcheon, 1986), 2) increased pCO_2 from thermal cracking of kerogens promoted carbonate cement dissolution (Jansa and Norrega, 1990), and/or 3) rapid deposition that trapped and overpressured pore waters in underlying sediments (Mudford and Best, 1989). Venture sandstones 8 to 5, which form the focus of this paper, are estimated to contain 35.9 million cubic meters of gas, which is ~50% of the original in-place gas in the Venture Field (Sable Offshore Energy, 1996).

4.4 Dataset and methodology

This study integrates core (955 m), well log data (12 wells), palynological data, and 2-D seismic data (Figure 4.3). Cores were described in 2.5 cm detail, noting sedimentary textures, physical and biogenic sedimentary structures, macrofossils, and macroscopic diagenetic features. Core data were used to calibrate well logs, which were then tied to seismic data using synthetic traces generated from sonic logs. Lithostratigraphic and seismic stratigraphic picks used in this study are the same as MacLean and Wade (1993). Picks for the Venture reservoirs were taken from the Sable Offshore Energy Development Plan (Sable Offshore Energy, 1996). Because no paleoflow data are available for Venture sandstones 8 to 5, dip versus strike cross-sections are oriented by assuming shorelines trended parallel to and prograded toward the Lower Missisauga shelf margin (*i.e.,* progradation towards the south).

4.5 Facies

Nine facies were identified in core (Table 4.2). These are described below.

Facies 1: Carbonate mudstone

Facies 1 consists of dark to light blue-grey carbonate mudstone (Figure 4.6). Bedding surfaces are difficult to identify, and the facies is massive to faintly laminated with no discernable vertical grain size trends. No physical sedimentary structures were observed. In thin section, brachiopod, bryozoa, and foraminifera bioclasts were identified. No potential framework building organisms were observed. The basal contact of Facies 1 has not been cored, although gamma log signatures suggest that Facies 1 overlies Facies 2 mudstone.

Interpretation: Shelf carbonates

Based on the fine-grained texture, absence of potential framebuilding organisms, and brachiopod-bryozoan dominated faunal assemblage, Facies 1 is interpreted to have been deposited under normal marine conditions below storm wave base in a distal unrimmed shelf or upper slope environment. Similar carbonate facies commonly occur near the shelf edge of temperate, mid-latitude modern shelves (*e.g.*, Collins, 1988; James, 1997).

Table 4.2 Facies descriptions and interpretations, Venture and West Venture fields

Facies	Lithology									Lower Contact		Vertical textural change			Physical Sedimentary Structures					Detrital coal	Trace Fossils		Fossil dinoflagellates	Diagenetic Features		Porosity (%)	Permeability (milliDarcies)	Interpretation
	Carbonate mudstone	Mudstone	Very fine	Fine	Medium	Coarse	Very coarse	Pebble	Rooted coal	Sharp	Gradational	Upward-fining	Upward-coarsening	None	High-angle x-strat (<5 cm)	High-angle x-strat (>5 cm)	Low-angle (<10°) x-strat	Horizontal lamination	Soft sediment deformation		Diversity	Density		Pyrite framboids	Pervasive carbonate cement			
1	X										X ?			X				x					-			<10	<0.1	Shelf carbonates
2		X	x								X		X		x		X	X		x	X	x	X			<10	<0.1	Inner shelf/lower shoreface
3			X	X							X		X		x		X	X		x	X	x	-			<30	ave <1; max 175	Lower shoreface
4					X					X				X	X	X	X	x		x	x	x	-					Upper shoreface
5		X		x	X					X		X		X	X	X		x	x	X	x	x	x ?			<10	ave <0.1; max 3540	Tide-influenced fluvial
6		X	x	X	x					X	X			X	X			X		X	x	x	-			<10	<0.2	tidal flat
7				x	X	X						x		X		X		x		X			-			<30	ave ~300 ; max 5360	Fluvial
8		X							X					X				x						X		<10	<0.1	Marsh
9		x	x	x	x	x	X	x						X	x		x	x		X	X	X	-		X	<20	<43	Transgr-essive lag

X is more common than x

"-" = not analyzed

Facies 2: Mudstone with low-angle cross-stratified sandstone beds

Facies 2 consists of mudstone with rare to common thin (<10 cm) siltstone and very fine sandstone beds (Figure 4.7). Siltstone and sandstone beds are typically planar to low-angle (<10°) cross-stratified and unbioturbated (rare *Ophiomorpha*). Low-angle cross-strata are flat to gently curved (concave or convex). Rare, low-angle truncation surfaces are present within sandstone beds. Sandstone beds are commonly capped by one to several thin, scoop-based high-angle (>15°) cross-sets (<5 cm thick). Bioturbation in the mudstone ranges from none to intense, and includes *Planolites*, *Palaeophycus, Asterosoma, Helminthopsis, Chondrites, Zoophycos, Terebellina, Teichichnus,* and *Rosselia.* Although palynomorph preservation was generally poor, several specimens of a *Circulodium*-like dinoflagellate and one *Subtilisphaera*-like specimen were observed in one of two collected palynology samples (Rob Fensome, personal communication, 2002). Facies 2 sharply overlies Facies 9 or gradationally overlies Facies 1.

Interpretation: Storm-dominated inner shelf/lower shoreface deposits

Facies 2 is interpreted to have been deposited below fairweather wave base at the transition between the lower shoreface and continental shelf (*sensu* Cowell *et al.*, 1999). Low angle (<10°) cross-stratification in sandstone interbeds is interpreted to be hummocky cross-stratification formed under the influence of large, long-period storm waves (*cf.* Southard *et al.*, 1990; Arnott and Southard, 1990; Dumas, 2004). Because long-period waves require sufficient distance (fetch), depth, and travel time to form (Barnett and Wilkerson, 1967), the presence of hummocky cross-stratification suggests that Facies 3 was deposited in a large and unrestricted basin. Sandstone interbeds are

interpreted to have been deposited during major storms that eroded sand from the upper shoreface and deposited it farther offshore on the lower shoreface and inner shelf (*e.g.* Niederoda *et al.*, 1985; Inman *et al.*, 1993). Because waves are effective at suspending sediment but not at transporting it 'quickly' (Bagnold, 1963), a downslope 'excess-weight' gravitational force (*e.g.*, Bagnold, 1963; Wright, 1987; Myrow and Southard, 1996) and/or offshore-directed storm surge-generated downwelling flow (*e.g.*, Morton, 1981; Niederoda *et al.*, 1985) likely facilitated cross-shore sand transport from upper to lower shoreface and inner shelf.

Facies 3: Low-angle (<10°) cross-stratified sandstone

Facies 3 gradationally overlies Facies 2, and is composed of well-sorted, very fine to fine buff-coloured sandstone with rare mudstone interbeds (Figure 4.8). Sandstone beds are commonly amalgamated, forming bedsets several meters thick (Figure 4.8a). Facies 3 is horizontally laminated to low-angle (<10°) cross-stratified. Cross-strata are either flat or gently curved (either concave or convex; Figure 4.8b). Rare, concave low-angle truncations are onlapped asymptotically by laminae that decrease in dip upward (Figure 4.8b). Rarely, sandstone beds are normally graded (Figure 4.8b). Sandstone beds are typically unbioturbated, but local, rare to common *Ophiomorpha*, *Rosselia*, and *?Cylindrichnus* burrows were observed. Mudstone interbeds are sparsely bioturbated, but contain *Planolites*, *Teichichnus, Palaeophycus, Terebellina, Chondrites, Ophiomorpha, Cylindrichnus, ?Asterosoma,* and *?Rosselia* burrows.

Interpretation: Storm-dominated lower shoreface deposits

Facies 3 is also interpreted to have been deposited below fairweather wave base on the lower shoreface (lower shoreface *sensu* Cowell *et al.*, 1999). Like Facies 2, the high diversity trace fossil assemblage suggests deposition under fully marine conditions, and low-angle (<10°) cross-stratification is interpreted to be hummocky (and possibly swaley) cross-stratification formed under the influence of large, long-period swell and storm waves (Southard *et al.*, 1990; Arnott and Southard, 1990; Dumas, 2004). Small-scale, scoop-based, high-angle cross-sets are interpreted to be small-scale wave ripple structures (*e.g.*, Boersma, 1970; de Raaf *et al.*, 1977). In contrast to Facies 2, the general lack of mudstone in Facies 3 suggests deposition higher on the lower shoreface but still below the 'transition depth' (*sensu* Clifton, 1976), where episodic, high-energy storms eroded fairweather-deposited mudstone and caused amalgamation of hummocky cross-stratified sandstone beds.

Facies 4: Interbedded high angle (>15°) and low angle (<10°) cross-stratified sandstone

Facies 4 is composed of moderately to well-sorted medium sandstone (Figure 4.9). Beds are high-angle (>15°) to low-angle (<10°) cross-stratified, and are 1 to 25 cm thick. Commonly, beds are organized into stacked, sharp-based upward-fining units that are each on average ~1 m thick. The lower two-thirds of each unit is generally high-angle cross-stratified medium sandstone, which fines upward into low-angle cross-stratified fine sandstone with common concave, low-angle (<10°) truncation surfaces and sparsely disseminated organic flecks. In the lower two-thirds of the upward-fining units, significant variation in the orientation of high-angle cross-stratification is observed.

Facies 4 is typically unbioturbated, although rare *Ophiomorpha* burrows are present. Facies 4 sharply overlies Facies 3.

Interpretation: Upper shoreface deposits

The sharp-based, upward-fining nature of Facies 4 units with rare *Ophiomorpha* suggests deposition by channel cut-and-fill in a marine or marine-influenced environment. Channel-form features are common in wave-dominated coastal sedimentary environments, both associated with and behind the wave-built barrier (*e.g.*, tidal inlets, tidal creeks, deltaic distributaries, inter-bar channels in tidal estuaries *etc.*) and in the surf zone of the upper shoreface (*e.g.*, rip channels, longshore troughs). However, because the upward-fining units are mud-poor, thin (ave. ~1 m), and capped by low-angle cross-stratification interpreted to be wave-influenced, Facies 4 is interpreted to have formed by a channel cut-and-fill process within the upper shoreface (*e.g.*, Thornton *et al.*, 1998). This interpretation is based on previous work that suggests upper shoreface channel fills are likely to be less muddy, an order of magnitude shallower, and contain more wave-formed sedimentary structures (*e.g.*, Davidson-Arnott and Greenwood, 1976; Aagaard *et al.*, 1997; Thornton *et al.*, 1998; Short, 1999) with respect to barrier-associated and back-barrier channel fills (*e.g.*, Heron *et al.*, 1984; Vilas *et al.*, 1988; Dalrymple *et al.*, 1990; Gastaldo *et al.*, 1995; Baker *et al.*, 1995; Allison *et al.*, 2003; Dalrymple *et al.*, 2003).

Facies 5: Mudstone with high-angle (> 15°) cross-stratified sandstone interbeds

Facies 5 erosively overlies Facies 3, 4 or 6, and consists of mudstone with rare to common sandstone interbeds (Figure 4.10). Sandstone interbeds are fine to coarse grained, and are 10 to 75 cm thick. The ratio of sandstone interbeds to mudstone ranges from <10 to ~70%. Centimeter-scale load casts and synaeresis cracks are common at the bases of sandstone interbeds, and rarely sandstone occurs as isolated, internally-deformed balls in mudstone. Sandstone beds are either massive or composed of several stacked, high-angle (>15°) cross-sets that are on average ~10 cm thick to a maximum of ~40 cm thick. Subjacent cross-sets commonly dip in opposing directions and toesets are commonly highlighted by organic-rich mud. Double mud-drapes are present but rare. Pebble-sized coal fragments and disseminated organic flecks are common. Sandstone beds are typically unbioturbated, but rare intensely burrowed intervals of *?Taenidium* occur (Figure 4.10b), and rare *Ophiomorpha* and *Diplocraterion* burrows are observed locally.

Like the sandstone beds, mudstone beds are generally unbioturbated, although *Teichichnus*, *Thalassinoides*, *?Rhyzocorallium* and small *Planolites* burrows are rarely present in monospecific, low- to high-density assemblages. Sharp-based, sharp-topped 'pinstripe' sandstone laminae (<2 mm thick) are common within mudstone beds, and rarely, sandstone laminae grade rhythmically in and out of mudstone (Figure 4.10c). One possible marine element, possibly a fossil dynoflagellate, was identified in one of four mudstone samples collected for palynological analysis (Rob Fensome, personal communication, 2002).

On a larger-scale, Facies 5 is either organized into sharp-based units that fine-upward over several meters (maximum ~11 m), or shows no obvious upward grain size trend (Figure 4.10a). In the upward-fining units, cross-set thickness tends to decrease and intensity of bioturbation and mudstone content tends to increase upward. Mud intraclasts are common near the base of upward-fining units. Elongate *Diplocraterion* burrows up to 30 cm in length are rarely observed in the 'transition zone' between basal sandstone-rich and upper mudstone-rich portions of the upward-fining units.

Interpretation: Tide-influenced fluvial deposits

Facies 5 is interpreted to be a channelized deposit strongly influenced both by fluvial outflow and tidal currents. Abundant coaly carbonaceous debris suggests deposition close to a terrestrial organic source. High-angle (>15°) sandstone cross sets are interpreted to have been deposited by ripple and dune bedforms migrating and aggrading under unidirectional flow (*e.g.*, Allen, 1973; Leclair and Bridge, 2001). Rhythmic stratification, bipolar dune and ripple cross-stratification, and double mud-drapes suggest deposition in a tidally influenced environment (Nio and Yang, 1991). Furthermore, monospecific trace fossil assemblages, diminutive *Planolites* burrows, and general lack (but not complete absence) of fossil dinoflagellates suggest brackish water conditions (Pemberton *et al.*, 2002).

Sharp-based, upward-fining and thinning units indicate upward-decreasing depositional energy, and are interpreted to be channel fill deposits. Assuming that the upward-fining units and the dune cross-strata within them scale to channel flow depth (*e.g.*, Leclair and Bridge, 2001; Bridge and Tye, 2000), the channels were likely roughly

between 3 and 11 m deep. This suggests that deposition occurred in larger tidally- and fluvially-influenced coastal plain channels as opposed to small, shallow tidal-flat creeks (*e.g.*, Gastaldo, 1995; Dalrymple *et al.*, 2003). Given the abundance of thick mudstone beds (up to 70% of total thickness), some of which are interbedded with the coarsest sandstone at the base of upward-fining units, it is possible (likely?) that fluid muds, which can occur in turbid, high-energy, tidally dominated environments, may have resided alongside coarse sand patches at the base of channels (*e.g.*, Dalrymple *et al.*, 2003; Dalrymple and Choi, 2003). (Arguably, this facies could be referred to as fluvially-influenced tidal channel deposits.)

Facies 6: Mudstone with pinstripe to lenticular laminated sandstone

Facies 6 consists of mudstone with interlaminated fine to very fine sandstone (Figure 4.11). Sandstone laminae are common, and commonly reach equal abundance with mudstone. Sandstone laminae are either lenticular- (pod-shaped) or pinstripe-shaped (mm-thick, flat, and discontinuous across the core), are typically high-angle (>15°) cross-stratified, and either have flat or scoop-shaped bases. Rare medium sandstone beds (<25 cm) composed of high-angle cross-sets (1 to 10 cm thick) are observed. Mudstone is typically unbioturbated, although rare small *Planolites* are present. Synaeresis cracks are rare and small root traces were observed once.

Interpretation: Tidal flat deposits

Facies 6 is interpreted to be a tidal flat deposit. The combined presence of 1) a low-diversity trace fossil assemblage, 2) the mix of vertical and horizontal burrows (a

mixed *Cruziana/Skolithos* assemblage), 3) small burrow size, and 4) synaeresis cracks suggests that the environment was most likely brackish during deposition (Pemberton *et al.*, 2002; Plummer and Gostin, 1981). High-angle cross-stratified laminae with flat bases are interpreted to be current or current-dominated combined-flow ripples, whereas those with markedly scoop-shaped bases are interpreted to be small wave-ripples (Boersma, 1970; Harms *et al.*, 1975; de Raaf *et al.*, 1977). The heterolithic nature of Facies 6 indicates that episodes of suspension deposition (mud) alternated with sand bedload transport by small waves and weak unidirectional flows, which are conditions consistent with tidal flat sedimentation (Postma, 1961; Reineck and Wunderlich, 1968; Amos and Collins, 1978; Dingler and Clifton, 1984). Furthermore, lenticular- and pinstripe-shaped sandstone laminae, although not unique to tidal flats (*e.g.,* Coleman and Gagliano, 1965), are nevertheless very common in tidal flat deposits (Reineck and Wunderlich, 1968; Weimer *et al.*, 1982; Ginsburg, 1975; Klein, 1976; Amos, 1995; Gingras *et al.*, 1999).

Facies 7: High angle (>15^{o}) cross-stratified sandstone

Facies 7 is composed of well-sorted coarse to medium sandstone (Figure 4.12). Oil staining is common. Strata of Facies 7 have excellent reservoir quality, with permeabilities on average between 100 to 700 milliDarcies and local maxima of >3 Darcies. Stratification is visible only where mudstone forms thin veneers on bedding surfaces and cross-strata. Beds are typically high-angle (>15^{o}) cross-stratified, and are a maximum 1 m thick. Pore-filling carbonate cement and pebble-sized coal fragments are

present locally. No trace fossils were observed. Beds are organized into ungraded units that are up to 6.5 m thick. Facies 7 erosively overlies Facies 5.

Interpretation: Fluvial deposits

Facies 7 is interpreted to be a fluvial channel fill deposit. The presence of coal suggests deposition in proximity to a terrestrial organic source, and the absence of trace fossils suggests that the environment was ecologically stressed. High-angle cross-stratification likely formed by the downstream migration and aggradation of dunes under unidirectional flow (Southard and Boguchwal, 1990; Leclair and Bridge, 2001).

Facies 8: Coal and pyrite-rich black mudstone

Facies 8 is composed of massive black mudstone (<50 cm thick) with small (<0.25 cm), roughly circular pyrite 'blebs' (Figure 4.13). Organic partings (1-2 mm) are common. The mudstone typically overlies a thin (<5 cm) rooted coal. Thin roots (~1 mm thick) extend down 25 cm below the coal. The rooted zone commonly has a rusty yellowish orange colour. Facies 8 overlies Facies 4 or 7.

Interpretation: Marsh deposits

Pyrite in Facies 8 suggests that the depositional environment was most probably marine-influenced. SO_4^{2-}, which is required to form early diagenetic pyrite, is typically abundant in the pore-waters of surficial sediments in marine environments but scarce in non-marine environments (Berner, 1970). Superposition of the pyrite-rich mudstone overtop of thin rooted coal suggests that the facies formed in conjunction with flooding of

a subareally exposed paleosol surface. As such, Facies 8 was likely deposited in a low-lying, vegetated region of the coastal plain that became progressively inundated by brackish or normal marine water (*e.g.*, Frey and Basan, 1978; Bohacs and Suter, 1997).

Facies 9: Poorly sorted sandstone

Facies 9 consists of poorly sorted, muddy fine to medium sandstone (Figure 4.14). Sandstone pebbles are common, as are dispersed white quartz sand grains and granules ('paint-speckles'). Facies 9 almost always reacts strongly with 10% hydrochloric acid. Pebble-size coal fragments, coal flakes, and mm-thick coal partings are common. Bioturbation is typically intense, and burrows are commonly thick walled and robust. The trace fossil assemblage is dominated by *Ophiomorpha* burrows, with less common *Chondrites*, *Skolithos*, *Palaeophycus*, *?Teichichnus*, and *?Rosselia/Cylindrichnus*. Facies 9 erosively overlies either Facies 8, 7, or 5.

Interpretation: Wave-ravinement lag

Facies 9 is interpreted to have formed by wave reworking of the shallow seafloor during rising relative sea level and shoreface retreat (*e.g.*, Fischer, 1961; Demarest and Kraft, 1987; Bhattacharya, 1993; Abbott, 1998; Snedden and Dalrymple, 1999; Rodriguez *et al.*, 2001; Hwang and Heller, 2002; Cattaneo and Steel, 2002). Robust, thick walled burrows of the *Skolithos* ichnofacies suggest deposition in open marine conditions (*e.g.* Pemberton *et al.*, 2002). Sandstone pebbles were likely eroded from underlying cemented sandstone units during transgressive ravinement (*e.g.*, Cleary *et al.*, 1996; Taylor and Gawthorpe, 2001).

4.6 Facies associations and stratal architecture

Two facies associations were identified in the stratigraphic interval studied (Table 4.3; Figures 4.15a and 4.15b): Facies Association 1, which is interpreted to have been deposited in a storm-dominated shallow marine environment, and Facies Association 2, which is interpreted to have been deposited in a tidally-dominated coastal plain environment.

Facies Association 1 forms upward-coarsening, sheet-like units (20-60 m) that pass gradationally upward from shelf mudstone (Facies 2) to shoreface sandstone (Facies 3 and 4). Thin (<10 cm) rooted coals and pyrite-rich mudstone (Facies 8) occur locally at the top of shoreface deposits. Tabular units of shelf carbonate (Facies 1; 30-40 m thick) rarely gradationally underlie the upward-coarsening units (*e.g.*, Venture limestone 9). Low-relief, areally-extensive erosion surfaces cap the upward-coarsening units; these are overlain by 1 to 2 meters of transgressive lag (Facies 9).

Table 4.3 Facies associations, Venture and West Venture fields

Facies Association	**Constituent facies**	**Nature of lower contact**	**Vertical textural change**	**Geometry parallel to depositional strike in Venture field**	**Geometry parallel to depositional dip in Venture field**
Facies Association 1: Storm-dominated shallow marine deposits	1,2,3,4,8	Trans-gressive wave ravinement surfaces	upward-coarsening	sheet-like; thickens towards Venture B-52	sheet-like; thicken northward into master growth fault
Facies Association 2: Coastal and alluvial plain deposits	5,6,7	Sequence boundaries	either upward-coarsening or upward-fining	channel form; channels 'hang' from Facies Association 1 'sheets'	?...not enough well data

Strata of Facies Association 2 fill channels eroded into Facies Association 1 sandstone. Channels are 10-25 m thick and 7-13 km wide, and have multi-storied fills (usually at least 3 stories) that either consist of tidally-influenced fluvial and tidal flat deposits, or coarsen-upward from tidally-influenced fluvial (Facies 5) to continental fluvial sandstone (Facies 7). Locally, fluvial strata are overlain by thin (<10 cm) rooted coal and pyrite-rich mudstone (Facies 8). The top of each multi-storied Facies Association 2 channel fill is truncated by an erosion surface overlain by <2 meters of transgressive lag. The erosion surfaces correlate laterally to the low-relief, areally extensive erosion surfaces that cap the upward-coarsening units of Facies Association 1 (Figure 4.15a).

Parallel to depositional strike, all of the Venture sandstones studied thicken into a growth-faulted area located between the Venture and West Venture Fields (Figure 4.15a). Facies Association 2 channel fills consistently occur in this area. In dip cross section, Venture sandstones 8 to 5 thicken northward into the master growth fault within the Venture Field (Figure 15b). (Because of limited well control within the Venture Field (*e.g.*, Figure 4.15b), this thickening trend is best imaged on 2-D seismic dip lines (*e.g.*, Figure 4.5)). Correlation updip across growth faults to the Arcadia J-16 suggests that Venture sandstones 8 to 5 thin significantly in a proximal direction, and, with the exception of Venture sandstone 6m, pinch out downdip into mudstone when correlated across a growth fault to South Venture O-59 (Figure 4.15b). In contrast, the upward-coarsening Venture sandstone 6m thickens significantly across a growth fault from ~60 m in the Venture Field to ~250 m at South Venture O-59 (Figure 4.15b).

4.7 Depositional model

Each of the abrupt wave-tidal transitions at Venture is interpreted to have formed during a single cycle of relative sea level fall and rise (Figure 4.16). During relative sea level rise, shelf starvation occurred and condensed sections formed. Condensed sections are expressed either as shelf carbonate units (up to 40 m thick – Venture limestone 9) or as cryptic condensed sections within shelf mudstone, at the center of which occur maximum flooding surfaces. During subsequent highstand and falling relative sea level storm-wave dominated shorelines migrated towards the shelf edge, forming upward-coarsening shallow marine successions (Facies Association 1). Incision of any detached forced-regressive shelf-phase deltaic wedges located updip of the shelf margin would have occurred during this time. During the late falling stage and early lowstand, relative sea level likely dropped below the shelf edge, which completed the valley incision process (*e.g.*, Butcher, 1989; Leeder and Stewart, 1996). As relative sea level started to rise, accommodation space was generated in coastal plain regions, and topsets began to onlap the sequence boundary (*i.e.*, the base of the incised valley and any associated interfluve paleosols – which were not observed, likely due to transgressive erosion). Because of their elongate geometry, incised valleys are inferred to have become tidally resonant as they were inundated, which led to the suppression of wave-formed estuary mouth barriers and development of tide-dominated estuaries. When fluvial sediment supply increased during valley infilling, valleys were infilled progradationally (*e.g.*, Venture sandstones 8 and 7), whereas valleys were infilled retrogradationally when fluvial sediment supply remained constant (*e.g.*, Venture sandstone 6m). As the valleys infilled, heightened frictional resistance caused tidal currents to diminish, which allowed

waves to progressively control estuarine geomorphology. This culminated in wave-dominated shoreface retreat over the filled incised valleys, which formed erosion surfaces capped by 1 to 2 m of transgressive lag that locally contains hummocky cross-stratification.

Two of the Venture sandstones studied (6l and 6u sandstones) are of note because they lack abrupt wave-tide transitions, but instead are composed of storm-wave dominated shoreface deposits (Figure 4.15a and 4.15b). Venture sandstone 6l consists of lower shoreface sandstone (Facies 3) that gradationally overlies offshore mudstone (Facies 2). Given the absence of an associated overlying incised valley, it is unclear whether Venture 6l formed by forced regression (*i.e.*, it is overlain by a sequence boundary) or by normal regression during lowstand (*i.e.*, it onlaps a sequence boundary; see Plint and Nummedal, 2000). Venture sandstone 6u also lacks an incised valley fill, but in contrast to sandstone 6l, abruptly overlies a transgressive wave ravinement surface and fines upwards from upper and lower shoreface sandstone into offshore mudstone. As such, Venture sandstone 6u is interpreted to be a shallow marine sandstone body formed in association with transgressive wave ravinement and shoreface retreat (*e.g.*, Snedden and Dalrymple, 1999).

4.8 Discussion

As argued previously, 2-D seismic data suggest that the stratigraphic interval investigated was deposited 5 to 20 kilometers updip of the shelf break (Figure 4.5). Supporting this interpretation is the significant stratigraphic variation observed when Venture sandstones 8 to 5 are correlated to the only well located downdip of the Venture

Field, South Venture O-59. In the Venture Field, upward-coarsening successions are between 20-60 m thick, but when correlated to South Venture O-59, either grade basinward into mudstone (Venture sandstones 8 and 7) or thicken significantly to ~250 m (Venture sandstone 6m; Figure 4.15b). Because shelf edge deltas are commonly several times thicker than their shelf-phase counterparts (*e.g.*, Winn *et al.*, 1998; Porebski and Steel, 2003; Sydow *et al.*, 2003), the thicker (~250 m) upward-coarsening succession observed in South Venture O-59 likely formed by progradation of a delta across the shelf edge and onto the upper slope. Thinner (40-60 m) upward-coarsening successions at Venture likely formed in a more proximal position on the outer shelf. Location of the shelf margin between Venture and South Venture Fields during deposition of Venture sandstones 8 to 5 is also consistent with the absence of Venture sandstones 8 and 7 in South Venture O-59, because progradation of the Venture sandstone 8 and 7 shorelines likely terminated at the shelf edge prior to reaching South Venture.

The development of stratal architecture and sand-body distribution both within and downdip of the Venture Field was likely controlled by differential subsidence at the Lower Missisauga shelf margin. In the Venture Field, Venture sandstones 8 to 5 thicken towards the master Venture growth fault (Figure 4.5; Figure 4.15b), suggesting that sand-body thickness increases northward (updip) within the Venture Field. Venture sandstones 8 to 5 also thicken toward an extensively growth-faulted zone between the Venture and West Venture Fields (Figure 4.15a). Incised valleys consistently cross-cut this zone, suggesting that over the course of several cycles of relative sea-level rise and fall, the axes of fluvio-deltaic systems, despite a natural tendency to stack in a laterally-offset or 'compensational' pattern at the shelf margin (*e.g.*, Sydow, 1996), were

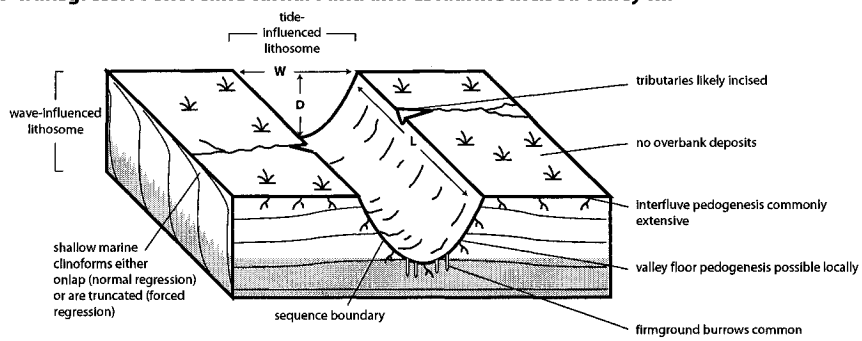
consistently diverted into the zone of maximum subsidence (*e.g.*, Bridge and Leeder, 1979; Mackay and Bridge, 1995; Morton and Suter, 1996; Sydow *et al.*, 2003). Because growth faults at depth are commonly better imaged than incised valleys by seismic data, this relationship may help improve the effectiveness of predicting reservoir distribution downdip of the shelf margin in regions where seismic resolution is poor and well control is lacking.

4.9 Conclusions

The abrupt transition from wave- to tide-dominated deposition in Venture sandstones 8 to 5 likely formed on the outer shelf just landward of the shelf edge during repetitive episodes of storm-dominated forced regression and tidally-influenced transgressive incised valley fill. Stratal architecture within the Venture Field was likely controlled by differences in syndepositional subsidence, which caused Venture sandstones to thicken northward, or updip, towards the master growth fault, as well as westward parallel to depositional strike towards a high subsidence zone located between the West Venture and Venture Fields. Differential subsidence within the Venture Field most probably also controlled downdip sandbody distribution and sediment supply, because the axes of fluvio-deltaic systems, which are expressed by incised valleys, appear to have repeatedly reoccupied the zone of high subsidence between the West Venture and Venture Fields over the course of several relative sea level cycles.

Figure 4.1 Characteristics of abrupt wave-tidal transitions caused by (**a**) regressive-to-transgressive shoreline turnaround and estuarine incised valley fill, (**b**) normal regression of a 'mixed-energy' tide- and wave-influenced delta, and (**c**) enhancement of tidal currents during regression due to the onset of tidal resonance. Data and concepts from Oomkens (1974), Zaitlin *et al.* (1994), Gastaldo (1996), Posamentier and Vail (1988), Muto and Steel (1992), Best and Ashworth (1997), Suter (2001), Willis and Gabel (2001, 2003), Martinsen *et al.* (2001), Posamentier, 2001; Berné *et al.* (2002), Pemberton *et al.* (2002), Yoshida *et al.* (2003), and Dalrymple *et al.*, 2003.

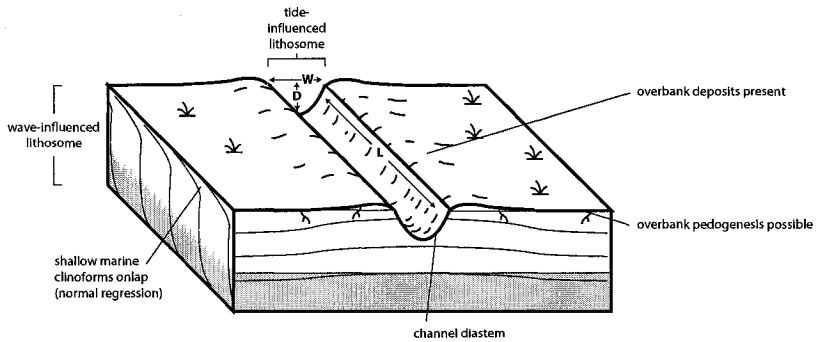
a) Regressive-to-transgressive shoreline turnaround and estuarine incised valley fill



Dimensions of tidally-influenced lithosome (estuarine incised valley fill)
- L is commonly large (no autoretreat problem if regression is forced)
- D can be large (often >5 mean channel depths; typically <100 m)
- W typically small (<10 km unless protracted forced regression and lowstand)

Stratal architecture of tidally-influenced lithosome (estuarine incised valley fill)
- Usually backstepping, although may be progradationally filled if fluvial input increases
- Channel fills within valley fill are commonly stacked (multi-storied)
- What cuts valley during regression does not necessarily fill it (nonetheless, fluvial sediments are common at the base of incised valleys...however, there is little fluvial accommodation during falling sea level, plus fluvial sediments can be eroded if tidal ravinement occurs, which would superimpose estuarine sediments directly over basal erosion surface)

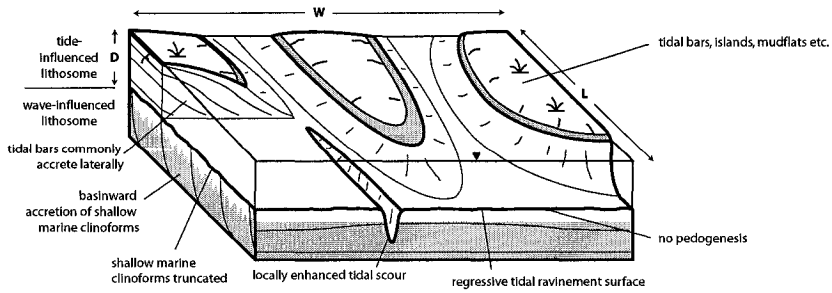
b) Normal regression of a wave- and tide-influenced 'mixed-energy' delta



Dimensions of tidally-influenced lithosome (tidally-influenced channel fill)
- L is commonly small (autoretreat typically stops long-distance normal regression)
- D is commonly small (< 5 mean channel depths (max.~30 m; typically < ~15 m))
- W is typically small (likely < several km unless high avulsion vs. subsidence)

Stratal architecture of tidally-influenced lithosome (tidally-influenced channel fill)
- Forward-stepping
- Channel fills typically not stacked (usually single storied)
- What cuts channel during regression likely overlies it (*i.e.* channel base overlain by fluvial or tidally-influenced fluvial deposits

c) Switch from wave- to tidally-dominated sedimentation during regression



Dimensions of tidally-dominated lithosome (tidally-dominated delta)
- L can be small or large (constrained by the shape of the tidally-resonant topographic depression)
- D is likely smaller (<20 m?), exept where localized tidal scour is intense
- W can be large (up to 300 km; constrained laterally by the shape of the basin)

Stratal architecture of tidally-dominated lithosome (tidally-dominated delta)
- Forward stepping to aggradational (although individual distributary channels fill by lateral accretion)
- What erodes surface during regression likely overlies it (*i.e.* erosion surface overlain by subtidal, heterolithic deposits (*e.g.* distributary channels))

Figure 4.2 Isopach map, Scotian Basin, offshore Nova Scotia. Contours are in kilometers. Modified from MacLean and Wade (1992)

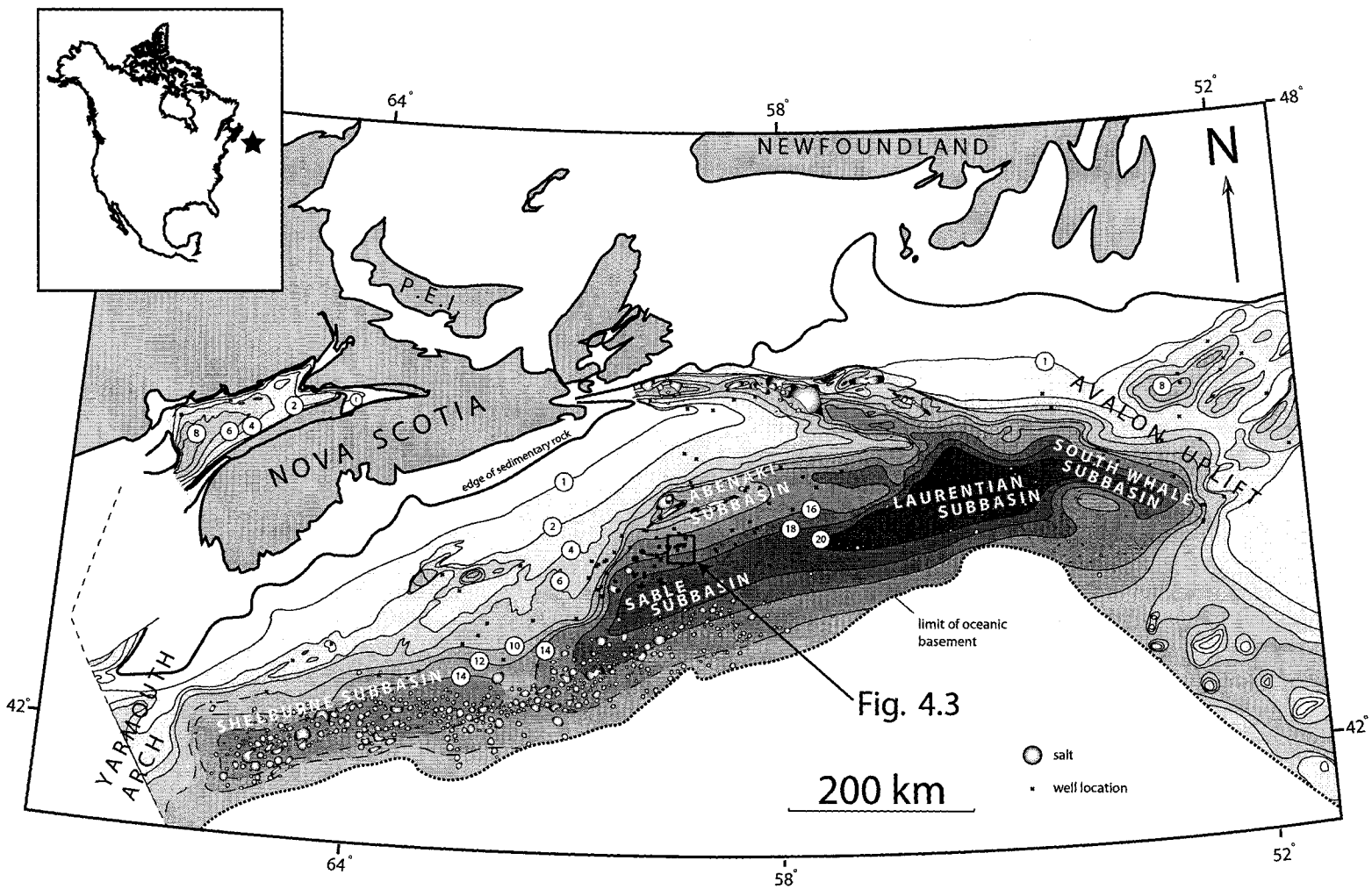

64°
58°
52°
48°
NEWFOUNDLAND
N
P.E.I
NOVA SCOTIA
edge of sedimentary rock
AVALON UPLIFT
SOUTH WHALE SUBBASIN
LAURENTIAN SUBBASIN
ABENAKI SUBBASIN
SABLE SUBBASIN
limit of oceanic basement
Fig. 4.3
YARMOUTH ARCH
SHELBURNE SUBBASIN
42°
salt
well location
200 km
64°
58°
52°

Figure 4.3 Dataset and structure, Venture Field region (modified from Canada Nova Scotia Offshore Petroleum Board, 2000).

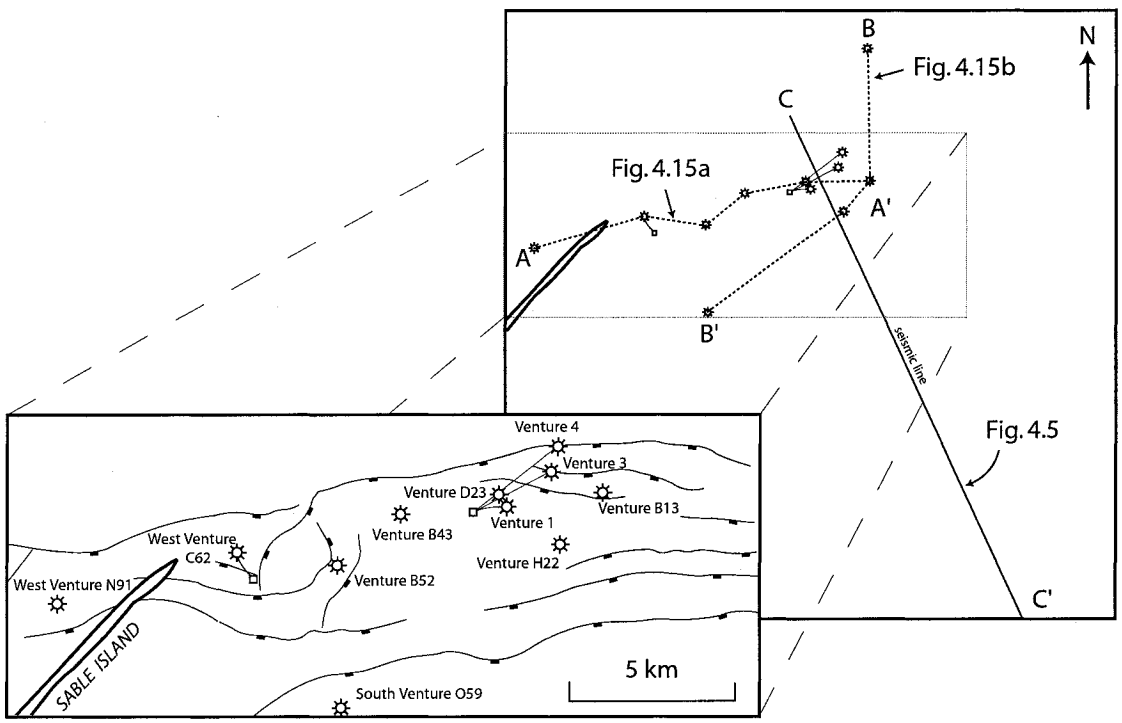

B
N
Fig. 4.15b
C
Fig. 4.15a
A'
A
B'
seismic line
Fig. 4.5
C'
Venture 4
Venture 3
Venture D23
Venture B13
Venture 1
Venture B43
West Venture
C62
Venture H22
West Venture N91
Venture B52
SABLE ISLAND
5 km
South Venture O59

Figure 4.4 Stratigraphy of sandstone reservoirs, Venture and West Venture fields (after Wade and MacLean (1990) and Sable Offshore Energy (1996).

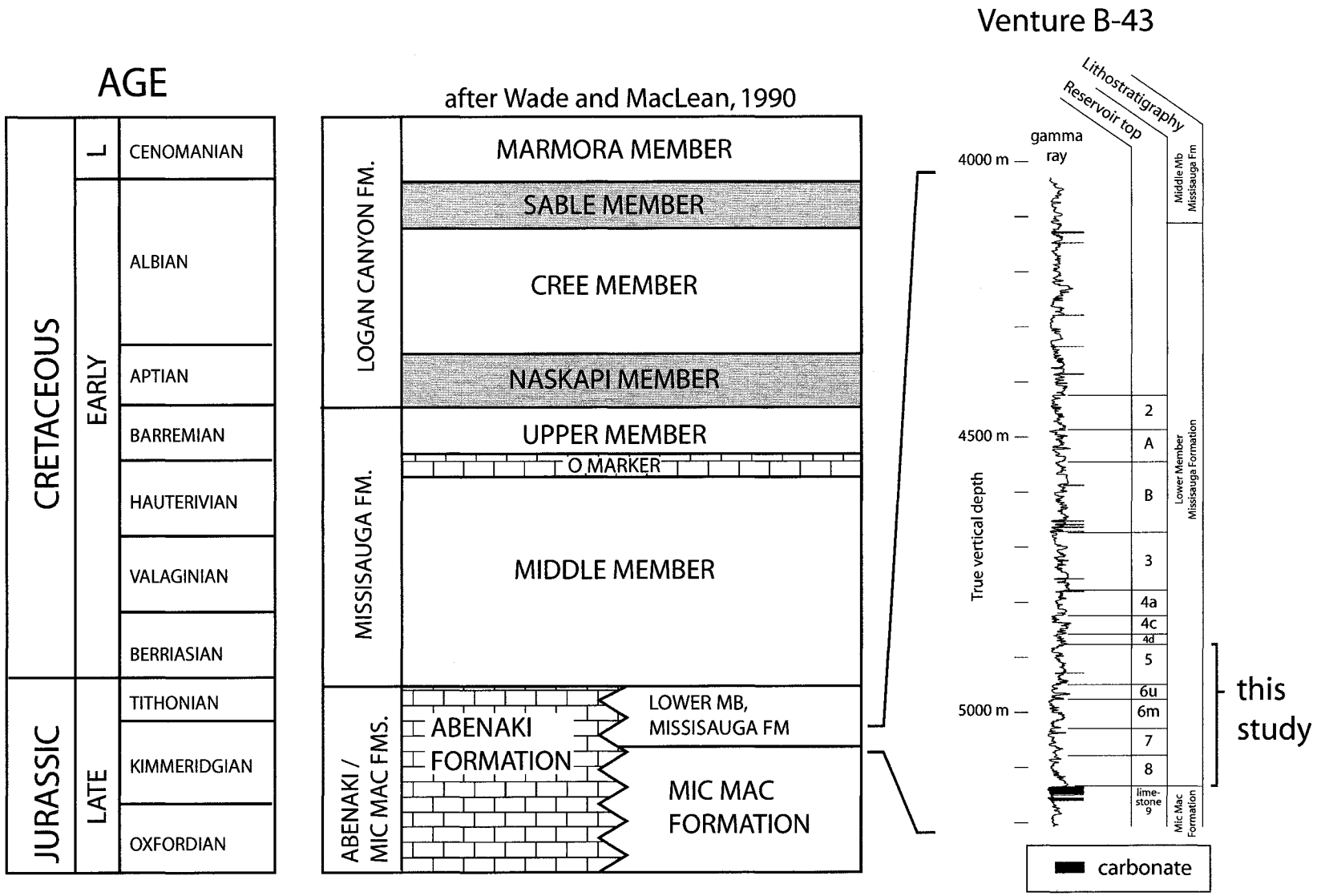
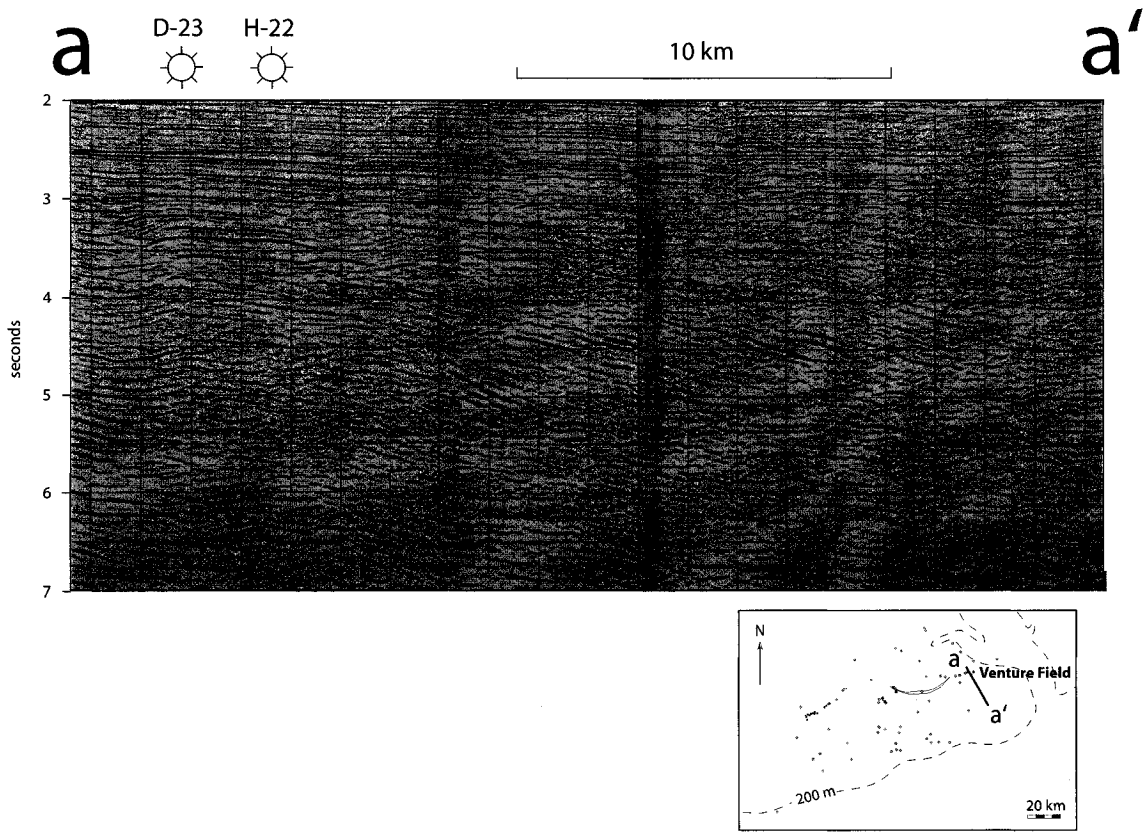

AGE
CRETACEOUS
JURASSIC
L
EARLY
LATE
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALAGINIAN
BERRIASIAN
TITHONIAN
KIMMERIDGIAN
OXFORDIAN
after Wade and MacLean, 1990
LOGAN CANYON FM.
MISSISAUGA FM.
ABENAKI / MIC MAC FMS.
MARMORA MEMBER
SABLE MEMBER
CREE MEMBER
NASKAPI MEMBER
UPPER MEMBER
O MARKER
MIDDLE MEMBER
ABENAKI FORMATION
LOWER MB, MISSISAUGA FM
MIC MAC FORMATION
Venture B-43
Lithostratigraphy
Reservoir top
gamma ray
4000 m
4500 m
5000 m
True vertical depth
2
A
B
3
4a
4c
4d
5
6u
6m
7
8
lime-stone 9
Middle Mb Missisauga Fm
Lower Member Missisauga Formation
Mic Mac Formation
this study
carbonate

Figure 4.5 Dip-oriented seismic cross-section, Venture Field region. Southward-dipping reflections located south of the Venture Field are interpreted to be progradational shelf-margin clinoforms.


a
D-23
H-22
10 km
a'
seconds
2
3
4
5
6
7
N
a
Venture Field
a'
200 m
20 km

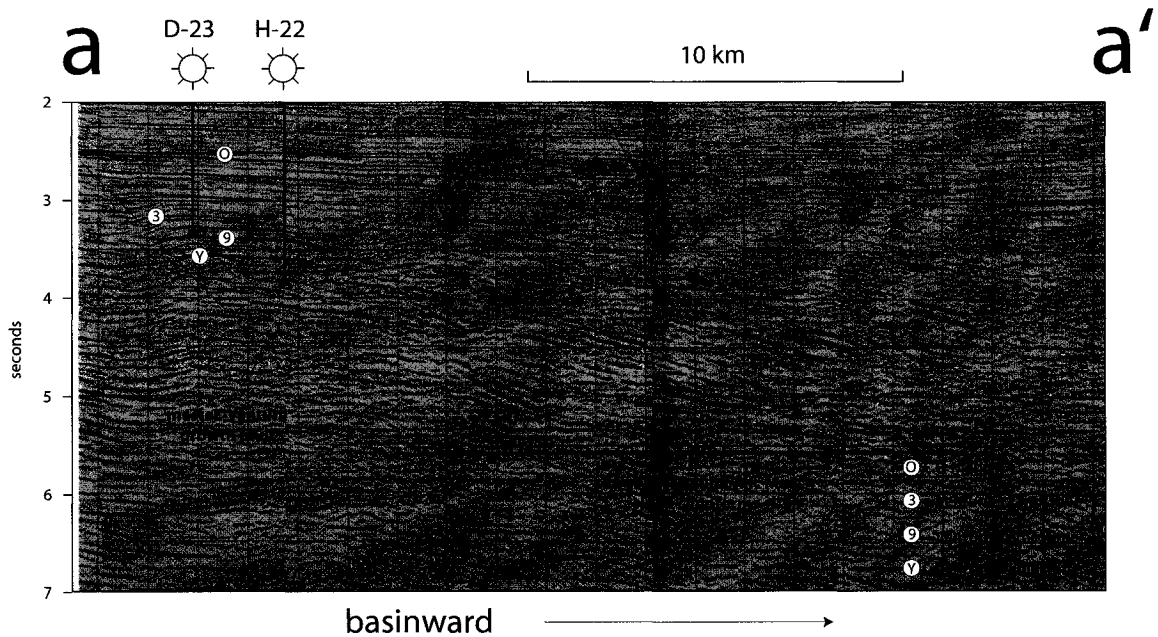

a
D-23
H-22
10 km
a'
seconds
2
3
4
5
6
7
O
B
9
Y
O
B
9
Y
basinward

Figure 4.6 Facies 1: carbonate mudstone (interpretation – condensed outer-shelf carbonate deposits). Facies 1 is a massive to faintly laminated carbonate mudstone that contains brachiopod, bryozoan and foraminifera bioclasts and lacks potential framework building organisms. Photo taken from West Venture C-62, core 13, box 12, 5275.44 m (measured depth).

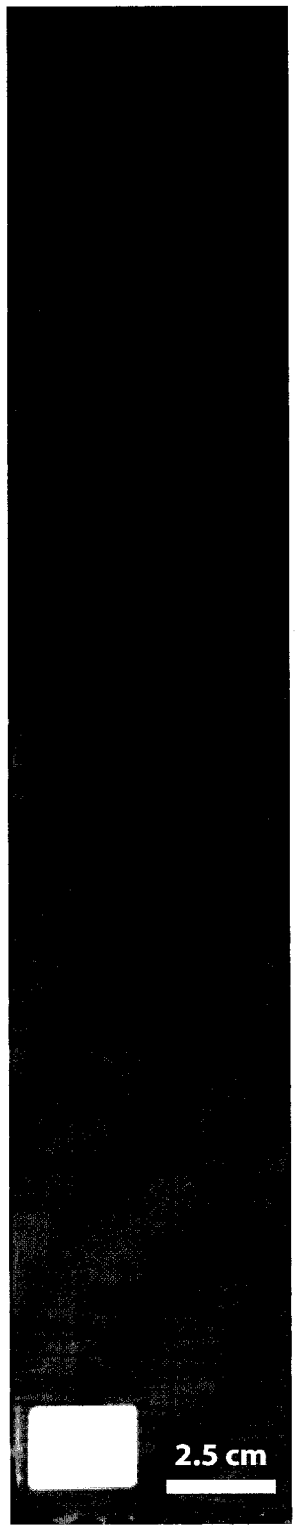

2.5 cm

Figure 4.7 Facies 2: Mudstone with low angle (<10°) cross-stratified sandstone interbeds (interpretation – storm-dominated offshore to lower shoreface deposits). Photo taken from West Venture C-62, core 9, box 24, 5190.3 m (measured depth).

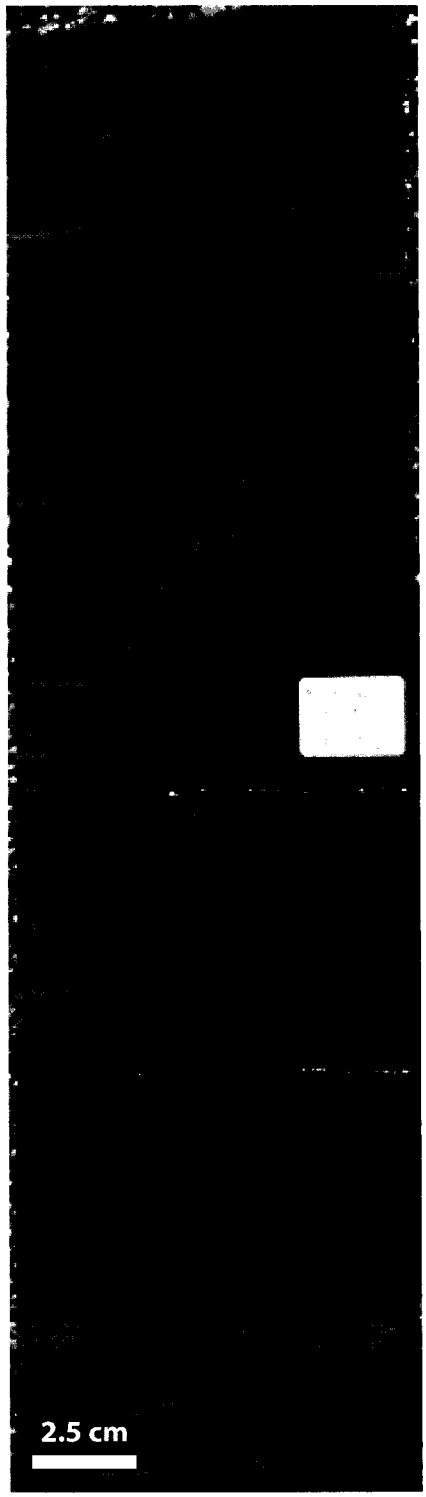
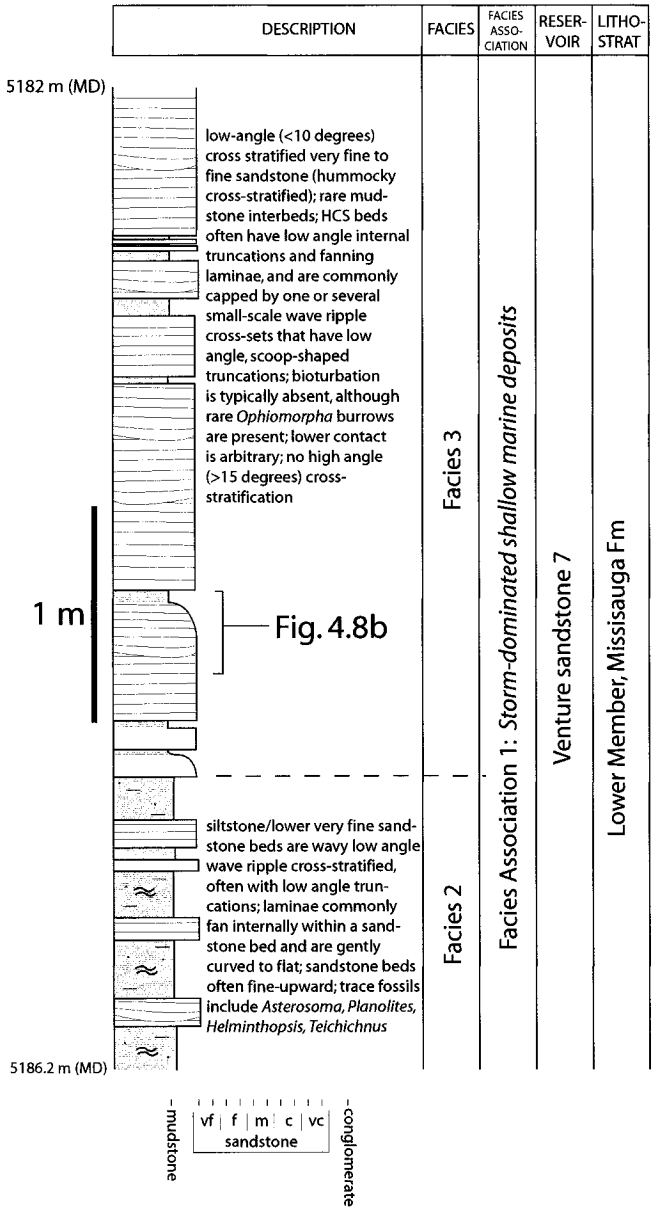
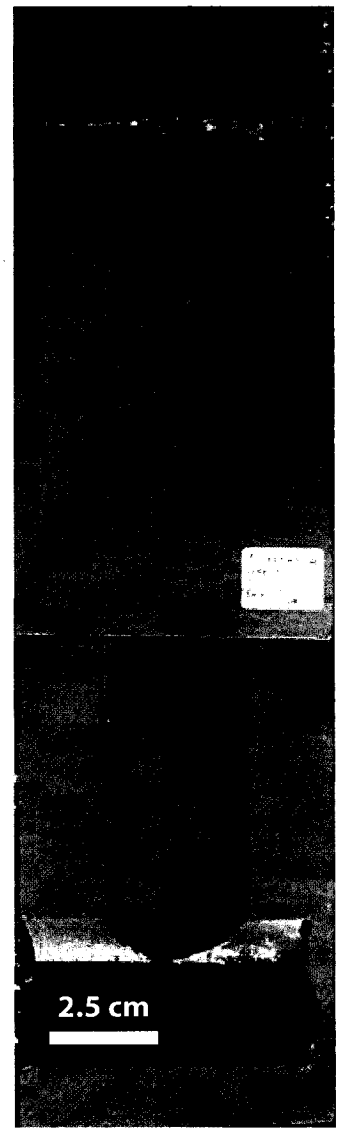

2.5 cm

Figure 4.8 Facies 3: Low-angle (<10°) cross-stratified sandstone (interpretation – storm-dominated lower shoreface deposits). (**a**) Sedimentological log from West Venture C-62, core 9, boxes 17 to 20, 5182-5186.2 m (measured depth), and (**b**) low angle (<10°) cross-stratified sandstone (Facies 3 - see Figure 4.8a for location). Note truncation surface (arrow), fining upward trend, and gentle fanning of laminae – features common to hummocky cross-stratification.


DESCRIPTION
FACIES
FACIES ASSO-CIATION
RESER-VOIR
LITHO-STRAT
5182 m (MD)
low-angle (<10 degrees) cross stratified very fine to fine sandstone (hummocky cross-stratified); rare mud-stone interbeds; HCS beds often have low angle internal truncations and fanning laminae, and are commonly capped by one or several small-scale wave ripple cross-sets that have low angle, scoop-shaped truncations; bioturbation is typically absent, although rare Ophiomorpha burrows are present; lower contact is arbitrary; no high angle (>15 degrees) cross-stratification
1 m
Fig. 4.8b
siltstone/lower very fine sand-stone beds are wavy low angle wave ripple cross-stratified, often with low angle trun-cations; laminae commonly fan internally within a sand-stone bed and are gently curved to flat; sandstone beds often fine-upward; trace fossils include Asterosoma, Planolites, Helminthopsis, Teichichnus
5186.2 m (MD)
Facies 3
Facies 2
Facies Association 1: Storm-dominated shallow marine deposits
Venture sandstone 7
Lower Member, Missisauga Fm
mudstone
vf | f | m | c | vc
sandstone
conglomerate

(a)


2.5 cm

(b)

Figure 4.9 Facies 4: Interstratified high angle (>15°) and low angle (<10°) cross-stratified sandstone (interpretation – upper shoreface deposits). Sedimentological log from West Venture N-91, core 8, boxes 16 to 7, 5124.65-5113.23 m (measured depth).

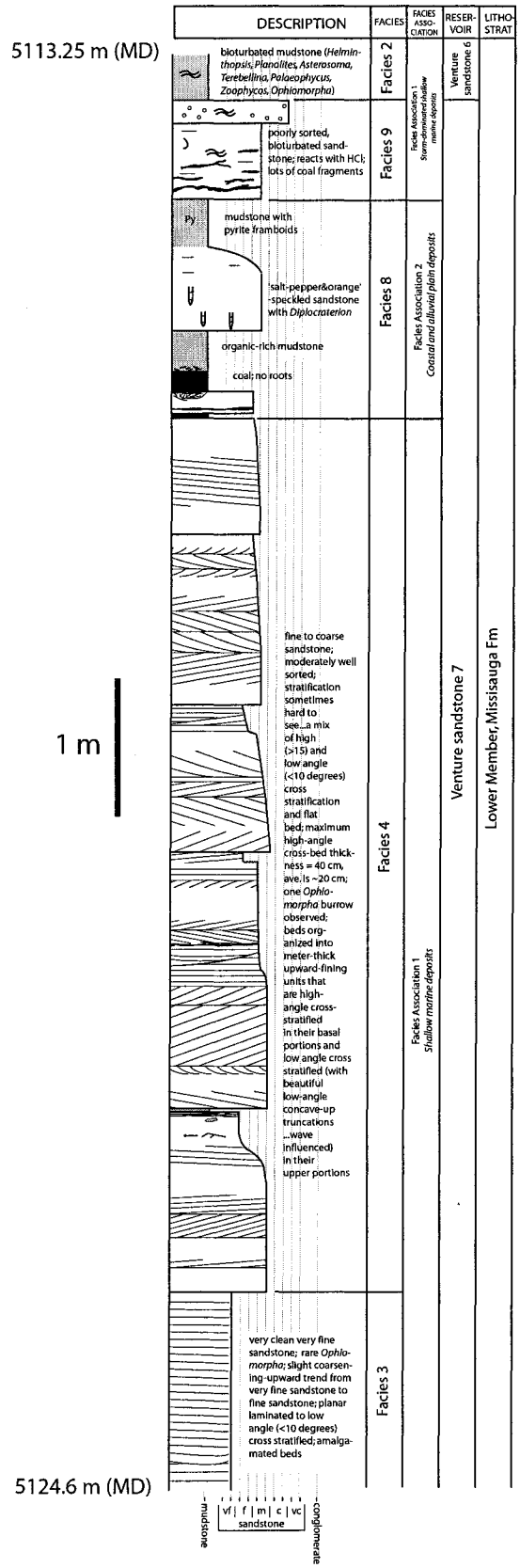
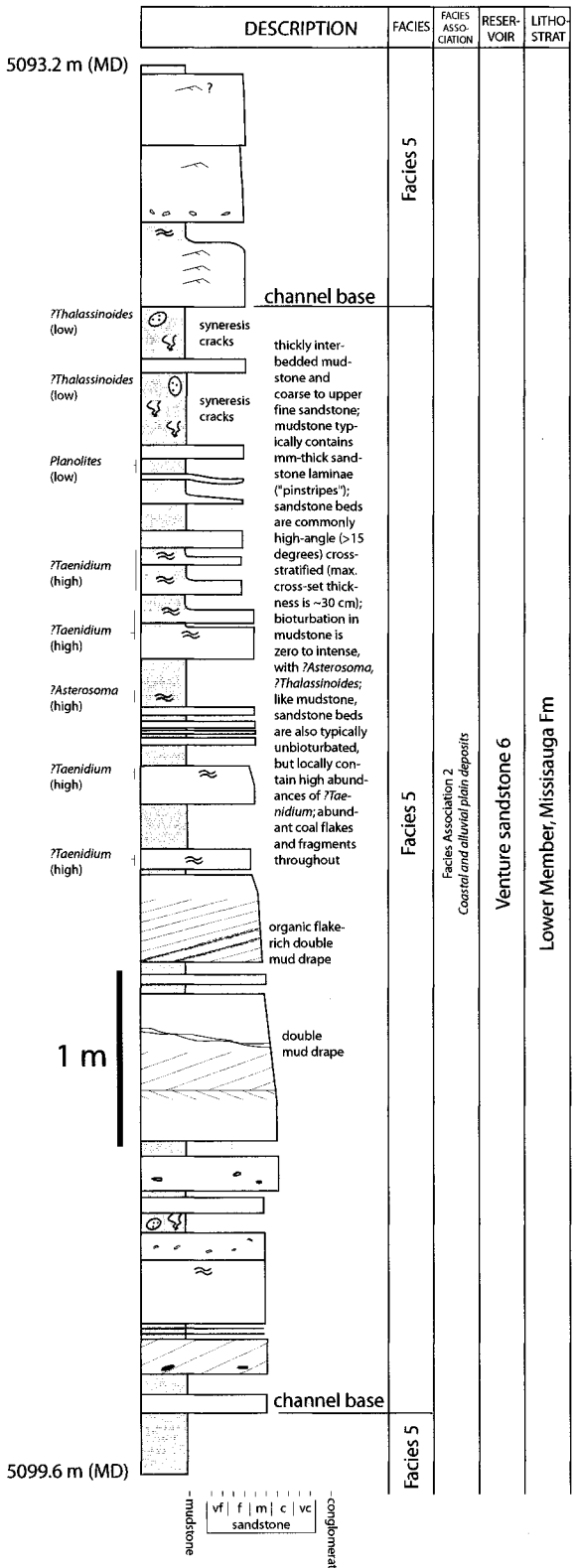
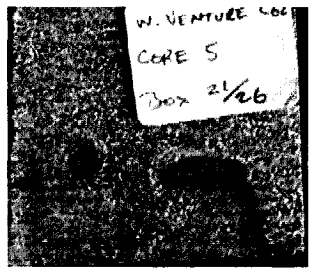

5113.25 m (MD)
5124.6 m (MD)
1 m
DESCRIPTION
FACIES
FACIES ASSOCIATION
RESERVOIR
LITHOSTRAT
bioturbated mudstone (Helminthopsis, Planalites, Asterosoma, Terebellina, Palaeophycus, Zoophycos, Ophiomorpha)
poorly sorted, bioturbated sandstone; reacts with HCl; lots of coal fragments
Py
mudstone with pyrite framboids
'salt-pepper&orange' speckled sandstone with Diplocraterion
organic-rich mudstone
coal; no roots
fine to coarse sandstone; moderately well sorted; stratification sometimes hard to see...a mix of high (>15) and low angle (<10 degrees) cross stratification and flat bed; maximum high-angle cross-bed thickness = 40 cm, ave. is ~20 cm; one Ophiomorpha burrow observed; beds organized into meter-thick upward-fining units that are high-angle cross-stratified in their basal portions and low angle cross stratified (with beautiful low-angle concave-up truncations ...wave influenced) in their upper portions
very clean very fine sandstone; rare Ophiomorpha; slight coarsening-upward trend from very fine sandstone to fine sandstone; planar laminated to low angle (<10 degrees) cross stratified; amalgamated beds
Facies 2
Facies 9
Facies 8
Facies 4
Facies 3
Facies Association 1 Storm-dominated shallow marine deposits
Facies Association 2 Coastal and alluvial plain deposits
Facies Association 1 Shallow marine deposits
Venture sandstone 6
Venture sandstone 7
Lower Member, Missisauga Fm
mudstone
vf | f | m | c | vc
sandstone
conglomerate

Figure 4.10 Facies 5: Mudstone with high-angle (>15°) cross-stratified sandstone interbeds (interpretation – tide-influenced fluvial deposits). (**a**) Upward-fining Facies 5 channel fill unit (West Venture C-62, core 5, boxes 25 to 18, 5099.6-5092 m (measured depth)), (**b**) *?Taenidium* burrows (West Venture C-62, core 5, box 21, 5096.14 m (measured depth)), and (**c**) rhythmically laminated mudstone and very fine sandstone (interpretation – tidal rhythmites; Venture H-22, core 2, box 1, 4895 m (measured depth)).

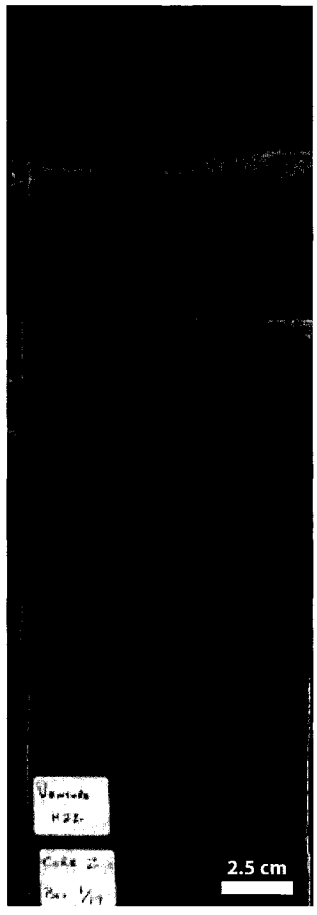

DESCRIPTION
FACIES
FACIES ASSO-CIATION
RESER-VOIR
LITHO-STRAT
5093.2 m (MD)
channel base
?Thalassinoides (low)
syneresis cracks
?Thalassinoides (low)
syneresis cracks
Planolites (low)
?Taenidium (high)
?Taenidium (high)
?Asterosoma (high)
?Taenidium (high)
?Taenidium (high)
thickly inter-bedded mud-stone and coarse to upper fine sandstone; mudstone typ-ically contains mm-thick sand-stone laminae ("pinstripes"); sandstone beds are commonly high-angle (>15 degrees) cross-stratified (max. cross-set thick-ness is ~30 cm); bioturbation in mudstone is zero to intense, with ?Asterosoma, ?Thalassinoides; like mudstone, sandstone beds are also typically unbioturbated, but locally con-tain high abund-ances of ?Tae-nidium; abund-ant coal flakes and fragments throughout
organic flake-rich double mud drape
double mud drape
1 m
channel base
5099.6 m (MD)
Facies 5
Facies 5
Facies 5
Facies Association 2
Coastal and alluvial plain deposits
Venture sandstone 6
Lower Member, Missisauga Fm
mudstone
vf | f | m | c | vc
sandstone
conglomerate

(a)


W. VENTURE
CORE 5
Box 21/26

2.5 cm

(b)


2.5 cm

(c)

Figure 4.11 Facies 6: Mudstone with lenticular and pinstripe-shaped sandstone laminae (interpretation – tidal flat deposits). Note small *Planolites* burrows (Pl), and lenticular (L) and pinstripe (P) shaped sandstone laminae. Photo taken from West Venture C-62, core 6, box 4, 5104.85 m (measured depth).

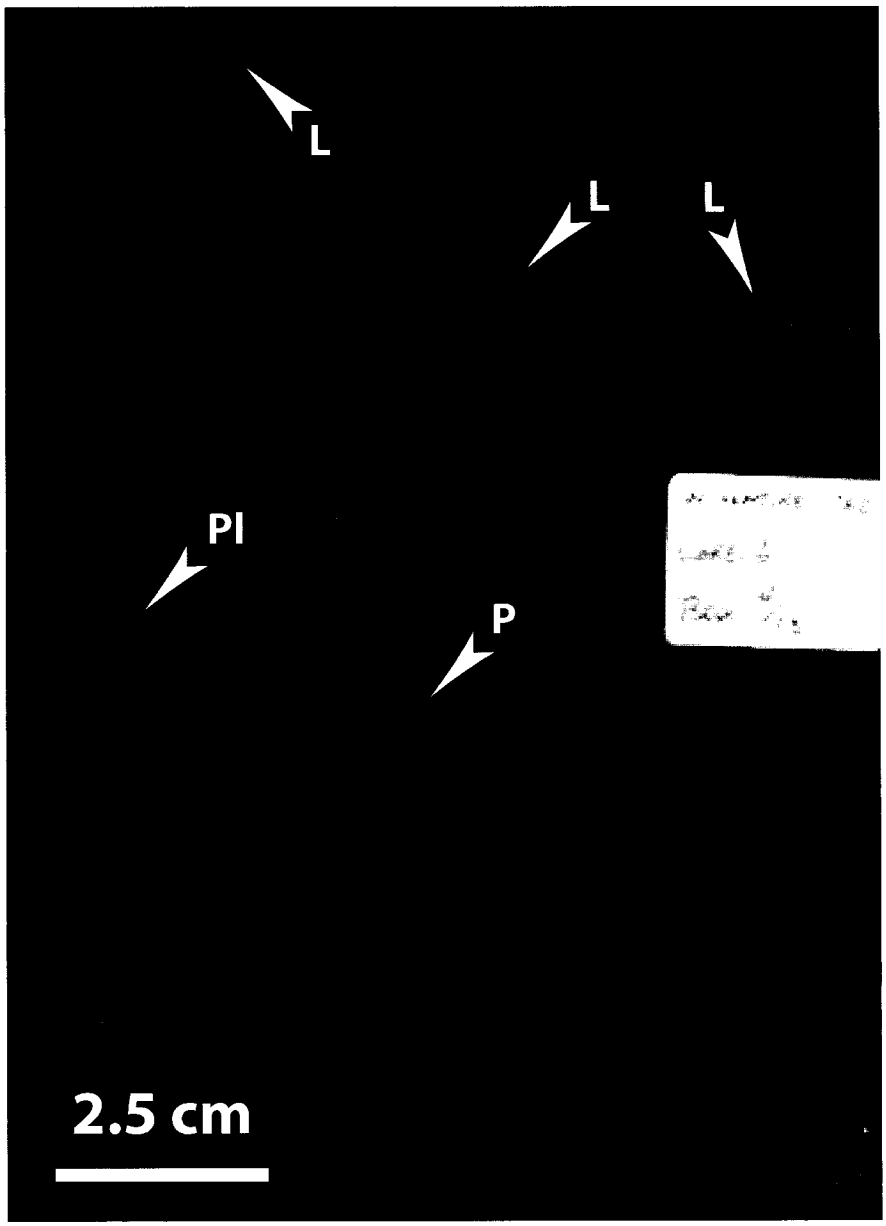
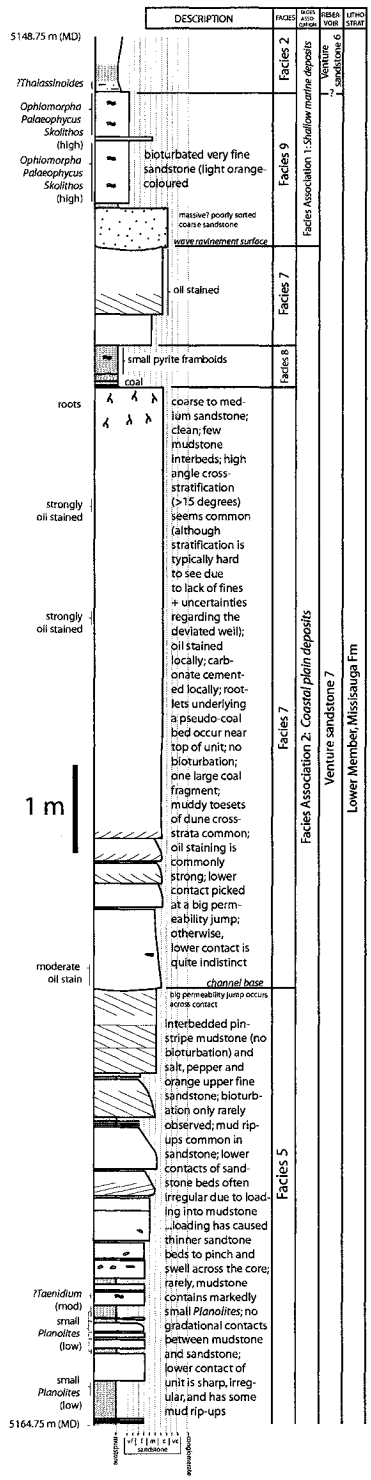
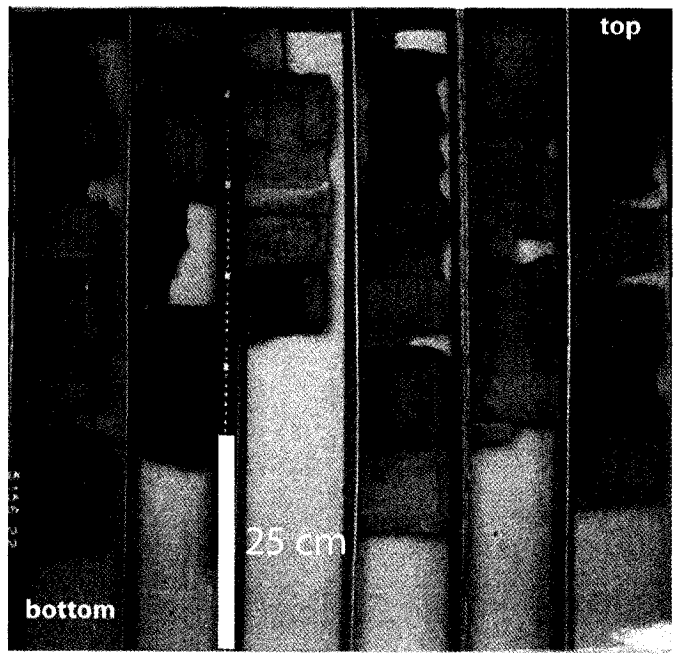

L
L
L
Pl
P
2.5 cm

Figure 4.12 Facies 7: High angle (>15°) cross-stratified sandstone (interpretation – fluvial deposits). (**a**) Sedimentologic log from West Venture C-62, core 8, boxes 18 to 3, 5164.75-5148.75 m (measured depth), and (**b**) photo of Facies 7 showing intense local oil staining from West Venture C-62, core 8, boxes 9 to 7, 5156.22-5153.18 m (measured depth).


DESCRIPTION
FACIES
BOSS ASSOCIATION
FISHER VOIR
LITHOSTRAT
5148.75 m (MD)
?Thalassinoides
Ophiomorpha Palaeophycus Skolithos (high)
Ophiomorpha Palaeophycus Skolithos (high)
bioturbated very fine sandstone (light orange-coloured
massive? poorly sorted coarse sandstone
wave ravinement surface
oil stained
small pyrite framboids
coal
roots
strongly oil stained
strongly oil stained
moderate oil stain
channel base
big permeability jump occurs across contact
?Taenidium (mod)
small Planolites (low)
small Planolites (low)
5164.75 m (MD)
coarse to medium sandstone; clean; few mudstone interbeds; high angle cross-stratification (>15 degrees) seems common (although stratification is typically hard to see due to lack of fines + uncertainties regarding the deviated well); oil stained locally; carbonate cemented locally; rootlets underlying a pseudo-coal bed occur near top of unit; no bioturbation; one large coal fragment; muddy toesets of dune cross-strata common; oil staining is commonly strong; lower contact picked at a big permeability jump; otherwise, lower contact is quite indistinct
interbedded pinstripe mudstone (no bioturbation) and salt, pepper and orange upper fine sandstone; bioturbation only rarely observed; mud rip-ups common in sandstone; lower contacts of sandstone beds often irregular due to loading into mudstone ...loading has caused thinner sandtone beds to pinch and swell across the core; rarely, mudstone contains markedly small Planolites; no gradational contacts between mudstone and sandstone; lower contact of unit is sharp, irregular, and has some mud rip-ups
1 m
Facies 2
Facies 9
Facies 7
Facies 8
Facies 7
Facies 5
Facies Association 1: Shallow marine deposits
Facies Association 2: Coastal plain deposits
Venture sandstone 6
Venture sandstone 7
Lower Member, Mississauga Fm
mudstone
sandstone
conglomerate

(a)


top
25 cm
bottom

(b)

Figure 4.13 Facies 8: Coal and pyrite-rich black mudstone (interpretation – drowned, marine-influenced marsh deposits). Photo taken from West Venture C-62, core 8, box 6, 5153.18 m (measured depth).

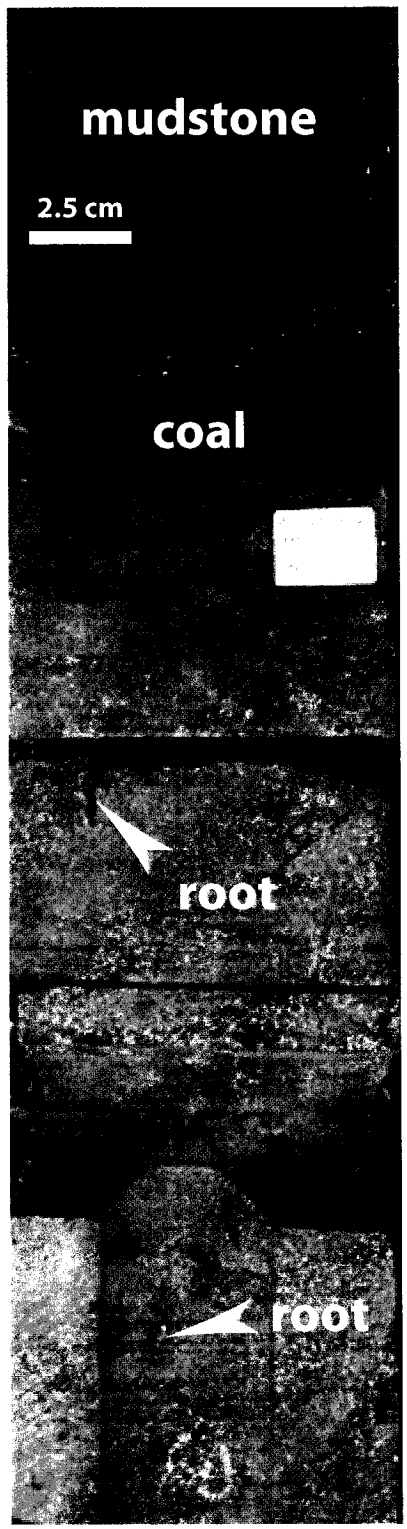

mudstone
2.5 cm
coal
root
root

Figure 4.14 Facies 9: Poorly sorted sandstone (interpretation – transgressive lag) erosively overlying mudstone with pyrite (Facies 7; interpretation – tidally influenced fluvial deposits). The erosion surface (interpretation – transgressive ravinement surface) is the contact between Venture sandstone 6m and Venture sandstone 6u. Photo taken from West Venture C-62, core 5, box 11, 5082.2 m (measured depth).

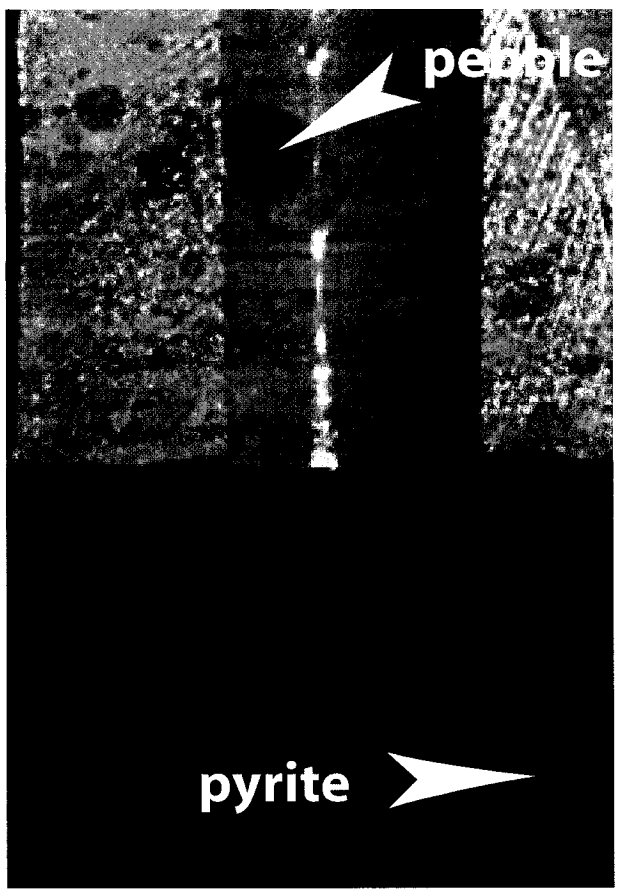

pebble
pyrite
2 cm

Figure 4.15a Strike-oriented well log cross-section, Venture and West Venture fields. Note how sandstones thicken into a zone of growth faults between the Venture and West Venture fields, which is also the site of most incised valleys.

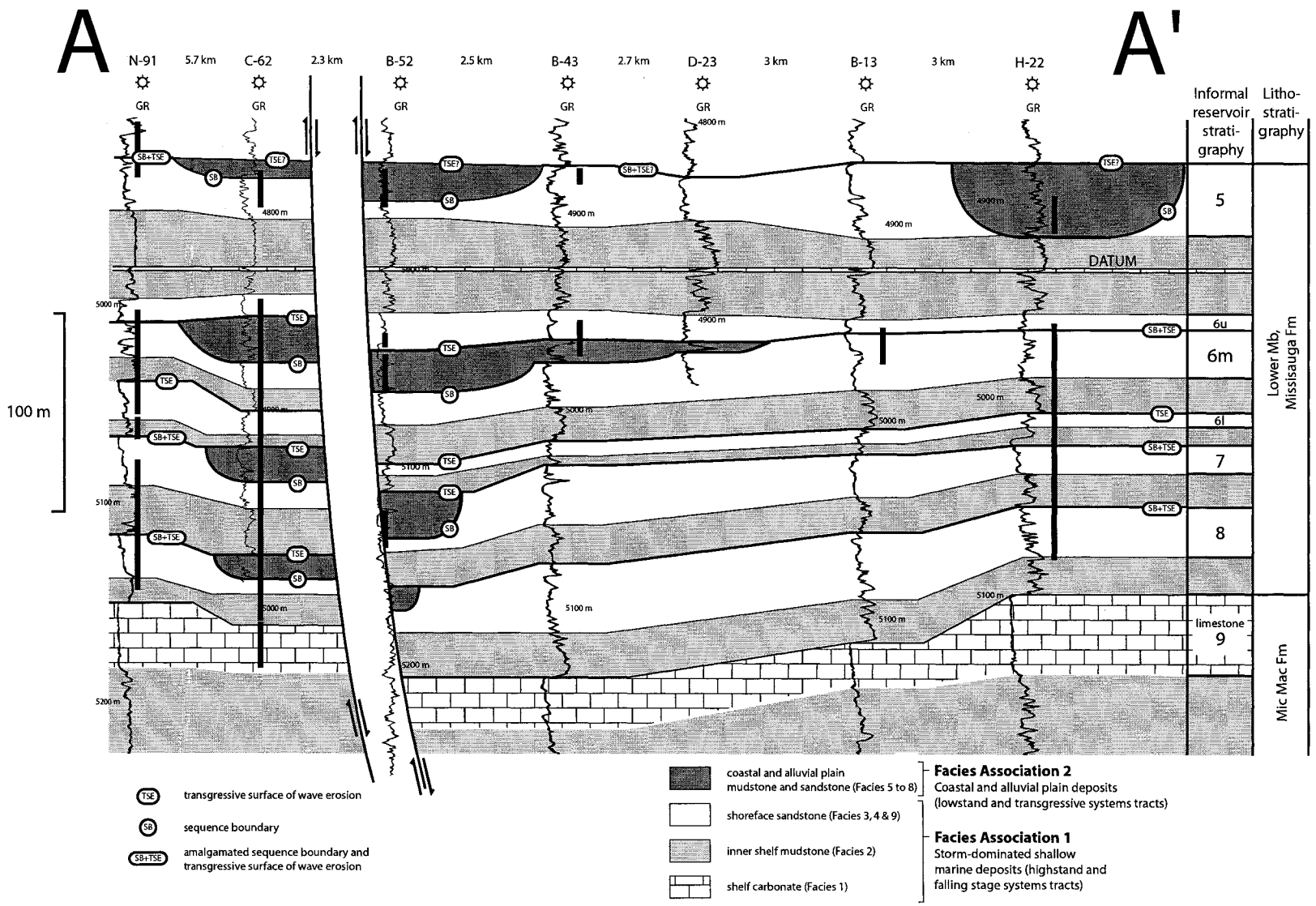

A
A'
N-91
5.7 km
C-62
2.3 km
B-52
2.5 km
B-43
2.7 km
D-23
3 km
B-13
3 km
H-22
GR
Informal reservoir stratigraphy
Litho-stratigraphy
DATUM
100 m
5
6u
6m
6l
7
8
limestone
9
Lower Mb, Missisauga Fm
Mic Mac Fm
4800 m
4900 m
5000 m
5100 m
5200 m
SB+TSE
TSE
SB
TSE?
SB+TSE?
transgressive surface of wave erosion
sequence boundary
amalgamated sequence boundary and transgressive surface of wave erosion
coastal and alluvial plain mudstone and sandstone (Facies 5 to 8)
shoreface sandstone (Facies 3, 4 & 9)
inner shelf mudstone (Facies 2)
shelf carbonate (Facies 1)
Facies Association 2
Coastal and alluvial plain deposits (lowstand and transgressive systems tracts)
Facies Association 1
Storm-dominated shallow marine deposits (highstand and falling stage systems tracts)

Figure 4.15b Dip-oriented well log cross-section, Venture Field. Note that correlation landward and basinward of the Venture Field is complicated by intervening growth faults. Also note the significantly more mudstone-rich nature of the South Venture O-59 well, located only ~8 km south of the Venture Field.

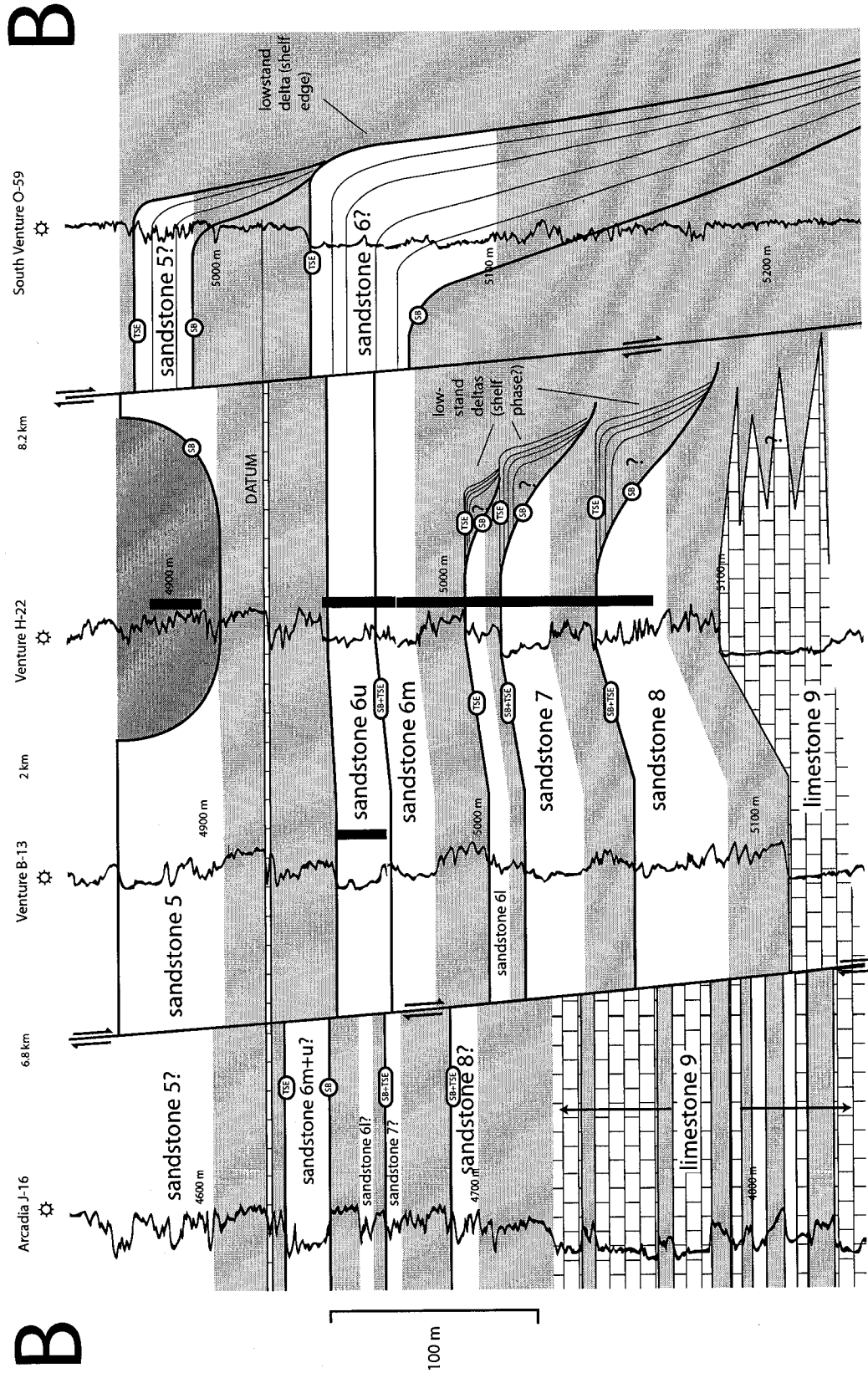
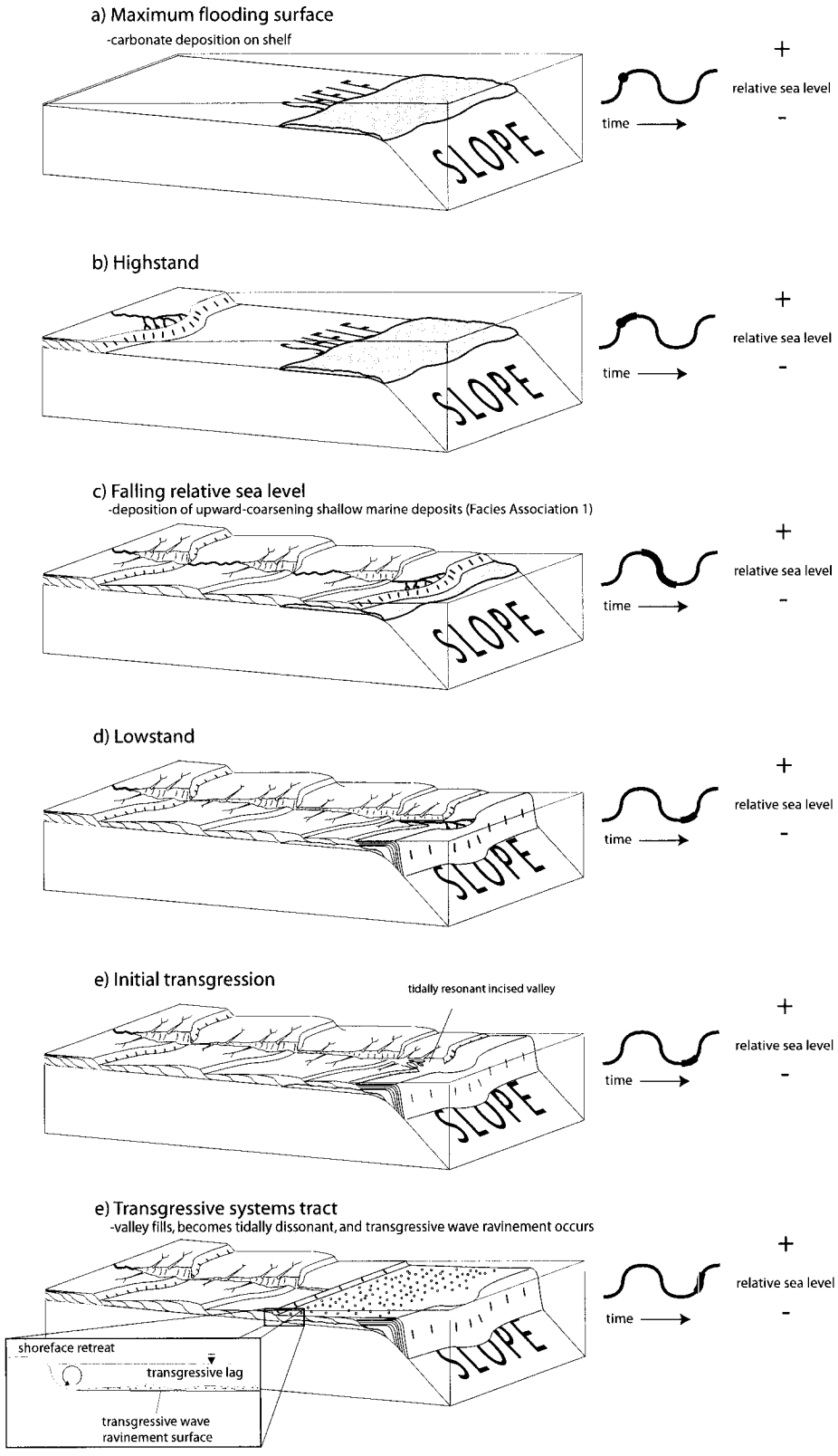

B
B'
Arcadia J-16
Venture B-13
Venture H-22
South Venture O-59
6.8 km
2 km
8.2 km
100 m
DATUM
sandstone 5?
sandstone 5
sandstone 6m+u?
sandstone 6l?
sandstone 7?
sandstone 8?
sandstone 6u
sandstone 6m
sandstone 6l
sandstone 7
sandstone 8
sandstone 6?
limestone 9
lowstand delta (shelf edge)
low-stand deltas (shelf phase?)
4600 m
4700 m
4900 m
5000 m
5100 m
5200 m
SB
TSE
SB+TSE
MFS

Figure 4.16 Depositional model, Venture sandstones 8 to 5, Venture and West Venture fields.


a) Maximum flooding surface
-carbonate deposition on shelf
SLOPE
time
+
relative sea level
-
b) Highstand
SLOPE
time
+
relative sea level
-
c) Falling relative sea level
-deposition of upward-coarsening shallow marine deposits (Facies Association 1)
SLOPE
time
+
relative sea level
-
d) Lowstand
SLOPE
time
+
relative sea level
-
e) Initial transgression
tidally resonant incised valley
SLOPE
time
+
relative sea level
-
e) Transgressive systems tract
-valley fills, becomes tidally dissonant, and transgressive wave ravinement occurs
SLOPE
shoreface retreat
transgressive lag
transgressive wave
ravinement surface
time
+
relative sea level
-

Chapter 5. Mesozoic shelf-margin deltas, offshore Nova Scotia, Canada: Significance to petroleum exploitation and exploration

5.1 Introduction

Following their identification in seismic data from the Gulf of Mexico in the 1960s (Curray and Moore, 1964; Lehner, 1969), shelf-margin deltas have been the focus of much research, not only because they commonly contain substantial hydrocarbon reserves (Hart *et al.*, 1997; Meckel, 2003), but because they form the basic building blocks of accretionary continental margins, are useful in delineating ancient shelf margin positions, and commonly act as staging areas for sediment delivered to downdip slope turbidite systems (Winker and Edwards, 1983; Suter and Berryhill, 1985; Porebski and Steel, 2003). Although they have now been identified in most hydrocarbon-rich passive margin basins (*e.g.*, offshore west Africa, Brazil, Gulf of Mexico), hydrocarbon-bearing shelf-margin deltas have not been explicitly recognized in the passive margin basin offshore Nova Scotia, perhaps because shelf-margin positions are rarely well resolved in seismic data at depth. However, it is argued that several of the largest hydrocarbon accumulations in the Missisauga Formation, the major hydrocarbon-bearing unit offshore Nova Scotia, are contained in deltaic sandstones deposited at or near the shelf margin. The objective of this article is to describe the sedimentology and stratigraphy of deposits in the Alma, Glenelg and Venture fields that are interpreted to have been deposited, at least in part, by shelf-margin deltas.

5.2 Dataset and methodology

The results of this study are based on the analysis of an integrated dataset from the Sable Subbasin, offshore Nova Scotia (Figure 5.1), including geophysical well logs and cuttings data from 89 wells, 1335 m of conventional core from 23 wells (Figure 5.2a), public and confidential biostratigraphic data (Figure 5.2b), ~1825 km of publicly available paper-format 2-D seismic data and an industry-donated digital 3-D seismic survey (96 km^2) from the Panuke Field cut off at 2.2 seconds (Figure 5.2c). Additionally, Rob Fensome (Geological Survey of Canada) analyzed seven palynology samples collected from conventional cores from the West Venture C-62 well (see Chapter 4).

Cores were described in 2.5 cm resolution (see Appendix 1), noting lithology, sedimentary textures and structures, body fossils, trace fossils, macroscopic diagenetic features, and the nature of stratigraphic contacts. Depositional processes and depositional environments were interpreted using a standard "process-oriented" facies analysis approach (*e.g.*, Harms *et al.*, 1975; Scholle and Spearing, 1982; Walker and James, 1992; Reading, 1996; Pemberton *et al.*, 2002). Geophysical well logs were calibrated using core data, and were tied to seismic data using synthetic seismograms generated from sonic or sonic and density logs. Seismic, well log, and core data were interpreted using standard sequence stratigraphic techniques and concepts (*e.g.*, Curray, 1964; Vail *et al.* (1977); Posamentier and Vail, 1988; Van Wagoner *et al.*, 1990; Emery and Myers, 1996; Posamentier and Allen, 1999).

5.3 Geological setting and stratigraphy

The Sable Subbasin is one of several interconnected Mesozoic-Cenozoic depocenters that make up the passive margin basin offshore Nova Scotia (Figure 5.1). The center of the Sable Subbasin is underlain by syn-rift salt, and contains numerous growth faults and salt tectonic features. Terrigenous clastic sediments are believed to have been fed southwestward into the subbasin by the paleo-St. Lawrence river, a sediment-charged, continental-scale fluvial system that likely drained much of Eastern Canada (Wade and MacLean, 1990; Grist *et al.*, 1992).

Fluvial to slope siliciclastics of the Missisauga Formation (Portlandian-Aptian) form a seaward-thickening wedge in the Sable Subbasin that reaches an estimated maximum thickness of ~3.5 km below the modern shelf edge (Figures 5.3 to 5.5). The Missisauga Formation contains ~75% of the original-gas-in-place reserves discovered offshore Nova Scotia, or ~192 x 10^6 m^3 (Canada Nova Scotia Offshore Petroleum Board, 2000). In the central Sable Subbasin, the Missisauga overlies a slightly more mudstone- and carbonate-rich unit, the Mic Mac Formation, and is overlain by mudstone of the Naskapi Member of the Logan Canyon Formation. In the western edge of the subbasin, the Missisauga is underlain by Jurassic carbonates of the Abenaki Formation.

Typically, the Missisauga Formation is subdivided into two or three members (Figure 5.3). The three-member framework, which was proposed by Wade and MacLean (1990) and elaborated on by MacLean and Wade (1993), is similar to the two-member frameworks of Given (1977) and Welsink *et al.*, (1989), but recognizes a third, older member in the central Sable Subbasin that is coeval with the terminal phases of Abenaki carbonate deposition. Although offering potentially better stratigraphic resolution,

regional correlation of the top of the lowermost member of Wade and MacLean (1990) in seismic or well log data is problematic (*cf.* Figure 9 in Wade, 1991; MacLean and Wade, 1993), which makes the three-member framework difficult to apply in practice.

The O Marker is the only prominent, regionally extensive seismic reflections occurring in the Missisauga Formation. The reflection is generated by a mixed mudstone-sandstone-oolitic limestone unit at the base of the Upper Missisauga. It is identifiable throughout the Sable Subbasin in regions northwest of the Onondaga field (Figure 5.6). On geophysical well logs, the most easily recognizable marker is the contact between sandstone of the Missisauga Formation and mudstone of the overlying Naskapi Member of the Logan Canyon Formation.

Below the modern continental shelf, the Missisauga Formation forms flat, parallel seismic reflections that dip gently toward the southeast (Figure 5.7)[16]. Core data suggests that the reflections are associated with fluvial and shallow marine deposits, suggesting that they are continental shelf topsets. Cycles of onlap and offlap are not obvious, so the Missisauga Formation is not readily amenable to Vail-type seismic stratigraphic analysis (Cloetingh *et al.*, 1989). When traced downdip, continental shelf topset reflections in the Missisauga Formation typically lose their coherency in a seismic noise zone below the modern continental shelf edge. As a result, large-scale clinoform reflections that would normally be interpreted as shelf margin and slope deposits are typically not resolved in seismic data, although important exceptions exist (see "Seismic Data" section below).

[16] Rare, small (*i.e.* maximum tens of meters thick) clinoform reflections interpreted to be deltaic in origin are locally visible between the flat, parallel reflections (John Harper, personal communication, 2003)

5.4 Sedimentology

Parts of the Missisauga Formation in the Alma, Glenelg and Venture fields contain thick (*i.e.*, typically tens- to hundreds-of-meters thick), upward-coarsening successions that overlie relatively mudstone-rich strata (Mic Mac or Verrill Canyon formations), that in turn are overlain by relatively sandstone-rich strata composed of thinner upward-coarsening successions (*i.e.*, each is at most several tens-of-meters thick). The sedimentology of these deposits is described below. For brevity, facies descriptions and interpretations are presented in table format (Tables 5.1 to 5.3)[17].

5.4.1 Sedimentology - Venture Field (Lower Missisauga)

The Venture D-23 well was drilled by Mobil *et al.* in 1978 to test for hydrocarbons in a rollover anticline trap formed in the hanging wall of an east-west-trending growth fault (Figure 5.8). Gas was encountered in sixteen isolated sandstone reservoirs in an interval that straddles the boundary between the Mic Mac Formation and the overlying Lower Member of the Missisauga Formation (Figure 5.9; Sable Offshore Energy, 1996; Canada-Nova Scotia Offshore Petroleum Board, 2000). Four delineation wells (Venture B-13, B-43, B-52 and H22) were drilled in the early 1980s, and four production wells (Venture V1, V2, V3 and V5) were drilled between 1998 and 2002 (Sable Offshore Energy, 1996). Original gas in-place is estimated to be 2341 billion cubic feet (~66.3 m^3 x 10^9), which is ~25% of the original in-place gas discovered to date offshore Nova Scotia (Canada-Nova Scotia Offshore Petroleum Board, 2000). Venture sandstones 8 to 5, which form the focus of this study, are all overpressured (Figure 5.10),

[17] Extended facies analyses for the Alma and Glenelg fields are available in Appendix 2, and in Chapters 3 and 4 for the Panuke and Venture fields, respectively.

Table 5.1 Facies descriptions and interpretations, Venture Field (Lower Missisauga)

Facies	Lithology and texture	Physical sedimentary structures	Biogenic features	Gamma ray log character	Interpretation
V1	light blue-gray carbonate mudstone	massive to faintly laminated	brachiopod, bryozoa, and foraminifera bioclasts	blocky	shelf carbonate deposits
V2	mudstone with rare to common thin (<10 cm) siltstone and very fine sandstone beds	Siltstone and sandstone beds are typically planar to low-angle (<10°) (hummocky) cross-stratified	sparse to intense bioturbation, with *Planolites, Palaeophycus, Asterosoma, Helminthopsis, Chondrites, Zoophycos, Terebellina, Teichichnus,* and *Rosselia*; several specimens of a *Circulodium*-like dinoflagellate and one *Subtilisphaera*- like specimen observed (Rob Fensome, personal communication, 2002)	upward-coarsening	inner shelf/lower shoreface deposits
V3	well-sorted, very fine to fine buff-coloured sandstone	sandstone is horizontally laminated to low-angle (<10°) (hummocky) cross-stratified	bioturbation is sparse, with *Ophiomorpha, Rosselia*, and *?Cylindrichnus* in sandstone, and *Teichichnus, Palaeophycus, Terebellina, Chondrites, Ophiomorpha, Cylindrichnus, ?Asterosoma,* and *?Rosselia* in rare mudstone beds	upward-coarsening to blocky	storm-dominated lower shoreface deposits
V4	moderately to well-sorted medium sandstone	sandstone beds (1-25 cm thick) are high-angle (>15°) to low-angle (<10°) cross-stratified	bioturbation is sparse, with rare *Ophiomorpha* burrows; rare layers of sparsely disseminated organic flecks in sandstone	blocky to upward-coarsening	storm-dominated upper shoreface deposits
V5	Mudstone with common fine to coarse sandstone interbeds (10-75 cm thick)	sandstone is high-angle (>15°) cross-stratified (subaqueous dunes) ; rare synaeresis cracks, load structures, double mud drapes, and rhythmically laminated intervals	bioturbation typically absent, but rare, intensely burrowed intervals of *?Taenidium* present in sandstone; also rare *Ophiomorpha* and *Diplocraterion* present in sandstone; mudstone contains rare *Teichichnus, Thalassinoides, ?Rhyzocorallium* and small *Planolites* pebble-sized abundant coal clasts and disseminated organic flecks; one possible dynoflagellate observed (Rob Fensome, personal communication, 2002)	sharp-based and serrated, units commonly fine upward slightly	tide-influenced fluvial deposits
V6	mudstone with pinstripe, wavy, and lenticular laminated very fine sandstone	sandstone laminae are typically high-angle (>15°) cross-stratified and have flat to scoop-shaped bases (wave and current ripples, respectively); rare synaeresis cracks	typically unbioturbated, although rare small *Planolites* burrows observed; root traces observed once	serrated	tidal flat deposits
V7	well sorted medium to coarse sandstone	beds are typically high-angle (>15°) cross-stratified (subaqueous dunes); cross sets are a maximum of ~1 m thick	no trace fossils observed; coal fragments present locally	blocky	fluvial deposits
V8	coal and pyrite-rich black mudstone		no trace fossils observed	usually thin bed (<1 m thick) with higher API values	marsh deposits
V9	poorly sorted, carbonate-cemented sandstone with a "paint-speckled" appearance	typically not visible due to intense bioturbation	bioturbation is commonly intense, with *Ophiomorpha, Chondrites, Skolithos, Palaeophycus, ?Teichichnus*, and *?Rosselia/Cylindrichnus*; pebble-size coal fragments, coal flakes, and mm-thick coal partings are common	usually thin bed (<1 m thick) with low API values	transgressive lag deposits

Table 5.2 Facies descriptions and interpretations, Alma Field (Upper Missisauga)

Facies	Lithology and texture	Physical sedimentary structures	Biogenic features	Gamma ray log character	Interpretation
A1	mudstone	microfaults are present locally, and thin (<1 mm), short (1 to 6 cm), light-coloured, vertical to subvertical "streaks" lacking organic particles are also observed locally (interpretation: pillar structures formed by water escape (see Druitt, 1994; Middleton *et al.*, 2003))	Bioturbation is absent or very minimal, and includes *Teichichnus, Planolites, Asterosoma, Helminthopsis, Chondrites, Zoophycos, ?Arenicolites, Palaeophycus, Terebellina*; shell fragments (echinoid, gastropod, ammonite, bivalve) and disseminated organic matter are common on beddings surfaces	upward-coarsening	mudstone with evidence of gravity-flow deposition; deposited below storm-weather wave base
A2	interstrat-ified mudstone and thin beds of (<10 cm), very fine sandstone	thin sandstone beds are typically planar to low-angle (<10°) cross-stratified (hummocky cross stratification), or rarely small-scale (<5 cm) high-angle (>15°) cross-stratified (current ripples – sometimes capping planar laminated beds – these are interpreted to be Bouma T_{bc} turbidites)	Bioturbation in mudstone is generally low, and includes *Asterosoma, Planolites, Teichichnus, Zoophycos,* and *?Cylindrichnus*; rare escape traces and *Ophiomorpha* in sandstone	upward-coarsening	storm-influenced delta front (lower shoreface?) heterolithics deposited above storm wave base
A3	very fine to medium sandstone	where not obscured by bioturbation, sandstone is either planar laminated, low-angle (<10°) cross-stratified (hummocky cross-stratified), or medium-scale (10-20 cm) high-angle cross-stratified	bioturbation is commonly intense, with *Ophiomorpha Palaeophycus, Helminthopsis, Planolites, Skolithos, Teichichnus, Zoophycos, Asterosoma, ?Thalassinoides, ?Conichnus* and *?Diplocraterion.*	upward-coarsening	Unstressed delta front (shoreface?) deposits
A4	poorly-sorted, carbonate cemented sandstone with "paint-speckled" appear-ance	Sedimentary structures are rarely preserved due to bioturbation	Bioturbation is typically intense, and includes *Ophiomorpha, Planolites, ?Asterosoma, ?Thalassinoides,* and *Helminthopsis*; bivalve, scaphopod, and gastropod shell fragments are common	usually occurs as a thin bed (<1 m thick) with low API values	transgressive lag
A5	poorly-sorted, muddy coarse to very fine sandstone	typically not visible due to intense bioturbation	bioturbation is intense, with large *Ophiomorpha* and *Palaeophycus* (trace fossils hard to ID due to intense bioturbation)	sharp-based, upward fining	transgressive shelf sandstone

Table 5.3 Facies descriptions and interpretations, Glenelg Field (Upper Missisauga)

Facies	Lithology and texture	Physical sedimentary structures	Biogenic features	Gamma ray log character	Interpretation
G1	mudstone with thin, very fine sandstone interbeds	sandstone beds are planar laminated to low-angle (<10°) cross-stratified (hummocky cross-stratified); sandstone beds are rarely normally graded; some rhythmically laminated intervals in both mudstone and sandstone interbeds (bundled tidal rhythmites); deformed muddy sandstone beds common	bioturbation in mudstone is typically very low, with *Planolites*, *Teichichnus*, *Terebellina,* and *Asterosoma*; rare *Ophiomorpha* in sandstone beds; disseminated organic flecks are common	upward-coarsening	Storm- and tide-influenced prodelta deposits
G2	interlaminated mudstone and very fine sandstone	rhythmically alternating mudstone and sandstone laminae (bundled tidal rhythmites); rhythmites typically form successions that progressively thicken and thin; contacts between sandstone and mudstone laminae are typically gradational	no bioturbation observed; disseminated coal flecks abundant throughout	slightly serrated	tide-dominated delta front deposits (delta front interpretation based on stratigraphic position above Facies G1 and below Facies G3)
G3	medium to very coarse sandstone with thick mudstone interbeds	sandstone beds (~20 cm ave.) are commonly high-angle (>15°) cross-stratified (subaqueous dune cross-stratification); bipolar cross-sets and double mud drapes observed; mud intraclasts present; rare rhythmically laminated intervals (like Facies G2) present	bioturbation very sparse, and includes *Skolithos*, *Diplocraterion* and *Ophiomorpha* in sandstone, and small *Planolites* in mudstone; pebble-sized coal clasts and disseminated coal flecks abundant throughout	serrated, sharp-based upward-fining	tide-influenced fluvial channel fill deposits
Facies G4	organic-rich mudstone with thin rooted coal beds	Stratification is typically not visible, although rare high-angle (>15°) cross-sets (~15 cm thick) are visible locally (subaqueous dune cross-stratification	bioturbation increases upward; trace fossils were hard to identify, but rare *Teichichnus* burrows observed locally	upward-fining	transgressive abandonment deposits (grades up from Facies G3 or G5)
Facies G5	coarse sandstone		bioturbation sparsely throughout (*Ophiomorpha*); rare pebble-sized coal clasts	sharp-based blocky	Tidal inlet fill (occurs over coastal plain (Facies G3 and G3) and under marine (Facies G6 and G7) deposits)
Facies G6	mudstone with thin, very fine sandstone interbeds	sandstone beds are horizontally laminated to low-angle (<10°) cross-stratified (hummocky cross-stratification)	bioturbation in mudstone is typically low, with *Planolites*, *Asterosoma*, *Zoophycos*, *Teichichnus*, *Terebellina,* and *Rosselia*; rare *Ophiomorpha, Cylindrichnus Chondrites* and *Palaeophycus* burrows are present in sandstone	upward-coarsening	Storm-dominated shoreface and offshore deposits
Facies G7	poorly sorted sandstone	typically not visible	bioturbation is locally intense, and *Ophiomorpha* burrows predominate; unlined, sandstone-filled *Thalassinoides* commonly penetrate down from Facies G7 into underlying mudstone	usually thin bed (<1 m thick) with low API values	transgressive lag

and are estimated to contain 35.9 million cubic meters of gas, which is ~50% of the original in-place gas in the Venture Field (Sable Offshore Energy, 2000). Information pertaining to the geology of the Venture Field is provided in Nantais (1983), Hutcheon (1986), Jansa and Noguera Urrea (1990), Drummond (1990), Sable Offshore Energy (1996), Mobil Oil Canada, (1997b,c), Kreisa *et al.*, (1998), Neil *et al.*, (1998), Canada-Nova Scotia Offshore Petroleum Board (2000), and Reimer (2003).

Venture sandstones 8 to 5 occur at the base of the Lower Member of the Missisauga Formation, and overlie the slightly more mudstone-rich strata of the Mic Mac Formation. In the Venture and West Venture fields, Venture sandstones 8 to 5 each consist of an upward-coarsening unit overlain locally by a sharp-based, channel-form unit (Figures 5.11 and 5.12; Table 5.1). Upward-coarsening units are 20-60 m thick, and grade upward from mudstone with sparsely bioturbated, planar laminated and hummocky cross-stratified sandstone interbeds (Figures 5.12a and 5.12b; Facies V2) into sparsely bioturbated sandstone with interstratified low- (<10°) and high-angle (>15°) cross-stratification (Figures 5.12a and 5.12b; Facies V3 and V4). Rarely, carbonate mudstone units occur at the base of upward-coarsening successions (Facies V1). Channel-form units that erosively overlie upward-coarsening units are 10-25 m deep by 7-13 km wide and contain abundant mudstone and high-angle (>15°) cross-stratified sandstone, rare rhythmic lamination, little bioturbation, and rare rooted coal (Figures 5.12c and 5.12d; Facies V5 to V8). A continuous thin layer (<1 m) of bioturbated, poorly sorted sandstone (Facies V9) erosively overlies the top of each upward-coarsening and channel fill succession.

In strike cross section, Venture sandstones 8 to 5 thicken towards a growth fault zone between the Venture and West Venture fields, which is also the location of most of the channel-form units (Figure 5.11a). In dip-cross section, sandstones pinch out downdip over <5 km except for Venture sandstone 6, which appears to thicken downdip to a >200 m-thick upward-coarsening succession (Figure 5.11b). Above Venture sandstones 8 to 5, upward-coarsening units are typically more isopachous and easier to correlate between Venture and South Venture wells.

Each upward-coarsening succession is interpreted to have formed during a single cycle of relative sea level fall and rise. Upward-coarsening successions with abundant low-angle (<10°) cross-stratified sandstone are inferred to be regressive storm-dominated prodelta and delta front deposits. Carbonate mudstone present at the base of some upward-coarsening successions likely represent marine condensed sections formed during maximum transgression and terrigenous sediment starvation. Channel-form erosion surfaces at the top of the upward-coarsening units are interpreted to be incised valleys formed during sea level fall, which were then filled with heterolithic facies (tide-dominated estuarine deposits) emplaced during subsequent sea level rise. The change from regressive, storm-dominated sedimentation to tide-dominated transgressive sedimentation suggests that once relative sea level started to rise, tidal currents were strengthened as incised valleys became progressively drowned.

5.4.2 Sedimentology - Alma Field (Upper Missisauga)

The Alma F-67 well was drilled by Shell/Petro-Canada *et al.* in 1983 to test for hydrocarbons in a rollover anticline trap formed in the hanging wall of an east-west-

trending growth fault (Figure 5.13). Gas was encountered in three heterolithic, vertically stacked and isolated Barremian reservoir intervals informally termed the Alma A, B, and C "sands" (Figure 5.14; Lentin, 1987; Sable Offshore Energy, 1996; Canada-Nova Scotia Offshore Petroleum Board, 2000). A second well, Alma K-85, was drilled in 1985 to delineate the field. Development drilling started in 2003 under the Sable Offshore Project (Sable Offshore Energy, 1996). Original gas in-place is estimated to be 630 billion cubic feet (~17.8 m^3 x 10^9), which is ~7% of the original gas in-place discovered offshore Nova Scotia prior to 2000 (Canada-Nova Scotia Offshore Petroleum Board, 2000). "Sand" A is the main Alma reservoir, and is estimated to contain ~77% of the original gas in-place in the Alma field (Canada-Nova Scotia Offshore Petroleum Board, 2000). Several unpublished studies contain data on the structure and sedimentology of the Alma field (Sable Offshore Energy, 1996; Mobil Oil Canada, 1998a; Canada-Nova Scotia Offshore Petroleum Board, 2000; Ingram, 2002).

At Alma, the Missisauga sandstone package is relatively thin (~268 m; MacLean and Wade, 1993) and young (Barremian to Aptian; Lentin, 1987; late Hauterivian to Barremian, Jason Crux, personal communication, 2004), and is interpreted to correlate with the Upper Member of the Missisauga Formation (*cf.* MacLean and Wade, 1993). Microfossil data from the Alma F-67 well suggests that rapid and substantial shallowing started to occur ~125 m below the base of the Upper Missisauga sandstones within mudstone of the Verrill Canyon Formation, and that rapid deepening occurred at the top of the Upper Missisauga (Lentin, 1988; Figure 5.14). The onset of overpressuring occurs ~400 m below the sandstone-rich Upper Missisauga within Verrill Canyon mudstone (Figure 5.10 and 5.14).

The Upper Missisauga at Alma consists entirely of stacked, upward-coarsening successions between 10 and ~200 m thick (Facies A1 to A4), with the exception of one ~30 m thick, intensely bioturbated, sharp-based upward-fining unit (Facies A5), which defines the transition between the sandstone-rich Upper Missisauga and monotonous mudstone of the Naskapi Member. Upward-coarsening units are commonly capped by a thin (<1 m), sharp-based layer of poorly sorted sandstone (Facies A4) and internally consist of mudstone (Facies A1) that either grades up into or is sharply-overlain by variably bioturbated, planar laminated and hummocky cross-stratified sandstone (Figure 5.15; Facies A2 and A3) . In general, the following upward trends were noted in the Upper Missisauga at Alma: 1) soft-sediment deformation become less common, 2) upward-coarsening units become thinner, 3) well-sorted sandstone that makes up the top half of upward-coarsening units are more commonly sharp-based, 4) thin layers of poorly sorted sandstone (Facies A4) that cap upward-coarsening units become better developed, and 5) the only upward-fining-unit occurs at the top of the Upper Missisauga immediately below thick, monotonous Naskapi mudstone.

Upward-coarsening units at Alma are interpreted to be regressive, storm-dominated prodelta and delta front deposits capped by thin lags formed by transgressive ravinement during shoreface retreat. Because no obvious incised-valley fills are present, the upward-coarsening units could equally be interpreted as regressive, storm-dominated shoreface deposits. The bioturbated, sharp-based, upward-fining unit at the top of the Upper Missisauga at Alma is interpreted to be a transgressively reworked lowstand sand - body (*e.g.*, Berné *et al.*, 1998; Snedden and Dalrymple, 1999). Trends in the data mentioned above are discussed below.

5.4.3 Sedimentology – Glenelg Field (Upper Missisauga)

The Glenelg J-48 well was drilled by Shell/Petro-Canada *et al.* in 1983 to test for hydrocarbons in a rollover anticline trap formed in the hanging wall of a northeast-southwest-trending growth fault (Figure 5.16). Economic volumes of gas were encountered in several sandstone reservoirs in the Upper Member of the Missisauga Formation (Figure 5.17). Three delineation wells were subsequently drilled in the early 1980s (Glenelg E-58 (plus a whipstock, E-58A), H-38, and N-49), and development drilling started in 2003 under the Sable Offshore Project (Sable Offshore Energy, 1996). Original gas in place is estimated to be 672 billion cubic feet (~19 m^3 x 10^9), which is ~7.6% of the original gas in-place discovered offshore Nova Scotia prior to 2000 (Canada-Nova Scotia Offshore Petroleum Board, 2000). Almost half of the gas at Glenelg occurs in two pools located in the top ~200 m of the Missisauga immediately below shale of the Naskapi Member (the Glenelg B and C pools; Sable Offshore Energy, 1996; Canada-Nova Scotia Offshore Petroleum Board, 2000). Several published papers, unpublished reports and conference abstracts present data on the structure and sedimentology of the Glenelg field reservoirs (Sable Offshore Energy, 1996; Welsink *et al.*, 1989; Canada-Nova Scotia Offshore Petroleum Board, 2000; Ingram, 2002; MacRae, 2003a).

At Glenelg, the Missisauga Formation forms a thick (up to 1.3 km), upward-coarsening succession that overlies monotonous shale of the Verrill Canyon Formation, which in turn is overlain by ~80 to 300 m of Naskapi shale (Figure 5.18). The onset of overpressuring occurs within mudstone-rich strata immediately below ~200 m of sandstone-rich strata at the top of the Missisauga (Figures 5.10 and 5.18).

Biostratigraphic data indicate that this sandstone-rich interval is Hauterivian to Barremian (Ascoli, 1990; Robertson Research, unpublished data; MacLean and Wade, 1993), suggesting that sand arrived simultaneously at Glenelg and Alma during deposition of the Missisauga Formation[18]. The O Marker, which is present at the base of the Upper Missisauga throughout the proximal Sable Subbasin, is only locally developed in the Glenelg wells (MacLean and Wade, 1993) and was not identified in seismic data (see Figures 5.6 and 5.7).

Deposition of the sandstone-rich uppermost ~300 m of the Missisauga Formation at Glenelg apparently occurred in three phases, and deposited three distinct units (Figures 5.18 and 5.19). The lowermost unit is a subtle, thick (~100 m) upward-coarsening succession that marks the transition from monotonous mudstone to sandstone approximately 350 m below the top of the Upper Missisauga. The unit is composed predominantly of variably bioturbated mudstone, and contains deformed beds, low-angle (<10°) cross-stratified sandstone beds, and thin (<1 m) rhythmically laminated intervals of sandstone and mudstone that become increasingly common upward (Figure 5.19a; Facies G1 and G2). Locally, this is erosively overlain by the second unit, a heterolithic, channel-form unit approximately ~50 m thick by (at least) 2.5 km wide. The heterotlithic channel-form unit contains rare bioturbation and rare rhythmically laminated intervals, abundant dune cross-stratified sandstone, coarser-grained sandstone, and rare, thin (<10 cm) rooted coals (Figure 5.19b; Facies G3, G4). The heterolithic, channel-form unit is overlain by the third unit, which consists of stacked, upward-coarsening successions. Each upward-coarsening succession grades upward from mudstone into planar laminated and hummocky cross-stratified sandstone (Figure 5.19c; Facies G6). In contrast to the

[18] Sandstones located below the Upper Missisauga at Glenelg may be slope turbidite deposits – see later

lowermost unit described above, which consists of a single, thick, upward-coarsening succession (~100 m), upward-coarsening successions in the uppermost unit are thinner (10 to 50 m), and contain no rhythmically laminated intervals and fewer deformed beds.

The three units identified at Glenelg are interpreted to reflect (1) an initial period of tide-influenced prodelta and delta front deposition, followed by (2) valley incision and tide-dominated estuarine infill, and (3) several episodes of storm-dominated deltaic regression. The upward-coarsening nature of the lowermost unit is interpreted to represent an initial phase of deltaic regression. Rhythmically laminated intervals and hummocky cross-stratified sandstone beds suggest that both tides and storms affected deposition (this point discussed more fully below). The sharp-based, heterolithic channel-form unit that locally erodes into the top of the upward-coarsening succession is interpreted to be a tide-dominated estuarine incised valley fill. This interpretation is based on its thickness (~50 m) and multi-storied fill (at least 3 upward-fining channel fills), on the abundance of mudstone, presence of tidal rhythmites and thin coals, and low density and diversity of trace fossils and fossil dinoflagellates. Stacked, upward-coarsening units that overlie the valley fill, which are the main hydrocarbon-reservoirs, contain abundant hummocky cross-stratified sandstone beds, and are interpreted to be regressive, storm-dominated prodelta and delta front deposits.

5.5 Seismic data

Large-scale (*i.e.*, a minimum of several hundred meters relief) clinoform reflections are observed within or downdip of the stratigraphic sections investigated in

the Venture and Alma fields (Figures 5.20 and 5.21). The resolution of seismic data from the Glenelg field is too low to image stratigraphy (Figure 5.7).

Lower Missisauga and Mic Mac seismic reflections in the Venture Field are interpreted to correlate downdip to a package of large-scale (*i.e.*, over one kilometer relief) clinoform reflections (Figure 5.20). The package of clinoform reflections is located 5 to 20 km downdip of the Venture Field. Although, correlation of individual reflections is not possible because of intervening faults, the general stratigraphic position of the clinoforms suggests that they are likely Upper Jurassic in age, and correlate with the upper parts of the Mic Mac Formation and the Lower Member of the Missisauga Formation. Because of their relief, Upper Jurassic clinoform reflections are interpreted to be continental slope as opposed to shelf delta deposits.

The Upper Missisauga at Alma correlates southsoutheastward with a package of large-scale (*i.e.*, >0.5 km relief) clinoform reflections (Figure 5.21). The O Marker, which demarcates the base of the Upper Missisauga, forms a gently southeastward-dipping reflections that plunges basinward of the master Alma growth fault that bounds the north side of the field. Basinward of the master Alma fault, the O Marker reflections is interpreted to downdrop and split into several strong, large-scale clinoform reflections located immediately below Upper Missisauga sandstones in the Alma Field (*e.g.*, MacLean and Wade, 1993). The relief of the clinoform reflections at Alma (>0.5 km) suggests they are continental slope deposits.

Although the anticlinal geometry of the trap at Glenelg can be imaged seimically (Figure 5.7), Upper Missisauga strata are poorly resolved at Glenelg because of low signal-to-noise ratio at depth. Accordingly, few conclusions can be made regarding the

paleogeographic setting at Glenelg during deposition of the Upper Missisauga based solely on seismic data.

The Tithonian (*i.e.*, Lower Missisauga) shelf margin is interpreted to be located between 5 and 25 km downdip of Venture. Limited seismic data suggests that the Tithonian shelf margin trends approximately E-W (Figure 5.23). The Barremian (*i.e.*, Upper Missisauga) shelf margin trend can be traced from Alma westward onto the lower-accommodation western rim of the subbasin, where it is unfaulted and clearly resolved in seismic data (Figure 5.22). The region east of Alma is the only place in the Sable Subbasin where Barremian slope clinoforms are clearly resolved in seismic data from shelf edge to toe of slope (Figure 5.22). Here, Barremian slope clinoform reflections have a relief of ~400 m and run-out distance of ~13 km. Growth faults are absent and there is no seismic evidence for basin floor fans, although the progradational nature of the clinoforms suggests sediment was transferred to the slope. East of Alma, the Barremian shelf margin trend is increasingly disrupted by growth faults, and becomes difficult to identify in seismic data as it enters a seismic noise zone below the modern shelf margin.

5.6 Identifying ancient shelf margin positions

The following discussion summarizes the case that can be made for a shelf margin delta interpretation for deposits investigated in the Alma, Glenelg and Venture fields. A shelf margin origin is suggested based on the following characteristics, which occur in some number in each of the three fields: (1) association with thick, upward-coarsening successions (>100 m), (2) proximity to large-scale (*i.e.*, at least several-hundred-meter relief) clinoform reflections, (3) occurrence above significantly more mudstone-rich

strata, (4) common occurrence of gravity-flow deposits, (5) association with conditions of pore fluid overpressure, (6) association with large-scale growth faults, and (7) paleoecological evidence suggesting rapid shallowing (Figure 5.24).

5.6.1 Thick upward-coarsening successions

Particularly thick upward-coarsening successions occur at the base of the stratal succession studied in the Alma, Glenelg and Venture fields (Figures 5.11, 5.14, and 5.18). At Alma, the upward-coarsening succession at the base of Upper Missisauga sandstones is ~100 m thick, and at Glenelg it is ~125 m thick. At Venture, the upward-coarsening succession associated with Venture sandstone 8 at the base of the Lower Missisauga is only ~55 m thick (measured from the middle of Venture limestone 9, which is interpreted to be a maximum flooding surface); however, in the top of the Mic Mac Formation upward-coarsening successions are typically more than 100 m thick. Also, Lower Missisauga upward-coarsening successions ~5 km south of Venture in the South Venture O-59 well are upwards of 250 m thick. These thick, upward-coarsening successions are interpreted to reflect shelf margin deposition and progradation.

Shelf margin deltas form where rivers cross the continental shelf and deposit their sediment on the outer shelf and upper slope. Although they can form during sea level highstand if sediment supply is sufficiently high (*e.g.*, the modern Balize lobe of the Mississippi River delta), shelf-margin deltas more commonly form during sea level fall and lowstand, because long-distance regression is likely easier to achieve during forced regression (Muto and Steel, 2002), which is independent of sediment supply[19]. During

[19] Relative sea level rises during normal regression (*e.g.*, during deposition of the highstand and lowstand systems tracts *sensu* Plint and Nummedal, 2000), which generates accommodation space in both deltaic topsets and foresets: the

the initial stages of forced regression in inner to mid shelf regions, deltas tend to deposit thin upward-coarsening successions, usually no more than several tens-of-meters, because water depths are shallow and accommodation remains negative as long as sea level keeps falling and shelf gradient does not increase (Posamentier *et al.*, 1992; Porebski and Steel, 2003). However, as deltas reach the outer shelf, they deposit thicker upward-coarsening successions because the rate of sea level fall tends to slow while subsidence rate and seafloor gradient tend to increase. If the delta shoreline reaches the shelf edge, sediment is delivered to the continental slope; at an extreme, delta foresets will downlap the entire continental slope[20]. Shelf-margin deltas, therefore, typically deposit much thicker upward-coarsening successions than their "shelf-phase" counterparts (Winker and Edwards, 1983; Suter and Berryhill, 1985).

5.6.2 Large-scale clinoform reflections

The large-scale (*i.e.*, hundreds-of-meters plus relief) clinoform reflections observed at Venture and Alma support a shelf margin paleogeographic setting (Figures 5.20 and 5.21). Regional subsidence associated with thermal cooling of the lithosphere and sediment loading cause water depth in front of an accreting passive continental margin to increase with time. As a consequence, the relief of continental slope clinoforms tends to increase with time as the passive margin basin matures. In modern

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topset-foreset area increases constantly. Because of this, at some point fluvial sediment discharge will not be able to prograde the shoreline further basinward, unless sediment influx also increases constantly or was very high to begin with. When fluvial sediment supply becomes insufficient to further prograde the deltaic shoreline, deltaic shoreline will not only halt, but may even start to retrograde, a phenomenon known as *autoretreat* (Muto and Steel, 1992; Swenson *et al.*, 2000). Because regression will occur during falling relative sea level irrespective of sediment flux to the shoreline, it is believed that long distance regression (*e.g.*, from the highstand shoreline to the shelf edge) is more easily accomplished by forced as opposed to normal regression (Muto and Steel, 2002).

[20] A continental slope (or simply "slope"), in contrast to a deltaic slope, is defined here as a clinoform surface that has surpassed some critical limit of relief and inclination, which observation suggests is commonly on the order of >180 m relief and >2° inclination, which in turn renders it sufficiently unstable to develop thick, sandy to heterolithic slope and basin-floor turbidite depositional systems (Porebski and Steel., 2003; Donovan, 2003)

passive margin basins, continental slope clinoforms commonly have a relief of several kilometers. For example, modern slope clinoforms (>1° gradient) offshore of the western margin of Africa and the eastern margins of North and South America have reliefs in excess of three kilometers (O'Grady *et al.*, 2000). As mentioned previously, shelf-phase delta clinoforms are commonly an order of magnitude smaller than those on mature continental margins (*i.e.* tens-of-meters versus hundreds-of-meters to kilometer relief). At Venture and Alma, therefore, the association of marginal marine strata with the large-scale (*i.e.*, < 0.5 km relief) clinoform reflections supports a shelf margin paleogeographic interpretation[21]

5.6.3 Stratigraphic position over relatively mudstone-rich deposits

The Upper Missisauga at Alma and Glenelg and the Lower Missisauga at Venture are comparatively more sandstone-rich than underlying strata (Figures 5.11, 5.14, and 5.18). This is interpreted to reflect shelf margin progradation. On modern unglaciated shelves, most sediment is trapped within several tens-of-kilometers of the shoreline because of several factors, including: 1) the "littoral fence" caused by asymmetric shoaling, fairweather wave orbitals, which rework sand onshore during fairweather periods; 2) a low downslope gravitational force caused by low shelf gradients (<0.1°), which hinders sand-rich turbidity current ignition; 3) rapid flocculation of mud suspended in river plumes; 4) the Coriolis force, which causes offshore-flowing currents to deviate parallel to shore; and 5) flood-dominance typical of coastal tidal currents, which trap sand

[21] Assuming that shelf-slope profiles during Missisauga deposition were analogous to modern shelf-slope profiles, Missisauga shelf-phase deltas could only have grown to a maximum of ~200 m relief, assuming that the shelf edge depth acted as the limit to upward growth. All clinoform reflections discussed here have at least twice that relief; they are therefore interpreted to have formed by progradation of the entire continental slope.

in zones of bedload convergence in estuaries and tidally influenced and dominated deltas (Postma, 1967; Pantin, 1979, 1983; Parker, 1982; Swift and Niederoda, 1985; Garvine, 1999; Droppo, 2001; Dalrymple and Choi, 2003; Dalrymple and Cummings, 2004; Geyer *et al.*, 2004). As a consequence, little new sediment (especially sand) is likely to reach the continental slope unless shorelines reach the shelf edge during regression. The occurrence of the sand-rich strata studied here above more mudstone-rich strata of the Verrill Canyon (Alma, Glenelg) and Mic Mac formations (Venture) is therefore interpreted to be a result of the shelf margin reaching those localities as it prograded incrementally basinward[22]. Sandstone-rich strata studied were therefore likely deposited at or slightly landward of the shelf edge, a hypothesis that is supported by the general upward-thinning of successive upward-coarsening units (*e.g.*, Figures 5.14 and 5.18).

5.6.4 Mass movement and gravity-flow deposits

The stratigraphic successions at Alma and Glenelg contain common mass movement and sediment gravity-flow deposits. As argued above, because continental slope clinoforms have steeper gradients (typically >2°; O'Grady *et al.*, 2000) and greater reliefs than shelf-phase deltaic clinoforms, sediment gravity-flows (turbidity currents, debris flows, slumps) are more likely to be initiated on deltas that downlap the continental slope (Pulham, 1989; Martinsen, 1989, 1990; Collinson *et al.*, 1991; Plink-Björklund *et al.*, 2001; Steel *et al.*, 2003; Mellere *et al.*, 2003; Donovan, 2003). Lack of gravity-flow deposits in the interval investigated at Venture may suggest deposition in slightly shallower water on the outer continental shelf, an interpretation supported by the

[22] Some of the sandstone bodies in the relatively mudstone-rich deposits that underlie the studied intervals are potential slope turbidite deposits

position of Venture ~5 to 20 km updip (paleolandward) of, as opposed to directly within (*e.g.*, Alma), a package of large-scale clinoform reflections. The upward decrease in abundance of sediment gravity-flow deposits in the Upper Missisauga at Alma and Glenelg is interpreted to reflect a change from upper slope to outer shelf deposition as the shelf margin prograded to and past these locations.

5.6.5 Growth faults

Major listric growth faults that occur in Alma, Glenelg and Venture fields are interpreted to reflect a shelf margin paleogeographic setting (Figure 5.7, 5.20, and 5.21). Gravity instability and sliding of continental slope strata tends to form a strongly extensional regime at the shelf margin. Growth faults are therefore common along shelf margins, especially those supplied by a high fluvial sediment flux (Winker and Edwards, 1983).

5.6.6 Overpressure

In the intensely growth-faulted central Sable Subbasin, the top of pore-fluid overpressure occurs in monotonous mudstone several tens- to hundreds-of-meters below the sandstone-rich Upper Missisauga reservoir intervals at Alma and Glenelg. At Venture, the top of overpressure occurs just below the top of the Lower Missisauga. In contrast, pore-fluid overpressure is absent on the periphery of the Sable Subbasin where growth faults are absent (*e.g.*, Panuke Field).

The top of overpressure in the Sable Subbasin is interpreted to be the result of unstable terrigenous clastic shelf-margin progradation. (Local anomalies in pore-fluid

overpressure below the top of overpressure ("hard overpressures") may be due to hydrocarbon generation or local variations in diagenetic processes (Nantais *et al.*, 2004).) In an accreting shelf margin, the upper slope just basinward of the shelf edge experiences the highest sedimentation rates, which in turn promotes shelf-margin progradation (Pirmez *et al.*, 1998). If, as discussed earlier, sediment supply is sufficiently high, the shelf margin becomes gravitationally unstable and growth faults form. Early movement along shelf-margin growth faults can hydraulically isolate underlying shelf margin and slope deposits, causing pore fluids to become trapped and overpressured as deposition and burial compaction continues. The observed basinward younging of the top of overpressure in the Sable Subbasin (Wade and MacLean, 1990; MacLean and Wade, 1993; Nantais *et al.*, 2004) is therefore consistent with unstable shelf-margin progadation (see Winker and Edwards, 1982).

5.6.7 Paleoecological evidence of rapid shallowing

Microfossil assemblages suggest that rapid shallowing occurred ~150 m below the base of the Upper Missisauga within shales of the Verrill Canyon Formation in the Alma F-67 well (Figure 5.14; Lentin, 1988). No similar microfossil data were available for Venture or Glenelg wells. Paleoecological evidence for significant and rapid shallowing, or what has been termed *foreshortened stratigraphy* (Posamentier and Morris, 2000), is commonly observed in shelf-margin delta deposits (Winn *et al.*, 1998), likely because physical and chemical conditions change substantially at the shelf margin (*e.g.*, substrate, energy level, food distribution, oxygenation, freshwater input) over the course of a long-distance regression that brings shorelines to the shelf edge.

5.7 Discussion

5.7.1 A tide-dominated shelf margin delta?

In passive margin basins, deltas are believed to commonly become more wave-influenced as they approach the shelf margin, and switch to a tidally-influenced state only upon transgression (Suter, 2001; Yoshida *et al.*, 2003). In theory, this hypothesis works well because (1) waves tend to experience less bottom friction as shelf widths decrease (Swift and Thorne, 1991), (2) tidal ranges tend to be amplified on particularly wide continental shelves (Archer and Hubbard, 2003), (3) the volume of water entering and exiting the coastal plain, termed the tidal prism, tends to increase as low-lying coastal plains are progressively flooded (Dalrymple, 1992), and (4) incised river valleys can become tidally-resonant when inundated (*e.g.*, Bay of Fundy; Dalrymple, 1992). Ancient wave-dominated shelf margin delta deposits have commonly been documented (*e.g.*, Morton and Suter, 1996; Porebski and Steel, 2003), as have fluvially-dominated examples presumably deposited in smaller, fetch-limited basins where wave energy at the shelf margin was low (*e.g.*, Pulham, 1989; Mellere *et al.*, 2003). In contrast, a strong tidal control on delta facies and architecture, although commonly observed in modern shelf-phase deltas (Dalrymple *et al.*, 2003), has not been interpreted in ancient shelf margin delta deposits.

In view of the above observations, it is tempting to interpret the tide-influenced (dominated?) ~125 m-thick upward-coarsening succession at Glenelg as something other than a shelf margin delta deposit. Tidal influence is unequivocal: rhythmically-laminated intervals are sparsely distributed throughout the upward-coarsening muddy prodelta deposits and become extremely well developed directly beneath the base of the incised

valley[23]. A possible explanation for this is that the delta prograded into a tidally-resonant bayhead of an incised valley. However, incised valleys are typically only several tens-of-meters deep, and tend only to be deeper if formed under extreme conditions of relative sea level fall, for instance during the draining of the Mediterranean in the Messinian (*e.g.*, Zaitlin *et al.*, 1994). A more likely interpretation is that topography similar to an incised valley existed at the shelf margin, perhaps at the head of an incised slope canyon[24]. Such a scenario could account for the presence of tidal rhythmites and thickness of the upward-coarsening succession located ~350 m below the top of the Missisauga at Glenelg (Figure 5.25). The tide-dominated shelf margin delta interpreted from the Glenelg Field suggests that current shelf margin delta models, just like early facies models for shelf-phase deltas (which were based almost exclusively on the Mississippi Delta), are perhaps based on too limited a dataset. It seems likely that as more data are collected and synthesized, a broader range of styles of shelf-margin deposition, perhaps similar to that currently documented for shelf-phase deltas (*e.g.*, Galloway, 1975; Reading and Collinson, 1996), will be recognized.

5.7.2 Offset vs. vertical lobe stacking

Shelf margin deltas commonly have an offset stacking pattern (*e.g.*, Roberts *et al.*, 2002), presumably because lowstand fluvial-detaic shorelines tend to prograde into topographic lows between older shelf margin sand bodies. However, Venture sandstones 8 to 5, interpreted to be shelf margin delta deposits, stack vertically with incised valleys

[23] Although more commonly associated with protected coastal plain regions (*e.g.*, mudflats, tidally-influenced fluvial point bars; Dalrymple *et al.*, 1991; Li *et al.*, 2000), convincing tidal rhythmites have also been reported in both modern and ancient delta front deposits (Smith *et al.*, 1990; Williams, 1991; Jaeger and Nittrouer, 1995; Kuehl *et al.*, 1996; Miller and Eriksson, 1997).

[24] It is useful to note that elongate topographic elements occur at the shelf margin, even in supply dominated settings (*e.g.*, Swatch of No Ground, offshore Ganges-Brahmaputra Delta).

located consistently in the thickest part of the deltaic sandstone body. This suggests that, if loaded sufficiently, shelf margin depocenters will have sufficient growth-fault related subsidence to negate depositional topography and create topographic lows through which subsequent lowstand fluvio-deltaic systems would preferentially flow. This hypothesis is supported by observations from the Late Pleistocene shelf margin offshore of the Orinoco River, Venezuela, where high rates of deposition and significant growth-fault related subsidence has created ~45 m deep fault scarps on the seafloor at the shelf margin (Sydow *et al.*, 2003). This observation has important implications for exploration downdip of the shelf margin; namely, that incised valleys, and thus the upper portions of any possible (downdip) slope turbidite systems, will most likely be located where shelf margin growth fault subsidence was greatest.

5.7.3 Turbidites vs. storm beds at the shelf margin

Shelf-margin delta deposits in all fields investigated are interpreted to consist, at least in part, of hummocky cross-stratified sandstone. In the Alma, Glenelg, and Venture fields hummocky cross-stratified sandstone forms the main reservoir. Although it can resemble antidune cross-stratification formed in shallow water flows or density-stratified turbidity currents (Alexander *et al.*, 2001), hummocky cross-stratification is typically inferred to form between storm and fairweather wave base under the influence of energetic, long period storm waves (Southard *et al.*, 1990; Arnott and Southard, 1990; Dumas, 2004). Hummocky cross-stratification has certain key features that allow it to be identified in core, including low-angle dip ($<10^{o}$) of curved and planar laminae, presence of low-angle truncations within a bed, gentle upward fanning of laminae, common

upward-fining trends, and association with small, capping wave-ripples. The abundance of hummocky cross-stratified sandstone at all localities suggests that shelf margin deltas were typically wave-dominated, with the exception of the tidally-dominated shelf margin delta at Glenelg discussed above.

However, as oscillatory velocity increases or unidirectional currents strengthen, storm waves can also deposit oscillatory (and combined flow) plane bed, which arguably will be indistinguishable from planar laminated sandstone deposited from turbidity currents (*i.e.*, Bouma T_b turbidites; unless laminae display subtle "wavyness"; see Arnott, 1993). As planar laminated turbidites are common in shelf margin delta front deposits (Steel *et al.*, 2003), many of the planar laminated sandstone beds observed in the Glenelg and Alma fields could be turbidity current deposits as opposed to oscillatory plane bed deposits (or perhaps a mix of both? *e.g.*, Myrow and Southard, 1996; Wright *et al.*, 2001). Turbidity current deposition is inferred to have occurred at Glenelg and Alma because current ripples, although rare, are present locally in prodelta and delta front deposits, either on top of planar laminated beds or isolated within mudstone. In contrast, current ripples were not observed in upward-coarsening successions in more proximally-located fields (*e.g.*, the Naskapi Member in the Panuke Field; see Chapter 3), where planar-laminated beds were capped by small wave ripple cross sets (if any). It is possible, therefore, that the type of ripple (wave vs. current) that caps planar-laminated beds in upward-coarsening successions may provide an additional criterion useful in differentiating shelf and shelf-margin paleogeographic settings.

5.7.4 Shoreface vs. delta front

All upward-coarsening successions at Alma, and most upward-coarsening successions at Glenelg, apparently lack associated fluvial deposits. Except for transgressive lags, upward-coarsening successions are composed entirely of regressively-deposited shallow-marine sandstone and mudstone. Traditionally, these strata would be interpreted as shoreface deposits because they lack obvious fluvial feeder systems. However, lack of fluvial deposits may simply be a result of transgressive ravinement, a process that is capable of removing all evidence of fluvial feeder systems (*ca.* 6-15 m of Holocene ravinement in Gulf Coast of Mexico – Rodriguez *et al.*, 2001). Furthermore, upward-coarsening successions are typically sparsely bioturbated, which might suggest deposition in a delta front setting that was stressed by fluvial discharge induced salinity fluctuations (Gingras *et al.*, 1998). Intense bioturbation in some upward-coarsening sandstones in the Alma Field may suggest deposition down-coast of the main fluvial input in a shoreface environment (Gingras *et al.*, 1998).

5.7.5 What is the Sable Delta?

Sable Delta is a colloquial term used to describe deposits of the Mic Mac and Missisauga formations accumulated during regression in the Sable Subbasin (*e.g.*, Eliuk, 1978; Wade and MacLean, 1990; Sable Offshore Energy, 1996; Canada Nova Scotia Offshore Petroleum Board, 2000). Net regression did indeed occur, as indicated by upward-coarsening trends observed in well log and cuttings data and large-scale, progradational clinoform reflections observed locally in seismic data (Figures 5.20 to 5.22). However, this large-scale, long-term regression was not strictly "deltaic" in

nature, but was related to progradation of the entire shelf margin. Although deltaic deposits form volumetrically-important but individually-minute stratigraphic building blocks within the Missisauga Formation, the use of the term "Sable Delta" to describe net regression during deposition of the Mic Mac and Missisauga formations is misleading. Simply put, the Sable Delta is a prograding shelf margin.

5.9 Summary

Approximately 128 m^3 x 10^6 (4527 BCF), or 50% of the original in-place gas reserves discovered offshore Nova Scotia are interpreted to be hosted in shelf-margin delta sandstones (Alma, Glenelg, and Venture/West Venture/South Venture fields; Canada Nova Scotia Offshore Petroleum Board, 2000). Although seemingly high, it is not anomalous when compared to other passive margin basins such as the U.S. Gulf Coast, where almost all of the largest hydrocarbon discoveries (*i.e.*, multiple Tcf) discoveries made in onshore and shelf regions over the past 30 years (*e.g.*, Wilcox, Frio, Vicksburg) are in shelf-margin delta deposits (Meckel, 2003).

Recognition of the shelf-margin delta play type offshore Nova Scotia will not only aid production strategies employed in existing fields, but will provide a framework to guide exploration in genetically related parts of the stratigraphic section. On a production scale, it is important to consider the shelf-margin-parallel form typical of shelf-margin delta sandbodies (*i.e.*, commonly over several tens of kilometers), which reflect subsidence along the shelf margin and alongshore wave reworking (Suter and Berryhill, 1985). On an exploration scale, identifying shelf-margin trends is important because shelf-margin deltas typically form simultaneously along a shelf margin,

producing what has been referred to as a "string of pearls" (Meckel, 2003). Shelf-margin deltas also commonly act as staging areas for sediment exiting shelf incised-valleys and entering slope and basin floor turbidite systems (Steel *et al.*, 2003). Identifying shelf-margin depocenters is therefore an important first step when developing deepwater exploration strategies in passive margin basins like offshore Nova Scotia.

Figure 5.1 Location map of study area, showing depth to basement of passive margin basin fill, offshore Nova Scotia. Contours are in kilometers (modified from MacLean and Wade, 1992).

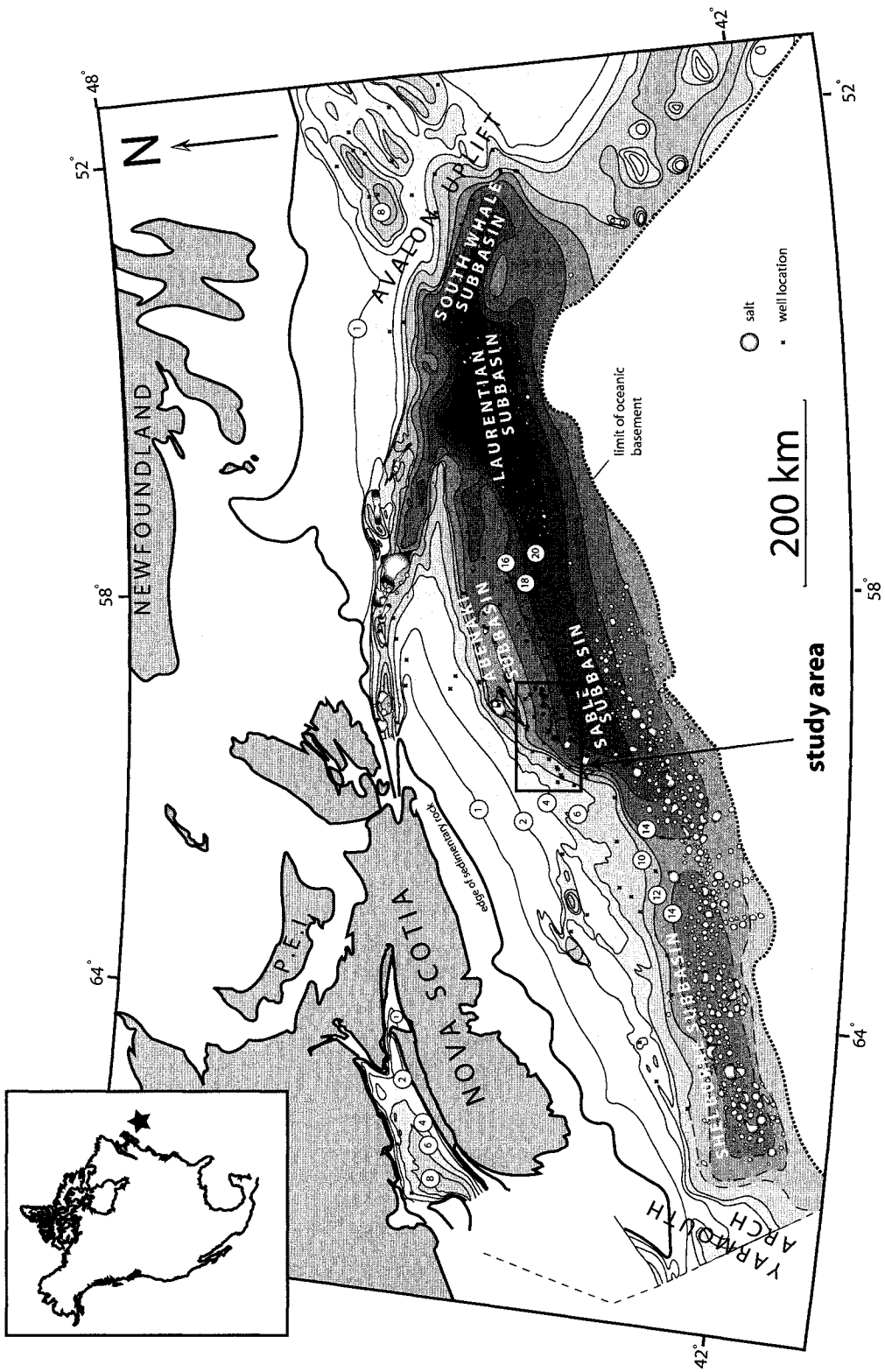

N
NEWFOUNDLAND
NOVA SCOTIA
P.E.I
AVALON UPLIFT
SOUTH WHALE SUBBASIN
LAURENTIAN SUBBASIN
SABLE SUBBASIN
YARMOUTH ARCH
edge of sedimentary rock
limit of oceanic basement
salt
well location
200 km
study area
48°
52°
58°
64°
42°

Figure 5.2a Location of core data from the Missisauga Formation used in this study, Sable Subbasin, offshore Nova Scotia.

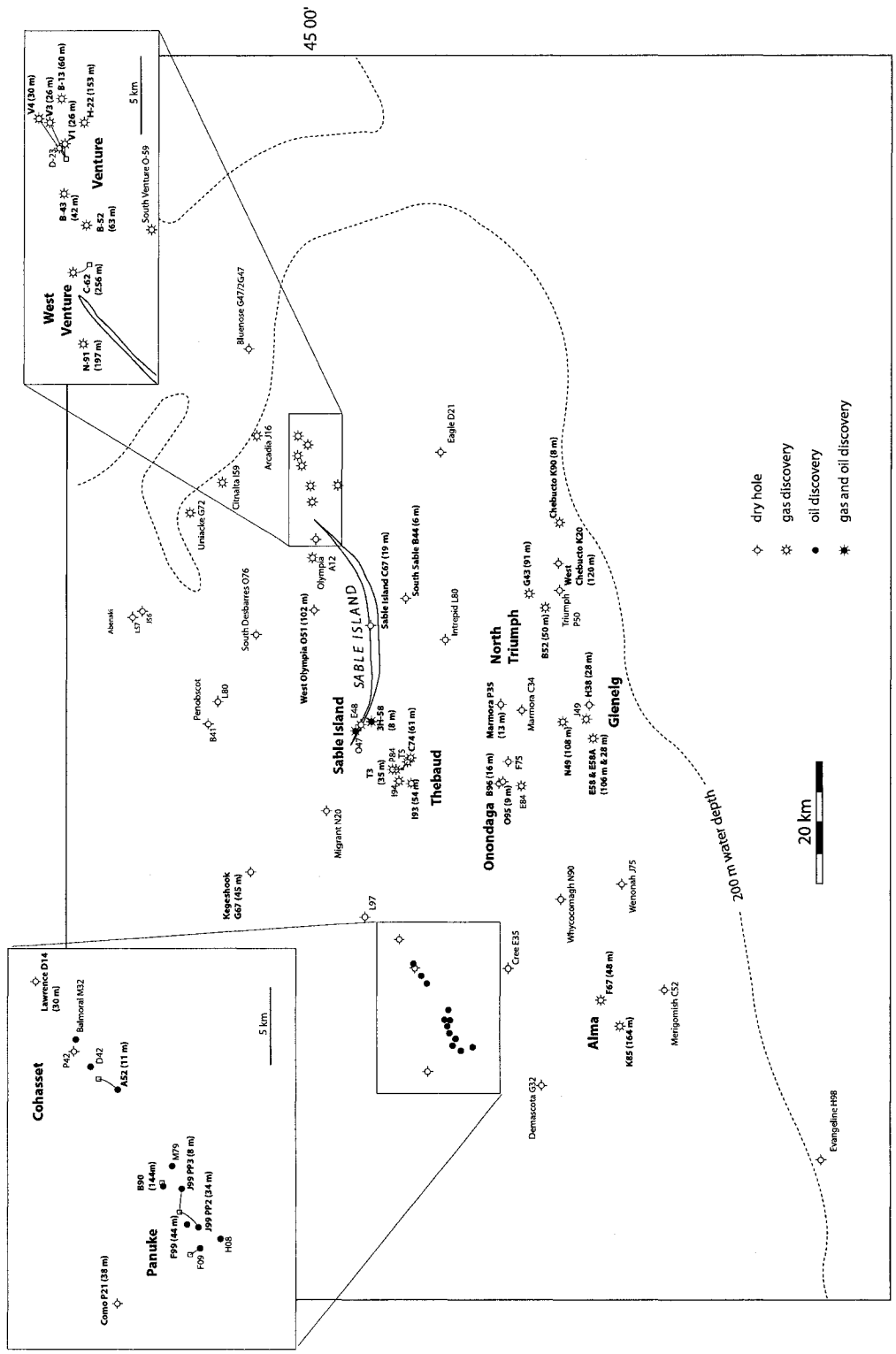

45 00'
60 00'
59 00'
61 00'
West Venture
N-91 (197 m)
C-62 (256 m)
Venture
B-43 (42 m)
B-52 (63 m)
South Venture O-59
V4 (30 m)
V3 (26 m)
V1 (26 m)
D-23
B-13 (60 m)
H-22 (153 m)
5 km
Bluenose G47/2G47
Arcadia J16
Cinnalta I59
Uniacke G72
Olympia A12
West Olympia O51 (102 m)
South Desbarres O76
Aberaki
L57
I65
Penobscot
B41
L80
SABLE ISLAND
Sable Island
E48
O47
3H-58 (8 m)
T3 (35 m)
I94
I84
I5
I93 (54 m)
C74 (61 m)
Thebaud
Migrant N20
Sable Island C67 (19 m)
South Sable B44 (6 m)
Intrepid L80
Eagle D21
Onondaga B96 (16 m)
O95 (9 m)
E84
F75
Marmora P35 (13 m)
Marmora C34
North Triumph
G43 (91 m)
B52 (50 m)
Triumph P50
West Chebucto K20 (120 m)
Chebucto K90 (8 m)
N49 (108 m)
J49
H38 (28 m)
Glenelg
E58 & E58A (106 m & 28 m)
Whycocomagh N90
Wenonah J75
Alma
F67 (48 m)
K85 (164 m)
Merigomish C32
Cree E35
Demascota G32
Kegeshook G67 (45 m)
L97
Lawrence D14 (30 m)
Balmoral M32
P42
D42
A52 (11 m)
Cohasset
Como P21 (38 m)
Panuke
B90 (144m)
M79
J99 PP3 (8 m)
J99 PP2 (34 m)
F99 (44 m)
F09
H08
5 km
200 m water depth
20 km
Evangeline H98
dry hole
gas discovery
oil discovery
gas and oil discovery

Figure 5.2b Location of biostratigraphic data used in this study, Sable Subbasin, offshore Nova Scotia.

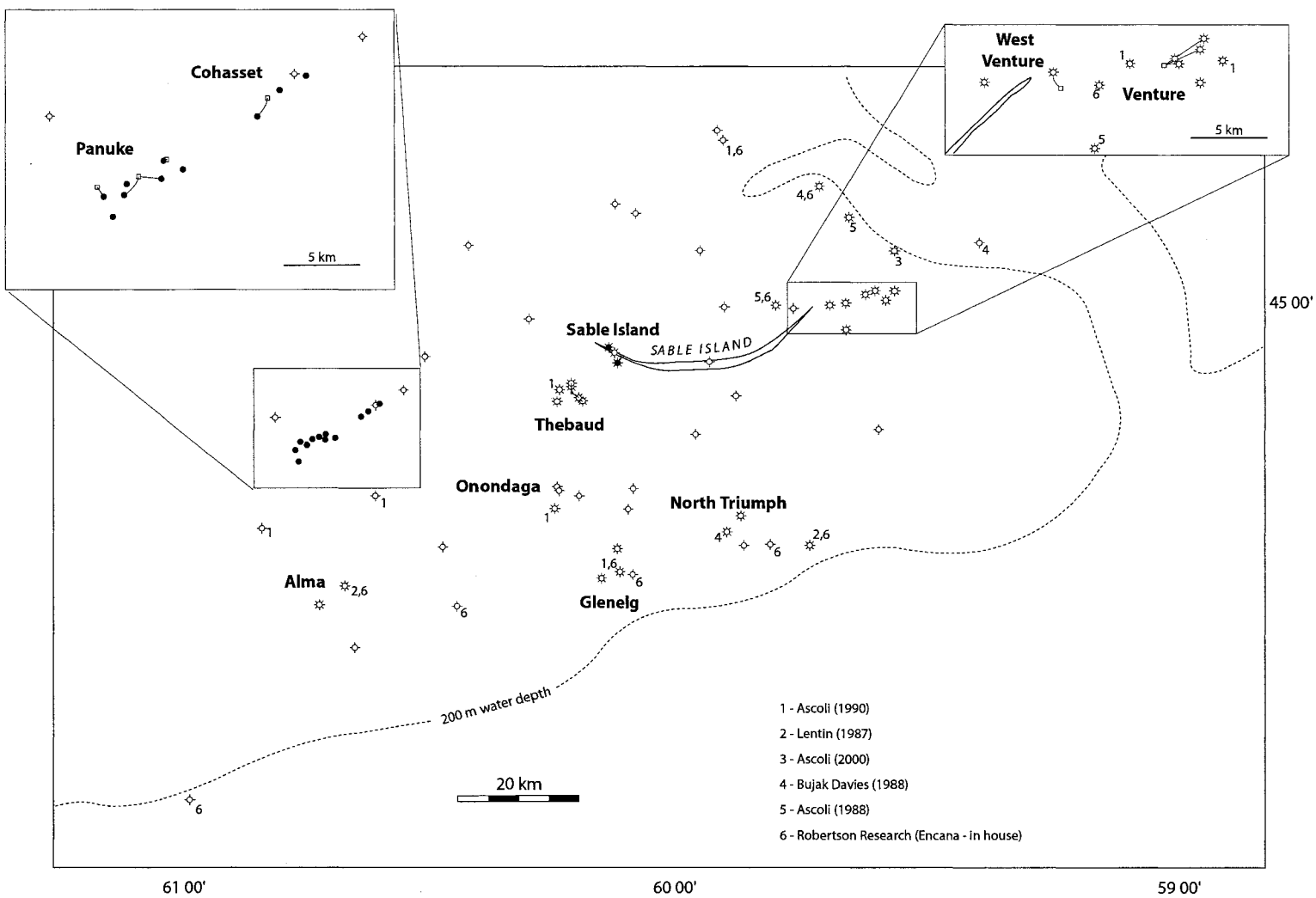

Cohasset
Panuke
5 km
West
Venture
Venture
5 km
Sable Island
SABLE ISLAND
Thebaud
Onondaga
North Triumph
Alma
Glenelg
200 m water depth
20 km
45 00'
61 00'
60 00'
59 00'
1 - Ascoli (1990)
2 - Lentin (1987)
3 - Ascoli (2000)
4 - Bujak Davies (1988)
5 - Ascoli (1988)
6 - Robertson Research (Encana - in house)

Figure 5.2c Location of seismic data used in this study, Sable Subbasin, offshore Nova Scotia.

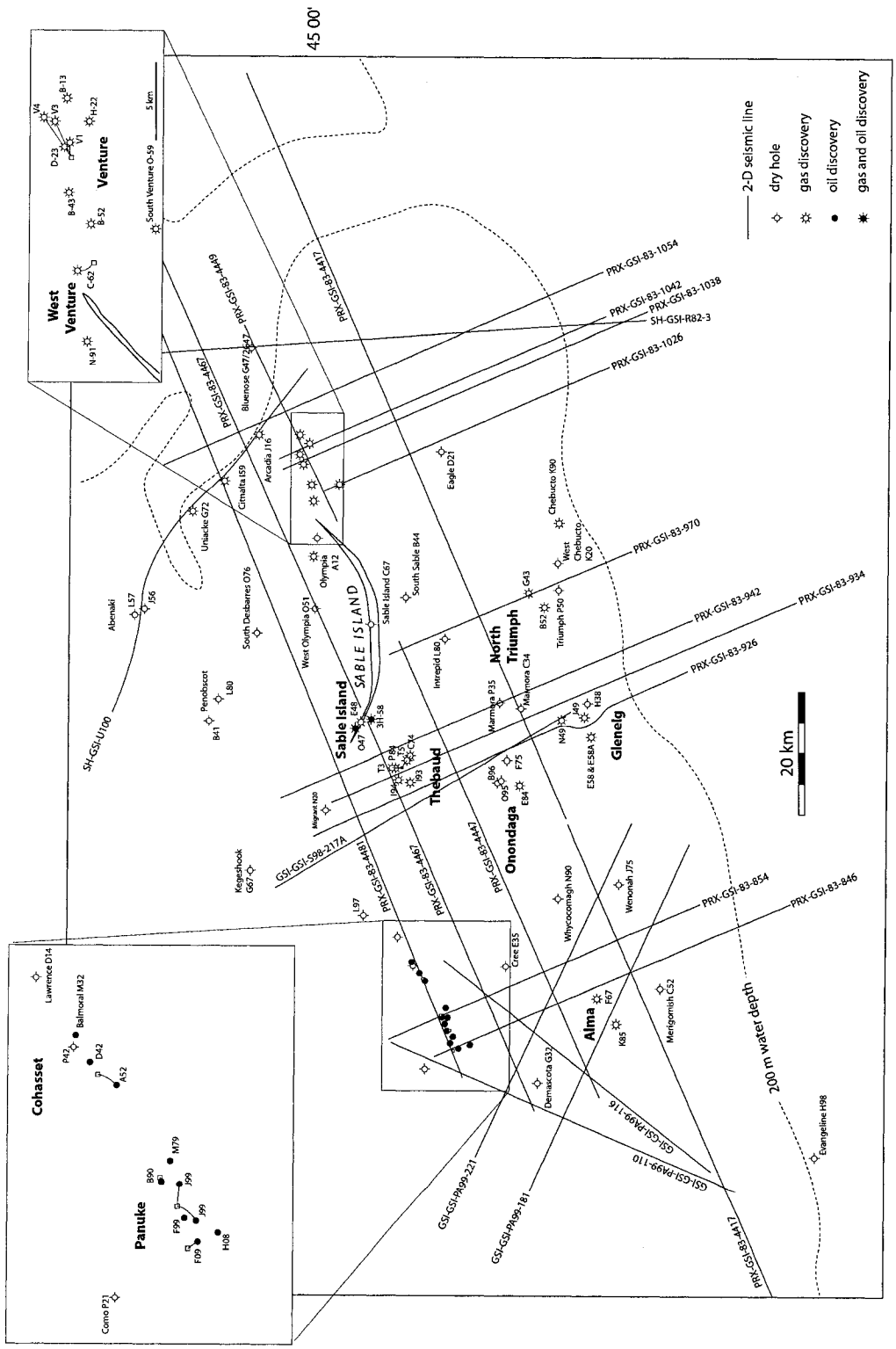

45 00'
60 00'
61 00'
59 00'
West Venture
Venture
South Venture O-59
5 km
2-D seismic line
dry hole
gas discovery
oil discovery
gas and oil discovery
PRX-GSI-83-1054
PRX-GSI-83-1042
PRX-GSI-83-1038
SH-GSI-R82-3
PRX-GSI-83-1026
PRX-GSI-83-970
PRX-GSI-83-942
PRX-GSI-83-934
PRX-GSI-83-926
PRX-GSI-83-854
PRX-GSI-83-846
PRX-GSI-83-A469
PRX-GSI-83-A467
PRX-GSI-83-A417
PRX-GSI-83-A418
PRX-GSI-83-A467
PRX-GSI-83-A447
GSI-GSI-S98-217A
SH-GSI-U100
GSI-GSI-PA99-221
GSI-GSI-PA99-181
GSI-GSI-PA99-110
GSI-GSI-PA99-116
SABLE ISLAND
Sable Island
Thebaud
Onondaga
North Triumph
Glenelg
Alma
Cohasset
Panuke
Como P21
Lawrence D14
Balmoral M32
P42
D42
A52
B90
M79
J99
F99
F09
H08
Abenaki
Penobscot
Kegeshook G67
Migrant K09
Uniacke G72
Citmalta I59
Arcadia J16
Bluenose G47
South Desbarres O76
West Olympia O51
Olympia A12
Sable Island G67
South Sable B44
Eagle D21
Chebucto K90
West Chebucto K20
Intrepid L80
Triumph P50
Marmora P35
Malmoma C34
Cree E35
Whycocomagh N90
Wenonah J75
Demascota G32
Menjomish C52
Evangeline H98
20 km
200 m water depth

Figure 5.3 Stratigraphic frameworks, Sable Subbasin, offshore Nova Scotia.

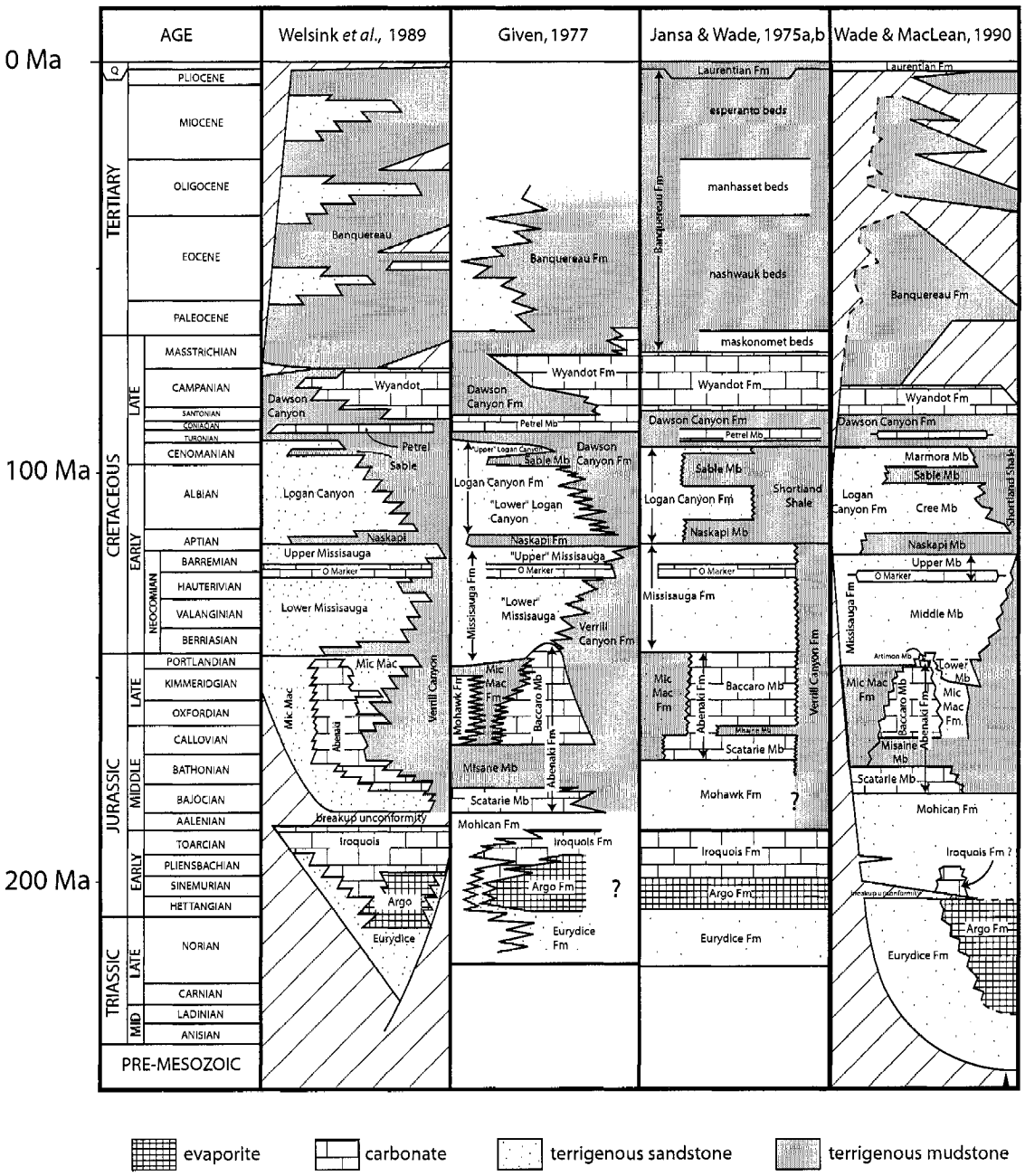
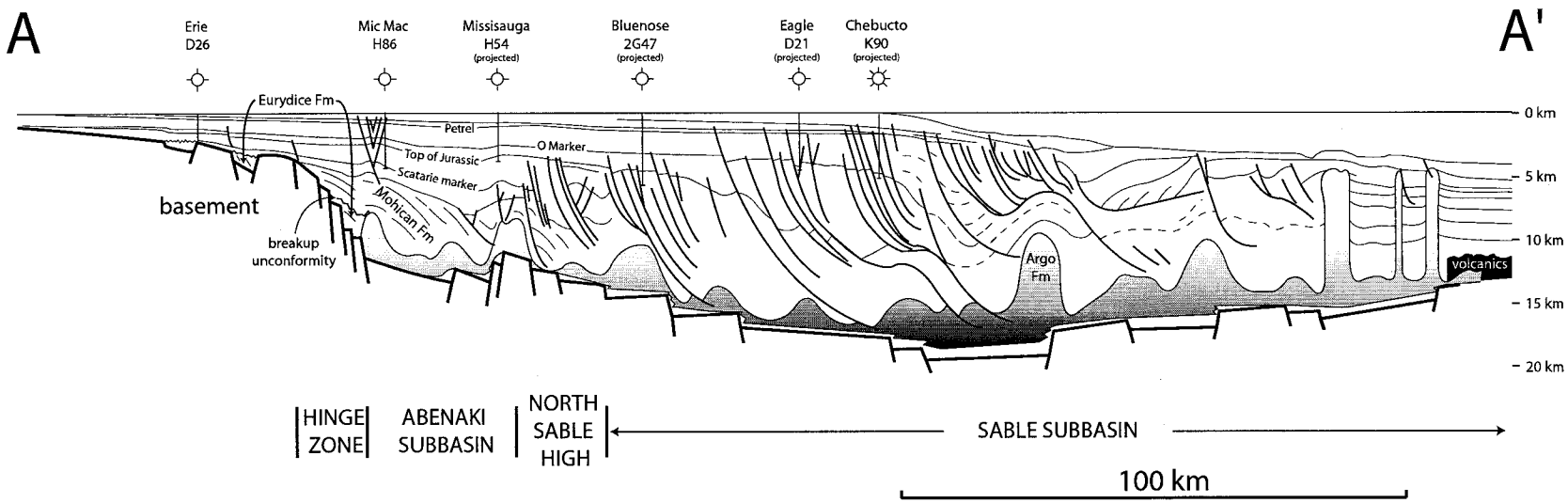

0 Ma
100 Ma
200 Ma
AGE
Welsink et al., 1989
Given, 1977
Jansa & Wade, 1975a,b
Wade & MacLean, 1990
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
TERTIARY
MASSTRICHIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
NEOCOMIAN
LATE
EARLY
CRETACEOUS
PORTLANDIAN
KIMMERIDGIAN
OXFORDIAN
CALLOVIAN
BATHONIAN
BAJOCIAN
AALENIAN
TOARCIAN
PLIENSBACHIAN
SINEMURIAN
HETTANGIAN
JURASSIC
NORIAN
CARNIAN
LADINIAN
ANISIAN
TRIASSIC
PRE-MESOZOIC
Banquereau
Wyandot
Dawson Canyon
Petrel
Sable
Logan Canyon
Naskapi
Upper Missisauga
O Marker
Lower Missisauga
Mic Mac
Abenaki
Verrill Canyon
breakup unconformity
Iroquois
Argo
Eurydice
Banquereau Fm
Wyandot Fm
Dawson Canyon Fm
Petrel Mb
Sable Mb
Logan Canyon Fm
"Lower" Logan Canyon
Naskapi Fm
"Upper" Missisauga
"Lower" Missisauga
Missisauga Fm
Verrill Canyon Fm
Mic Mac Fm
Mohawk Fm
Baccaro Mb
Abenaki Fm
Misaine Mb
Scatarie Mb
Mohican Fm
Iroquois Fm
Argo Fm
Eurydice Fm
?
Laurentian Fm
esperanto beds
manhasset beds
nashwauk beds
maskonomet beds
Shortland Shale
Marmora Mb
Cree Mb
Upper Mb
Middle Mb
Lower Mb
Artinon Mb
Iroquois Fm ?
evaporite
carbonate
terrigenous sandstone
terrigenous mudstone

Figure 5.4 Interpreted dip-oriented seismic cross-section, Sable Subbasin (modified from Wade and MacLean, 1990).


A
A'
Erie
D26
Mic Mac
H86
Missisauga
H54
(projected)
Bluenose
2G47
(projected)
Eagle
D21
(projected)
Chebucto
K90
(projected)
Eurydice Fm
Petrel
O Marker
Top of Jurassic
Scatarie marker
Mohican Fm
basement
breakup
unconformity
Argo
Fm
volcanics
0 km
5 km
10 km
15 km
20 km
HINGE
ZONE
ABENAKI
SUBBASIN
NORTH
SABLE
HIGH
SABLE SUBBASIN
100 km

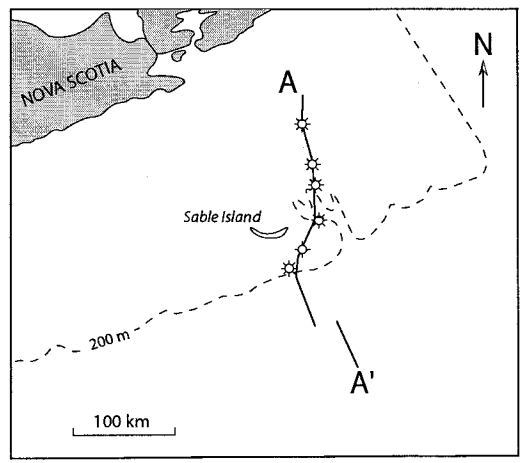

NOVA SCOTIA
N
A
Sable Island
200 m
A'
100 km

Figure 5.5 Isopach map, Missisauga Formation (modified from Wade, 1991a and MacLean and Wade, 1992).

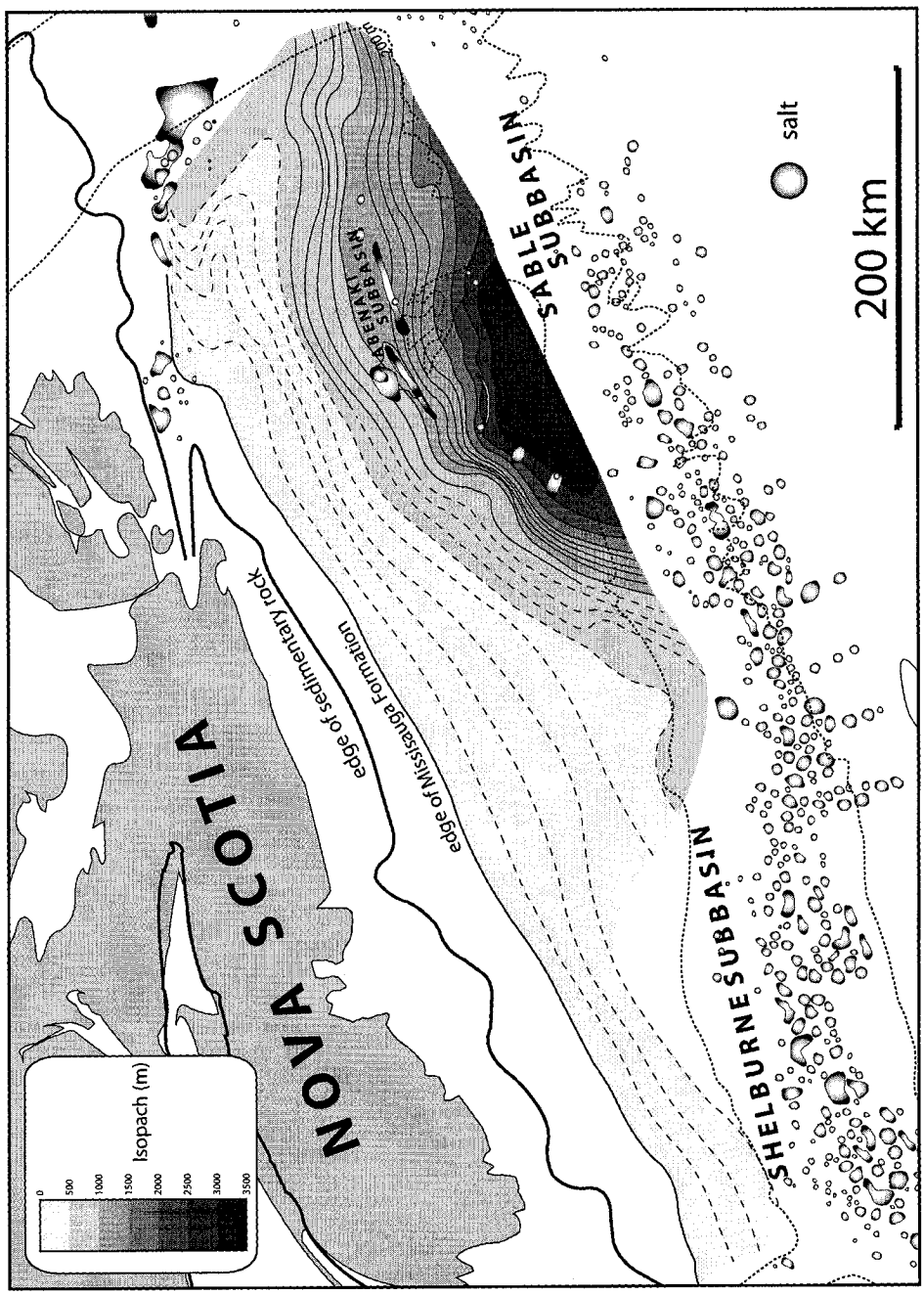

NOVA SCOTIA
Isopach (m)
0
500
1000
1500
2000
2500
3000
3500
edge of sedimentary rock
edge of Mississauga Formation
SABLE SUBBASIN
SHELBURNE SUBBASIN
CAPE BRETON SUBBASIN
salt
200 km

Figure 5.6 Time-structure map of the O Marker reflection, Sable Subbasin. Reconstructed from seismic data (see Figure 5.2c for seismic line locations).

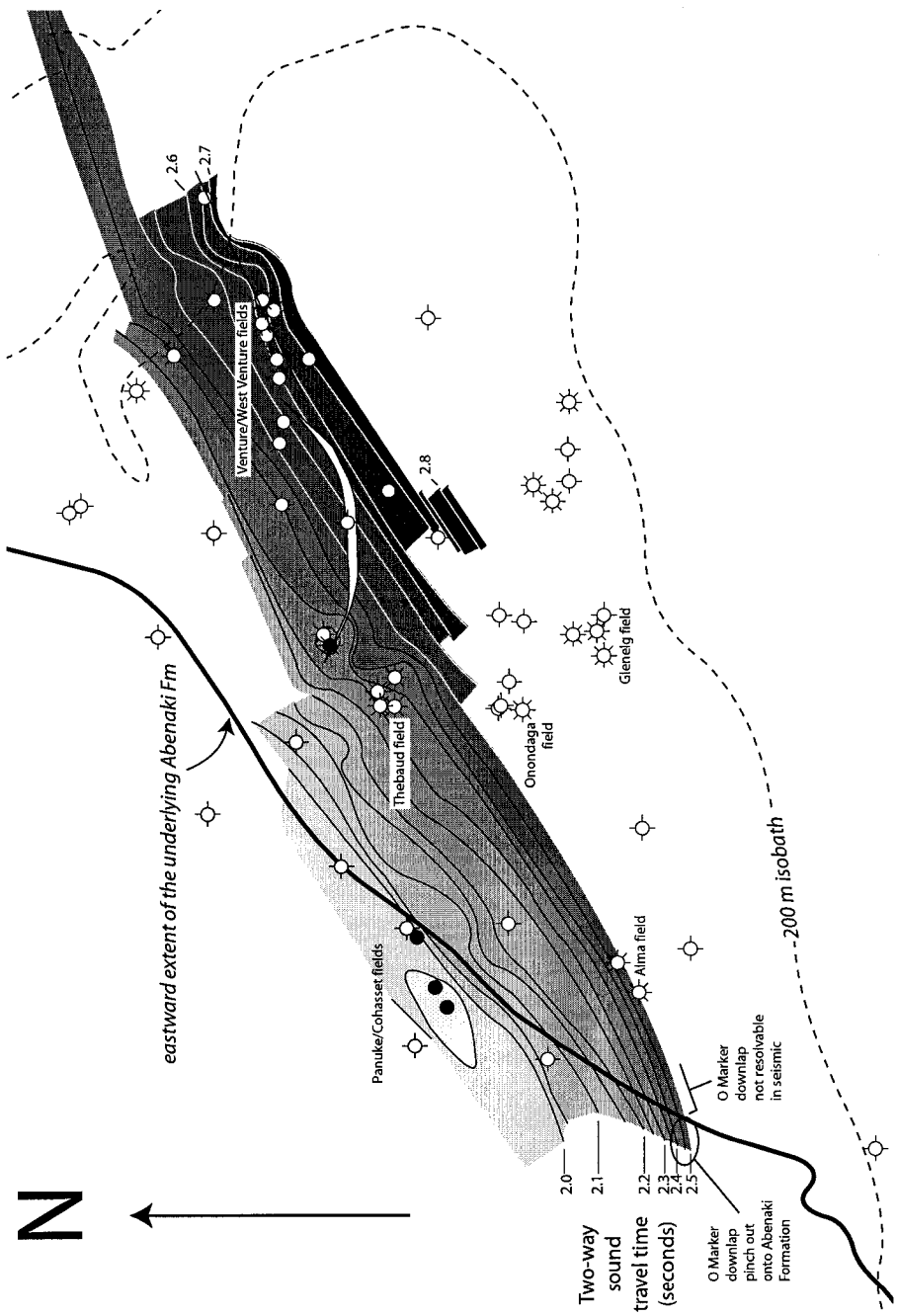
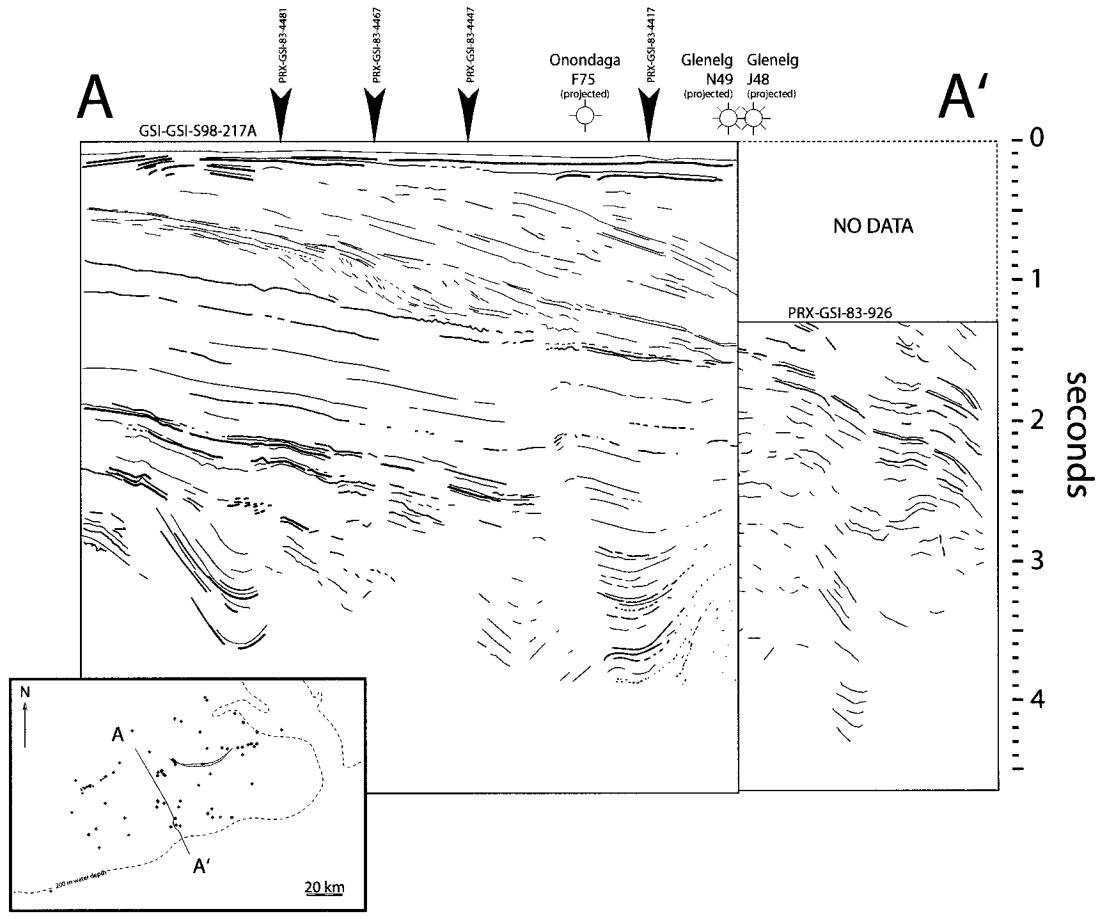

N
eastward extent of the underlying Abenaki Fm
200 m isobath
Two-way sound travel time (seconds)
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
Venture/West Venture fields
Thebaud field
Onondaga field
Glenelg field
Alma field
Panuke/Cohasset fields
O Marker downlap not resolvable in seismic
O Marker downlap pinch out onto Abenaki Formation

Figure 5.7 Uninterpreted and interpreted dip-oblique seismic form line traces, Onondaga and Glenelg fields, central Sable Subbasin (GSI-GSI-S98-217A and PRX-GSI-83-926 lines). Note: 1) the lack of obvious onlap/offlap cycles in the Missisauga Formation, 2) the absence(?) of the O Marker reflection basinward of the Onondaga master growth fault, and 3) the anticlinal form of the Glenelg stucture. Seismic picks used are the same as in MacLean and Wade (1993).


A
A'
PRX-GSI-83-4481
PRX-GSI-83-4467
PRX-GSI-83-4447
PRX-GSI-83-4417
Onondaga F75 (projected)
Glenelg N49 (projected)
Glenelg J48 (projected)
GSI-GSI-S98-217A
NO DATA
PRX-GSI-83-926
seconds
0
1
2
3
4
N
A
A'
20 km

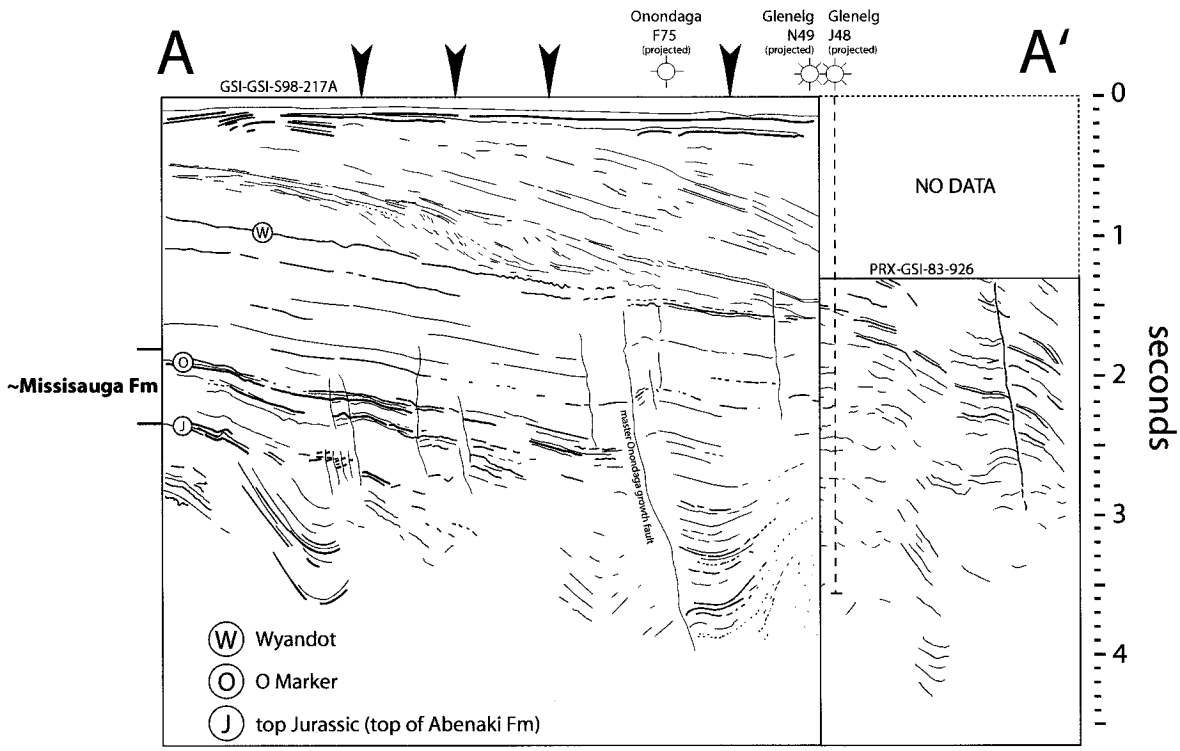

A
A'
Onondaga F75 (projected)
Glenelg N49 (projected)
Glenelg J48 (projected)
GSI-GSI-S98-217A
NO DATA
PRX-GSI-83-926
seconds
0
1
2
3
4
~Missisauga Fm
W
O
J
master Onondaga growth fault
W Wyandot
O O Marker
J top Jurassic (top of Abenaki Fm)

Figure 5.8 Structure map, top of Venture sandstone 6, Venture Field region (modified from Sable Offshore Energy, 1996).

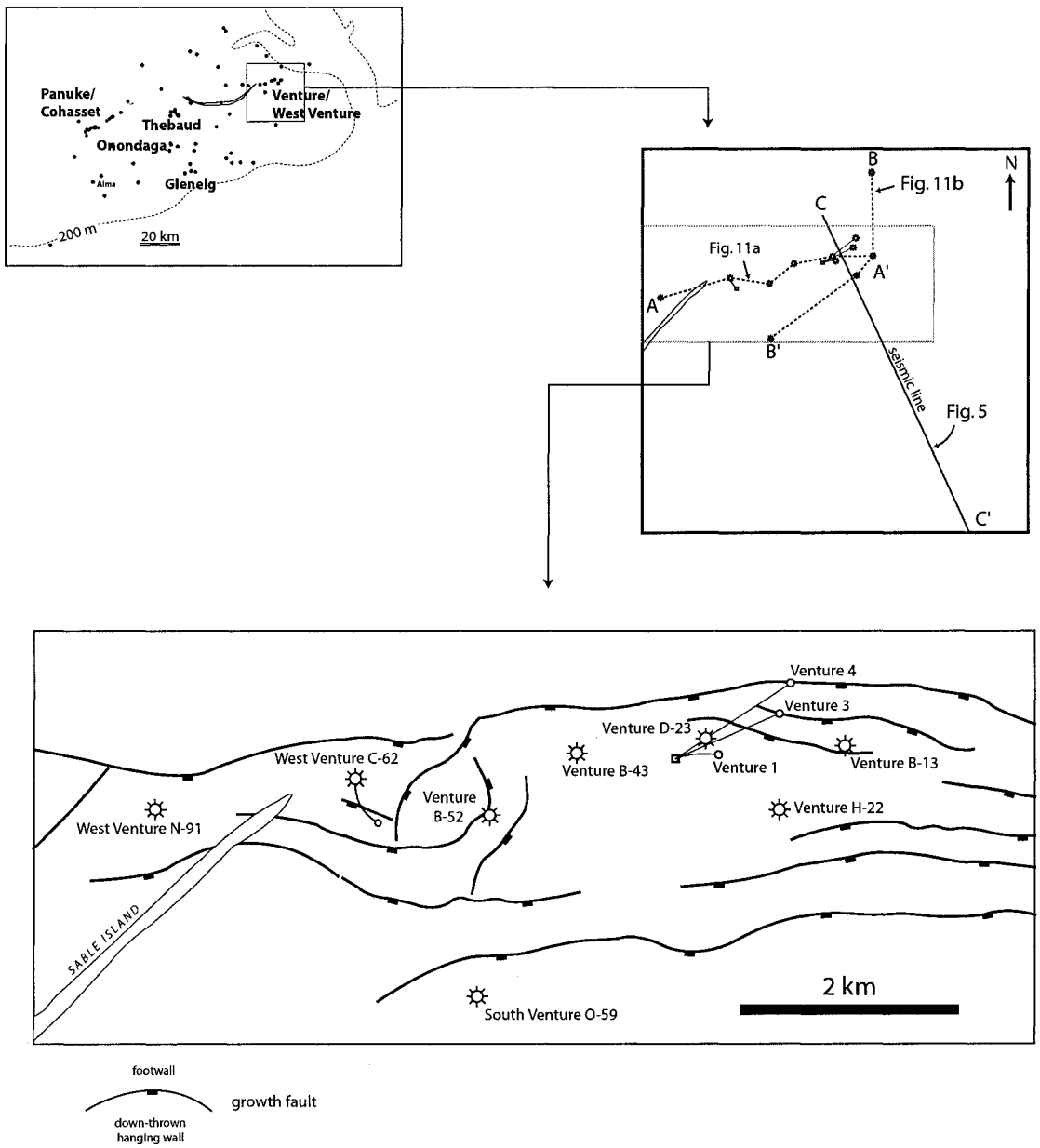

Panuke/
Cohasset
Thebaud
Onondaga
Alma
Glenelg
Venture/
West Venture
200 m
20 km
B
Fig. 11b
N
C
Fig. 11a
A'
A
B'
seismic line
Fig. 5
C'
Venture 4
Venture 3
Venture D-23
Venture 1
Venture B-13
Venture B-43
West Venture C-62
Venture
B-52
West Venture N-91
Venture H-22
SABLE ISLAND
South Venture O-59
2 km
footwall
growth fault
down-thrown
hanging wall

Figure 5.9 Stratigraphy of sandstone reservoirs, Venture and West Venture fields (modified in part from Wade and MacLean, 1990, and in part from Sable Offshore Energy, 1996).

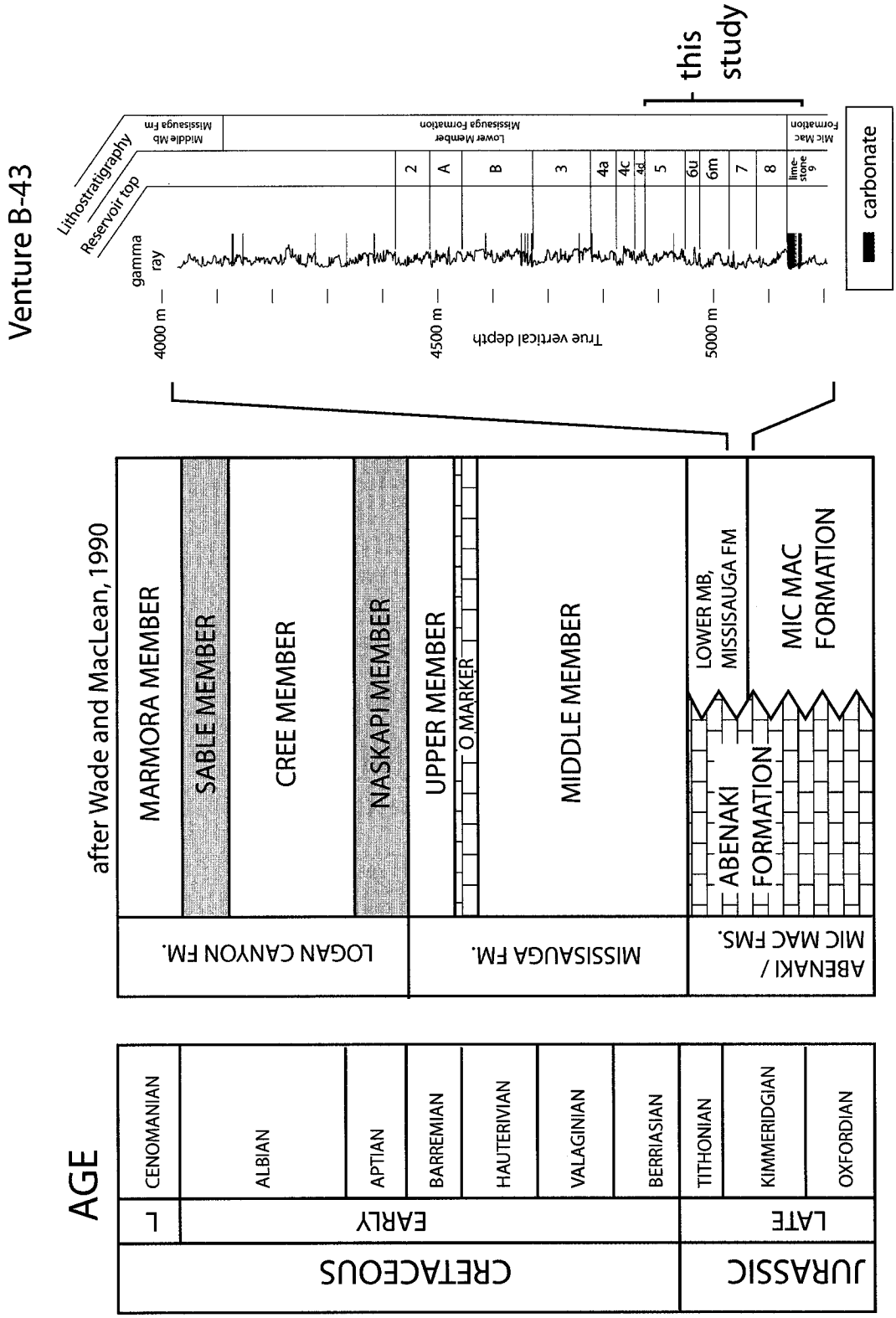

Venture B-43
this study
carbonate
gamma ray
Lithostratigraphy
Reservoir top
Middle Mb
Mississaga Fm
Lower Member
Mississaga Formation
Mic Mac Formation
2
A
B
3
4a
4c
4d
5
6u
6m
7
8
lime-stone 9
4000 m
4500 m
5000 m
True vertical depth
after Wade and MacLean, 1990
MARMORA MEMBER
SABLE MEMBER
CREE MEMBER
NASKAPI MEMBER
UPPER MEMBER
O MARKER
MIDDLE MEMBER
LOWER MB, MISSISAUGA FM
ABENAKI FORMATION
MIC MAC FORMATION
LOGAN CANYON FM.
MISSISAUGA FM.
ABENAKI / MIC MAC FMS.
AGE
CRETACEOUS
JURASSIC
EARLY
LATE
L
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALAGINIAN
BERRIASIAN
TITHONIAN
KIMMERIDGIAN
OXFORDIAN

Figure 5.10 Pressure data for wells in the (**a**) Glenelg, (**b**) Alma, (**c**) Venture, and (**d**) Panuke fields. Note that overpressured conditions exist in all cases except (d), and that the top of overpressure is located in older, deeper strata in the Venture Field and in younger, shallower strata in the more basinward Alma and Glenelg fields (*i.e.*, the top of overpressure rises stratigraphically in a basinward direction).

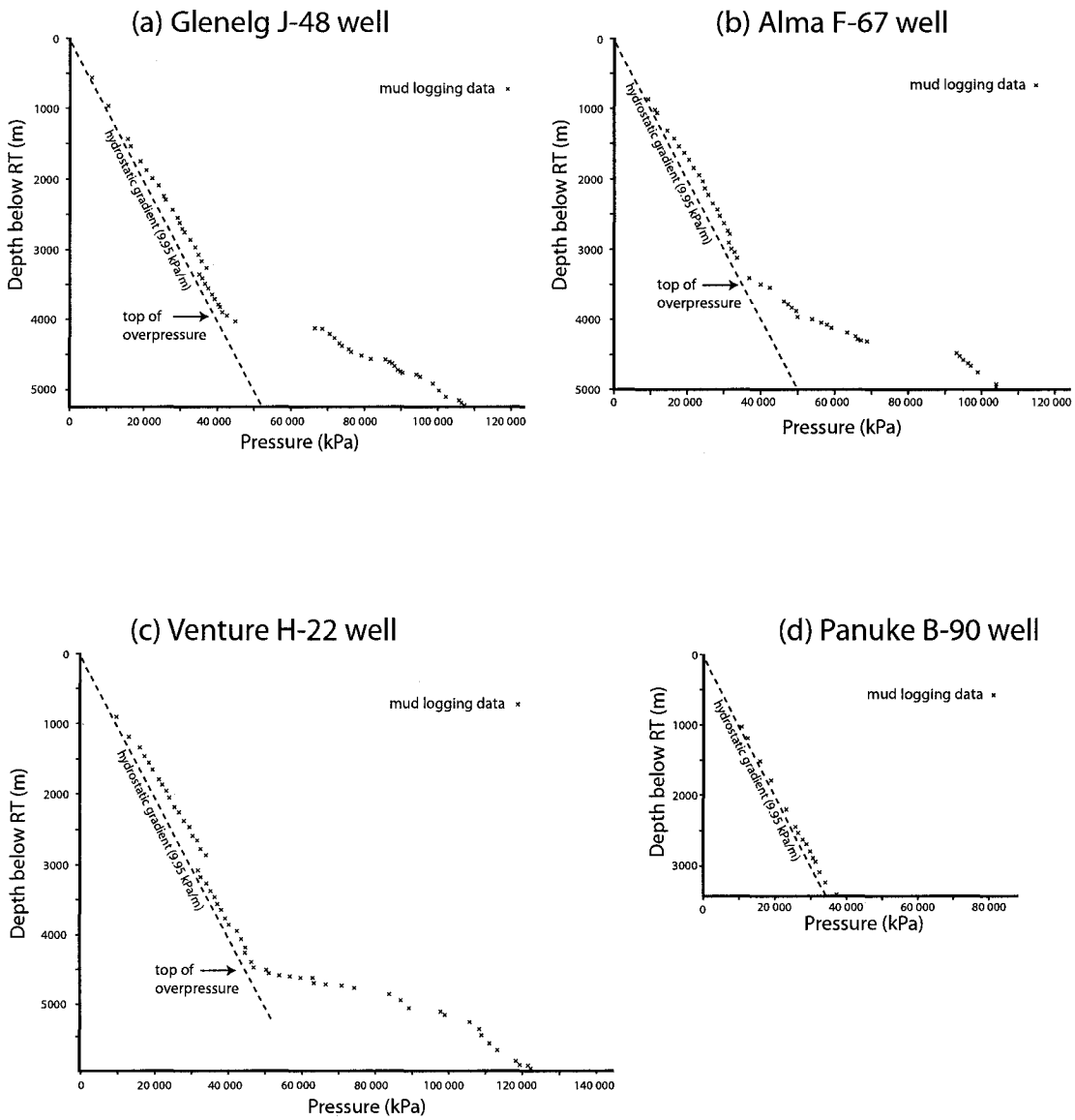

(a) Glenelg J-48 well
mud logging data
hydrostatic gradient (9.95 kPa/m)
top of overpressure
Depth below RT (m)
Pressure (kPa)
(b) Alma F-67 well
mud logging data
hydrostatic gradient (9.95 kPa/m)
top of overpressure
Depth below RT (m)
Pressure (kPa)
(c) Venture H-22 well
mud logging data
hydrostatic gradient (9.95 kPa/m)
top of overpressure
Depth below RT (m)
Pressure (kPa)
(d) Panuke B-90 well
mud logging data
hydrostatic gradient (9.95 kPa/m)
Depth below RT (m)
Pressure (kPa)

Figure 5.11a Interpreted strike-oriented well log cross-section, Venture and West Venture fields. See Figure 5.8 for cross-section location.

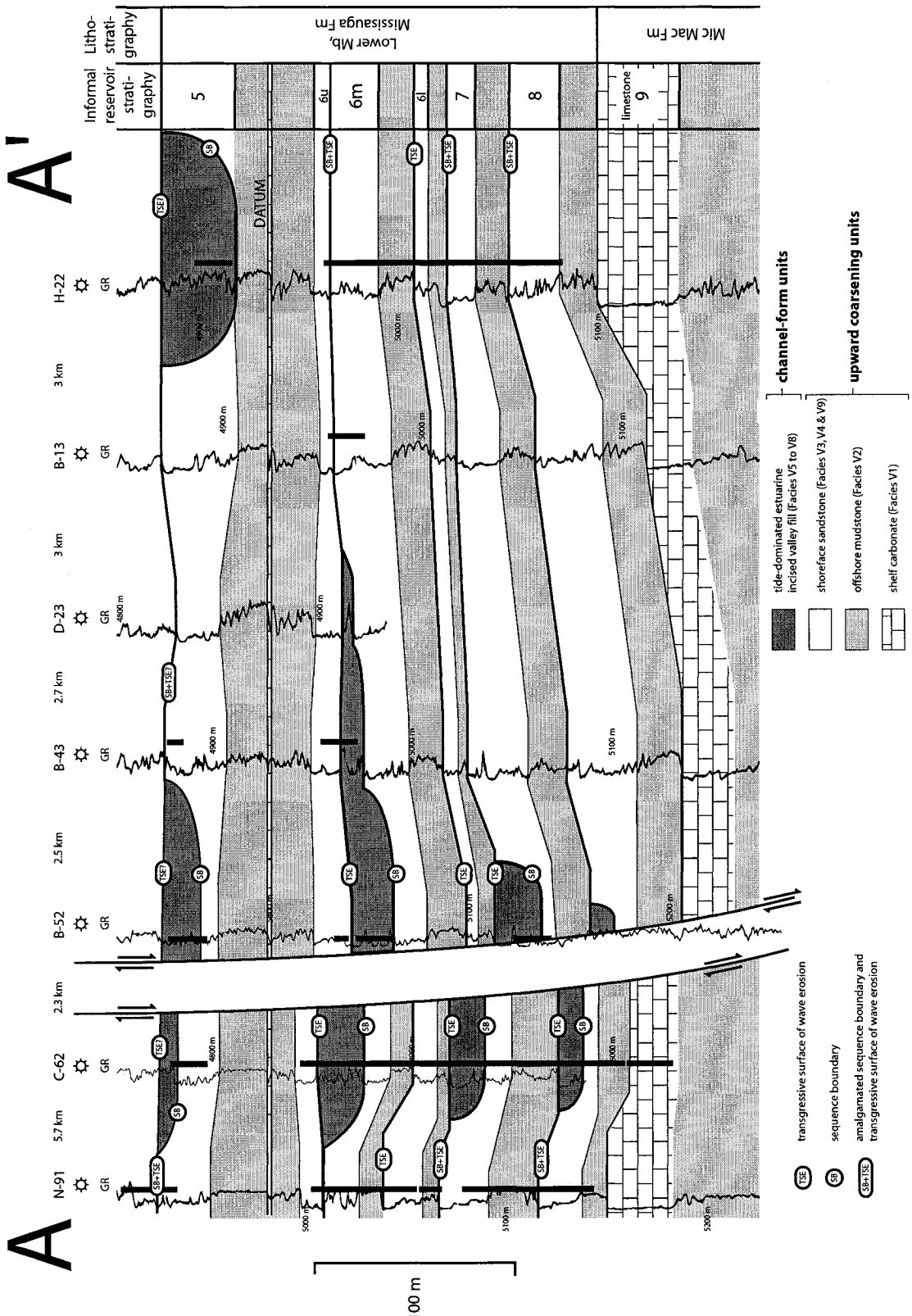

A
A'
N-91
C-62
B-52
B-43
D-23
B-13
H-22
5.7 km
2.3 km
2.5 km
2.7 km
3 km
3 km
GR
Litho-stratigraphy
Informal reservoir stratigraphy
Lower Mb, Missisauga Fm
Mic Mac Fm
5
n9
6m
l9
7
8
limestone
9
DATUM
TSE
SB
SB+TSE
4900 m
5000 m
5100 m
100 m
transgressive surface of wave erosion
sequence boundary
amalgamated sequence boundary and transgressive surface of wave erosion
channel-form units
upward coarsening units
tide-dominated estuarine incised valley fill (Facies V5 to V8)
shoreface sandstone (Facies V3, V4 & V9)
offshore mudstone (Facies V2)
shelf carbonate (Facies V1)

Figure 5.11b Interpreted dip-oriented well log cross-section, Venture Field. See Figure 5.8 for cross-section location.

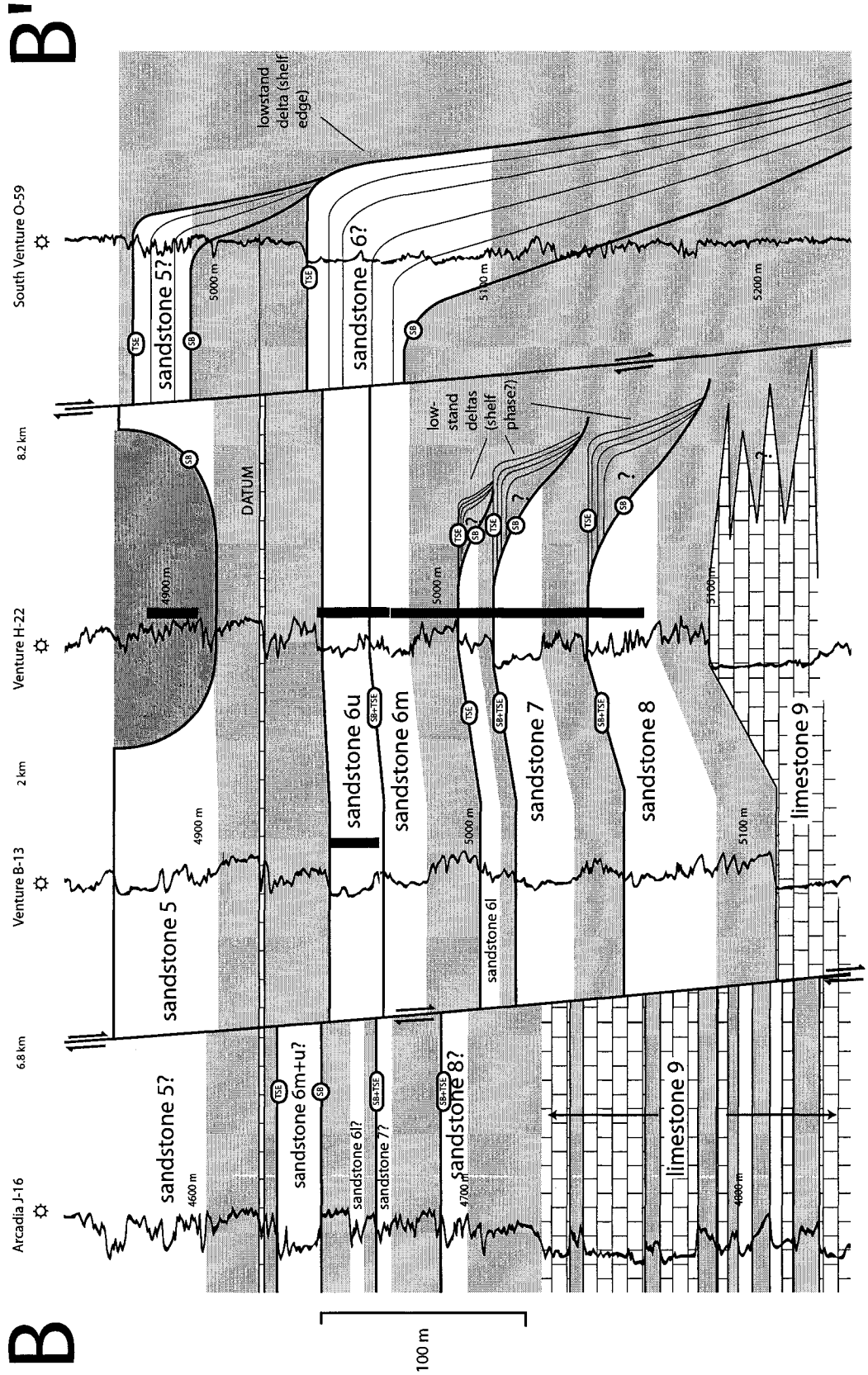

B
B'
Arcadia J-16
Venture B-13
Venture H-22
South Venture O-59
6.8 km
2 km
8.2 km
100 m
DATUM
sandstone 5?
sandstone 5
sandstone 6m+u?
sandstone 6l?
sandstone 7?
sandstone 8?
sandstone 6u
sandstone 6m
sandstone 6l
sandstone 7
sandstone 8
limestone 9
sandstone 6?
lowstand delta (shelf edge)
low-stand deltas (shelf phase?)
4900 m
5000 m
5100 m
5200 m
4700 m
4600 m
TSE
SB
SB+TSE

Figure 5.12 Selected core photos and sedimentological logs from Venture sandstones 8 to 5, Lower Member of the Missisauga Formation, Venture and West Venture fields. (**a**) sedimentological log of part of an upward-coarsening unit (interpretation – storm-dominated delta-front deposits; West Venture C-62, core 9, boxes 20 to 17, 5186.2-5181.99 m (measured depth)), (**b**) low-angle (<10°) cross-stratified sandstone common in upward-coarsening units (Facies V3; interpretation – hummocky cross-stratified sandstone; West Venture C-62, core 9, box 19, 5184.64 m (measured depth)), (**c**) a portion of a heterolithic channel-form unit (Facies V5; interpretation – tide-influenced fluvial deposits; West Venture C-62, core 5, boxes 25 to 18, 5099.6-5092 m (measured depth)), and (**d**) rhythmic stratification, which is rarely observed in the heterolithic channel-form units (Facies V7; Venture H-22, core 2, box 1, 4895 m (measured depth)).

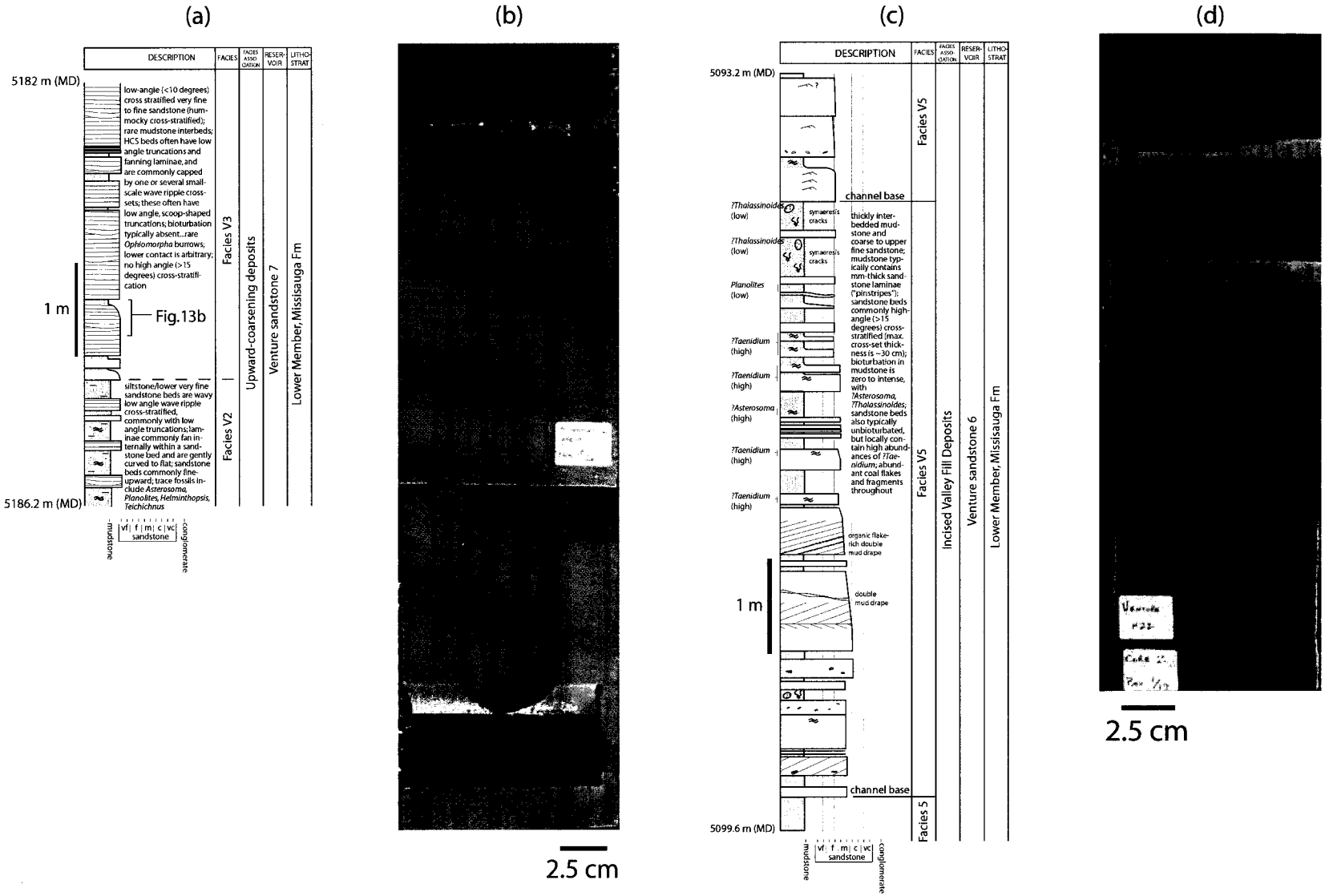

(a)
(b)
(c)
(d)
DESCRIPTION
FACIES
FACIES ASSOCIATION
RESERVOIR
LITHOSTRAT
5182 m (MD)
5186.2 m (MD)
low-angle (<10 degrees) cross stratified very fine to fine sandstone (hummocky cross-stratified); rare mudstone interbeds; HCS beds often have low angle truncations and fanning laminae, and are commonly capped by one or several small-scale wave ripple cross-sets; these often have low angle, scoop-shaped truncations; bioturbation typically absent...rare Ophiomorpha burrows; lower contact is arbitrary; no high angle (>15 degrees) cross-stratification
1 m
Fig.13b
siltstone/lower very fine sandstone beds are wavy low angle wave ripple cross-stratified, commonly with low angle truncations; laminae commonly fan internally within a sandstone bed and are gently curved to flat; sandstone beds commonly fine-upward; trace fossils include Asterosoma, Planolites, Helminthopsis, Teichichnus
Facies V3
Facies V2
Upward-coarsening deposits
Venture sandstone 7
Lower Member, Missisauga Fm
mudstone
vf | f | m | c | vc
sandstone
conglomerate
2.5 cm
5093.2 m (MD)
5099.6 m (MD)
channel base
?Thalassinoides (low)
synaeresis cracks
thickly interbedded mudstone and coarse to upper fine sandstone; mudstone typically contains mm-thick sandstone laminae ("pinstripes"); sandstone beds commonly high-angle (>15 degrees) cross-stratified (max. cross-set thickness is ~30 cm); bioturbation in mudstone is zero to intense, with ?Asterosoma, ?Thalassinoides; sandstone beds also typically unbioturbated, but locally contain high abundances of ?Taenidium; abundant coal flakes and fragments throughout
Planolites (low)
?Taenidium (high)
?Asterosoma (high)
organic flake-rich double mud drape
double mud drape
1 m
Facies V5
Facies 5
Incised Valley Fill Deposits
Venture sandstone 6
Lower Member, Missisauga Fm
2.5 cm

Figure 5.13 Structure map, top of the Missisauga Formation (Alma A "sand"), Alma Field (modified from Sable Offshore Energy, 1996 and Mobil Oil, 1998a).

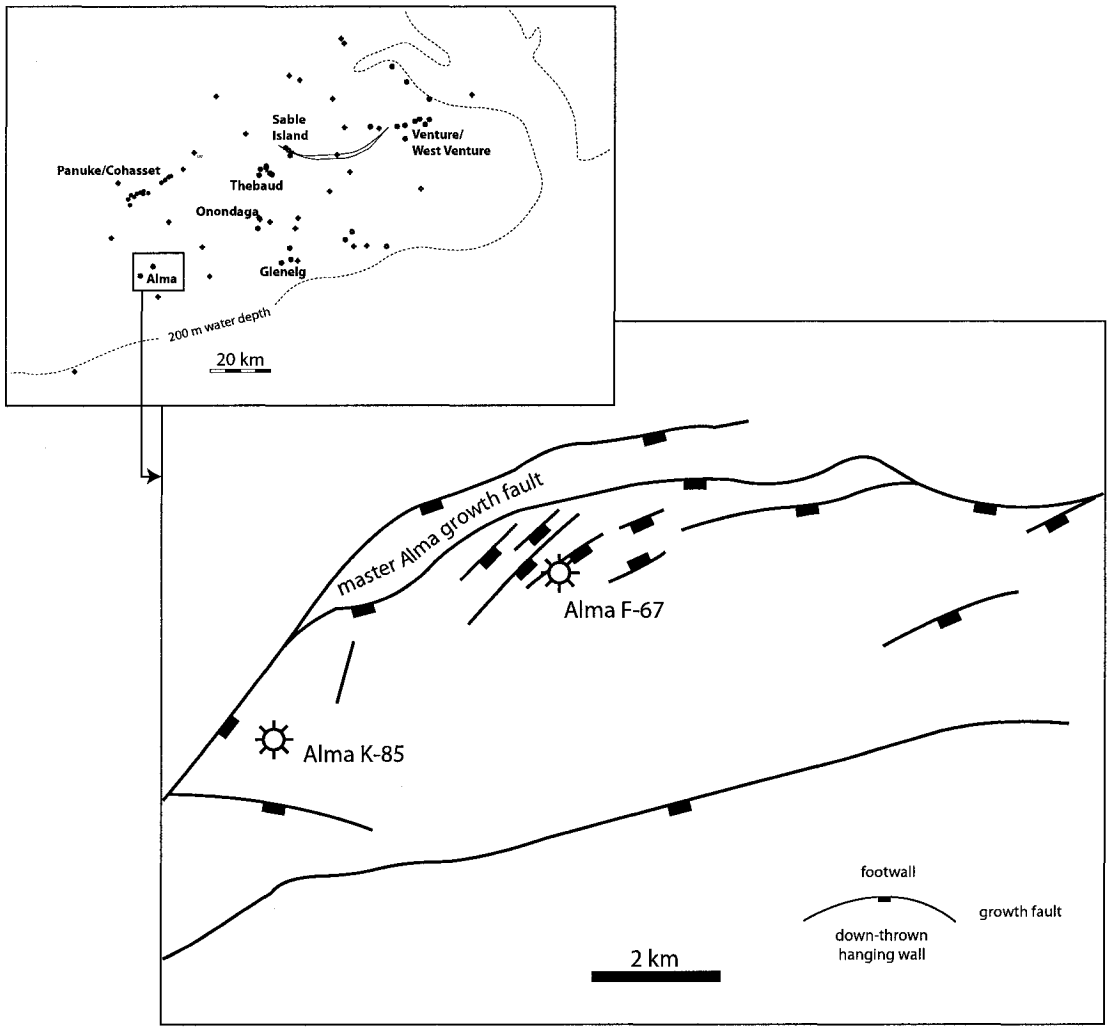

Sable Island
Venture/ West Venture
Panuke/Cohasset
Thebaud
Onondaga
Alma
Glenelg
200 m water depth
20 km
master Alma growth fault
Alma F-67
Alma K-85
footwall
growth fault
down-thrown hanging wall
2 km

Figure 5.14 Interpreted strike-oblique well log cross-section, Alma Field. Transgressive surface of erosion (TSE) and sequence boundary (SB). For details on individual facies, see Table 5.2.

INTERPRETATIONS

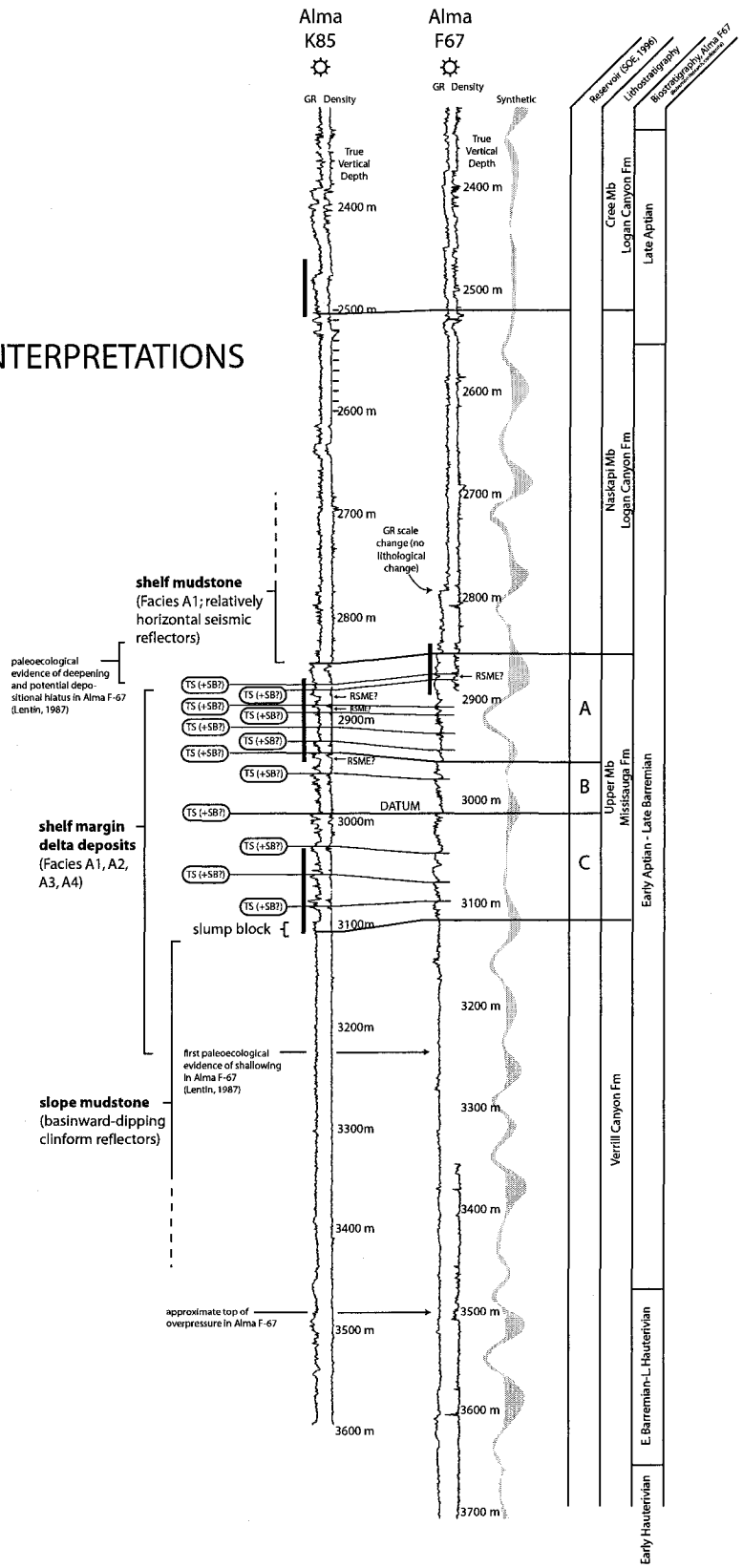


Figure 5.15 Part of an upward-coarsening succession, Alma C "sand", Upper Missisauga, Alma Field (Alma K-85, core 6, boxes 6 to 3, 3030.84-3025.58 m (measured depth)).

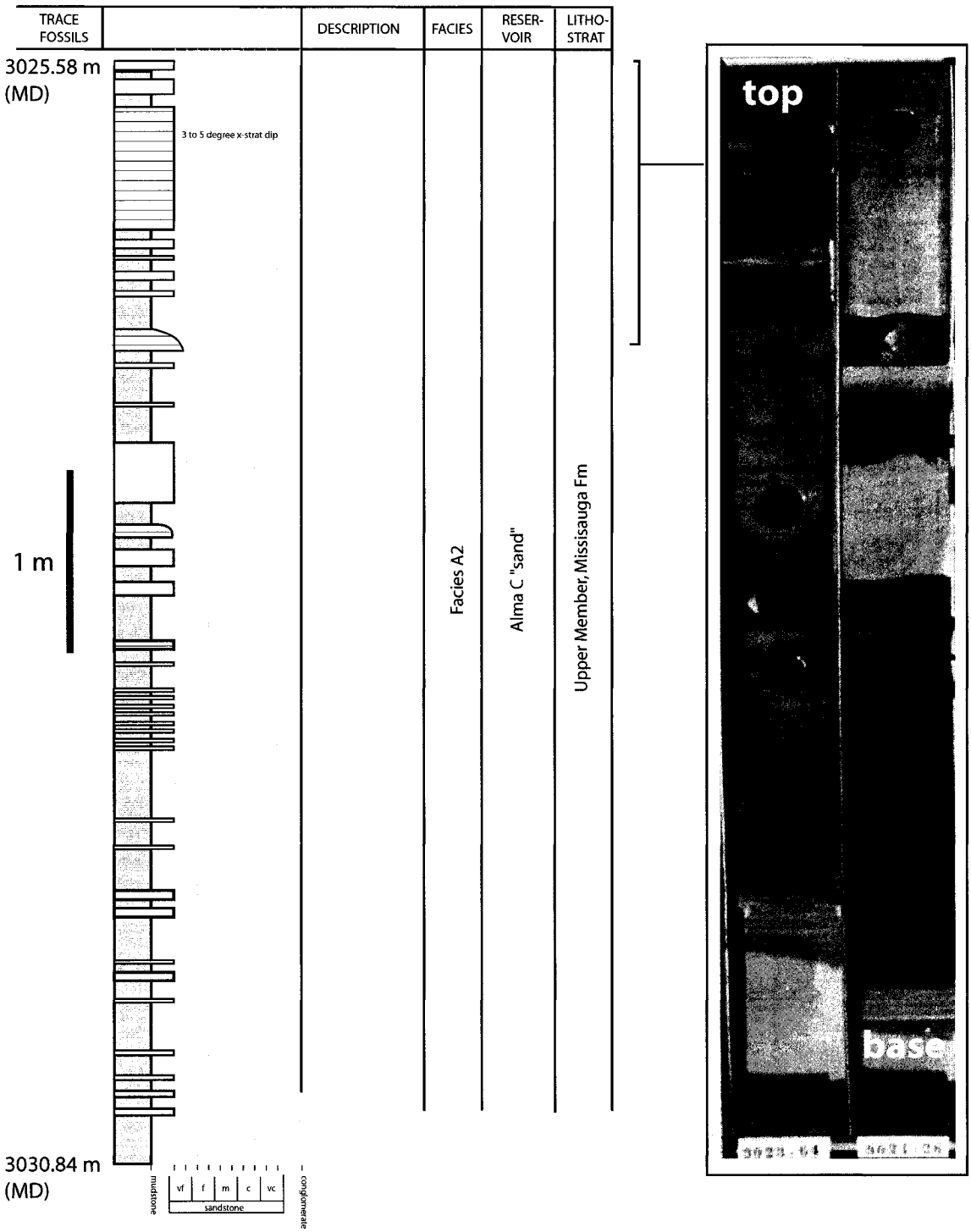

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
3025.58 m (MD)
3 to 5 degree x-strat dip
1 m
3030.84 m (MD)
Facies A2
Alma C "sand"
Upper Member, Missisauga Fm
top
base
mudstone
vf
f
m
c
vc
sandstone
conglomerate

Figure 5.16 Structure map, top of the Glenelg B pool, Upper Missisauga, Glenelg Field (modified from Sable Offshore Energy, 1996).

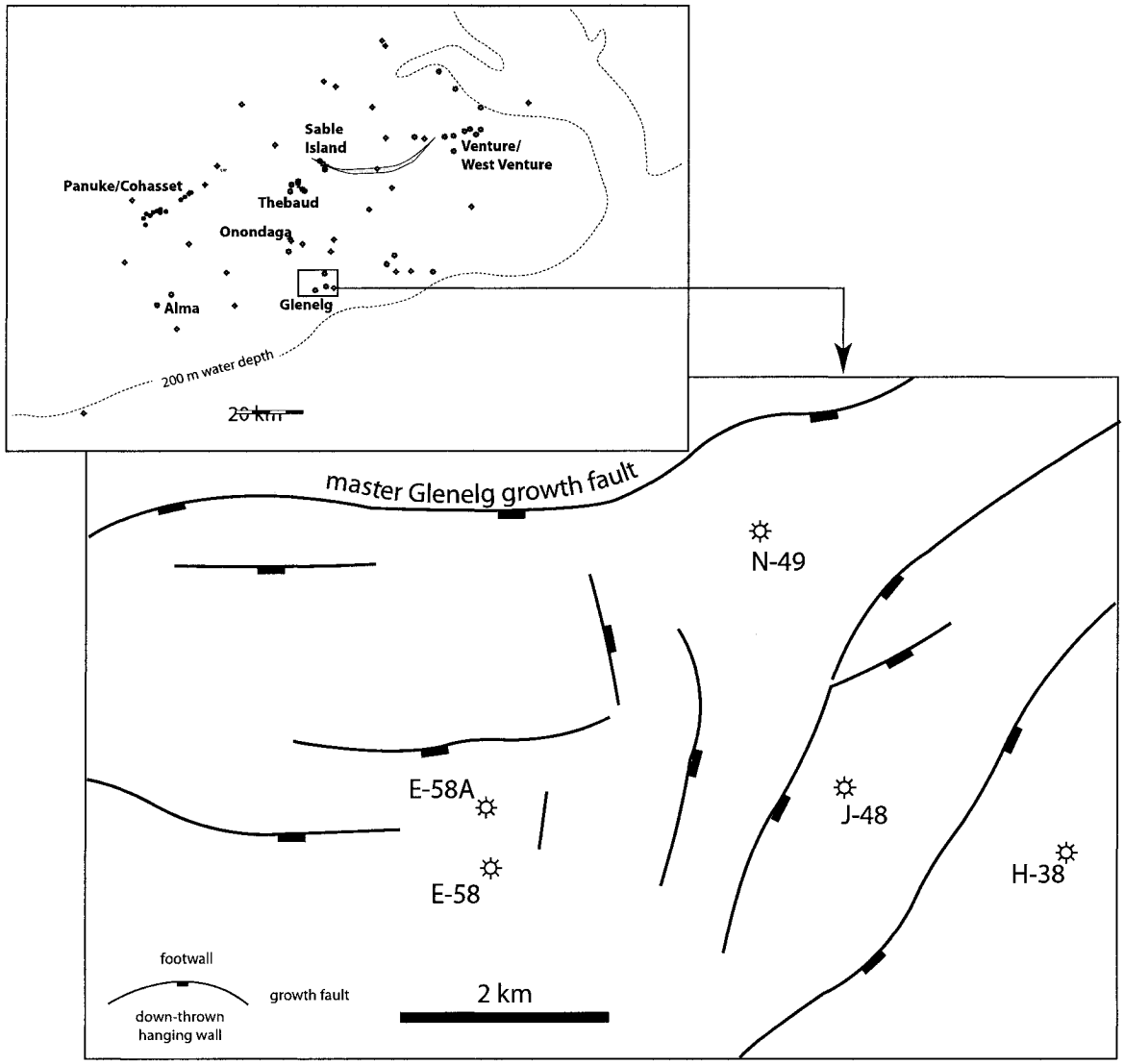

Sable Island
Venture/ West Venture
Panuke/Cohasset
Thebaud
Onondaga
Alma
Glenelg
200 m water depth
20 km
master Glenelg growth fault
N-49
E-58A
J-48
E-58
H-38
footwall
down-thrown hanging wall
growth fault
2 km

Figure 5.17 Gas pools, Glenelg Field (from Sable Offshore Energy, 1996; MacLean and Wade, 1993). Biostratigraphic data is not available for the Glenelg N-49 well; however, biostratigraphy from the nearby Glenelg J-48 well suggests the Glenelg B and C1 pools were deposited between the Hauterivian and Barremian (see Ascoli, 1990).

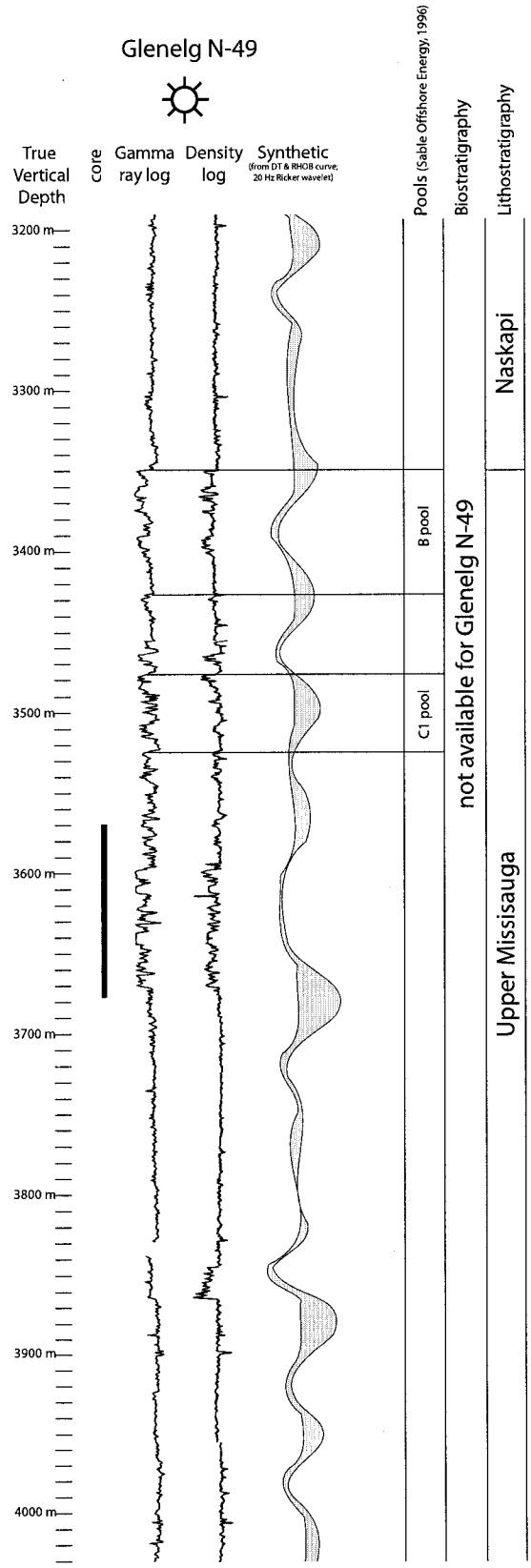
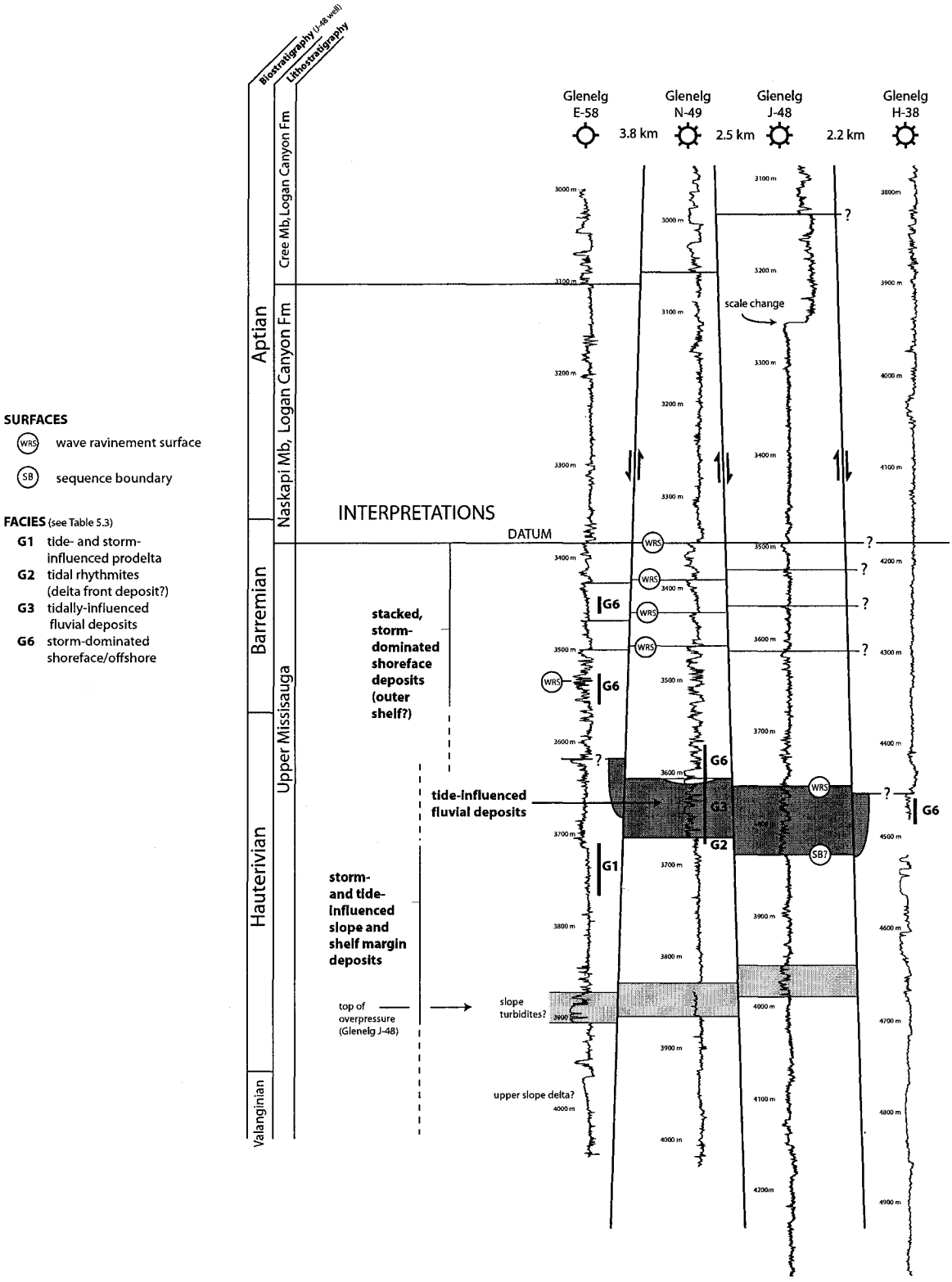

Glenelg N-49
True Vertical Depth
core
Gamma ray log
Density log
Synthetic
(from DT & RHOB curve; 20 Hz Ricker wavelet)
Pools (Sable Offshore Energy, 1996)
Biostratigraphy
Lithostratigraphy
3200 m
3300 m
3400 m
3500 m
3600 m
3700 m
3800 m
3900 m
4000 m
B pool
C1 pool
not available for Glenelg N-49
Naskapi
Upper Missisauga

Figure 5.18 Interpreted strike-oblique(?) well log cross-section, Glenelg Field. Lithostratigraphic picks are from MacLean and Wade (1993), except for Glenelg H-38. Biostratigraphic picks for the Glenelg J-48 well are from Ascoli (1990).



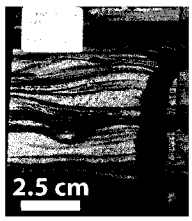
SURFACES

- WRS wave ravinement surface
- SB sequence boundary

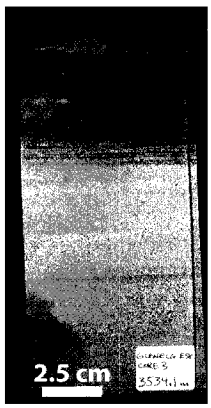
FACIES (see Table 5.3)

- **G1** tide- and storm-influenced prodelta
- **G2** tidal rhythmites (delta front deposit?)
- **G3** tidally-influenced fluvial deposits
- **G6** storm-dominated shoreface/offshore

Figure 5.19a Facies G1 (interpretation – tide- and storm-influenced prodelta deposits), Upper Missisauga, Glenelg Field: (**a**) *Teichichnus* burrow cross-cutting a thin, small-scale wave ripple cross-stratified sandstone bed (Glenelg E-58, core 2, 3450.10 m (measured depth)); (**b**) normally graded, horizontally laminated very fine sandstone bed (Glenelg E-58, core 3, 3534.10 m (measured depth)); (**c**) normally graded, low-angle cross-stratified very fine sandstone bed (Glenelg E-58, core 4, 3545.38 m (measured depth)); (**d**) soft sediment deformation (Glenelg E-58, core 5, 3730.97 m (measured depth)); (**e**) sheared layer (Glenelg E-58, core 5, 3727.2 m (measured depth)); (**f**) small "domino-style" normal faults (Genelg E-58 well, core 5, 3729.4 m (measured depth)); (**g**) rhythmically laminated sandstone bed (tidal rhythmites; Glenelg E-58A, core 7, box 3); (**h**) rhythmically laminated sandstone beds (tidal rhythmites; Glenelg E-58, core 5, 3709.36 m (measured depth)).



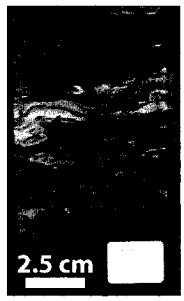
(a)



(b)



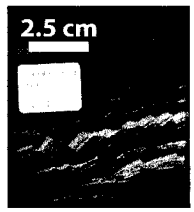
(c)



(d)



(e)



(f)

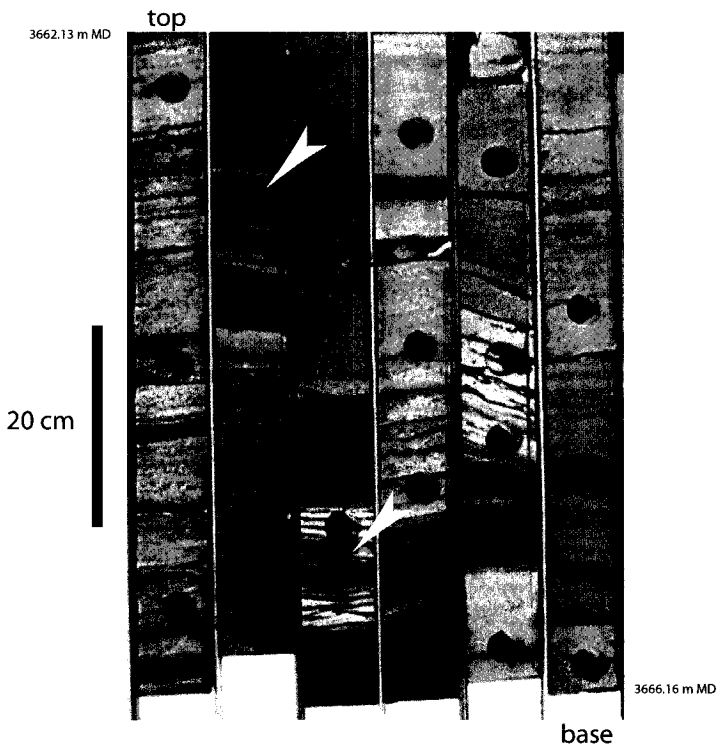


(g)

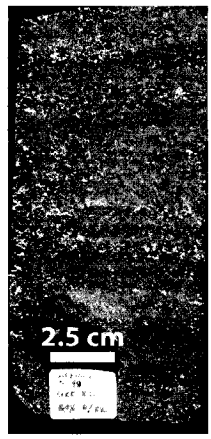


(h)

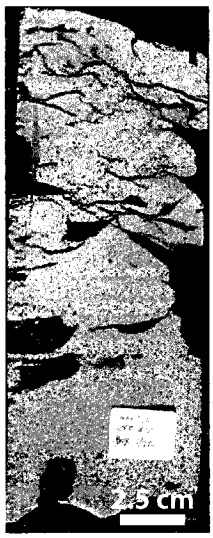
Figure 5.19b Facies G3 (tidally influenced fluvial deposits), Upper Missisauga, Glenelg Field. Core photos are from Glenelg N-49 well, cores 6 and 5 (3666.16 to 3628.8 m measured depth). These show (**a**) rhythmically laminated intervals (tidal rhythmites; white arrows) and thick mudstone interbeds, (**b**) bipolar cross-stratification, (**c**) angular mudstone interclasts, (**d**) a thick double mudstone drape, (**e**) a large *Diplocraterion* burrow, and (**f**) the upward-fining nature of a Facies G3 channel fill.


top
3662.13 m MD
20 cm
3666.16 m MD
base

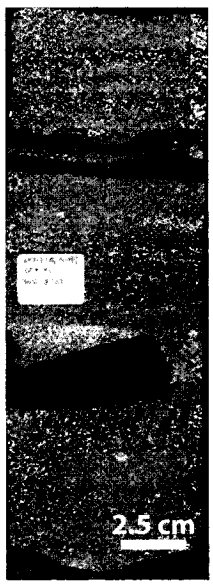
(a)


2.5 cm

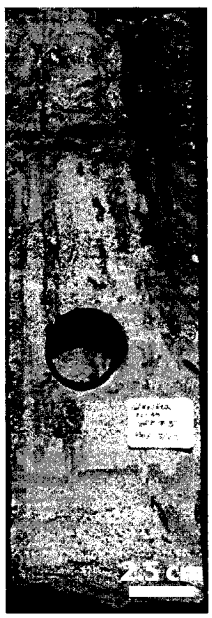
(b)


2.5 cm

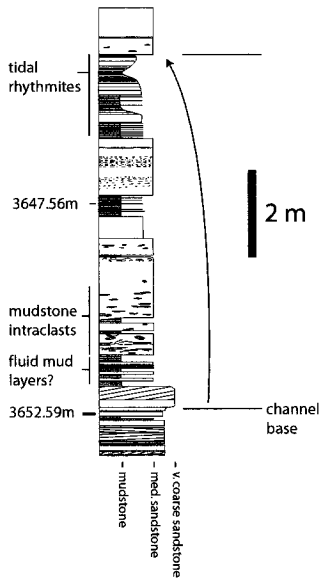
(c)


2.5 cm

(d)


2.5 cm

(e)


tidal rhythmites
3647.56m
2 m
mudstone intraclasts
fluid mud layers?
3652.59m
channel base
mudstone
med sandstone
v.coarse sandstone

(f)

Figure 5.19c An interpreted section of Upper Missisauga core from the Glenelg N-49 well, showing an upward transition from tidally influenced fluvial to storm-dominated marine deposits.

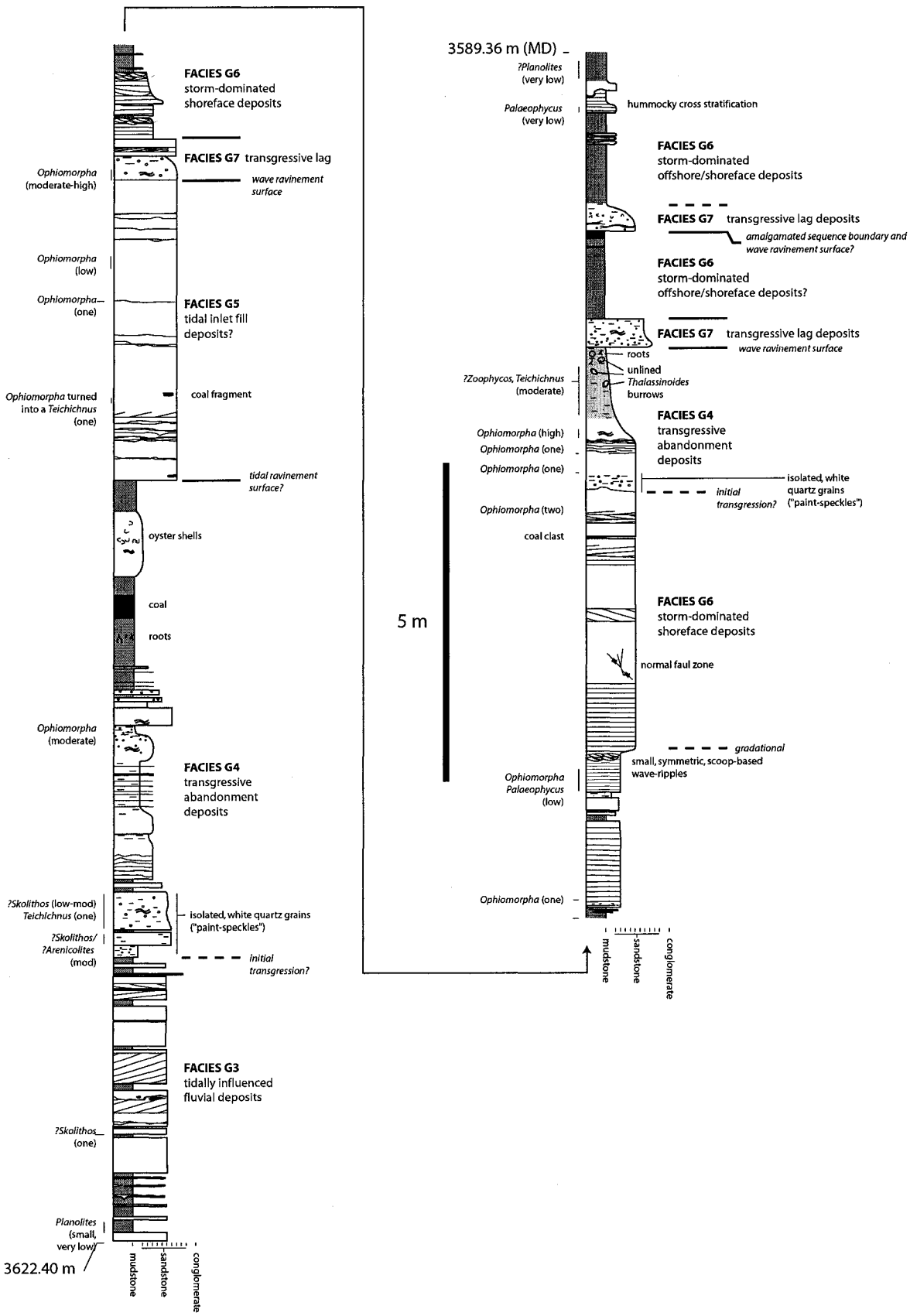

3589.36 m (MD)
?Planolites (very low)
Palaeophycus (very low)
hummocky cross stratification
FACIES G6 storm-dominated offshore/shoreface deposits
FACIES G7 transgressive lag deposits
amalgamated sequence boundary and wave ravinement surface?
FACIES G6 storm-dominated offshore/shoreface deposits?
FACIES G7 transgressive lag deposits
wave ravinement surface
roots
?Zoophycos, Teichichnus (moderate)
unlined Thalassinoides burrows
FACIES G4 transgressive abandonment deposits
Ophiomorpha (high)
Ophiomorpha (one)
Ophiomorpha (one)
isolated, white quartz grains ("paint-speckles")
initial transgression?
Ophiomorpha (two)
coal clast
5 m
FACIES G6 storm-dominated shoreface deposits
normal faul zone
gradational
small, symmetric, scoop-based wave-ripples
Ophiomorpha Palaeophycus (low)
Ophiomorpha (one)
mudstone
sandstone
conglomerate
FACIES G6 storm-dominated shoreface deposits
FACIES G7 transgressive lag
wave ravinement surface
Ophiomorpha (moderate-high)
Ophiomorpha (low)
Ophiomorpha (one)
FACIES G5 tidal inlet fill deposits?
Ophiomorpha turned into a Teichichnus (one)
coal fragment
tidal ravinement surface?
oyster shells
coal
roots
Ophiomorpha (moderate)
FACIES G4 transgressive abandonment deposits
?Skolithos (low-mod) Teichichnus (one)
?Skolithos/ ?Arenicolites (mod)
isolated, white quartz grains ("paint-speckles")
initial transgression?
FACIES G3 tidally influenced fluvial deposits
?Skolithos (one)
Planolites (small, very low)
3622.40 m
mudstone
sandstone
conglomerate

Figure 5.20 Uninterpreted and interpreted dip-oriented seismic cross-section, Venture Field, Sable Subbasin (PRX-GSI-83-1042 seismic line). Note large-scale (>1 km relief) accretionary clinoform reflectors downdip of the Venture Field interpreted to be Mic Mac and Lower Missisauga continental slope clinoforms. Well-to-seismic ties are the same as those outlined in MacLean and Wade (1993) and Mobil Oil Canada (1997b)

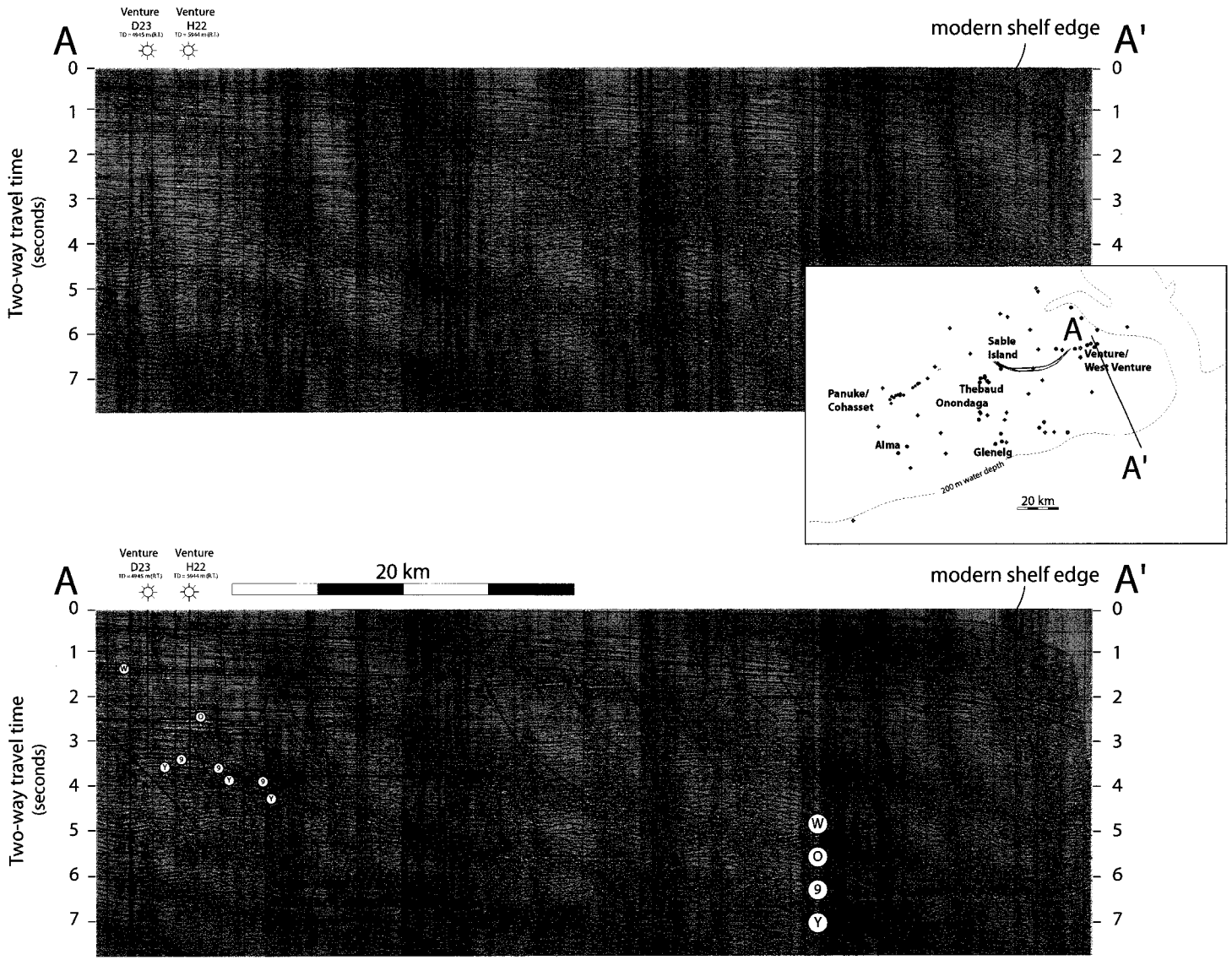

Venture D23
Venture H22
A
A'
modern shelf edge
Two-way travel time (seconds)
0
1
2
3
4
5
6
7
Sable Island
Venture/ West Venture
Thebaud
Onondaga
Panuke/ Cohasset
Alma
Glenelg
200 m water depth
20 km
W
O
9
Y

Figure 5.21 Uninterpreted and interpreted dip-oblique seismic cross-section, Alma Field, Sable Subbasin (PRX-GSI-83-846C seismic line). Note the apparent increase in dip of the O Marker basinward of the master Alma growth fault.

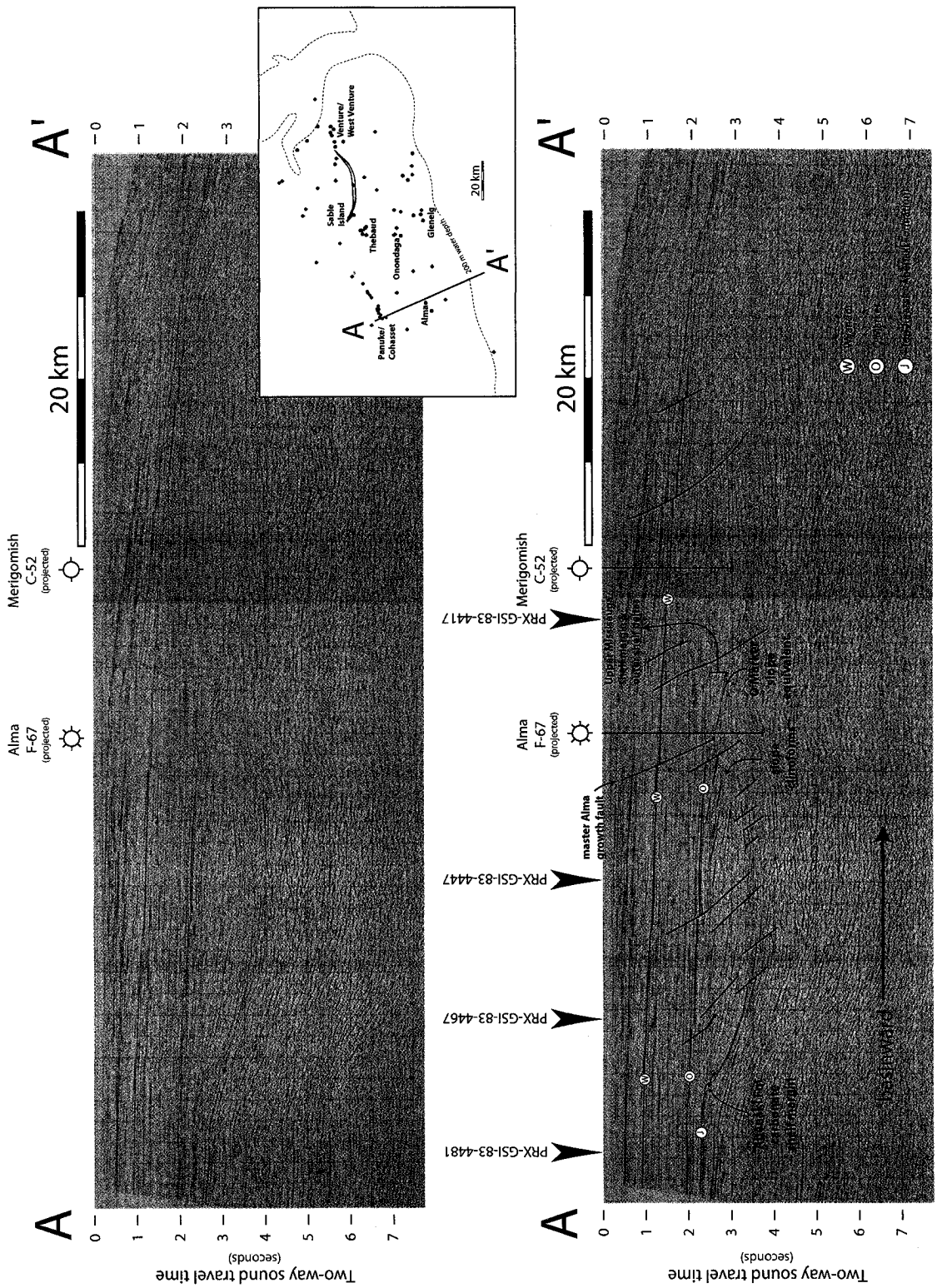

A
A'
Two-way sound travel time (seconds)
Alma F-67 (projected)
Merigomish C-52 (projected)
20 km
PRX-GSI-83-4481
PRX-GSI-83-4467
PRX-GSI-83-4447
PRX-GSI-83-4417
master Alma growth fault
Basement
Sable Island
Venture/ West Venture
Thebaud
Onondaga
Glenelg
Alma
Panuke/ Cohasset
20 km
A
A'

Figure 5.22 Uninterpreted and interpreted dip-oblique seismic cross-section, Panuke Field, western edge of the Sable Subbasin (GSI-GSI-PA99-110 seismic line). Relief of the Barremian (*i.e.*, Upper Missisauga) continental slope clinoform in this low accommodation part of the subbasin is approximately 400 m, and slope run-out distance is approximately 13 km. Note the progradational nature of the Missisauga slope clinoforms, lack of growth faults, and the relaxation of slope clinoform gradient at the contact between the Upper Missisauga and the overlying Naskapi shales

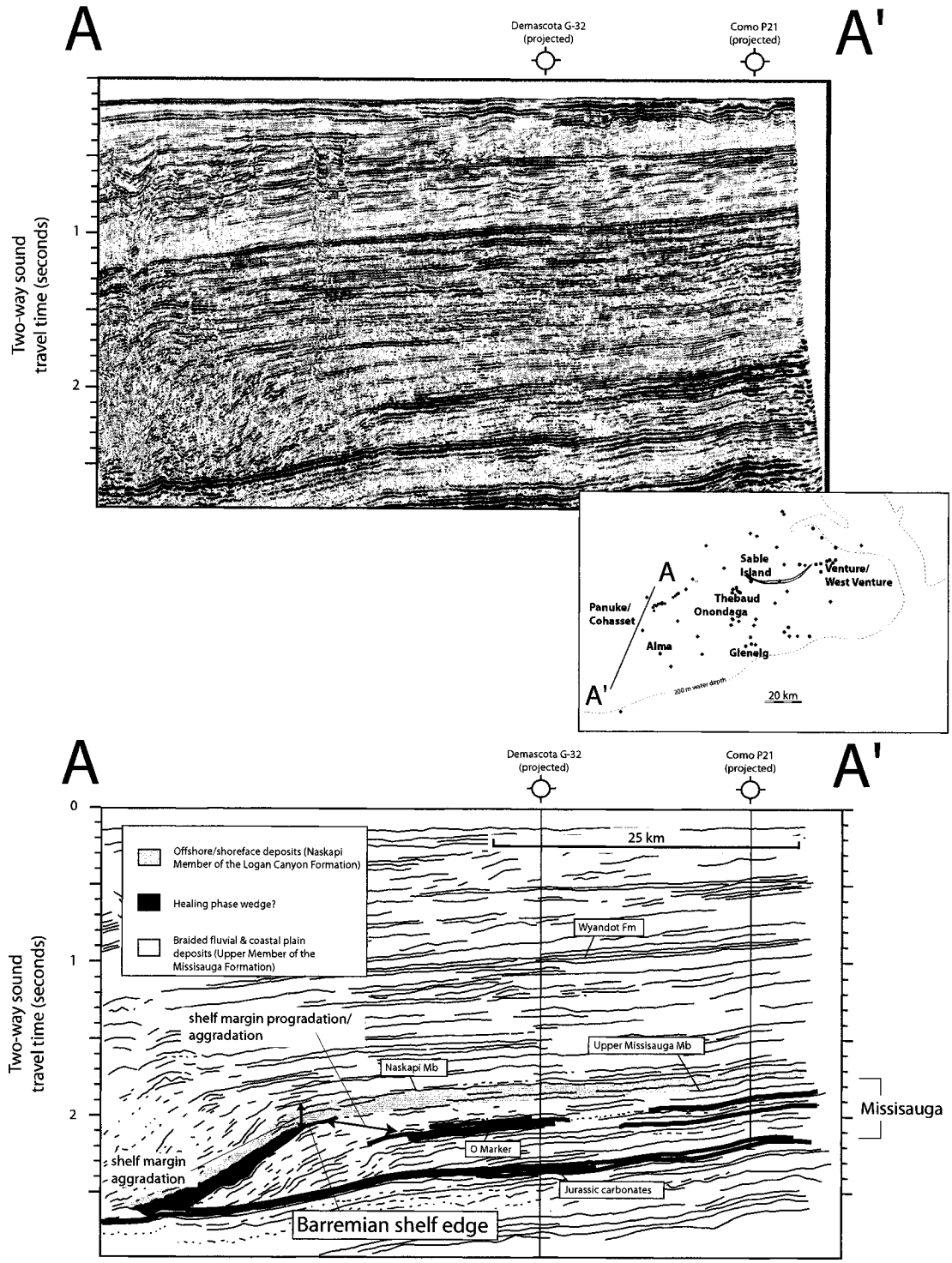

A
A'
Demascota G-32
(projected)
Como P21
(projected)
Two-way sound
travel time (seconds)
1
2
Sable
Island
Venture/
West Venture
Thebaud
Onondaga
Panuke/
Cohasset
Alma
Glenelg
200 m water depth
20 km
0
Offshore/shoreface deposits (Naskapi
Member of the Logan Canyon Formation)
Healing phase wedge?
Braided fluvial & coastal plain
deposits (Upper Member of the
Missisauga Formation)
25 km
Wyandot Fm
shelf margin progradation/
aggradation
Upper Missisauga Mb
Naskapi Mb
Missisauga
O Marker
shelf margin
aggradation
Jurassic carbonates
Barremian shelf edge

Figure 5.23 Tithonian (Lower Missisauga) and Barremian (Upper Missisauga) shelf-margin trends interpreted from subsurface data, Sable Subbasin. Solid grey zones indicate seismically resolvable shelf-margins; hatched zones indicate shelf-margin positions inferred from well log, sedimentological, and biostratigraphic data.

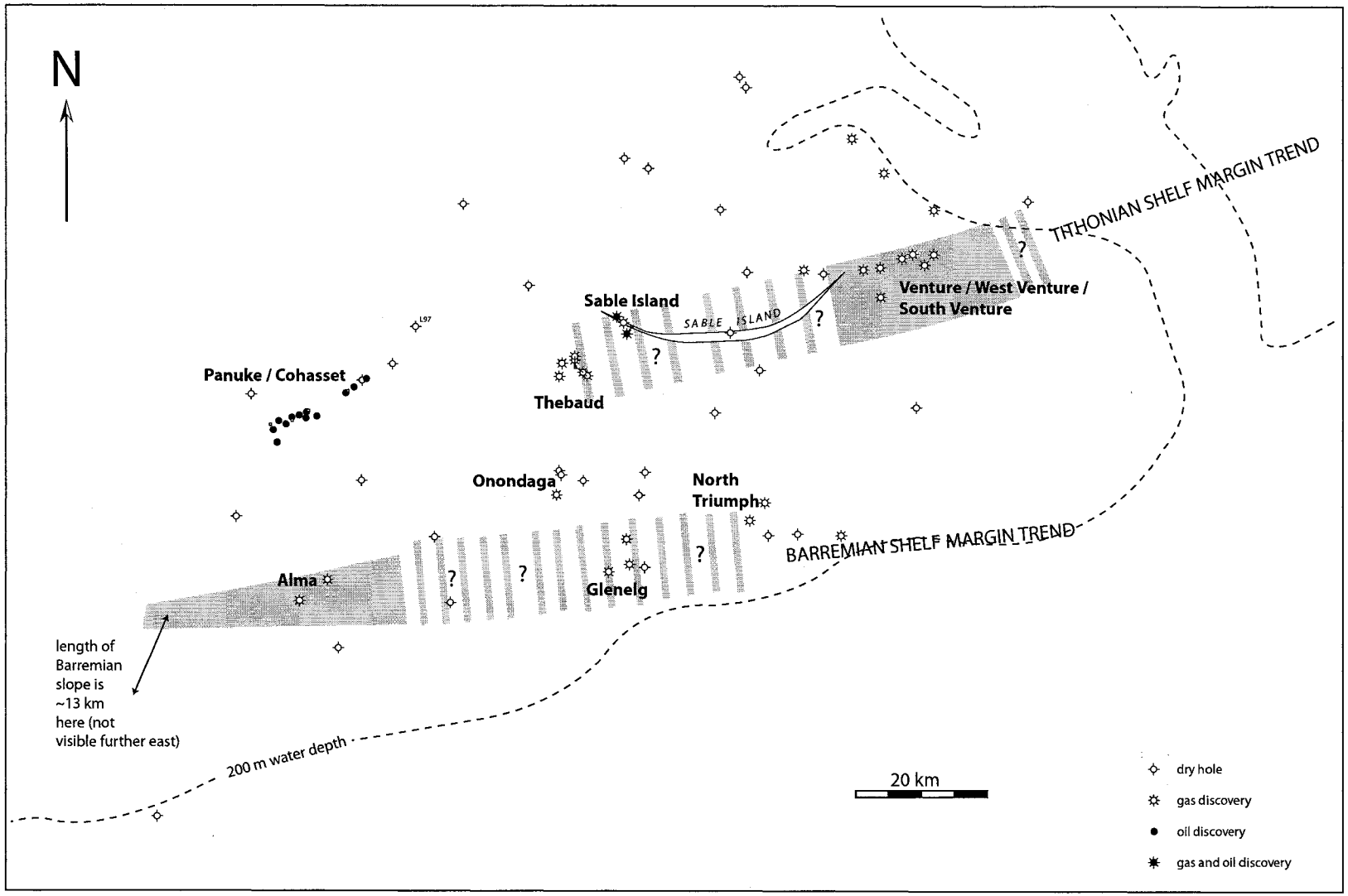

N
TITHONIAN SHELF MARGIN TREND
45 00'
Sable Island
SABLE ISLAND
Venture / West Venture /
South Venture
Panuke / Cohasset
Thebaud
Onondaga
North
Triumph
BARREMIAN SHELF MARGIN TREND
Alma
Glenelg
length of
Barremian
slope is
~13 km
here (not
visible further east)
200 m water depth
20 km
dry hole
gas discovery
oil discovery
gas and oil discovery
61 00'
60 00'
59 00'

Figure 5.24 Features common to the shelf-margin delta play-type, Missisauga Formation, offshore Nova Scotia.

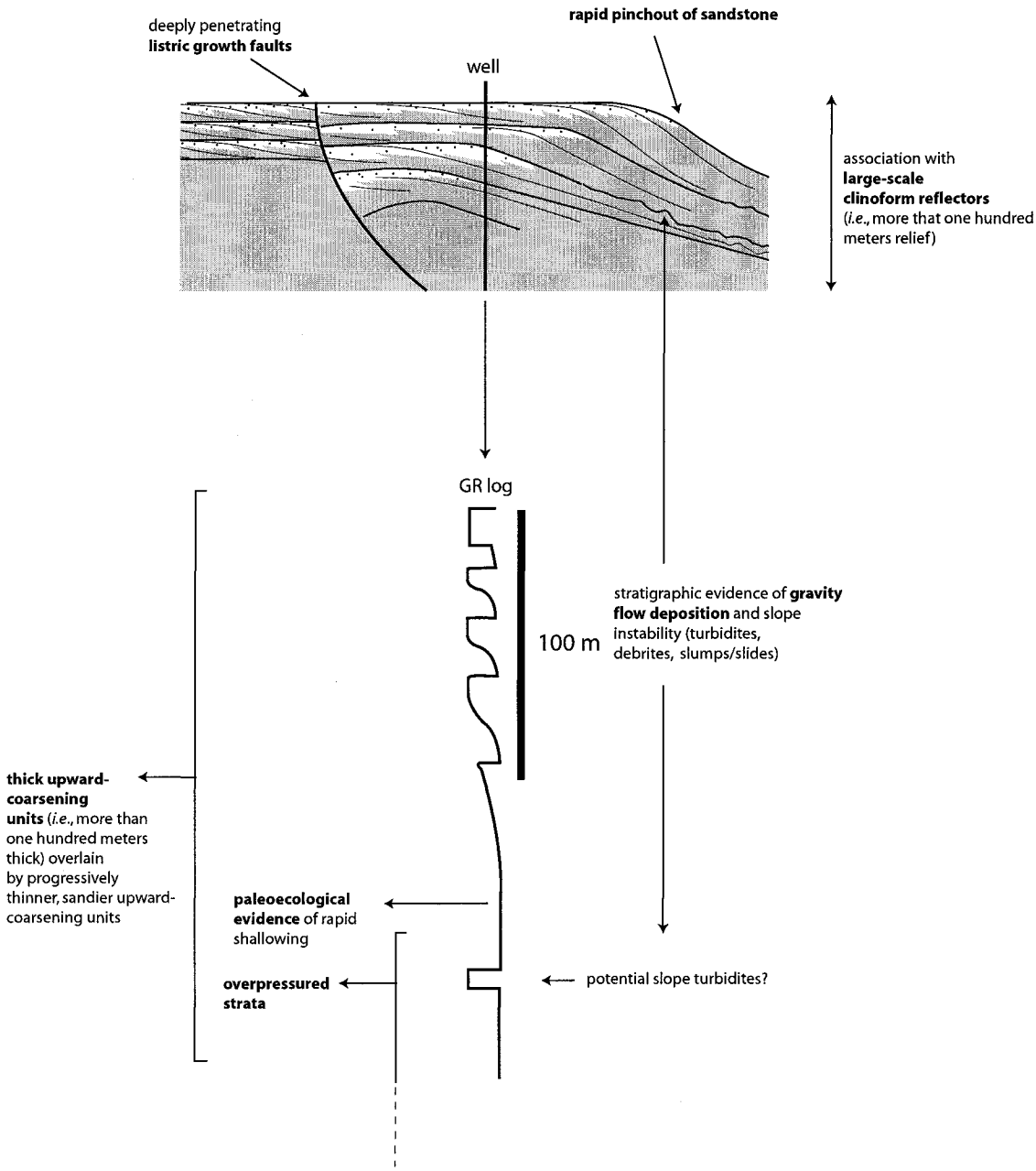
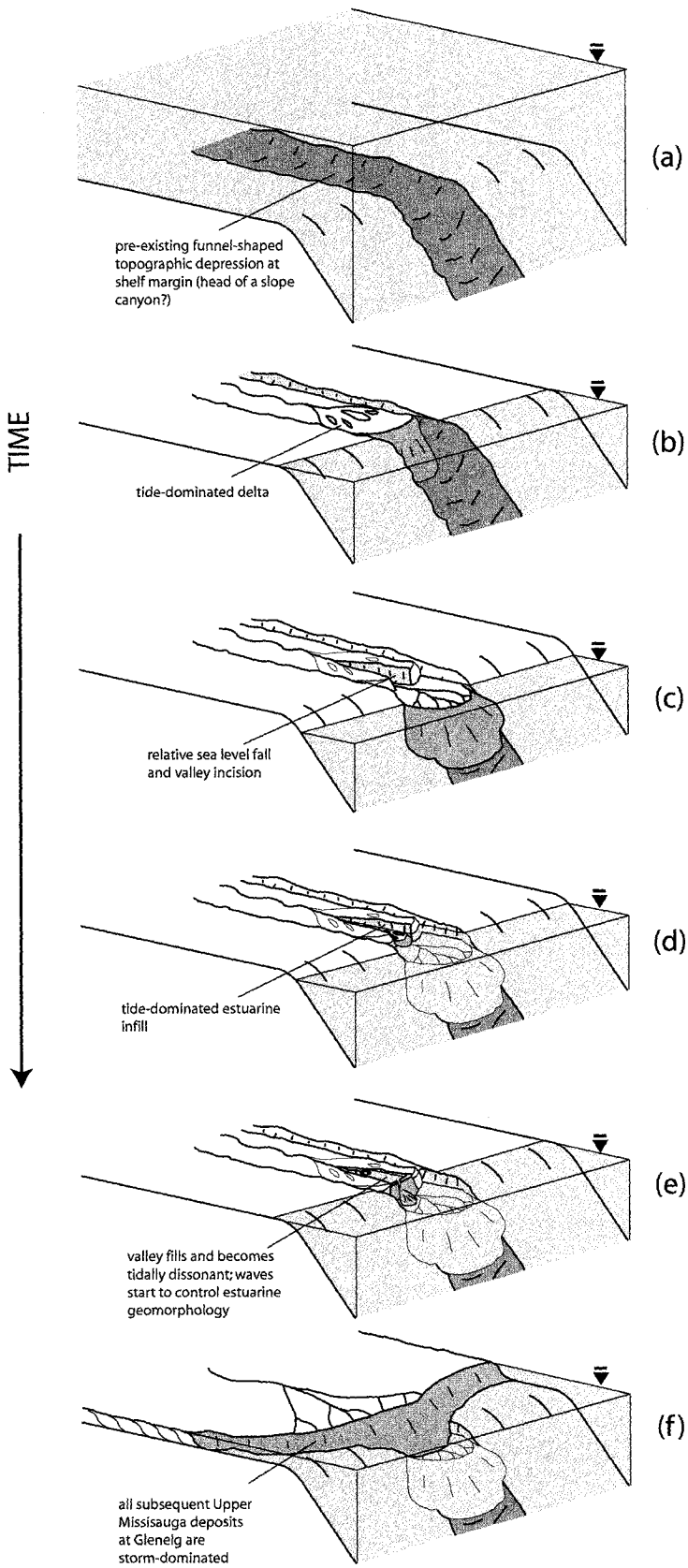

deeply penetrating
listric growth faults
well
rapid pinchout of sandstone
association with
large-scale
clinoform reflectors
(*i.e.*, more that one hundred
meters relief)
GR log
100 m
stratigraphic evidence of **gravity**
flow deposition and slope
instability (turbidites,
debrites, slumps/slides)
thick upward-
coarsening
units (*i.e.*, more than
one hundred meters
thick) overlain
by progressively
thinner, sandier upward-
coarsening units
paleoecological
evidence of rapid
shallowing
overpressured
strata
potential slope turbidites?

Figure 5.25 Depositional model for the Upper Member of the Missisauga Formation, Glenelg Field. (**a**) irregular, funnel-shaped antecedent topography at shelf margin (*e.g.*, Swatch of No Ground, offshore Ganges-Brahmaputra); (**b**) initial shallow marine sedimentation is tide-influenced; (**c**) further relative sea level fall causes incision of delta plain; (**d**) estuarine sedimentation in incised valley during initial transgression is tide-dominated; (**e**) as valley fills, it becomes tidally dissonant, and a wave-formed barrier-inlet forms at the estuary mouth; (**f**) all subsequent shallow marine sedimentation is storm-wave dominated (main Glenelg reservoirs are storm-dominated shallow marine sandstones).


TIME
(a)
pre-existing funnel-shaped topographic depression at shelf margin (head of a slope canyon?)
(b)
tide-dominated delta
(c)
relative sea level fall and valley incision
(d)
tide-dominated estuarine infill
(e)
valley fills and becomes tidally dissonant; waves start to control estuarine geomorphology
(f)
all subsequent Upper Missisauga deposits at Glenelg are storm-dominated

Chapter 6. Conclusions

1) High terrigenous sediment influx and high frequency, small amplitude relative sea level falls transferred abundant fluvial sediment to the shelf margin during deposition of the Missisauga Formation (Tithonian-Barremian). Because of limited well control, it is unclear whether the high-frequency relative sea level cycles affected the entire basin or were only local in extent. These high frequency relative sea level falls caused the shelf margin to prograde despite net low frequency, large amplitude relative sea level rise. High sediment supply caused gravity sliding of shelf margin and slope deposits, which resulted in the formation of large listric shelf-margin growth faults in the central Sable Subbasin. The Tithonian (Lower Missisauga) shelf margin was located several kilometers basinward of the Venture Field, and trended approximately E-W. Between the Tithonian and the Barremian, the Missisauga shelf margin prograded approximately ~40 km south to a position just basinward of the Alma and Glenelg fields.

2) Missisauga shelf margins are typically poorly resolved in seismic data in the Sable Subbasin. However, their location can be inferred based on a combination of the following criteria (in approximate order of decreasing importance):

- large relief (*i.e.*, several hundred meters plus) clinoform reflections
- thick (*i.e.*, one hundred meters or more) upward-coarsening successions
- common gravity-flow deposits
- superposition of sandstone-rich over mudstone-rich strata
- large, listric growth faults
- paleoecological evidence indicating rapid shallowing
- the top of overpressure

3) Growth-faulted shelf-margin deltas in the Missisauga Formation constitute an important but previously unrecognized play type that host at least half of the currently discovered in-place gas reserves offshore Nova Scotia. Upward-coarsening shelf margin delta successions typically contain abundant hummocky cross-stratified sandstone, suggesting that storm waves commonly controlled shelf margin delta morphology and facies distribution. Amalgamated, hummocky cross-stratified sandstone is the main reservoir type at Alma, Glenelg, and Venture/West Venture/South Venture fields. However, shelf-margin delta successions locally contain abundant tidal rhythmites, suggesting that, at least locally, tide-dominated shelf margin deltas formed. Estuarine incised valley fills, where cored (*e.g.*, Venture/West Venture and Glenelg fields), are composed primarily of very muddy, tidally influenced fluvial deposits, suggesting that incised valleys commonly became tidally resonant during transgression.

4) In contrast to coeval upward-coarsening deltaic units located downdip in the Glenelg and Alma fields, the Upper Member of the Missisauga Formation in the Panuke Field is characterized by two sharp-based, upward-fining units. 3-D seismic data suggest the base of the lowermost upward-fining unit is a fluvially eroded incised valley at the top of the O Marker. Seismic data show the incised valley to correlate downdip to progradational slope clinoforms, suggesting that it formed during relative sea level fall below the shelf edge. The uppermost sharp-based unit passes upward from a 50 m thick braided fluvial sandstone into a 50 m thick heterolithic coastal plain unit, which in turn is overlain by ~150 m of offshore mudstone. The base of the uppermost sharp-based unit is interpreted to be a wide (>20 km) incised valley formed during a slow relative sea level fall in the Barremian. However, shelf-margin progradation occurred until the end of

coastal plain deposition in the Panuke Field (*i.e.,* the Missisauga-Naskapi boundary), suggesting that although net transgression was occurring, high frequency relative sea level falls episodically caused fluvial systems to bypass the shelf and deliver sediment to the shelf margin. The main Panuke reservoir is a sharp-based, transgressively deposited shallow marine sand-body located between heterolithic coastal plain deposits of the Missisauga Formation and offshore mudstone of the Naskapi Member of the Logan Canyon Formation.

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APPENDIX 1: DETAILED CORE LOGS

Appendix 1, table 1 Facies descriptions and interpretations, Alma Field (Upper Missisauga)*

Facies	Lithology and texture	Physical sedimentary structures	Biogenic features	Gamma ray log character	Interpretation
A1	mudstone	microfaults are present locally, and thin (<1 mm), short (1 to 6 cm), light-coloured, vertical to subvertical "streaks" barren of organic particles are also observed locally (interpretation = pillar (dewatering) structures)	Bioturbation is absent or very minimal, and includes *Teichichnus, Planolites, Asterosoma, Helminthopsis, Chondrites, Zoophycos, ?Arenicolites, Palaeophycus, Terebellina*; shell fragments (echinoid, gastropod, ammonite, bivalve) and disseminated organic matter are common on beddings surfaces	upward-coarsening	prodelta mudstone with evidence of mass movement and gravity flow deposition
A2	Inter-stratified mudstone and thin beds of (<10 cm), very fine sandstone	thin sandstone beds are typically planar to low-angle (<10°) cross-stratified, or rarely small-scale (<5 cm) high-angle (>15°) cross-stratified	Bioturbation in mudstone is generally low, and includes *Asterosoma, Planolites, Teichichnus, Zoophycos,* and *?Cylindrichnus*; rare escape traces and and *Ophiomorpha* in sandstone	upward-coarsening	storm-influenced delta front and prodelta heterolithics
A3	very fine to medium sandstone	where not obscured by bioturbation, sandstone is either planar laminated, low-angle (<10°) cross-stratified, or medium-scale (10-20 cm) high-angle cross-stratified	bioturbation is commonly intense, with *Ophiomorpha Palaeophycus, Helminthopsis, Planolites, Skolithos, Teichichnus, Zoophycos, Asterosoma, ?Thalassinoides, ?Conichnus* and *?Diplocraterion.*	upward-coarsening	unstressed shoreface deposits
A4	Poorly-sorted, carbonate cemented sandstone with "paint-speckled" appearance	Sedimentary structures are rarely preserved due to bioturbation	Bioturbation is typically intense, and includes *Ophiomorpha, Planolites, ?Asterosoma, ?Thalassinoides,* and *Helminthopsis*; bivalve, scaphopod, and gastropod shell fragments are common	usually thin bed (<1 m thick) with low API values	transgressive lag
A5	Poorly-sorted, muddy coarse to very fine sandstone	typically not visible due to intense bioturbation	bioturbation is intense, with large *Ophiomorpha* and *Palaeophycus* (trace fossils hard to ID due to intense bioturbation)	sharp-based, upward fining	transgressive shelf sandstone

*An extended facies analysis for the Alma Field is presented in Appendix 2.

Appendix 1, table 2 Facies descriptions and interpretations, Glenelg Field (Upper Missisauga)*

Facies	Lithology and texture	Physical sedimentary structures	Biogenic features	Gamma ray log character	Interpretation
G1	mudstone with thin, very fine sandstone interbeds	sandstone beds are horizontally to low-angle (<10°) cross stratified; sandstone beds are rarely normally graded; some rhythmically laminated intervals in both mudstone and sandstone interbeds; deformed muddy sandstone beds common	bioturbation in mudstone is typically very low, with *Planolites*, *Teichichnus*, *Terebellina*, and *Asterosoma*; rare *Ophiomorpha* in sandstone beds; disseminated organic flecks are common	upward-coarsening	Storm- and tide-influenced prodelta deposits
G2	Interlam-inated mudstone and very fine sandstone	rhythmically alternating mudstone and sandstone laminae; rhythmites typically form successions that progressively thicken and thin (interpretation – tidal rhythmites); contacts between sandstone and mudstone laminae in rhythmites are typically gradational	no bioturbation observed; disseminated coal flecks abundant throughout	Slightly serrated	tide-dominated delta front deposits (delta front interpretation based on stratigraphic position overlying Facies G1 and underlying Facies G3)
G3	medium to very coarse sandstone with thick mudstone interbeds	sandstone beds (~20 cm ave.) are commonly high-angle (>15°) cross-stratified; bipolar cross-sets and double mud drapes observed; mud intraclasts present; rare rhythmically laminated intervals (like Facies G2) present	bioturbation very sparse, and includes *Skolithos*, *Diplocraterion* and *Ophiomorpha* in sandstone, and small *Planolites* in mudstone; pebble-sized coal clasts and disseminated coal flecks abundant throughout	serrated, sharp-based upward-fining	tide-influenced fluvial channel fill deposits
Facies G4	organic-rich mudstone with thin rooted coal beds	stratification is typically not visible, although rare, high-angle (>15°) cross-sets (~15 cm thick) are visible locally	bioturbation increases upward; trace fossils were hard to ID, but rare *Teichichnus* burrows observed locally	upward-fining	transgressive abandonment deposits (grades up from Facies G3 or G5)
Facies G5	Coarse sandstone		bioturbation sparse throughout (*Ophiomorpha*); rare pebble-sized coal clasts	sharp-based blocky	Tidal inlet fill (occurs over coastal plain (Facies G3 and G3) and under marine (Facies G6 and G7) deposits)
Facies G6	mudstone with thin, very fine sandstone interbeds	sandstone beds are horizontally laminated to low-angle (<10°) cross stratified	bioturbation in mudstone is typically low, with *Planolites*, *Asterosoma*, *Zoophycos*, *Teichichnus*, *Terebellina*, and *Rosselia*; rare *Ophiomorpha*, *Cylindrichnus Chondrites* and *Palaeophycus* burrows are present in sandstone	upward-coarsening	storm-dominated delta front and offshore deposits (main Glenelg reservoirs)
Facies G7	Poorly sorted sandstone	typically not visible	bioturbation is locally intense, and *Ophiomorpha* burrows are typically predominant; unlined, sandstone-filled *Thalassinoides* commonly penetrate down from Facies G7 into underlying mudstone	usually thin bed (<1 m thick) with low API values	transgressive lag

*An extended facies analysis for the Glenelg Field is presented in Appendix 2.

Appendix 1, table 3 Facies descriptions and interpretations, Panuke/Cohasset field region (Upper Missisauga)*

Facies	Lithology and texture	Physical sedimentary structures	Biogenic features	Gamma ray log character	Facies in Venture, Glenelg, and Alma fields with similar aspect	Interpretation
P1	medium to coarse sandstone	beds are typically high-angle(>15°) cross-stratified or planar laminated; cross-sets are 10-100 cm thick; mud intraclasts and coal fragments are common	no trace fossils observed	Blocky		braided fluvial channel fills (braided channel pattern inferred based on a braid-bar like feature observed in 3-D seismic data)
P2	medium to coarse sandstone	beds are typically high-angle(>15°) cross-stratified or planar laminated; cross-sets are 10-100 cm thick; mud intraclasts and coal fragments are common; rare double mud drapes	several *Skolithos* burrows observed	Blocky		tide- and marine-influenced braided fluvial channel fills
P3	mudstone with oyster shells	siltstone interbeds are planar lamianted to low-angle (<10°) cross-stratified	Bioturbation is generally absent, but is locally intense. Trace fossils include small *Planolites*, *Teichichnus*, *Asterosoma*, *Zoophycos*, *?Cylindrichnus* and *Rosselia*.	Muddy		lagoonal deposits
P4	mudstone with fine sandstone laminae	sandstone laminae are lenticular (pod-shaped), wavy (undulating top and bottom contacts), or pinstripe shaped (mm-thick, flat, and discontinuous across the core; synaeresis cracks, small-scale concave normal faults, and microfaults are present; decimeter-thick, rhythmically-interstratified mudstone and fine sandstone also occur rarely	Bioturbation is generally low, but locally intense. Trace fossils include small *Planolites*, *Arenicolites*, *Teichichus*, *Chondrites*, *Diplocraterion*, *?Skolithos*, *?Thalassinoides*, and *?Rosselia*; coal fragments and flakes are common	Serrated		tidal flat deposits
P5	fine sandstone	sandstone beds are planar laminated, small-scale (<5 cm) to large-scale (5-20 cm) high-angle (>15°) cross-stratified	Trace fossils are rare, and include *Skolithos*, *Ophiomorpha*, small *Planolites* and escape traces; rare, unlined, passively-filled *Thalassinoides* burrows subtend from sharp-basal contact; roots, carbonaceous mudstone, and a thin cm-thick coal bed are observed at the top of one of the sharp-based units	blocky to upward-fining		small tidal channel deposits
P6	very fine to fine sandstone	sandstone is either planar laminated or small- (<5 cm) to	bioturbation is generally absent, but small *Planolities* burrows occur in thin	Upward-coarsening		bayhead delta deposits

		large-scale (5-10 cm) high-angle (>15°) cross-stratified; sub-angular to round mudstone clasts are common	mudstone interbeds, and rare *Ophiomorpha* burrows occur in sandstone; disseminated organic flecks are abundant			
P7	poorly sorted sandstone	structures typically obscured by bioturbation; rare glauconite and carbonate-coated granules and sandstone pebbles present	Bioturbation is typically intense and includes *Ophiomorpha, Palaeophycus, ?Cylindrichnus, Teichichnus,* and *Chondrites.*; shell fragments (oyster, gastropod, scaphopod) are common; facies typically has subtending, unlined *Thalassinoides* burrows below sharp-basal contact	Blocky		transgressive lag
P8	very fine to medium sandstone	sedimentary structures typically not visible; dispersed, white-coloured quartz sand grains and granules ("paint-speckles") are common.	bioturbation is typically moderate to intense; trace fossil assemblage is dominated by *Ophiomorpha,* with less common *Cylindrichnus, Skolithos, ?Rosselia,* and *Chondrites* (in the *?Rosselia*); shells present locally	Blocky		transgressive shallow marine sandstone deposits
P9	mudstone with thin sandstone interbeds	sandstone beds are commonly low-angle (<10°) cross-stratified	bioturbation is typically low, with *Planolites, Teichichnus, Palaeophycus, Terebellina, Chondrites, Ophiomorpha, Cylindrichnus, ?Asterosoma,* and *?Rosselia.*; one ammonite shell was observed	Upward-coarsening		offshore mudstone
P10	well-sorted, very fine to fine sandstone with mudstone interbeds	sandstone beds are commonly low-angle (<10°) cross-stratified	sandstone is sparsely bioturbated with rare *Ophiomorpha* burrows; mudstone interbeds are also sparsely bioturbated, and contain *Planolites, Teichichnus, Paleophycos, Terebelina, Chondrites, Ophiomorpha, Cylindrichnus, ?Asterosoma,* and *?Rosselia* burrows.	Upward-coarsening		storm-dominated lower shoreface deposits

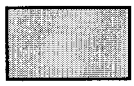
*An extended facies analysis for the Panuke/Cohasset region is presented in Chapter 3.

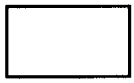
Appendix 1, table 4 Facies descriptions and interpretations, Venture sandstones 8 to 5, Venture and West Venture fields (Lower Missisauga)*

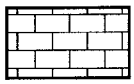
Facies	Lithology and texture	Physical sedimentary structures	Biogenic features	Gamma ray log character	Interpretation
V1	light blue-gray carbonate mudstone	massive to faintly laminated	brachiopod, bryozoa, and foraminifera bioclasts	blocky	shelf carbonate deposits
V2	mudstone with rare to common thin (<10 cm) siltstone and very fine sandstone beds	Siltstone and sandstone beds are typically planar to low-angle (<10°) cross-stratified	sparse to intense bioturbation, with *Planolites*, *Palaeophycus*, *Asterosoma*, *Helminthopsis*, *Chondrites*, *Zoophycos*, *Terebellina*, *Teichichnus*, and *Rosselia*; several specimens of a *Circulodium*-like dinoflagellate and one *Subtilisphaera*- like specimen observed (Rob Fensome, personal communication, 2002)	upward-coarsening	offshore/distal storm-dominated delta front deposits
V3	Well-sorted, very fine to fine buff-coloured sandstone	sandstone is horizontally laminated to low-angle (<10°) cross-stratified	bioturbation is sparse, with *Ophiomorpha*, *Rosselia*, and *?Cylindrichnus* in sandstone, and *Teichichnus*, *Paleophycos*, *Terebellina*, *Chondrites*, *Ophiomorpha*, *Cylindrichnus*, *?Asterosoma*, and *?Rosselia* in rare mudstone beds	upward-coarsening to blocky	storm-dominated delta-front deposits
V4	moderately to well-sorted medium sandstone	sandstone beds (1-25 cm thick) are high-angle (>15°) to low-angle (<10°) cross-stratified	bioturbation is sparse, with rare *Ophiomorpha* burrows; rare layers of sparsely disseminated organic flecks in sandstone	blocky to upward-coarsening	storm-dominated upper delta-front deposits
V5	Mudstone with common fine to coarse sandstone interbeds (10-75 cm thick)	sandstone is high-angle (>15°) cross-stratified; rare synaeresis cracks, load structures, double mud drapes, and rhythmically laminated intervals	bioturbation typically absent, but rare, intensely burrowed intervals of *?Taenidium* present in sandstone; also rare *Ophiomorpha* and *Diplocraterion* present in sandstone; mudstone contains rare *Teichichnus*, *Thalassinoides*, *?Rhyzocorallium* and small *Planolites* pebble-sized abundant coal clasts and dissemin-ated organic flecks; one possible dynoflagellate observed (Rob Fensome, personal communication, 2002)	sharp-based and serrated, units commonly fine upward slightly	tide- influenced fluvial deposits
V6	mudstone with pinstripe, wavy, and lenticular laminated very fine sandstone	sandstone laminae are typically high-angle (>15°) cross-stratified and have flat to scoop-shaped bases; rare synaeresis cracks present	typically unbioturbated, although rare small *Planolites* burrows observed; root traces observed once	serrated	tidal flat deposits
V7	well sorted medium to coarse sandstone	beds are typically high-angle (>15°) cross-stratified; cross sets are a maximum of ~1 m thick	no trace fossils observed; coal fragments present locally	blocky	fluvial deposits
V8	coal and pyrite-rich black mudstone		no trace fossils observed	usually thin bed (<1 m thick) with higher API values	marsh deposits
V9	poorly sorted, carbonate cemented sandstone with a "paint-speckled" appearance	typically not visible due to intense bioturbation	bioturbation is commonly intense, with *Ophiomorpha*, *Chondrites*, *Skolithos*, *Palaeophycus*, *?Teichichnus*, and *?Rosselia/Cylindrichnus*; pebble-size coal fragments, coal flakes, and mm-thick coal partings are common	usually thin bed (<1 m thick) with low API values	transgressive lag

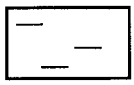
*An extended facies analysis for the Venture and West Venture fields is presented in Chapter 4.

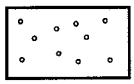
SYMBOLS USED IN CORE LOGS

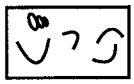

mudstone

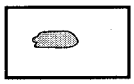

sandstone


limestone


muddy sandstone

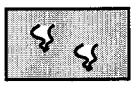

sandstone with pebbles and/or granules


shells and/or shell fragments

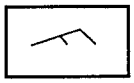

mudstone intraclast

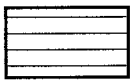

coal fragment

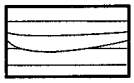

intensely bioturbated interval

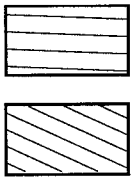

synaeresis cracks


small-scale wave-ripple cross-stratification (estimated ripple wavelengths <30 cm)

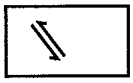

current-ripple cross-stratification


horizontal lamination

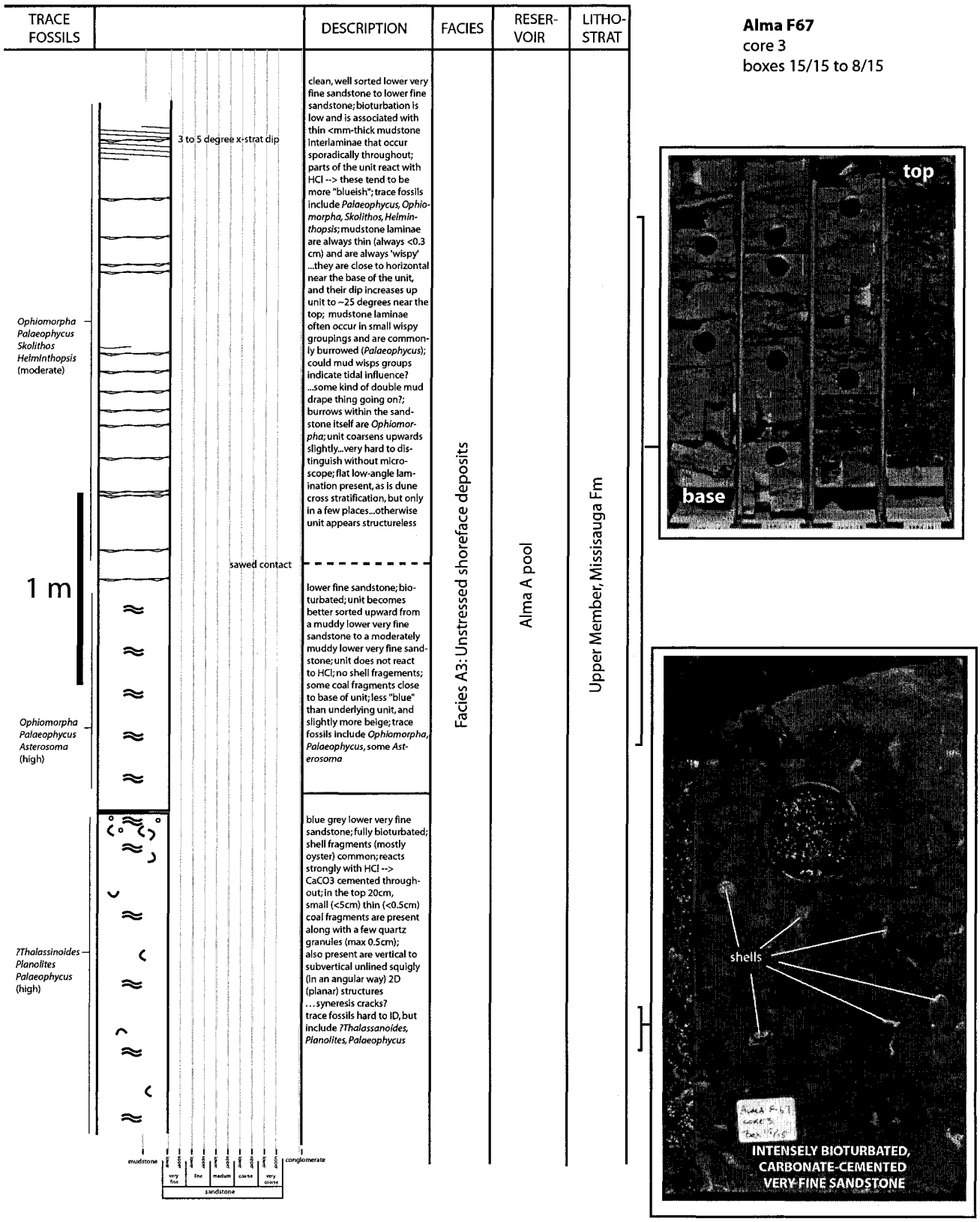

low-angle, concave-up truncation within a sandstone bed

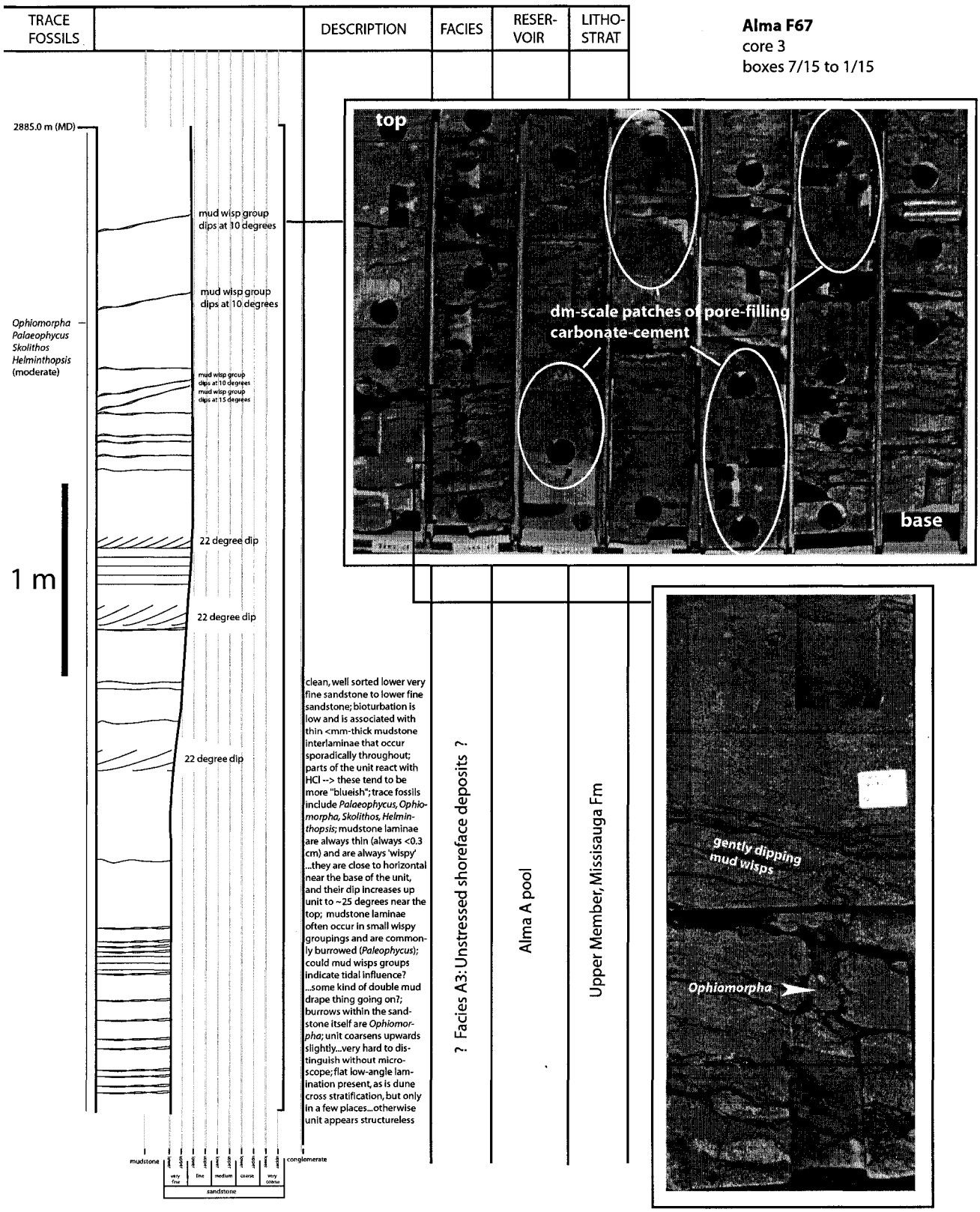

cross-stratification

NOTE: cross-strata dip angle depicted in core logs are the same as that measured in core unless well is deviated(e.g., West Venture C-62), whereupon dip angle depicted should only be taken as a rough estimate of the true value

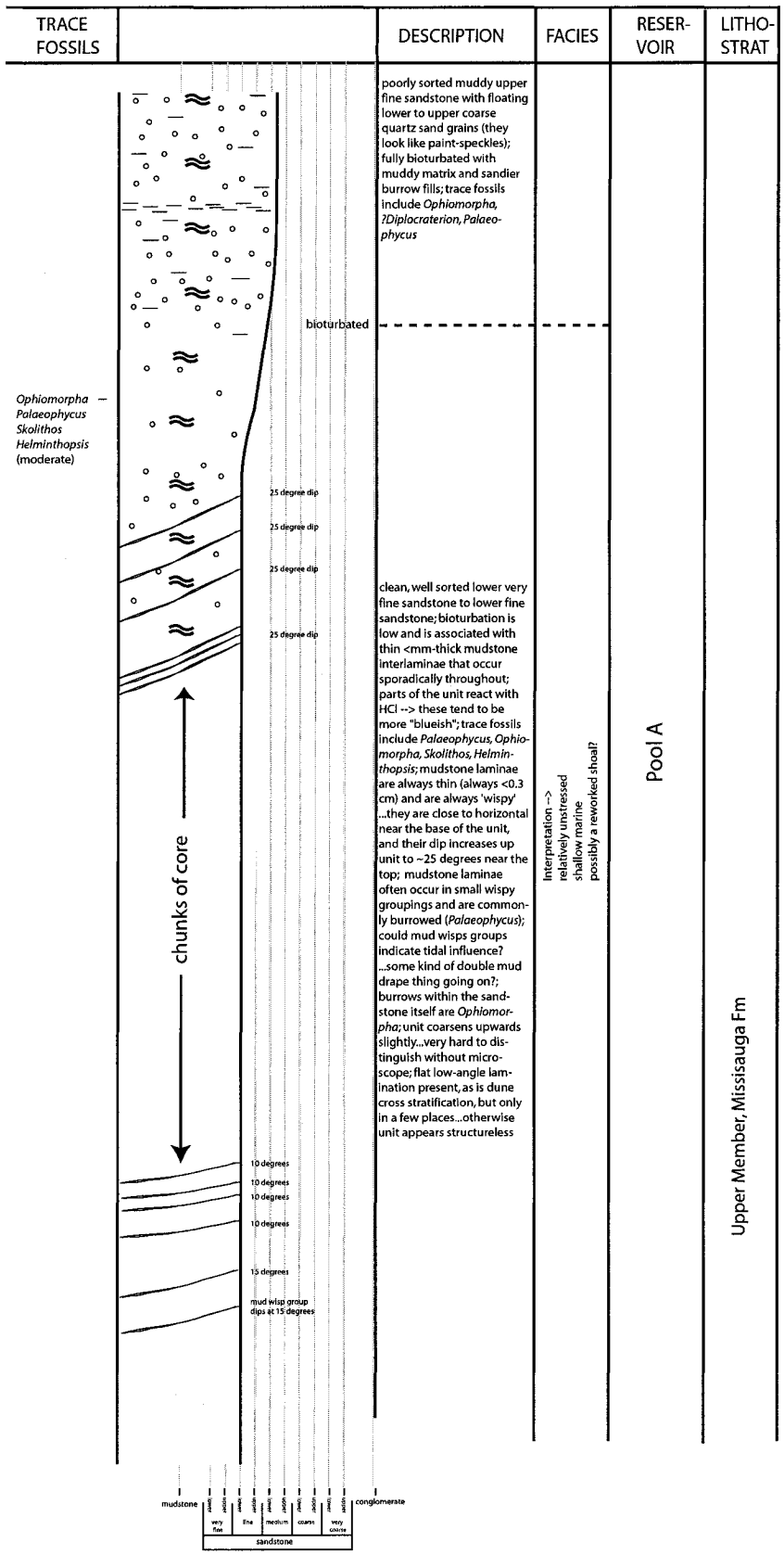

fault

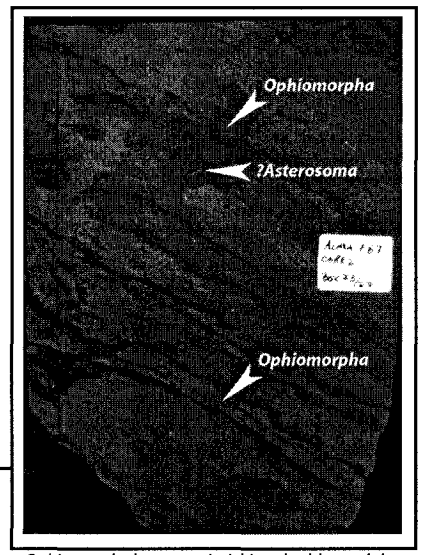
Alma F67
core 3
boxes 15/15 to 8/15




TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Alma F67
core 3
boxes 7/15 to 1/15
top
base
dm-scale patches of pore-filling carbonate-cement
2885.0 m (MD)
mud wisp group dips at 10 degrees
mud wisp group dips at 10 degrees
Ophiomorpha
Palaeophycus
Skolithos
Helminthopsis
(moderate)
mud wisp group dips at 10 degrees
mud wisp group dips at 15 degrees
1 m
22 degree dip
22 degree dip
22 degree dip
clean, well sorted lower very fine sandstone to lower fine sandstone; bioturbation is low and is associated with thin <mm-thick mudstone interlaminae that occur sporadically throughout; parts of the unit react with HCl --> these tend to be more "blueish"; trace fossils include Palaeophycus, Ophiomorpha, Skolithos, Helminthopsis; mudstone laminae are always thin (always <0.3 cm) and are always 'wispy' ...they are close to horizontal near the base of the unit, and their dip increases up unit to ~25 degrees near the top; mudstone laminae often occur in small wispy groupings and are commonly burrowed (Paleophycus); could mud wisps groups indicate tidal influence? ...some kind of double mud drape thing going on?; burrows within the sandstone itself are Ophiomorpha; unit coarsens upwards slightly...very hard to distinguish without microscope; flat low-angle lamination present, as is dune cross stratification, but only in a few places...otherwise unit appears structureless
? Facies A3: Unstressed shoreface deposits ?
Alma A pool
Upper Member, Missisauga Fm
gently dipping mud wisps
Ophiomorpha
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone

Alma F67
core 2
boxes 27/27 to 20/27
vertical well

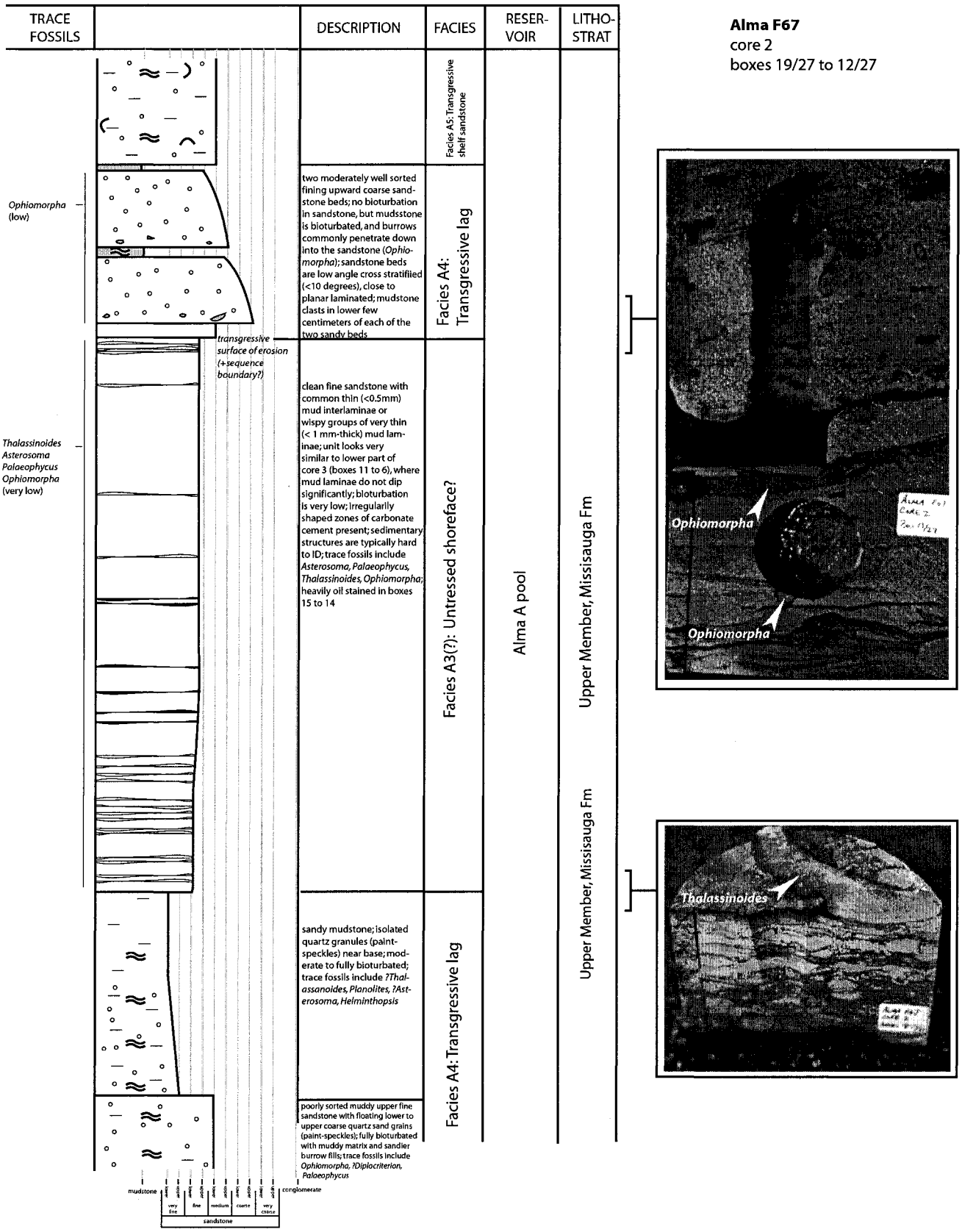




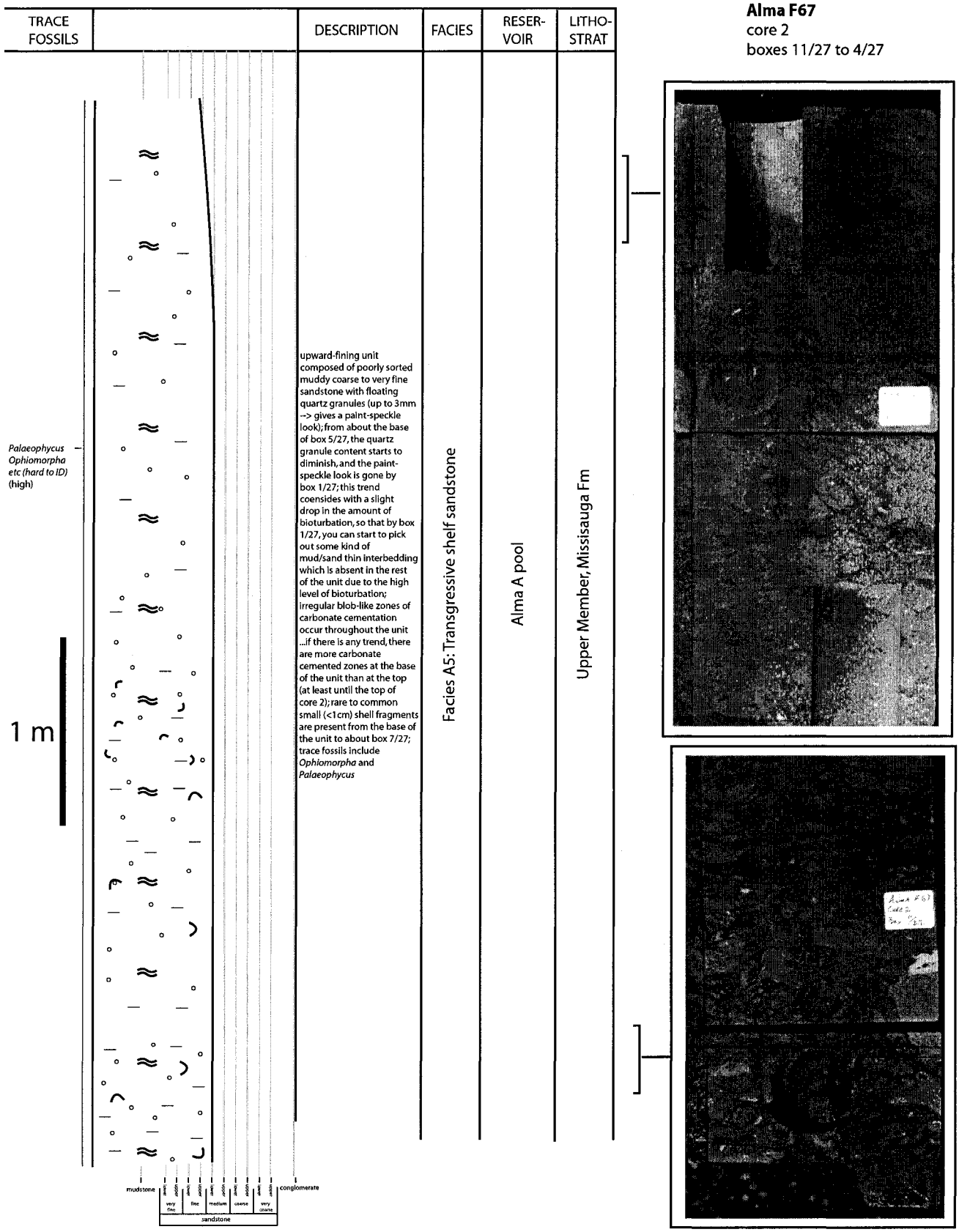
Ophiomorpha burrow mimicking double mud drape



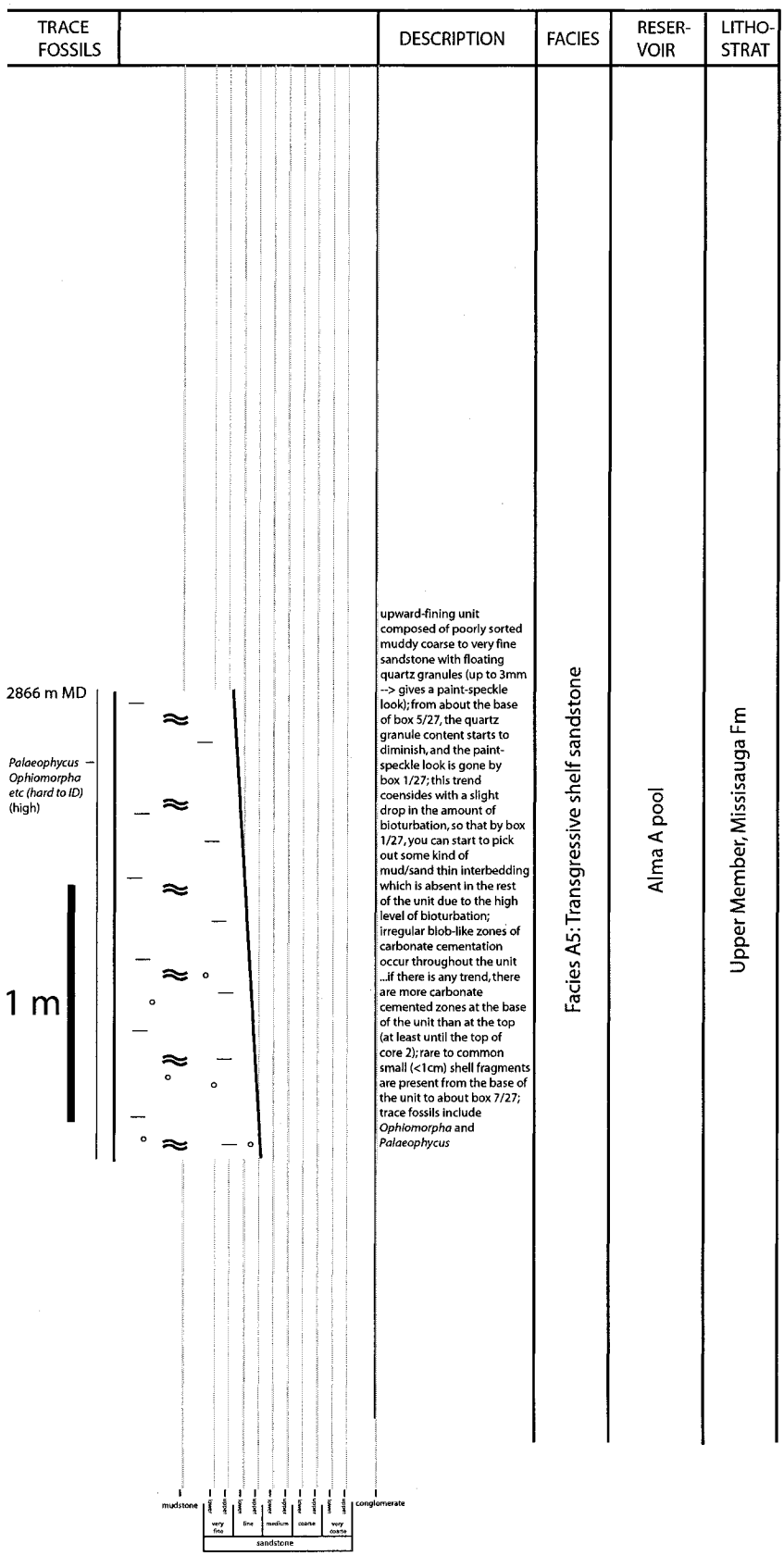
Alma F67
core 2
boxes 19/27 to 12/27



Alma F67
core 2
boxes 11/27 to 4/27



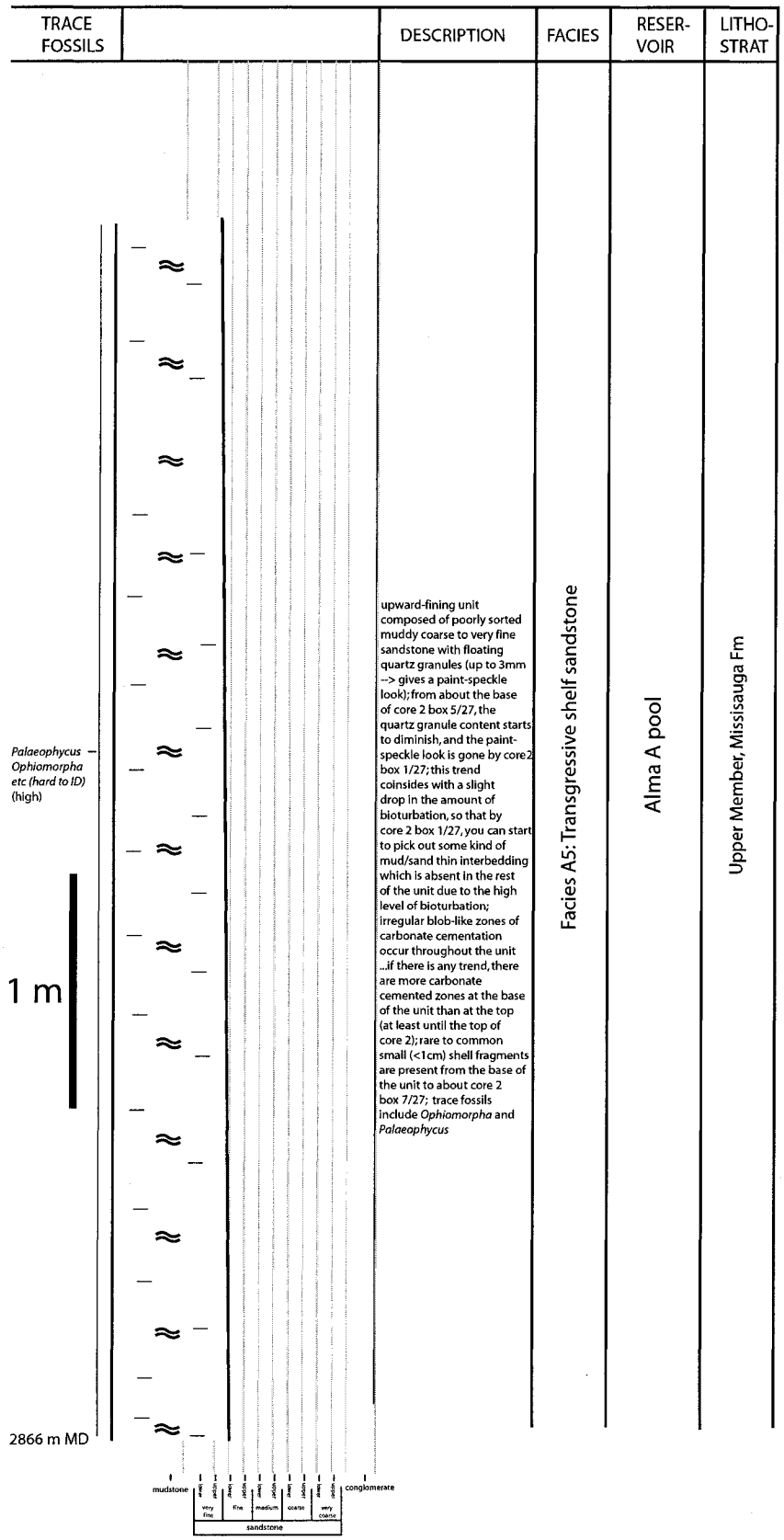
Alma F67
core 2
boxes 3/27 to 1/27

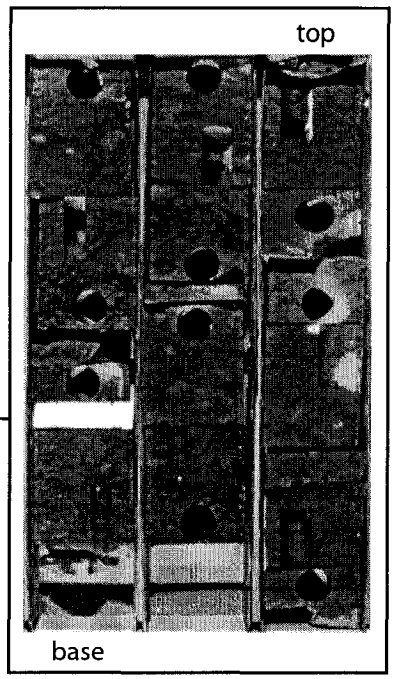




note high level of bioturbation and isolated white-coloured quartz sand grains ("paint-speckles")

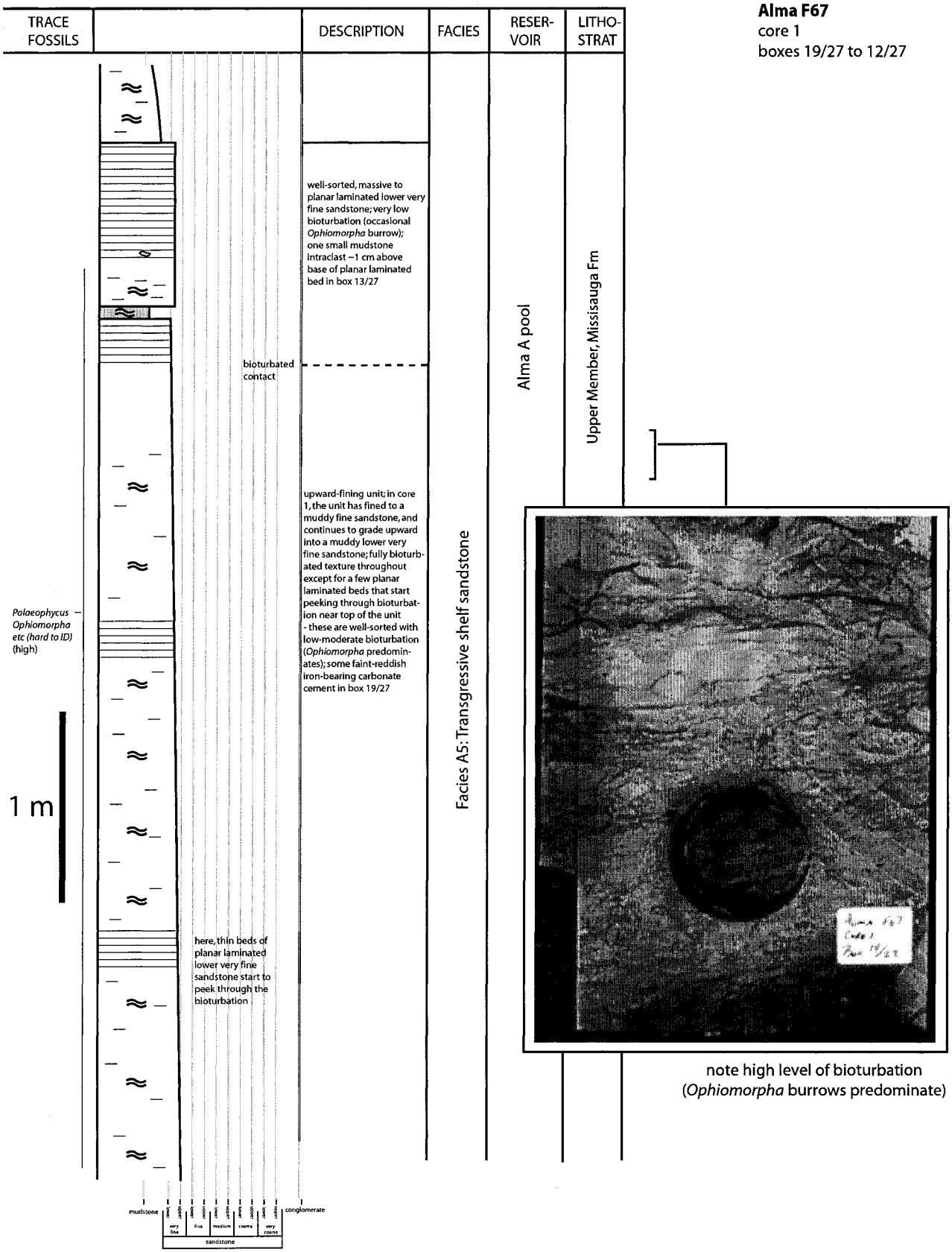
Alma F67
core 1
boxes 27/27 to 20/27



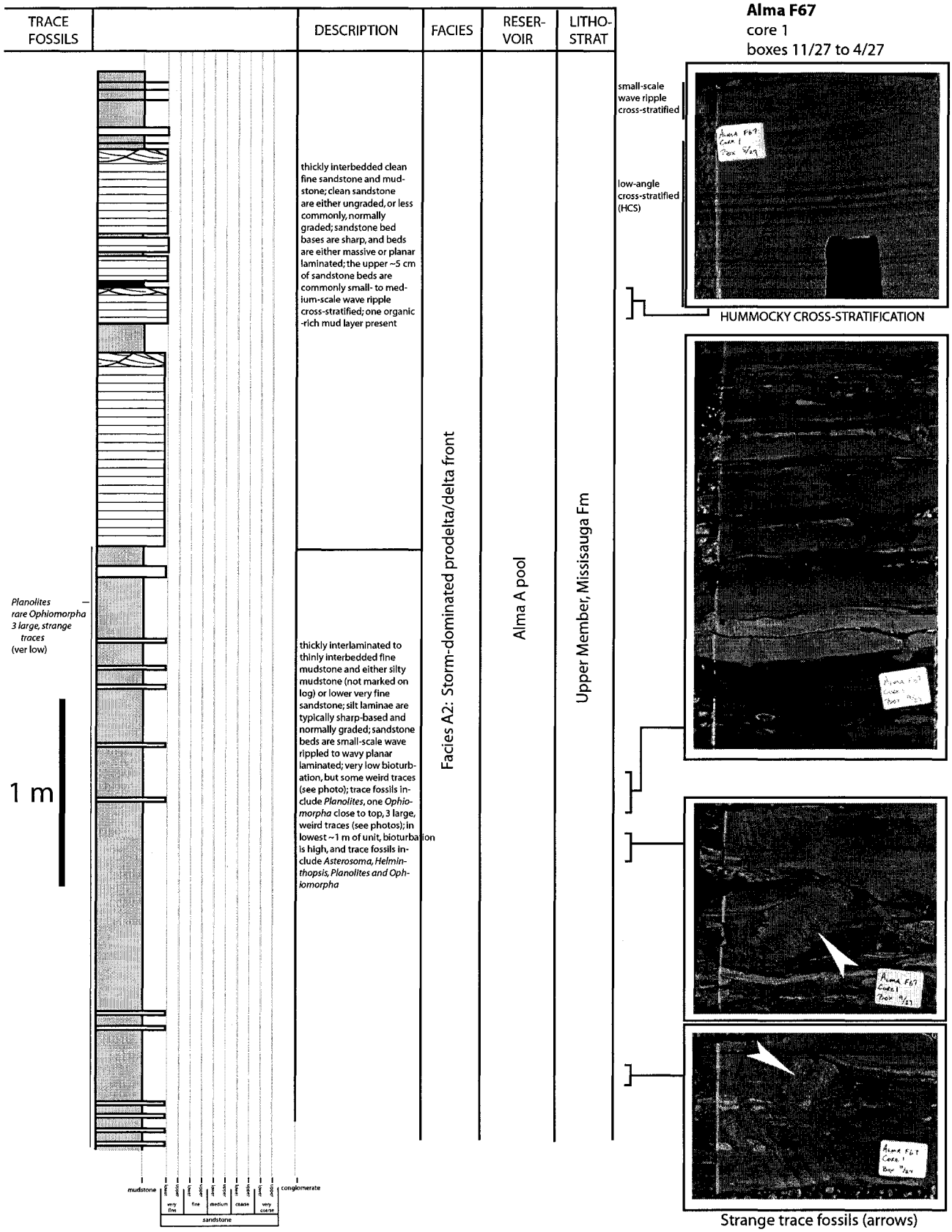


note high level of bioturbation

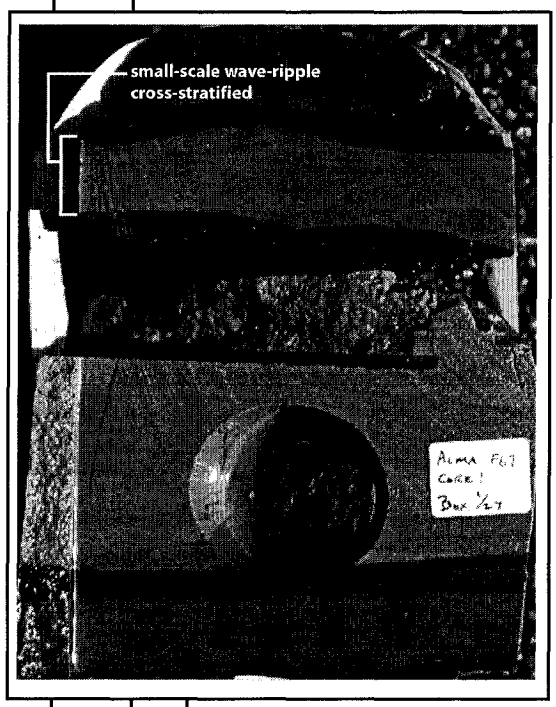
Alma F67
core 1
boxes 19/27 to 12/27



note high level of bioturbation
(*Ophiomorpha* burrows predominate)

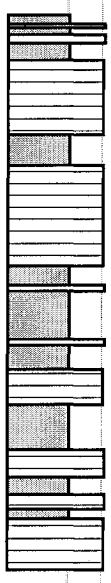

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
thickly interbedded clean fine sandstone and mudstone; clean sandstone are either ungraded, or less commonly, normally graded; sandstone bed bases are sharp, and beds are either massive or planar laminated; the upper ~5 cm of sandstone beds are commonly small- to medium-scale wave ripple cross-stratified; one organic-rich mud layer present
thickly interlaminated to thinly interbedded fine mudstone and either silty mudstone (not marked on log) or lower very fine sandstone; silt laminae are typically sharp-based and normally graded; sandstone beds are small-scale wave rippled to wavy planar laminated; very low bioturbation, but some weird traces (see photo); trace fossils include Planolites, one Ophiomorpha close to top, 3 large, weird traces (see photos); in lowest ~1 m of unit, bioturbation is high, and trace fossils include Asterosoma, Helminthopsis, Planolites and Ophiomorpha
Planolites
rare Ophiomorpha
3 large, strange traces
(ver low)
1 m
Facies A2: Storm-dominated prodelta/delta front
Alma A pool
Upper Member, Missisauga Fm
mudstone
conglomerate
very fine
fine
medium
coarse
very coarse
sandstone
Alma F67
core 1
boxes 11/27 to 4/27
small-scale wave ripple cross-stratified
low-angle cross-stratified (HCS)
HUMMOCKY CROSS-STRATIFICATION
Strange trace fossils (arrows)

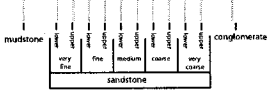
Alma F67
core 1
boxes 3/27 to 1/27



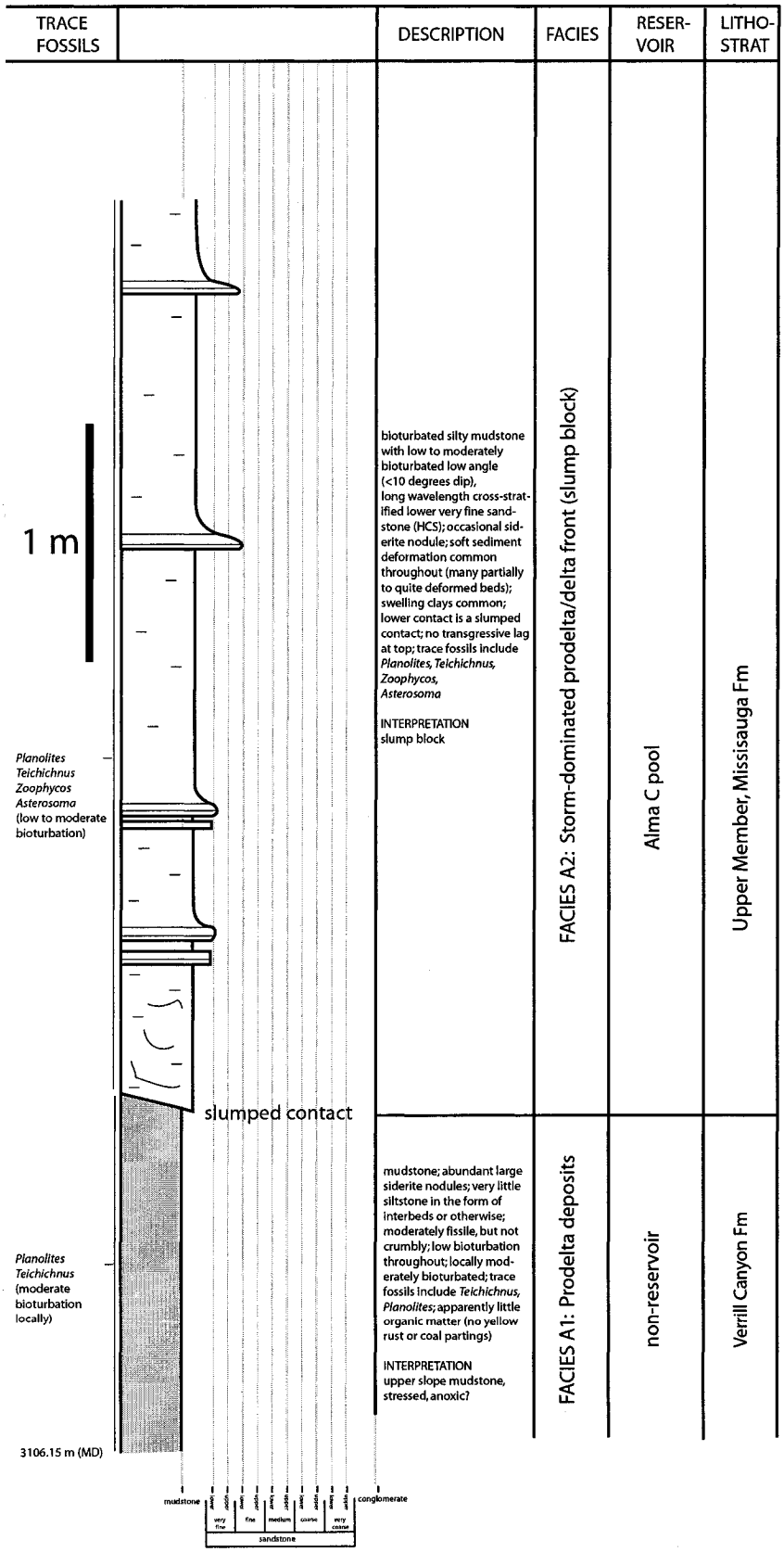
TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
		thickly interbedded clean fine sandstone and mudstone; clean sandstone are either ungraded, or less commonly, normally graded; sandstone bed bases are sharp, and beds are either massive or planar laminated; the upper ~5 cm of sandstone beds are commonly small- to medium-scale wave ripple cross-stratified; one organic-rich mud layer present	Facies A5: Transgressive shelf sandstone	Alma A pool	Upper Member, Missisauga Fm

1 m

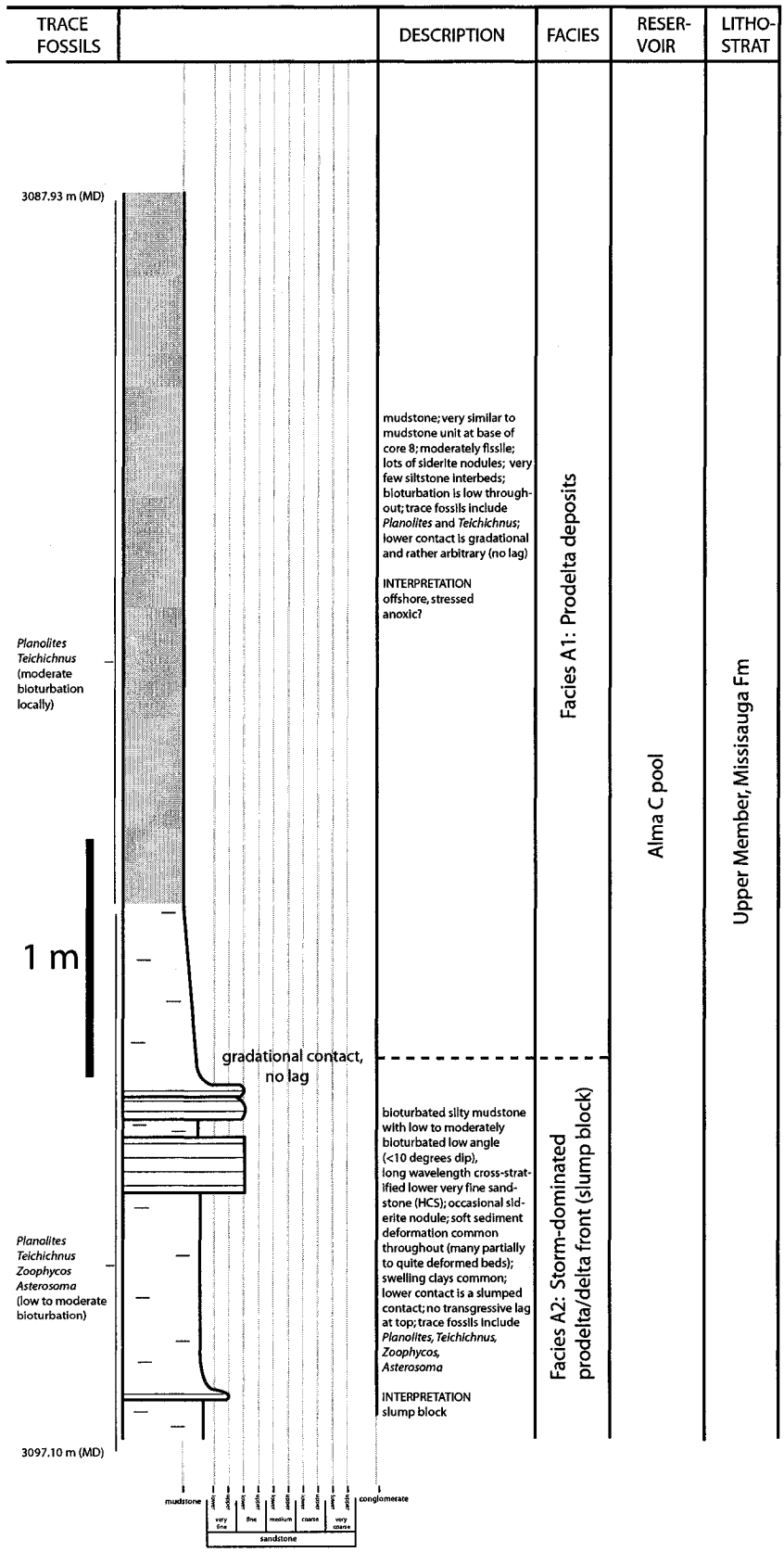


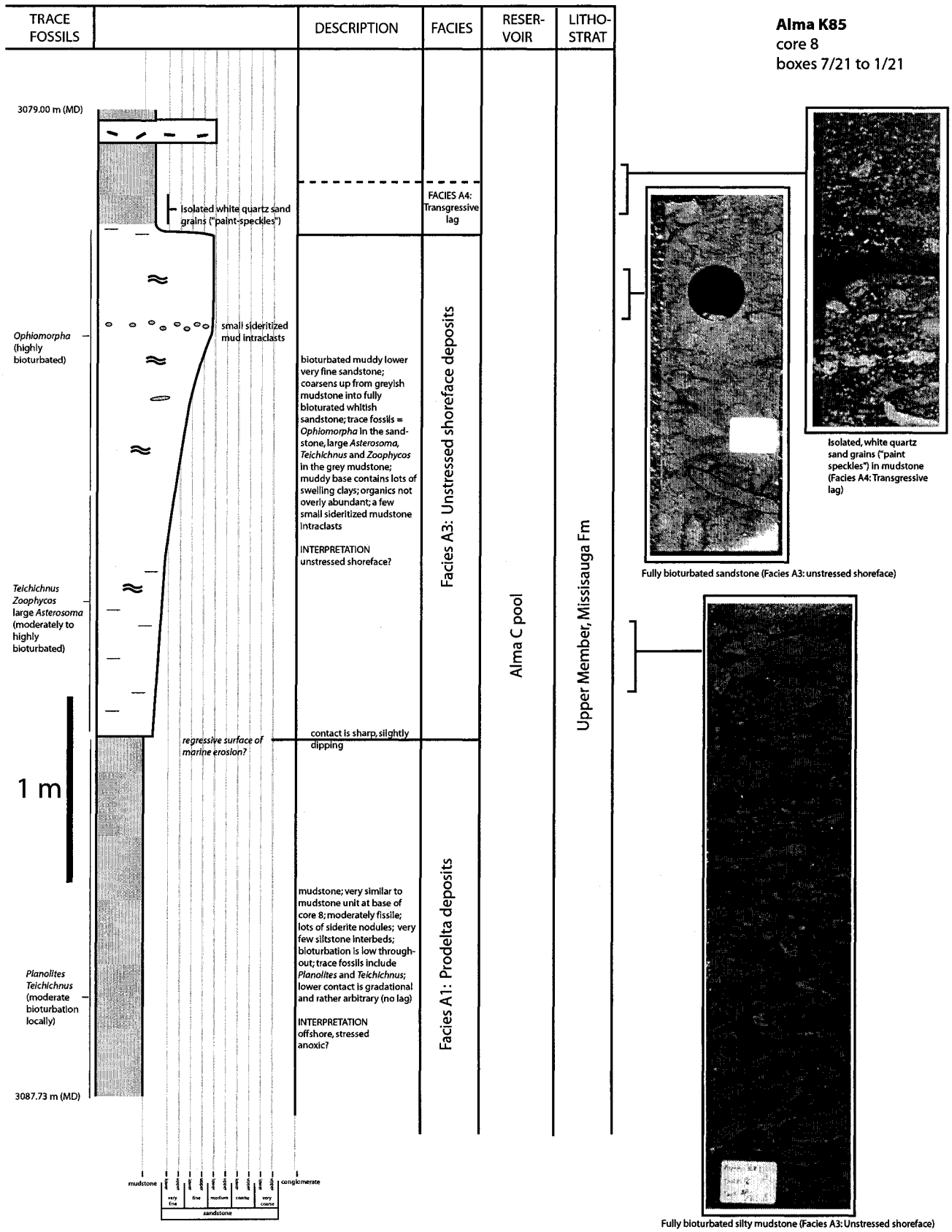


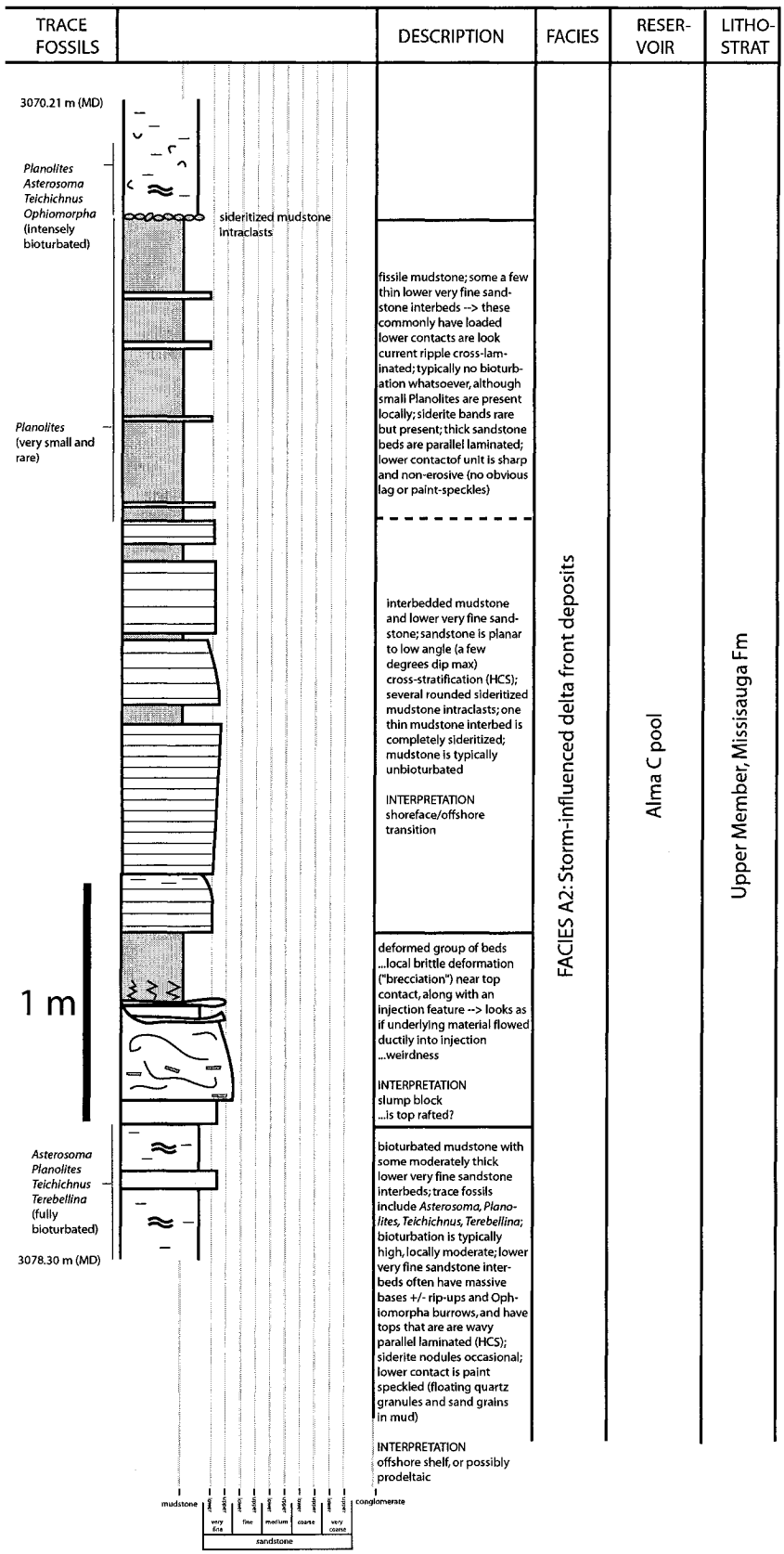
Alma K85
core 8
boxes 21/21 to 15/21



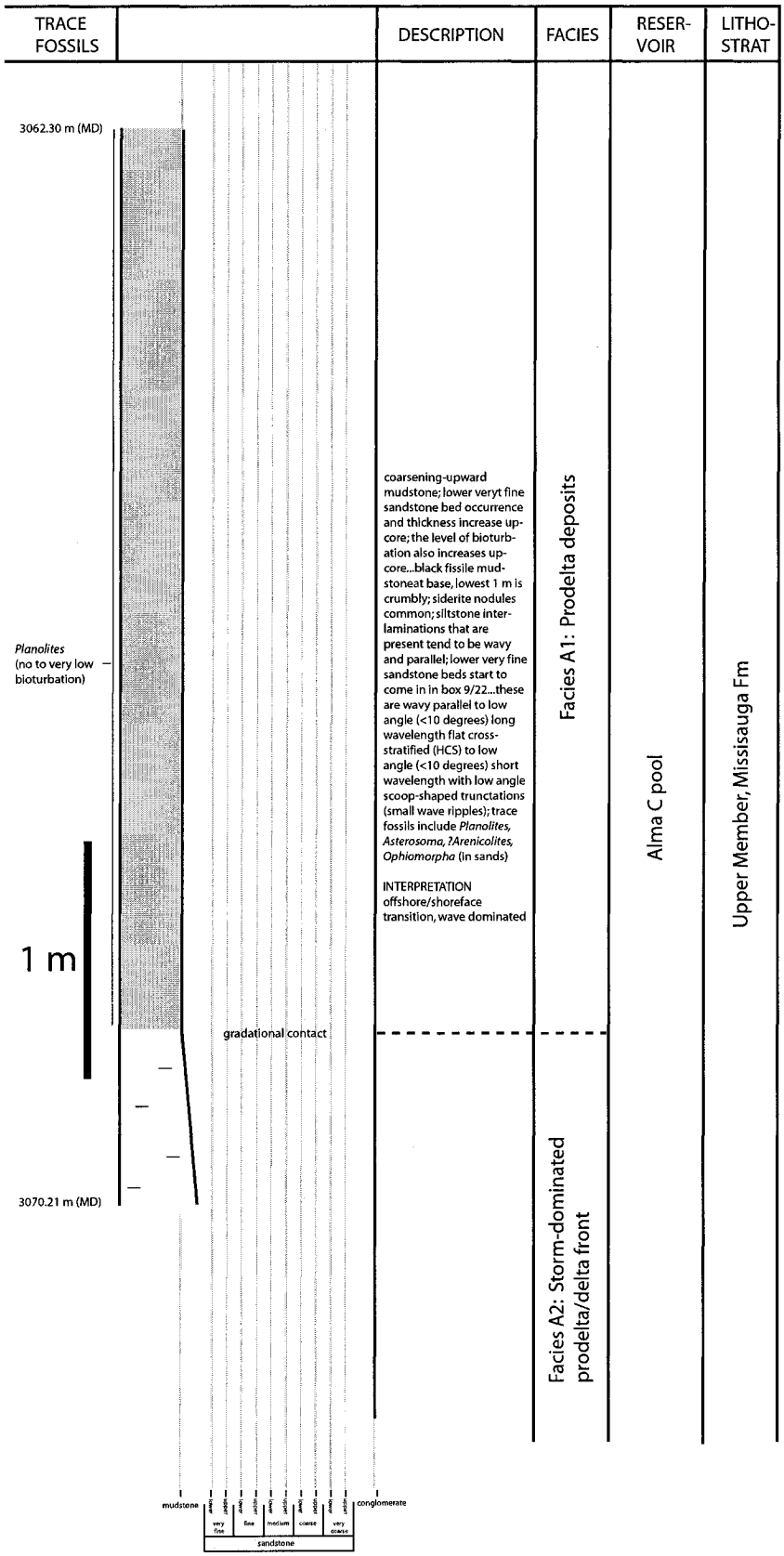
Alma K85
core 8
boxes 14/21 to 8/21




TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Alma K85
core 8
boxes 7/21 to 1/21
3079.00 m (MD)
Isolated white quartz sand grains ("paint-speckles")
FACIES A4: Transgressive lag
small sideritized mud intraclasts
Ophiomorpha (highly bioturbated)
bioturbated muddy lower very fine sandstone; coarsens up from greyish mudstone into fully bioturated whitish sandstone; trace fossils = Ophiomorpha in the sandstone, large Asterosoma, Teichichnus and Zoophycos in the grey mudstone; muddy base contains lots of swelling clays; organics not overly abundant; a few small sideritized mudstone intraclasts
INTERPRETATION unstressed shoreface?
Facies A3: Unstressed shoreface deposits
Teichichnus Zoophycos large Asterosoma (moderately to highly bioturbated)
Alma C pool
Upper Member, Missisauga Fm
regressive surface of marine erosion?
contact is sharp, slightly dipping
1 m
mudstone; very similar to mudstone unit at base of core 8; moderately fissile; lots of siderite nodules; very few siltstone interbeds; bioturbation is low throughout; trace fossils include Planolites and Teichichnus; lower contact is gradational and rather arbitrary (no lag)
INTERPRETATION offshore, stressed anoxic?
Facies A1: Prodelta deposits
Planolites Teichichnus (moderate bioturbation locally)
3087.73 m (MD)
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone
Isolated, white quartz sand grains ("paint speckles") in mudstone (Facies A4: Transgressive lag)
Fully bioturbated sandstone (Facies A3: unstressed shoreface)
Fully bioturbated silty mudstone (Facies A3: Unstressed shoreface)

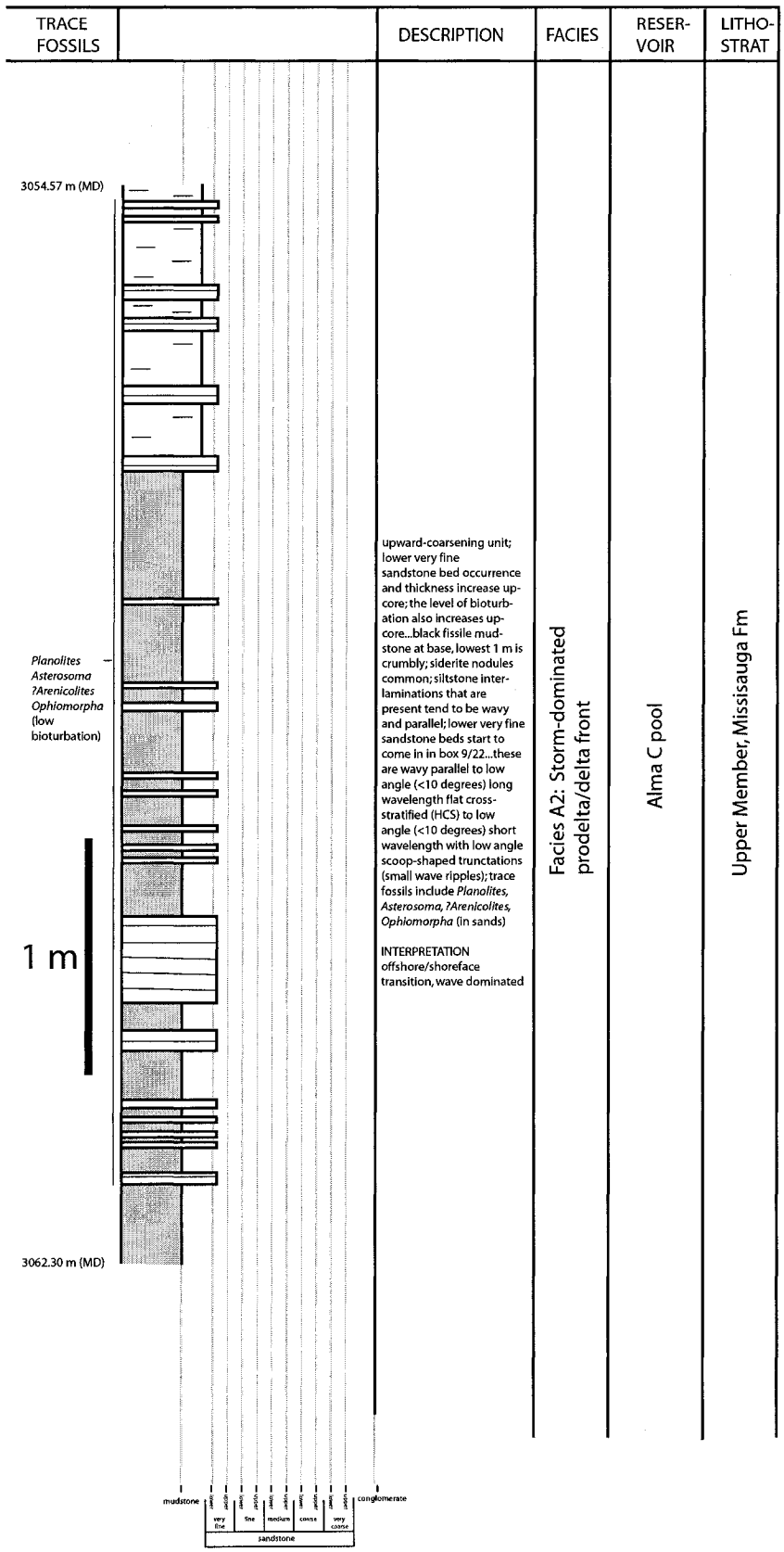


Alma K85
core 7
boxes 22/22 to 16/22

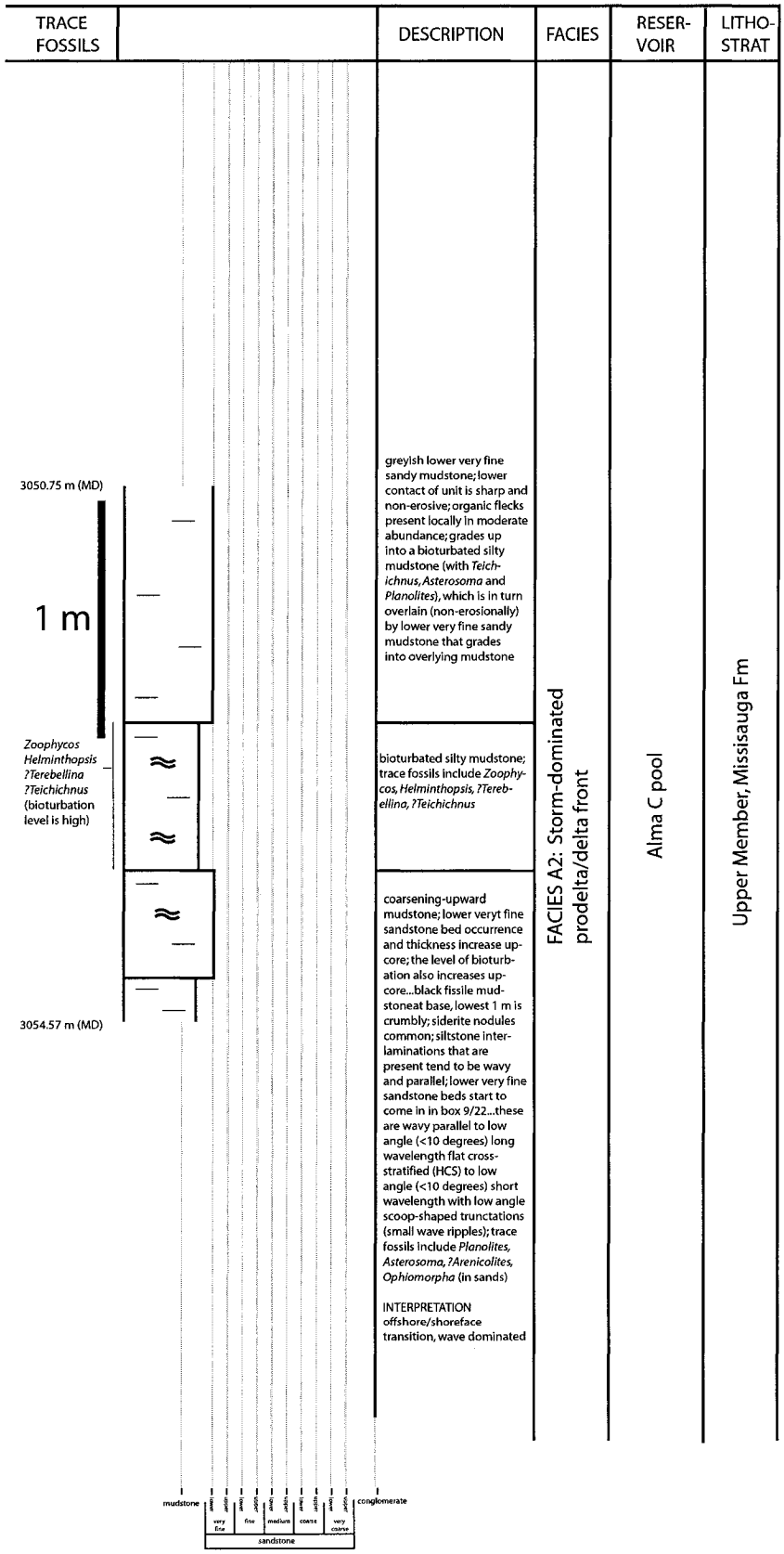


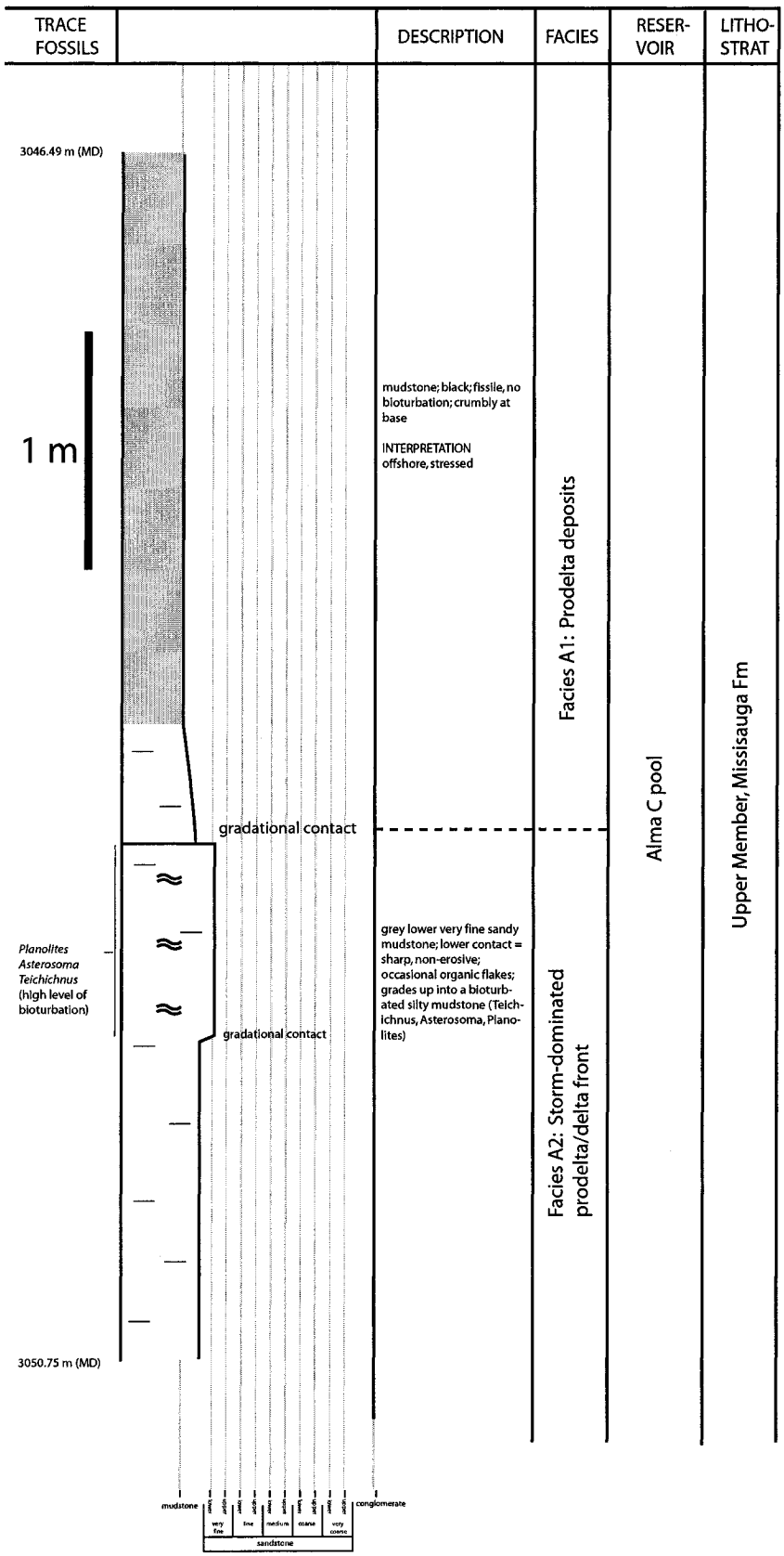
Alma K85
core 7
boxes 15/22 to 10/22

Alma K85
core 7
boxes 9/22 to 4/22



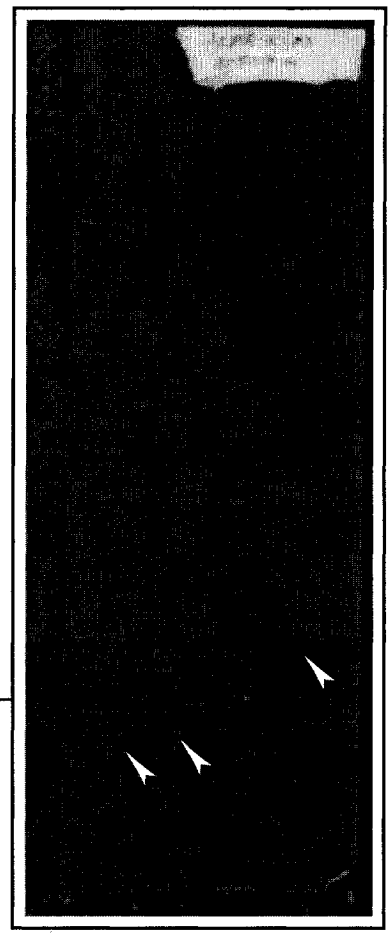
Alma K85
core 7
boxes 3/22 to 1/22

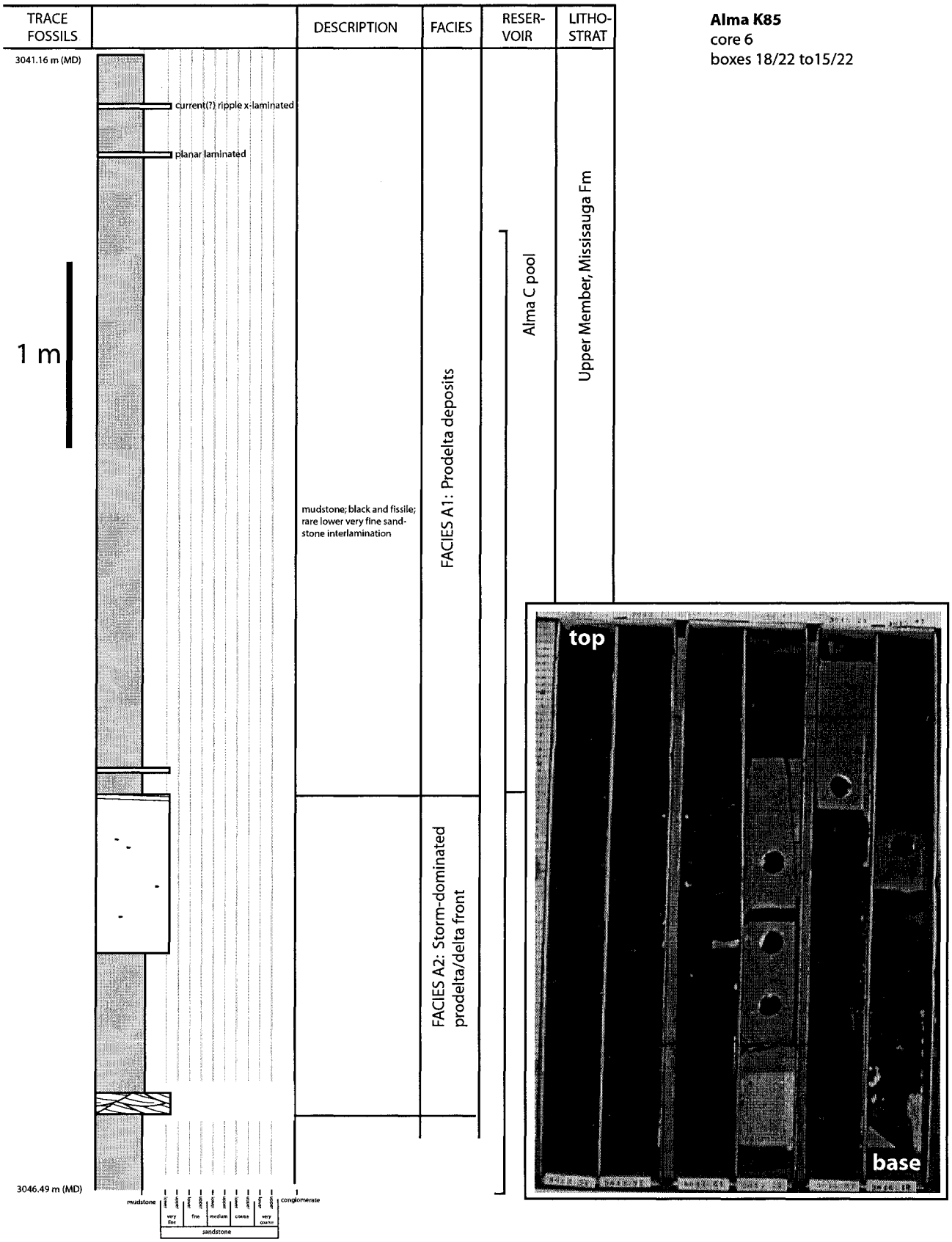




Alma K85
core 6
boxes 22/22 to19/22

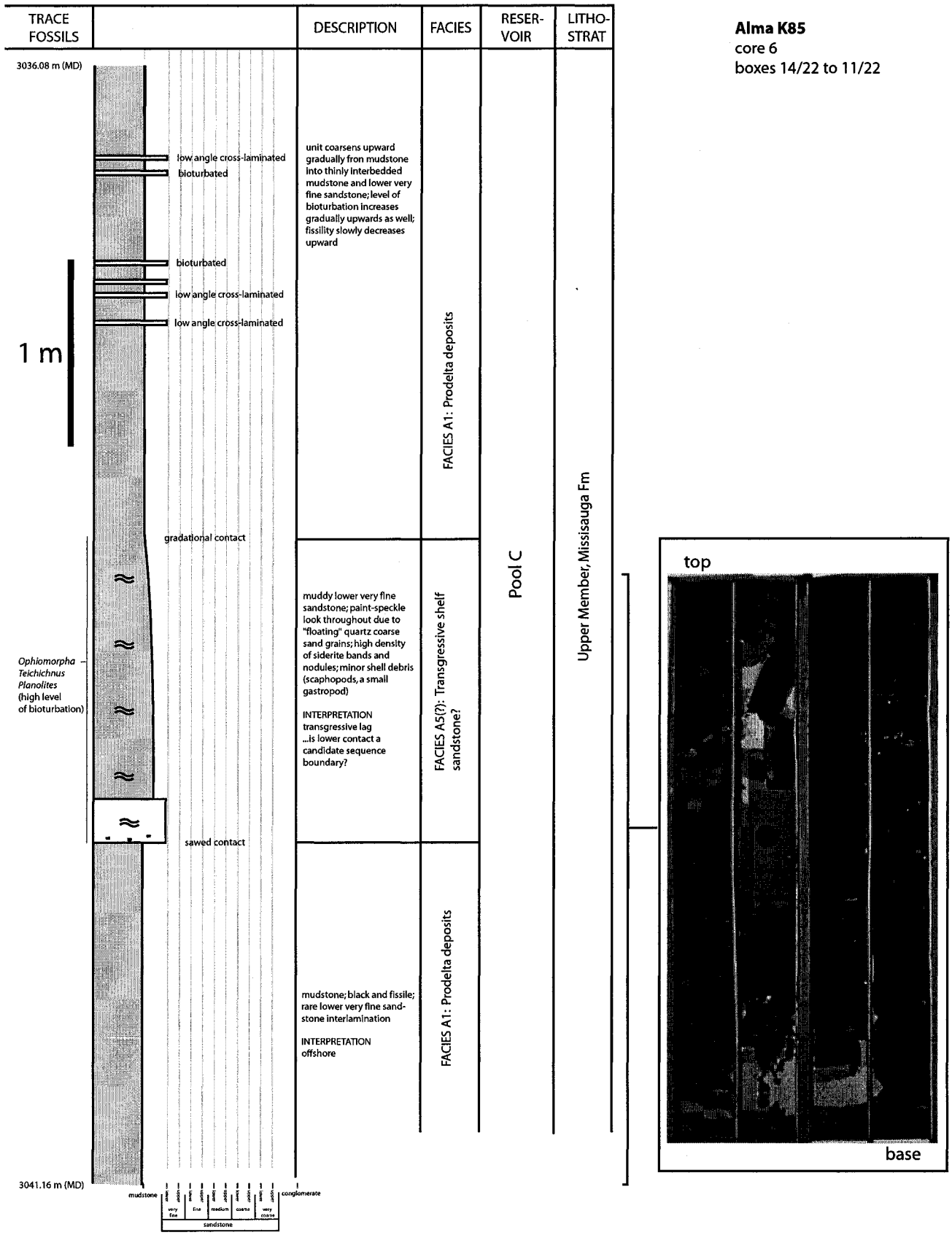
dewatering (pillar) structures (arrows)?
(elsewhere, I've also called these "knife-scratches")

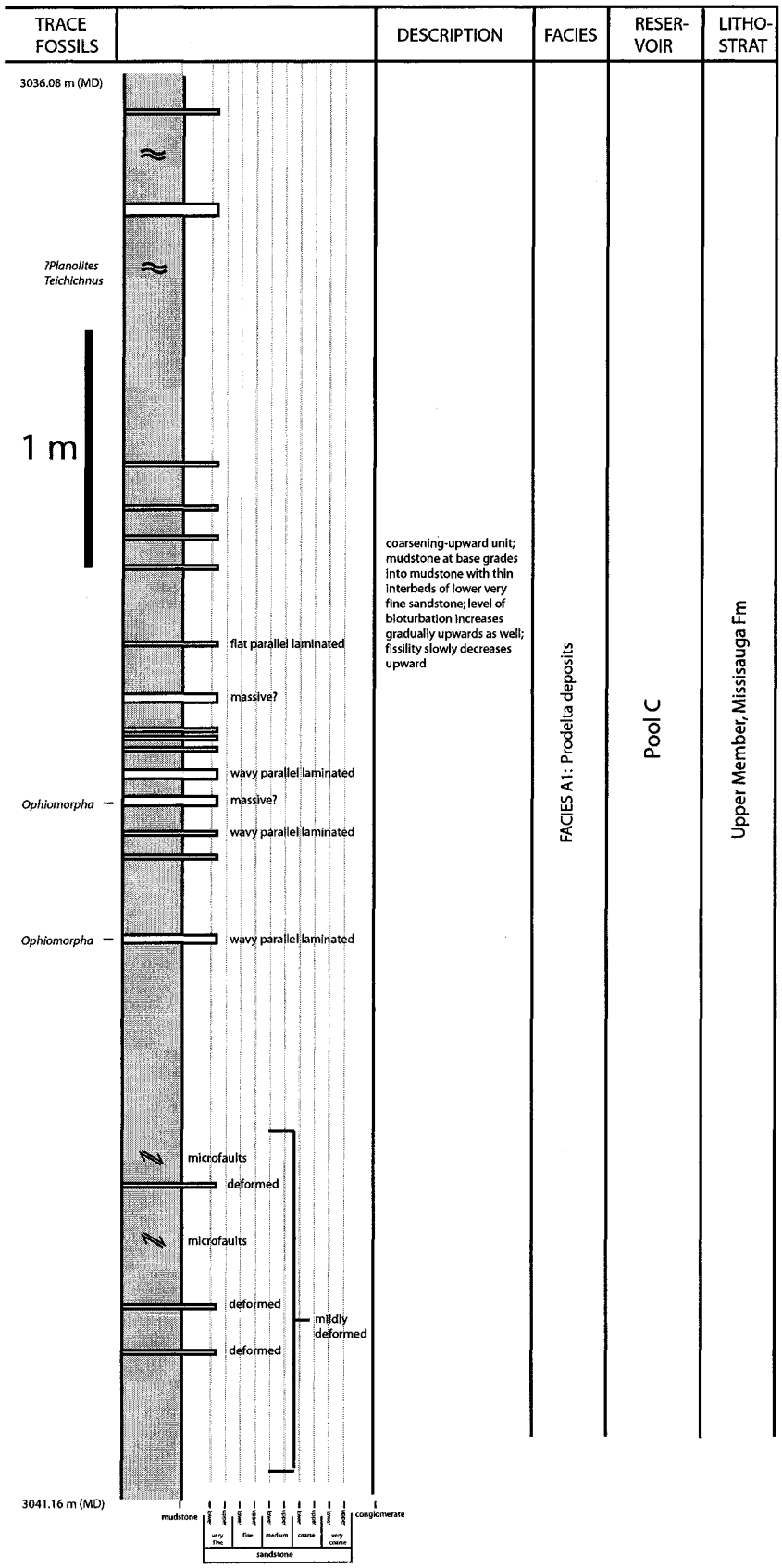




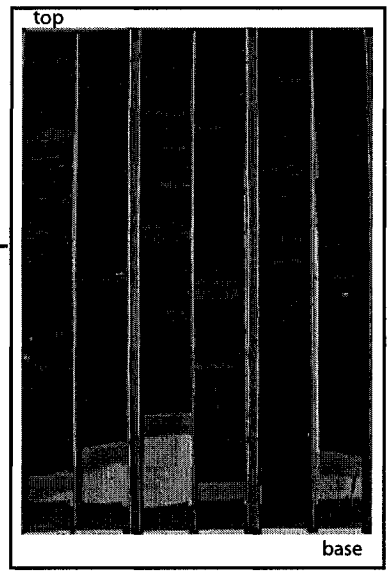
Alma K85
core 6
boxes 18/22 to15/22

Alma K85
core 6
boxes 14/22 to 11/22

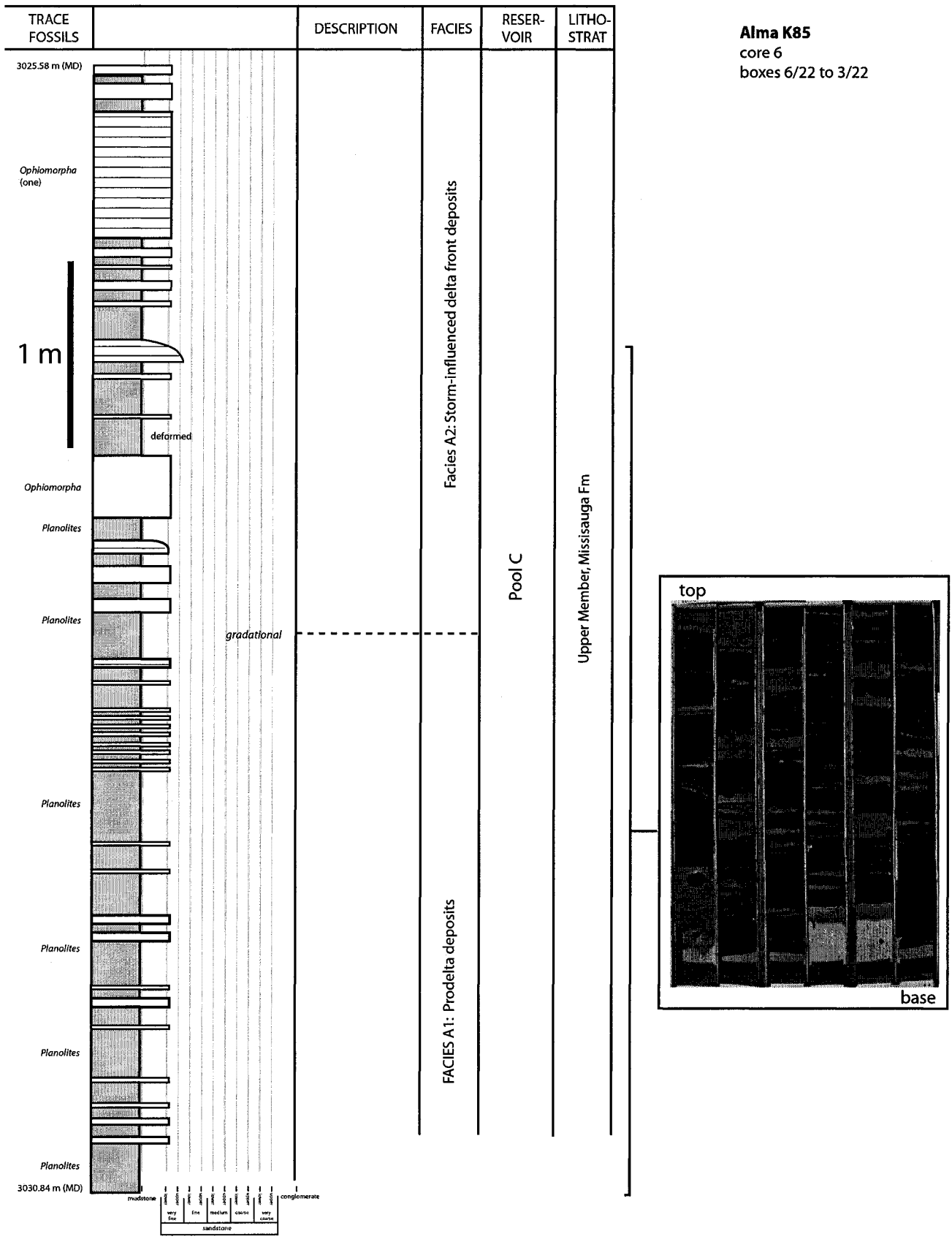




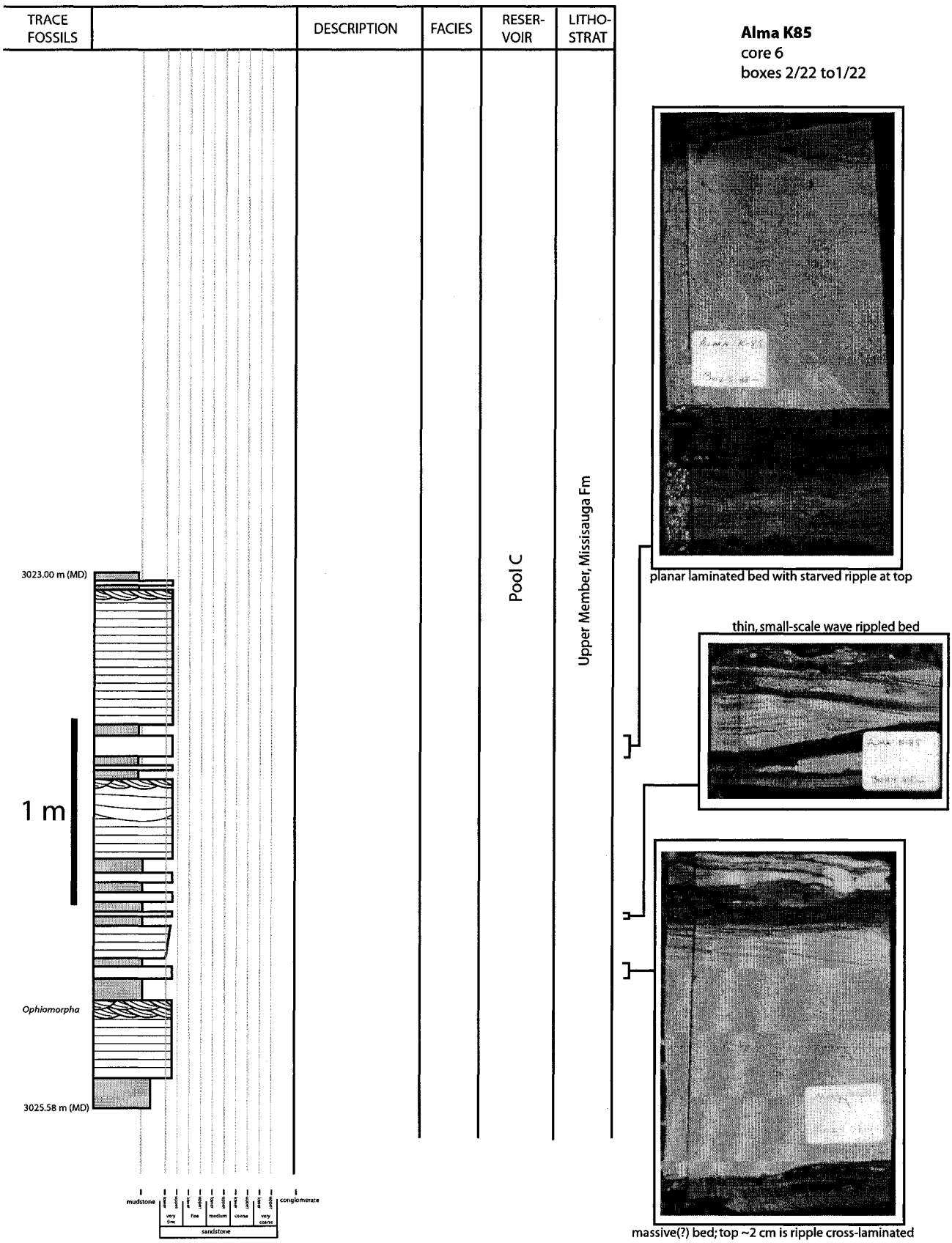
Alma K85
core 6
boxes 10/22 to 7/22

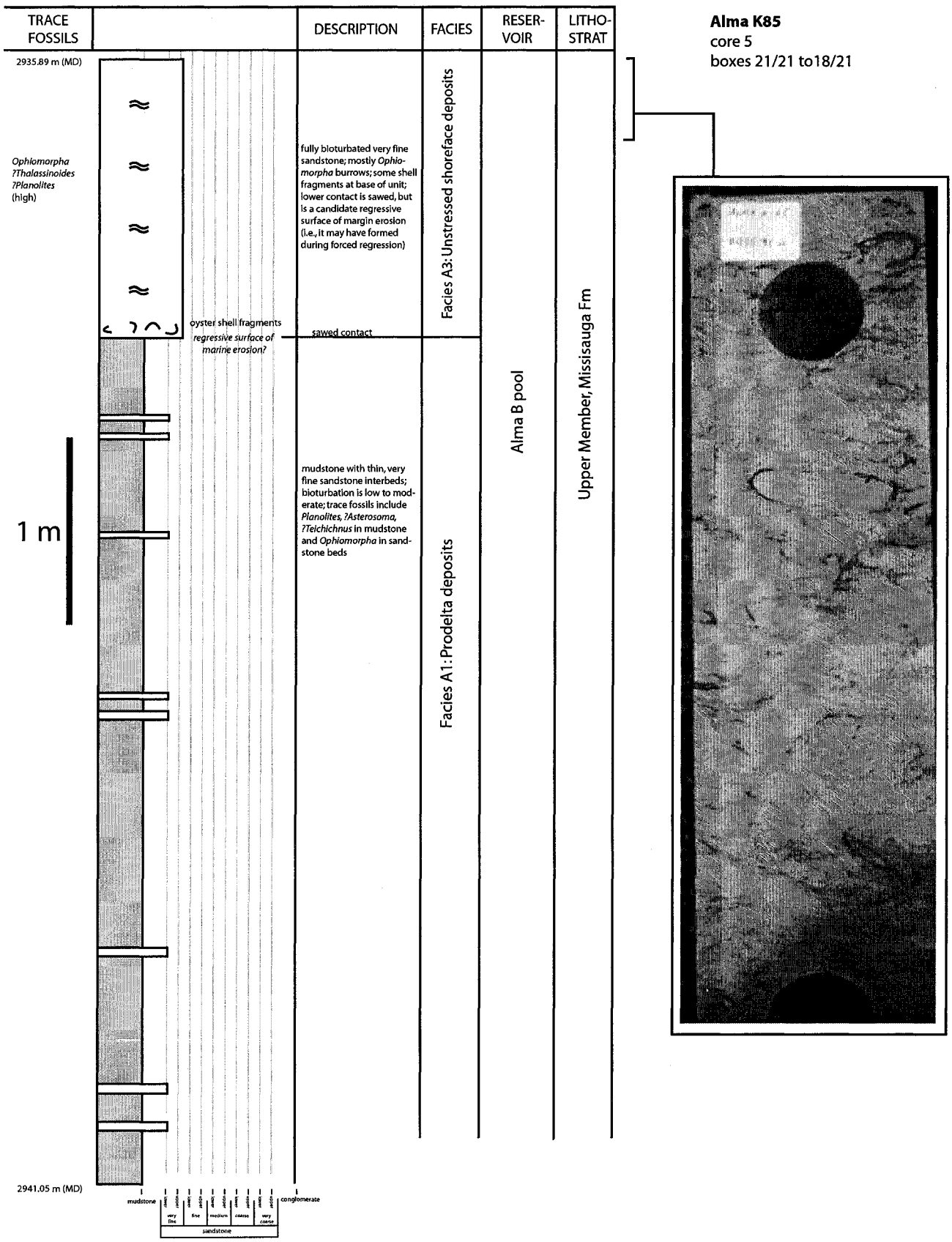


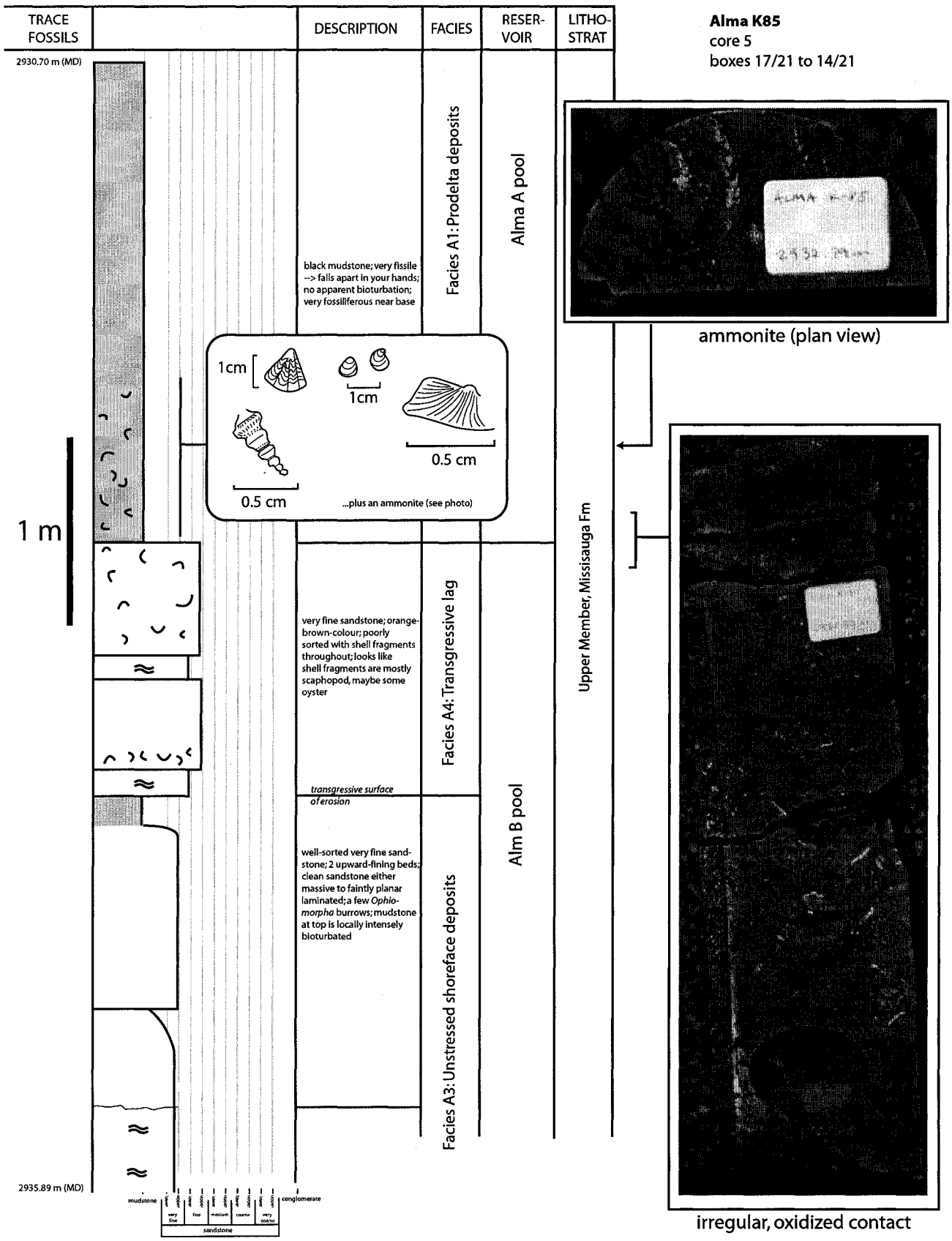
FACIES A1

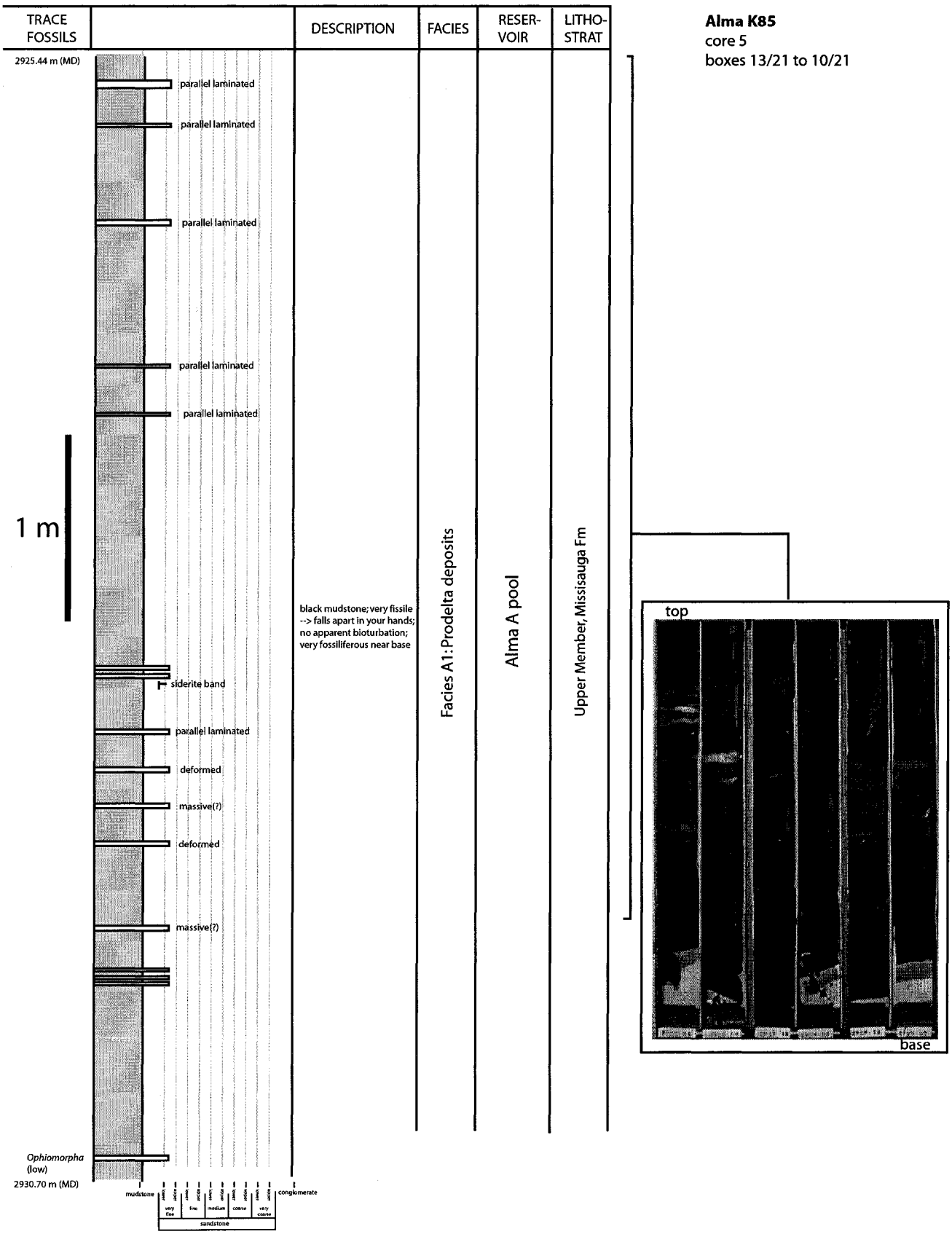


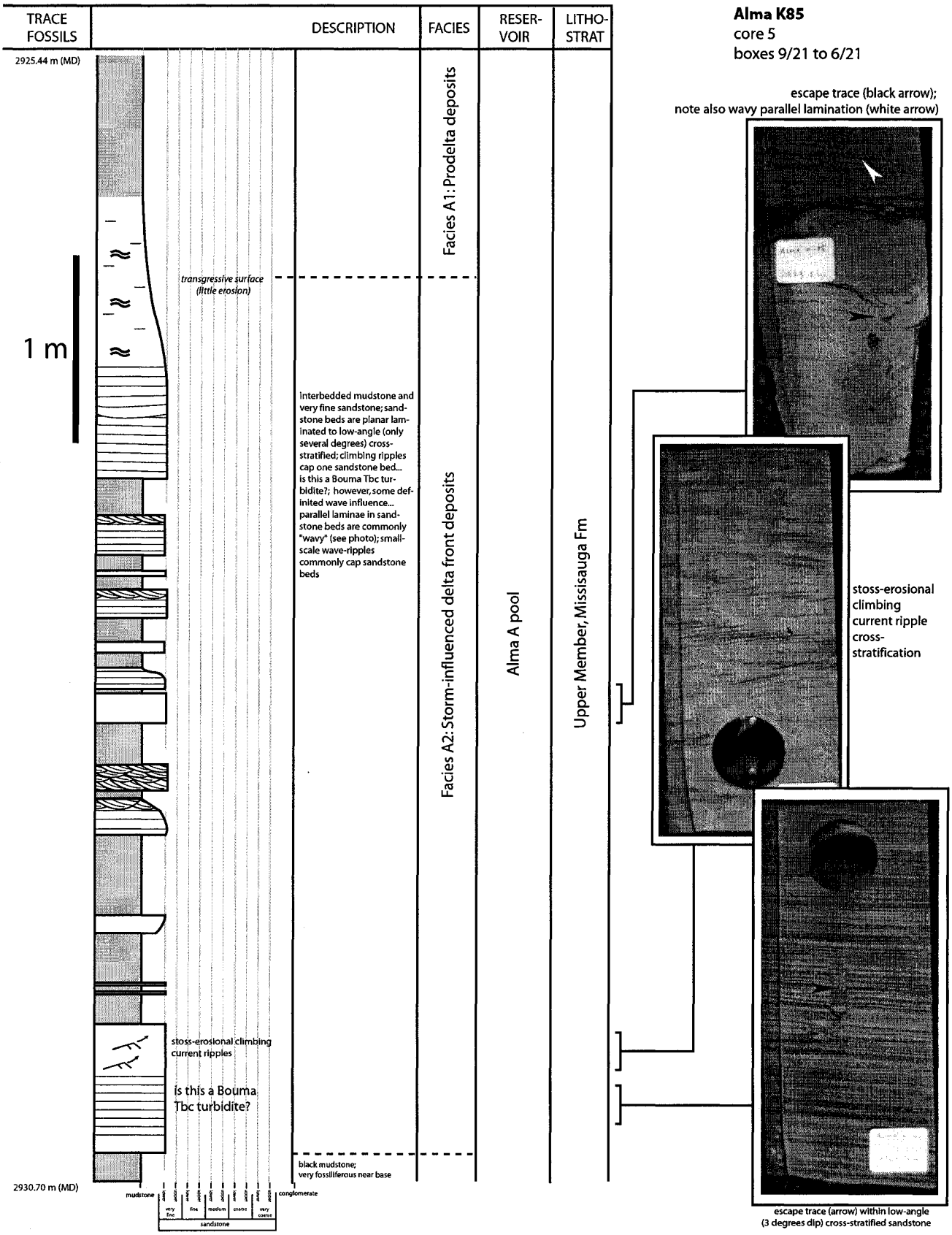
Alma K85
core 6
boxes 6/22 to 3/22


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Alma K85
core 6
boxes 2/22 to1/22
3023.00 m (MD)
1 m
Ophiomorpha
3025.58 m (MD)
Pool C
Upper Member, Missisauga Fm
planar laminated bed with starved ripple at top
thin, small-scale wave rippled bed
massive(?) bed; top ~2 cm is ripple cross-laminated
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone

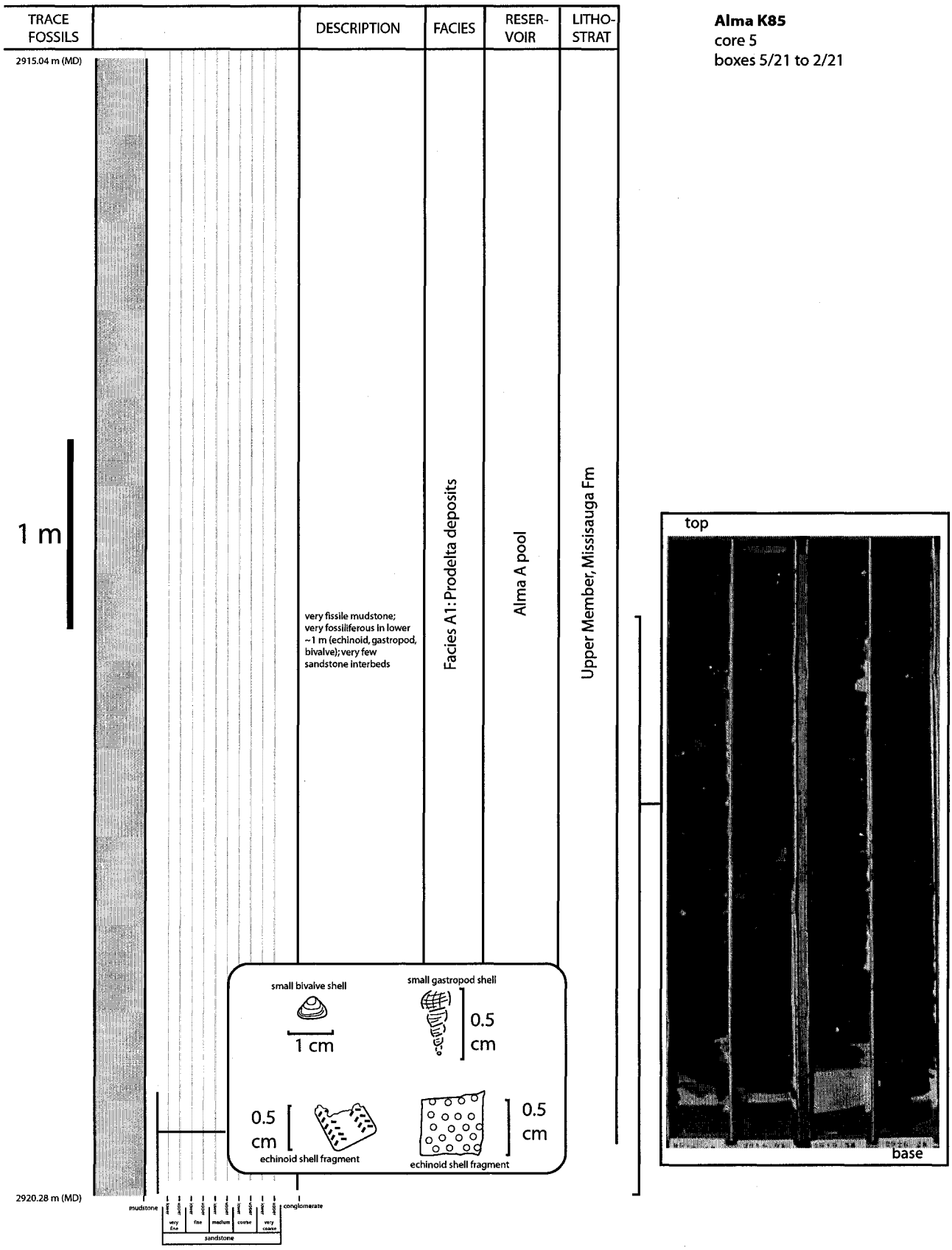

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
2935.89 m (MD)
Ophiomorpha
?Thalassinoides
?Planolites
(high)
fully bioturbated very fine sandstone; mostly Ophio-morpha burrows; some shell fragments at base of unit; lower contact is sawed, but is a candidate regressive surface of margin erosion (i.e., it may have formed during forced regression)
Facies A3: Unstressed shoreface deposits
oyster shell fragments
regressive surface of marine erosion?
sawed contact
1 m
mudstone with thin, very fine sandstone interbeds; bioturbation is low to mod-erate; trace fossils include Planolites, ?Asterosoma, ?Teichichnus in mudstone and Ophiomorpha in sand-stone beds
Facies A1: Prodelta deposits
Alma B pool
Upper Member, Missisauga Fm
2941.05 m (MD)
mudstone
clay
silt
very fine
fine
medium
coarse
very coarse
sandstone
conglomerate
Alma K85
core 5
boxes 21/21 to18/21

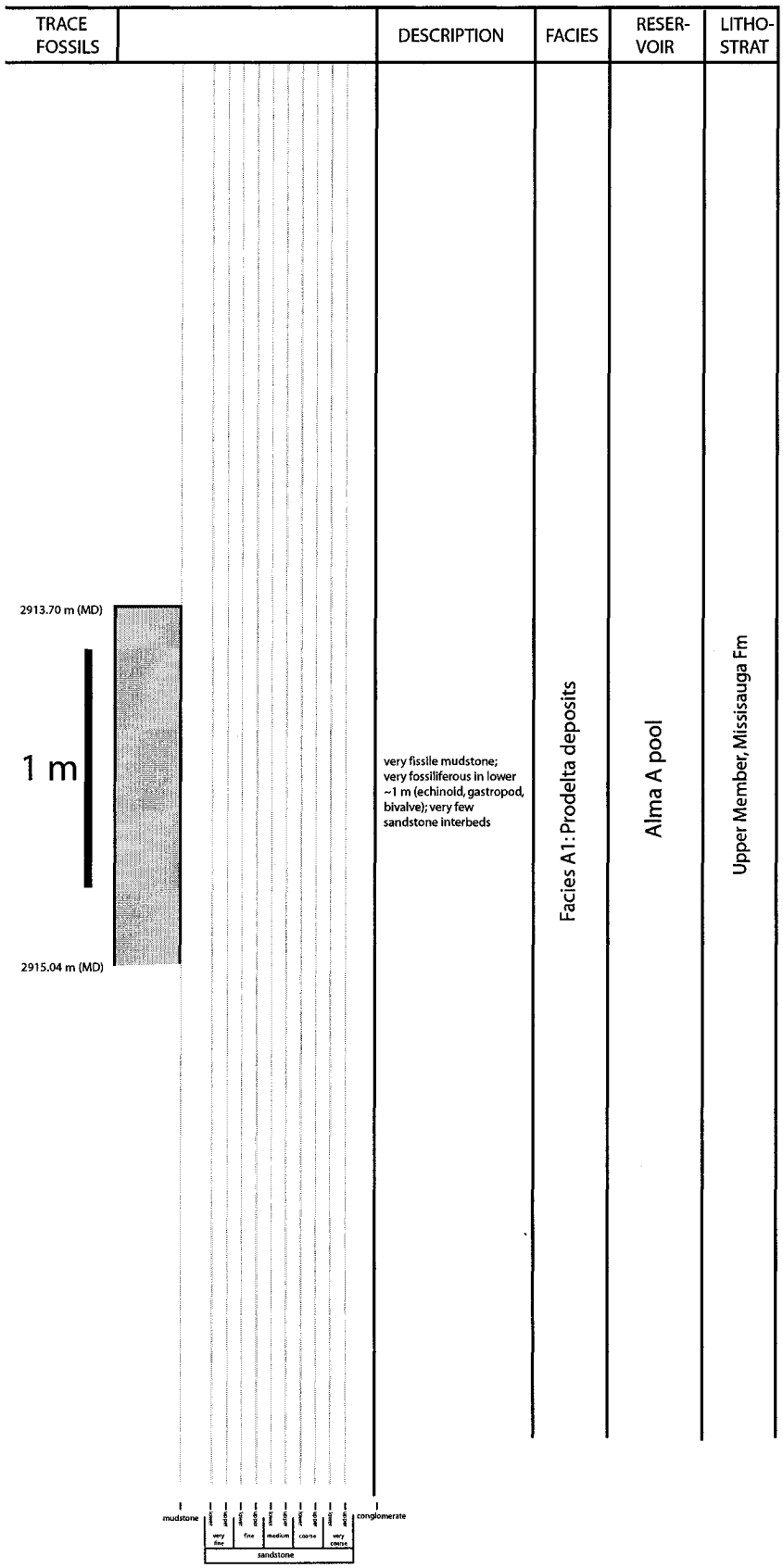

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Alma K85
core 5
boxes 17/21 to 14/21
2930.70 m (MD)
2935.89 m (MD)
1 m
black mudstone; very fissile --> falls apart in your hands; no apparent bioturbation; very fossiliferous near base
Facies A1: Prodelta deposits
Alma A pool
1cm
1cm
0.5 cm
0.5 cm
...plus an ammonite (see photo)
ammonite (plan view)
very fine sandstone; orange-brown-colour; poorly sorted with shell fragments throughout; looks like shell fragments are mostly scaphopod, maybe some oyster
Facies A4: Transgressive lag
transgressive surface of erosion
well-sorted very fine sand-stone; 2 upward-fining beds; clean sandstone either massive to faintly planar laminated; a few Ophio-morpha burrows; mudstone at top is locally intensely bioturbated
Facies A3: Unstressed shoreface deposits
Alm B pool
Upper Member, Missisauga Fm
irregular, oxidized contact
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
2925.44 m (MD)
parallel laminated
parallel laminated
parallel laminated
parallel laminated
parallel laminated
1 m
siderite band
parallel laminated
deformed
massive(?)
deformed
massive(?)
black mudstone; very fissile --> falls apart in your hands; no apparent bioturbation; very fossiliferous near base
Facies A1: Prodelta deposits
Alma A pool
Upper Member, Missisauga Fm
Ophiomorpha (low)
2930.70 m (MD)
mudstone
conglomerate
very fine
fine
medium
coarse
very coarse
sandstone
Alma K85
core 5
boxes 13/21 to 10/21
top
base

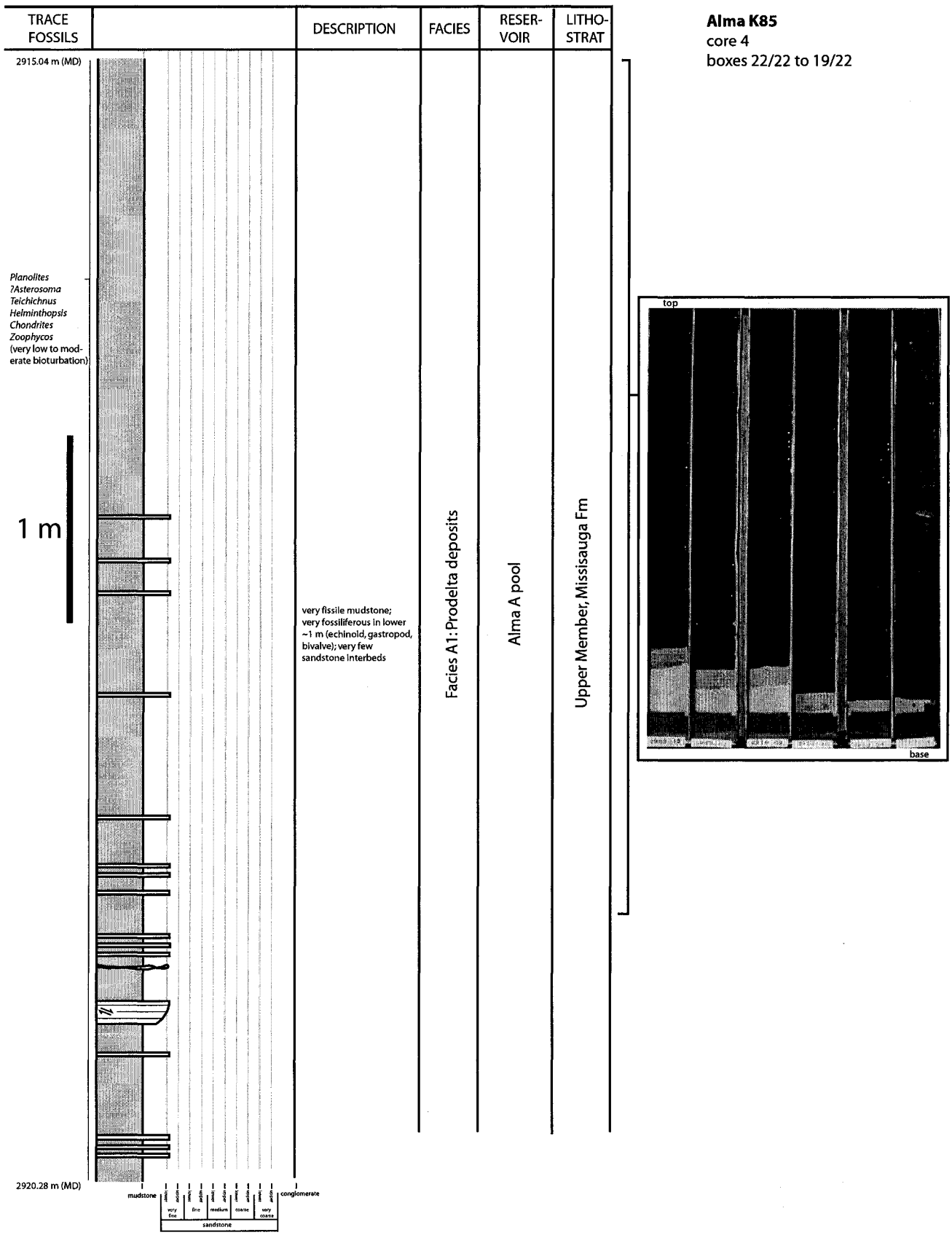

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
2925.44 m (MD)
1 m
transgressive surface (little erosion)
Interbedded mudstone and very fine sandstone; sandstone beds are planar laminated to low-angle (only several degrees) cross-stratified; climbing ripples cap one sandstone bed... is this a Bouma Tbc turbidite?; however, some definited wave influence... parallel laminae in sandstone beds are commonly "wavy" (see photo); small-scale wave-ripples commonly cap sandstone beds
stoss-erosional climbing current ripples
is this a Bouma Tbc turbidite?
black mudstone; very fossiliferous near base
2930.70 m (MD)
mudstone
conglomerate
very fine
fine
medium
coarse
very coarse
sandstone
Facies A1: Prodelta deposits
Facies A2: Storm-influenced delta front deposits
Alma A pool
Upper Member, Missisauga Fm
Alma K85
core 5
boxes 9/21 to 6/21
escape trace (black arrow); note also wavy parallel lamination (white arrow)
stoss-erosional climbing current ripple cross-stratification
escape trace (arrow) within low-angle (3 degrees dip) cross-stratified sandstone

Alma K85
core 5
boxes 5/21 to 2/21

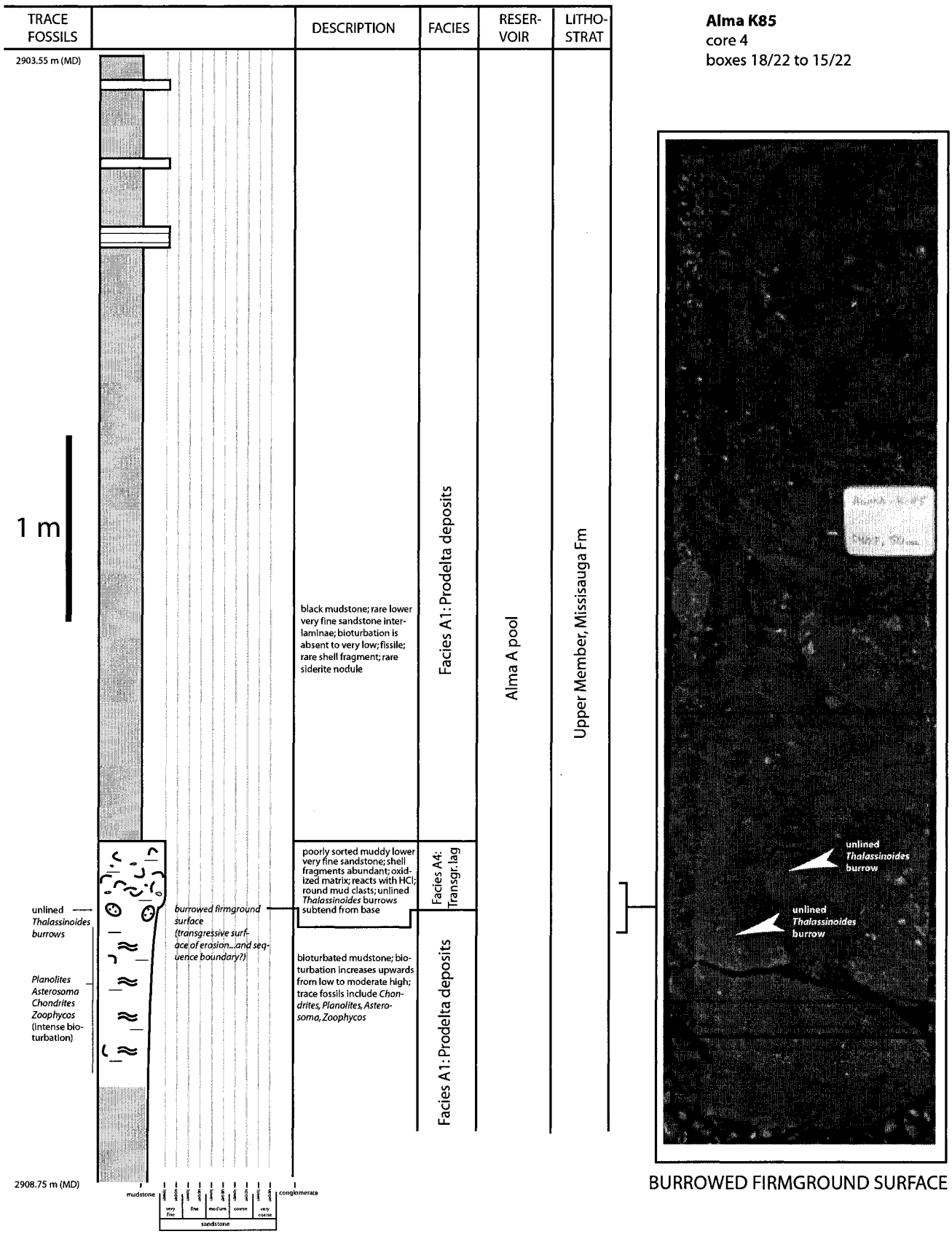


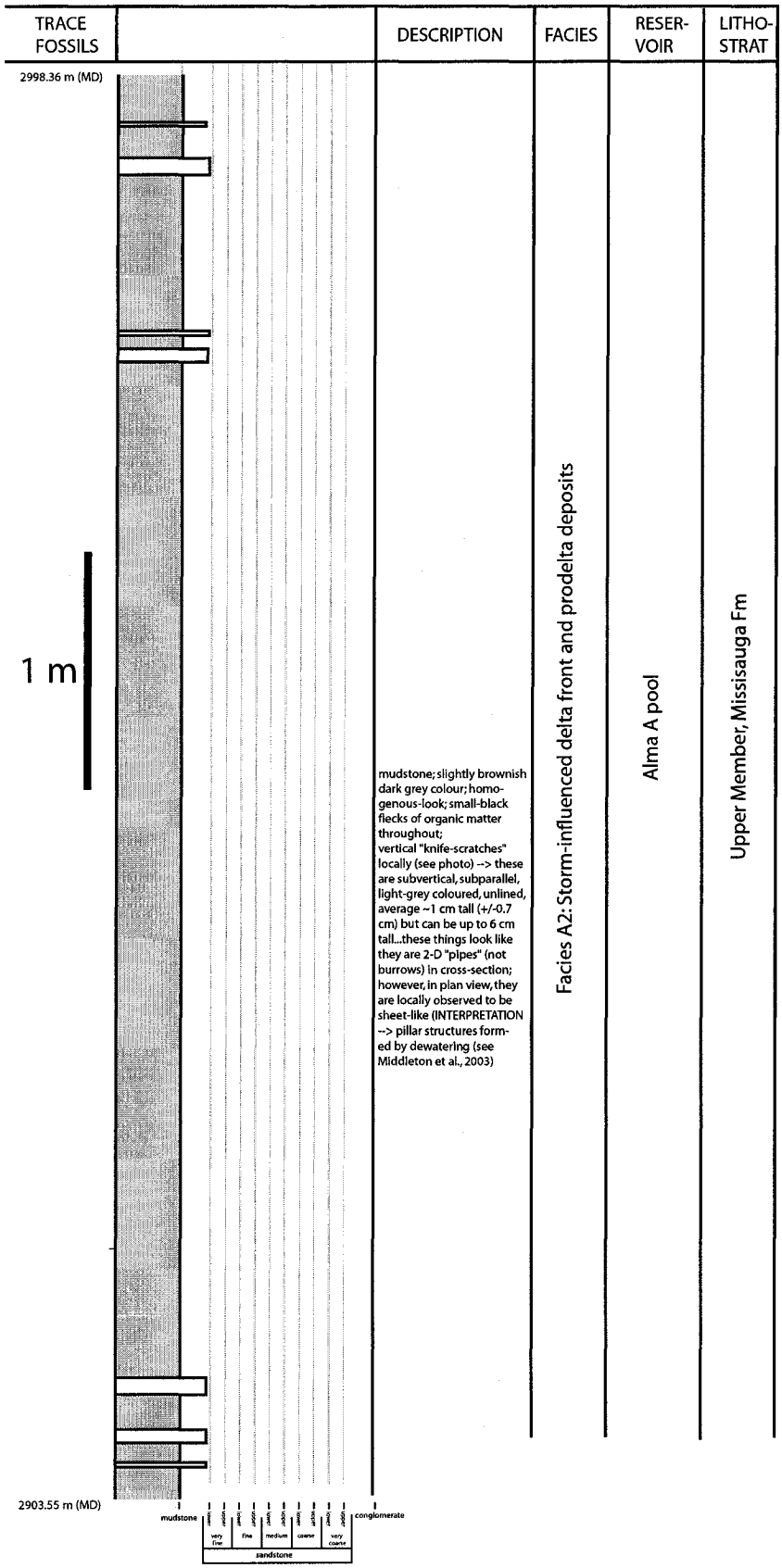


Alma K85
core 5
boxes 1/21

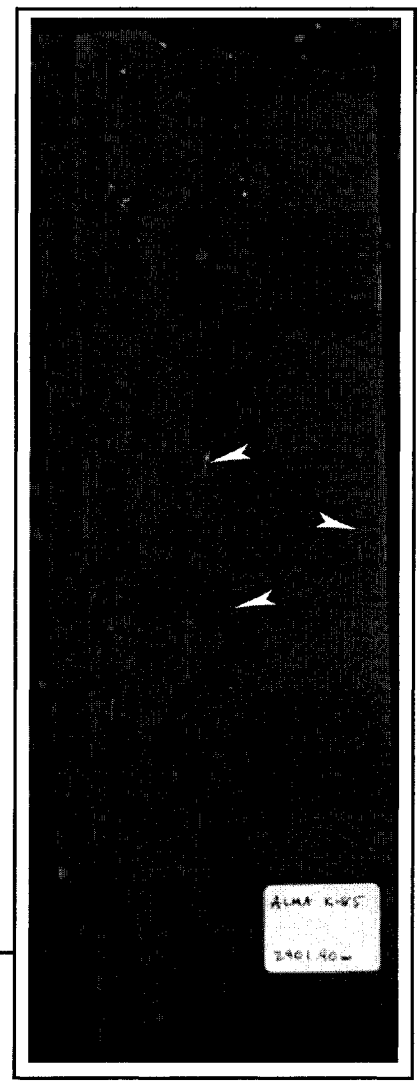


Alma K85
core 4
boxes 22/22 to 19/22


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
2903.55 m (MD)
1 m
2908.75 m (MD)
black mudstone; rare lower very fine sandstone interlaminae; bioturbation is absent to very low; fissile; rare shell fragment; rare siderite nodule
Facies A1: Prodelta deposits
Alma A pool
Upper Member, Missisauga Fm
poorly sorted muddy lower very fine sandstone; shell fragments abundant; oxidized matrix; reacts with HCl; round mud clasts; unlined Thalassinoides burrows subtend from base
Facies A4: Transgr.lag
unlined Thalassinoides burrows
burrowed firmground surface (transgressive surface of erosion...and sequence boundary?)
Planolites
Asterosoma
Chondrites
Zoophycos
(intense bioturbation)
bioturbated mudstone; bioturbation increases upwards from low to moderate high; trace fossils include Chondrites, Planolites, Asterosoma, Zoophycos
Facies A1: Prodelta deposits
mudstone
conglomerate
very fine
fine
medium
coarse
very coarse
sandstone
Alma K85
core 4
boxes 18/22 to 15/22
unlined Thalassinoides burrow
unlined Thalassinoides burrow
BURROWED FIRMGROUND SURFACE



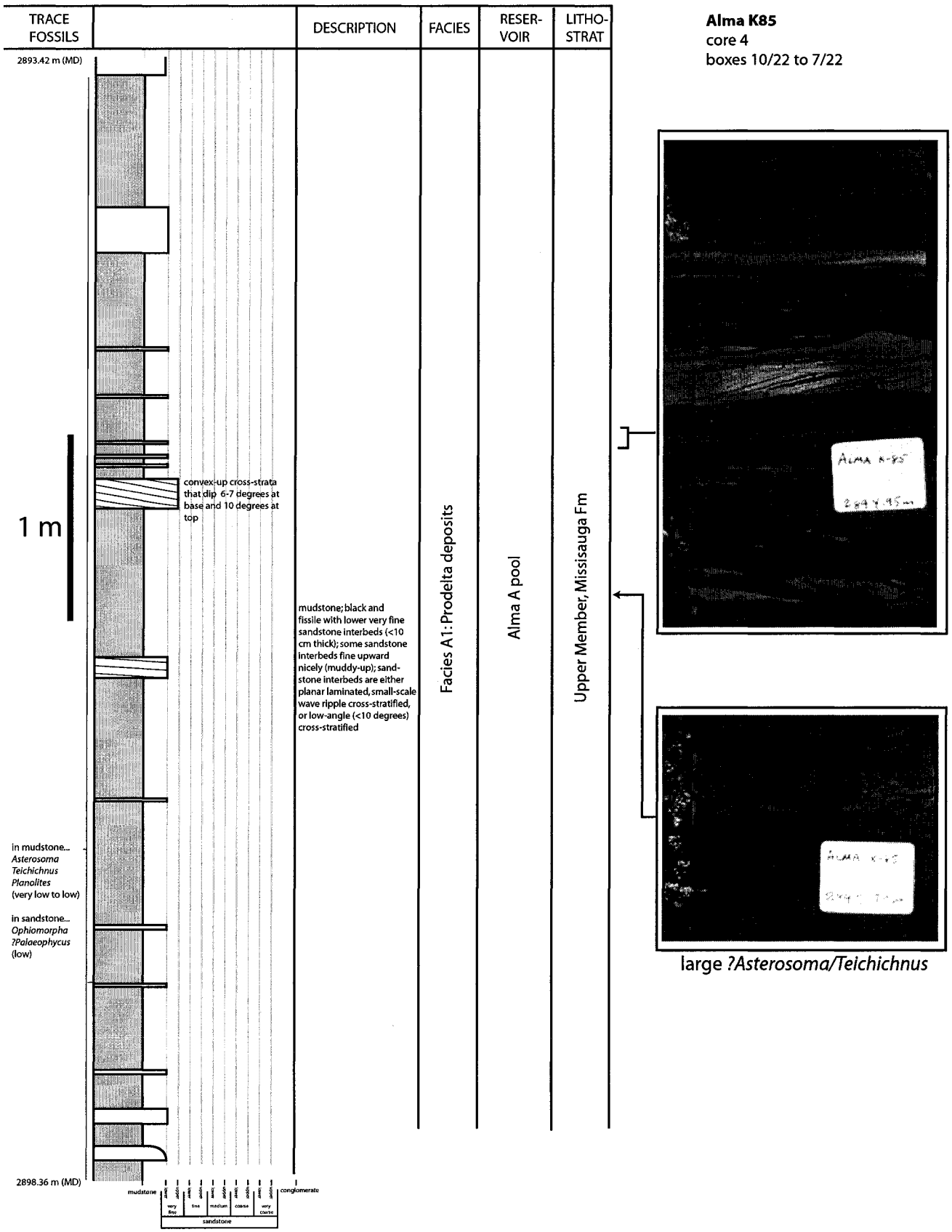
Alma K85
core 4
boxes 14/22 to 11/22

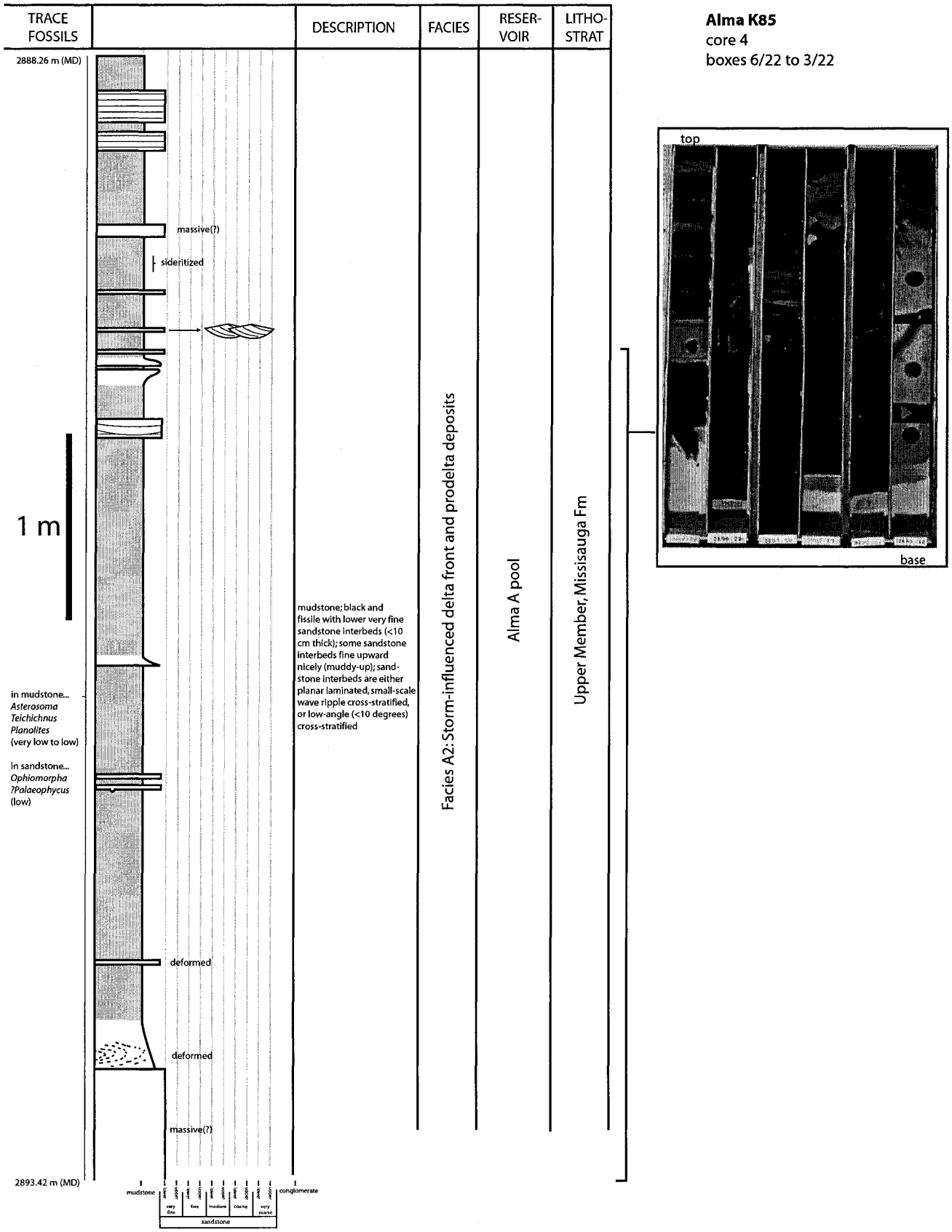


VERTICAL "KNIFE-SCRATCHES"

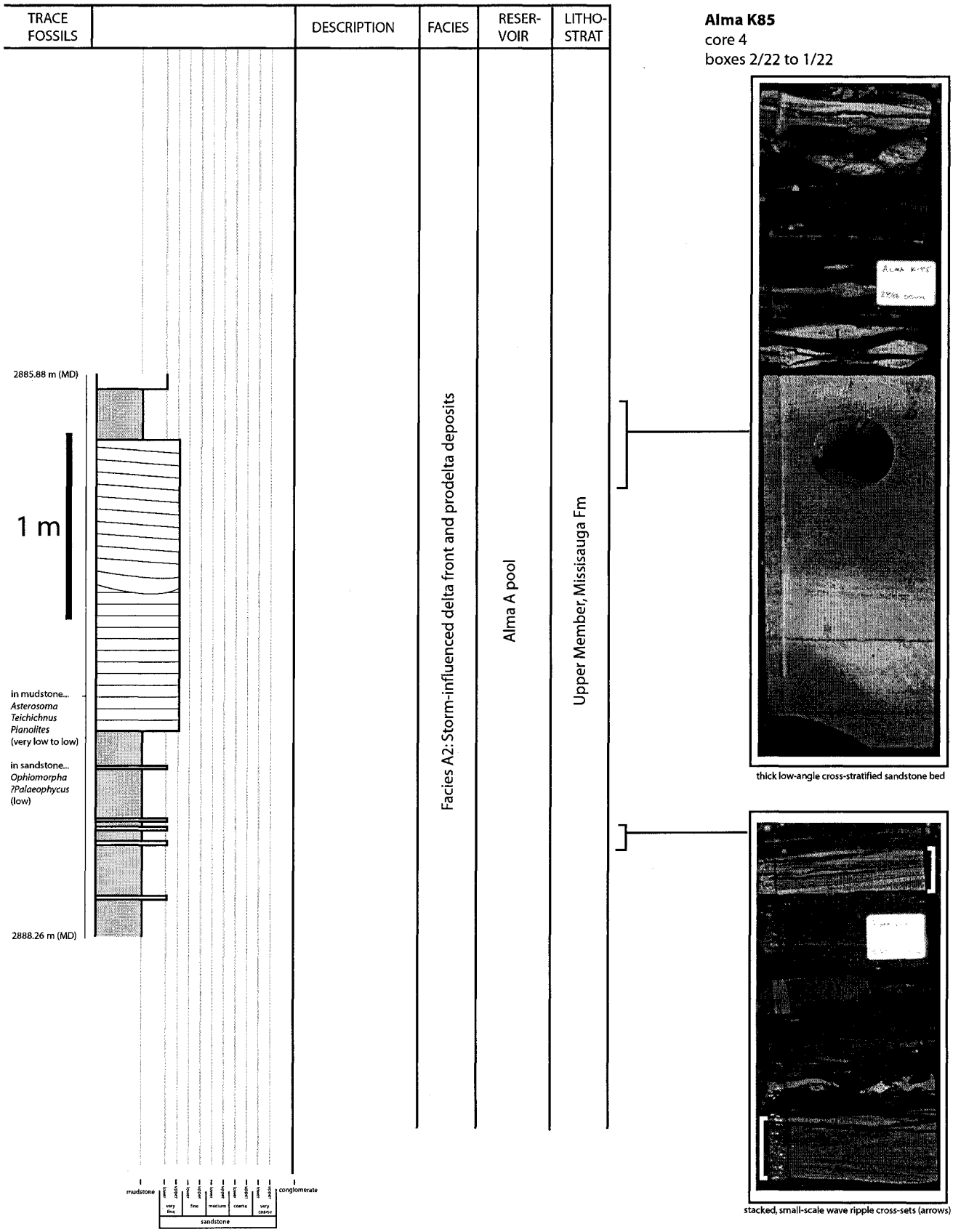
Note 1) complete absence of bioturbation, 2) association with streaky "amphibole-look" mudstone (i.e., mudstone with horizontal streaks -- this facies commonly occurs above planar laminated sandstone "event" beds)

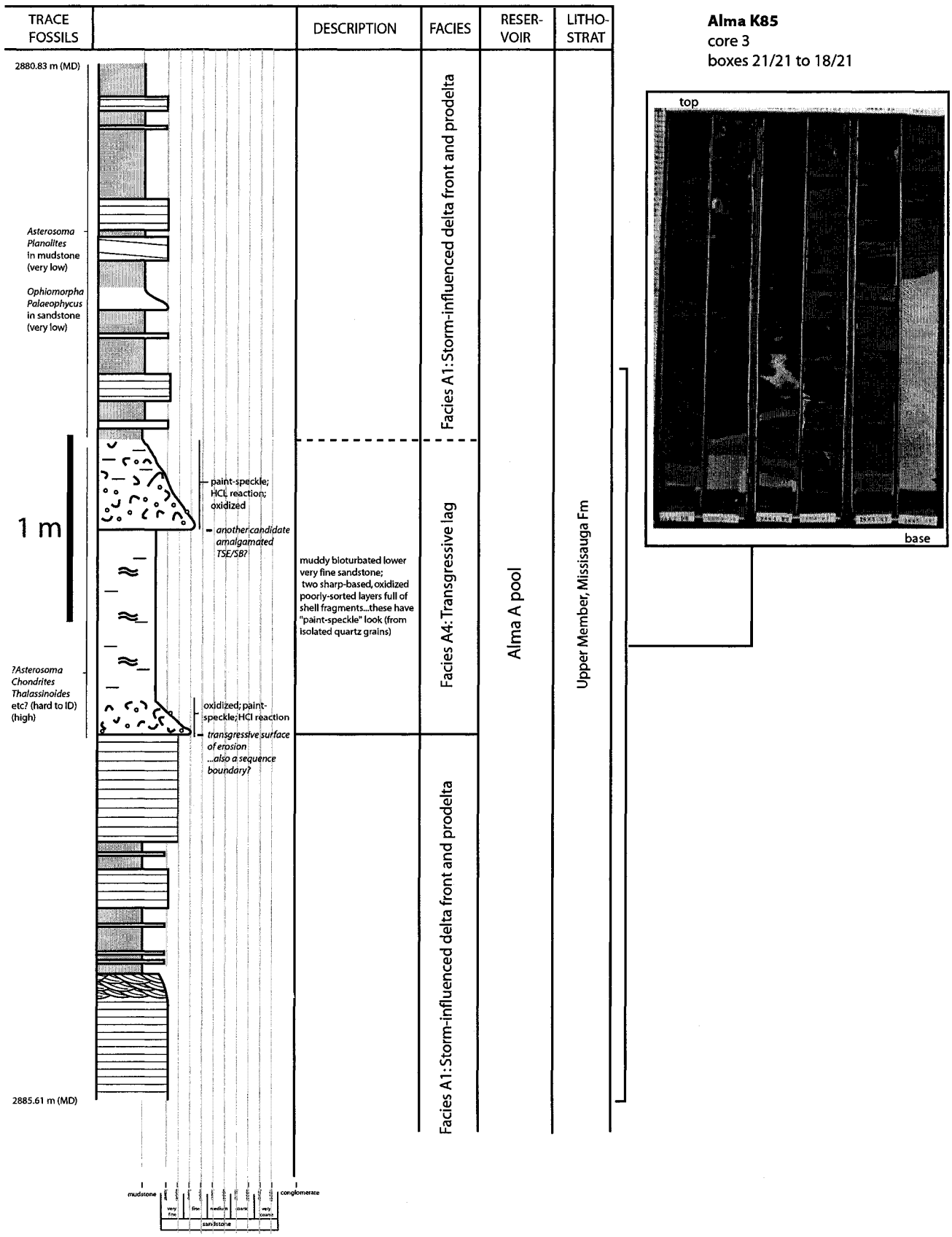
INTERPRETATION --> dewatering features (pillar structures) ...they look like superficial, vertical "knife-scratches" on the core, but are actually vertical, organic-free (and hence, white-coloured) sheet-like features, that look very similar to pillar structures described in Middleton et al., 2003


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
2893.42 m (MD)
1 m
convex-up cross-strata that dip 6-7 degrees at base and 10 degrees at top
mudstone; black and fissile with lower very fine sandstone interbeds (<10 cm thick); some sandstone interbeds fine upward nicely (muddy-up); sand-stone interbeds are either planar laminated, small-scale wave ripple cross-stratified, or low-angle (<10 degrees) cross-stratified
Facies A1: Prodelta deposits
Alma A pool
Upper Member, Missisauga Fm
in mudstone...
Asterosoma
Teichichnus
Planolites
(very low to low)
in sandstone...
Ophiomorpha
?Palaeophycus
(low)
2898.36 m (MD)
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone
Alma K85
core 4
boxes 10/22 to 7/22
large ?Asterosoma/Teichichnus



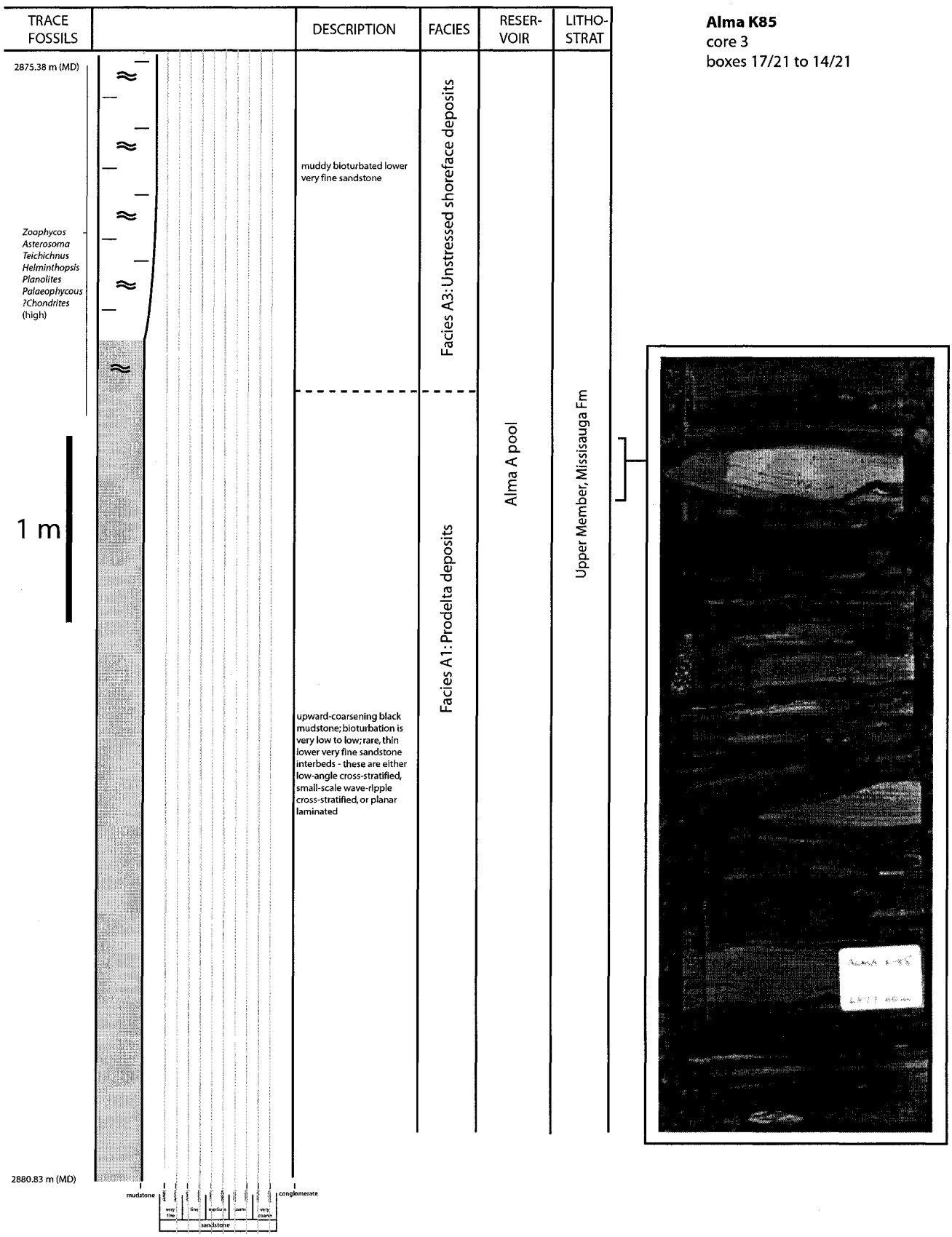
Alma K85
core 4
boxes 6/22 to 3/22

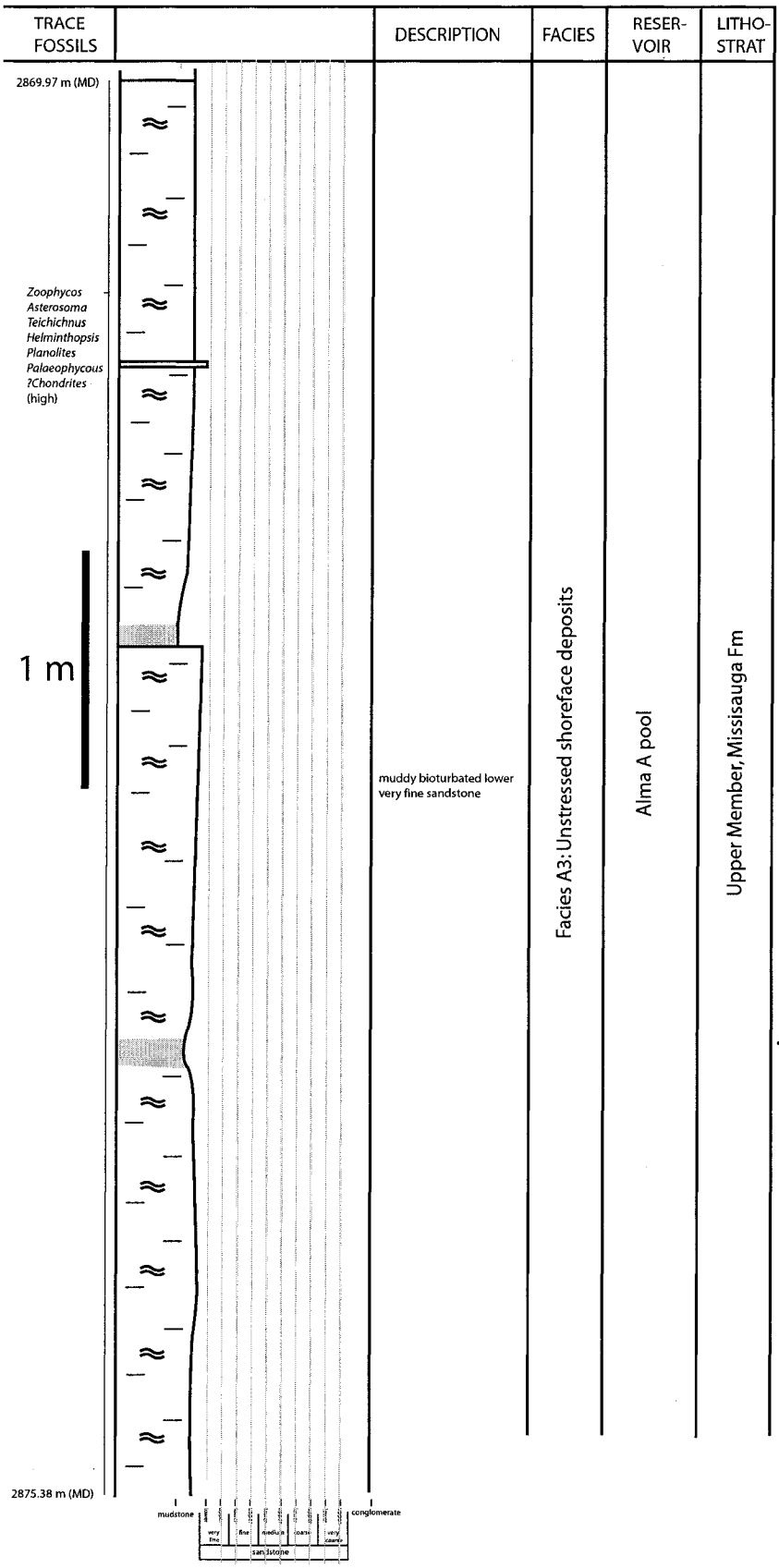

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
2885.88 m (MD)
1 m
in mudstone...
Asterosoma
Teichichnus
Planolites
(very low to low)
in sandstone...
Ophiomorpha
?Palaeophycus
(low)
2888.26 m (MD)
Facies A2: Storm-influenced delta front and prodelta deposits
Alma A pool
Upper Member, Missisauga Fm
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone
Alma K85
core 4
boxes 2/22 to 1/22
thick low-angle cross-stratified sandstone bed
stacked, small-scale wave ripple cross-sets (arrows)



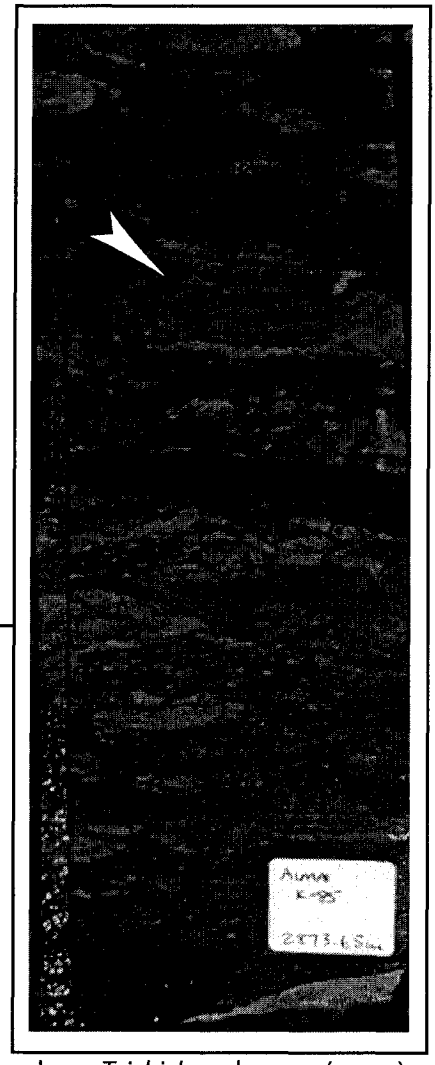
Alma K85
core 3
boxes 21/21 to 18/21

Alma K85
core 3
boxes 17/21 to 14/21

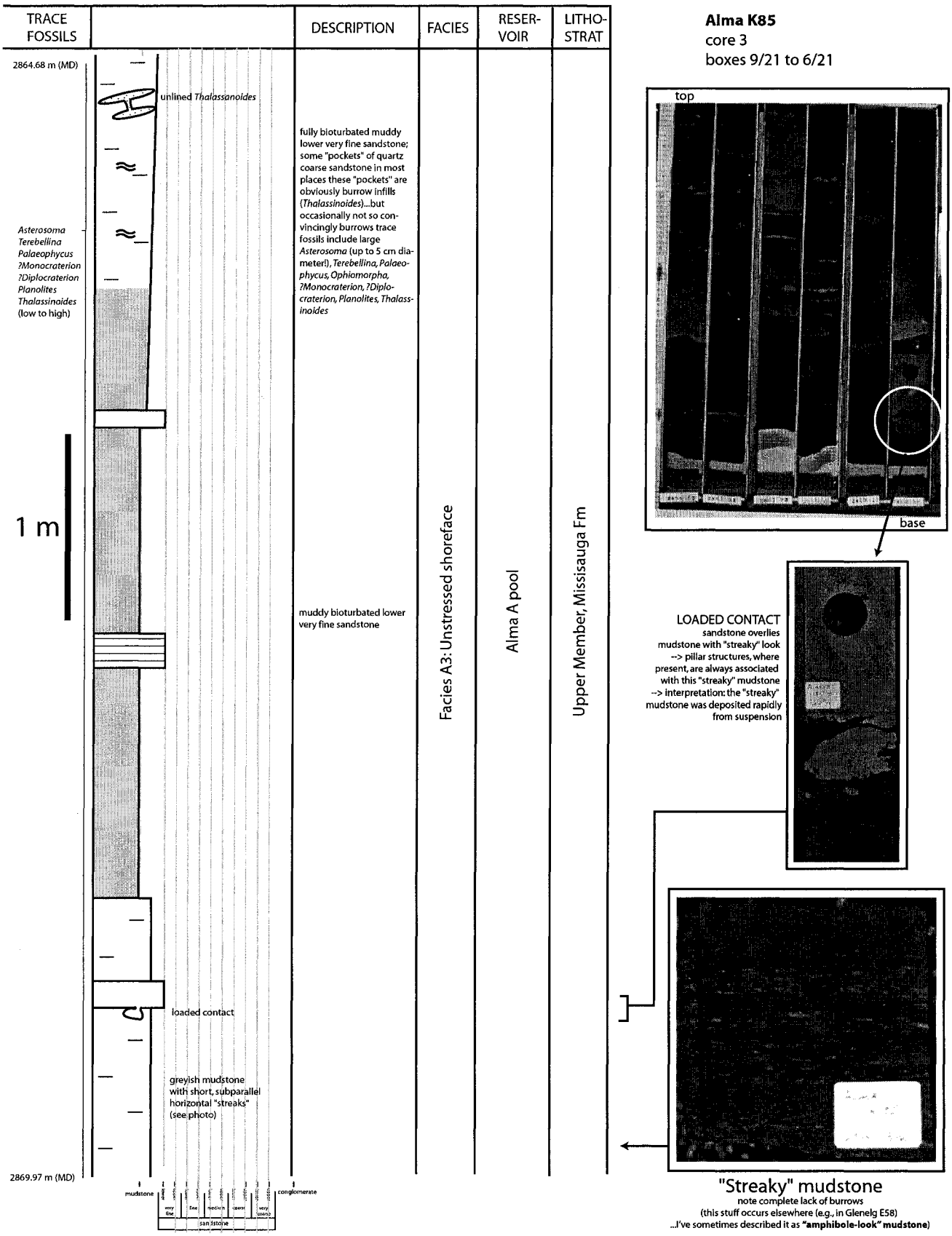


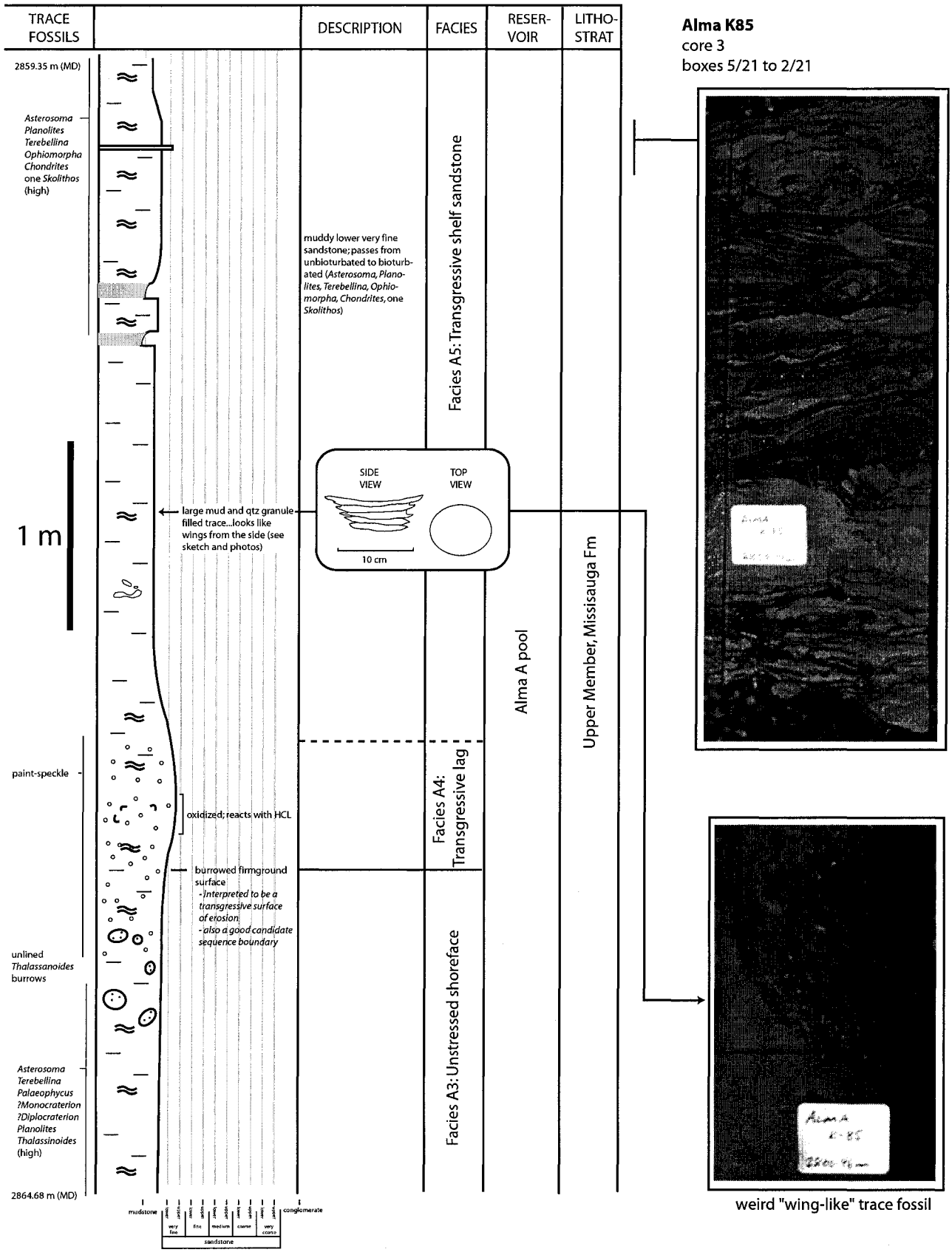


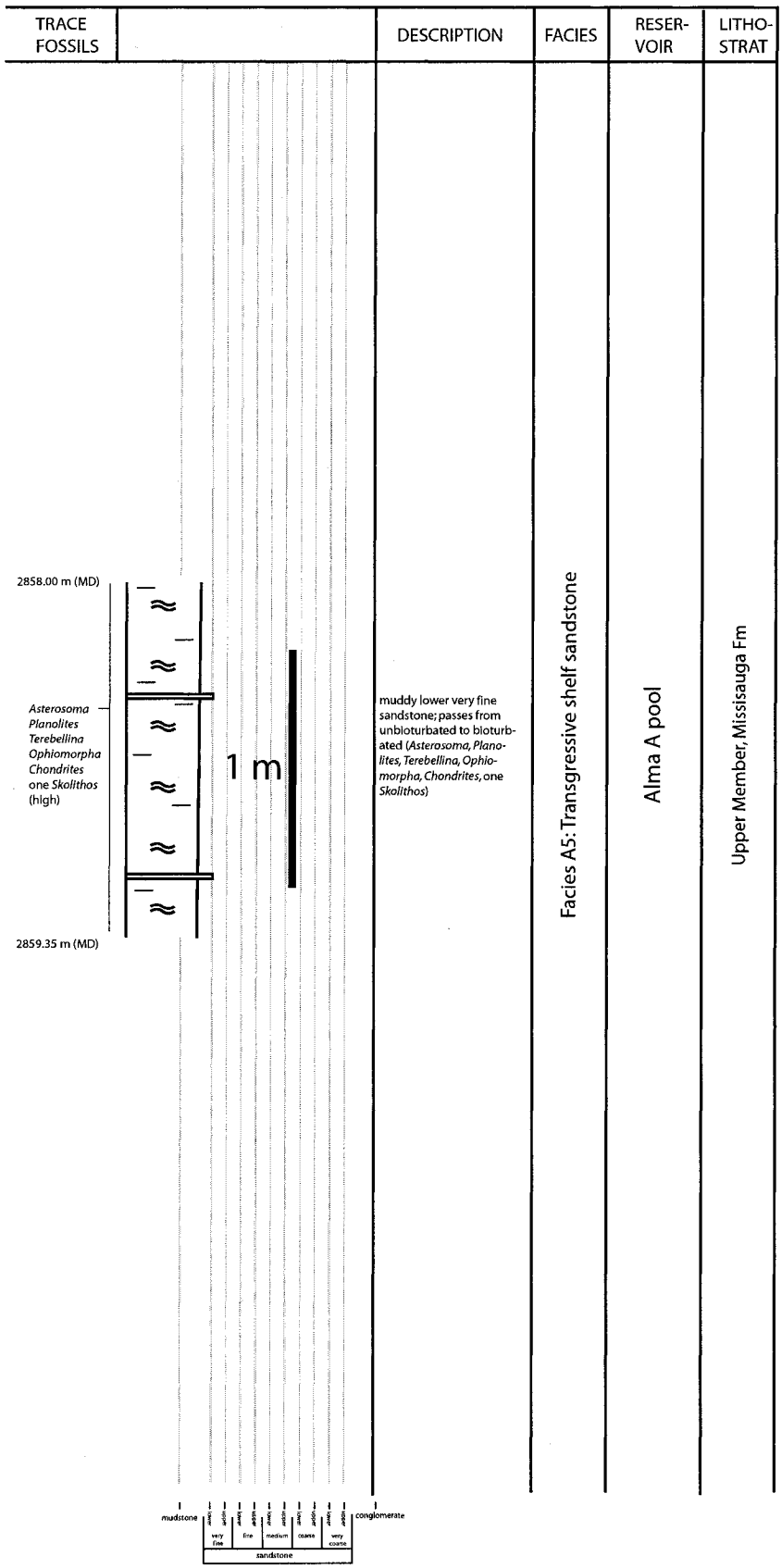
Alma K85
core 3
boxes 13/21 to 10/21



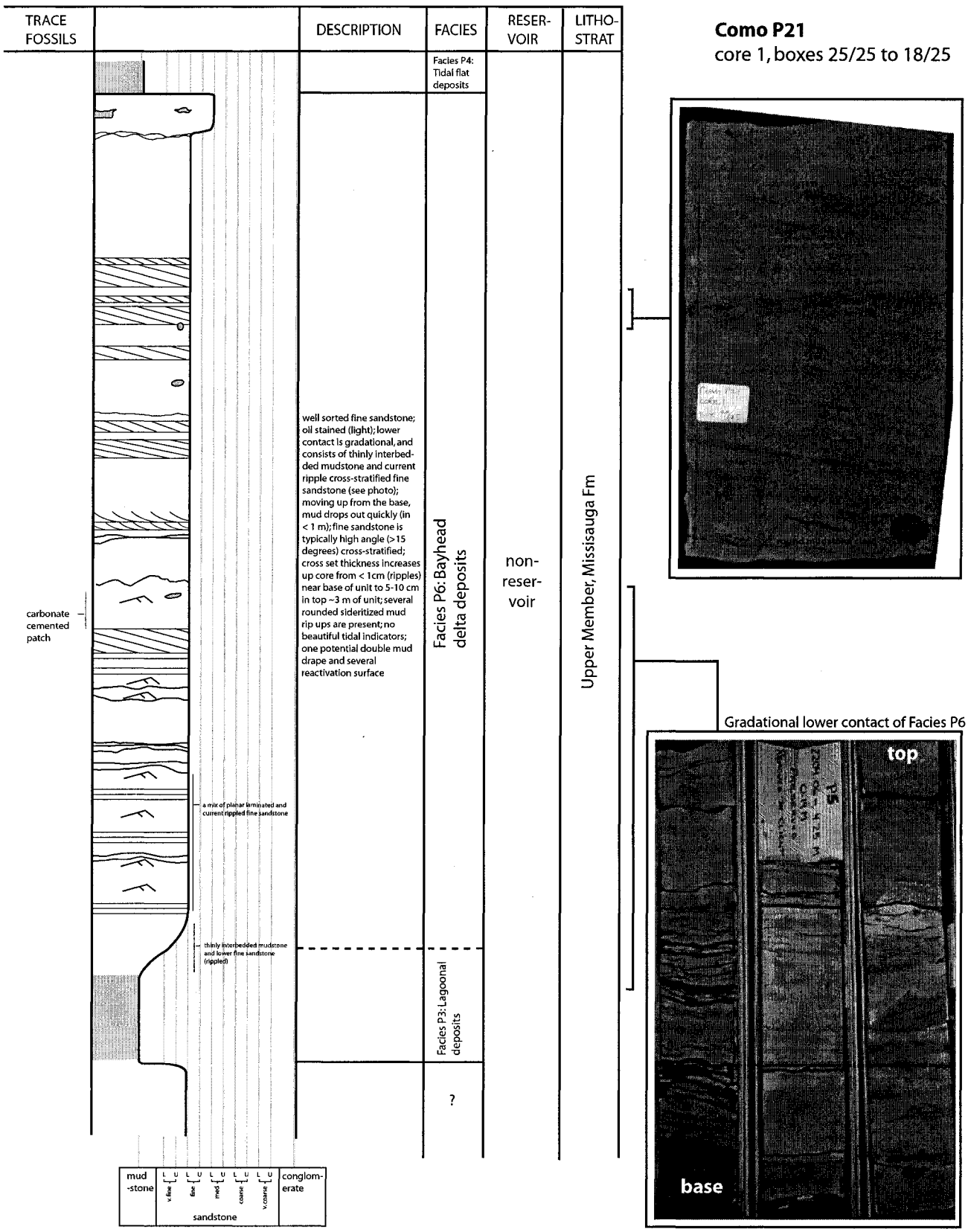
large *Teichichnus* burrow (arrow)

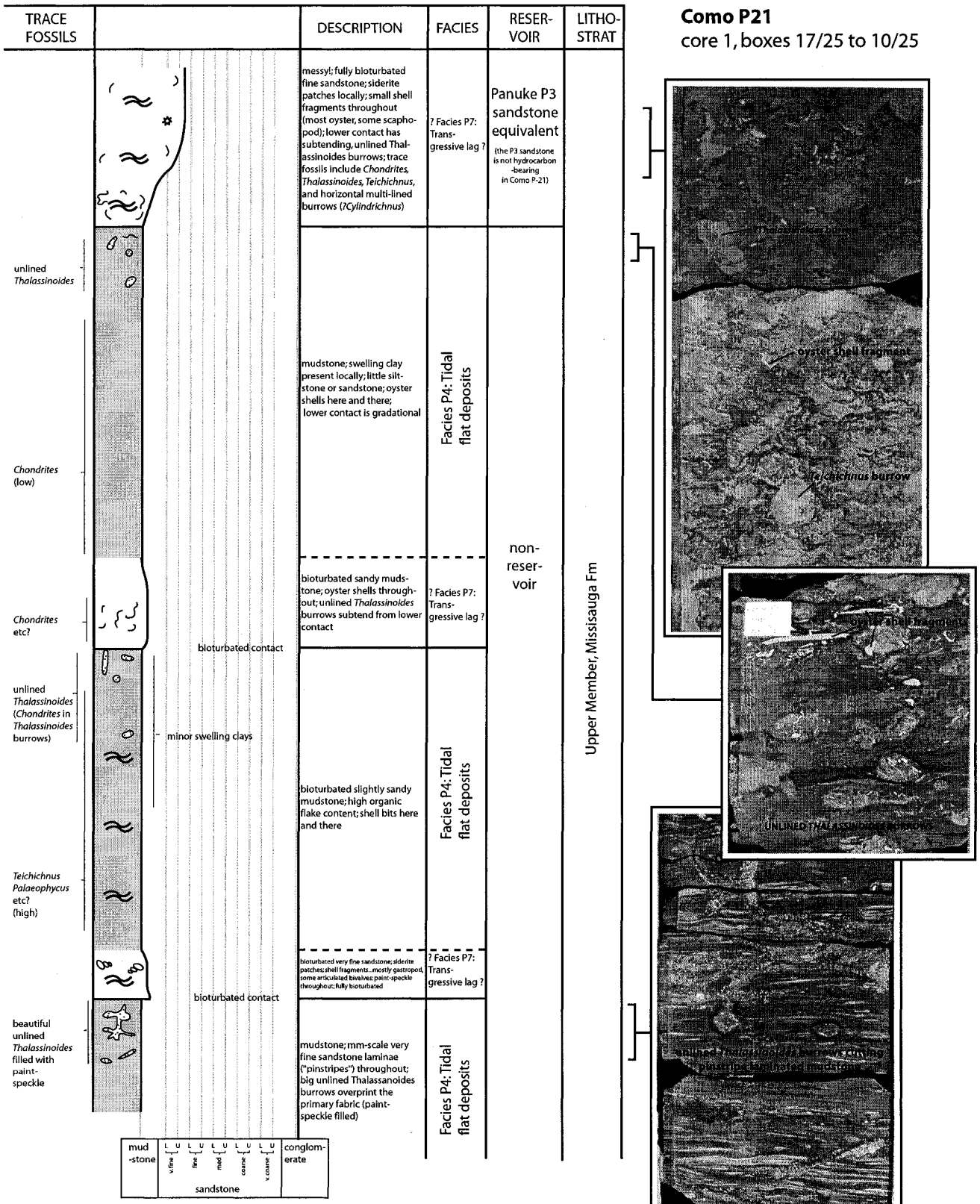

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
2864.68 m (MD)
unlined Thalassanoides
Asterosoma
Terebellina
Palaeophycus
?Monocraterion
?Diplocraterion
Planolites
Thalassinoides
(low to high)
fully bioturbated muddy lower very fine sandstone; some "pockets" of quartz coarse sandstone in most places these "pockets" are obviously burrow infills (Thalassinoides)...but occasionally not so convincingly burrows trace fossils include large Asterosoma (up to 5 cm diameter!), Terebellina, Palaeophycus, Ophiomorpha, ?Monocraterion, ?Diplocraterion, Planolites, Thalassinoides
1 m
muddy bioturbated lower very fine sandstone
Facies A3: Unstressed shoreface
Alma A pool
Upper Member, Missisauga Fm
loaded contact
greyish mudstone with short, subparallel horizontal "streaks" (see photo)
2869.97 m (MD)
mudstone
conglomerate
sandstone
Alma K85
core 3
boxes 9/21 to 6/21
top
base
LOADED CONTACT
sandstone overlies mudstone with "streaky" look
--> pillar structures, where present, are always associated with this "streaky" mudstone
--> interpretation: the "streaky" mudstone was deposited rapidly from suspension
"Streaky" mudstone
note complete lack of burrows
(this stuff occurs elsewhere (e.g., in Glenelg E58)
...I've sometimes described it as "amphibole-look" mudstone)

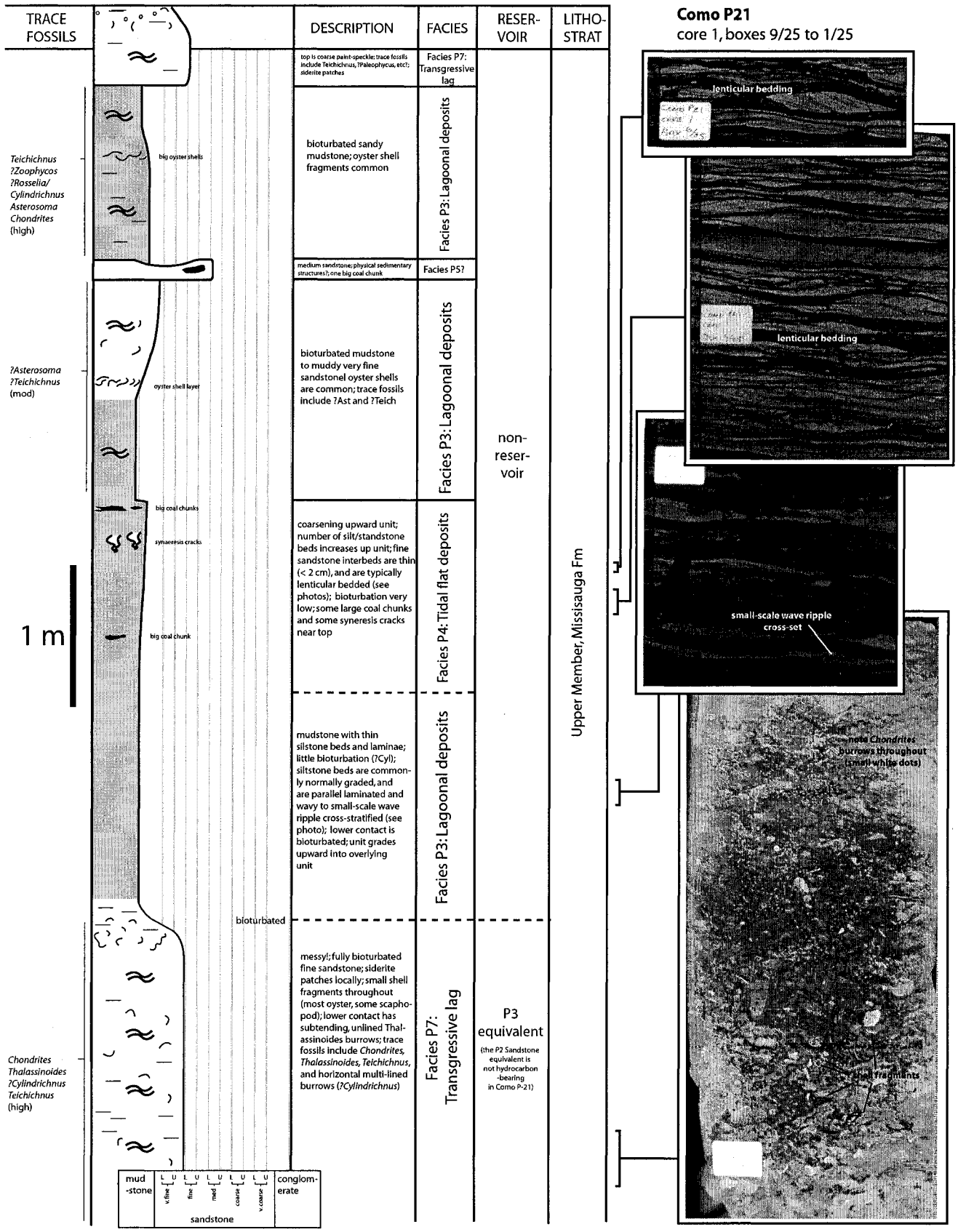

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
2859.35 m (MD)
Asterosoma
Planolites
Terebellina
Ophiomorpha
Chondrites
one Skolithos
(high)
muddy lower very fine sandstone; passes from unbioturbated to bioturbated (Asterosoma, Planolites, Terebellina, Ophiomorpha, Chondrites, one Skolithos)
Facies A5: Transgressive shelf sandstone
SIDE VIEW
TOP VIEW
10 cm
1 m
large mud and qtz granule filled trace...looks like wings from the side (see sketch and photos)
Alma A pool
Upper Member, Missisauga Fm
paint-speckle
oxidized; reacts with HCL
burrowed firmground surface
- Interpreted to be a transgressive surface of erosion
- also a good candidate sequence boundary
Facies A4: Transgressive lag
unlined Thalassanoides burrows
Asterosoma
Terebellina
Palaeophycus
?Monocraterion
?Diplocraterion
Planolites
Thalassinoides
(high)
Facies A3: Unstressed shoreface
2864.68 m (MD)
mudstone
conglomerate
very fine
fine
medium
coarse
very coarse
sandstone
Alma K85
core 3
boxes 5/21 to 2/21
weird "wing-like" trace fossil

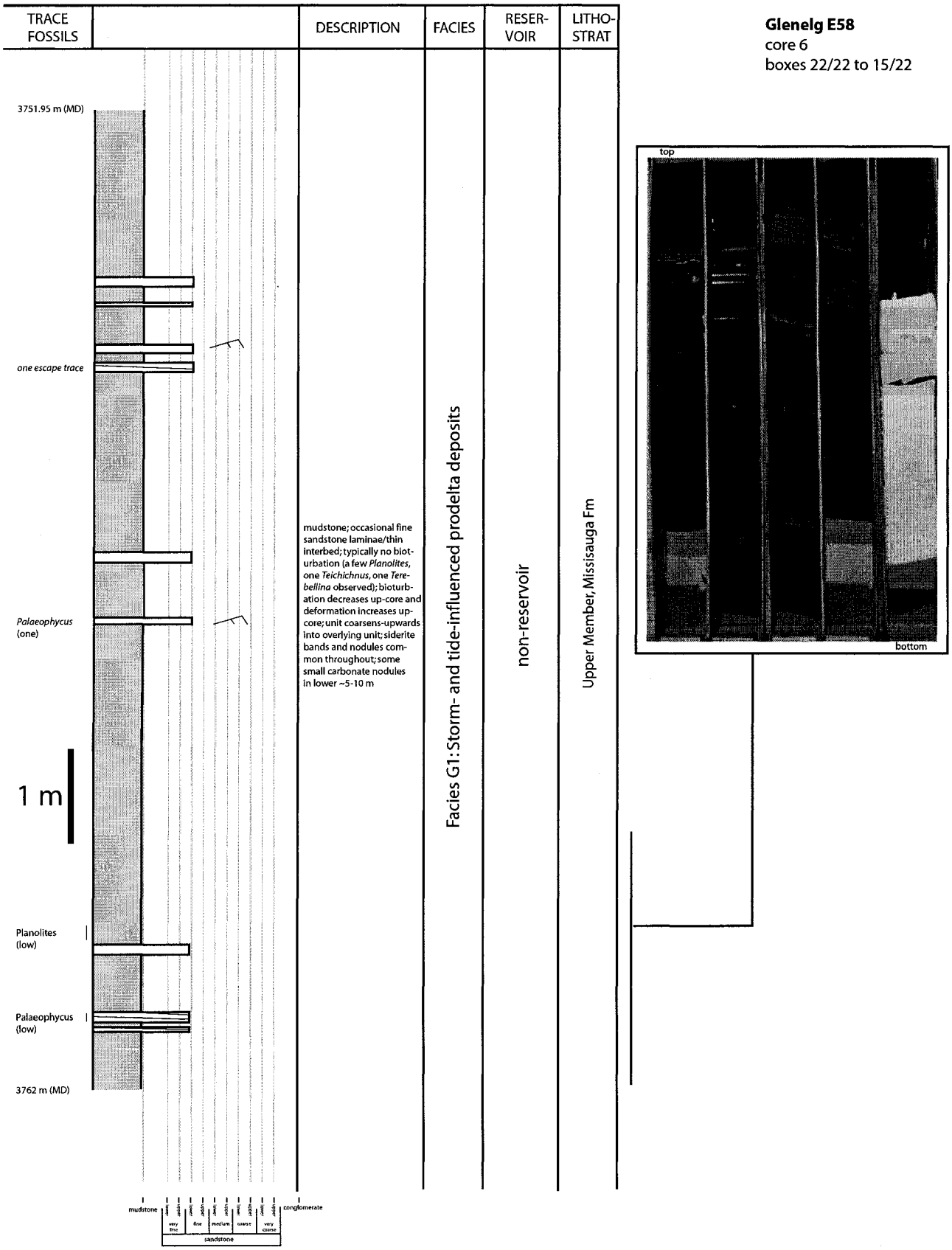


Alma K85
core 3
box 1/21

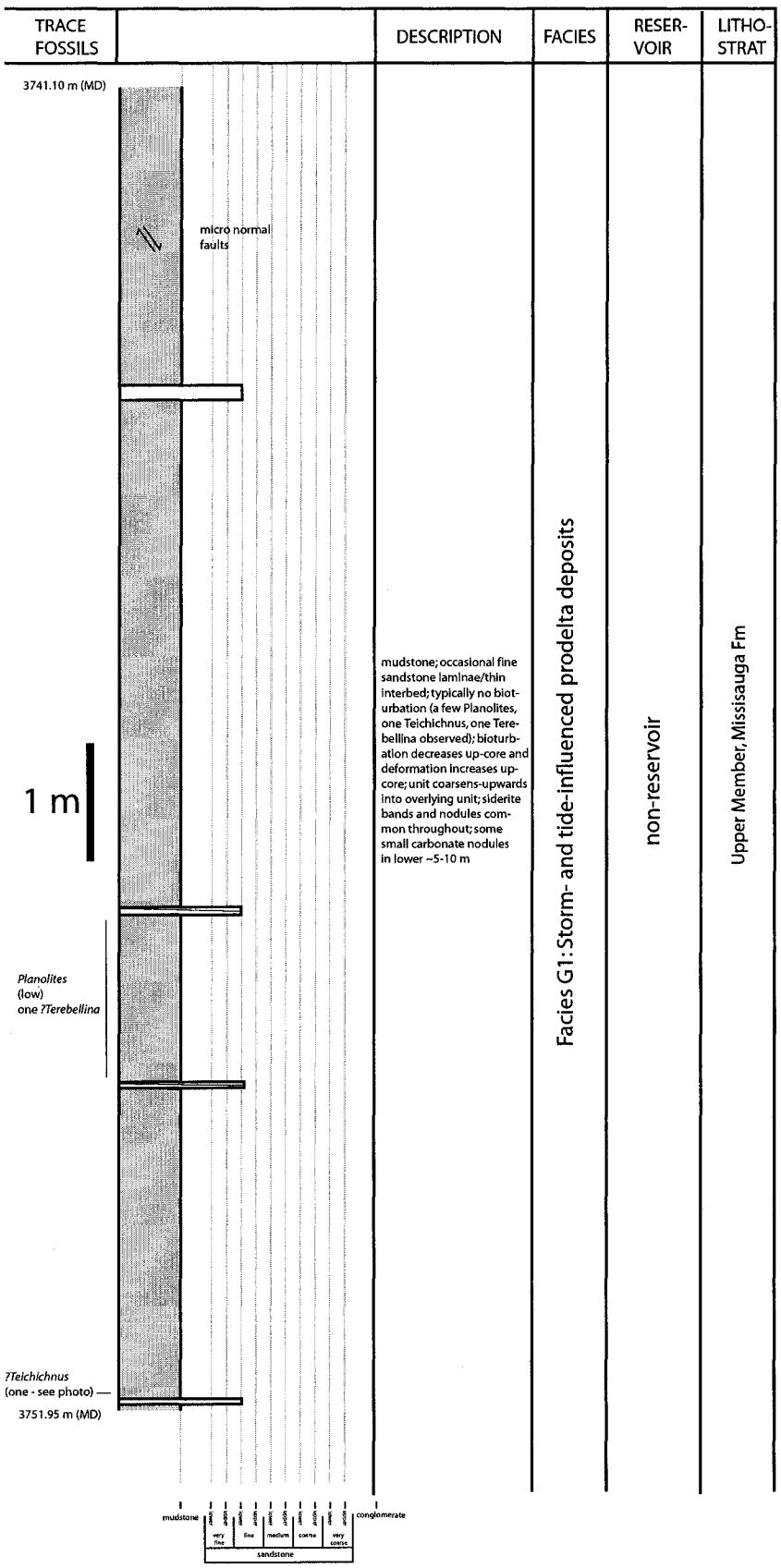

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Facies P4: Tidal flat deposits
well sorted fine sandstone; oil stained (light); lower contact is gradational, and consists of thinly interbedded mudstone and current ripple cross-stratified fine sandstone (see photo); moving up from the base, mud drops out quickly (in < 1 m); fine sandstone is typically high angle (>15 degrees) cross-stratified; cross set thickness increases up core from < 1cm (ripples) near base of unit to 5-10 cm in top ~3 m of unit; several rounded sideritized mud rip ups are present; no beautiful tidal indicators; one potential double mud drape and several reactivation surface
Facies P6: Bayhead delta deposits
non-reser-voir
Upper Member, Missisauga Fm
carbonate cemented patch
a mix of planar laminated and current rippled fine sandstone
thinly interbedded mudstone and lower fine sandstone (rippled)
Facies P3: Lagoonal deposits
?
mud -stone
v.fine
fine
med.
coarse
v.coarse
sandstone
conglom-erate
Como P21
core 1, boxes 25/25 to 18/25
Gradational lower contact of Facies P6
top
base


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
messyl; fully bioturbated fine sandstone; siderite patches locally; small shell fragments throughout (most oyster, some scaphopod); lower contact has subtending, unlined Thalassinoides burrows; trace fossils include Chondrites, Thalassinoides, Teichichnus, and horizontal multi-lined burrows (?Cylindrichnus)
? Facies P7: Trans-gressive lag ?
Panuke P3 sandstone equivalent
(the P3 sandstone is not hydrocarbon -bearing in Como P-21)
unlined Thalassinoides
mudstone; swelling clay present locally; little silt-stone or sandstone; oyster shells here and there; lower contact is gradational
Facies P4: Tidal flat deposits
Chondrites (low)
non-reser-voir
Chondrites etc?
bioturbated sandy muds-tone; oyster shells through-out; unlined Thalassinoides burrows subtend from lower contact
? Facies P7: Trans-gressive lag ?
bioturbated contact
unlined Thalassinoides (Chondrites in Thalassinoides burrows)
minor swelling clays
bioturbated slightly sandy mudstone; high organic flake content; shell bits here and there
Facies P4: Tidal flat deposits
Teichichnus Palaeophycus etc? (high)
bioturbated very fine sandstone; siderite patches; shell fragments...mostly gastroped, some articulated bivalves; paint-speckle throughout; fully bioturbated
? Facies P7: Trans-gressive lag ?
bioturbated contact
beautiful unlined Thalassinoides filled with paint-speckle
mudstone; mm-scale very fine sandstone laminae ("pinstripes") throughout; big unlined Thalassanoides burrows overprint the primary fabric (paint-speckle filled)
Facies P4: Tidal flat deposits
Upper Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
Como P21
core 1, boxes 17/25 to 10/25
oyster shell fragment
Teichichnus burrow
oyster shell fragments
UNLINED THALASSINOIDES BURROWS
unlined Thalassinoides burrows running
pinstripe laminated mudstone


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Como P21
core 1, boxes 9/25 to 1/25
top is coarse paint-speckle; trace fossils include Teichichnus, ?Paleophycus, etc?; siderite patches
Facies P7: Transgressive lag
bioturbated sandy mudstone; oyster shell fragments common
Facies P3: Lagoonal deposits
medium sandstone; physical sedimentary structures?; one big coal chunk
Facies P5?
bioturbated mudstone to muddy very fine sandstonel oyster shells are common; trace fossils include ?Ast and ?Teich
Facies P3: Lagoonal deposits
non-reser-voir
coarsening upward unit; number of silt/standstone beds increases up unit; fine sandstone interbeds are thin (< 2 cm), and are typically lenticular bedded (see photos); bioturbation very low; some large coal chunks and some syneresis cracks near top
Facies P4: Tidal flat deposits
mudstone with thin silstone beds and laminae; little bioturbation (?Cyl); siltstone beds are commonly normally graded, and are parallel laminated and wavy to small-scale wave ripple cross-stratified (see photo); lower contact is bioturbated; unit grades upward into overlying unit
Facies P3: Lagoonal deposits
bioturbated
messy!; fully bioturbated fine sandstone; siderite patches locally; small shell fragments throughout (most oyster, some scaphopod); lower contact has subtending, unlined Thalassinoides burrows; trace fossils include Chondrites, Thalassinoides, Teichichnus, and horizontal multi-lined burrows (?Cylindrichnus)
Facies P7: Transgressive lag
P3 equivalent
(the P2 Sandstone equivalent is not hydrocarbon -bearing in Como P-21)
Upper Member, Missisauga Fm
Teichichnus
?Zoophycos
?Rosselia/
Cylindrichnus
Asterosoma
Chondrites
(high)
?Asterosoma
?Teichichnus
(mod)
Chondrites
Thalassinoides
?Cylindrichnus
Teichichnus
(high)
big oyster shells
oyster shell layer
big coal chunks
syneeresis cracks
big coal chunk
1 m
mud -stone
v.fine
fine
med
coarse
v.coarse
sandstone
conglom-erate
lenticular bedding
lenticular bedding
small-scale wave ripple cross-set
note Chondrites burrows throughout (small white dots)
shell fragments

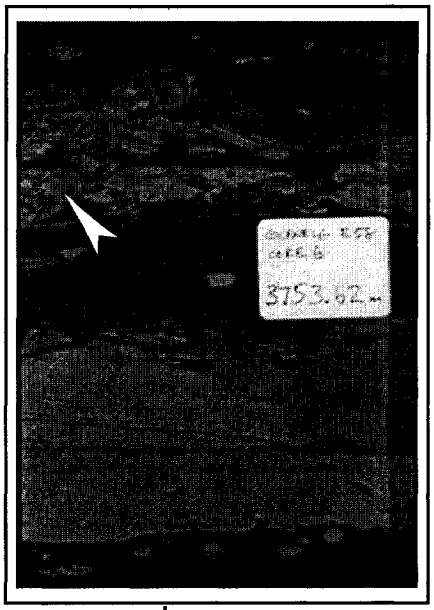


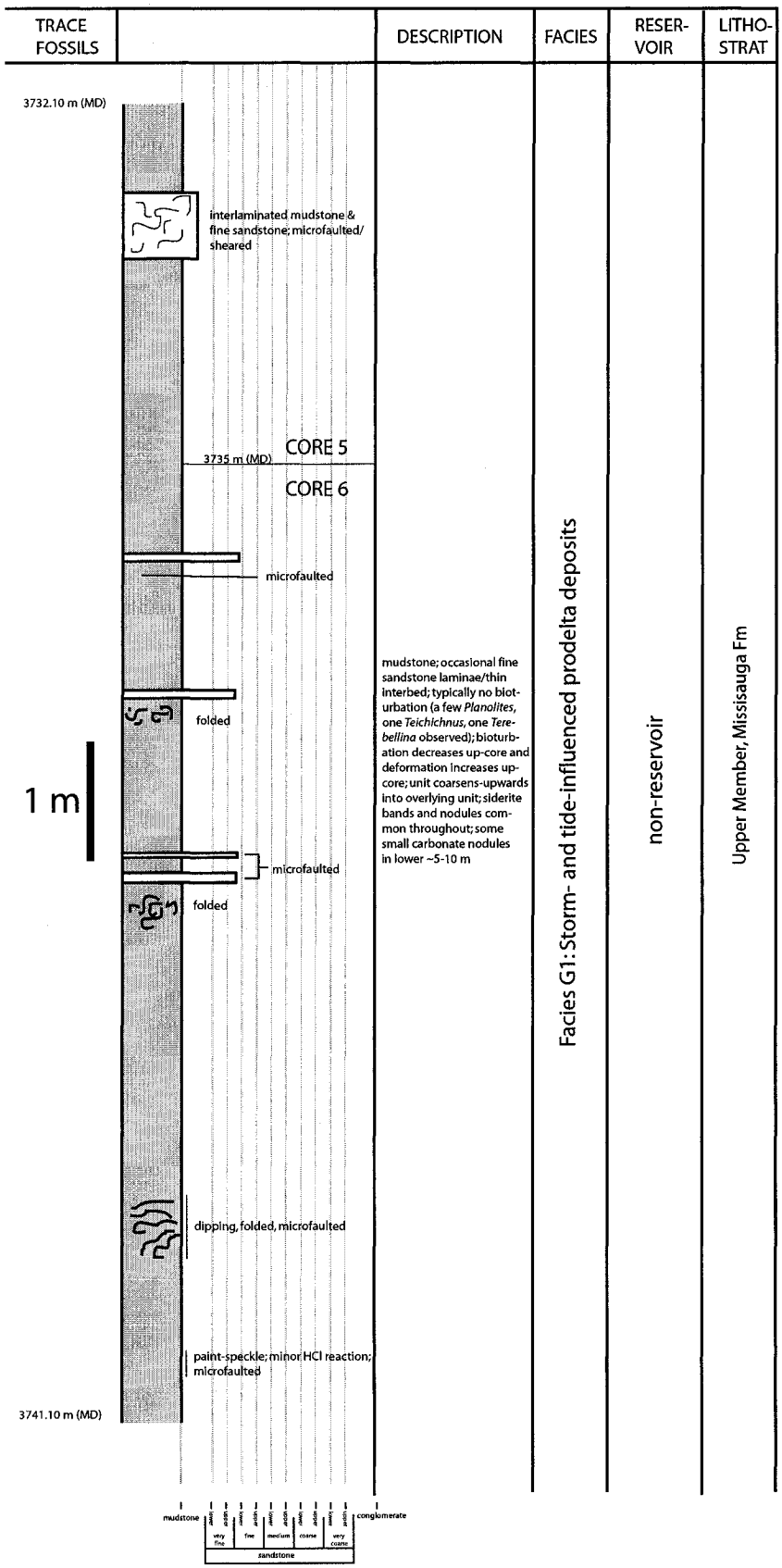
Glenelg E58
core 6
boxes 22/22 to 15/22



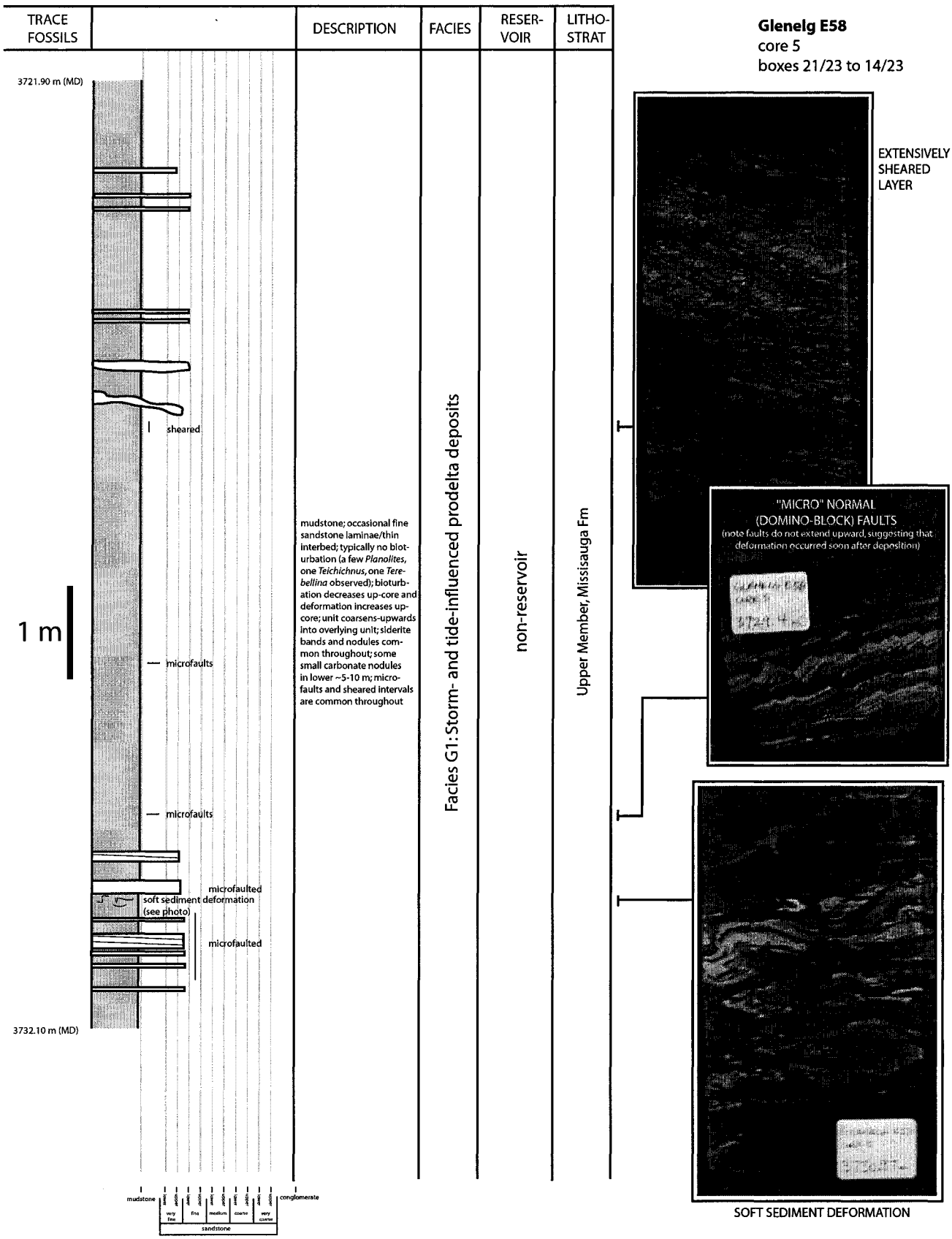
Glenelg E58
core 6
boxes 14/22 to 7/22

?Teichichnus burrow (arrow)

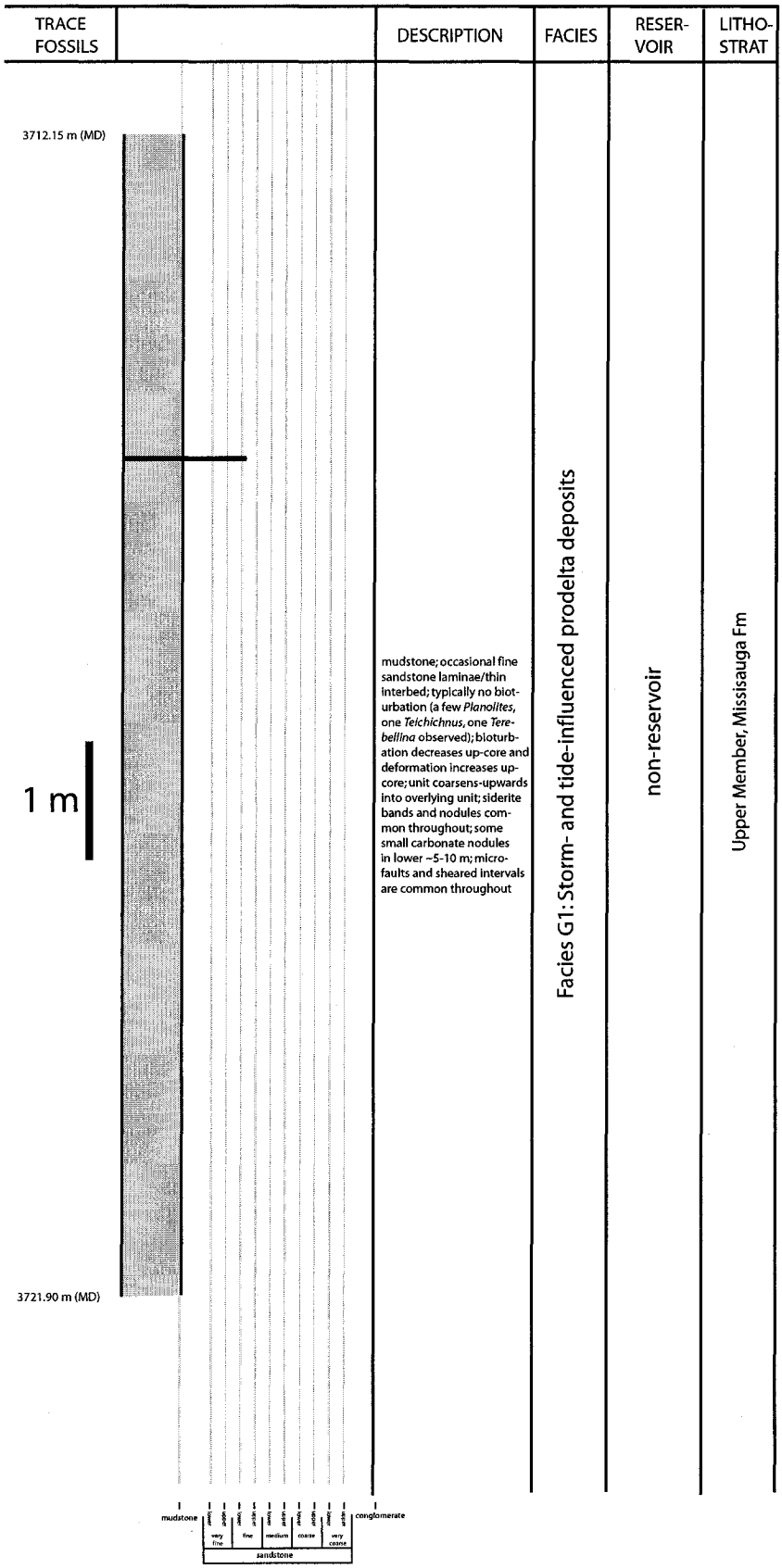




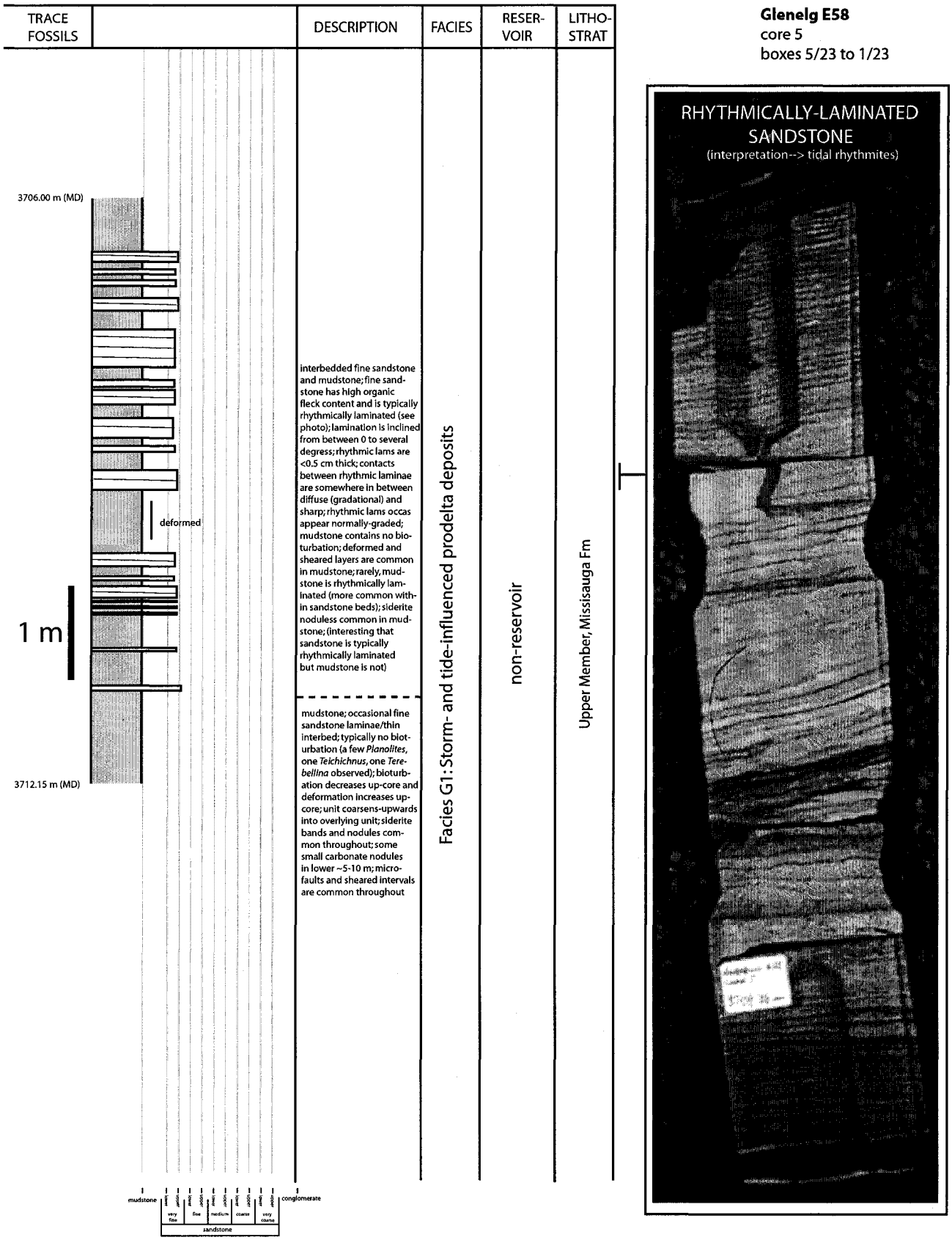
Glenelg E58
core 6, box 6/22 to
core 5, box 22/23


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
3721.90 m (MD)
sheared
1 m
microfaults
microfaults
microfaulted
soft sediment deformation (see photo)
microfaulted
3732.10 m (MD)
mudstone; occasional fine sandstone laminae/thin interbed; typically no bioturbation (a few Planolites, one Teichichnus, one Terebellina observed); bioturbation decreases up-core and deformation increases up-core; unit coarsens-upwards into overlying unit; siderite bands and nodules common throughout; some small carbonate nodules in lower ~5-10 m; microfaults and sheared intervals are common throughout
Facies G1: Storm- and tide-influenced prodelta deposits
non-reservoir
Upper Member, Missisauga Fm
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone
Glenelg E58
core 5
boxes 21/23 to 14/23
EXTENSIVELY SHEARED LAYER
"MICRO" NORMAL (DOMINO-BLOCK) FAULTS
(note faults do not extend upward, suggesting that deformation occurred soon after deposition)
SOFT SEDIMENT DEFORMATION

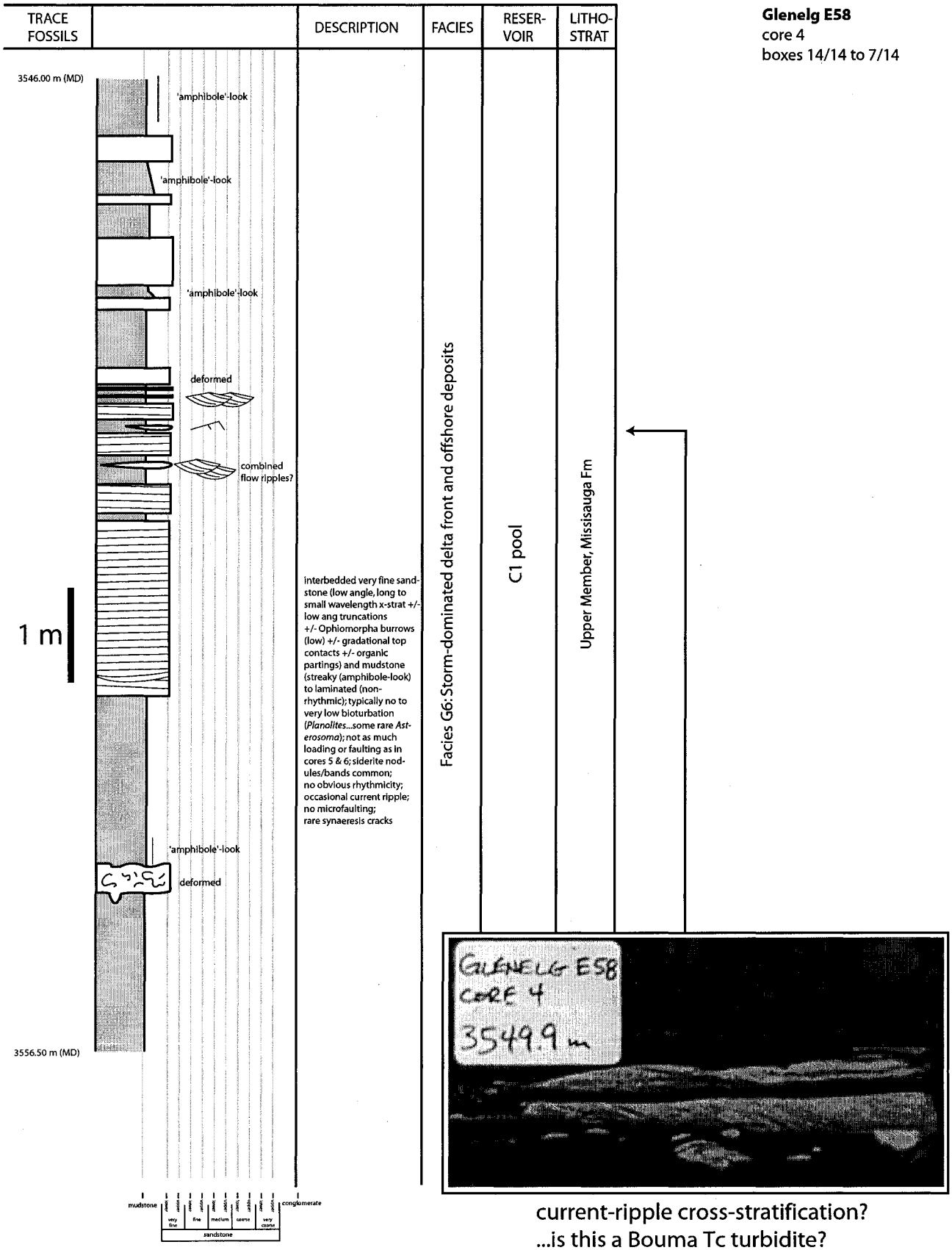
Glenelg E58
core 5
boxes 13/23 to 6/23



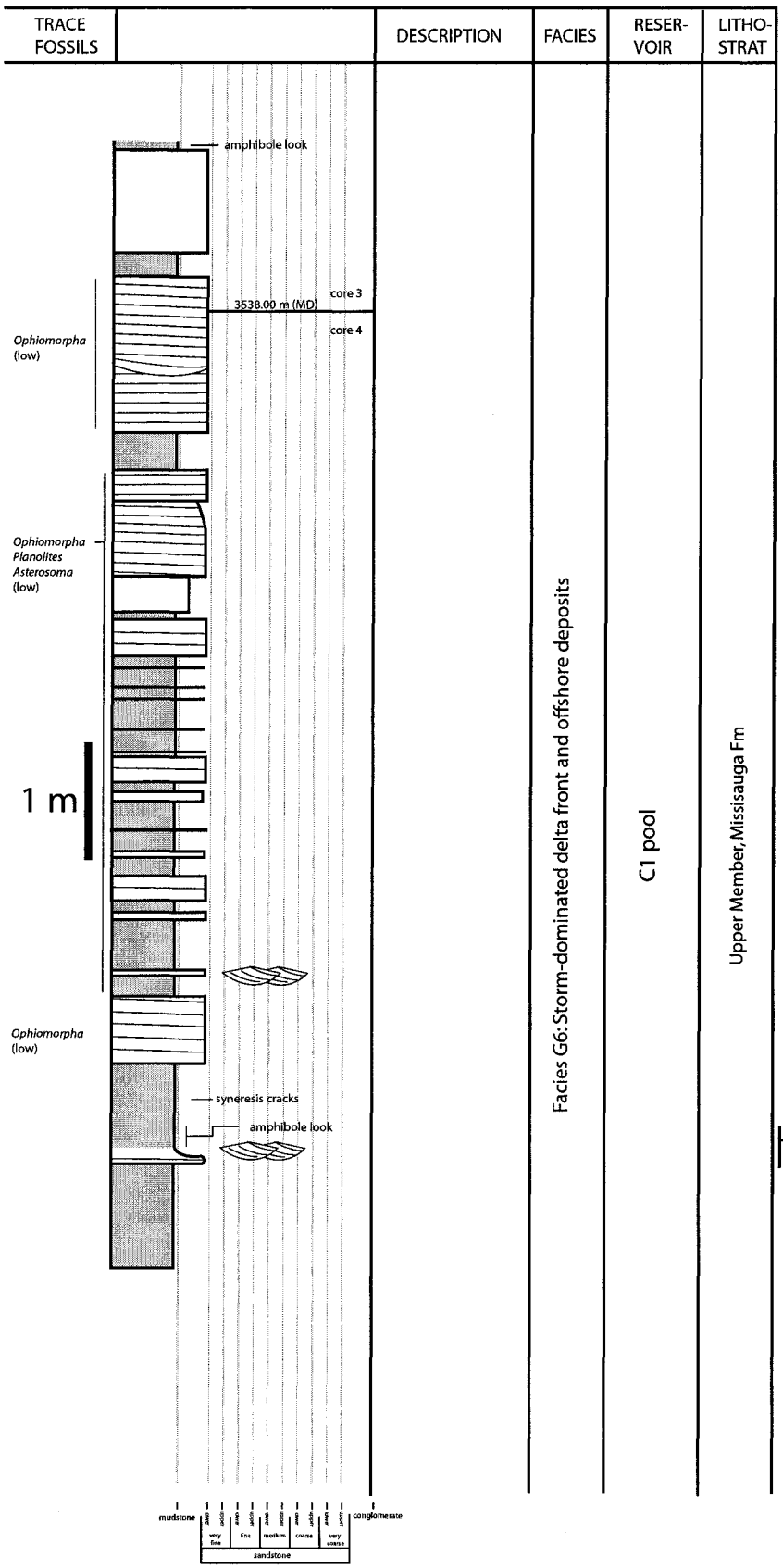
Glenelg E58
core 5
boxes 5/23 to 1/23



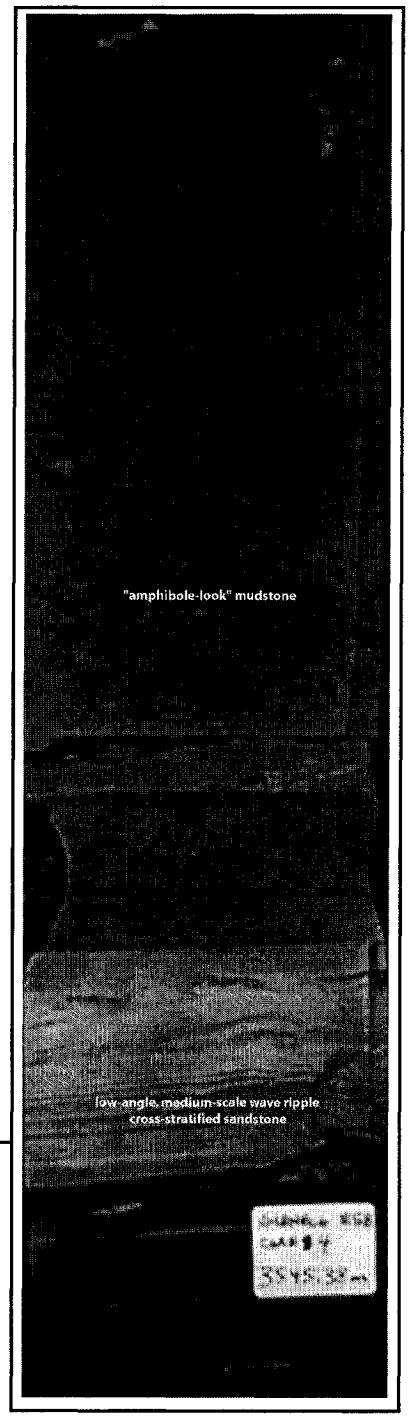
Glenelg E58
core 4
boxes 14/14 to 7/14



current-ripple cross-stratification?
...is this a Bouma Tc turbidite?



Glenelg E58
core 4, box 6/14 to
core 3, box 11/12

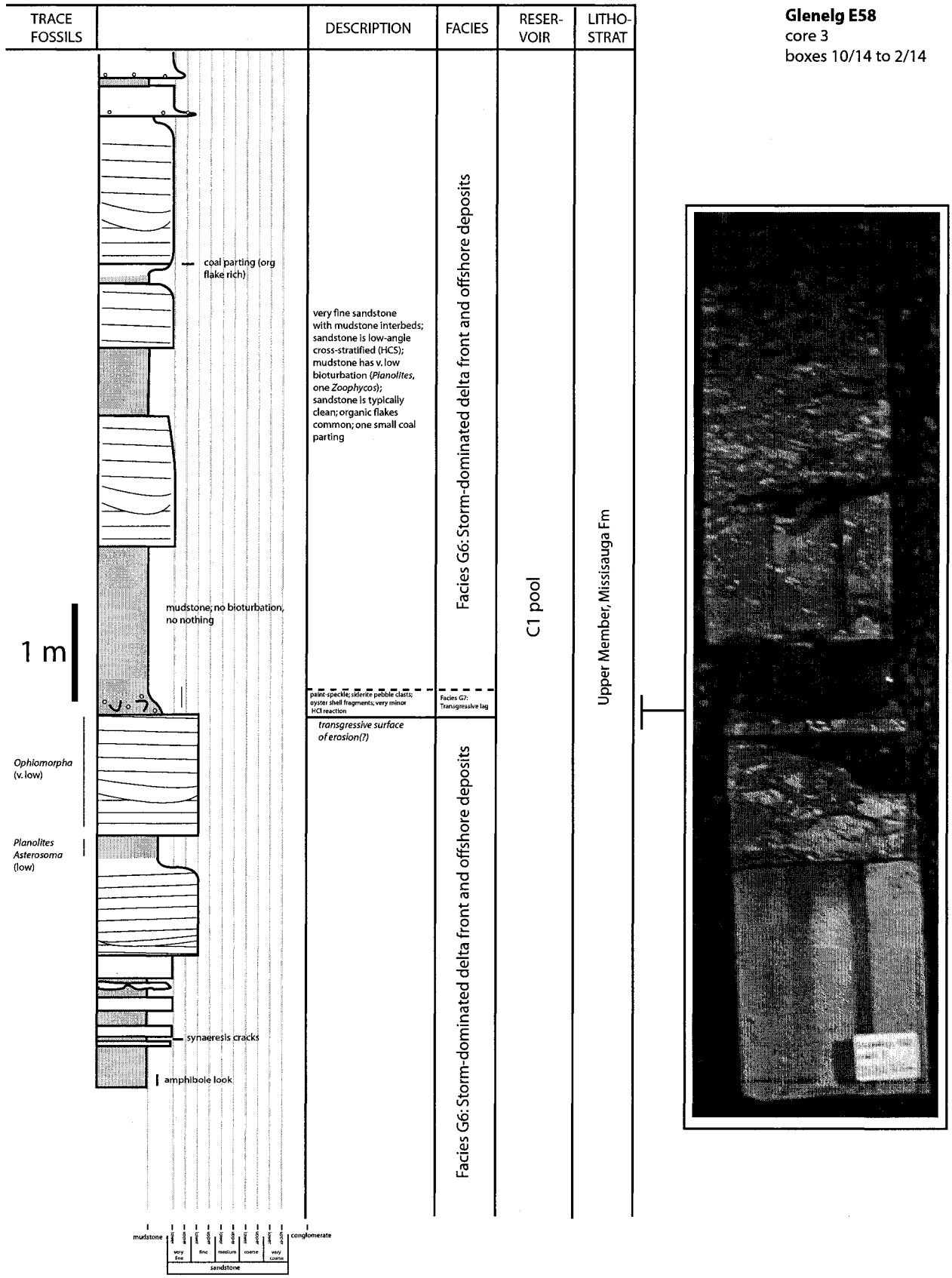


LOW-ANGLE MEDIUM-SCALE WAVE RIPPLE CROSS-STRATIFIED SANDSTONE GRADATIONALLY OVERLAIN BY STREAKY ("AMPHIBOLE-LOOK") MUDSTONE

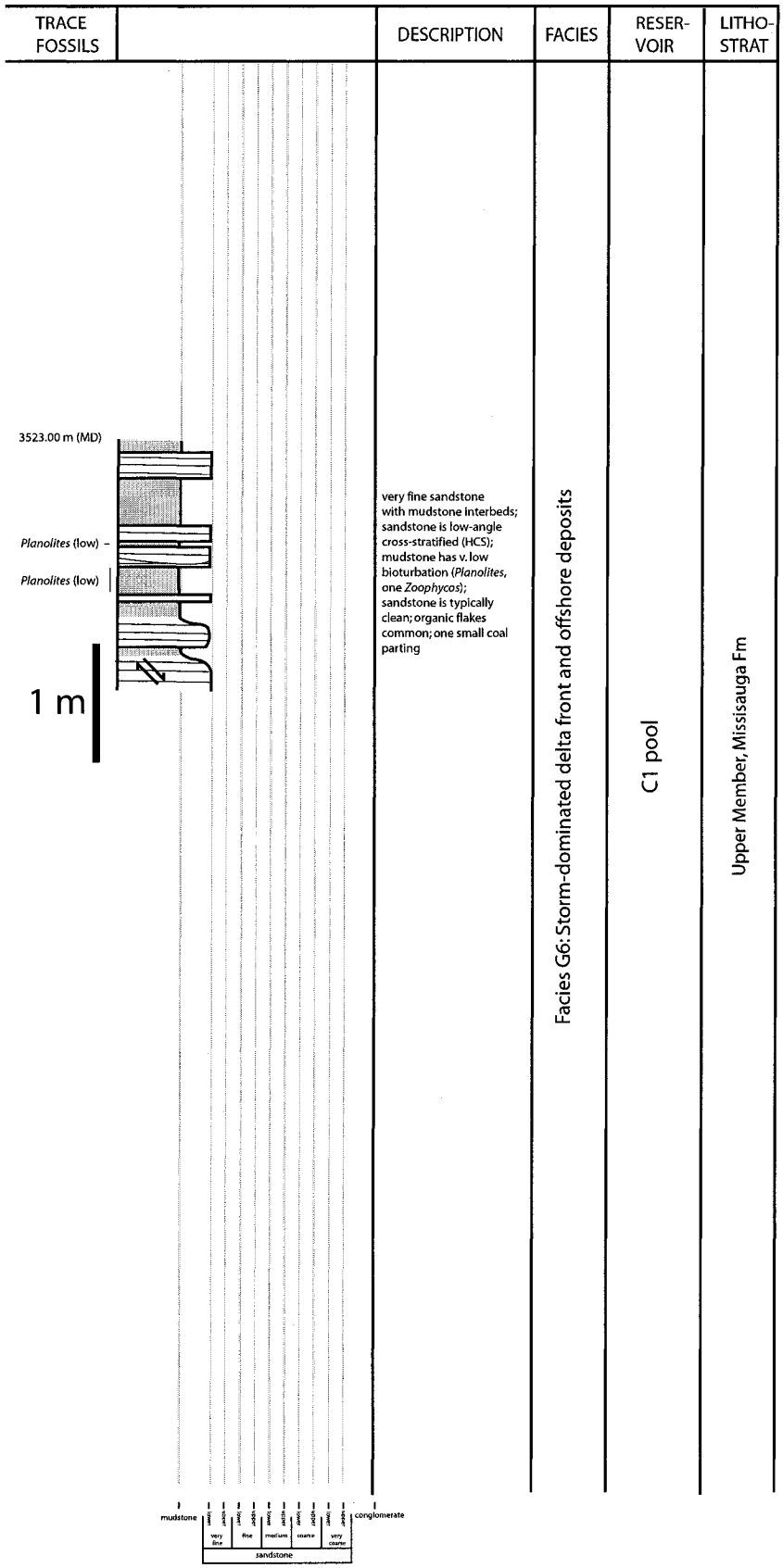
INTERPRETATION--> "amphibole-look" mudstone forms as a result of rapid suspension fallout

The "amphibole-look" mudstone, which is present in Glenelg and Alma cores, is an enigmatic facies; what causes the horizontal streaks? Several observations suggest that the "amphibole-look" (which is not well depicted in this photo) forms due to rapid suspension fallout. In this photo, "amphibole-look" mudstone gradationally overlies a wave-rippled storm event bed, suggesting that it was deposited from suspension following peak bedload transport as storm conditions waned. (Other supporting evidence includes lack of burrowing or fissility in the "amphibole-look" mudstone, and, in the Alma cores, rare association with dewatering (pillar) structures.)

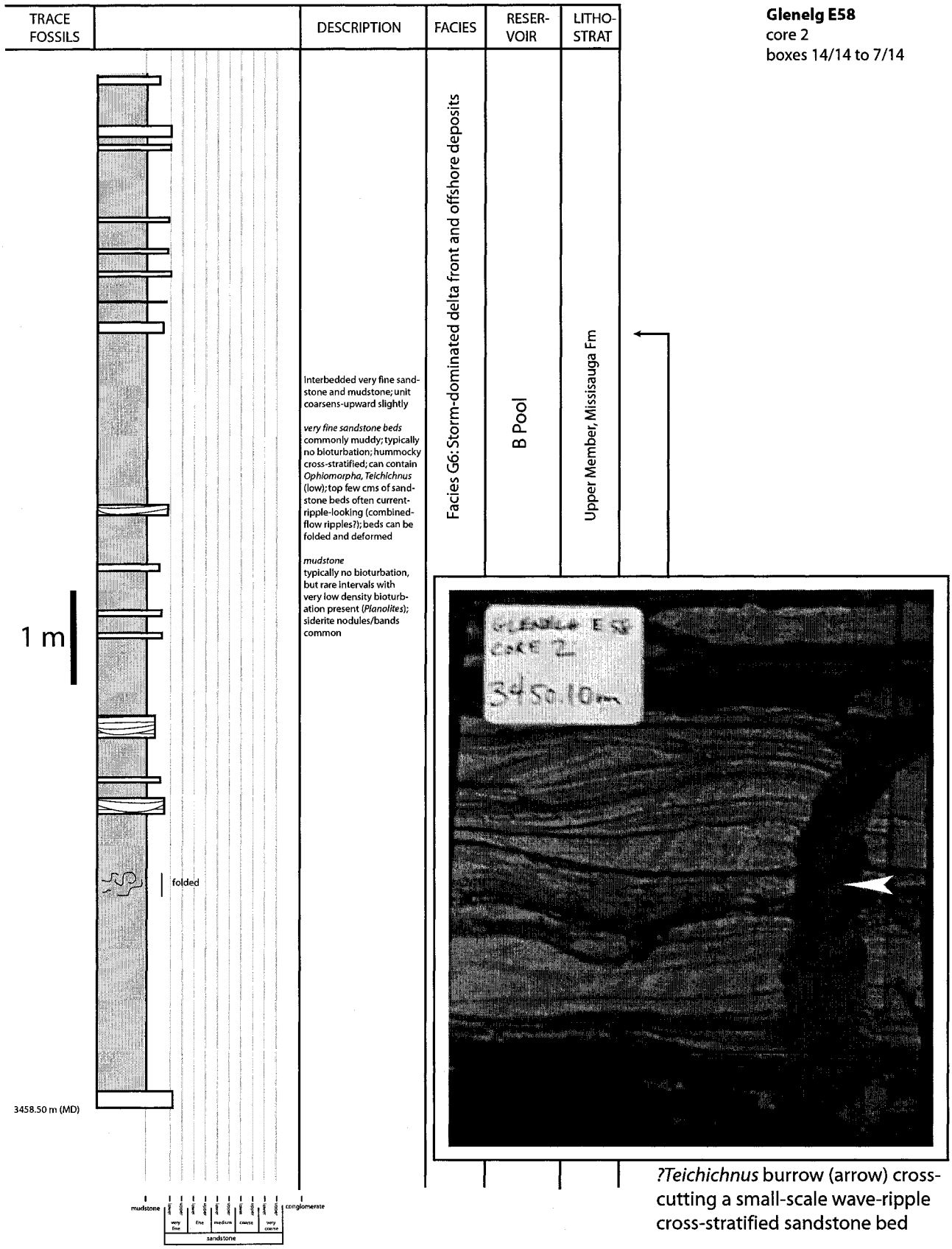
Glenelg E58
core 3
boxes 10/14 to 2/14



Glenelg E58
core 3
boxes 2/14 to 1/14

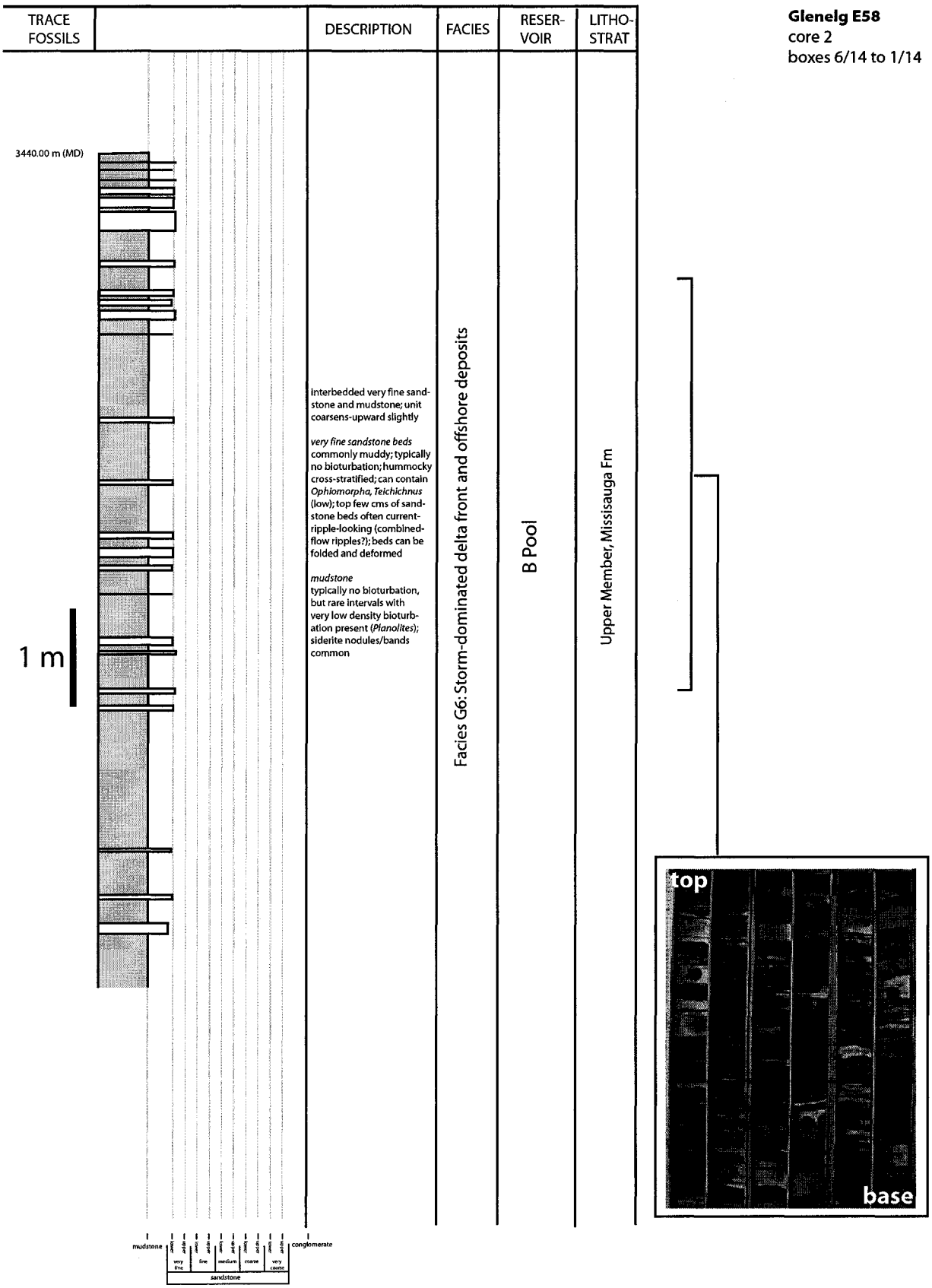


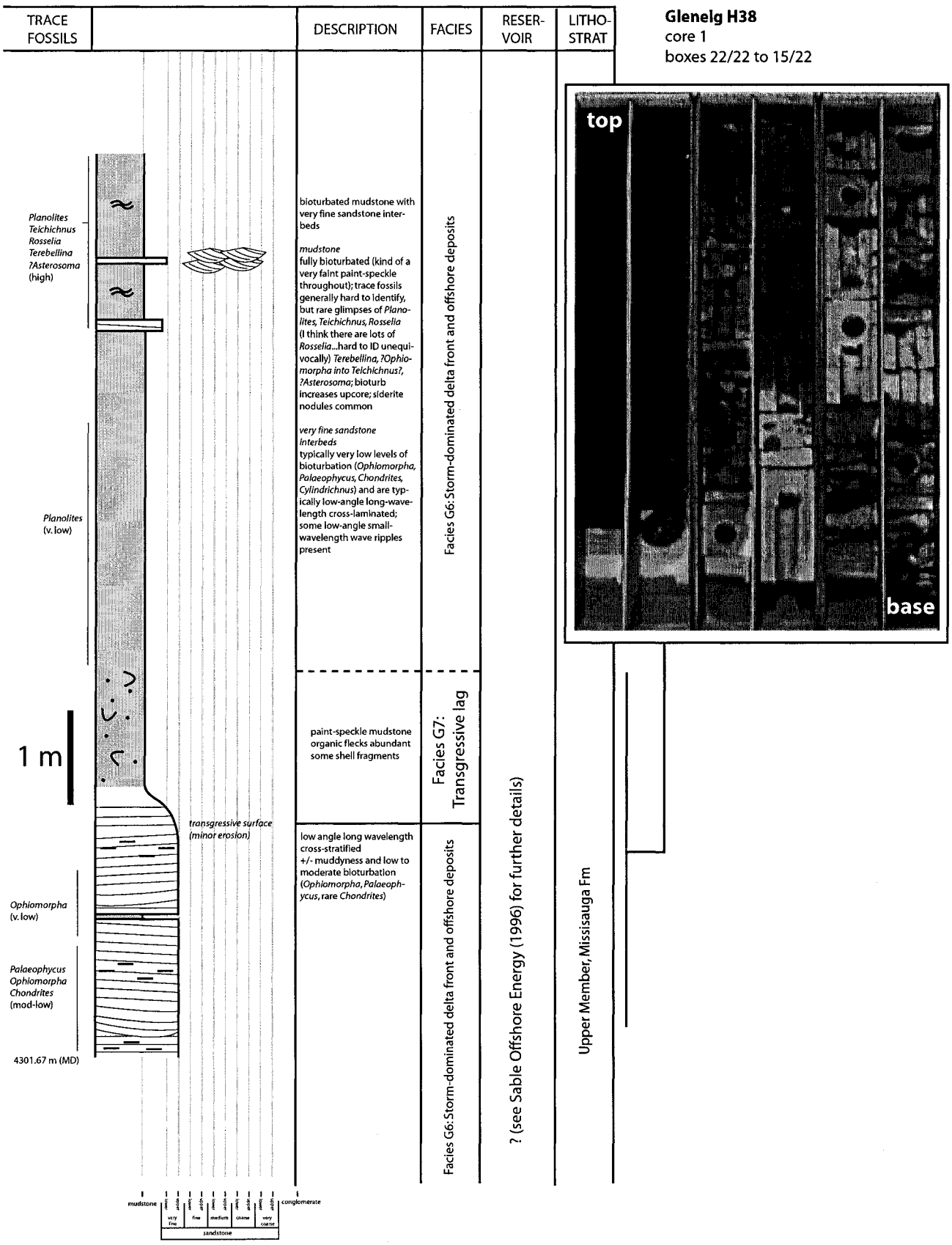
Glenelg E58
core 2
boxes 14/14 to 7/14



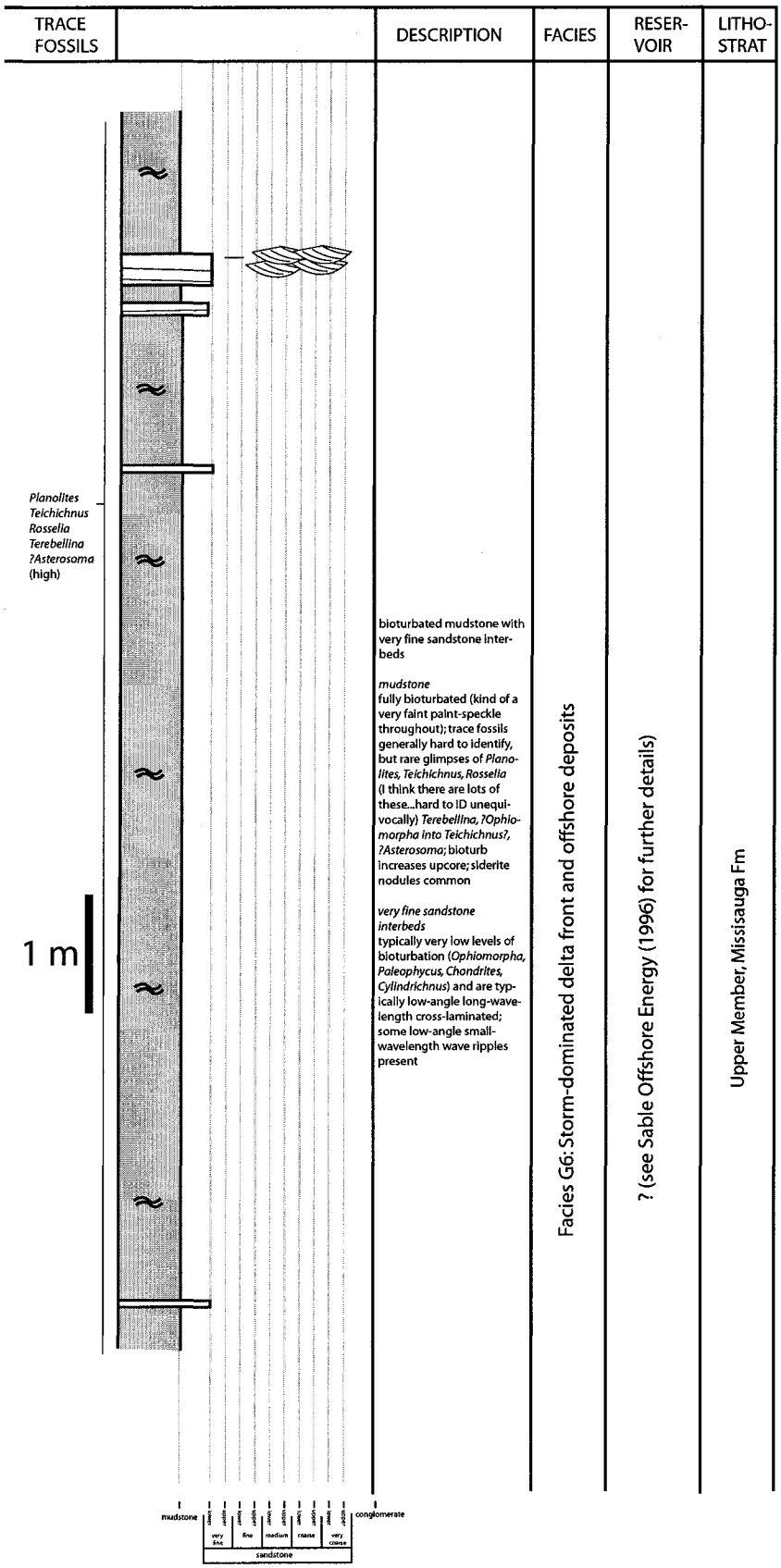
?Teichichnus burrow (arrow) cross-cutting a small-scale wave-ripple cross-stratified sandstone bed

Glenelg E58
core 2
boxes 6/14 to 1/14

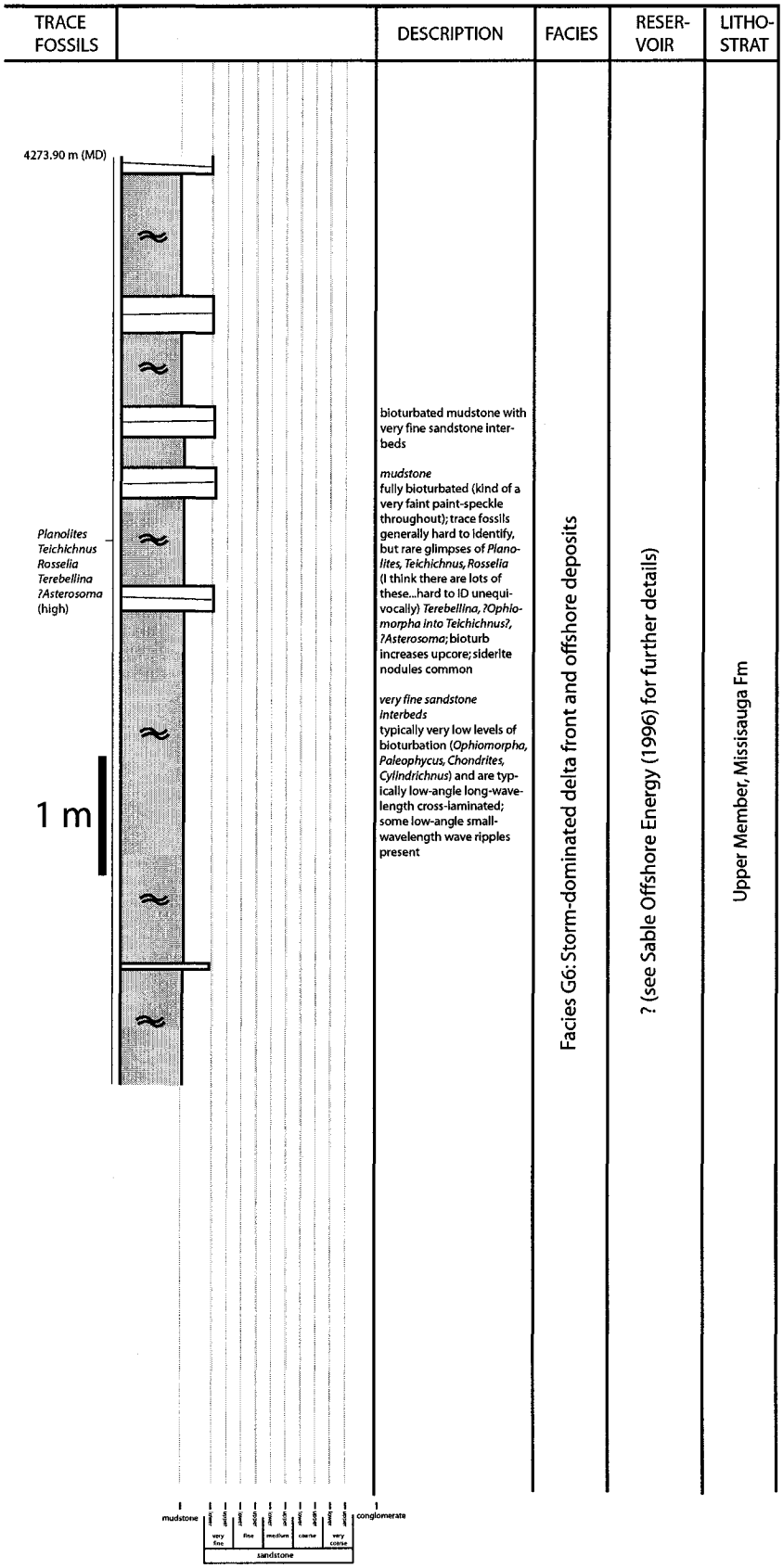



TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Glenelg H38
core 1
boxes 22/22 to 15/22
top
base
Planolites
Teichichnus
Rosselia
Terebellina
?Asterosoma
(high)
Planolites
(v. low)
1 m
transgressive surface
(minor erosion)
Ophiomorpha
(v. low)
Palaeophycus
Ophiomorpha
Chondrites
(mod-low)
4301.67 m (MD)
bioturbated mudstone with very fine sandstone interbeds
mudstone
fully bioturbated (kind of a very faint paint-speckle throughout); trace fossils generally hard to identify, but rare glimpses of Planolites, Teichichnus, Rosselia (I think there are lots of Rosselia...hard to ID unequivocally) Terebellina, ?Ophiomorpha into Telchichnus?, ?Asterosoma; bioturb increases upcore; siderite nodules common
very fine sandstone interbeds
typically very low levels of bioturbation (Ophiomorpha, Palaeophycus, Chondrites, Cylindrichnus) and are typically low-angle long-wavelength cross-laminated; some low-angle small-wavelength wave ripples present
Facies G6: Storm-dominated delta front and offshore deposits
paint-speckle mudstone
organic flecks abundant
some shell fragments
Facies G7: Transgressive lag
low angle long wavelength cross-stratified
+/- muddyness and low to moderate bioturbation (Ophiomorpha, Palaeophycus, rare Chondrites)
Facies G6: Storm-dominated delta front and offshore deposits
? (see Sable Offshore Energy (1996) for further details)
Upper Member, Missisauga Fm
mudstone
conglomerate
very fine
fine
medium
coarse
very coarse
sandstone

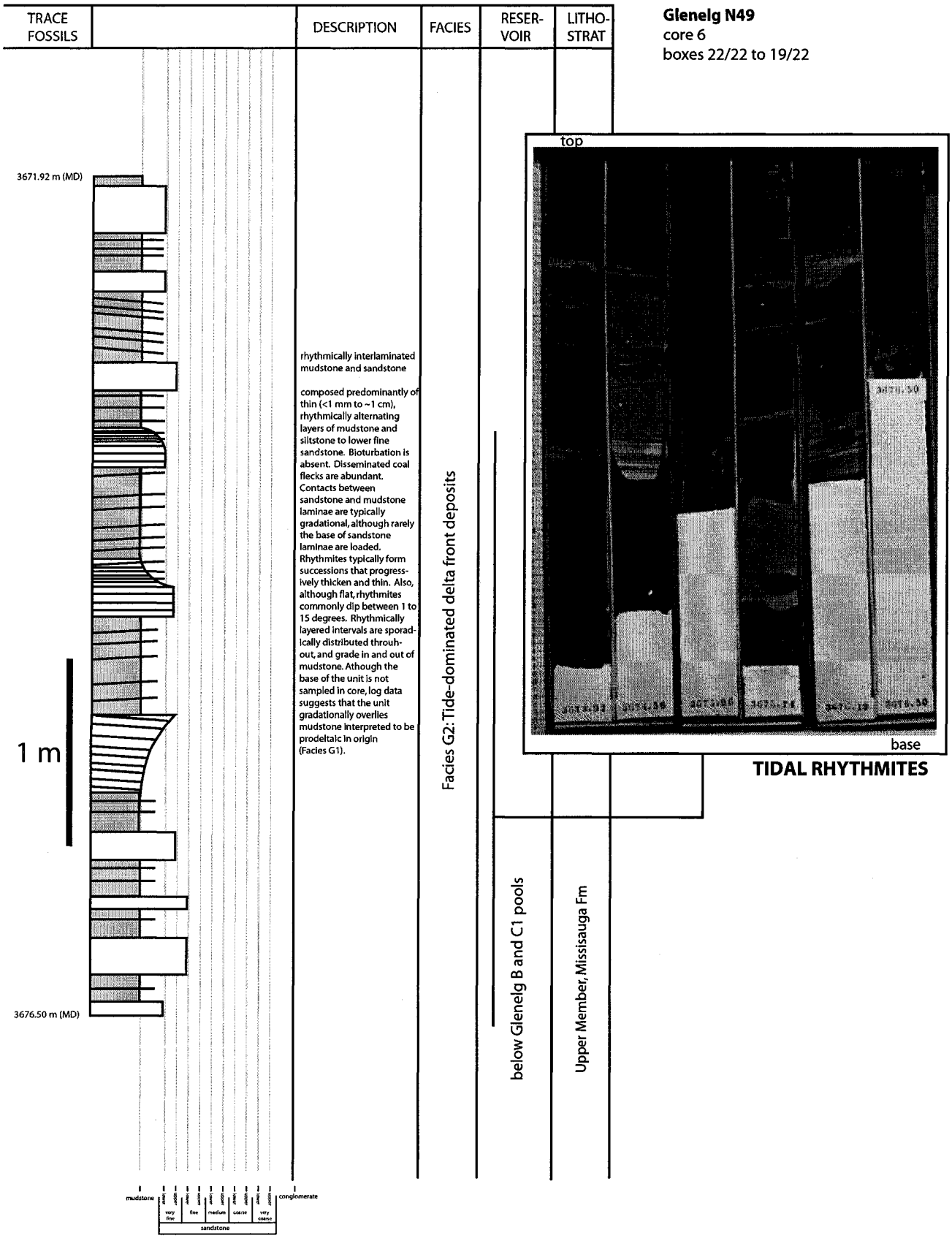
Glenelg H38
core 1
boxes 14/22 to 7/22



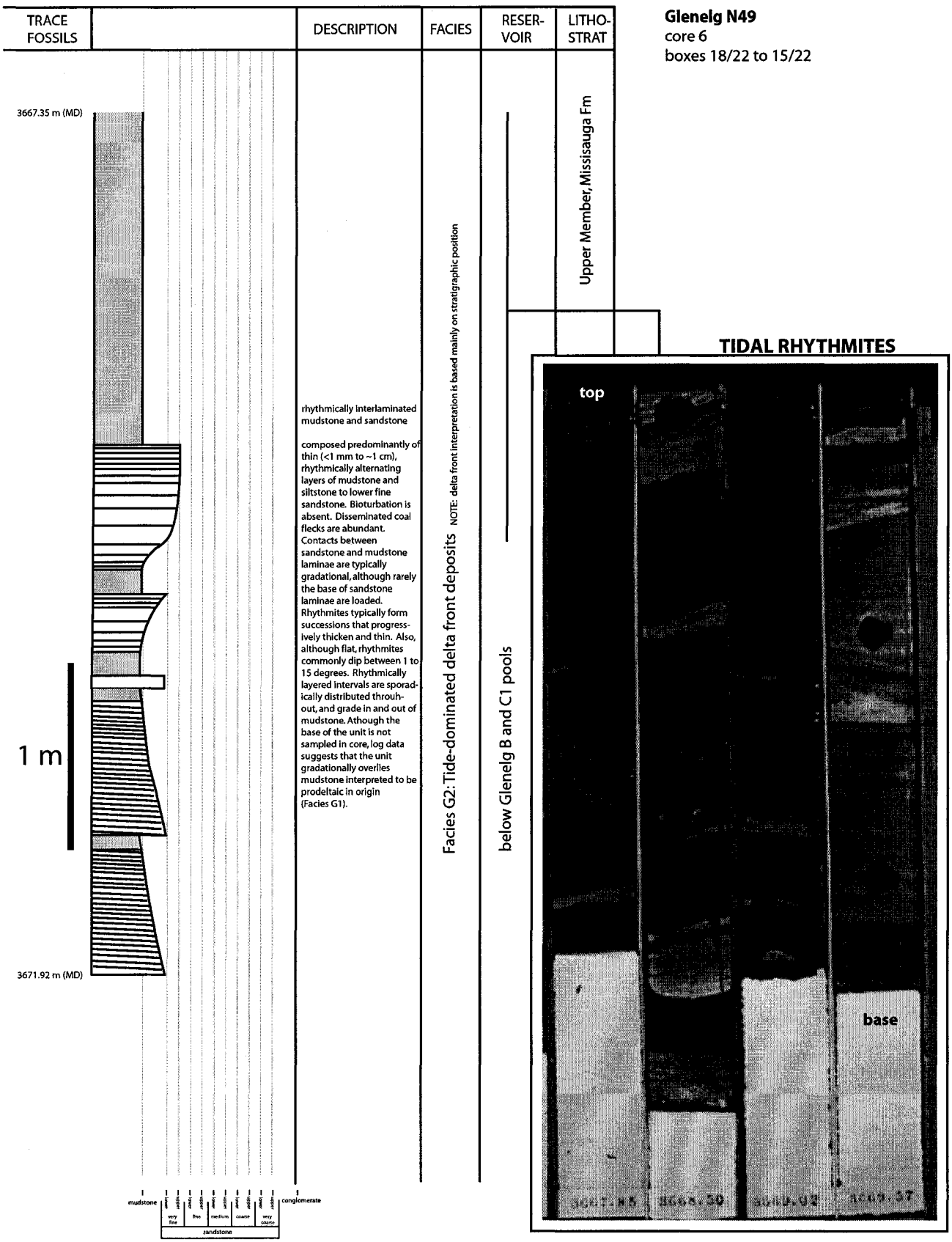
Glenelg H38
core 1
boxes 6/22 to 1/22

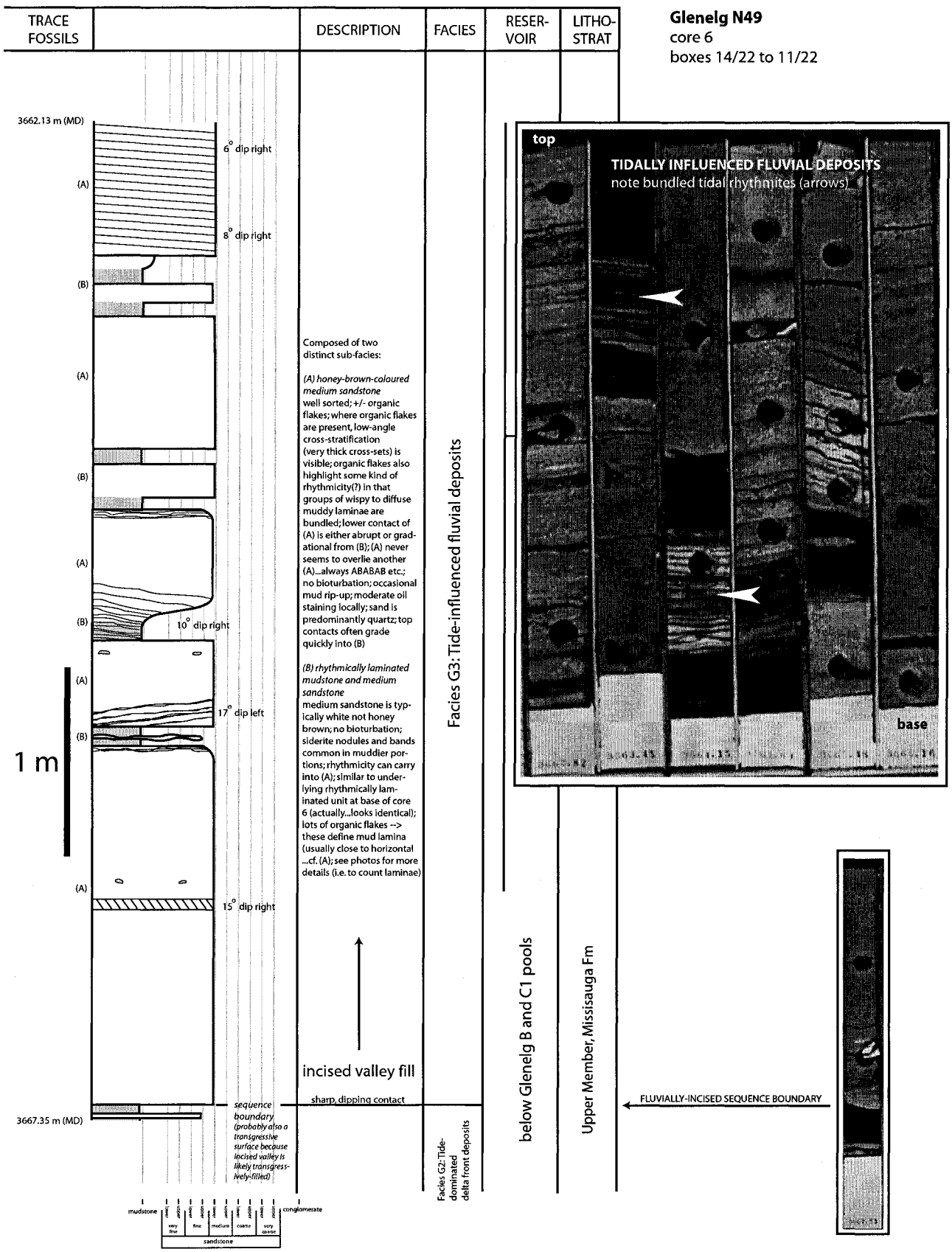


Glenelg N49
core 6
boxes 22/22 to 19/22

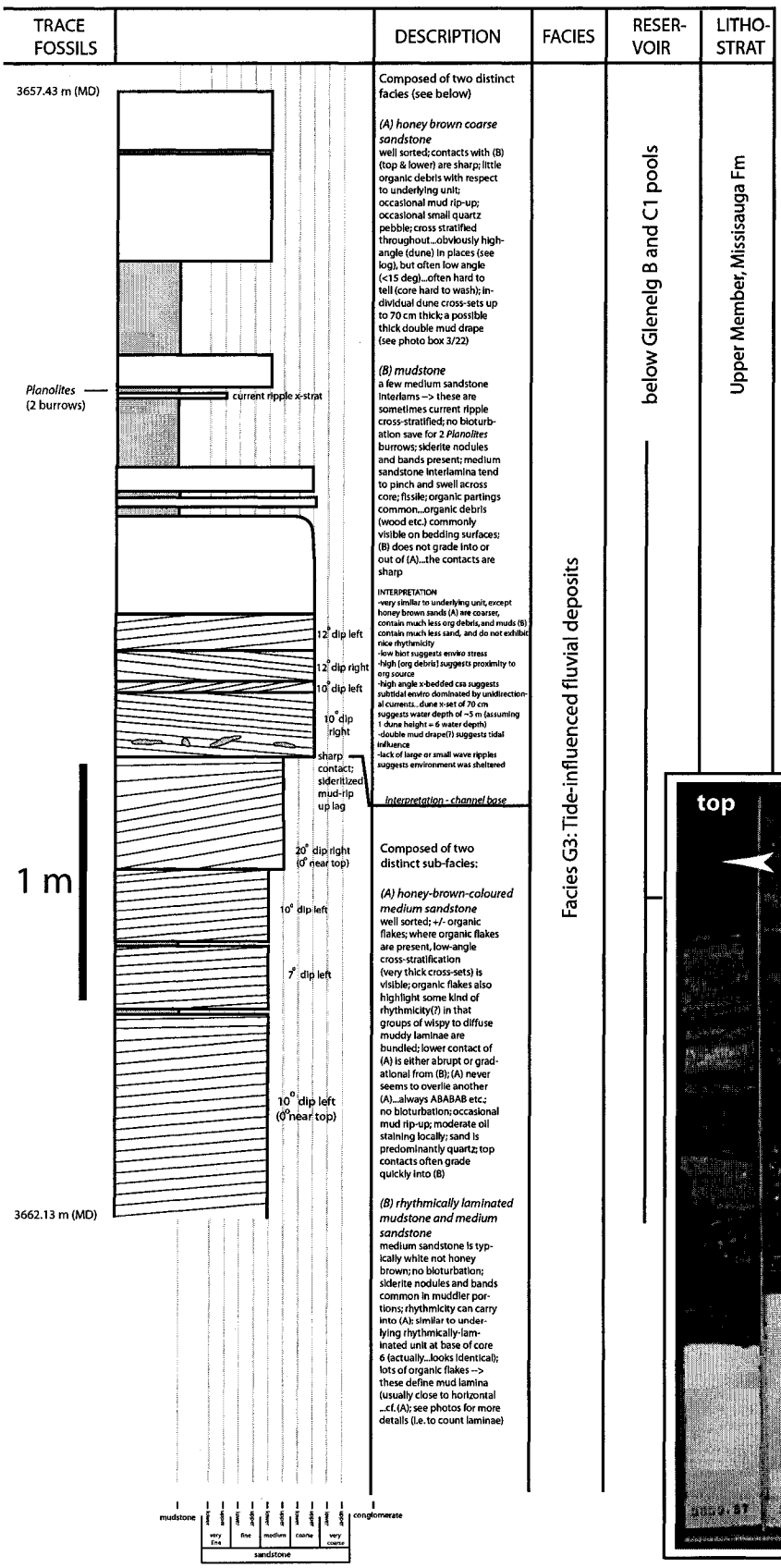


Glenelg N49
core 6
boxes 18/22 to 15/22

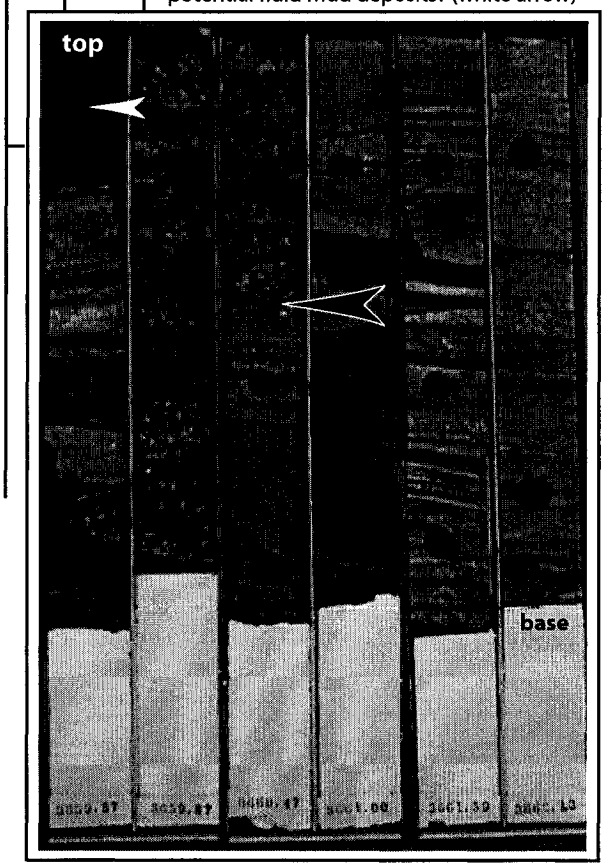


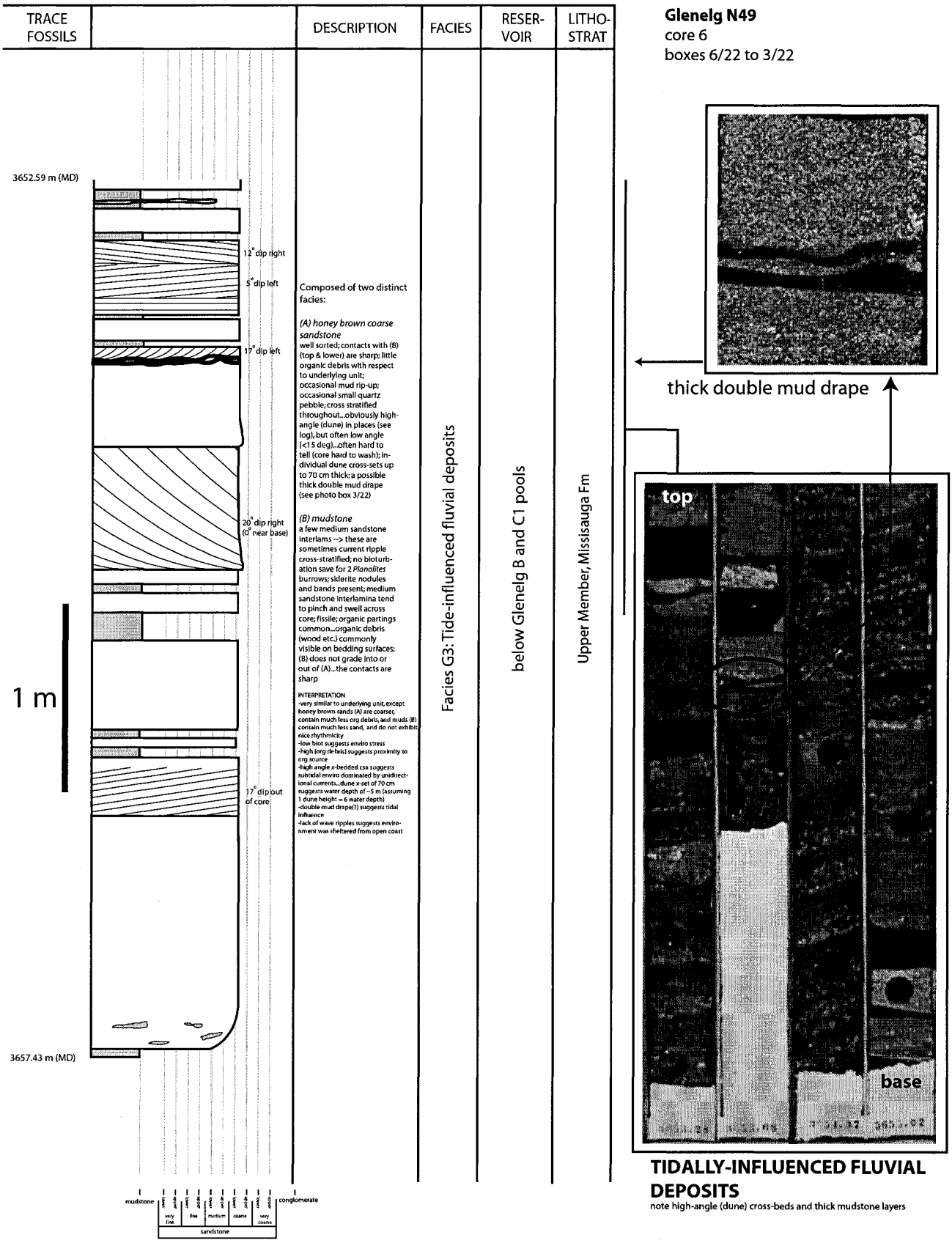

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Glenelg N49
core 6
boxes 14/22 to 11/22
3662.13 m (MD)
6° dip right
8° dip right
10° dip right
17° dip left
15° dip right
(A)
(B)
1 m
3667.35 m (MD)
Composed of two distinct sub-facies:
(A) honey-brown-coloured medium sandstone
well sorted; +/- organic flakes; where organic flakes are present, low-angle cross-stratification (very thick cross-sets) is visible; organic flakes also highlight some kind of rhythmicity(?) in that groups of wispy to diffuse muddy laminae are bundled; lower contact of (A) is either abrupt or gradational from (B); (A) never seems to overlie another (A)...always ABABAB etc.; no bioturbation; occasional mud rip-up; moderate oil staining locally; sand is predominantly quartz; top contacts often grade quickly into (B)
(B) rhythmically laminated mudstone and medium sandstone
medium sandstone is typically white not honey brown; no bioturbation; siderite nodules and bands common in muddier portions; rhythmicity can carry into (A); similar to underlying rhythmically laminated unit at base of core 6 (actually...looks identical); lots of organic flakes --> these define mud lamina (usually close to horizontal ...cf. (A); see photos for more details (i.e. to count laminae)
incised valley fill
sharp, dipping contact
sequence boundary (probably also a transgressive surface because incised valley is likely transgressively-filled)
Facies G3: Tide-influenced fluvial deposits
Facies G2: Tide-dominated delta front deposits
top
TIDALLY INFLUENCED FLUVIAL DEPOSITS
note bundled tidal rhythmites (arrows)
base
below Glenelg B and C1 pools
Upper Member, Missisauga Fm
FLUVIALLY-INCISED SEQUENCE BOUNDARY
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone

Glenelg N49
core 6
boxes 10/22 to 7/22



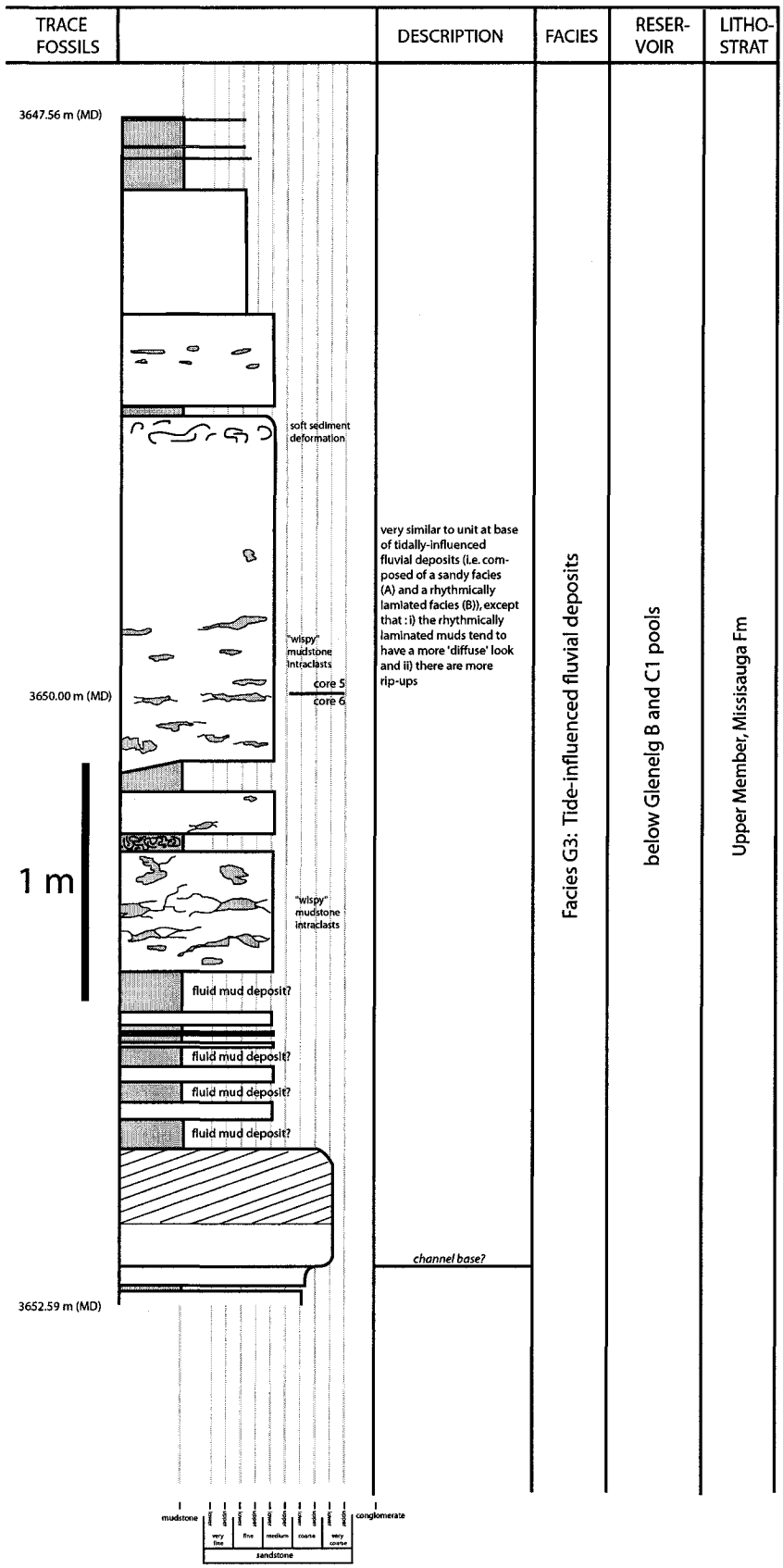
TIDALLY-INFLUENCED FLUVIAL DEPOSITS
interpreted channel base (black arrow)
potential fluid mud deposits? (white arrow)



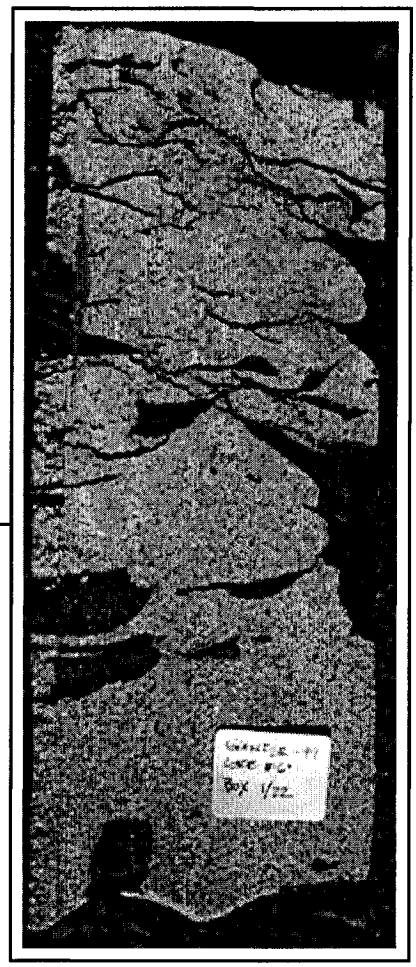


TIDALLY-INFLUENCED FLUVIAL DEPOSITS

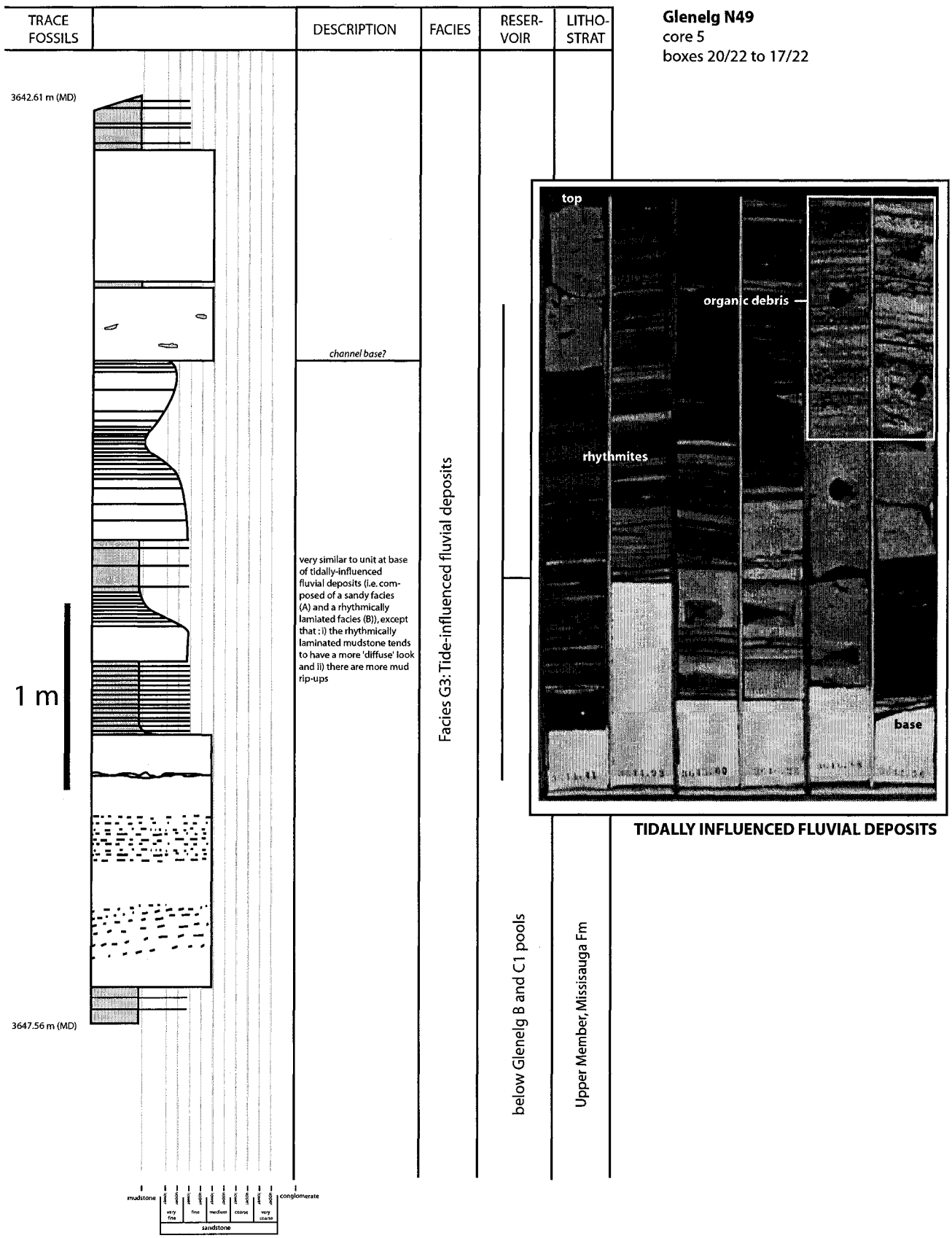
note high-angle (dune) cross-beds and thick mudstone layers



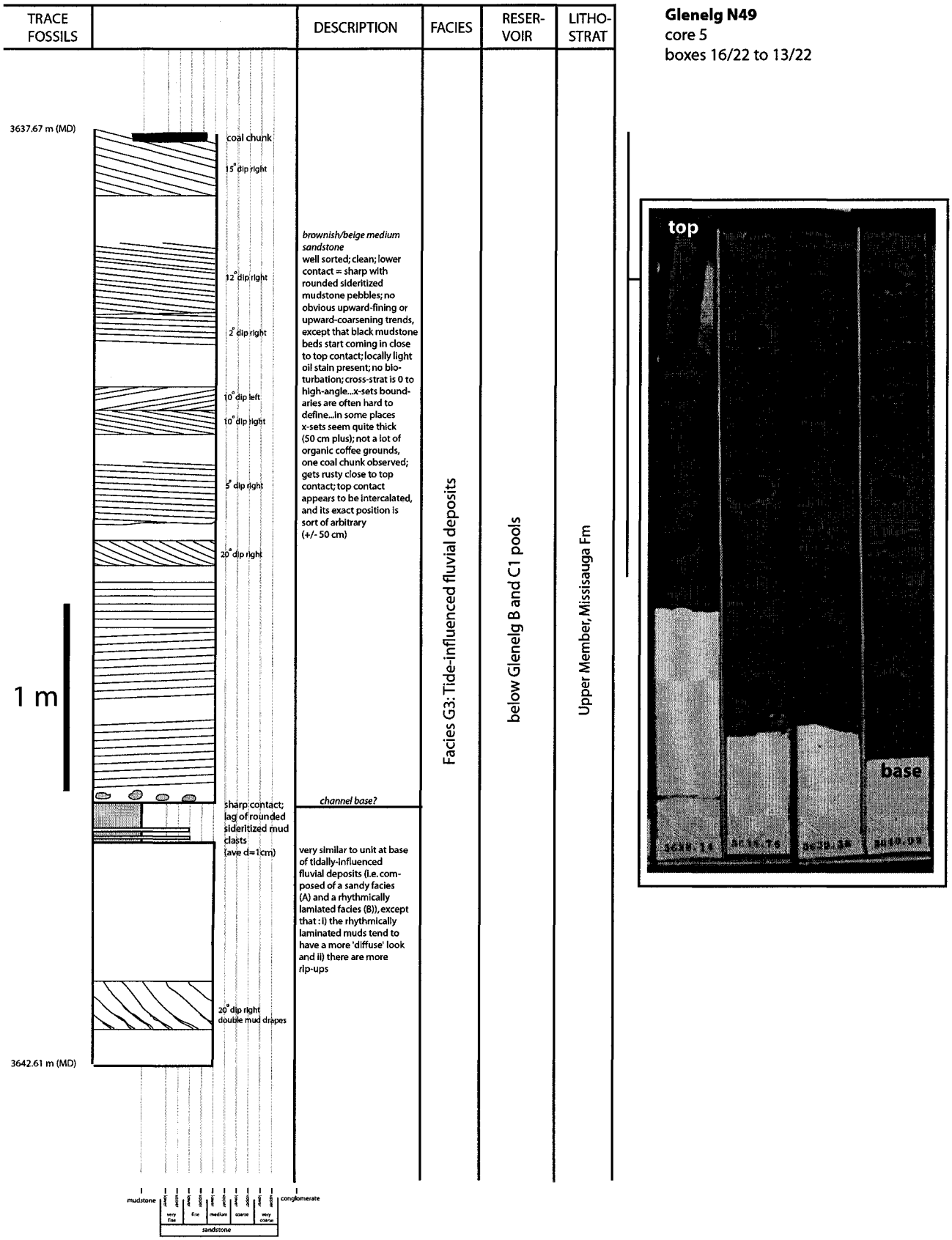
Glenelg N49
core 6, box 2/22 to
core 5, box 21/22



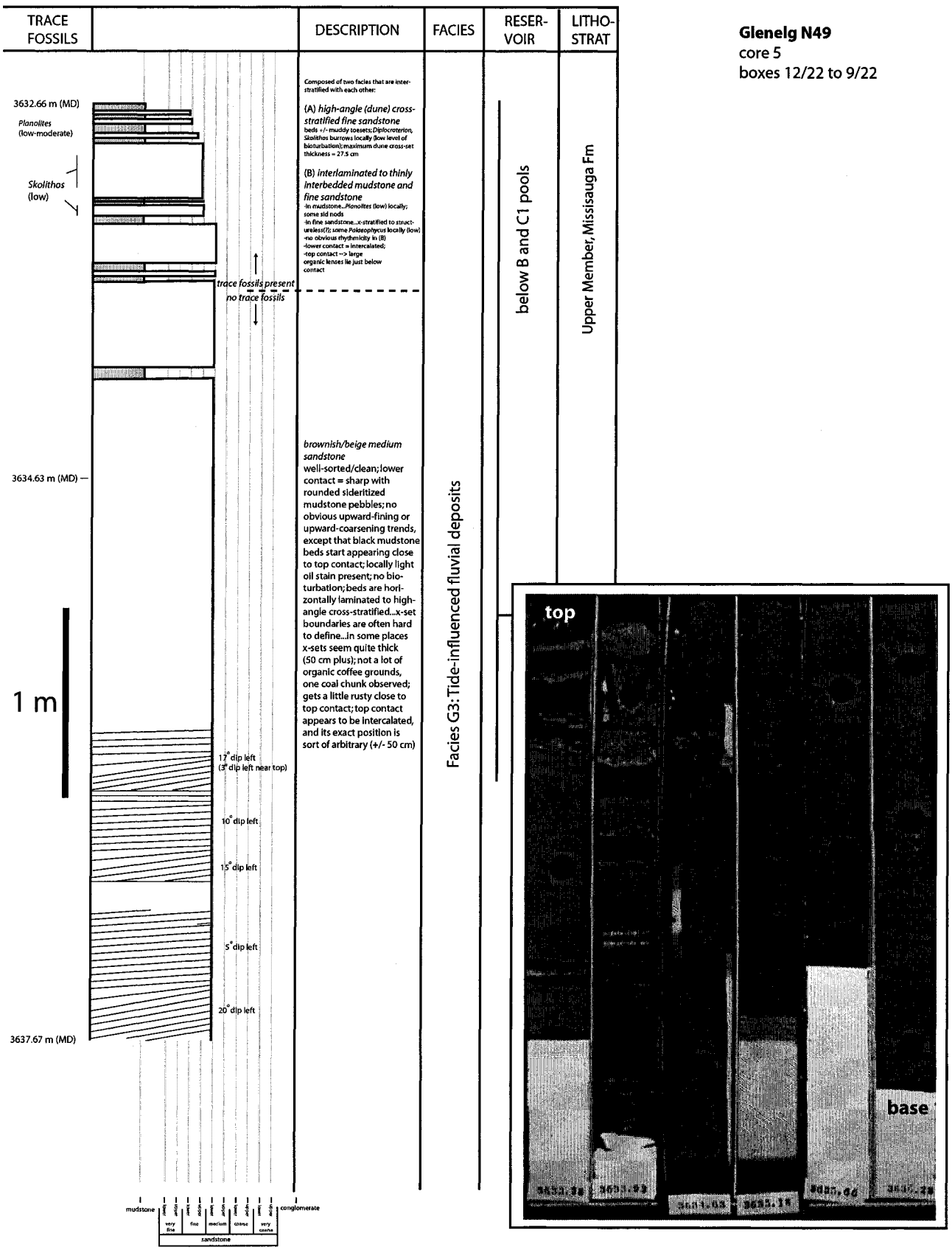
"WISPY" ANGULAR MUDSTONE INTRACLASTS
(interpretation --> channel bank failure deposits)

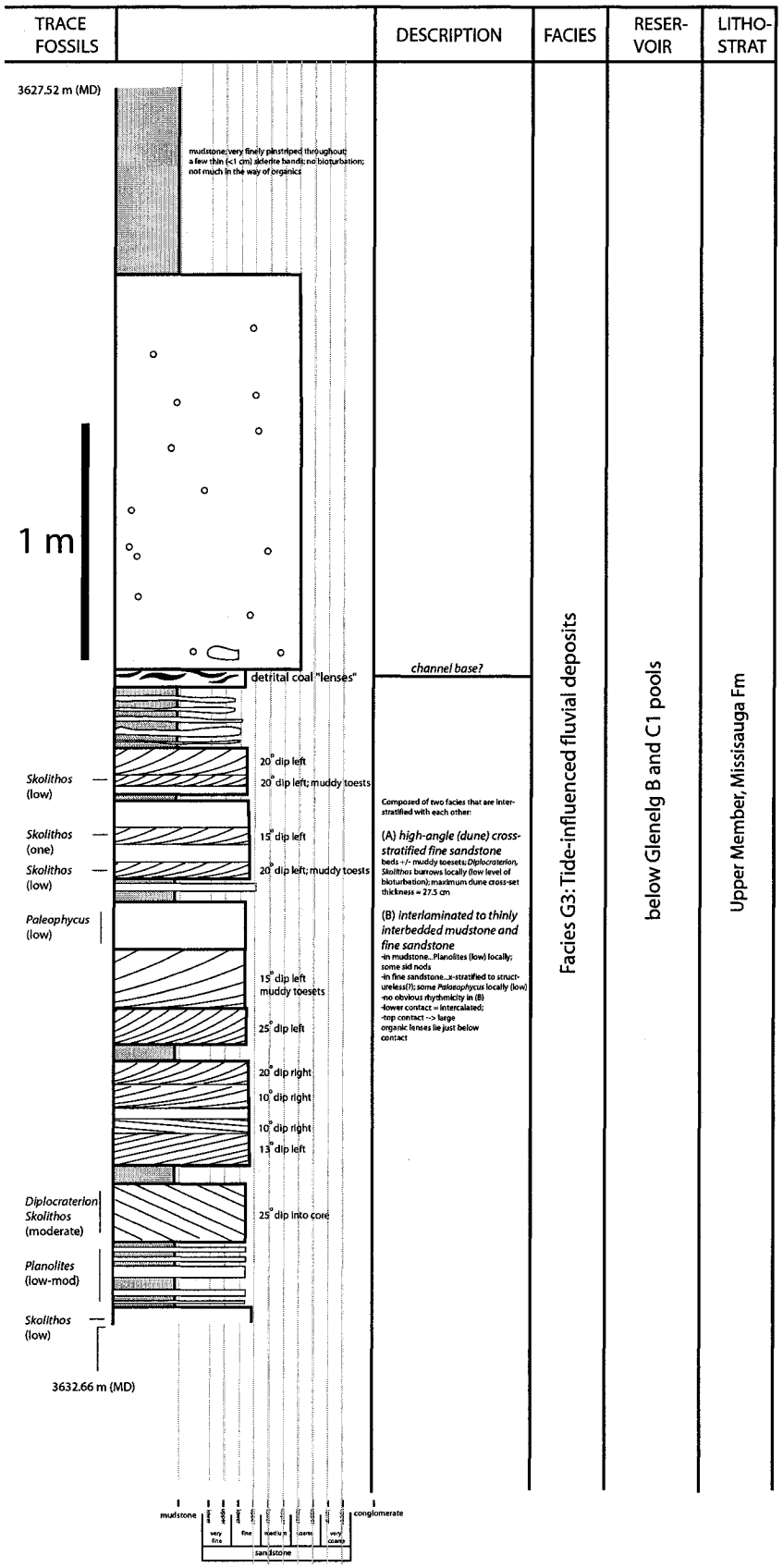

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Glenelg N49
core 5
boxes 20/22 to 17/22
3642.61 m (MD)
channel base?
very similar to unit at base of tidally-influenced fluvial deposits (i.e. composed of a sandy facies (A) and a rhythmically lamiated facies (B)), except that : i) the rhythmically laminated mudstone tends to have a more 'diffuse' look and ii) there are more mud rip-ups
1 m
3647.56 m (MD)
Facies G3: Tide-influenced fluvial deposits
top
organic debris
rhythmites
base
TIDALLY INFLUENCED FLUVIAL DEPOSITS
below Glenelg B and C1 pools
Upper Member, Missisauga Fm
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone

Glenelg N49
core 5
boxes 16/22 to 13/22

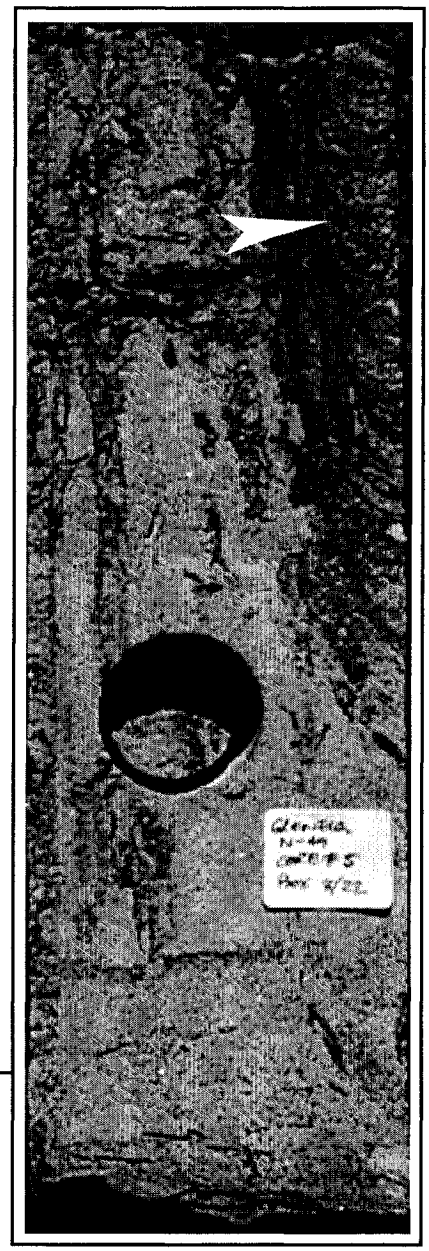


Glenelg N49
core 5
boxes 12/22 to 9/22

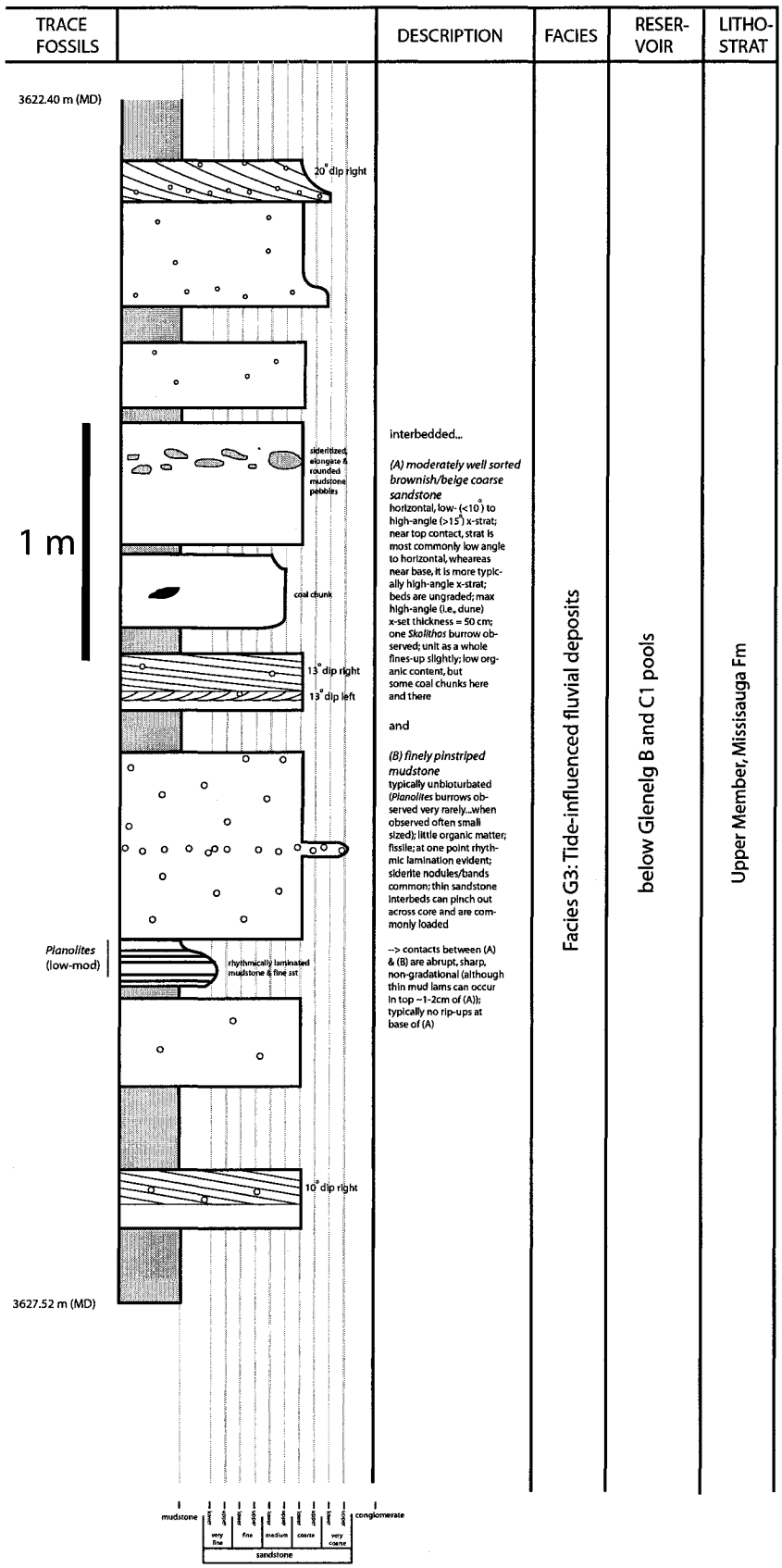




Glenelg N49
core 5
boxes 8/22 to 5/22



large *Diplocraterion* burrow (arrow)

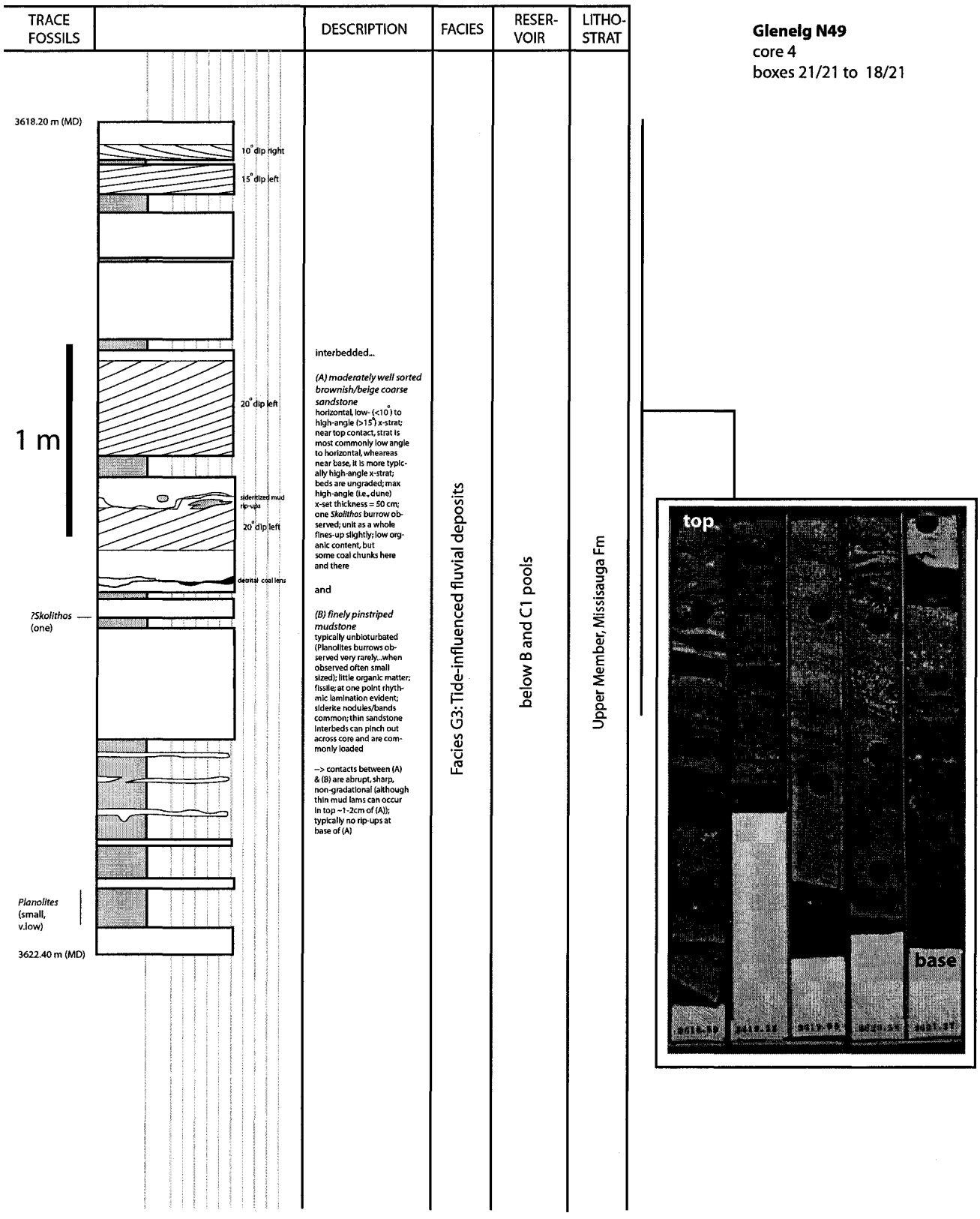


Glenelg N49
core 5
boxes 4/22 to 1/22

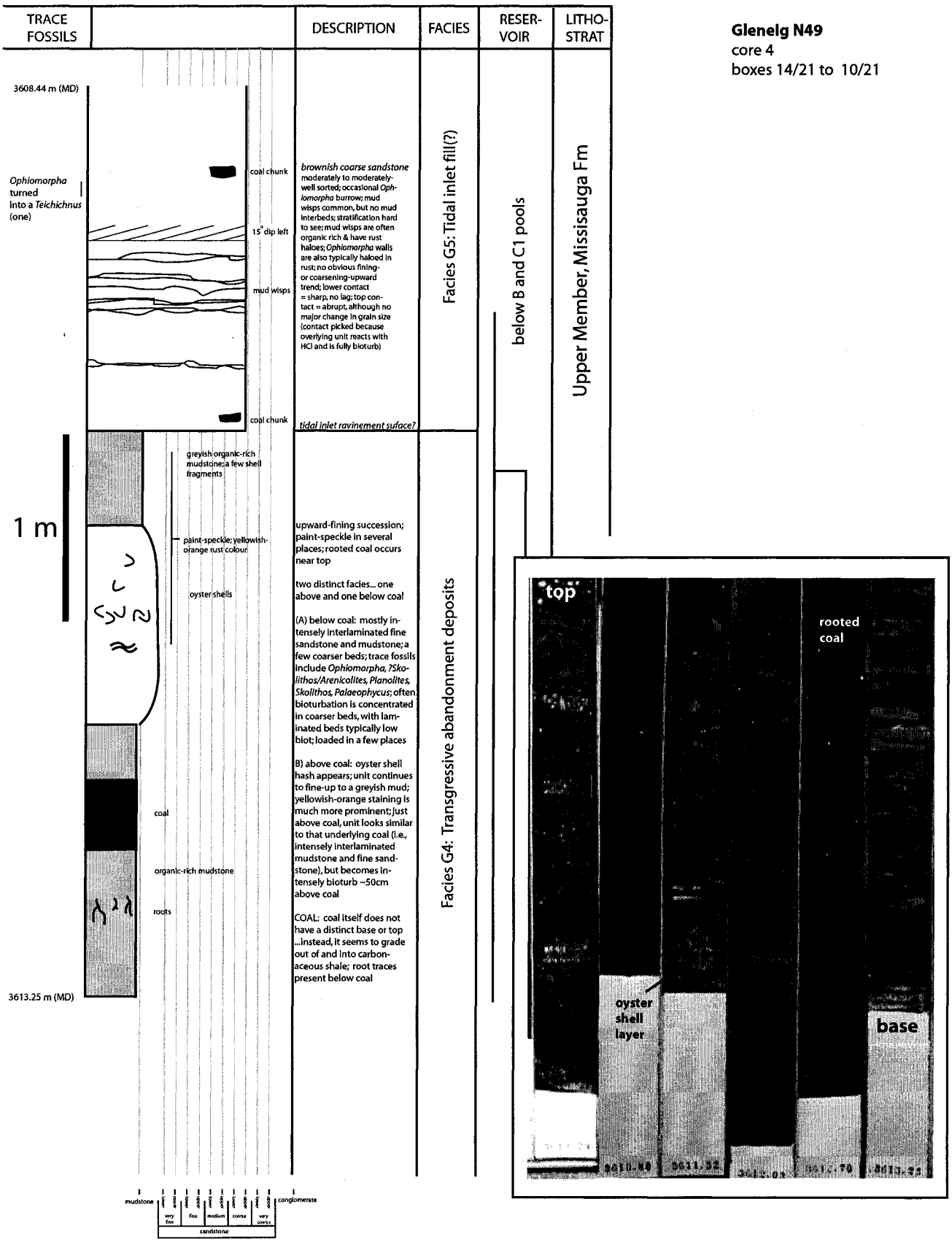


note large mudstone intraclasts (white arrow) and coal fragment (black arrow)

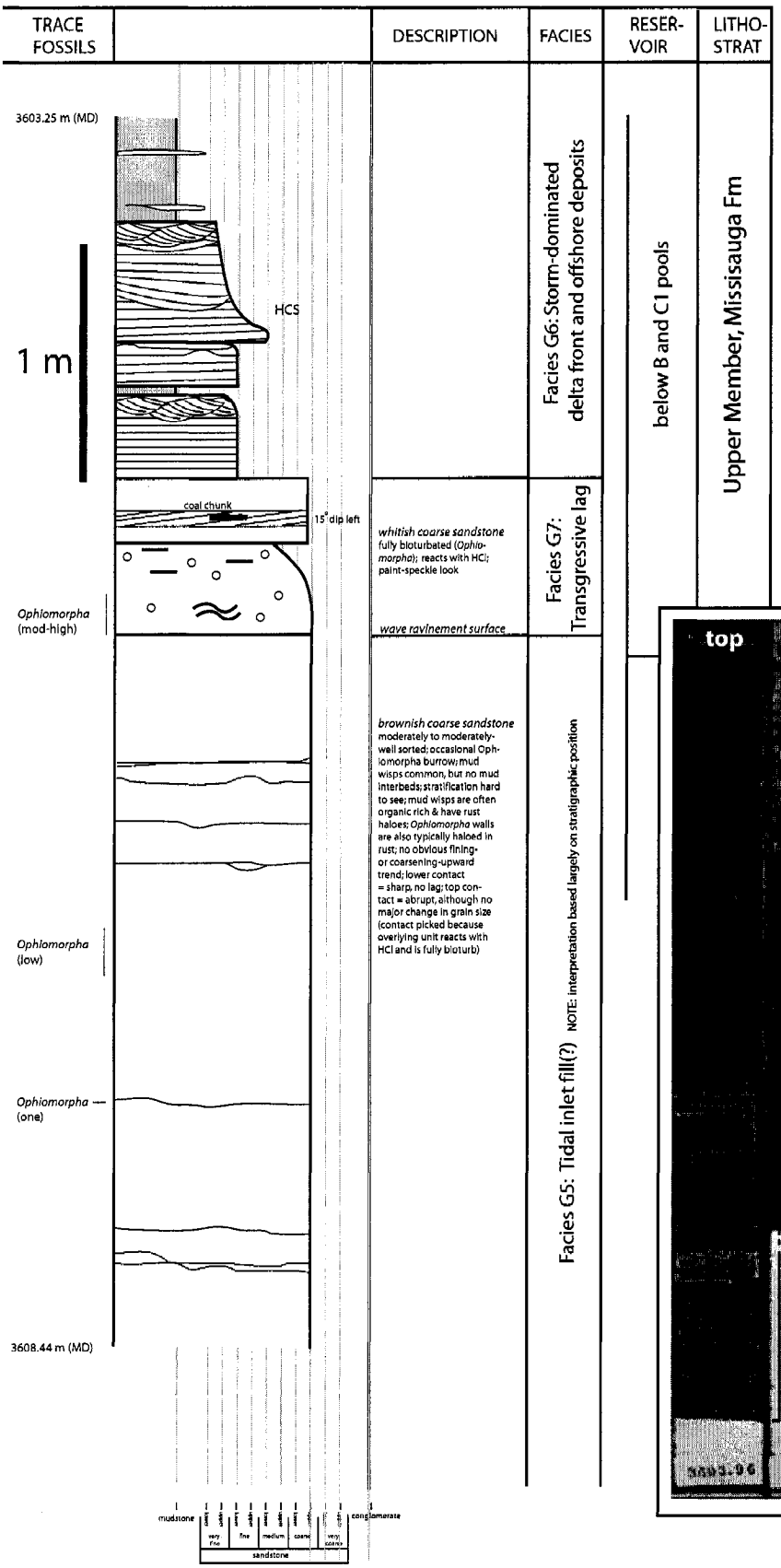
Glenelg N49
core 4
boxes 21/21 to 18/21

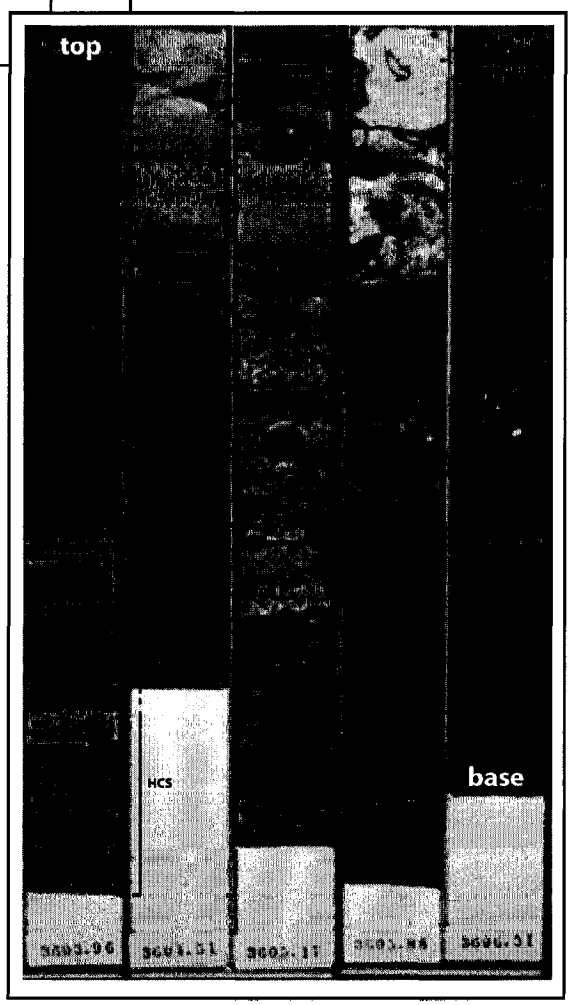


Glenelg N49
core 4
boxes 14/21 to 10/21

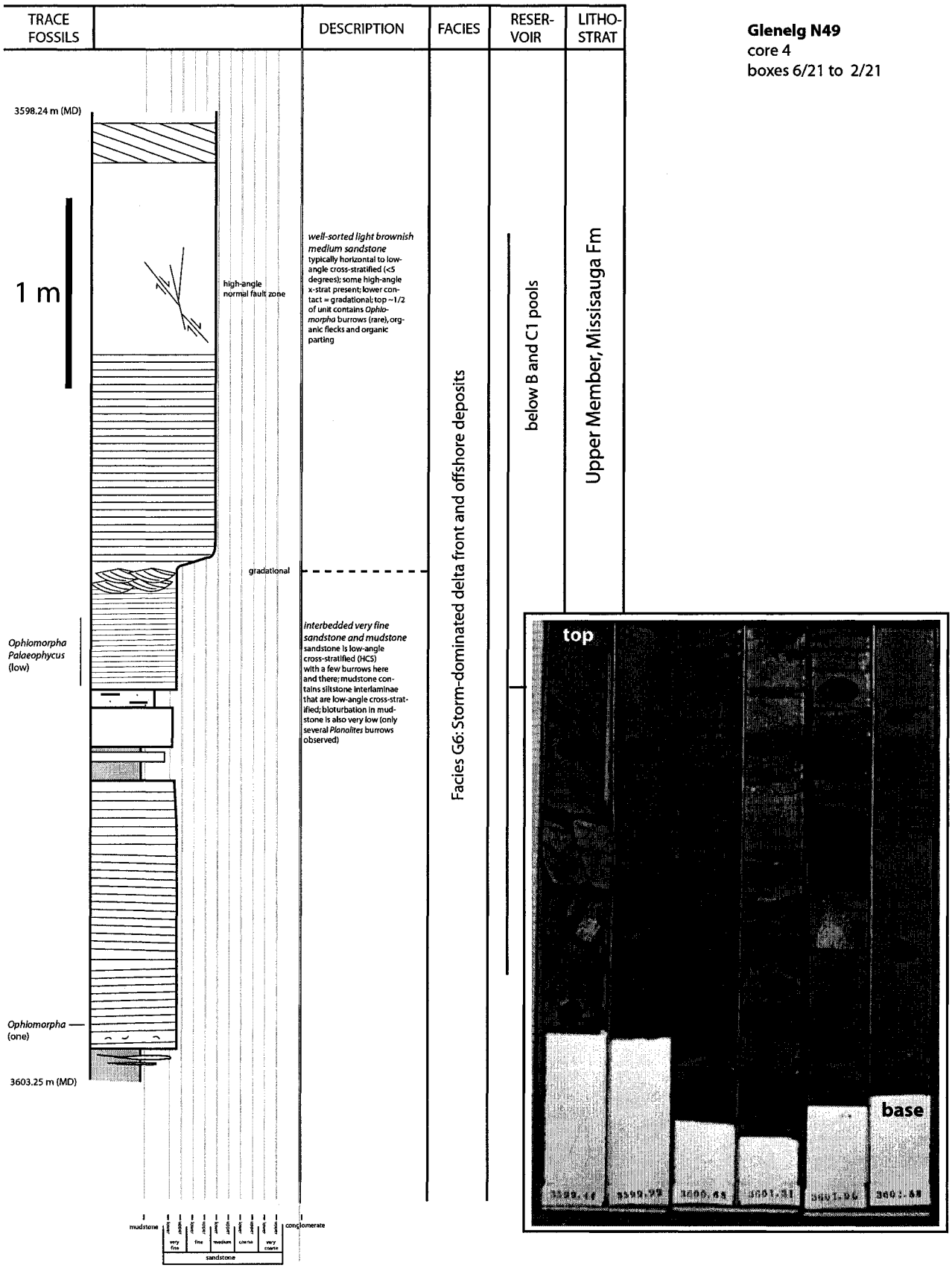


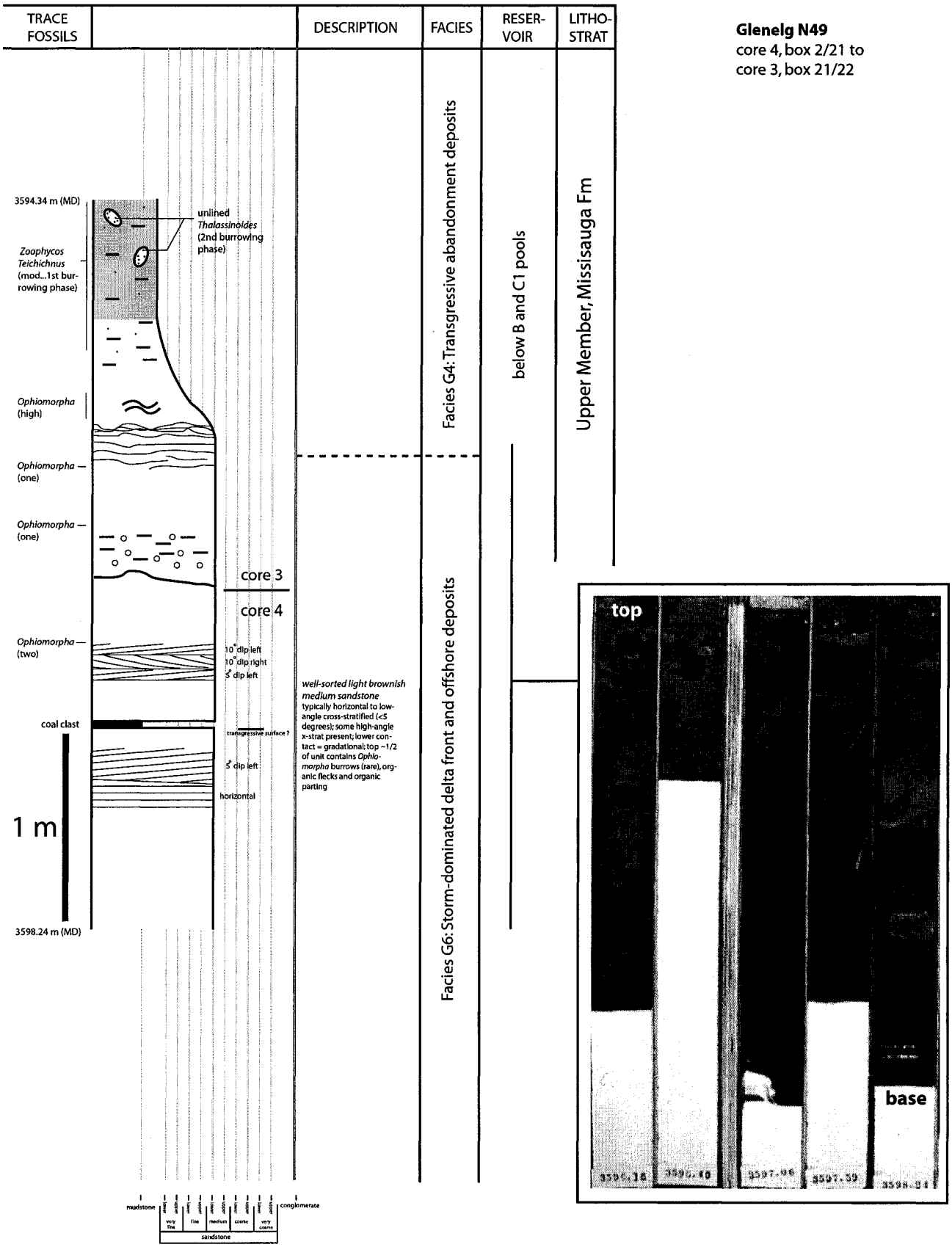
Glenelg N49
core 4
boxes 10/21 to 6/21



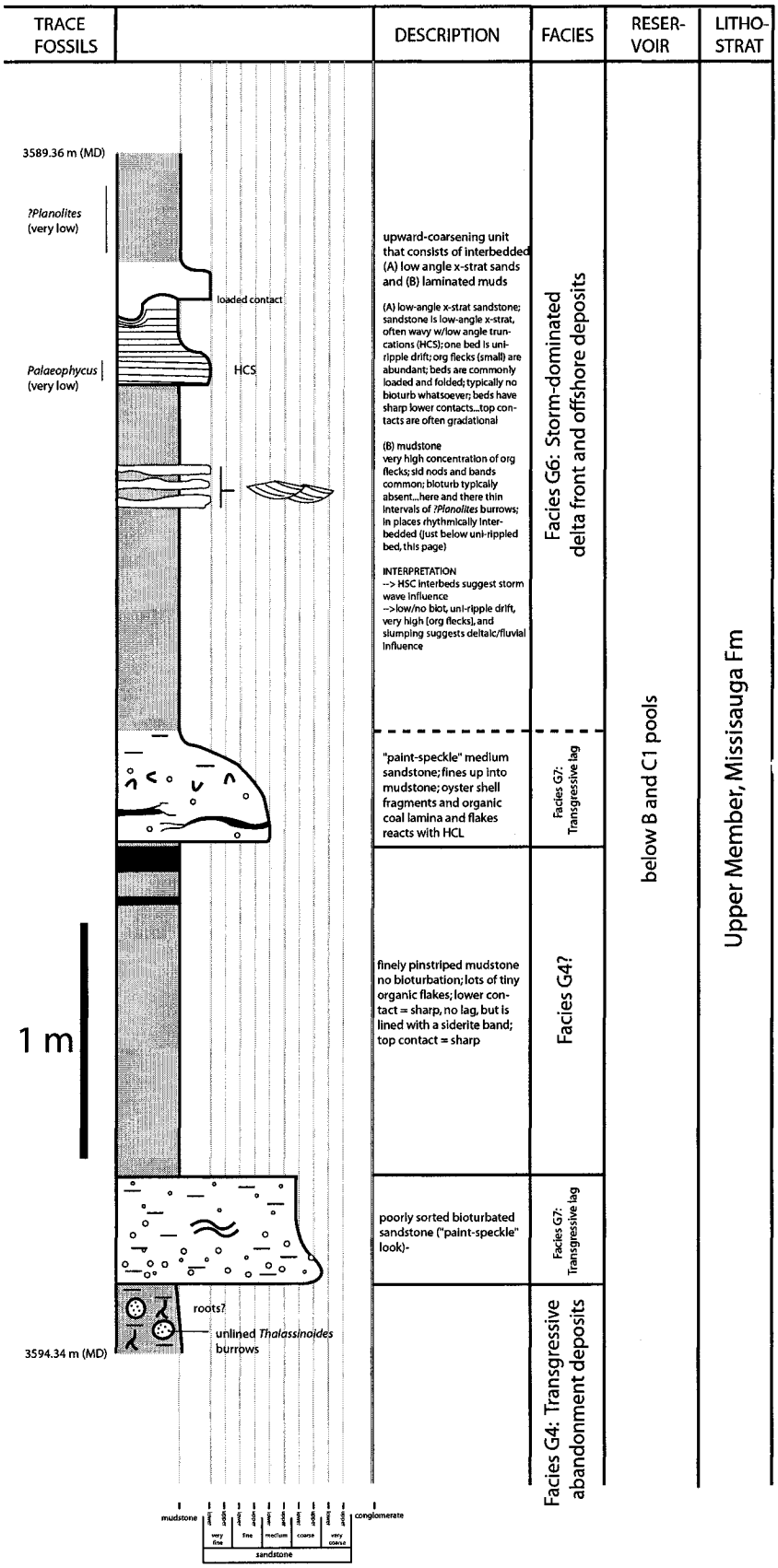


Glenelg N49
core 4
boxes 6/21 to 2/21





Glenelg N49
core 4, box 2/21 to
core 3, box 21/22

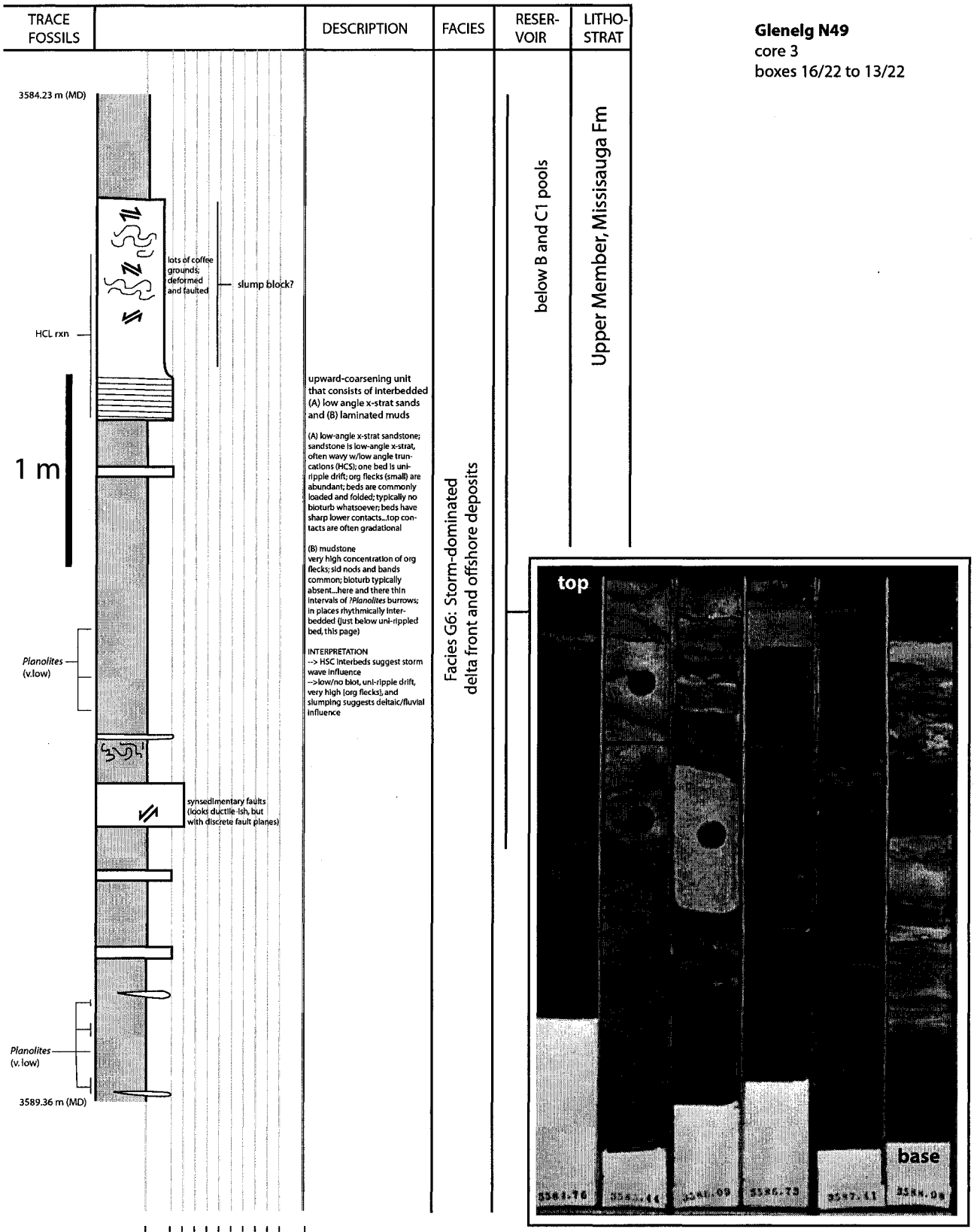


Glenelg N49
core 3
boxes 20/22 to 17/22

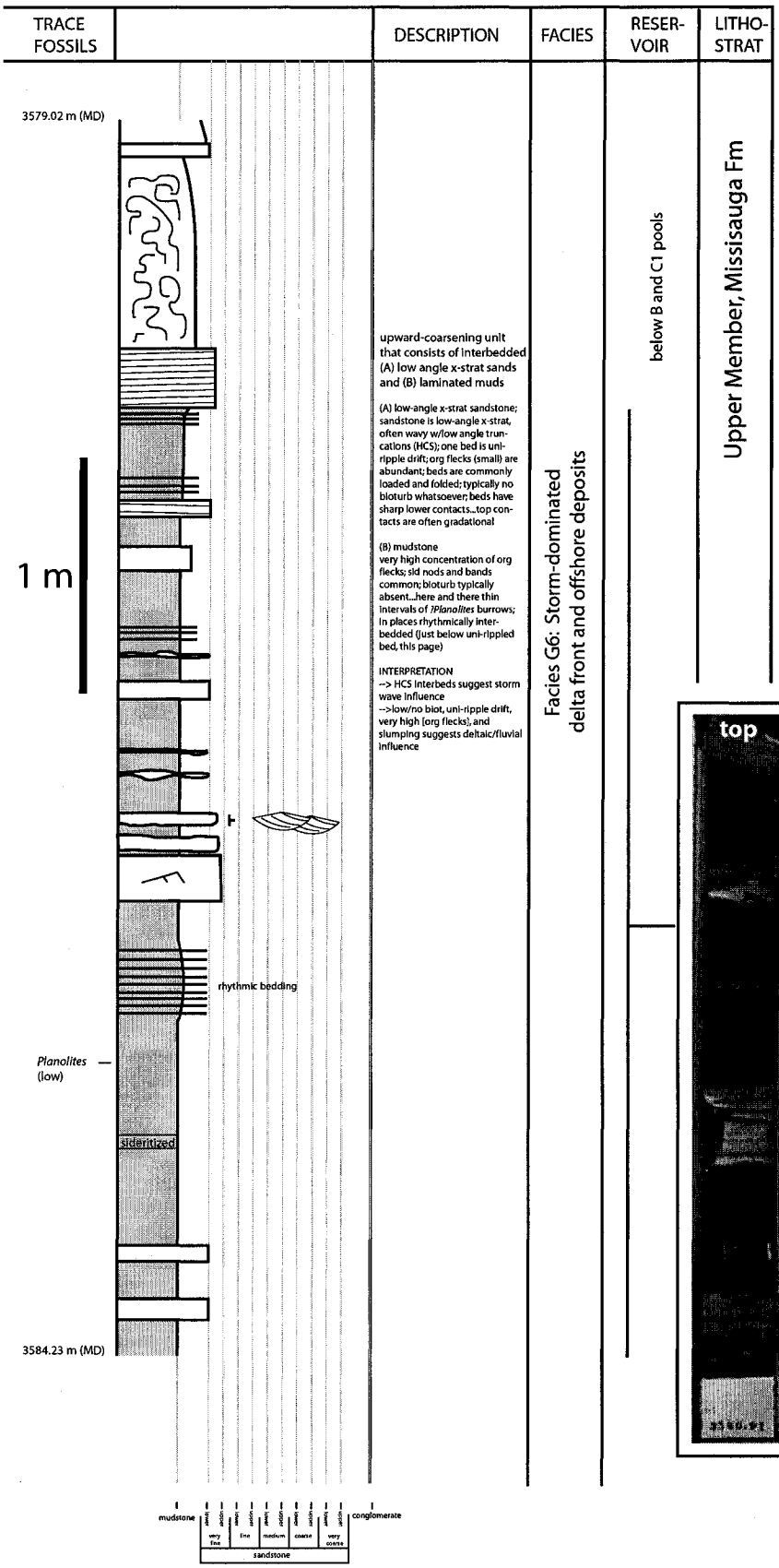


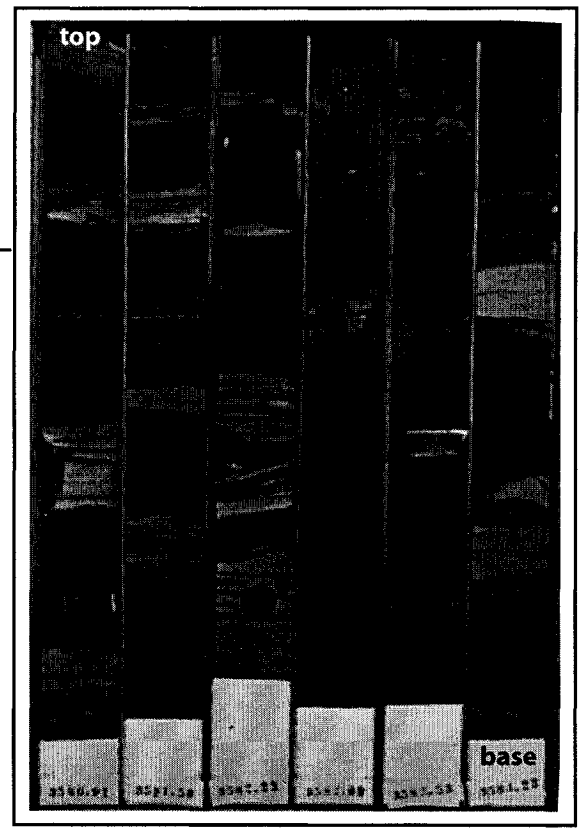
BURROWED FIRMGROUND SURFACE
note unlined *Thalassinoides* burrows (arrows)

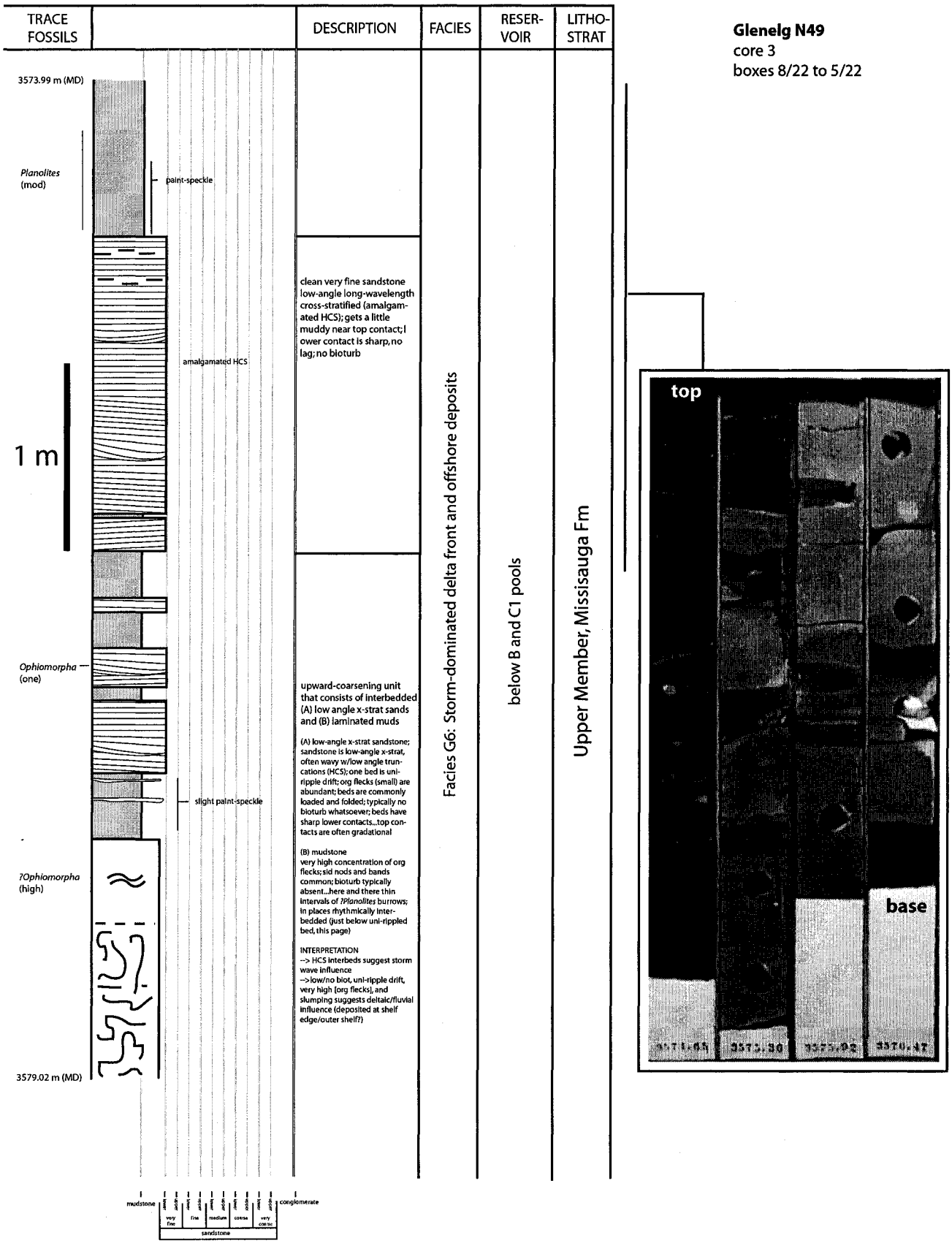
Glenelg N49
core 3
boxes 16/22 to 13/22



Glenelg N49
core 3
boxes 12/22 to 9/22

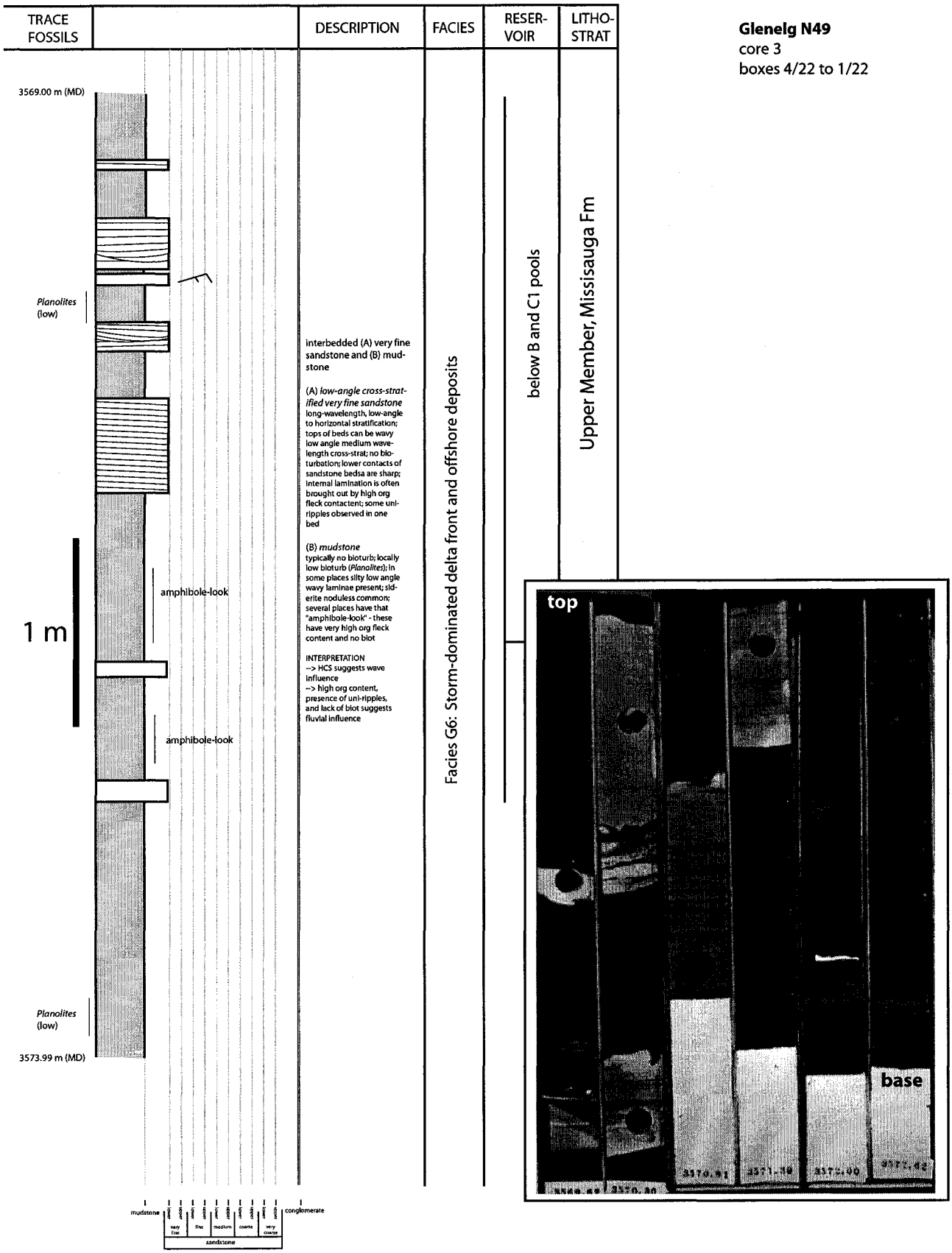


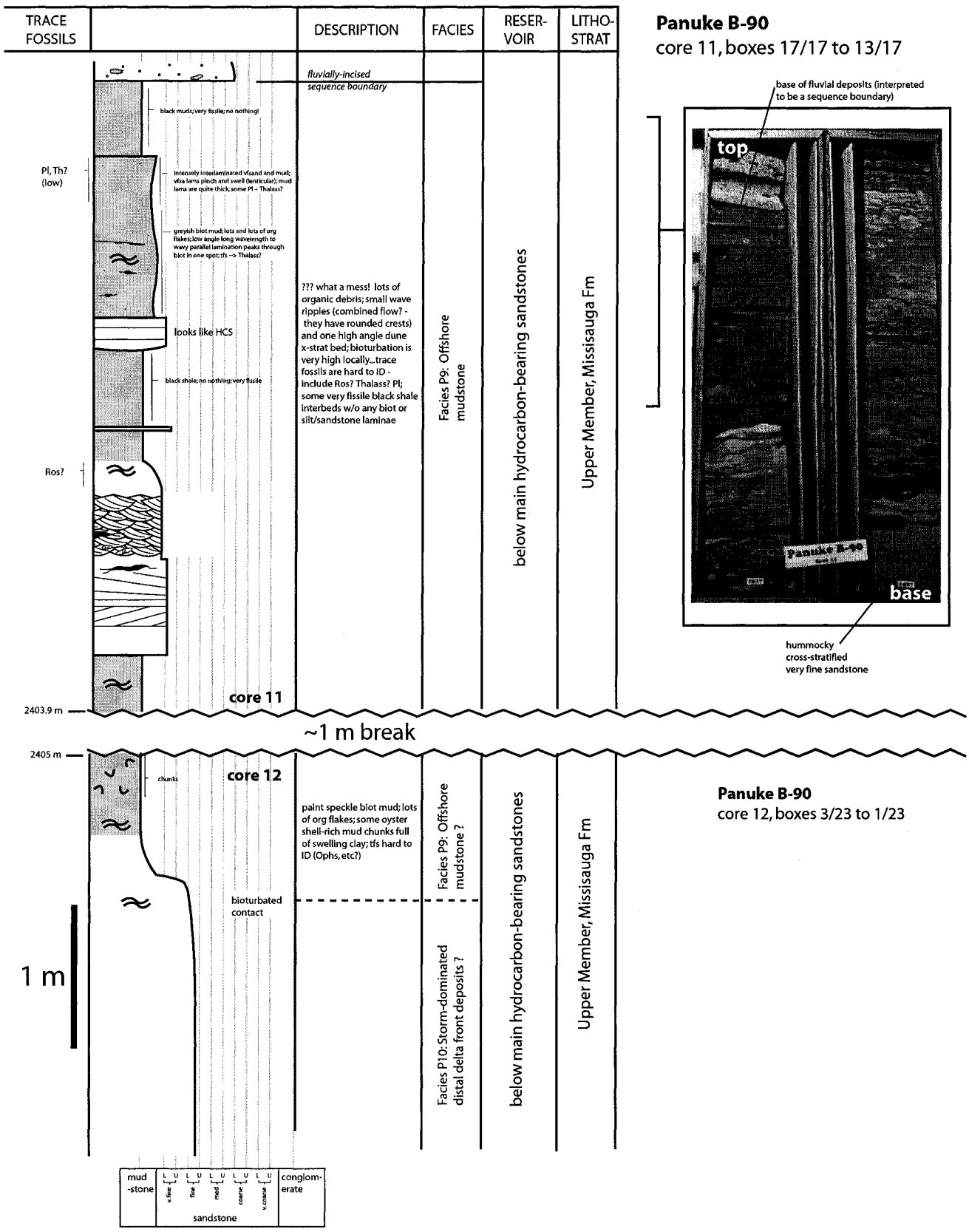


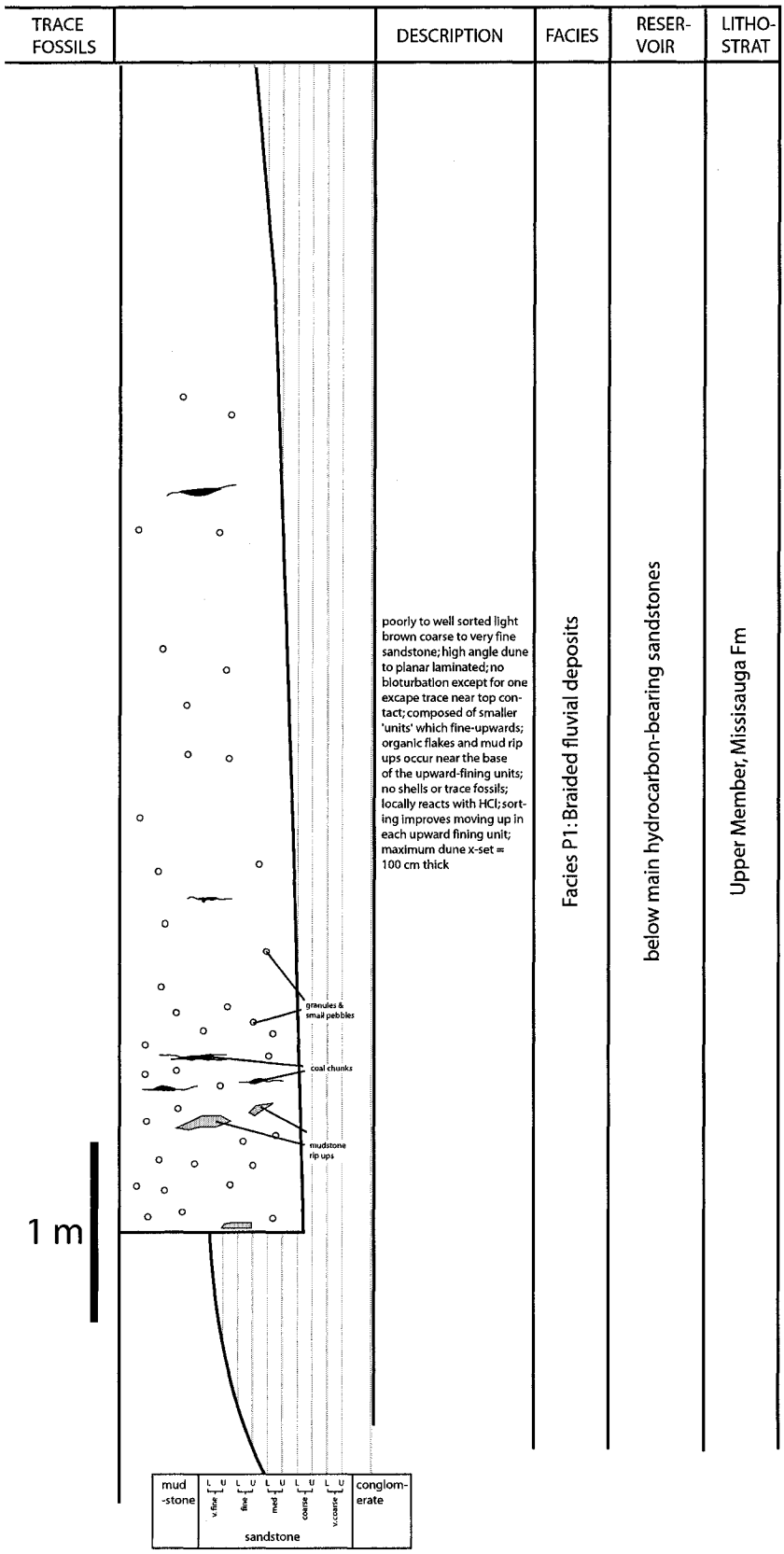


Glenelg N49
core 3
boxes 8/22 to 5/22

Glenelg N49
core 3
boxes 4/22 to 1/22

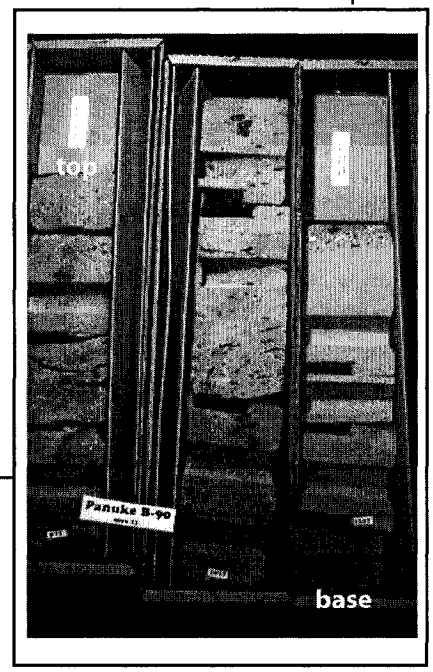


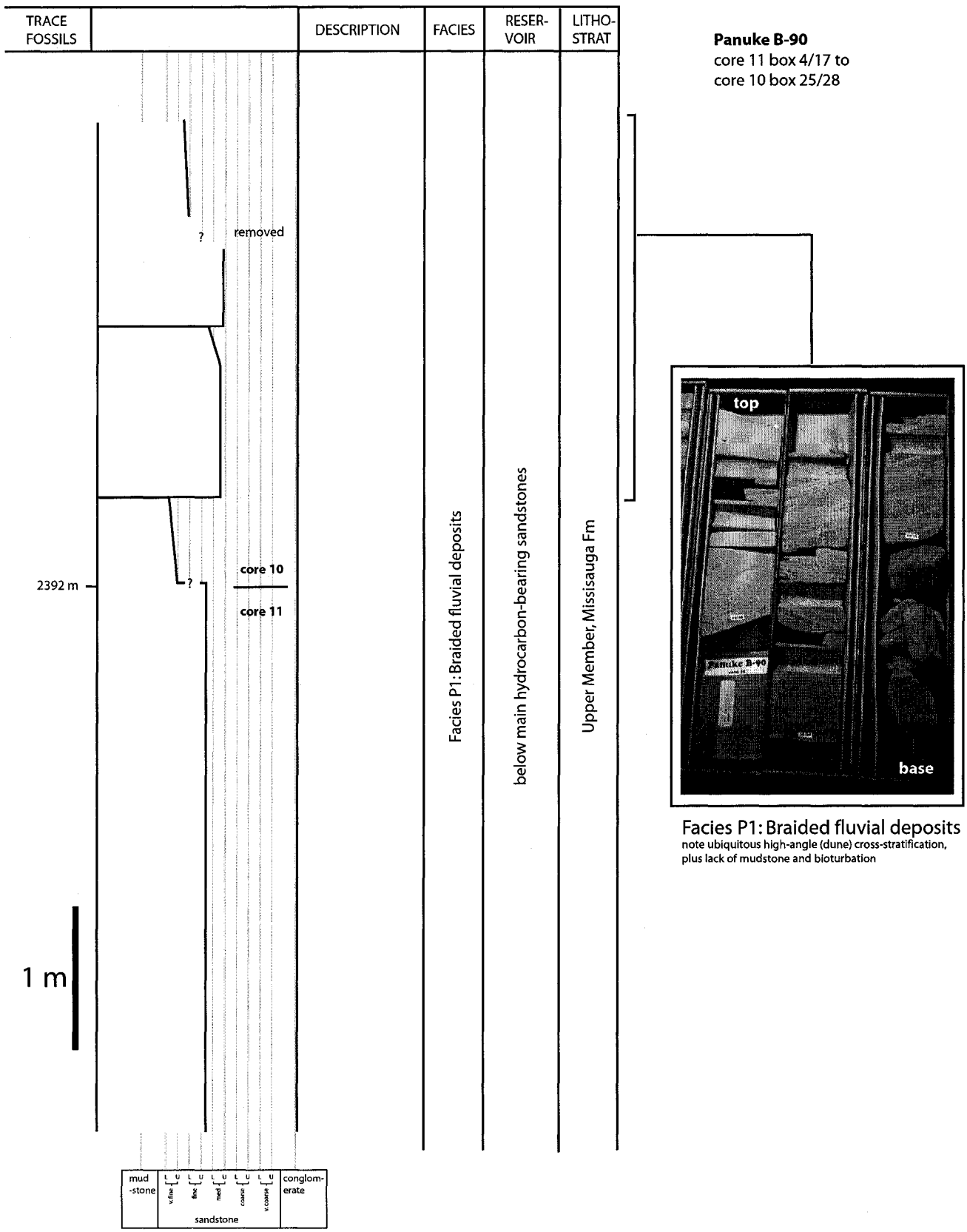

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
fluvially-incised sequence boundary
black muds; very fissile; no nothing!
Pl, Th? (low)
intensely interlaminated v/sand and mud; v/sa lams pinch and swell (lenticular); mud lams are quite thick; some Pl + Thalass?
greyish biot mud; lots and lots of org flakes; low angle long wavelength to wavy parallel lamination peaks through biot in one spot; tfs -> Thalass?
looks like HCS
black shale; no nothing; very fissile
Ros?
??? what a mess! lots of organic debris; small wave ripples (combined flow? - they have rounded crests) and one high angle dune x-strat bed; bioturbation is very high locally...trace fossils are hard to ID - include Ros? Thalass? Pl; some very fissile black shale interbeds w/o any biot or silt/sandstone laminae
Facies P9: Offshore mudstone
below main hydrocarbon-bearing sandstones
Upper Member, Missisauga Fm
core 11
2403.9 m
~1 m break
2405 m
chunks
core 12
paint speckle biot mud; lots of org flakes; some oyster shell-rich mud chunks full of swelling clay; tfs hard to ID (Ophs, etc?)
bioturbated contact
Facies P9: Offshore mudstone ?
Facies P10: Storm-dominated distal delta front deposits ?
1 m
mud -stone
v. fine
fine
med
coarse
v. coarse
conglom-erate
sandstone
Panuke B-90
core 11, boxes 17/17 to 13/17
base of fluvial deposits (interpreted to be a sequence boundary)
top
base
hummocky cross-stratified very fine sandstone
Panuke B-90
core 12, boxes 3/23 to 1/23



Panuke B-90
core 11, boxes 12/17 to 5/17

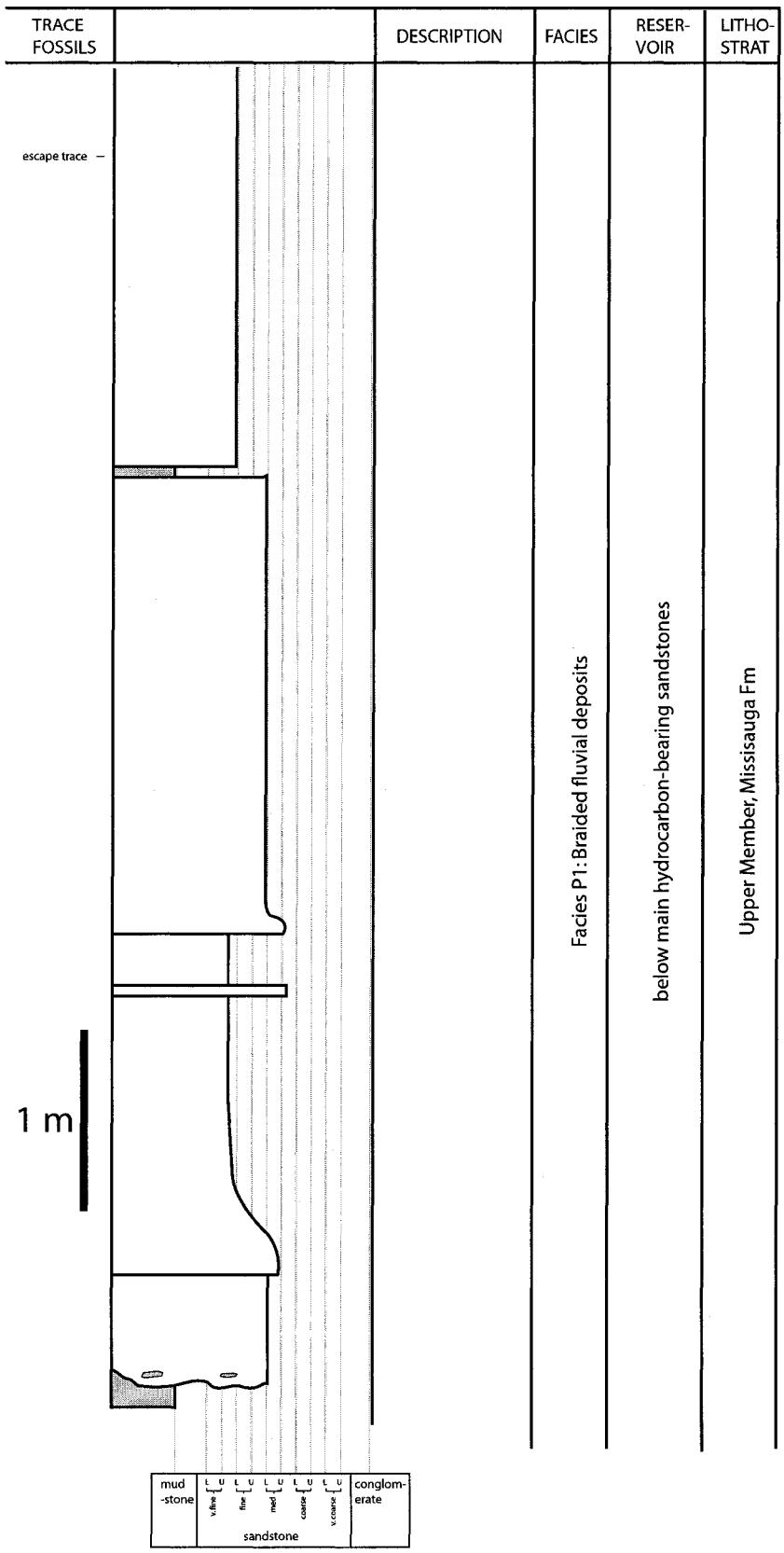
Facies P1: Braided fluvial deposits



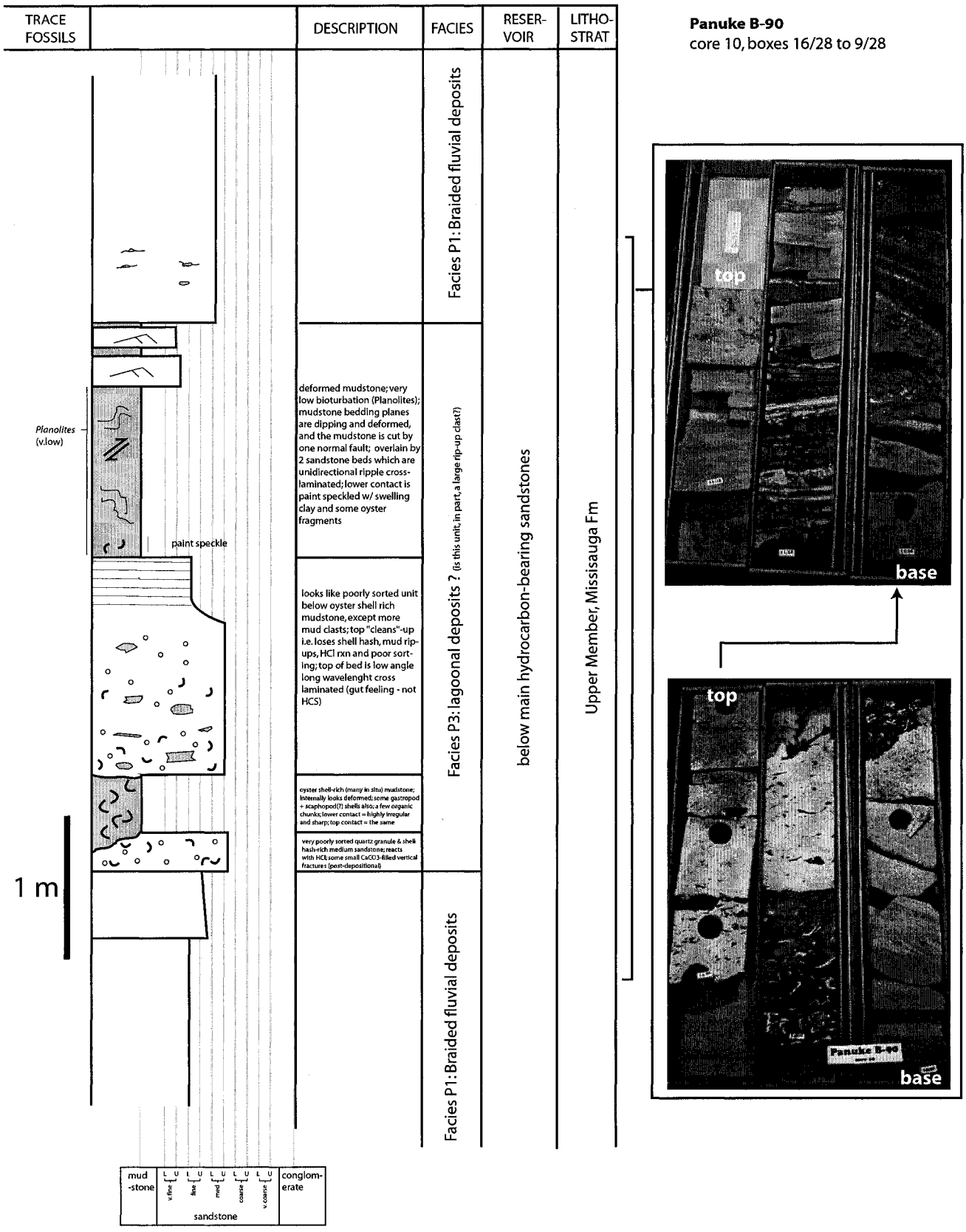


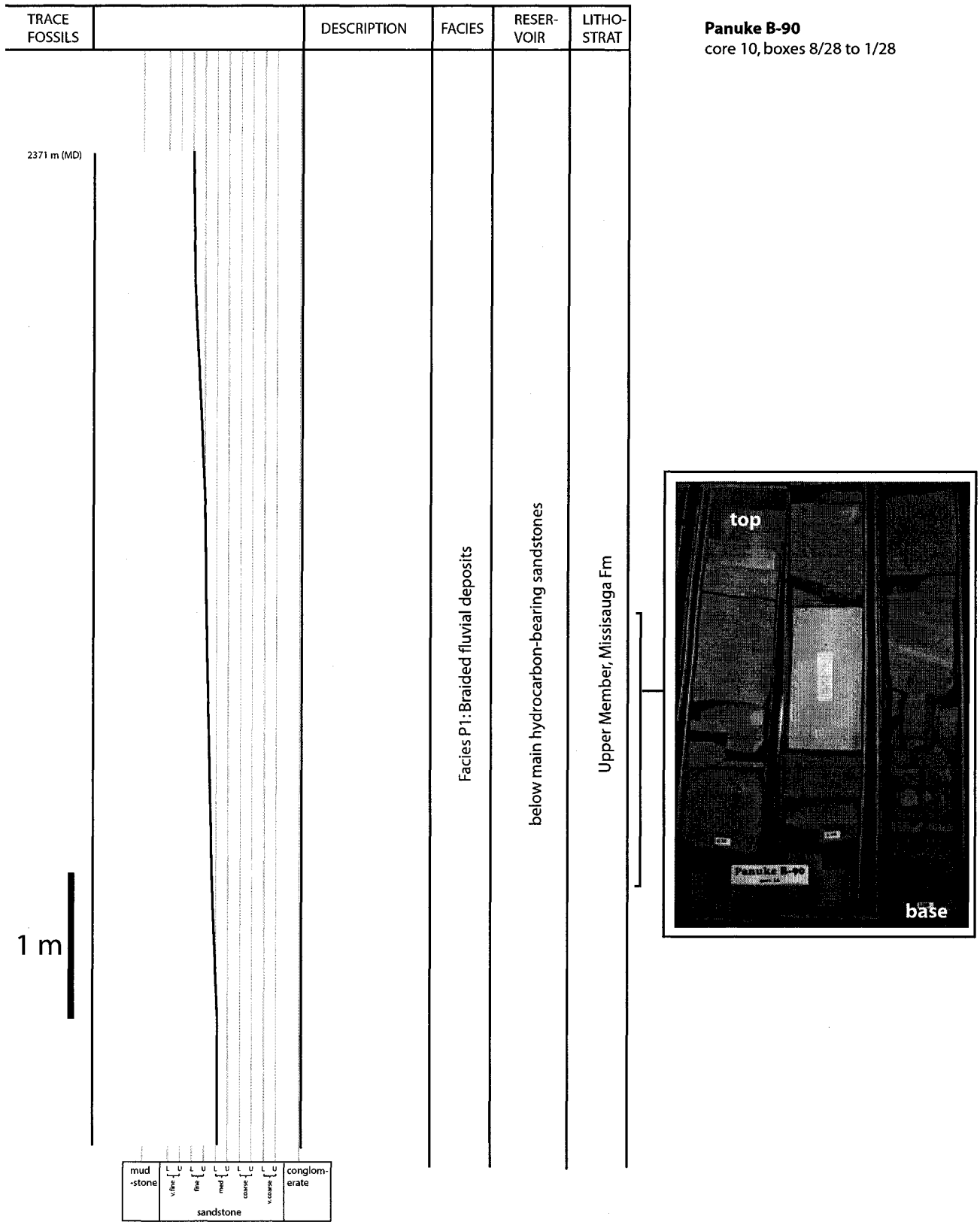
Panuke B-90
core 11 box 4/17 to
core 10 box 25/28

Facies P1: Braided fluvial deposits
note ubiquitous high-angle (dune) cross-stratification, plus lack of mudstone and bioturbation

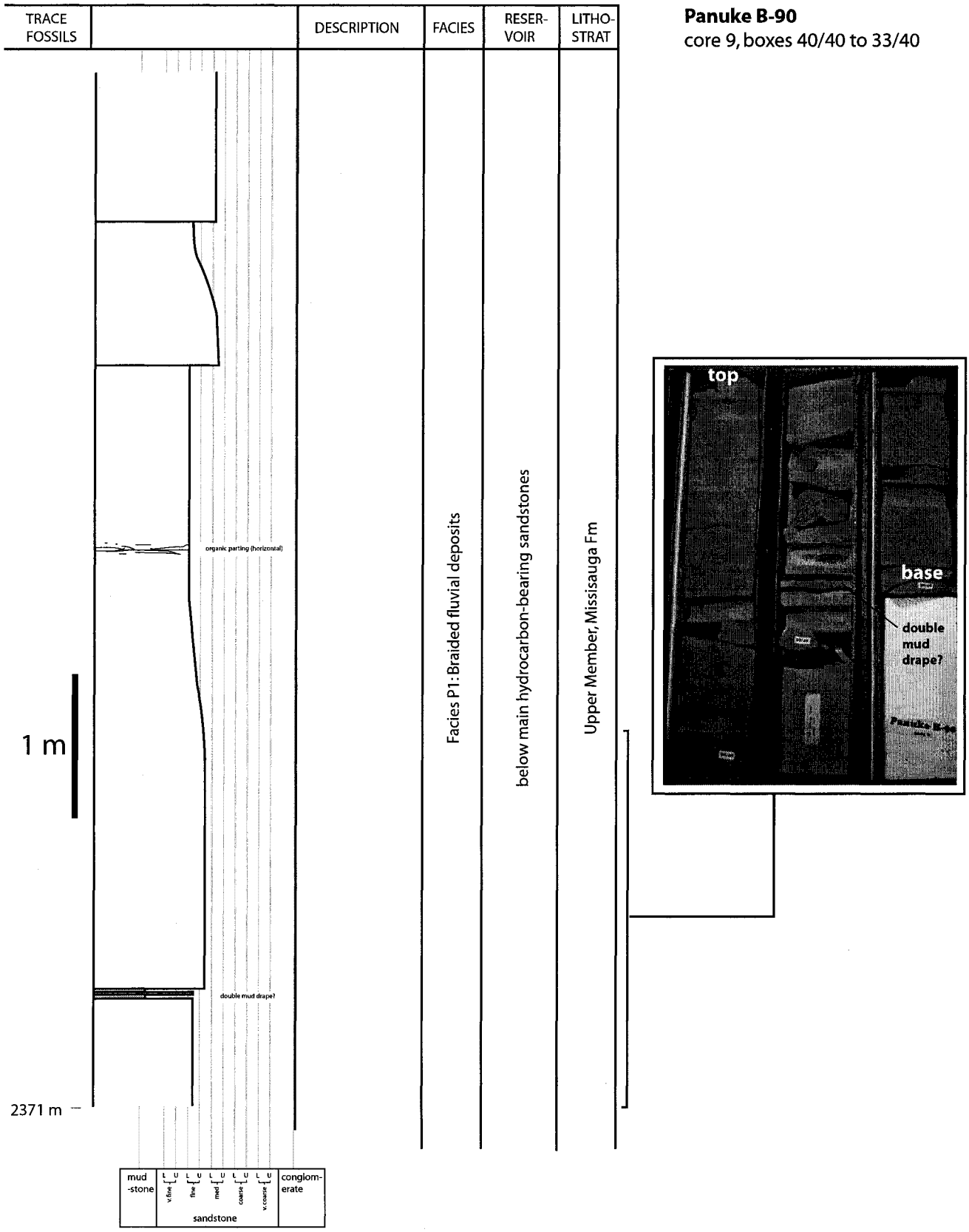


Panuke B-90
core 10, boxes 24/28 to 17/28

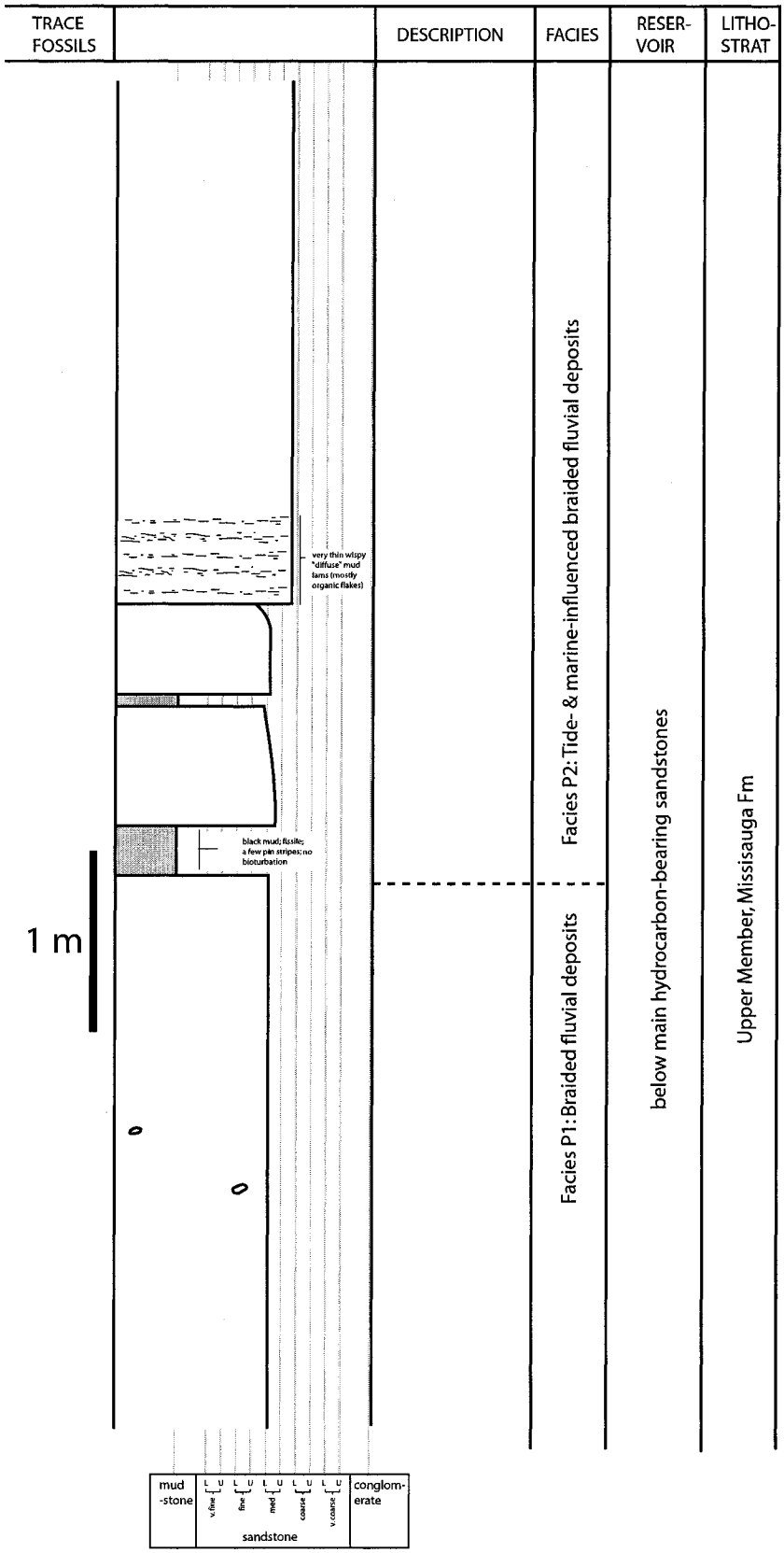

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Panuke B-90
core 10, boxes 16/28 to 9/28
Planolites (v.low)
paint speckle
1 m
deformed mudstone; very low bioturbation (Planolites); mudstone bedding planes are dipping and deformed, and the mudstone is cut by one normal fault; overlain by 2 sandstone beds which are unidirectional ripple cross-laminated; lower contact is paint speckled w/ swelling clay and some oyster fragments
looks like poorly sorted unit below oyster shell rich mudstone, except more mud clasts; top "cleans"-up i.e. loses shell hash, mud rip-ups, HCl rxn and poor sorting; top of bed is low angle long wavelenght cross laminated (gut feeling - not HCS)
oyster shell-rich (many in situ) mudstone; internally looks deformed; some gastropod + scaphopod(?) shells also; a few organic chunks; lower contact = highly irregular and sharp; top contact = the same
very poorly sorted quartz granule & shell hash-rich medium sandstone; reacts with HCl; some small CaCO3-filled vertical fractures (post-depositional)
Facies P1: Braided fluvial deposits
Facies P3: lagoonal deposits ? (is this unit, in part, a large rip-up clast?)
Facies P1: Braided fluvial deposits
below main hydrocarbon-bearing sandstones
Upper Member, Missisauga Fm
top
base
top
base
Panuke B-90
mud -stone
v.fine
fine
mud
coarse
v. coarse
conglom-erate
sandstone



Panuke B-90
core 10, boxes 8/28 to 1/28

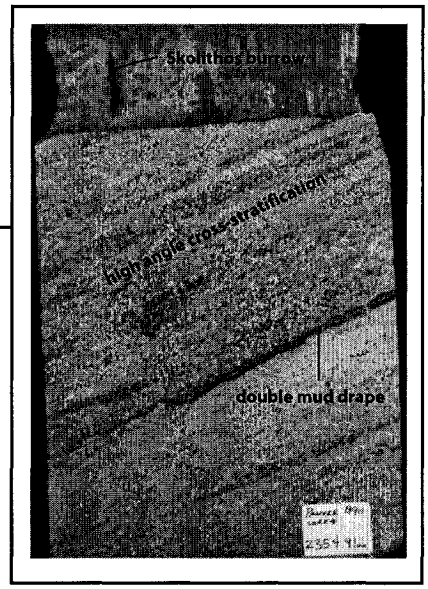


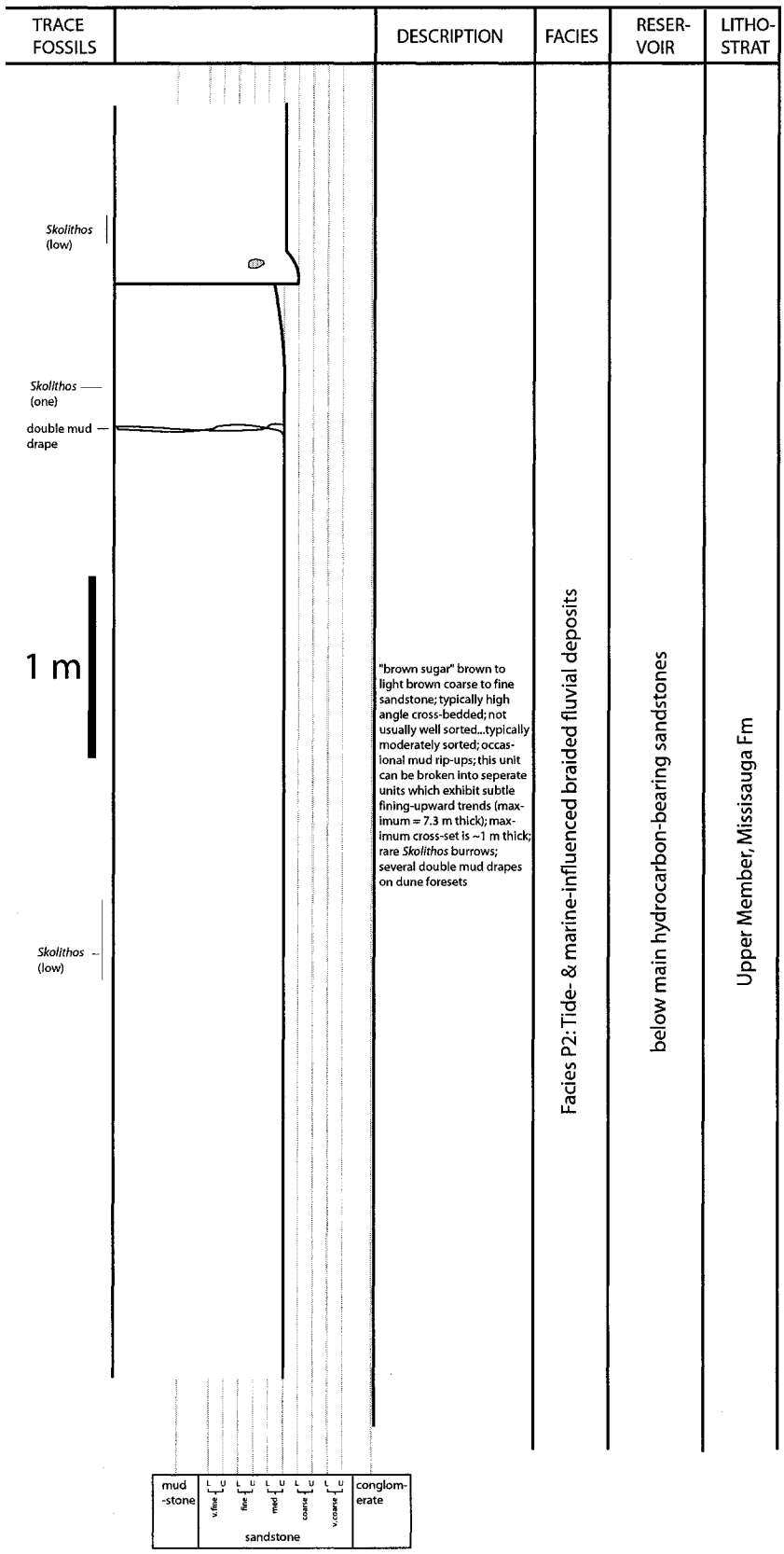
Panuke B-90
core 9, boxes 40/40 to 33/40

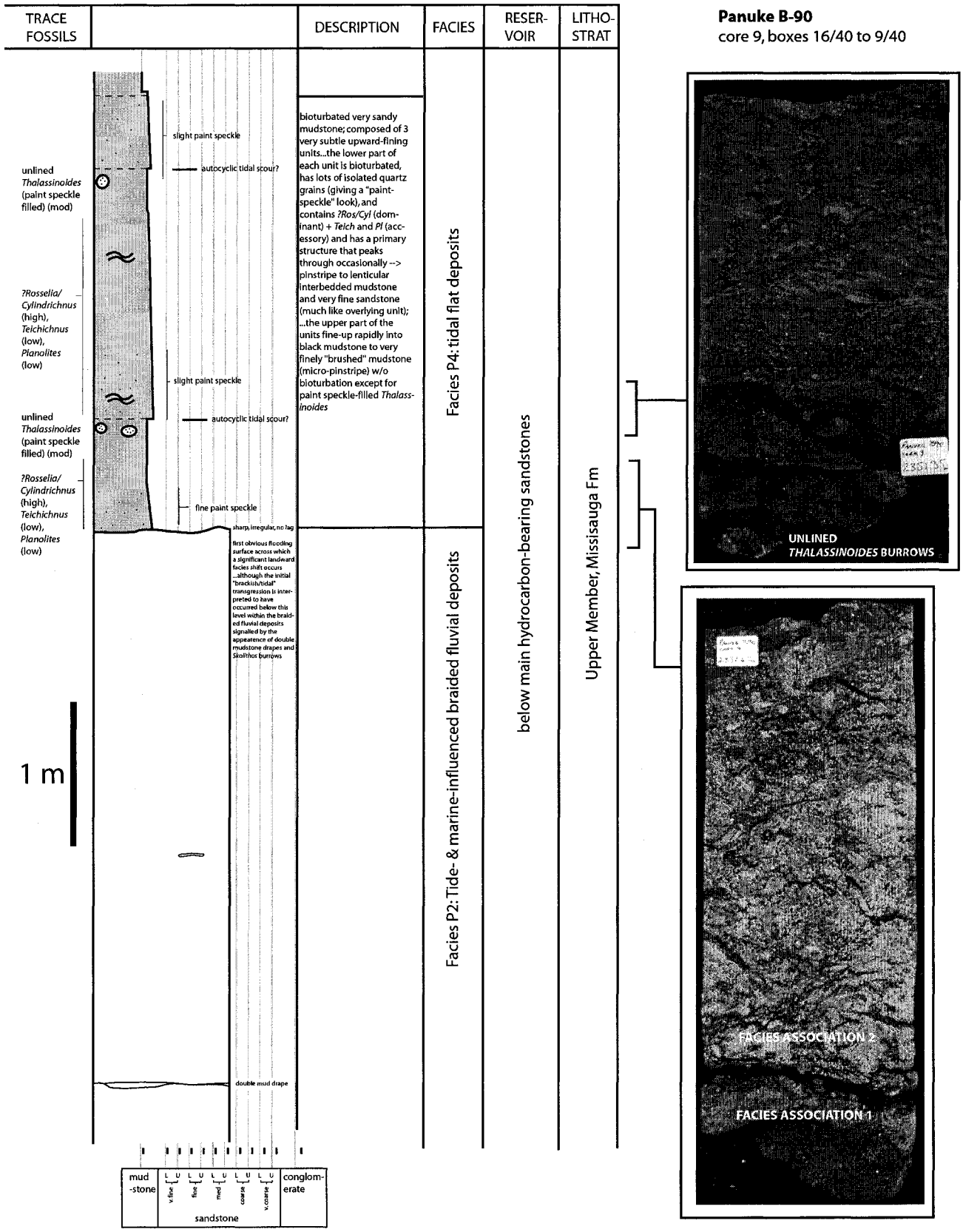


Panuke B-90
core 9, boxes 32/40 to 25/40

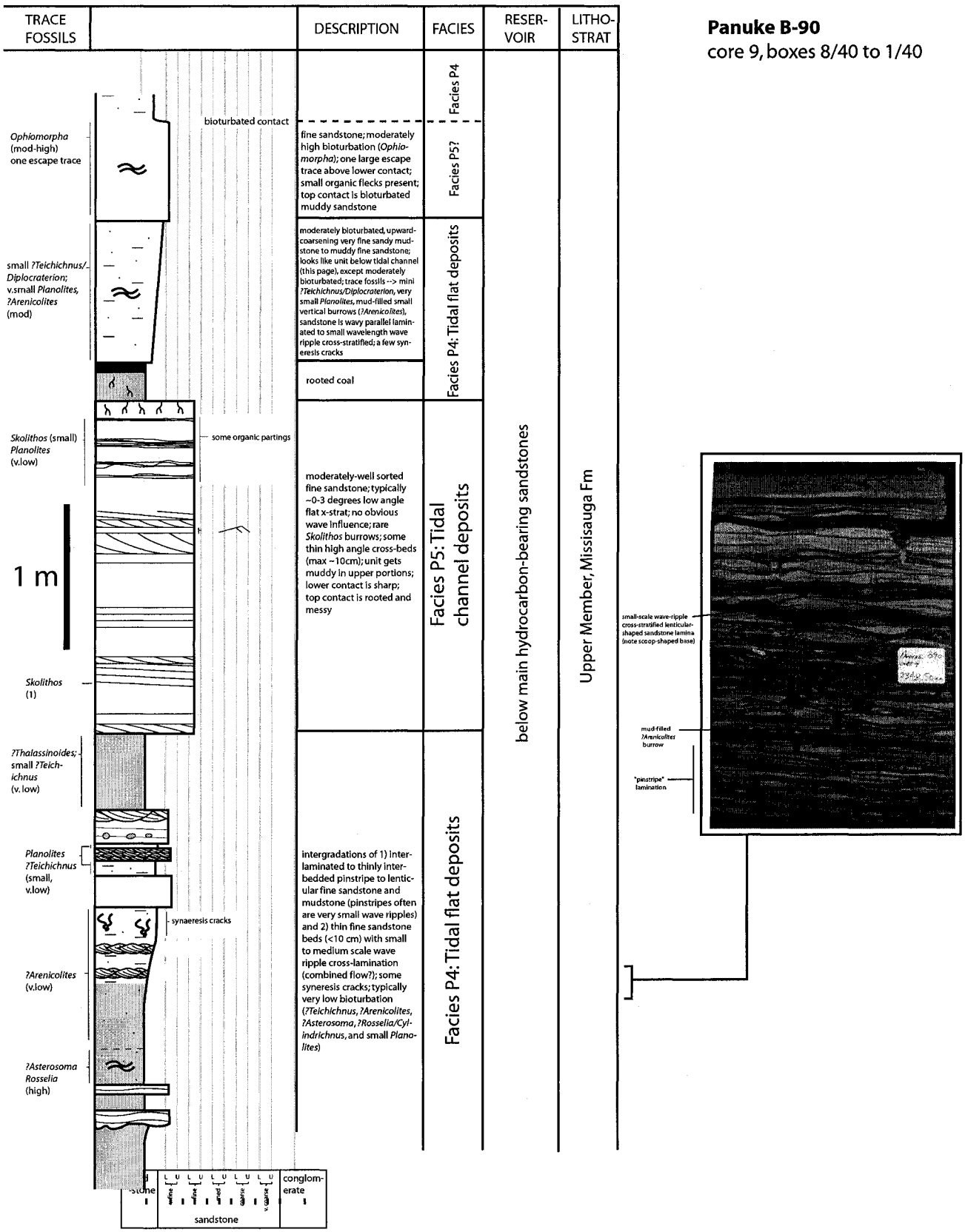
Panuke B-90
core 9
boxes 24/40 to 17/40

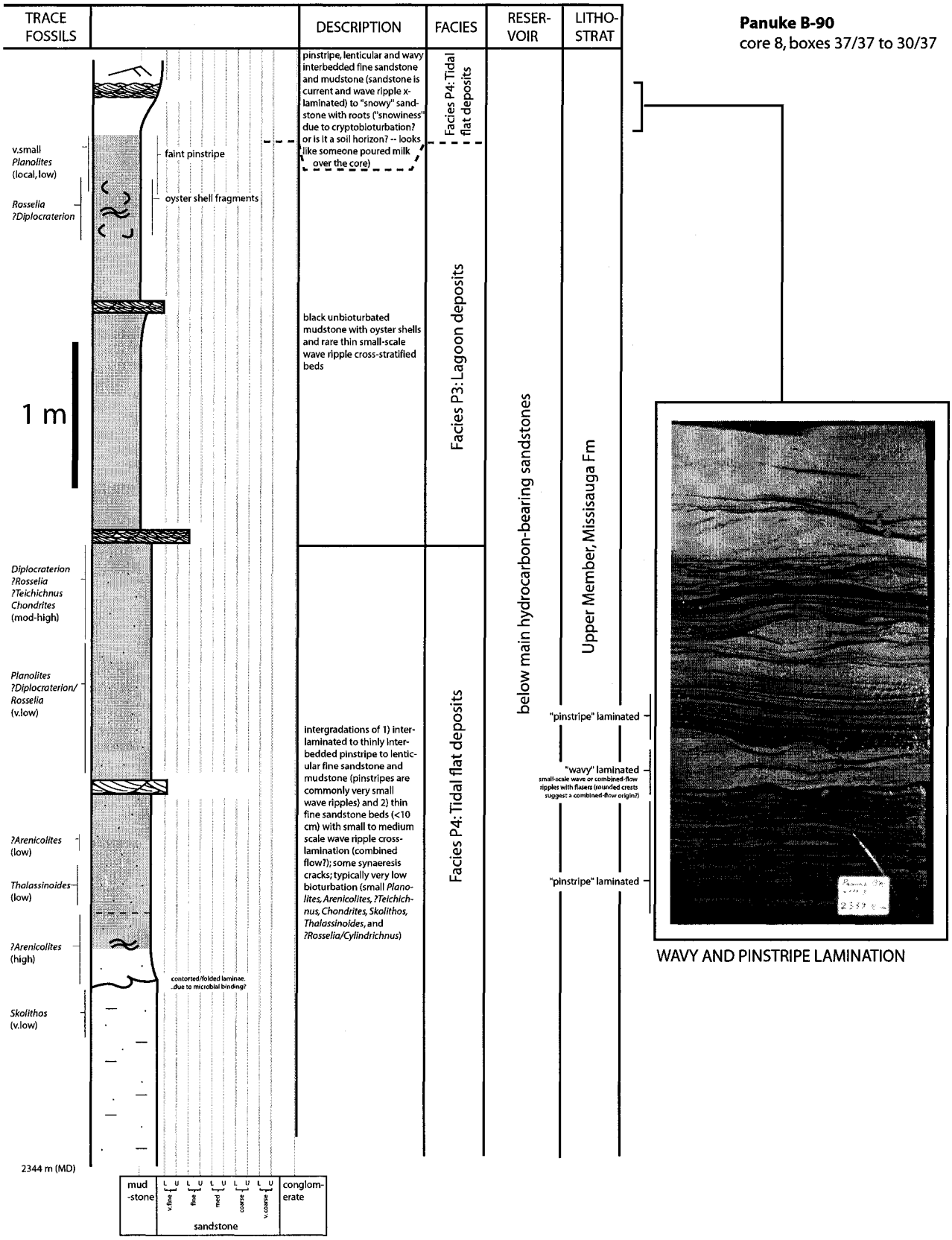


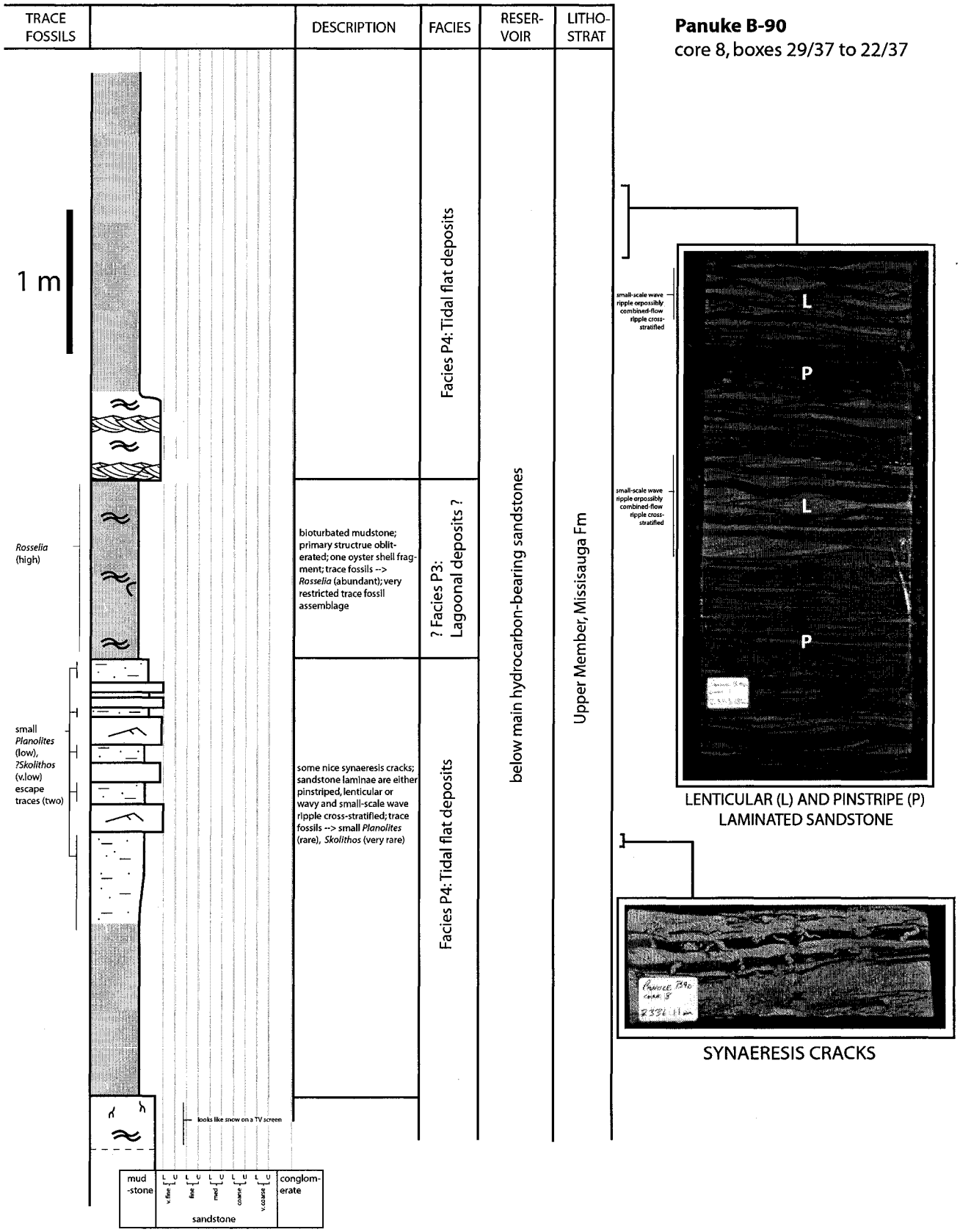




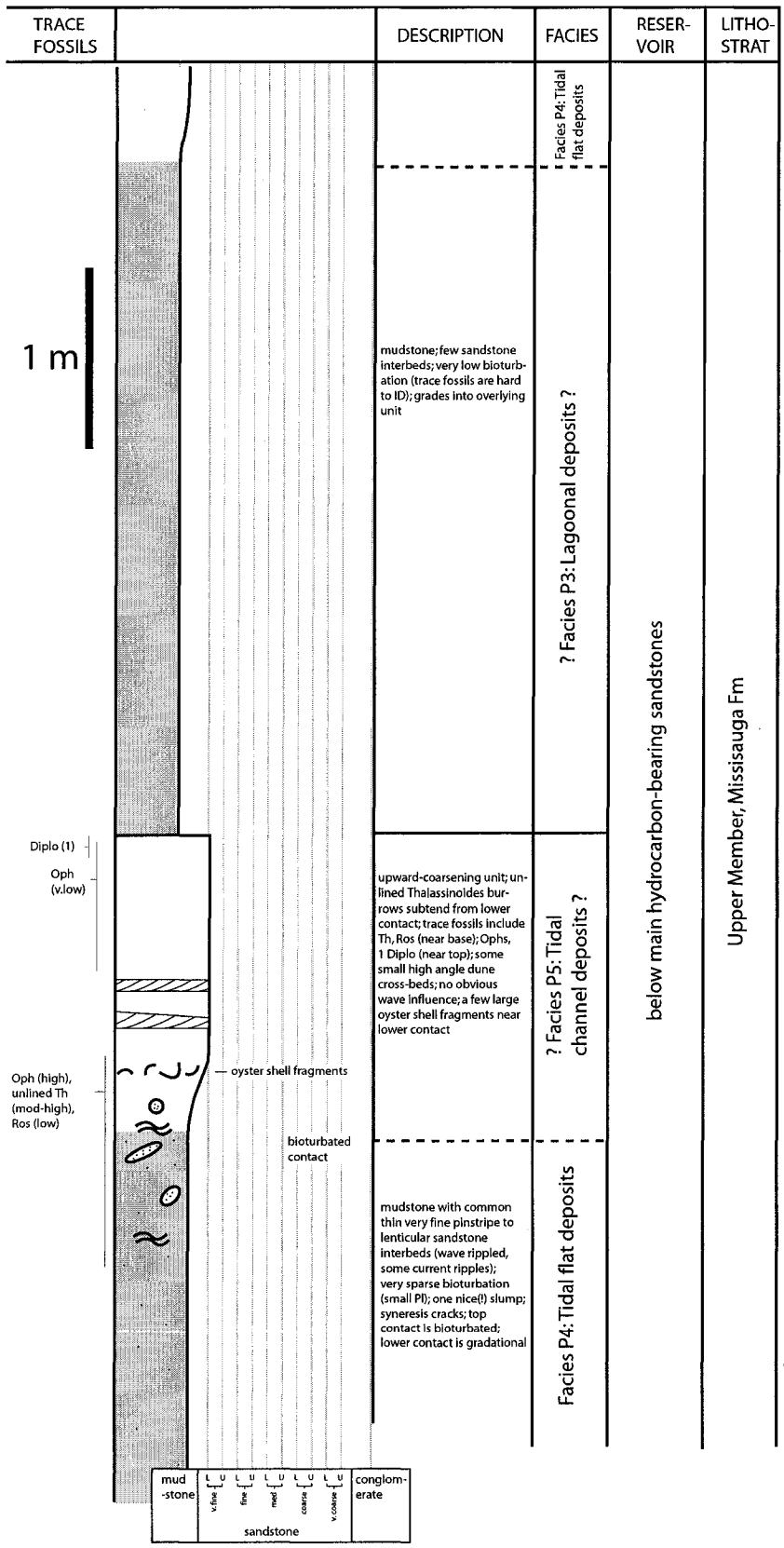
Panuke B-90
core 9, boxes 16/40 to 9/40


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Panuke B-90
core 9, boxes 8/40 to 1/40
bioturbated contact
Ophiomorpha (mod-high) one escape trace
small ?Teichichnus/ Diplocraterion; v.small Planolites, ?Arenicolites (mod)
Skolithos (small) Planolites (v.low)
some organic partings
1 m
Skolithos (1)
?Thalassinoides; small ?Teich-ichnus (v. low)
Planolites ?Teichichnus (small, v.low)
synaeresis cracks
?Arenicolites (v.low)
?Asterosoma Rosselia (high)
fine sandstone; moderately high bioturbation (Ophio-morpha); one large escape trace above lower contact; small organic flecks present; top contact is bioturbated muddy sandstone
Facies P4
Facies P5?
moderately bioturbated, upward-coarsening very fine sandy mud-stone to muddy fine sandstone; looks like unit below tidal channel (this page), except moderately bioturbated; trace fossils --> mini ?Teichichnus/Diplocraterion, very small Planolites, mud-filled small vertical burrows (?Arenicolites), sandstone is wavy parallel lamin-ated to small wavelength wave ripple cross-stratified; a few syn-eresis cracks
rooted coal
Facies P4: Tidal flat deposits
moderately-well sorted fine sandstone; typically ~0-3 degrees low angle flat x-strat; no obvious wave influence; rare Skolithos burrows; some thin high angle cross-beds (max ~10cm); unit gets muddy in upper portions; lower contact is sharp; top contact is rooted and messy
Facies P5: Tidal channel deposits
intergradations of 1) inter-laminated to thinly inter-bedded pinstripe to lentic-ular fine sandstone and mudstone (pinstripes often are very small wave ripples) and 2) thin fine sandstone beds (<10 cm) with small to medium scale wave ripple cross-lamination (combined flow?); some syneresis cracks; typically very low bioturbation (?Teichichnus, ?Arenicolites, ?Asterosoma, ?Rosselia/Cyl-indrichnus, and small Plano-lites)
Facies P4: Tidal flat deposits
below main hydrocarbon-bearing sandstones
Upper Member, Missisauga Fm
small-scale wave-ripple cross-stratified lenticular-shaped sandstone lamina (note scoop-shaped base)
mud-filled ?Arenicolites burrow
"pinstripe" lamination
mudstone
sandstone
conglom-erate

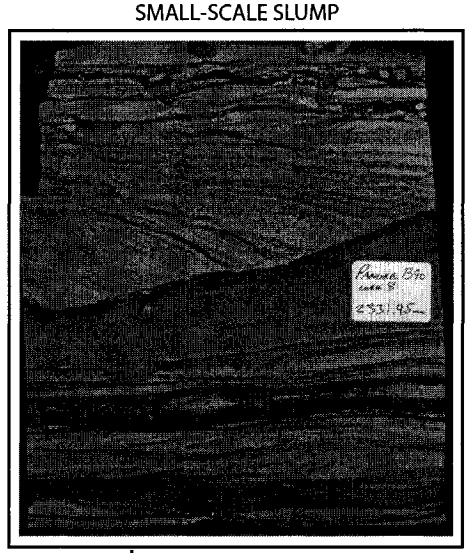

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Panuke B-90
core 8, boxes 37/37 to 30/37
pinstripe, lenticular and wavy interbedded fine sandstone and mudstone (sandstone is current and wave ripple x-laminated) to "snowy" sandstone with roots ("snowiness" due to cryptobioturbation? or is it a soil horizon? -- looks like someone poured milk over the core)
Facies P4: Tidal flat deposits
v.small Planolites (local, low)
faint pinstripe
Rosselia ?Diplocraterion
oyster shell fragments
black unbioturbated mudstone with oyster shells and rare thin small-scale wave ripple cross-stratified beds
Facies P3: Lagoon deposits
1 m
Diplocraterion ?Rosselia ?Teichichnus Chondrites (mod-high)
Planolites ?Diplocraterion/ Rosselia (v.low)
intergradations of 1) interlaminated to thinly interbedded pinstripe to lenticular fine sandstone and mudstone (pinstripes are commonly very small wave ripples) and 2) thin fine sandstone beds (<10 cm) with small to medium scale wave ripple cross-lamination (combined flow?); some synaeresis cracks; typically very low bioturbation (small Planolites, Arenicolites, ?Teichichnus, Chondrites, Skolithos, Thalassinoides, and ?Rosselia/Cylindrichnus)
Facies P4: Tidal flat deposits
below main hydrocarbon-bearing sandstones
Upper Member, Missisauga Fm
?Arenicolites (low)
Thalassinoides (low)
?Arenicolites (high)
contorted/folded laminae, ..due to microbial binding?
Skolithos (v.low)
"pinstripe" laminated
"wavy" laminated
small-scale wave or combined-flow ripples with flasers (rounded crests suggest a combined-flow origin?)
"pinstripe" laminated
2344 m (MD)
mud -stone
v.fine
fine
med
coarse
v.coarse
sandstone
conglom-erate
WAVY AND PINSTRIPE LAMINATION

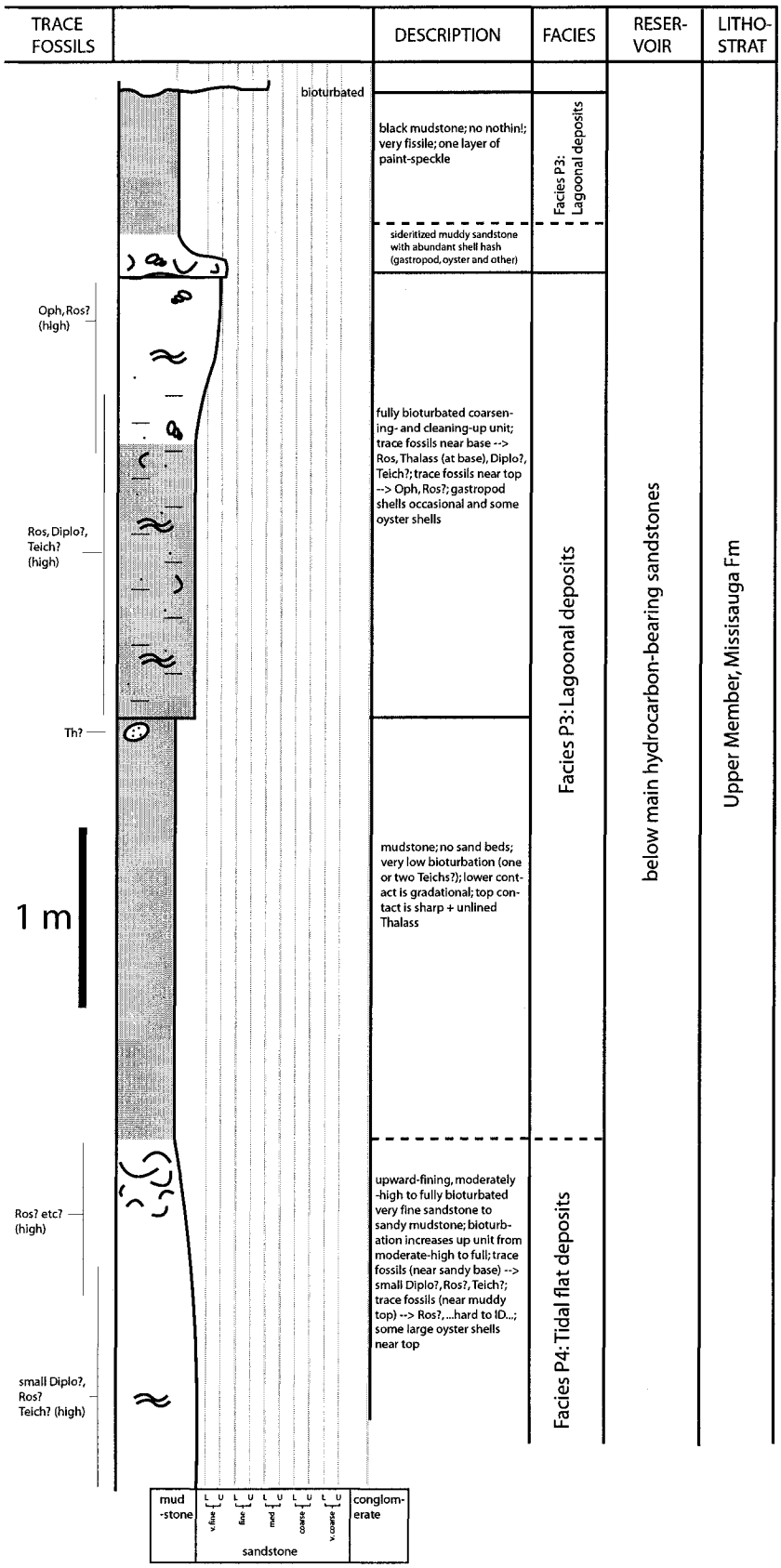

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Panuke B-90
core 8, boxes 29/37 to 22/37
1 m
Rosselia (high)
small Planolites (low), ?Skolithos (v.low) escape traces (two)
bioturbated mudstone; primary structrue obliterated; one oyster shell fragment; trace fossils --> Rosselia (abundant); very restricted trace fossil assemblage
some nice synaeresis cracks; sandstone laminae are either pinstriped, lenticular or wavy and small-scale wave ripple cross-stratified; trace fossils --> small Planolites (rare), Skolithos (very rare)
looks like snow on a TV screen
Facies P4: Tidal flat deposits
? Facies P3: Lagoonal deposits ?
Facies P4: Tidal flat deposits
below main hydrocarbon-bearing sandstones
Upper Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
small-scale wave ripple orpossibly combined-flow ripple cross-stratified
small-scale wave ripple orpossibly combined-flow ripple cross-stratified
L
P
L
P
LENTICULAR (L) AND PINSTRIPE (P) LAMINATED SANDSTONE
SYNAERESIS CRACKS

Panuke B-90
core 8, boxes 21/37 to 14/3

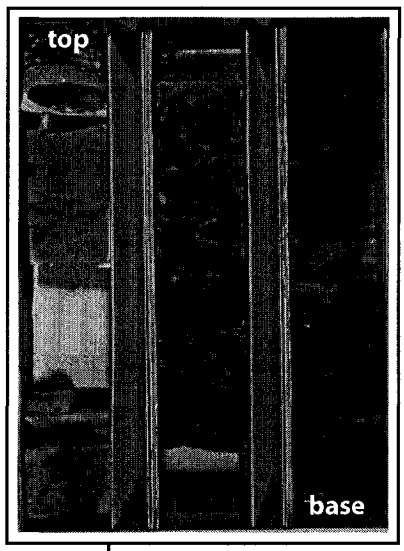


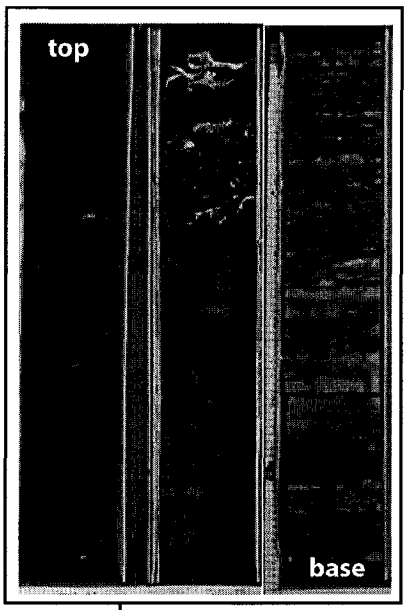
SMALL-SCALE SLUMP

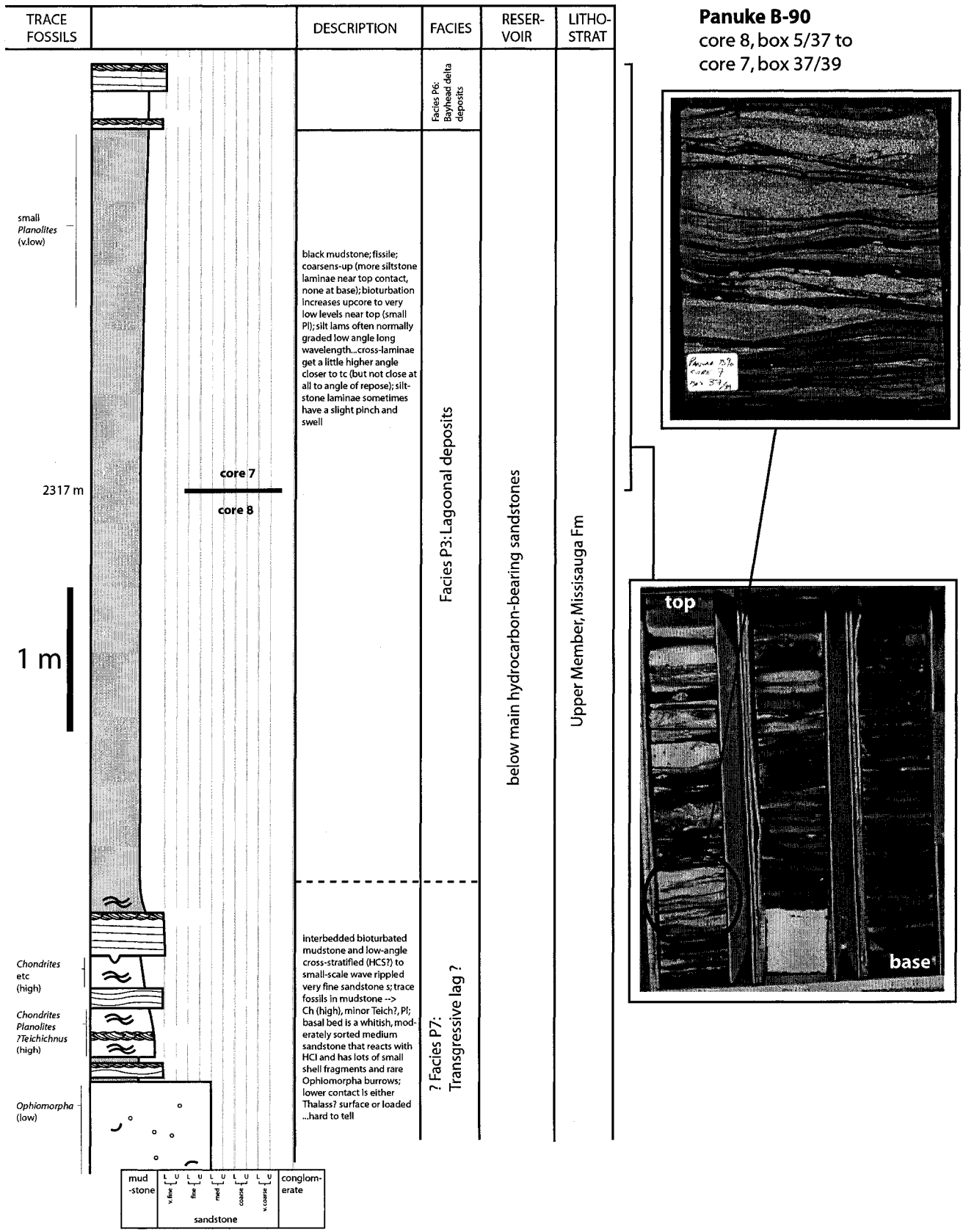


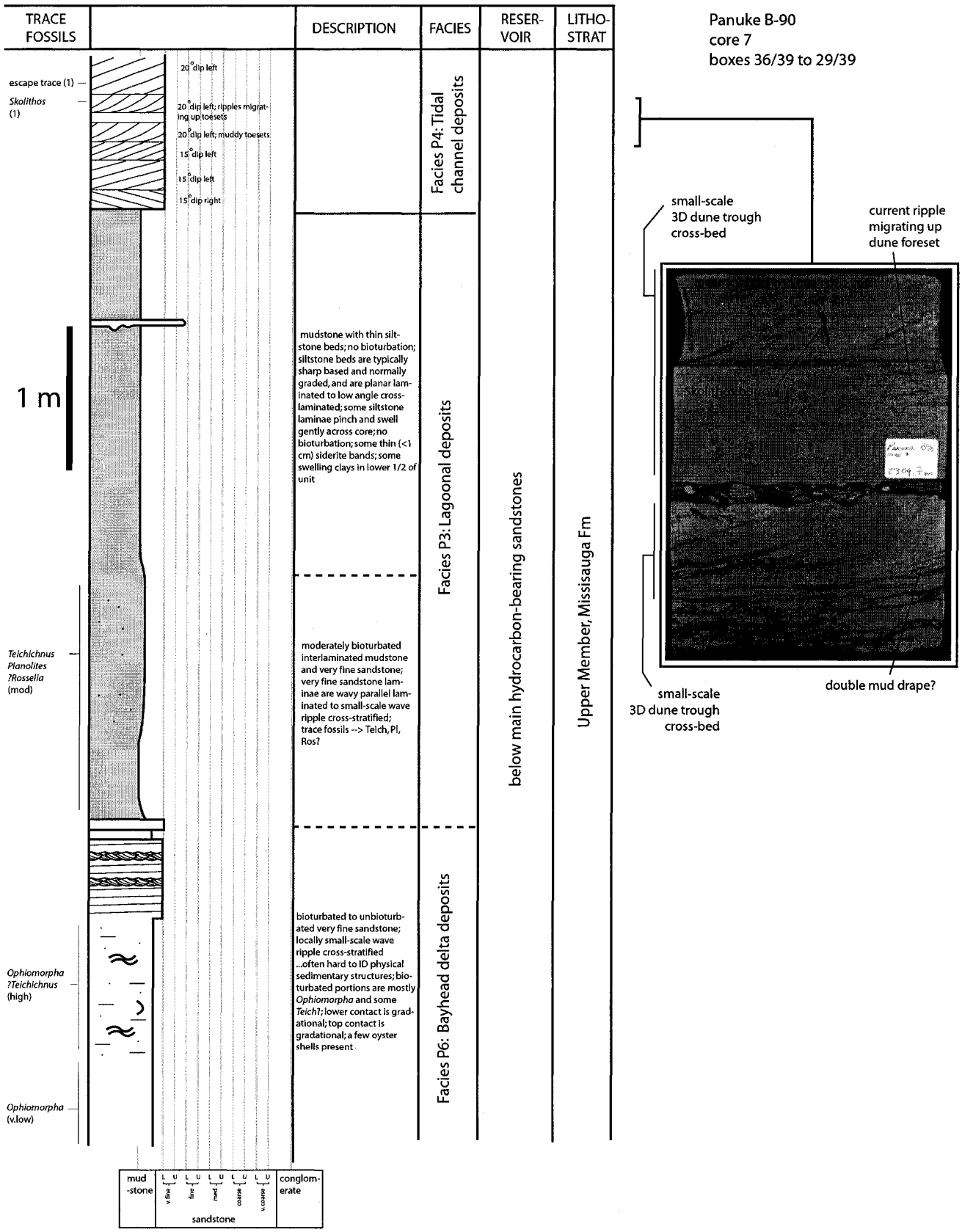


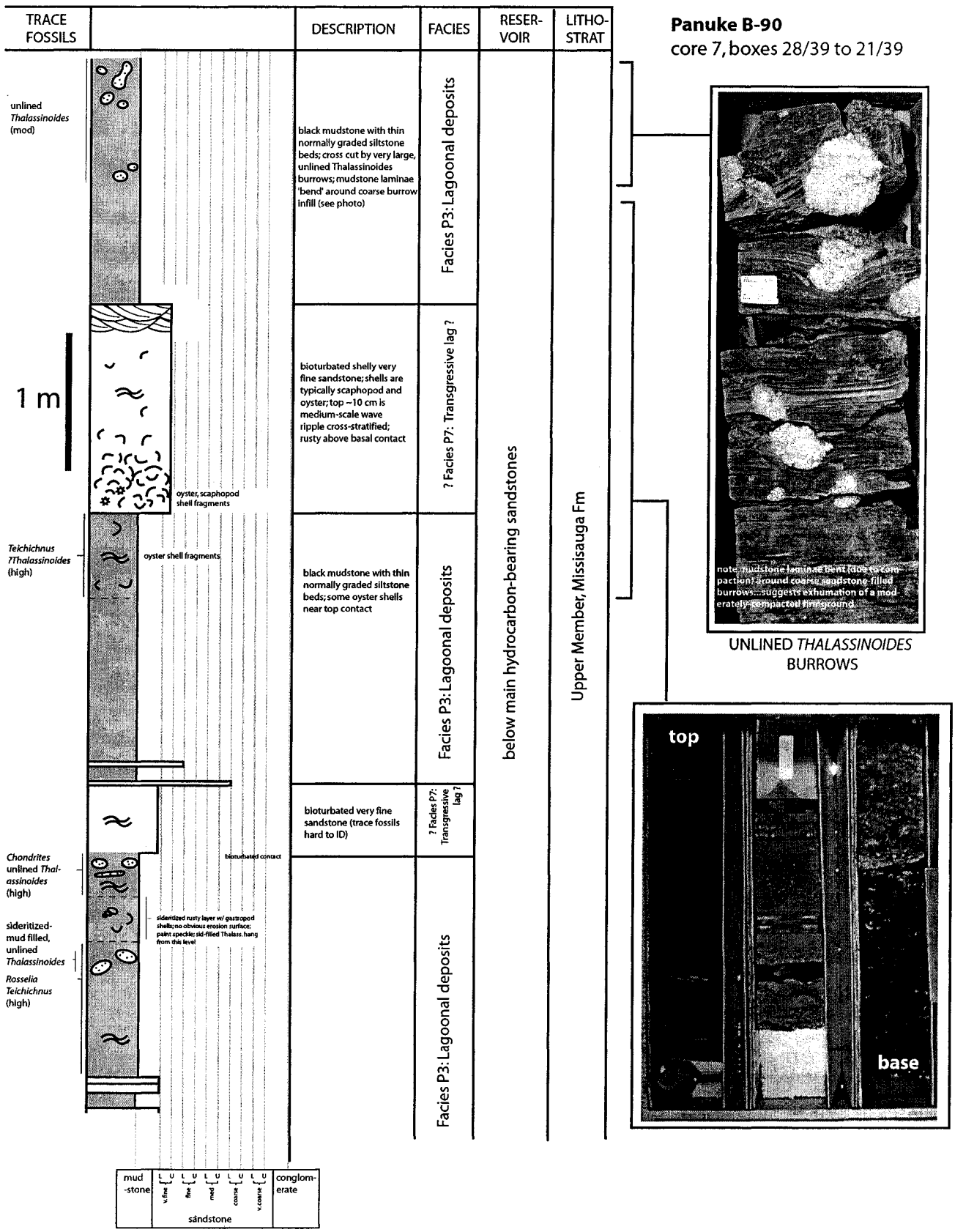
Panuke B-90
core 8, boxes 13/37 to 6/37





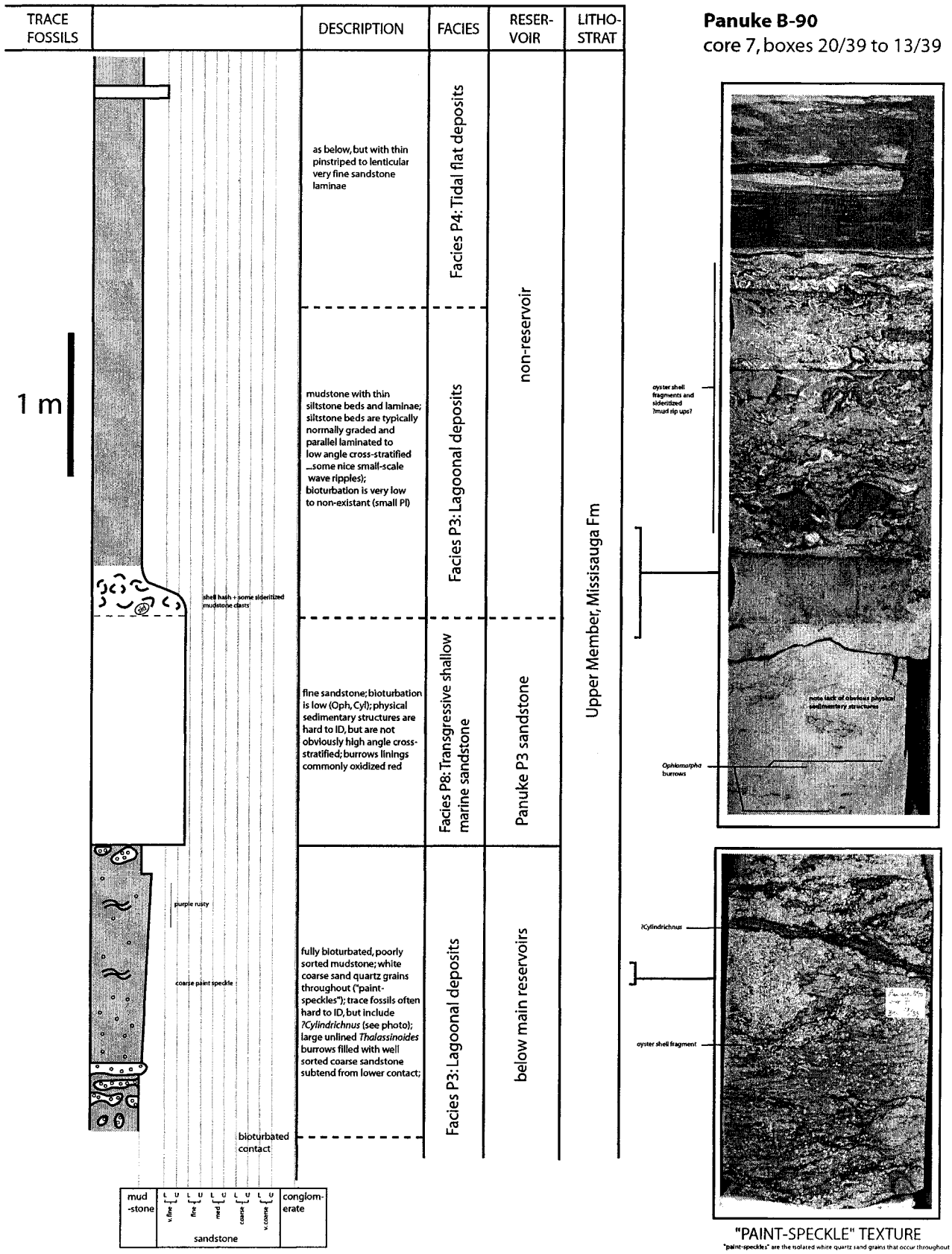

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Facies P6: Bayhead delta deposits
small Planolites (v.low)
black mudstone; fissile; coarsens-up (more siltstone laminae near top contact, none at base); bioturbation increases upcore to very low levels near top (small Pl); silt lams often normally graded low angle long wavelength...cross-laminae get a little higher angle closer to tc (but not close at all to angle of repose); siltstone laminae sometimes have a slight pinch and swell
Facies P3: Lagoonal deposits
below main hydrocarbon-bearing sandstones
Upper Member, Missisauga Fm
2317 m
core 7
core 8
1 m
Chondrites etc (high)
Chondrites Planolites ?Teichichnus (high)
Ophiomorpha (low)
interbedded bioturbated mudstone and low-angle cross-stratified (HCS?) to small-scale wave rippled very fine sandstone s; trace fossils in mudstone --> Ch (high), minor Teich?, Pl; basal bed is a whitish, moderately sorted medium sandstone that reacts with HCl and has lots of small shell fragments and rare Ophiomorpha burrows; lower contact is either Thalass? surface or loaded ...hard to tell
? Facies P7: Transgressive lag ?
mud -stone
v.fine
fine
med
coarse
v.coarse
sandstone
conglom-erate
Panuke B-90
core 8, box 5/37 to
core 7, box 37/39
top
base

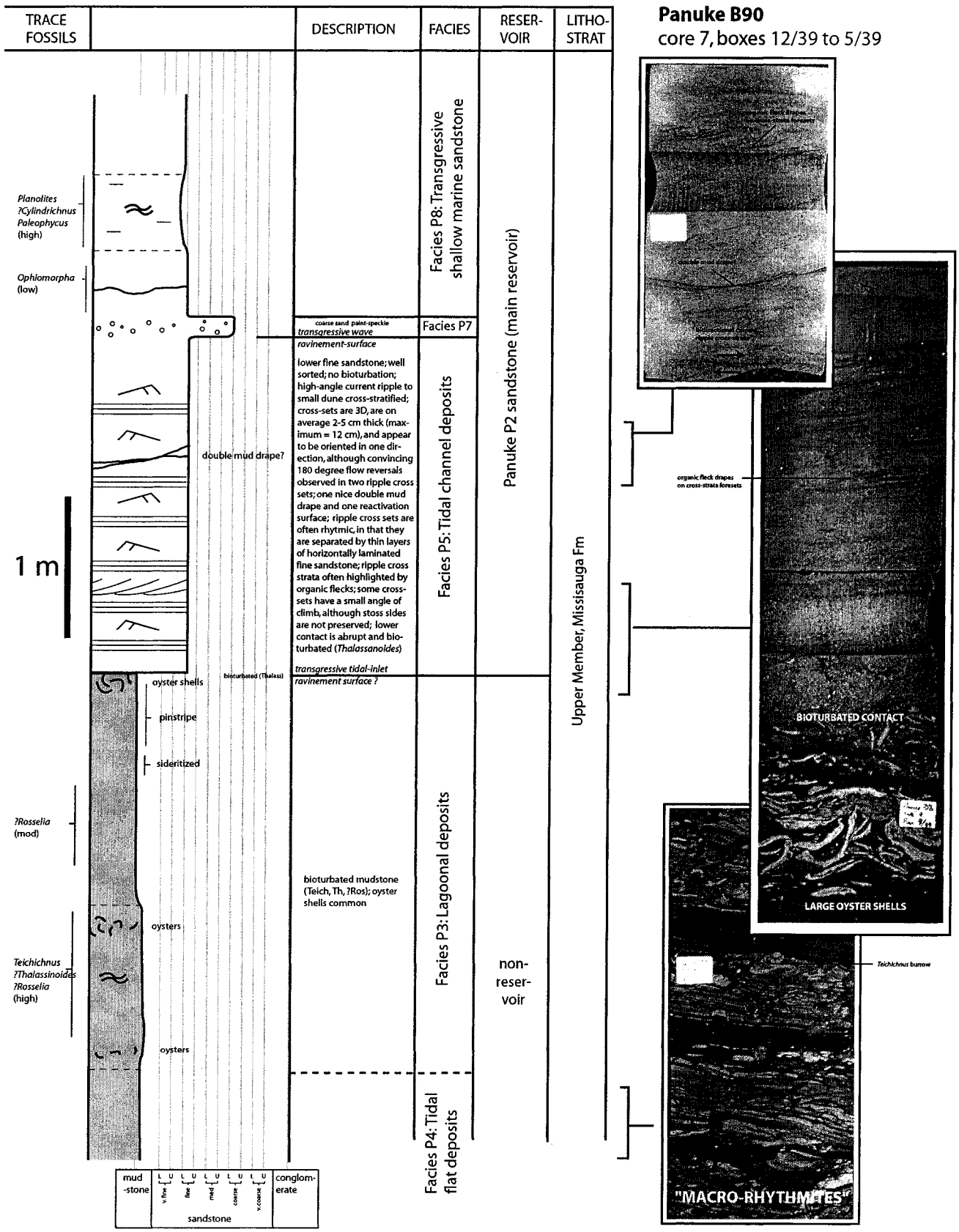

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
escape trace (1)
Skolithos (1)
20° dip left
20° dip left; ripples migrating up toesets
20° dip left; muddy toesets
15° dip left
15° dip left
15° dip right
1 m
mudstone with thin siltstone beds; no bioturbation; siltstone beds are typically sharp based and normally graded, and are planar laminated to low angle cross-laminated; some siltstone laminae pinch and swell gently across core; no bioturbation; some thin (<1 cm) siderite bands; some swelling clays in lower 1/2 of unit
Facies P4: Tidal channel deposits
Facies P3: Lagoonal deposits
Teichichnus
Planolites
?Rosselia
(mod)
moderately bioturbated interlaminated mudstone and very fine sandstone; very fine sandstone laminae are wavy parallel laminated to small-scale wave ripple cross-stratified; trace fossils --> Telch, Pl, Ros?
Ophiomorpha
?Teichichnus
(high)
bioturbated to unbioturbated very fine sandstone; locally small-scale wave ripple cross-stratified ...often hard to ID physical sedimentary structures; bioturbated portions are mostly Ophiomorpha and some Teich?; lower contact is gradational; top contact is gradational; a few oyster shells present
Facies P6: Bayhead delta deposits
Ophiomorpha
(v.low)
below main hydrocarbon-bearing sandstones
Upper Member, Missisauga Fm
mud-stone
v. fine
fine
med
coarse
v. coarse
conglom-erate
sandstone
Panuke B-90
core 7
boxes 36/39 to 29/39
small-scale 3D dune trough cross-bed
current ripple migrating up dune foreset
double mud drape?
small-scale 3D dune trough cross-bed

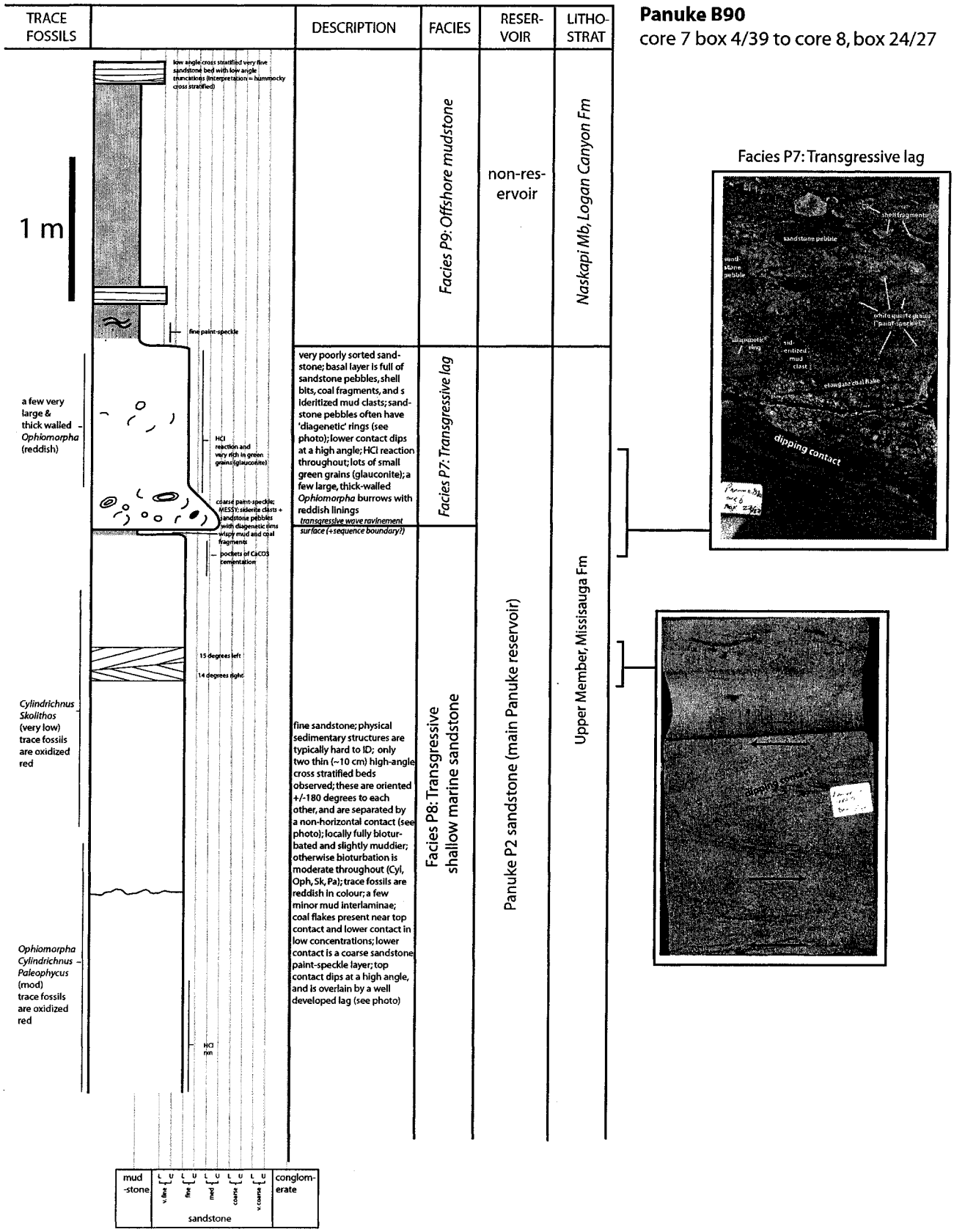


Panuke B-90
core 7, boxes 28/39 to 21/39

UNLINED *THALASSINOIDES* BURROWS

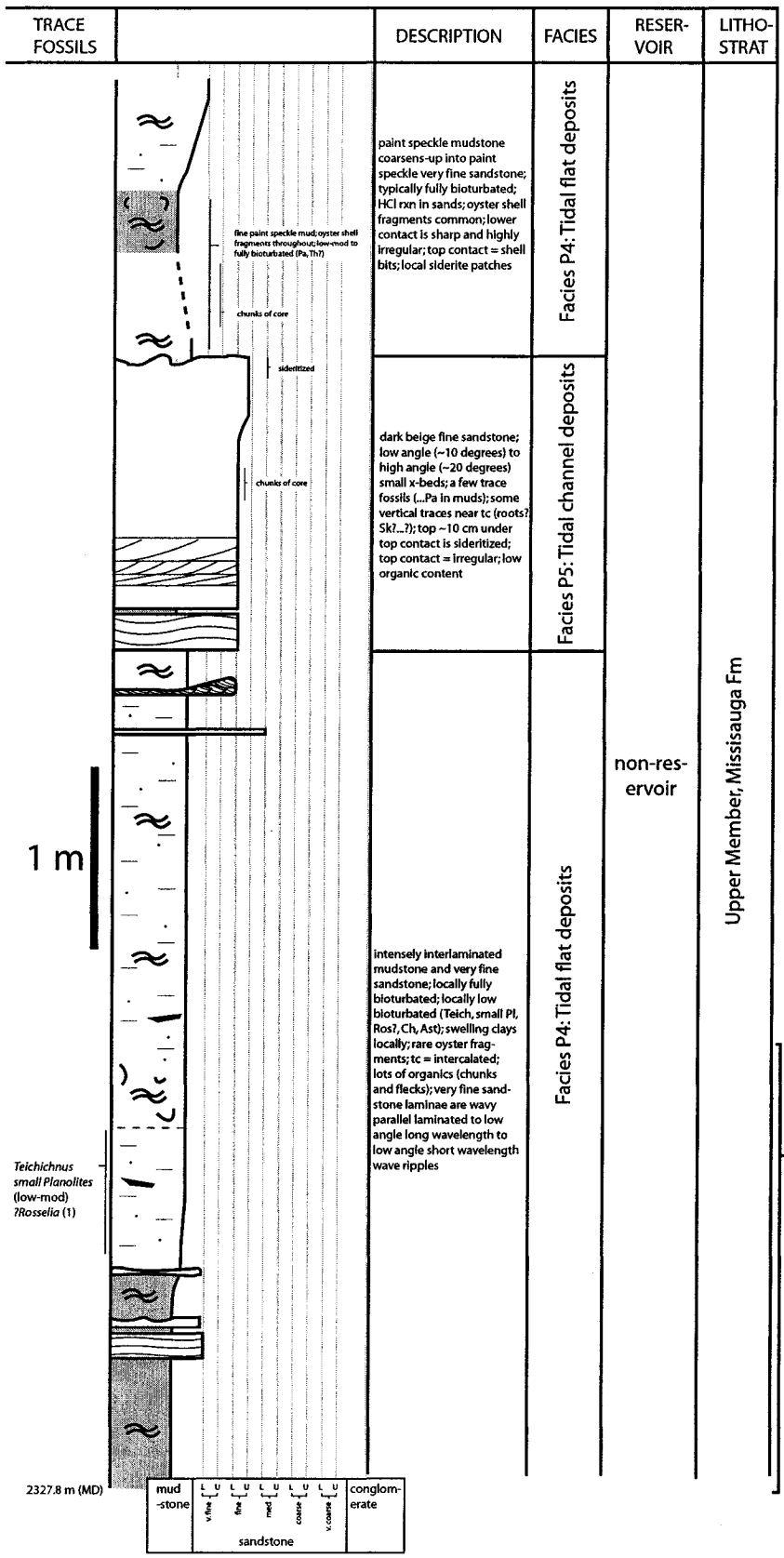

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
1 m
as below, but with thin pinstriped to lenticular very fine sandstone laminae
mudstone with thin siltstone beds and laminae; siltstone beds are typically normally graded and parallel laminated to low angle cross-stratified ...some nice small-scale wave ripples); bioturbation is very low to non-existant (small Pl)
fine sandstone; bioturbation is low (Oph, Cyl); physical sedimentary structures are hard to ID, but are not obviously high angle cross-stratified; burrows linings commonly oxidized red
fully bioturbated, poorly sorted mudstone; white coarse sand quartz grains throughout ("paint-speckles"); trace fossils often hard to ID, but include ?Cylindrichnus (see photo); large unlined Thalassinoides burrows filled with well sorted coarse sandstone subtend from lower contact;
Facies P4: Tidal flat deposits
Facies P3: Lagoonal deposits
Facies P8: Transgressive shallow marine sandstone
Facies P3: Lagoonal deposits
non-reservoir
Panuke P3 sandstone
below main reservoirs
Upper Member, Missisauga Fm
shell hash + some sideritized mudstone clasts
purple rusty
coarse paint speckle
bioturbated contact
mud -stone
v. fine
fine
med
coarse
v. coarse
conglom-erate
sandstone
Panuke B-90
core 7, boxes 20/39 to 13/39
oyster shell fragments and sideritized ?mud rip ups?
note lack of obvious physical sedimentary structures
Ophiomorpha burrows
?Cylindrichnus
oyster shell fragment
"PAINT-SPECKLE" TEXTURE
"paint-speckles" are the isolated white quartz sand grains that occur throughout


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Panuke B90
core 7, boxes 12/39 to 5/39
Planolites
?Cylindrichnus
Paleophycus
(high)
Ophiomorpha
(low)
1 m
coarse sand paint-speckle
transgressive wave
ravinement-surface
Facies P7
Facies P8: Transgressive shallow marine sandstone
lower fine sandstone; well sorted; no bioturbation; high-angle current ripple to small dune cross-stratified; cross-sets are 3D, are on average 2-5 cm thick (maximum = 12 cm), and appear to be oriented in one direction, although convincing 180 degree flow reversals observed in two ripple cross sets; one nice double mud drape and one reactivation surface; ripple cross sets are often rhytmic, in that they are separated by thin layers of horizontally laminated fine sandstone; ripple cross strata often highlighted by organic flecks; some cross-sets have a small angle of climb, although stoss sides are not preserved; lower contact is abrupt and bioturbated (Thalassanoides)
double mud drape?
Facies P5: Tidal channel deposits
Panuke P2 sandstone (main reservoir)
Upper Member, Missisauga Fm
organic fleck drapes on cross-strata foresets
transgressive tidal-inlet
ravinement surface ?
bioturbated (Thalass)
oyster shells
pinstripe
sideritized
?Rosselia
(mod)
bioturbated mudstone (Teich, Th, ?Ros); oyster shells common
oysters
Teichichnus
?Thalassinoides
?Rosselia
(high)
oysters
Facies P3: Lagoonal deposits
non-reser-voir
Facies P4: Tidal flat deposits
BIOTURBATED CONTACT
LARGE OYSTER SHELLS
Teichichnus burrow
"MACRO-RHYTHMITES"
mud -stone
v.fine
fine
med
coarse
v.coarse
sandstone
conglom-erate

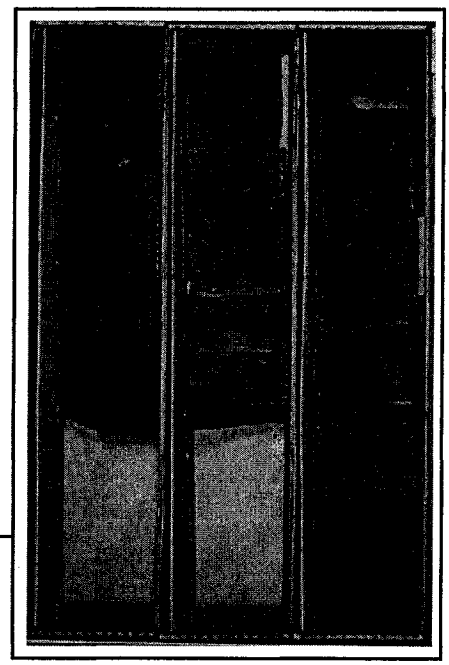


Panuke B90
core 7 box 4/39 to core 8, box 24/27

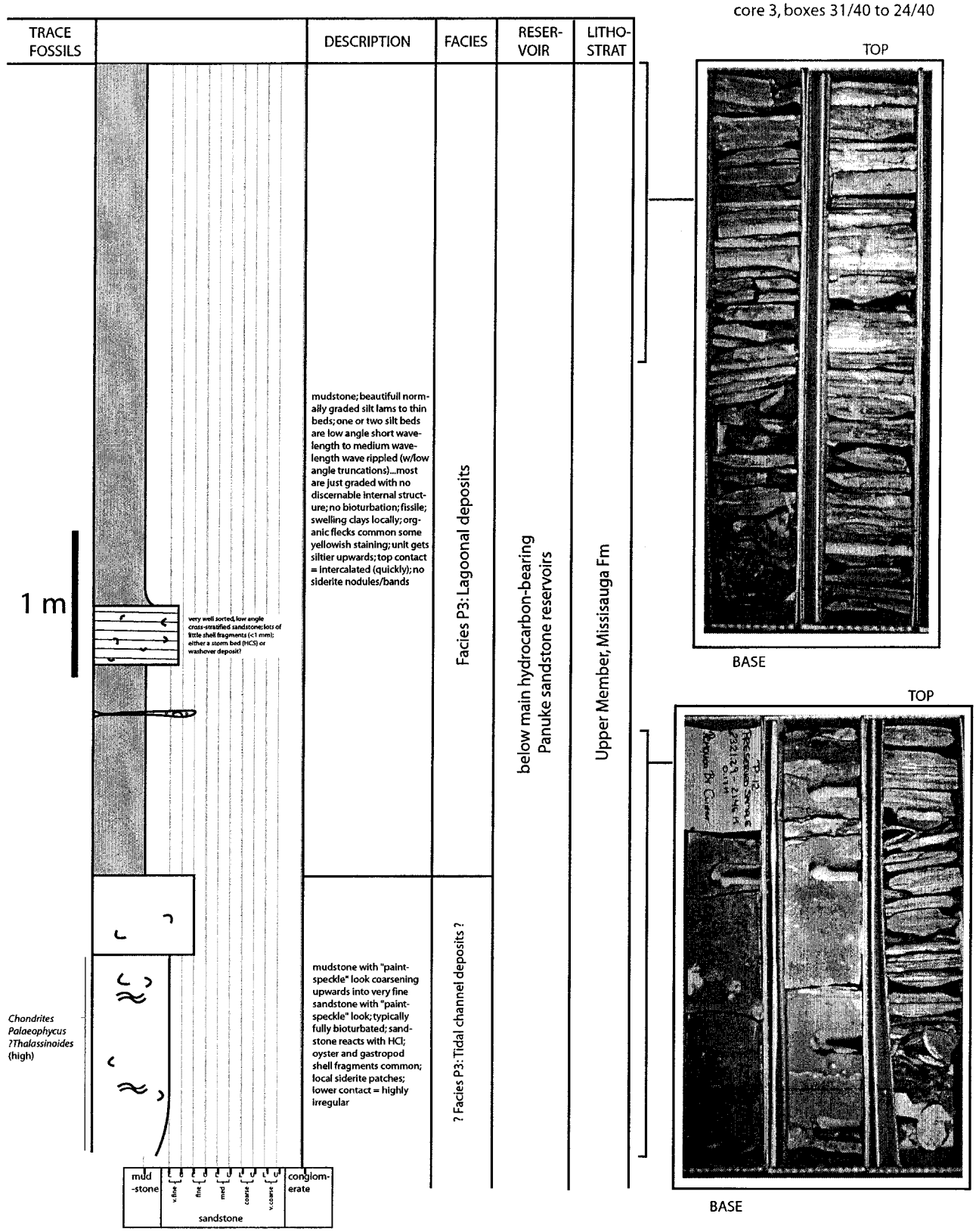
Facies P7: Transgressive lag

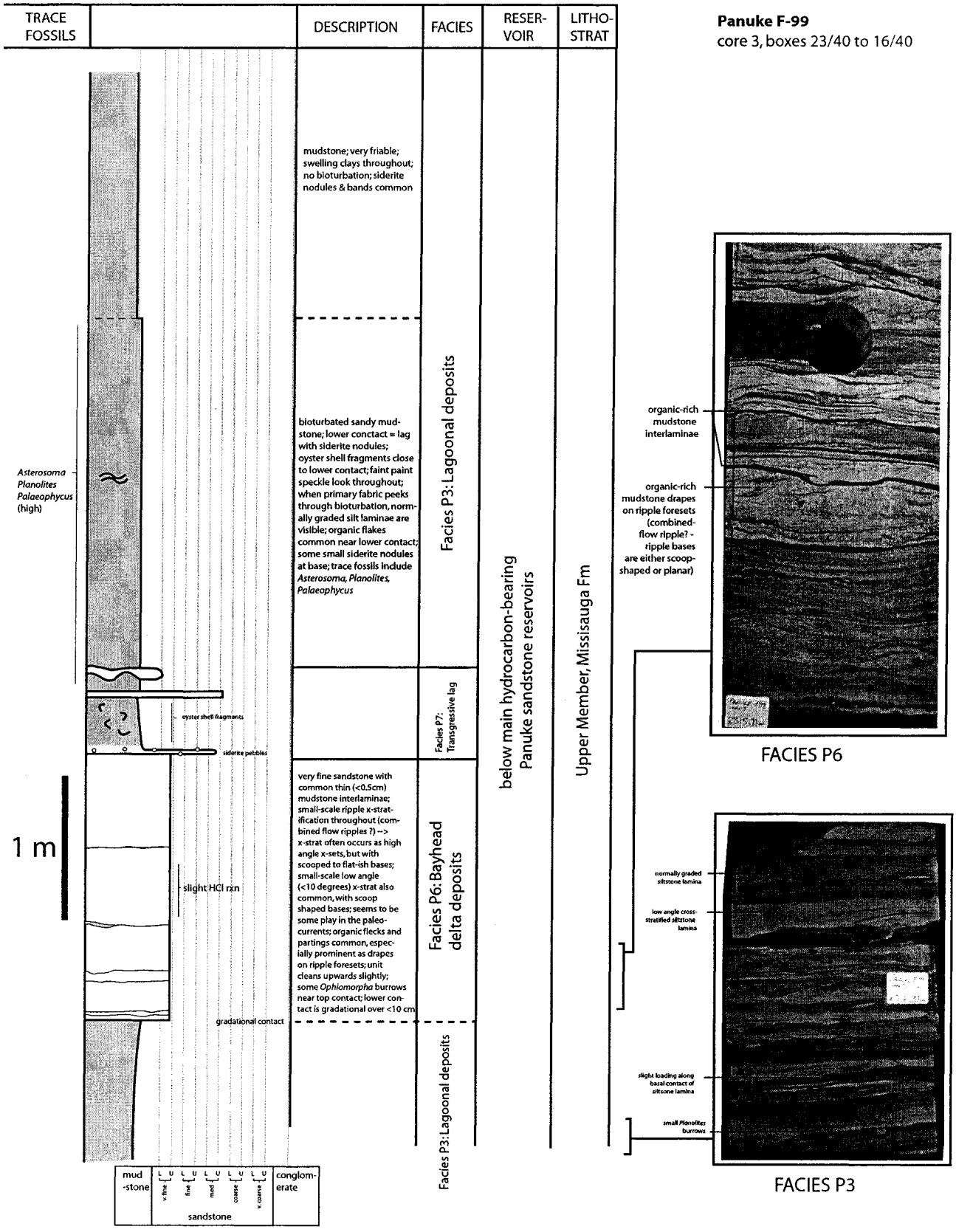


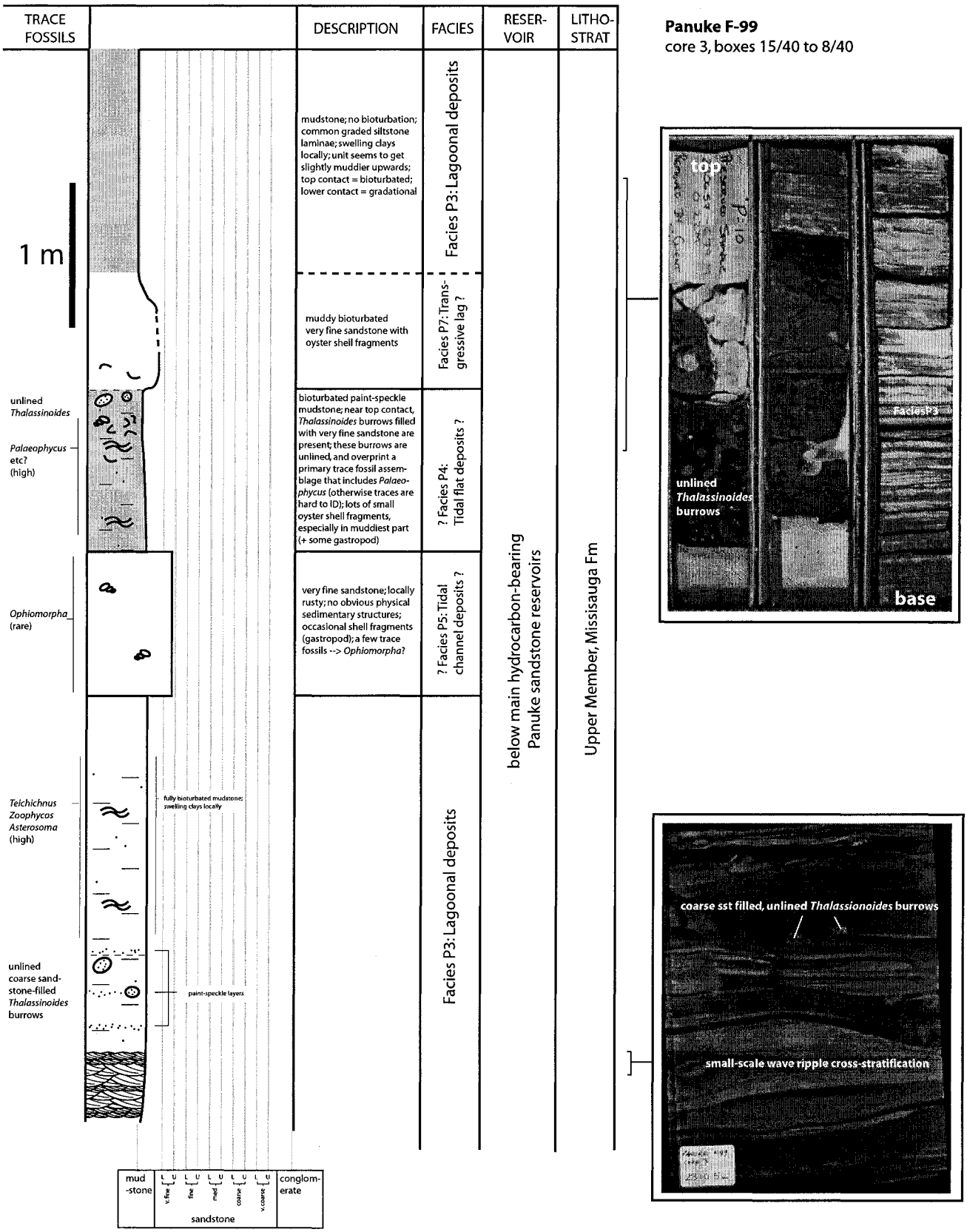
Panuke F-99
core 3, boxes 40/40 to 32/40



Panuke F-99
core 3, boxes 31/40 to 24/40

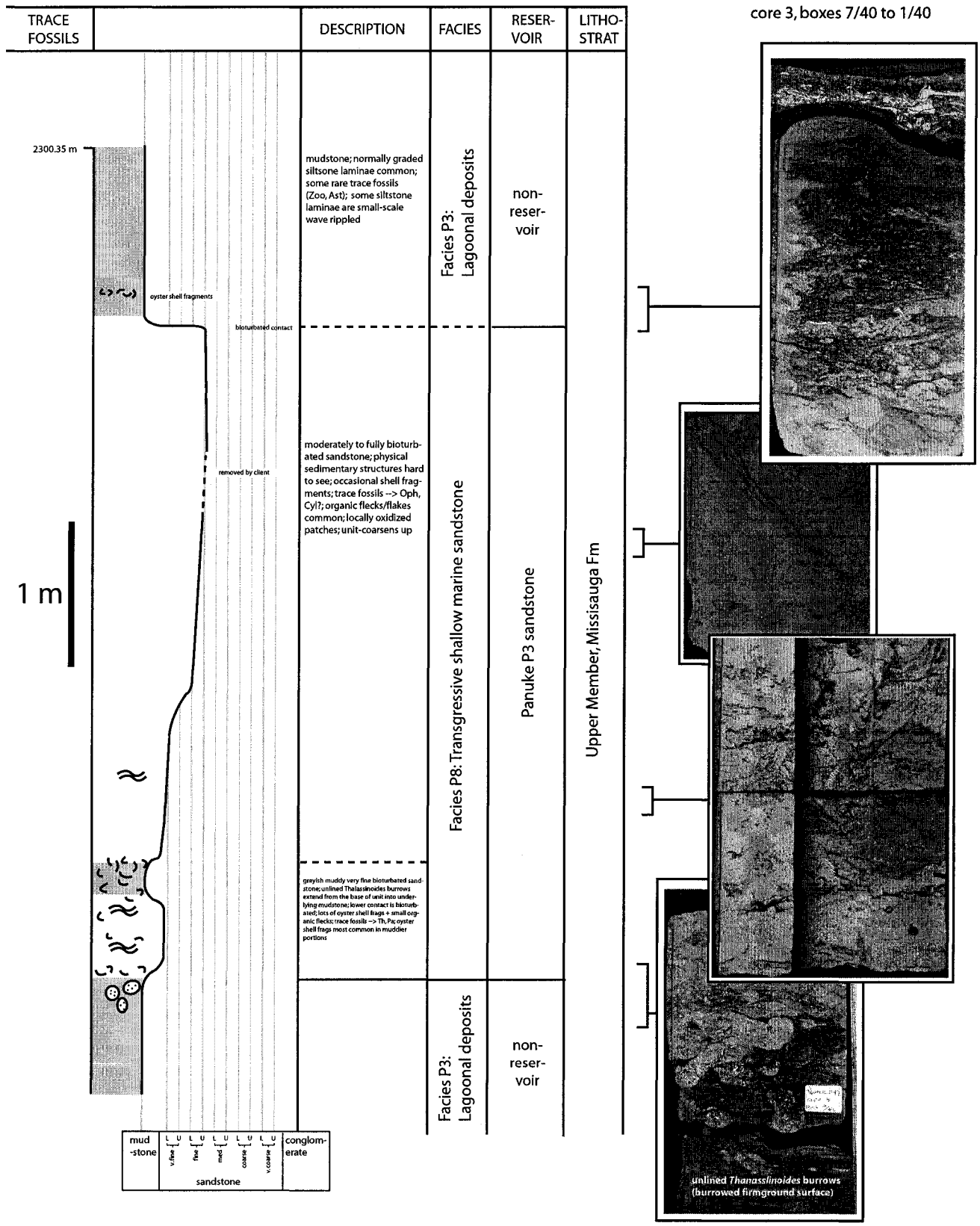


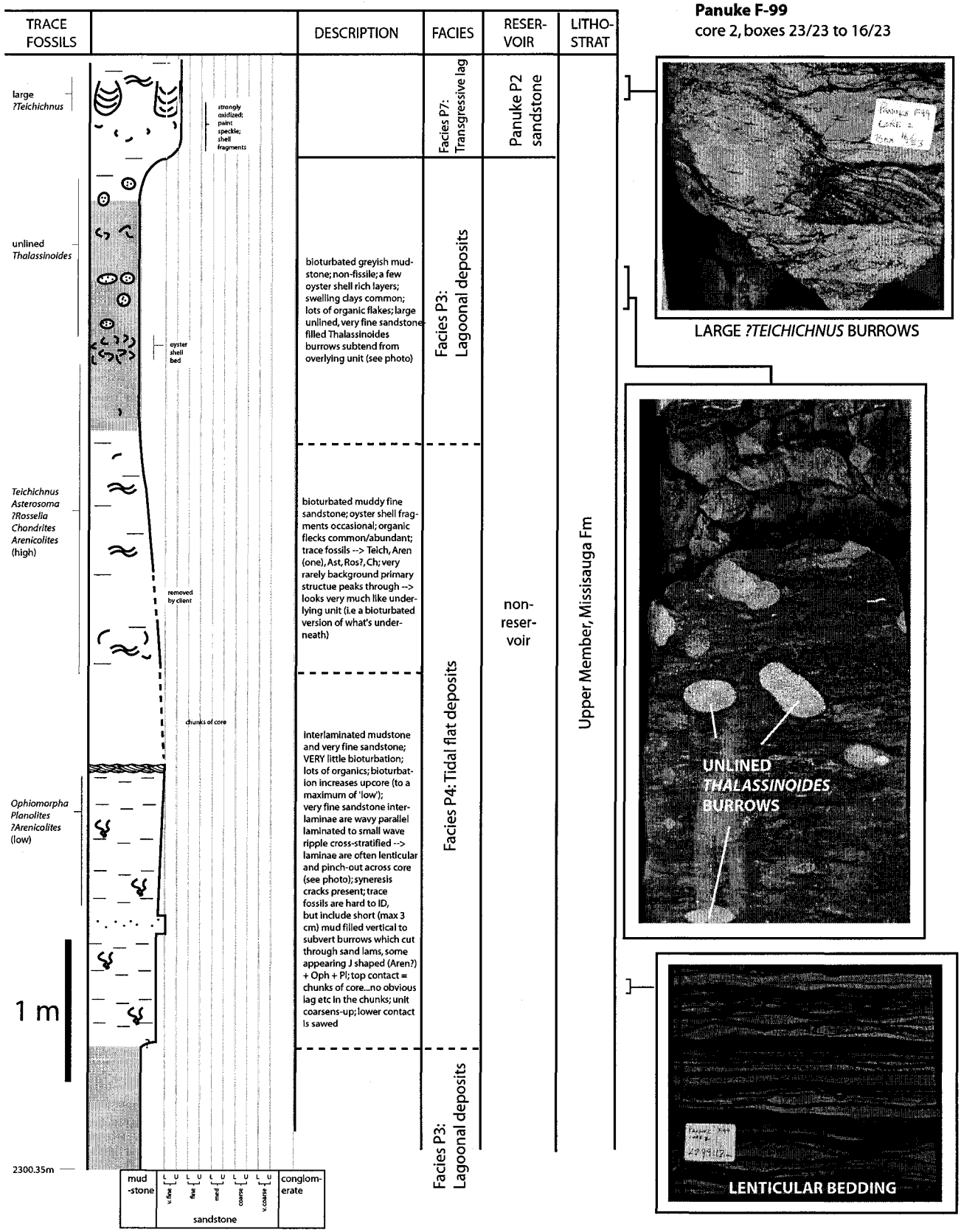

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Panuke F-99
core 3, boxes 23/40 to 16/40
mudstone; very friable; swelling clays throughout; no bioturbation; siderite nodules & bands common
bioturbated sandy mud-stone; lower contact = lag with siderite nodules; oyster shell fragments close to lower contact; faint paint speckle look throughout; when primary fabric peeks through bioturbation, norm-ally graded silt laminae are visible; organic flakes common near lower contact; some small siderite nodules at base; trace fossils include Asterosoma, Planolites, Palaeophycus
Facies P3: Lagoonal deposits
Asterosoma
Planolites
Palaeophycus
(high)
oyster shell fragments
siderite pebbles
Facies P7: Transgressive lag
very fine sandstone with common thin (<0.5cm) mudstone interlaminae; small-scale ripple x-strat-ification throughout (com-bined flow ripples ?) --> x-strat often occurs as high angle x-sets, but with scooped to flat-ish bases; small-scale low angle (<10 degrees) x-strat also common, with scoop shaped bases; seems to be some play in the paleo-currents; organic flecks and partings common, espec-ially prominent as drapes on ripple foresets; unit cleans upwards slightly; some Ophiomorpha burrows near top contact; lower con-tact is gradational over <10 cm
Facies P6: Bayhead delta deposits
below main hydrocarbon-bearing Panuke sandstone reservoirs
Upper Member, Missisauga Fm
1 m
slight HCl rxn
gradational contact
Facies P3: Lagoonal deposits
mud-stone
v. fine
fine
med
coarse
v. coarse
sandstone
conglom-erate
organic-rich mudstone interlaminae
organic-rich mudstone drapes on ripple foresets (combined-flow ripple? - ripple bases are either scoop-shaped or planar)
FACIES P6
normally graded siltstone lamina
low angle cross-stratified siltstone lamina
slight loading along basal contact of siltsone lamina
small Planolites burrows
FACIES P3



Panuke F-99
core 3, boxes 15/40 to 8/40

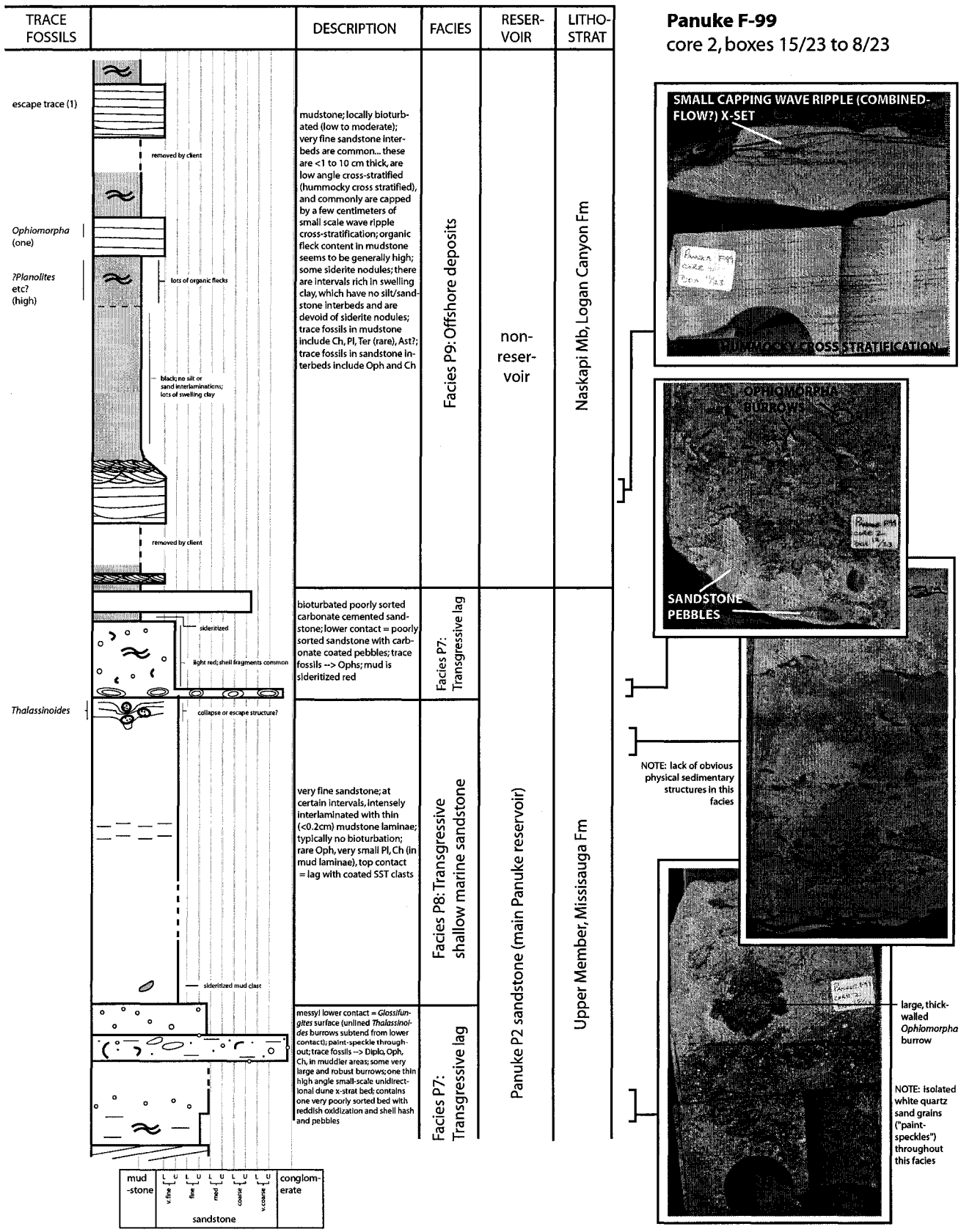
Panuke F-99
core 3, boxes 7/40 to 1/40

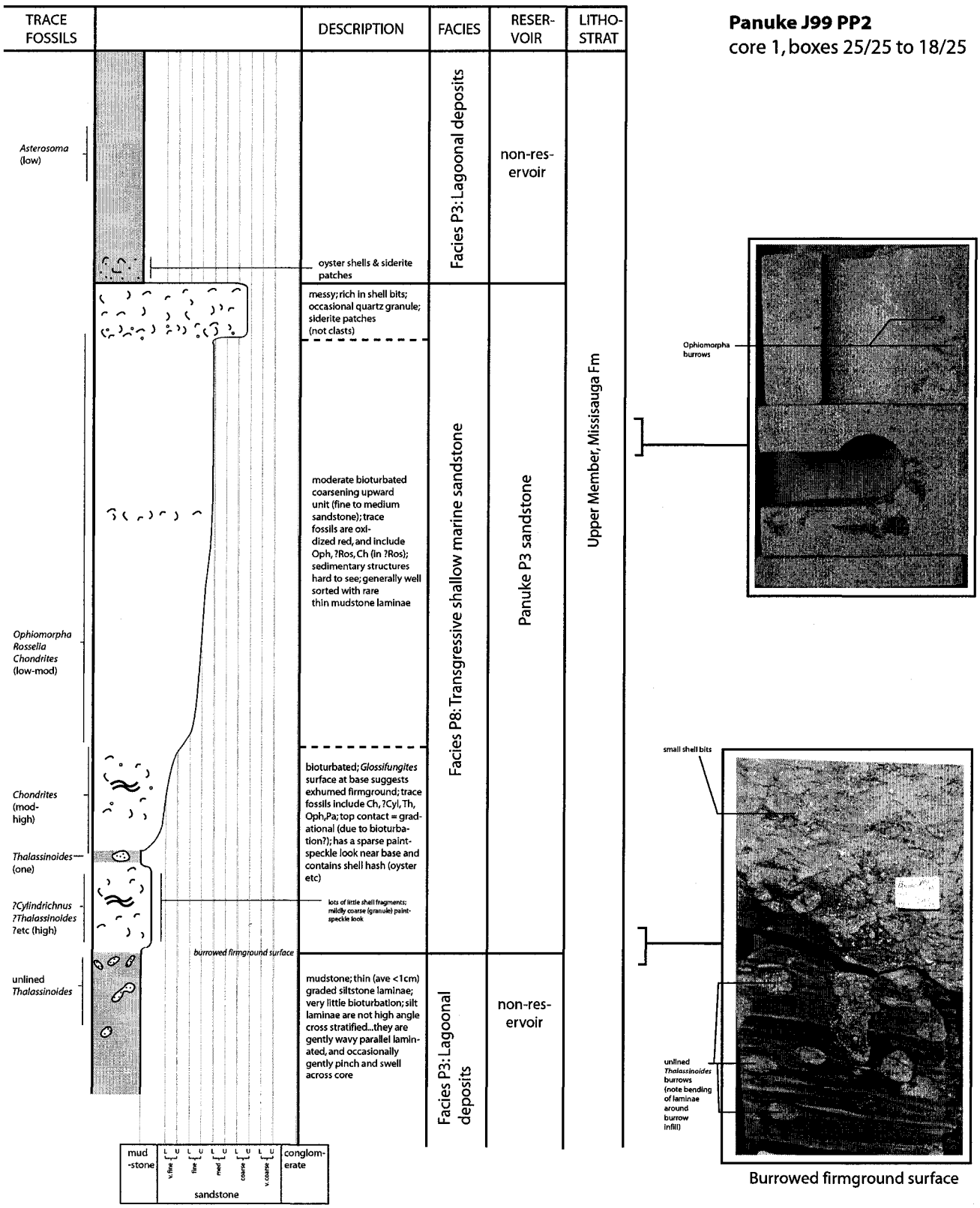




Panuke F-99
core 2, boxes 23/23 to 16/23

LARGE *?TEICHICHNUS* BURROWS

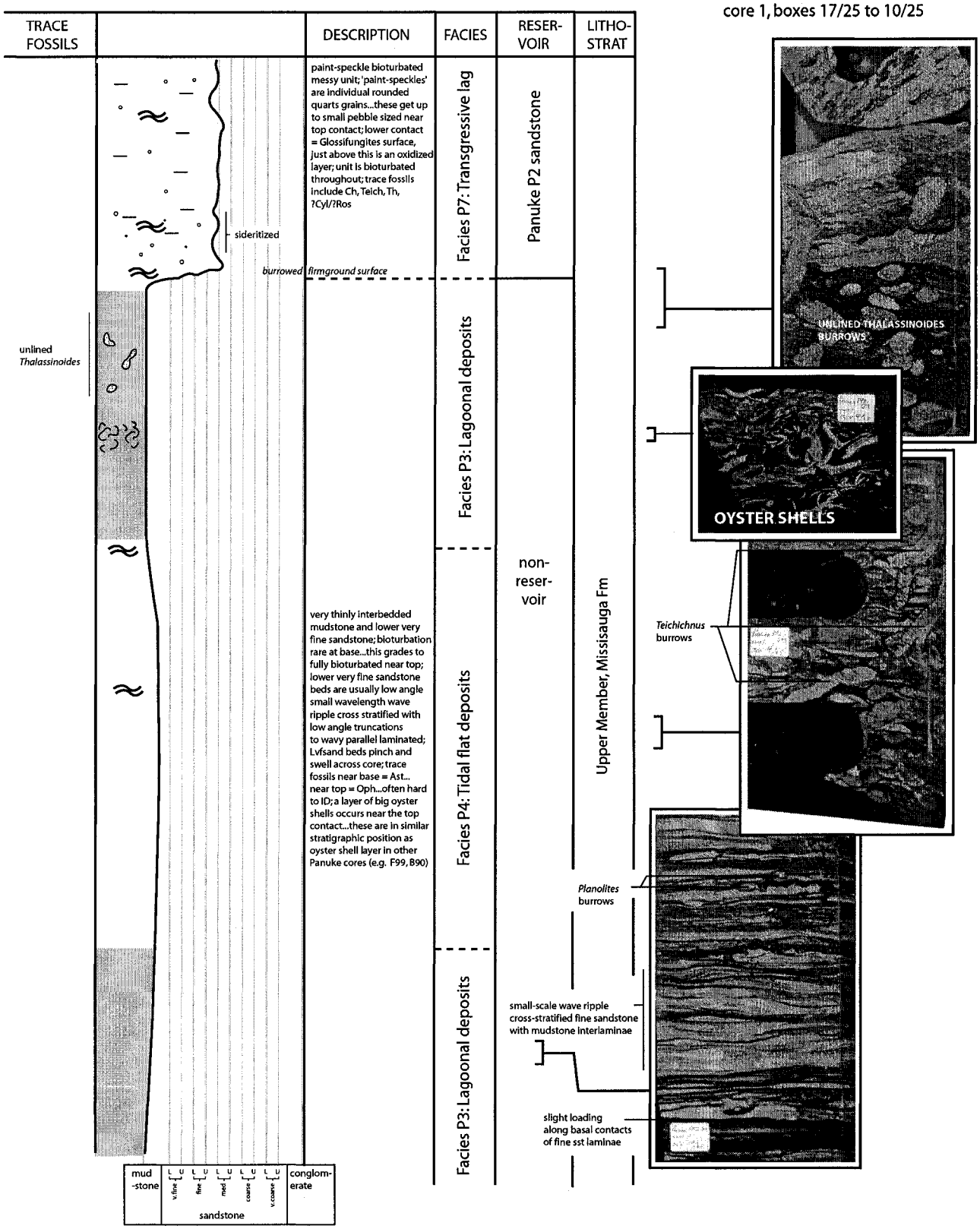

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
escape trace (1)
removed by client
Ophiomorpha (one)
?Planolites etc? (high)
lots of organic flecks
black; no silt or sand interlaminations; lots of swelling clay
removed by client
sideritized
light red; shell fragments common
Thalassinoides
collapse or escape structure?
sideritized mud clast
mudstone; locally bioturbated (low to moderate); very fine sandstone interbeds are common... these are <1 to 10 cm thick, are low angle cross-stratified (hummocky cross stratified), and commonly are capped by a few centimeters of small scale wave ripple cross-stratification; organic fleck content in mudstone seems to be generally high; some siderite nodules; there are intervals rich in swelling clay, which have no silt/sandstone interbeds and are devoid of siderite nodules; trace fossils in mudstone include Ch, Pl, Ter (rare), Ast?; trace fossils in sandstone interbeds include Oph and Ch
Facies P9: Offshore deposits
non-reservoir
Naskapi Mb, Logan Canyon Fm
bioturbated poorly sorted carbonate cemented sandstone; lower contact = poorly sorted sandstone with carbonate coated pebbles; trace fossils --> Ophs; mud is sideritized red
Facies P7: Transgressive lag
very fine sandstone; at certain intervals, intensely interlaminated with thin (<0.2cm) mudstone laminae; typically no bioturbation; rare Oph, very small Pl, Ch (in mud laminae), top contact = lag with coated SST clasts
Facies P8: Transgressive shallow marine sandstone
Panuke P2 sandstone (main Panuke reservoir)
Upper Member, Missisauga Fm
messyl lower contact = Glossifungites surface (unlined Thalassinoides burrows subtend from lower contact); paint-speckle throughout; trace fossils --> Diplo, Oph, Ch, in muddier areas; some very large and robust burrows; one thin high angle small-scale unidirectional dune x-strat bed; contains one very poorly sorted bed with reddish oxidization and shell hash and pebbles
Facies P7: Transgressive lag
mud -stone
v. fine
fine
med
coarse
v. coarse
sandstone
conglom-erate
Panuke F-99
core 2, boxes 15/23 to 8/23
SMALL CAPPING WAVE RIPPLE (COMBINED-FLOW?) X-SET
HUMMOCKY CROSS STRATIFICATION
OPHIOMORPHA BURROWS
SANDSTONE PEBBLES
NOTE: lack of obvious physical sedimentary structures in this facies
large, thick-walled Ophiomorpha burrow
NOTE: isolated white quartz sand grains ("paint-speckles") throughout this facies

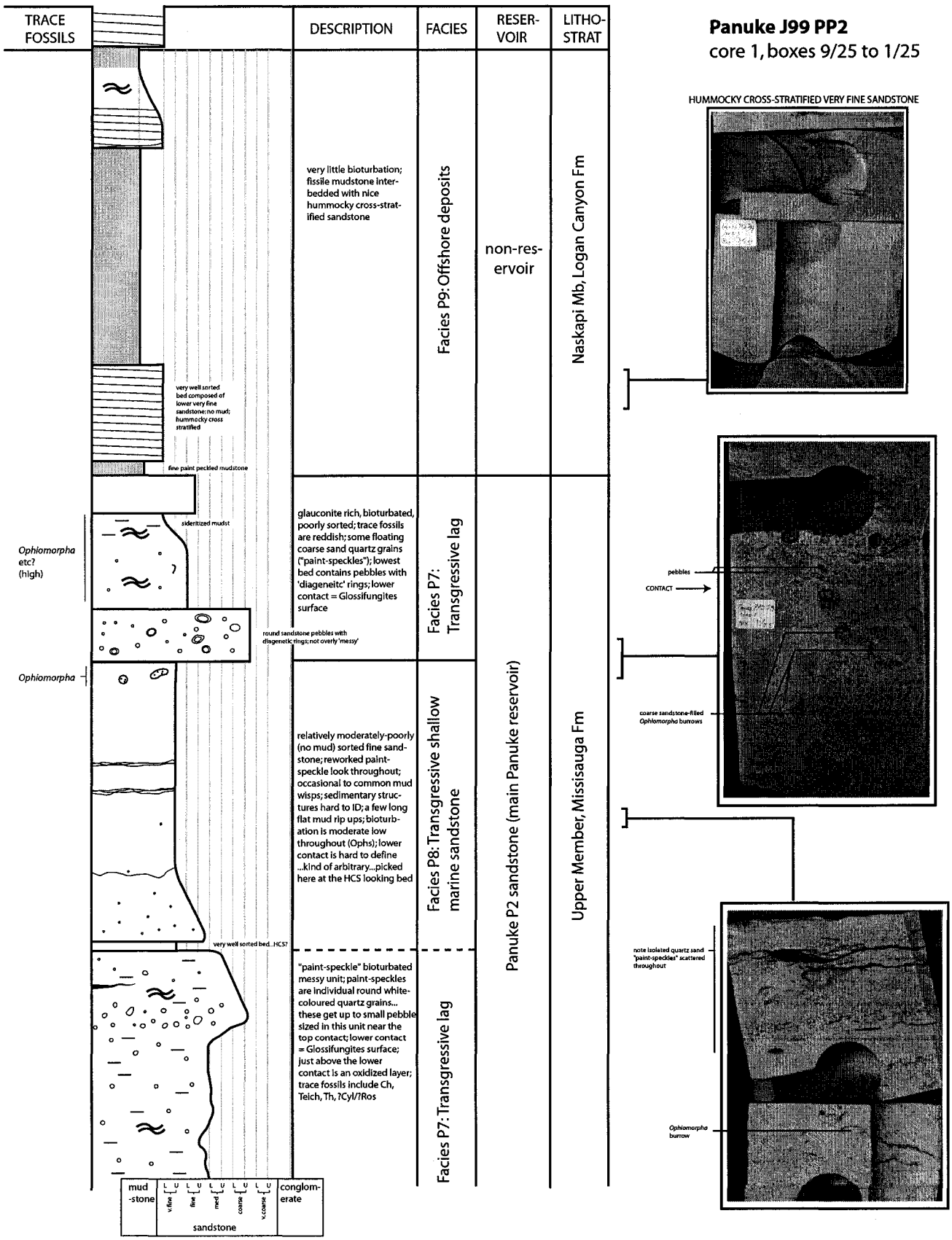


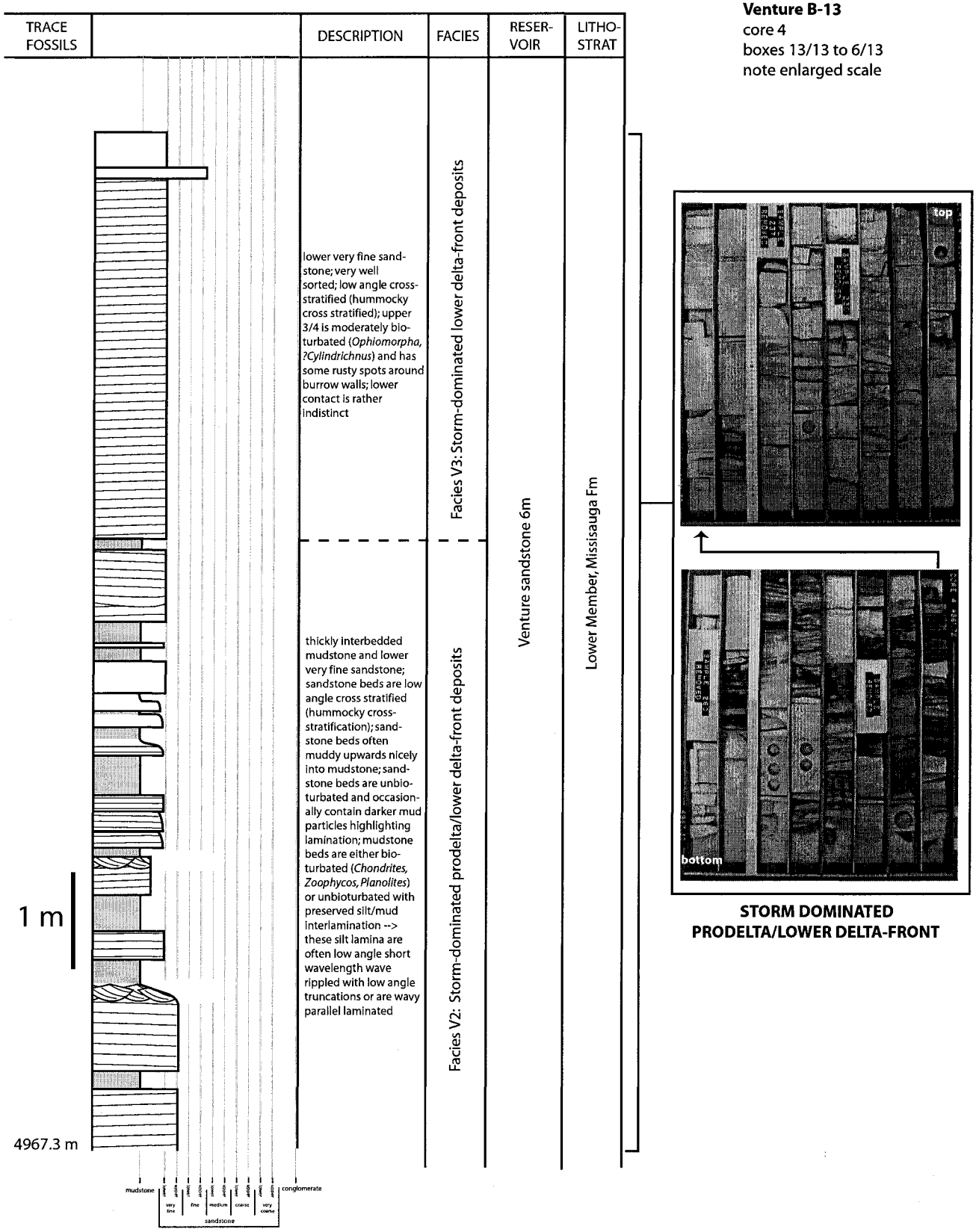
Panuke J99 PP2
core 1, boxes 25/25 to 18/25

Burrowed firmground surface

Panuke J99 PP2
core 1, boxes 17/25 to 10/25



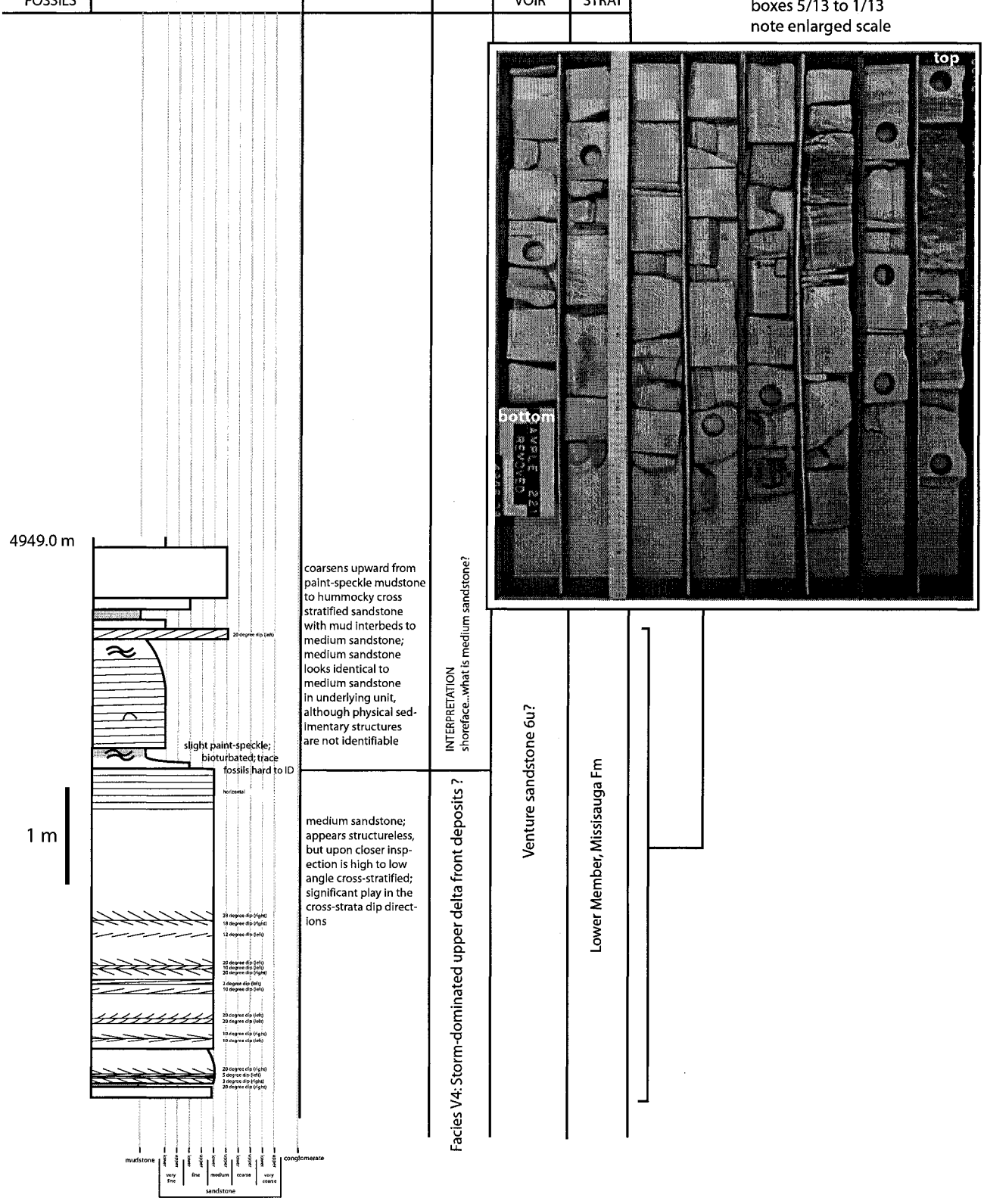

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
very little bioturbation; fissile mudstone inter-bedded with nice hummocky cross-strat-ified sandstone
Facies P9: Offshore deposits
non-res-ervoir
Naskapi Mb, Logan Canyon Fm
very well sorted bed composed of lower very fine sandstone; no mud; hummocky cross stratified
fine paint peckled mudstone
sideritized mudst
Ophiomorpha etc? (high)
glauconite rich, bioturbated, poorly sorted; trace fossils are reddish; some floating coarse sand quartz grains ("paint-speckles"); lowest bed contains pebbles with 'diageneitc' rings; lower contact = Glossifungites surface
Facies P7: Transgressive lag
round sandstone pebbles with diagenetic rings; not overly 'messy'
Ophiomorpha
relatively moderately-poorly (no mud) sorted fine sand-stone; reworked paint-speckle look throughout; occasional to common mud wisps; sedimentary struc-tures hard to ID; a few long flat mud rip ups; bioturb-ation is moderate low throughout (Ophs); lower contact is hard to define ...kind of arbitrary...picked here at the HCS looking bed
Facies P8: Transgressive shallow marine sandstone
Panuke P2 sandstone (main Panuke reservoir)
Upper Member, Missisauga Fm
very well sorted bed...HCS?
"paint-speckle" bioturbated messy unit; paint-speckles are individual round white-coloured quartz grains... these get up to small pebble sized in this unit near the top contact; lower contact = Glossifungites surface; just above the lower contact is an oxidized layer; trace fossils include Ch, Teich, Th, ?Cyl/?Ros
Facies P7: Transgressive lag
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
Panuke J99 PP2
core 1, boxes 9/25 to 1/25
HUMMOCKY CROSS-STRATIFIED VERY FINE SANDSTONE
pebbles
CONTACT
coarse sandstone-filled Ophiomorpha burrows
note isolated quartz sand "paint-speckles" scattered throughout
Ophiomorpha burrow

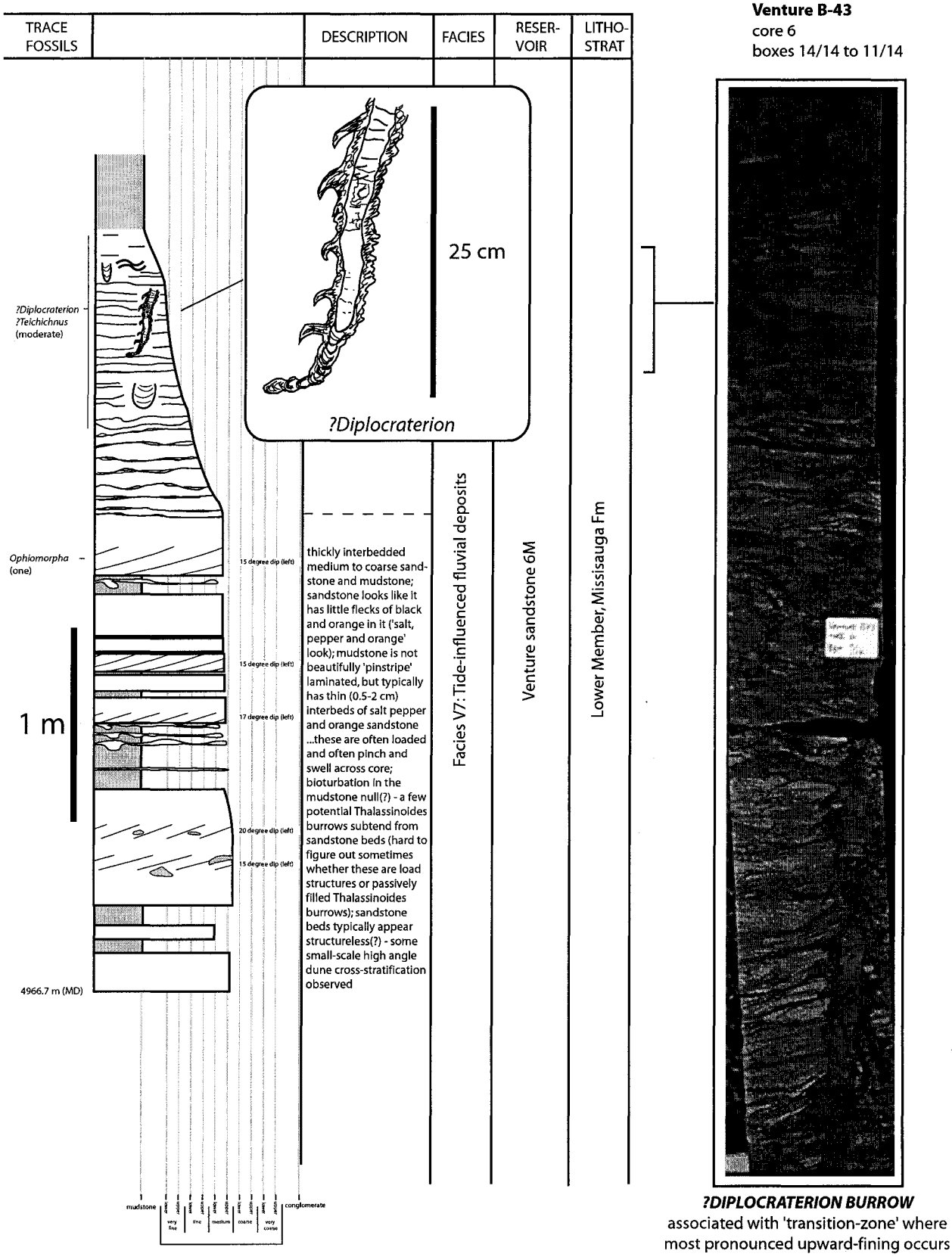


Venture B-13
core 4
boxes 13/13 to 6/13
note enlarged scale

STORM DOMINATED PRODELTA/LOWER DELTA-FRONT

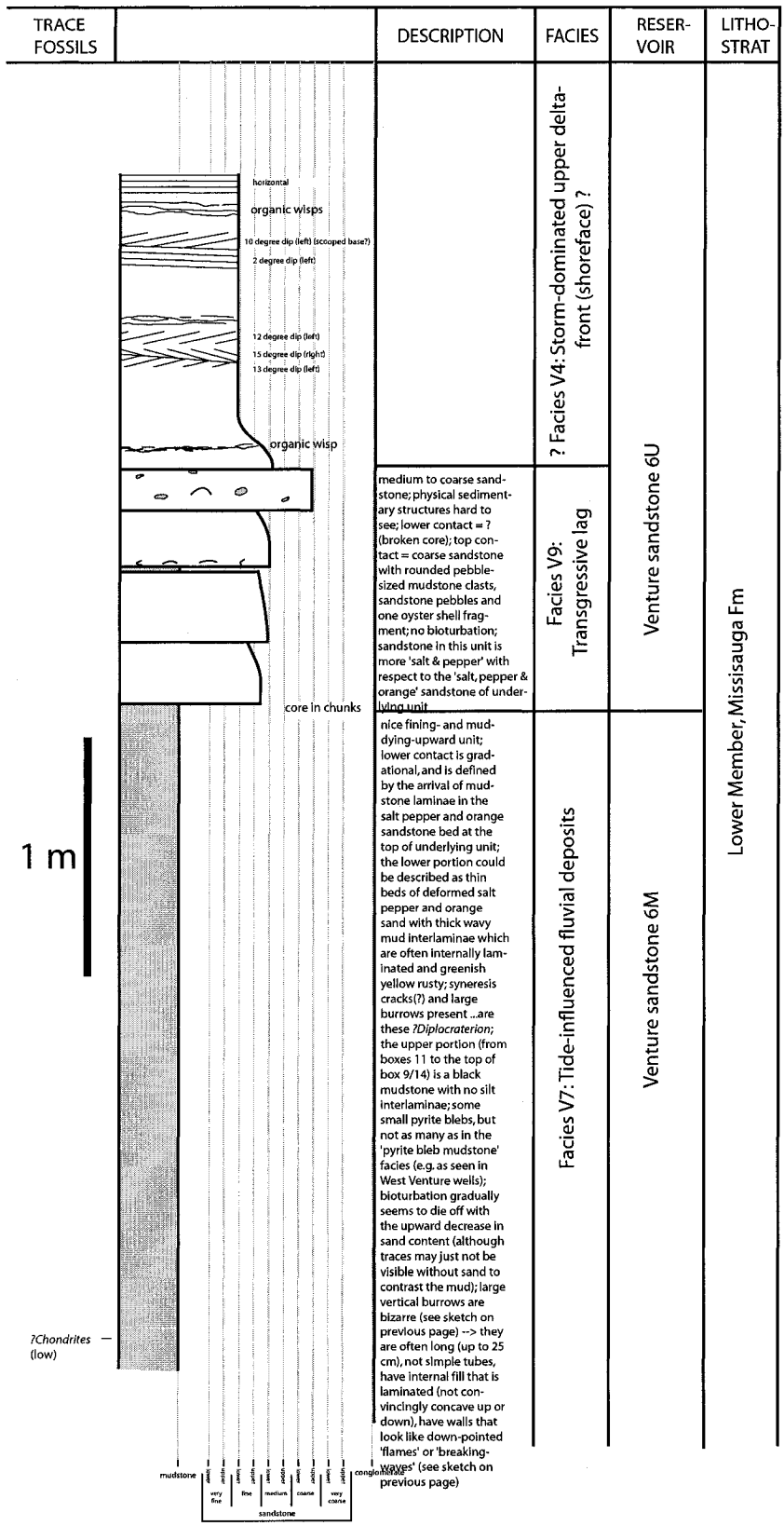
Venture B-13
core 4
boxes 5/13 to 1/13
note enlarged scale



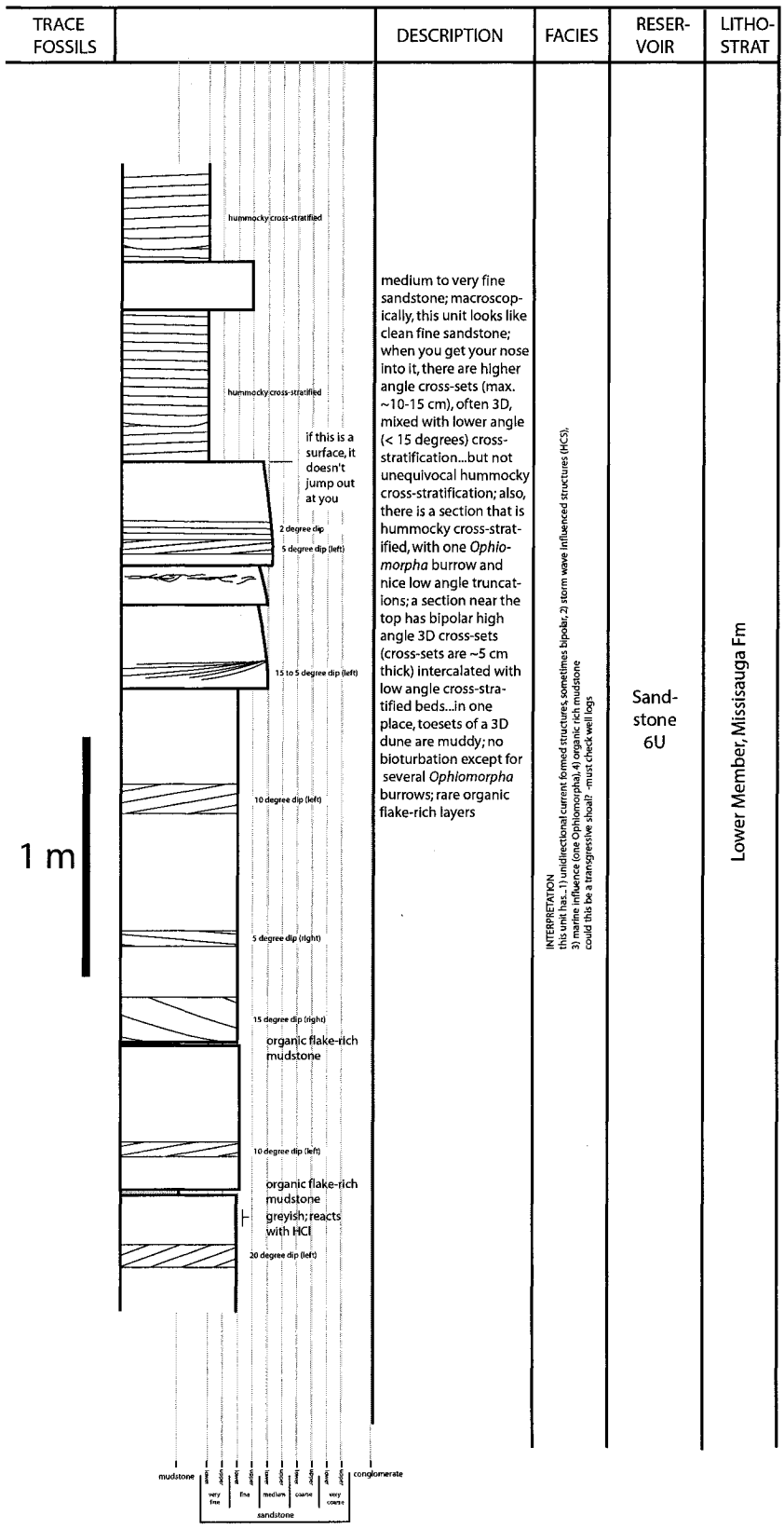


?DIPLOCRATERION BURROW
associated with 'transition-zone' where most pronounced upward-fining occurs

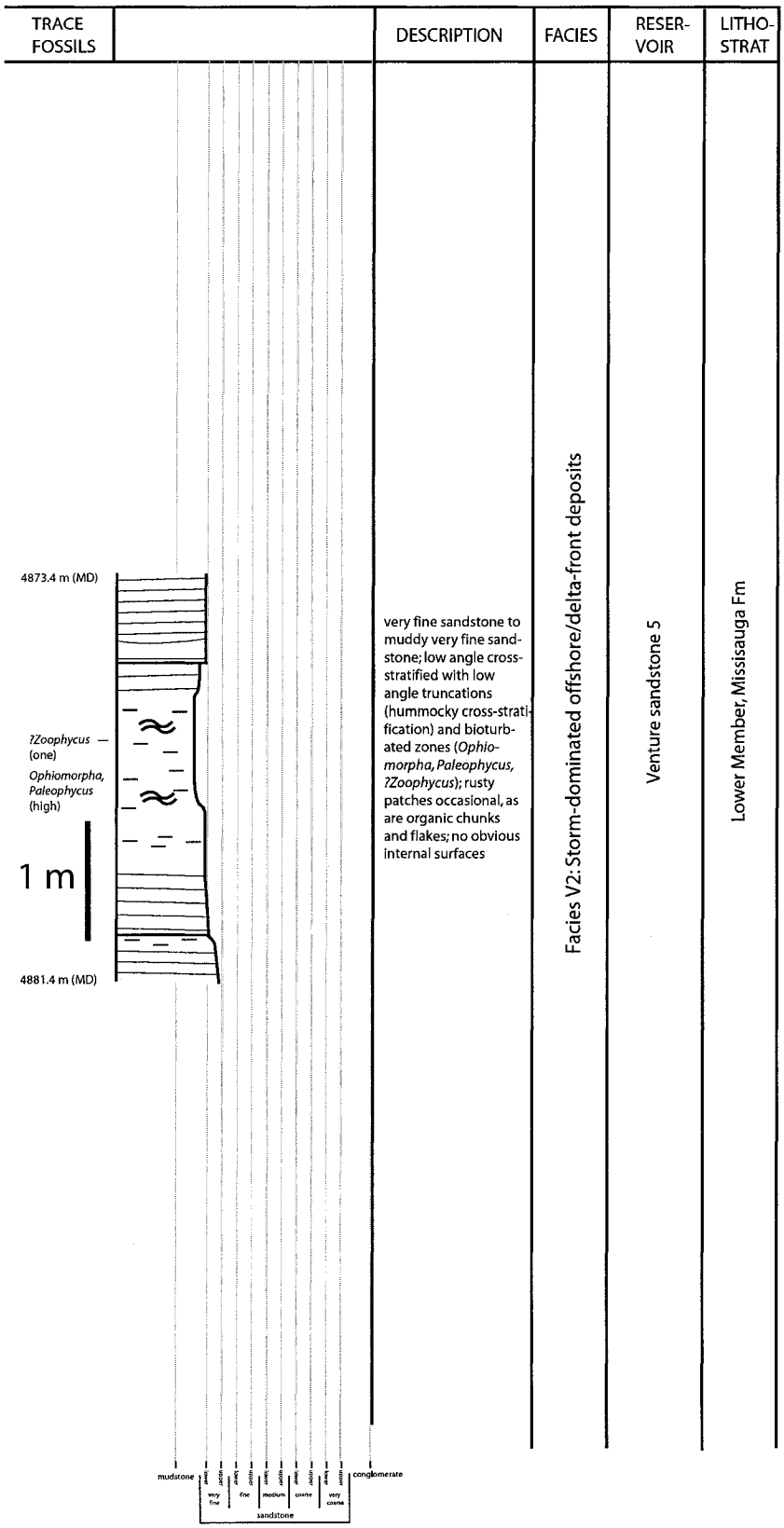
Venture B-43
core 6
boxes 10/14 to 7/14



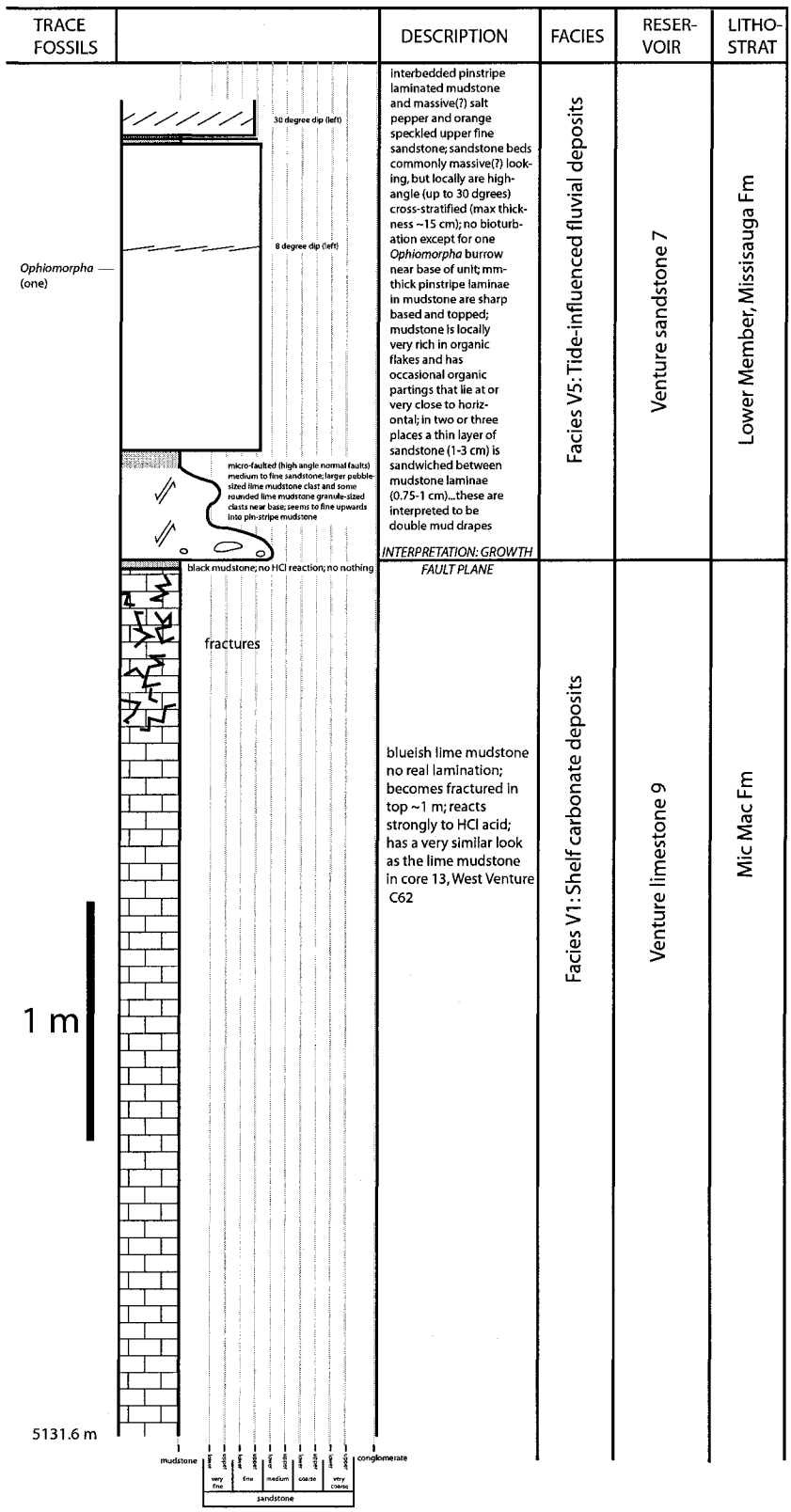
Venture B-43
core 6
boxes 6/14 to3/14



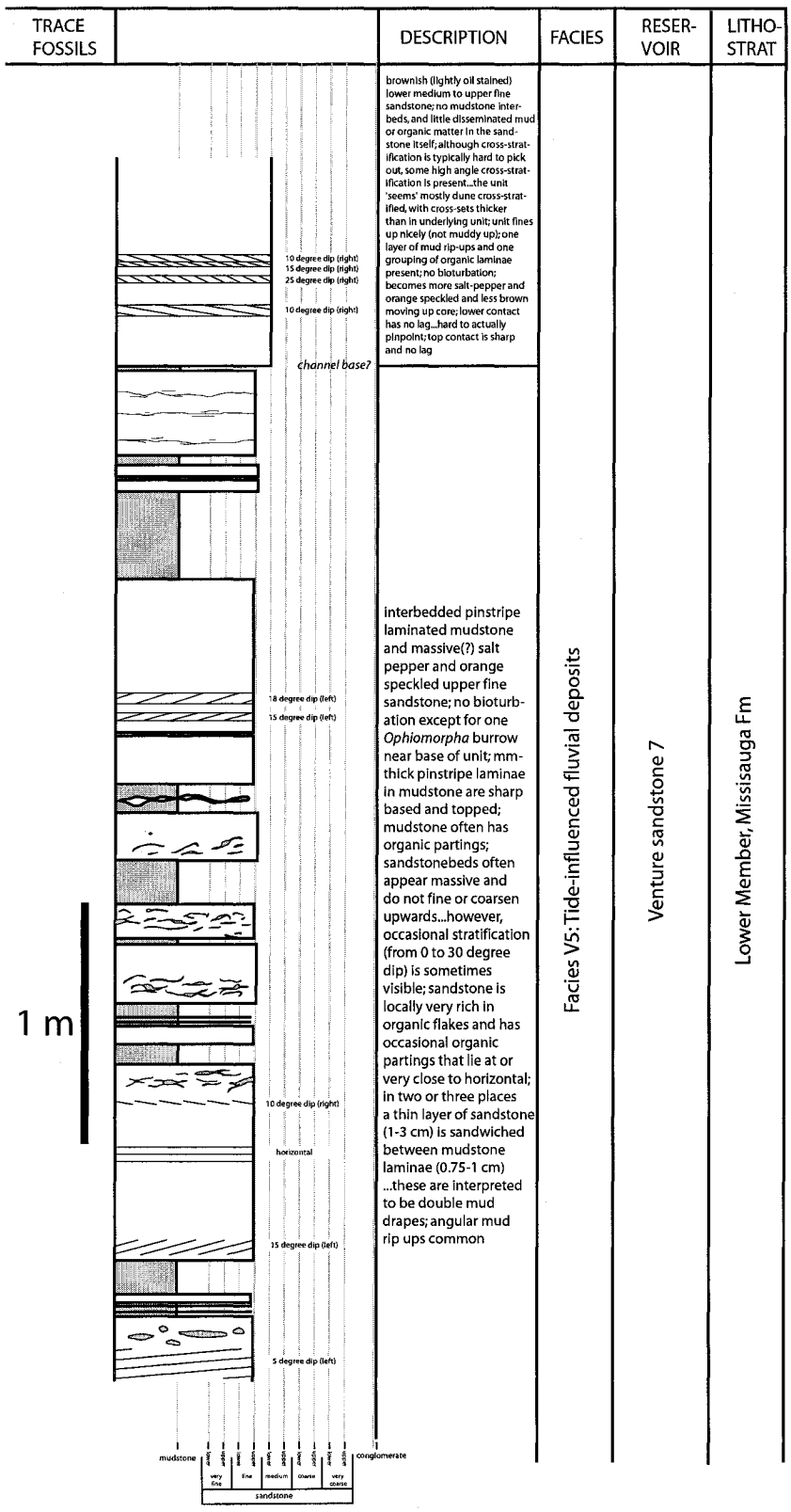
Venture B-43
core 5
boxes 4/4 to 1/4
note scale

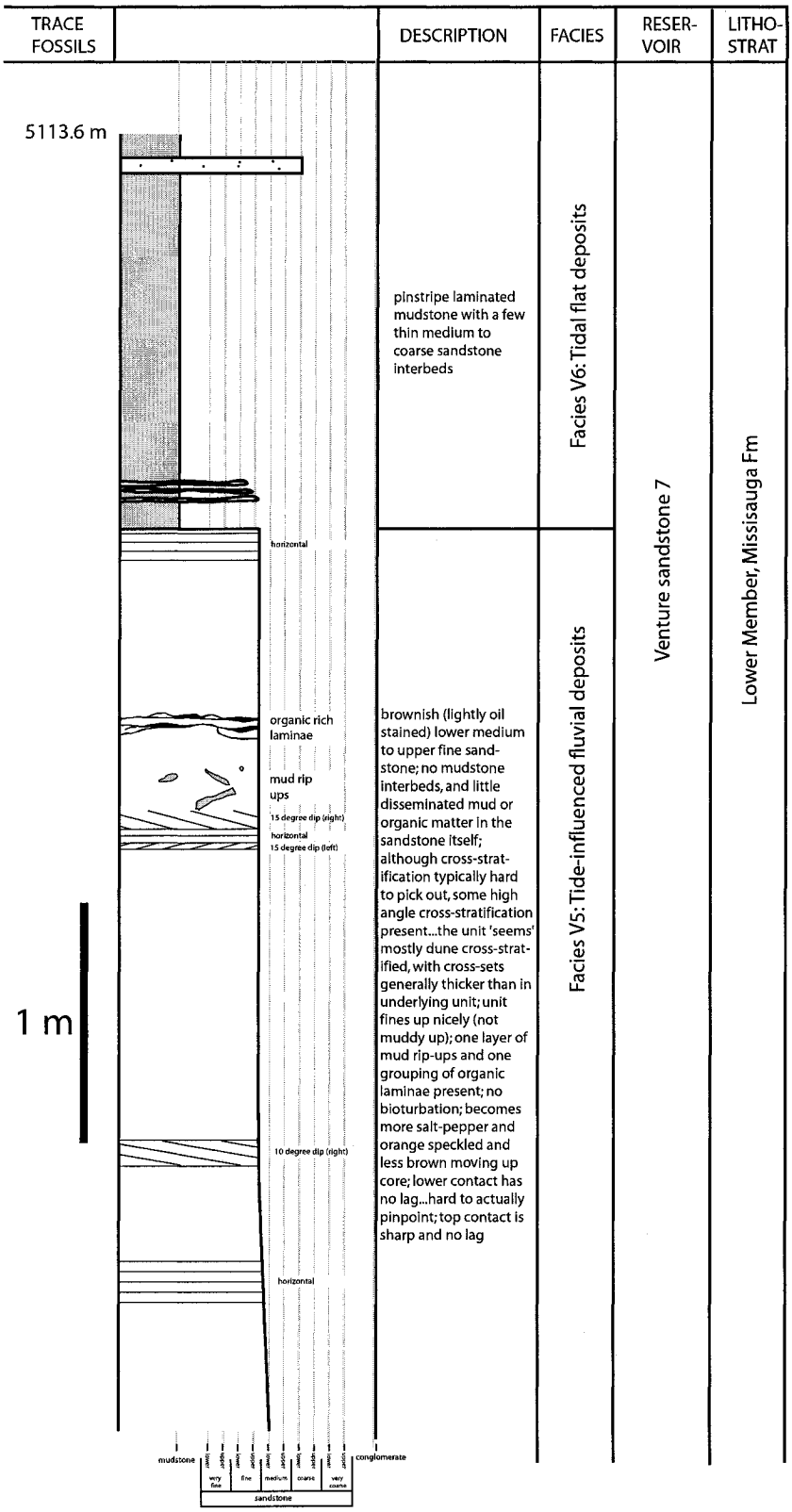


Venture B-52
core 5
boxes 12/12 to 9/12

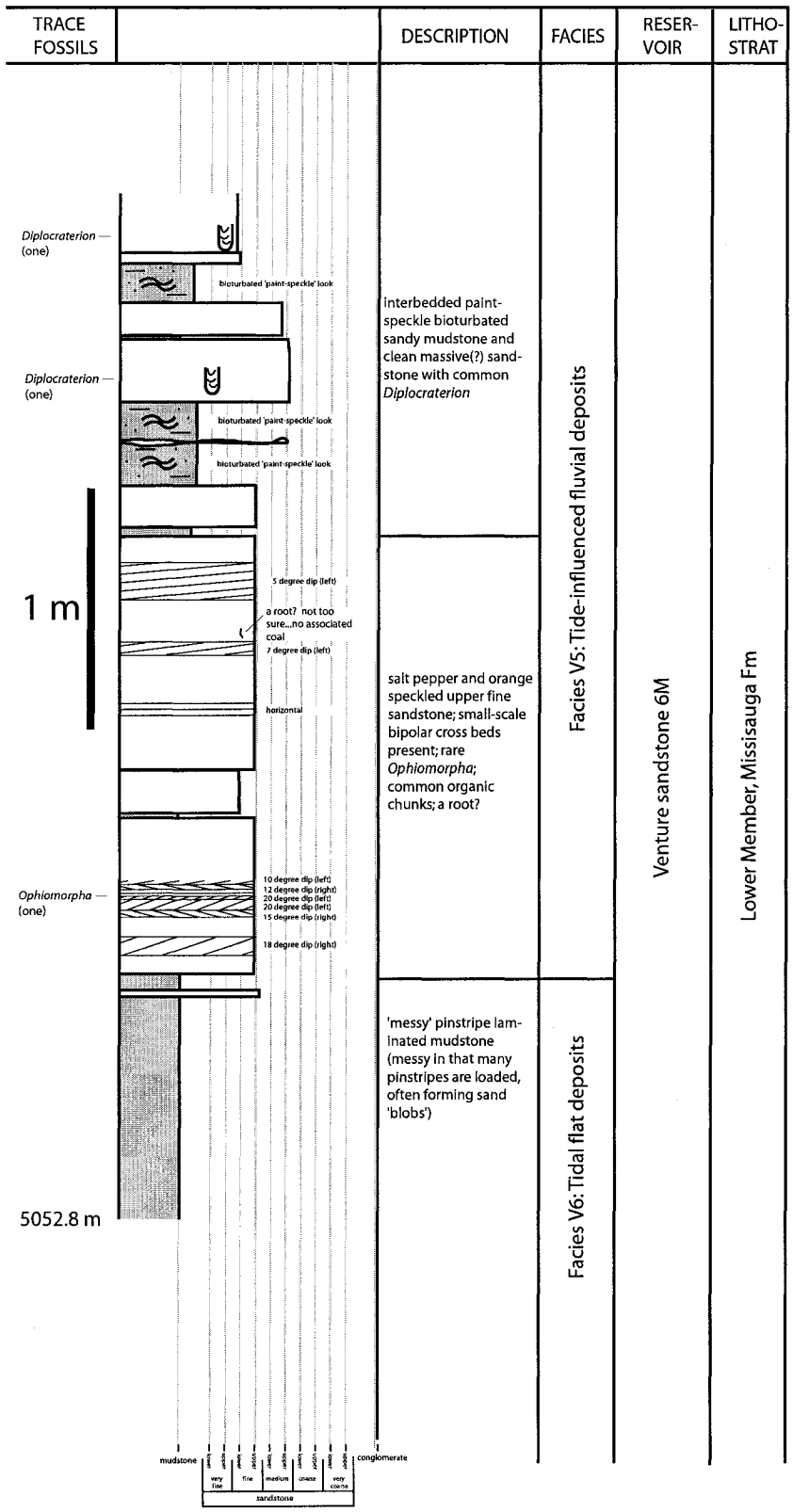


Venture B-52
core 5
boxes 8/12 to 5/12

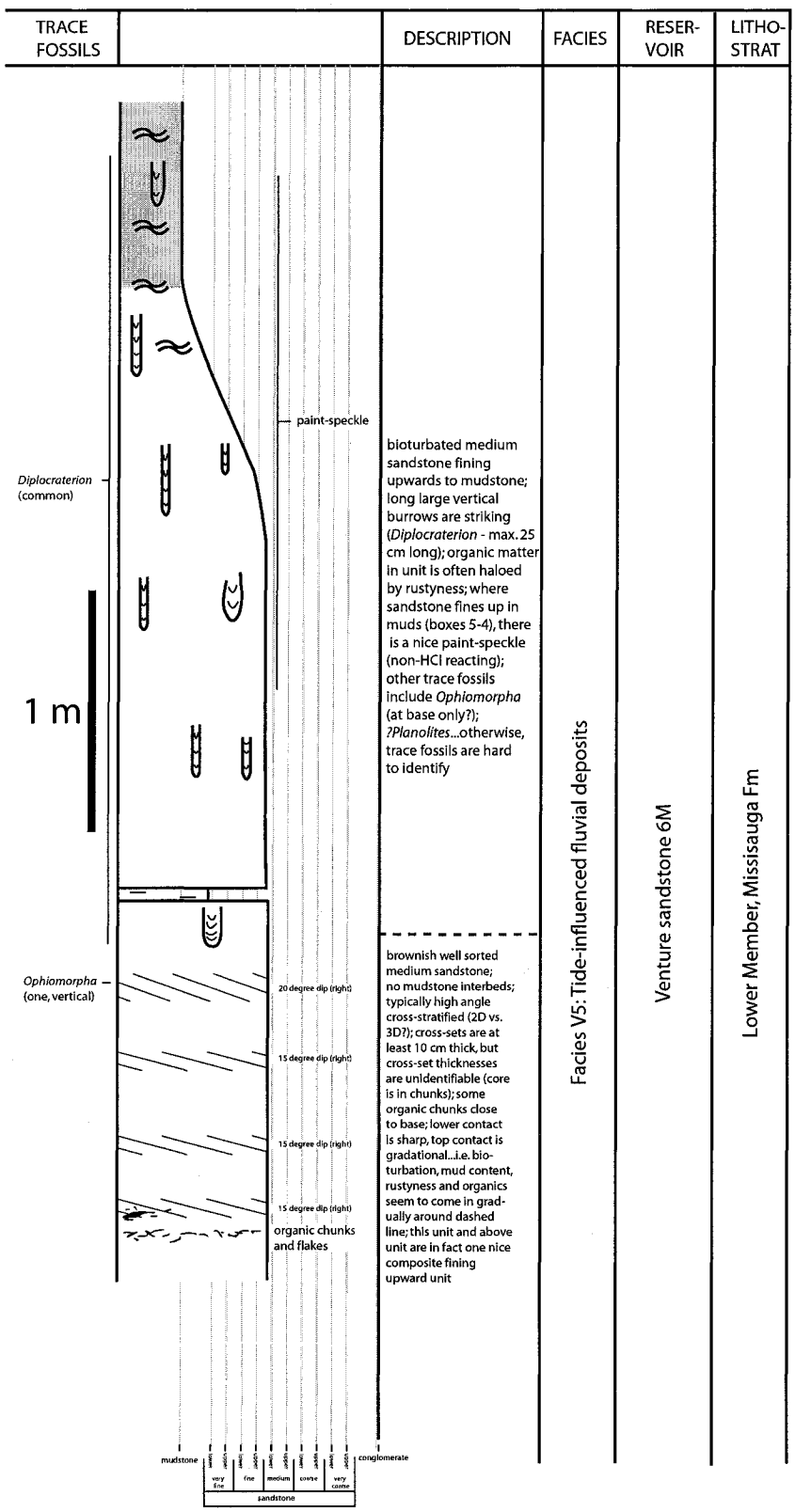




Venture B-52
core 5
boxes 4/12 to 1/12

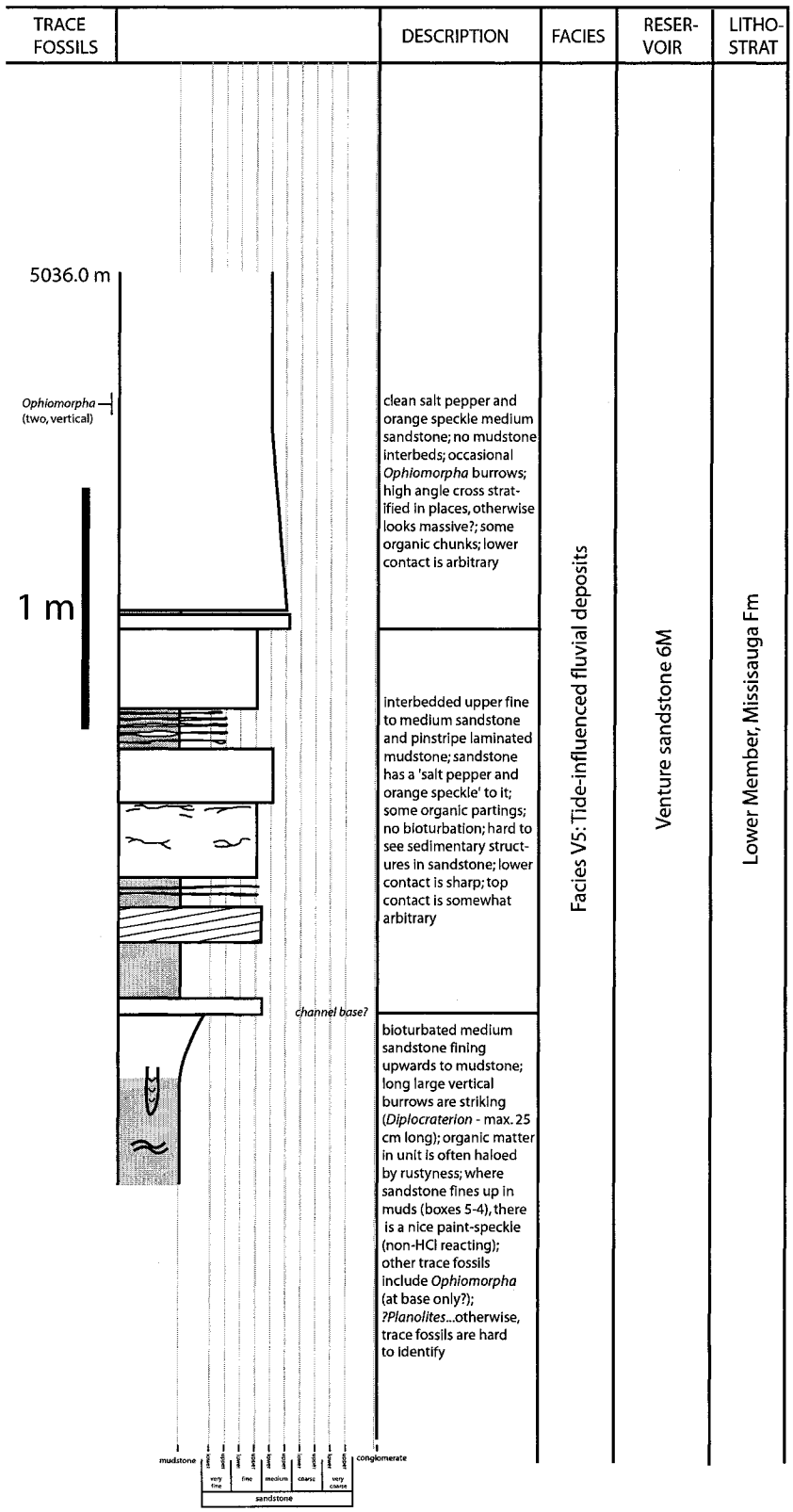


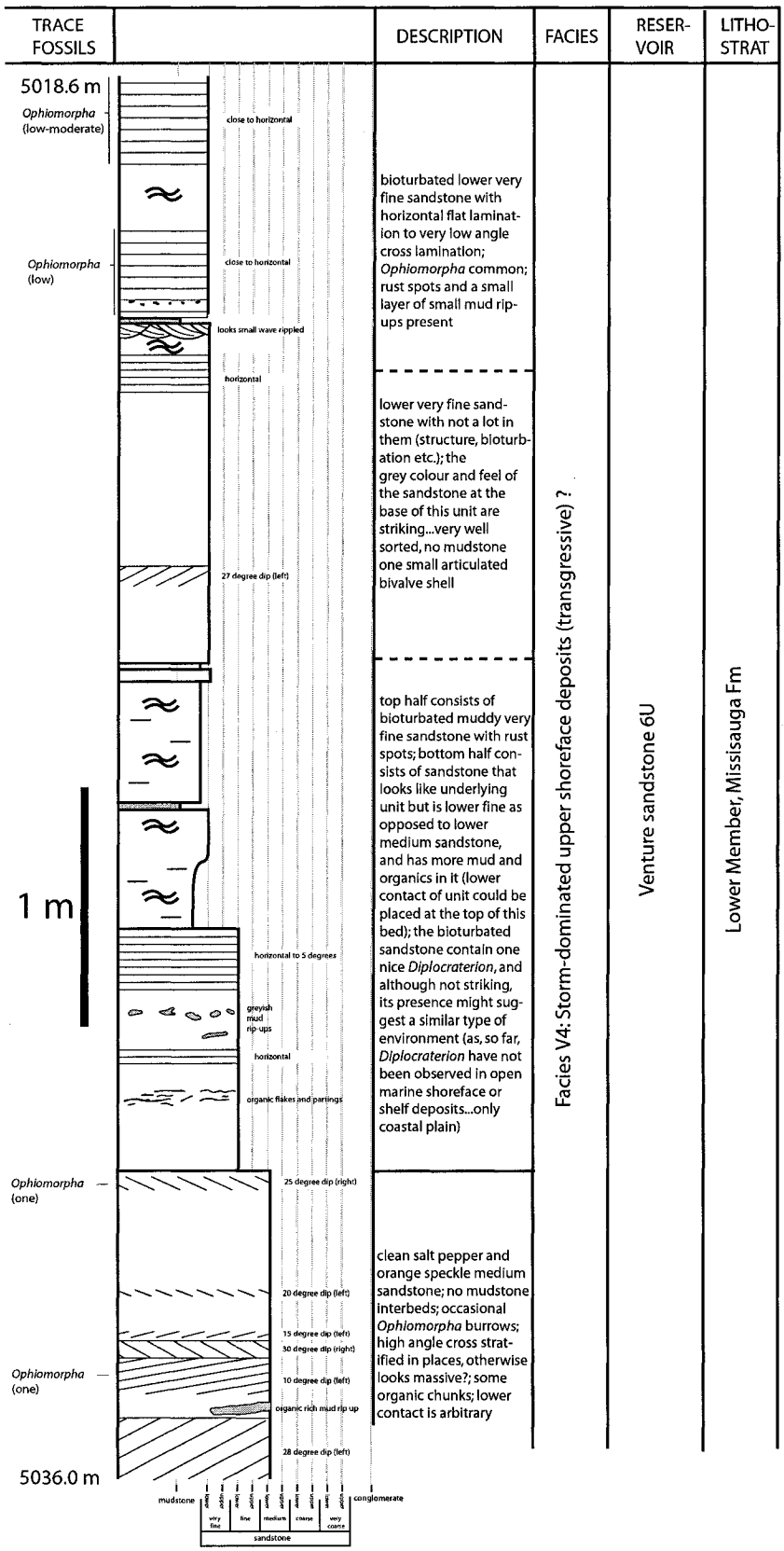
Venture B-52
core 4
boxes 11/11 to 8/11



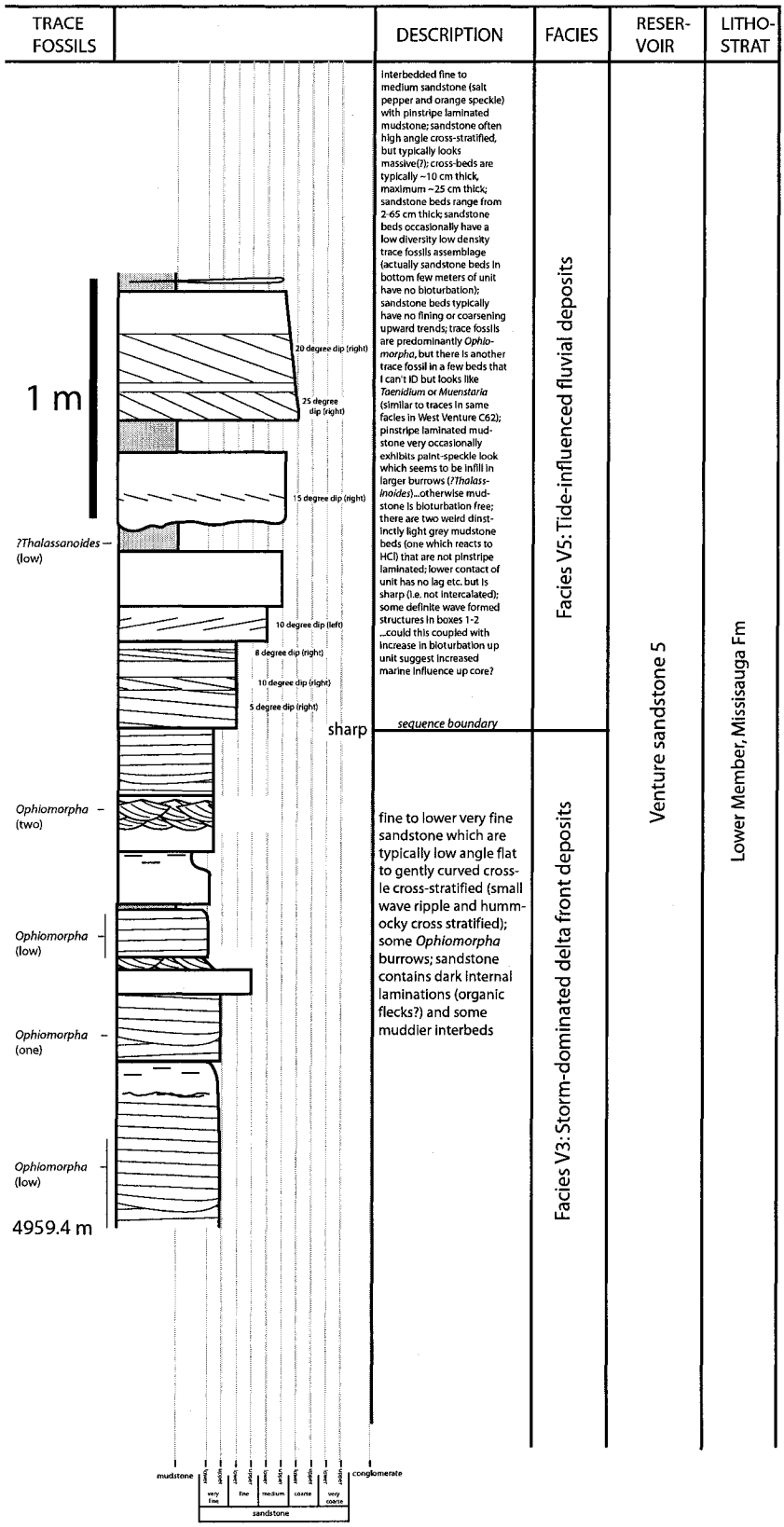
Venture B-52
core 4
boxes 7/11 to 4/11

Venture B-52
core 4
boxes 3/11 to 1/11

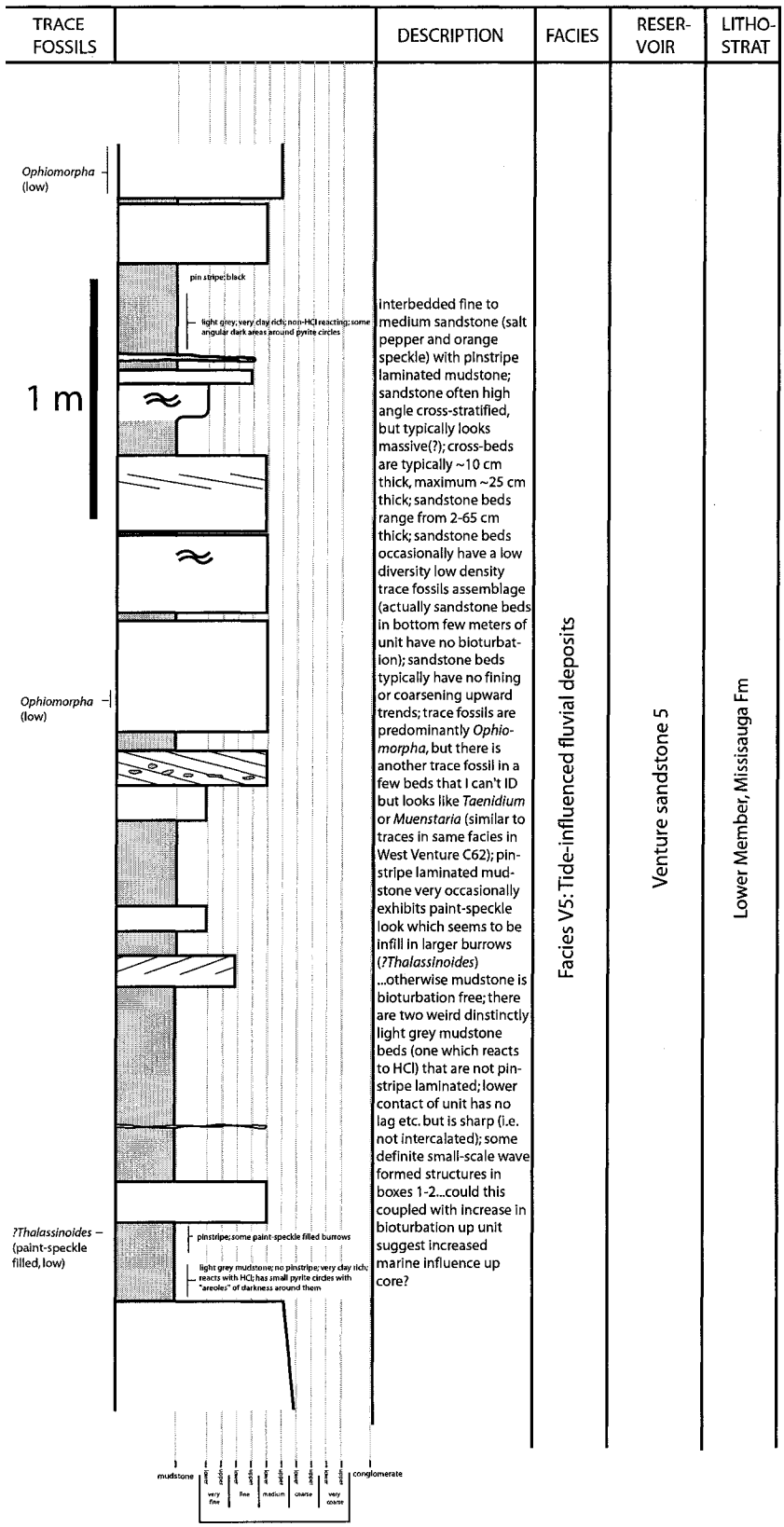




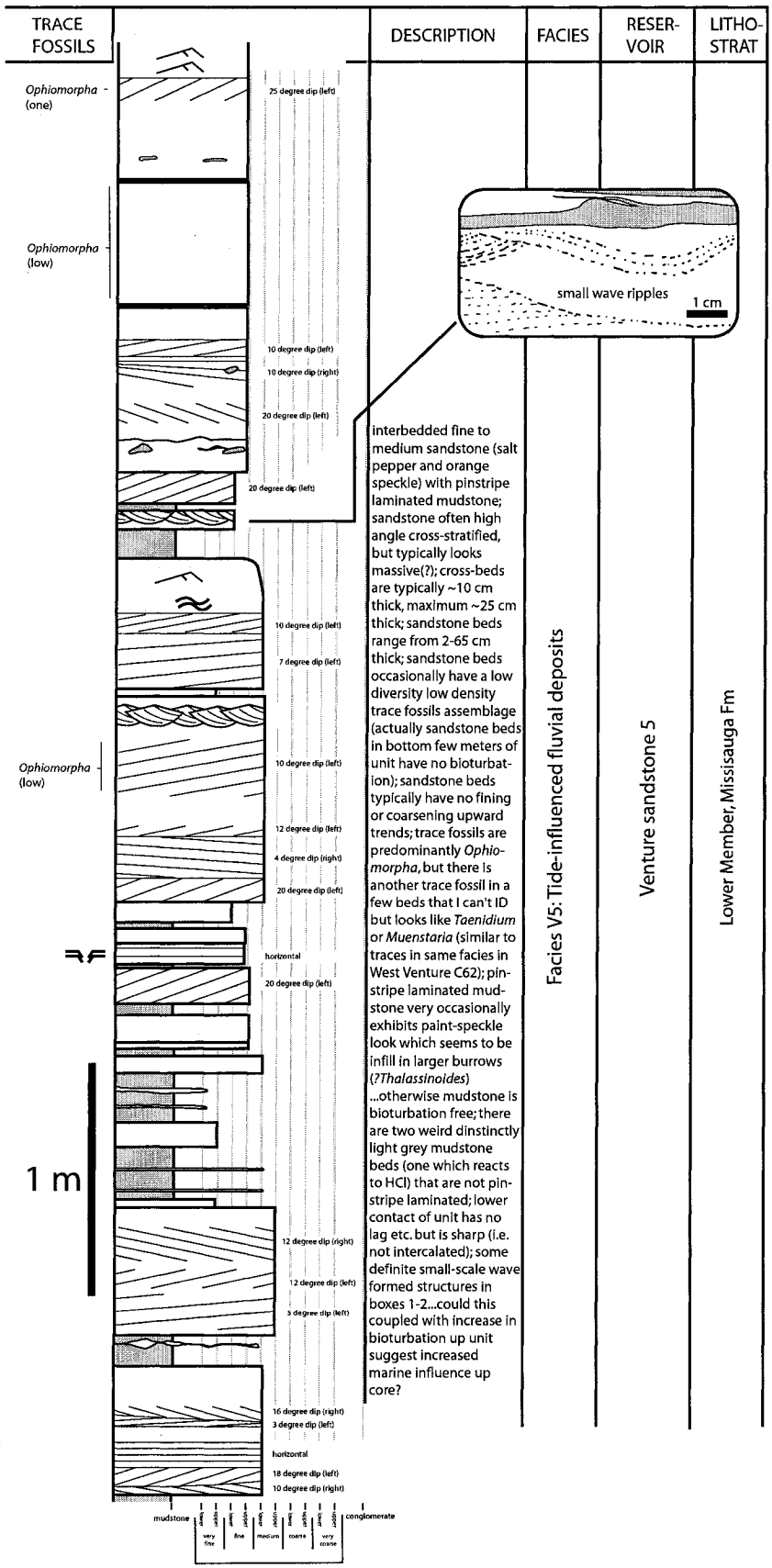
Venture B-52
core 3
boxes 5/5 to 1/5



Venture B-52
core 2
boxes 13/13 to 10/13

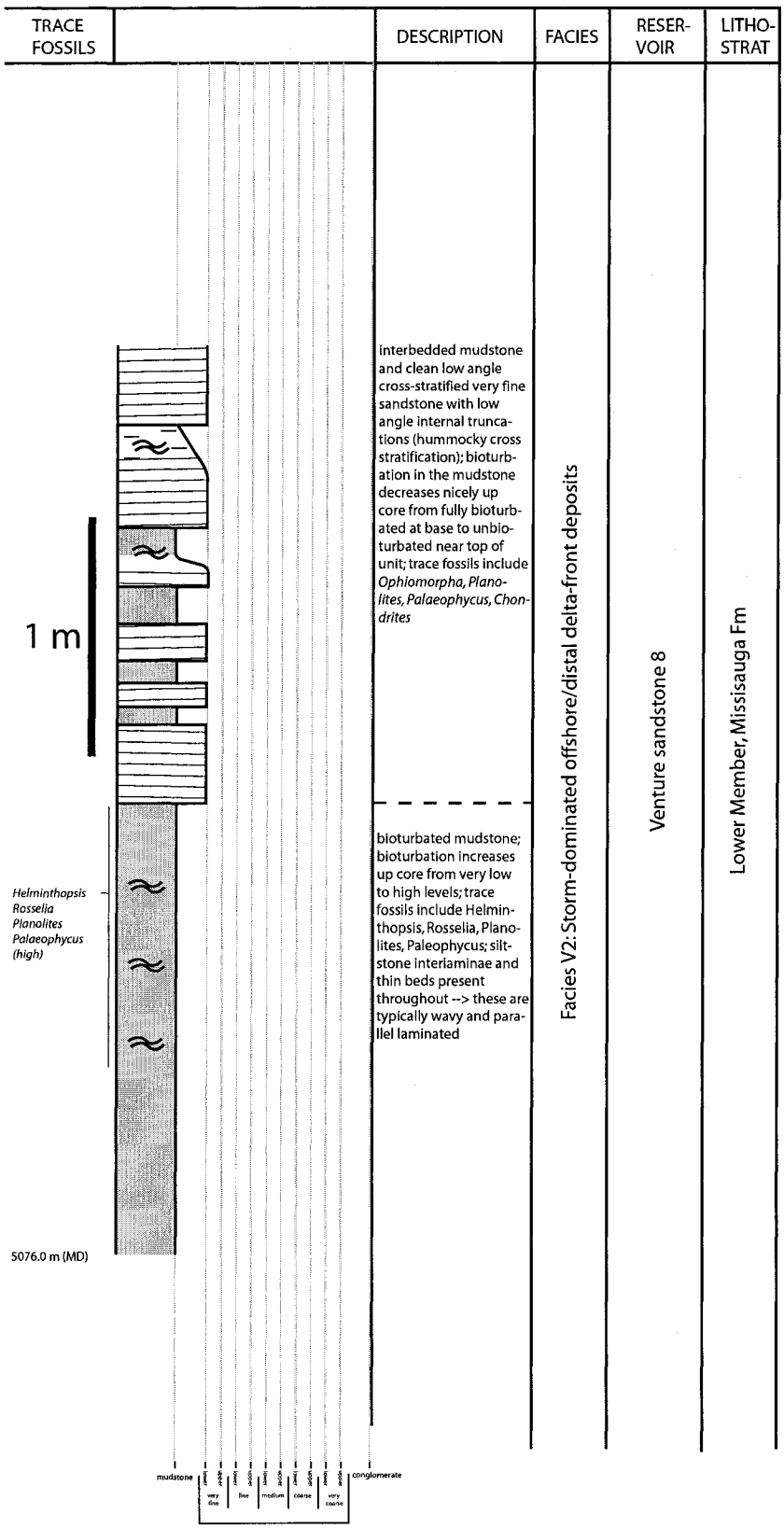


Venture B-52
core 2
boxes 9/13 to 6/13

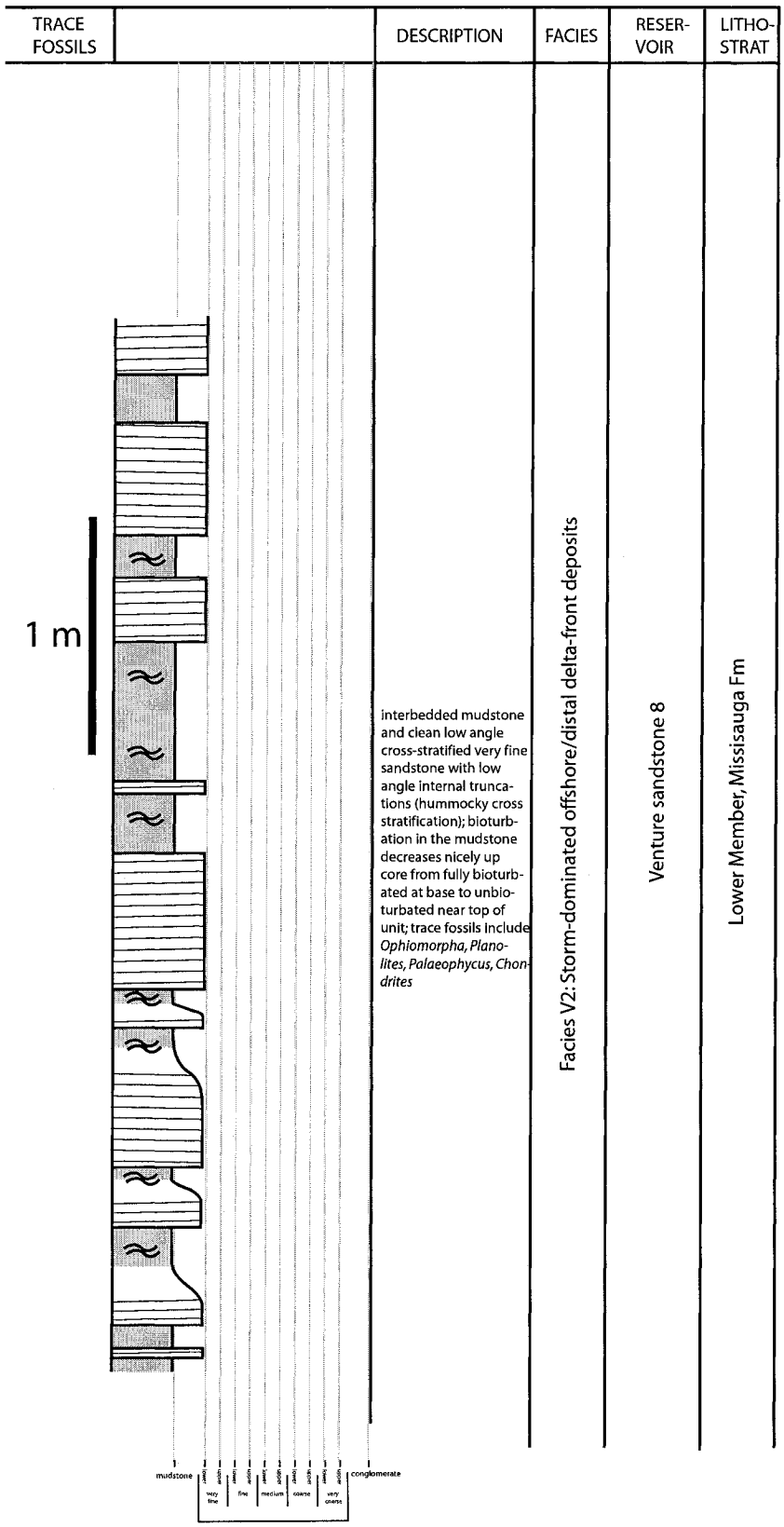


Venture B-52
core 2
boxes 5/13 to 1/13

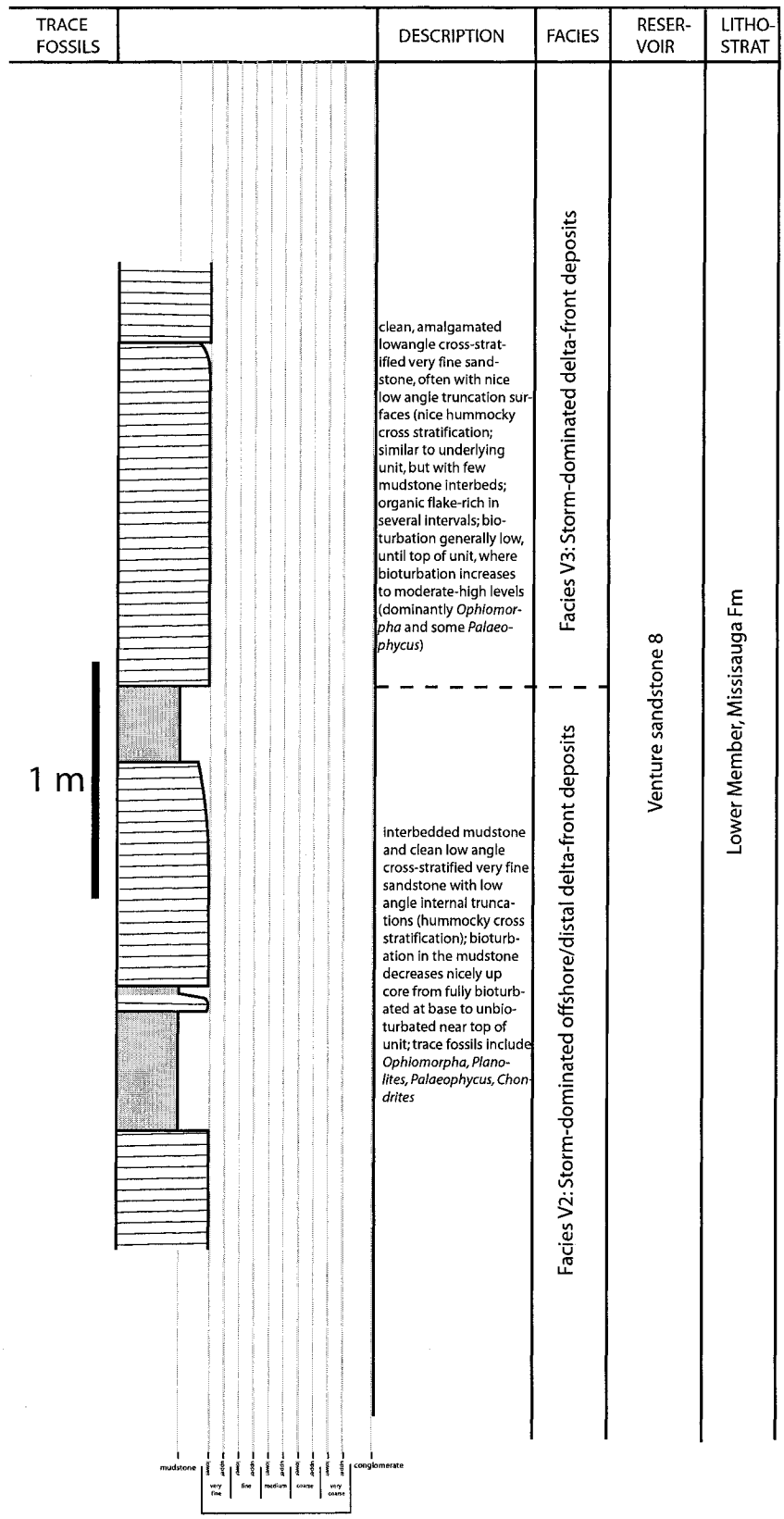
Venture H-22
core 7
boxes 26/26 to 23/26



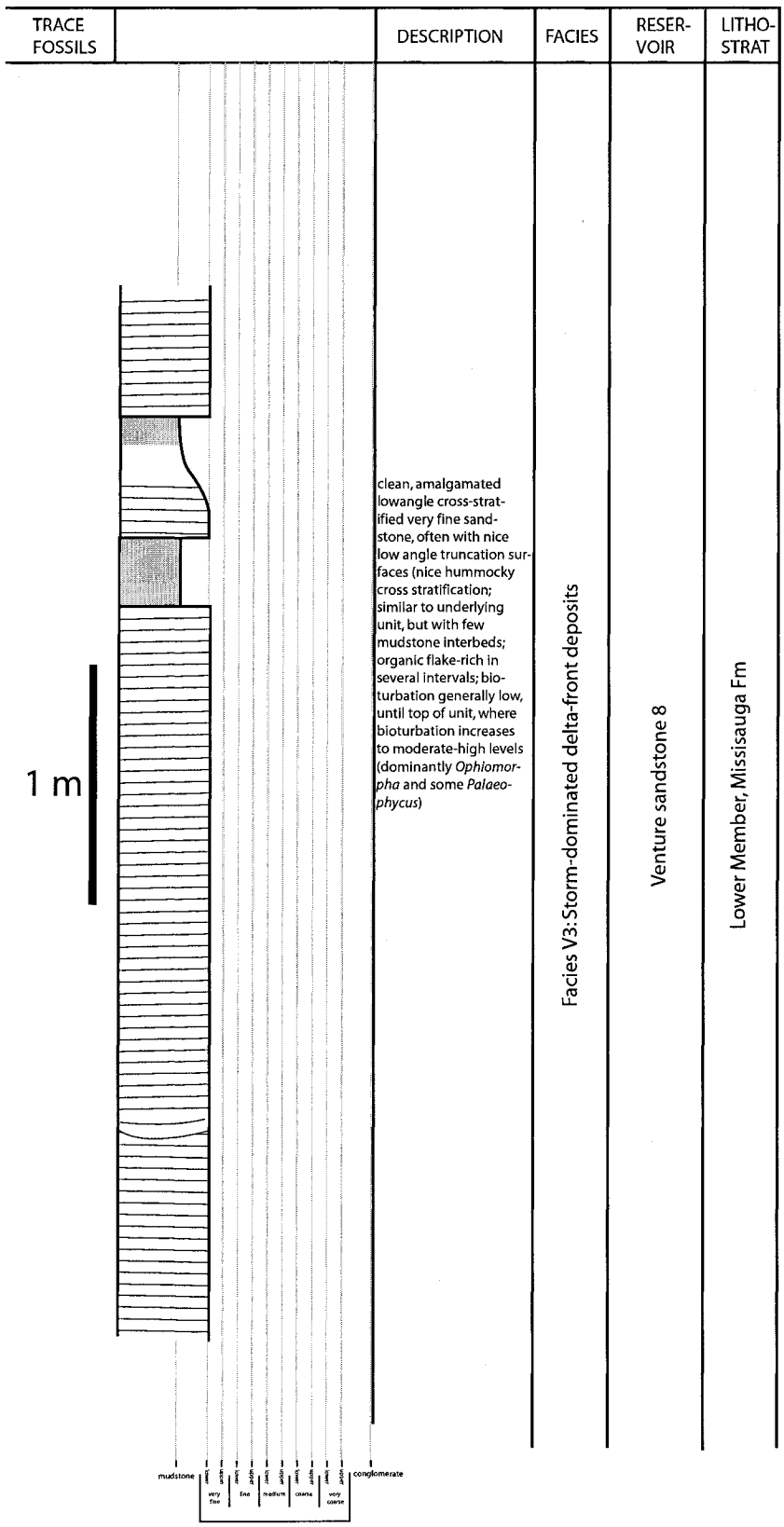
Venture H-22
core 7
boxes 22/26 to 19/26



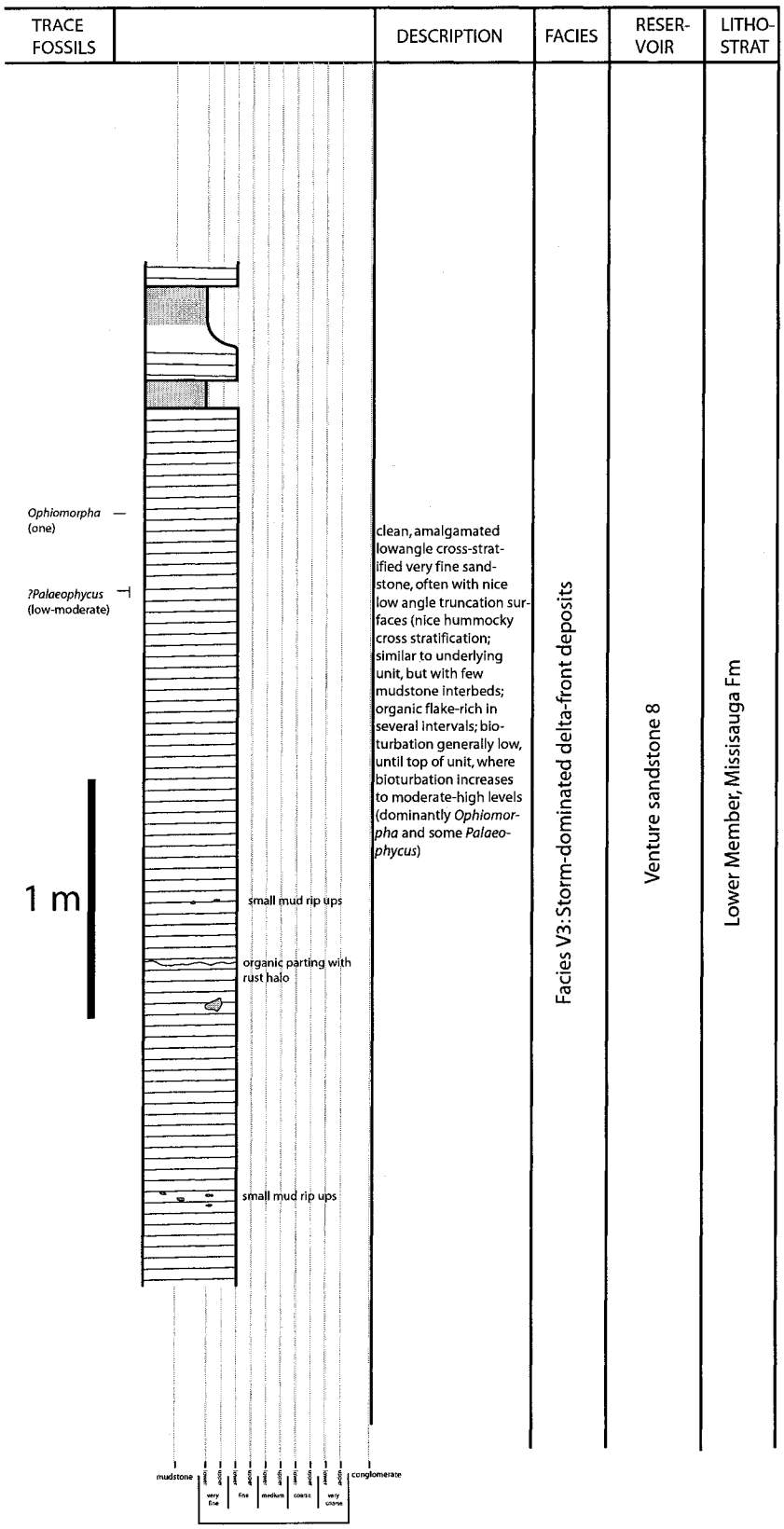
Venture H-22
core 7
boxes 18/26 to 15/26



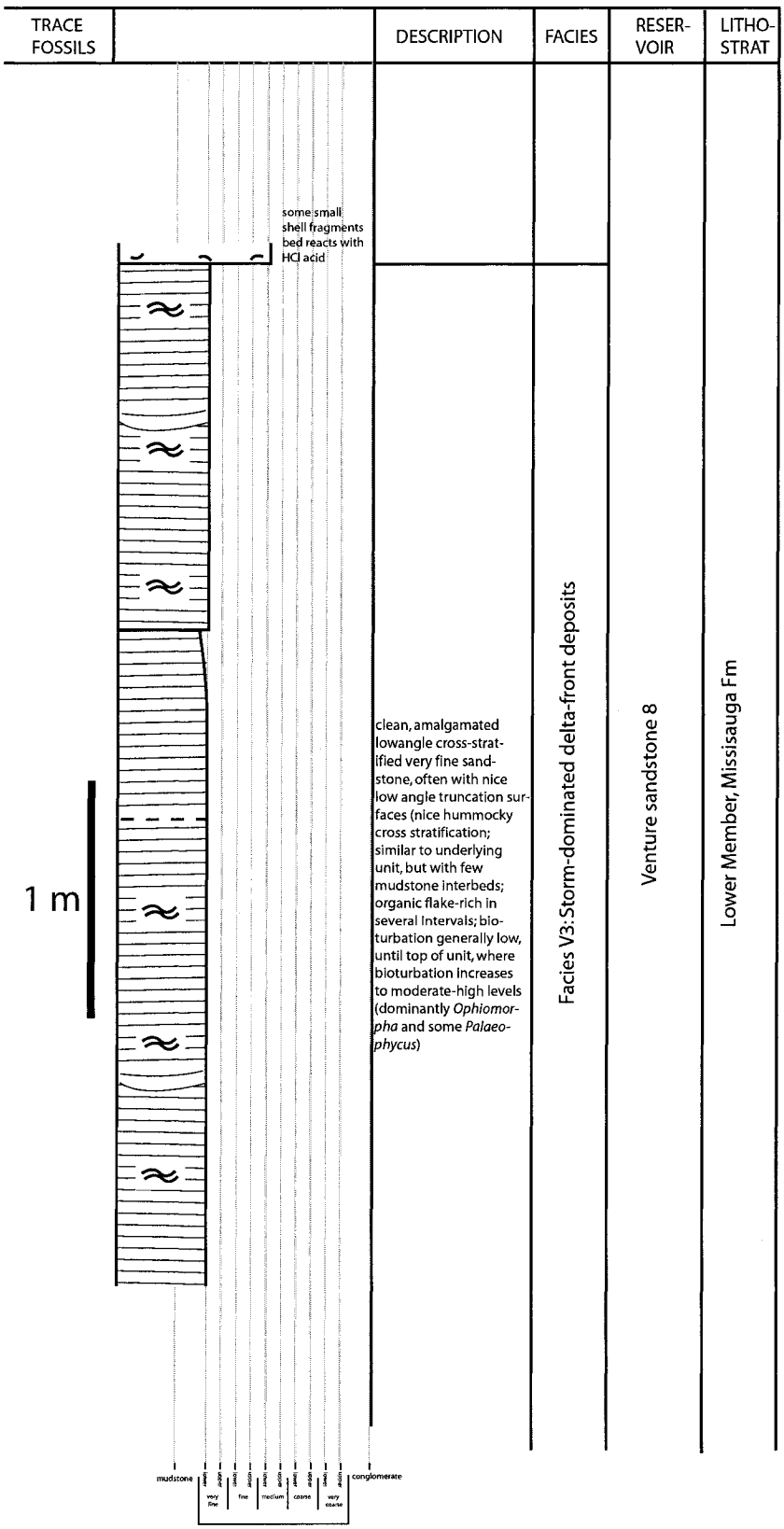
Venture H-22
core 7
boxes 14/26 to 11/26



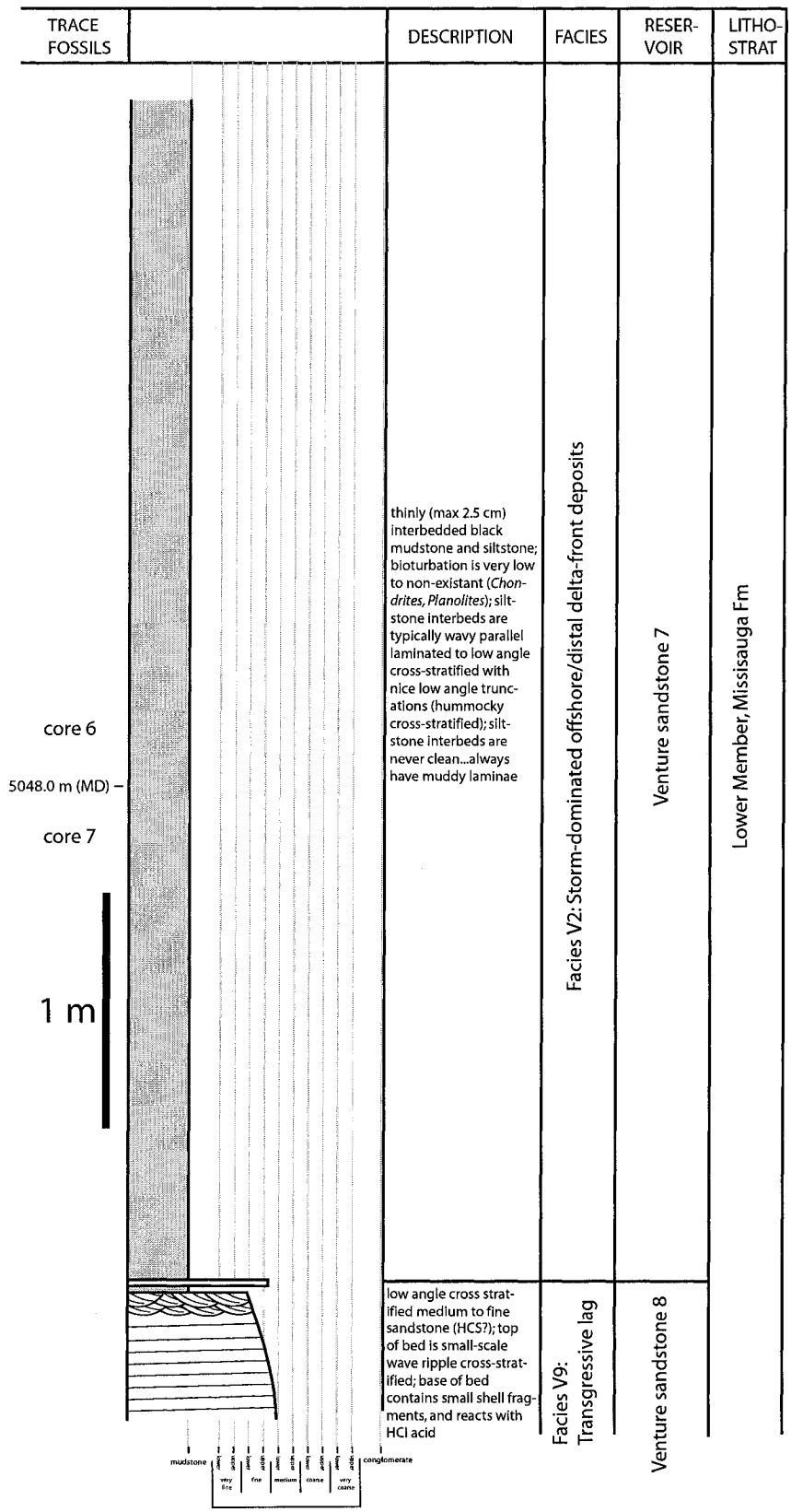
Venture H-22
core 7
boxes 10/26 to 7/26



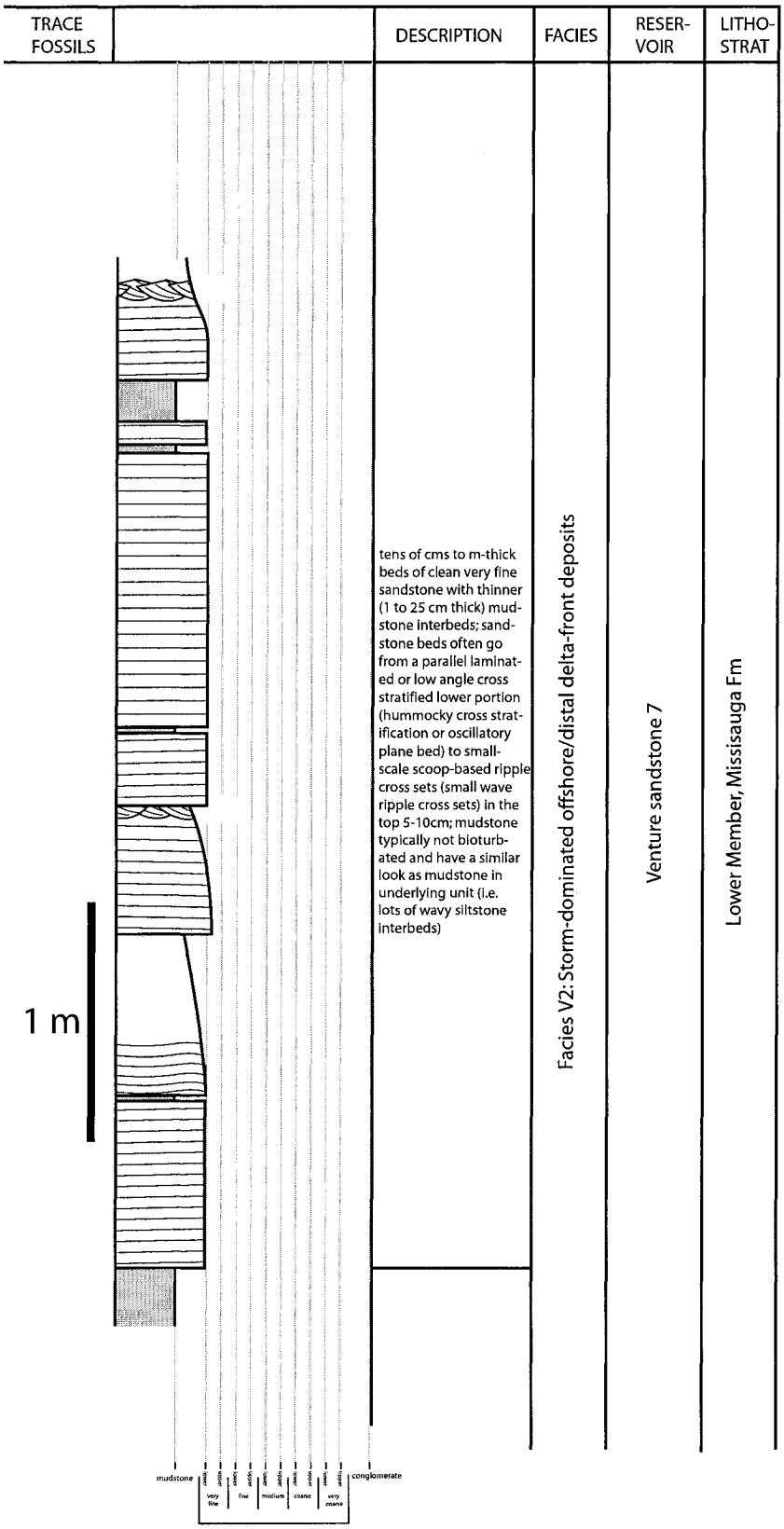
Venture H-22
core 7
boxes 6/26 to 3/26



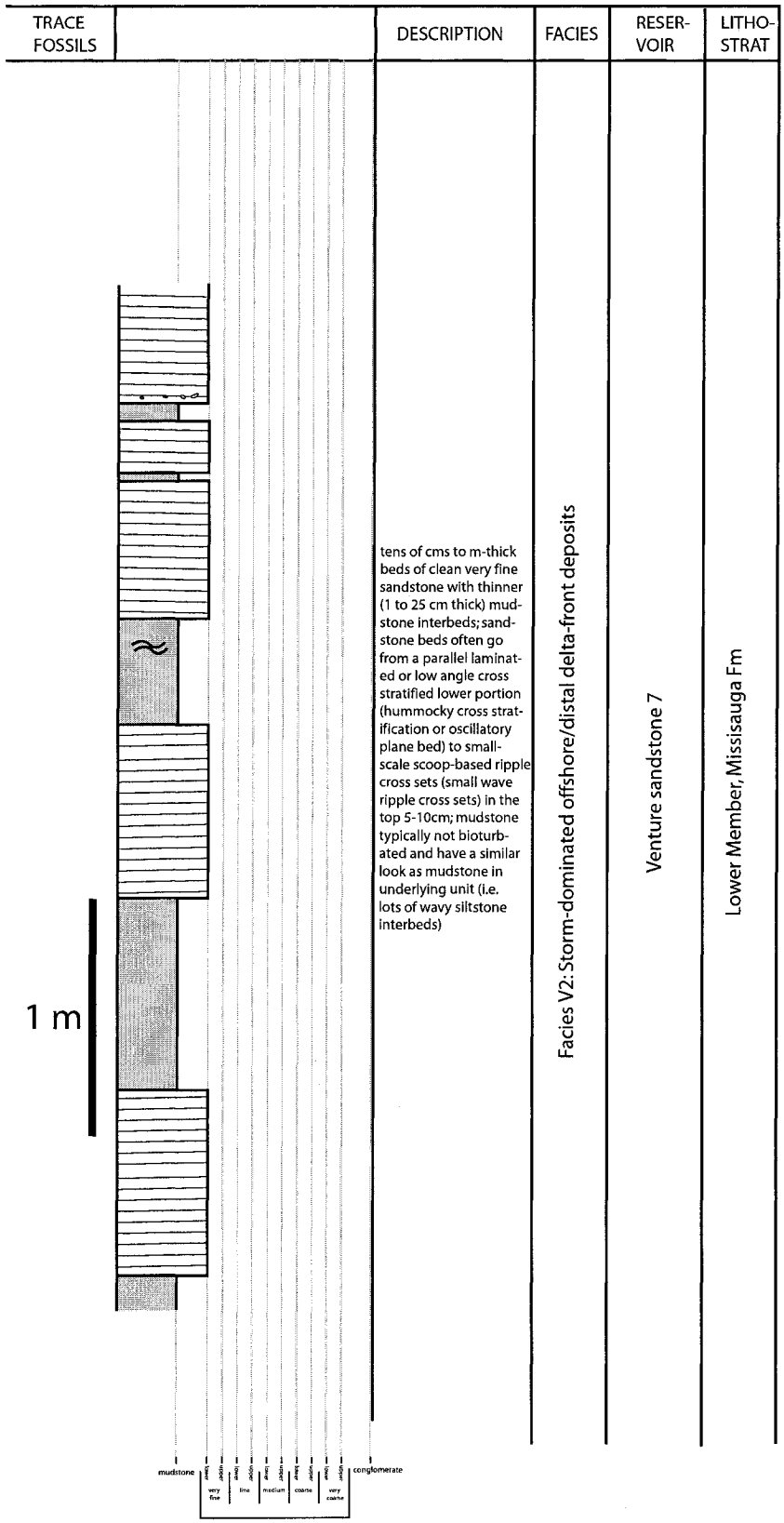
Venture H-22
core 7, box 2/26 to
core 6, box 23/24



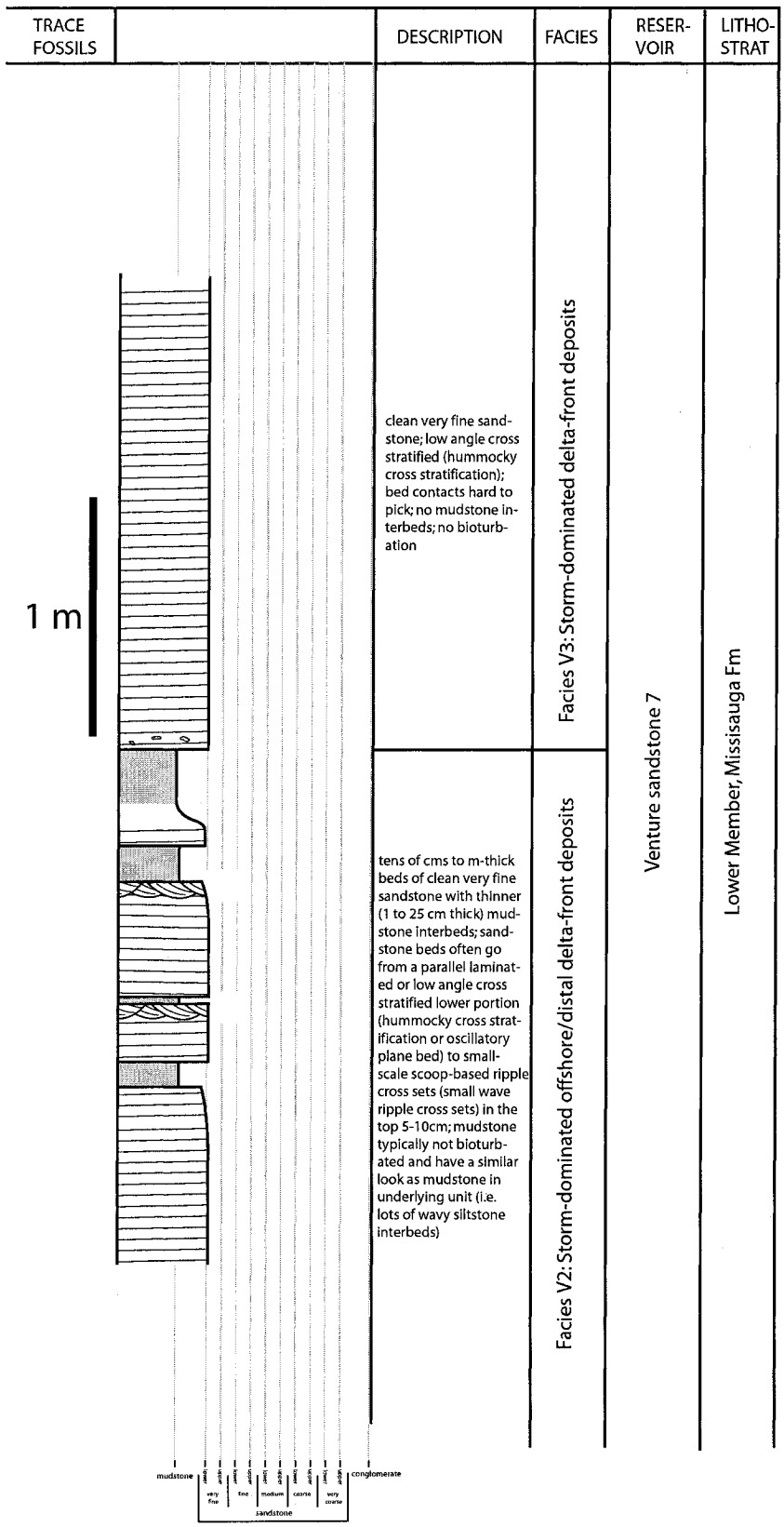
Venture H-22
core 6
boxes 22/24 to 19/24



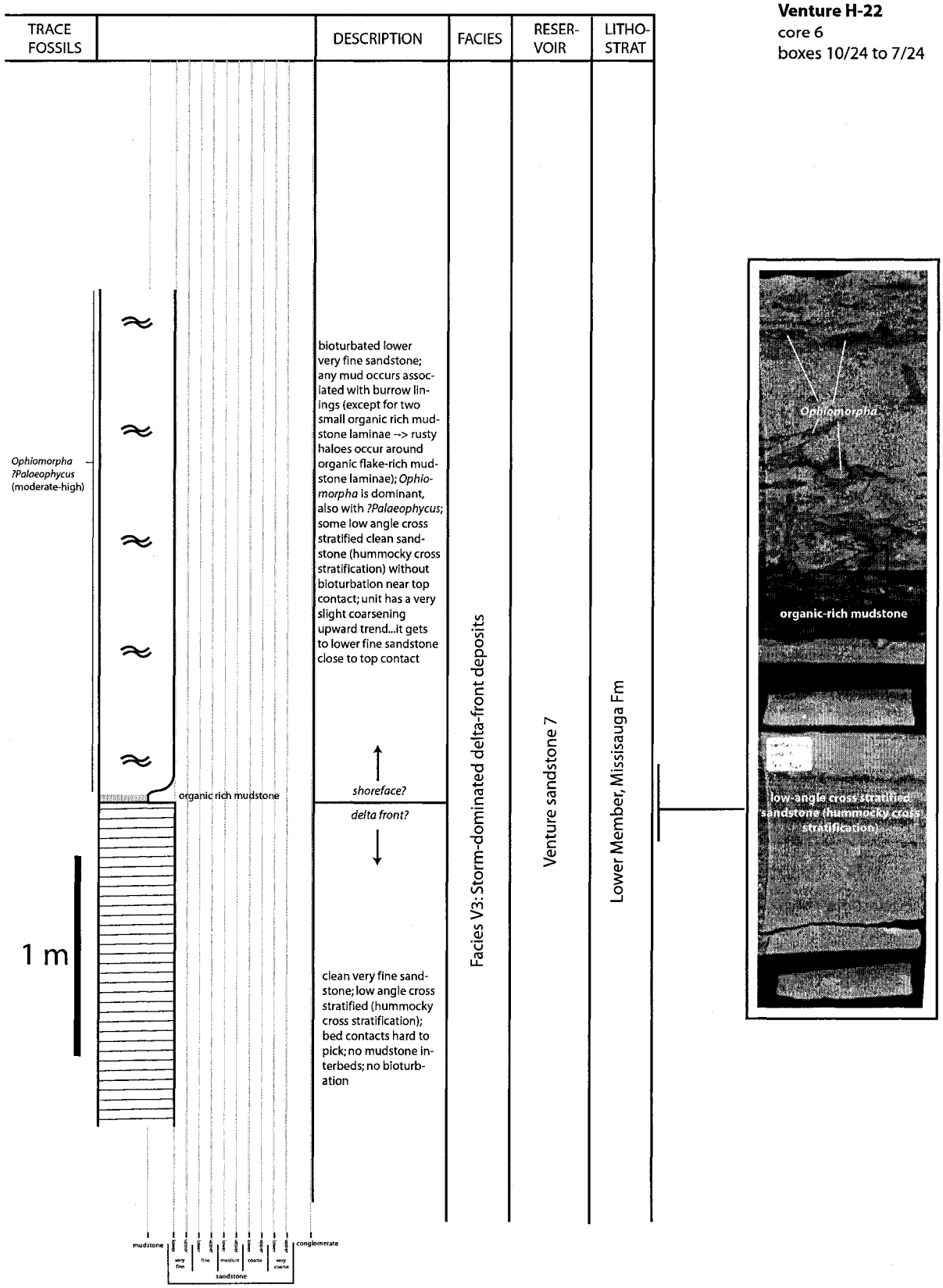
Venture H-22
core 6
boxes 18/24 to 15/24



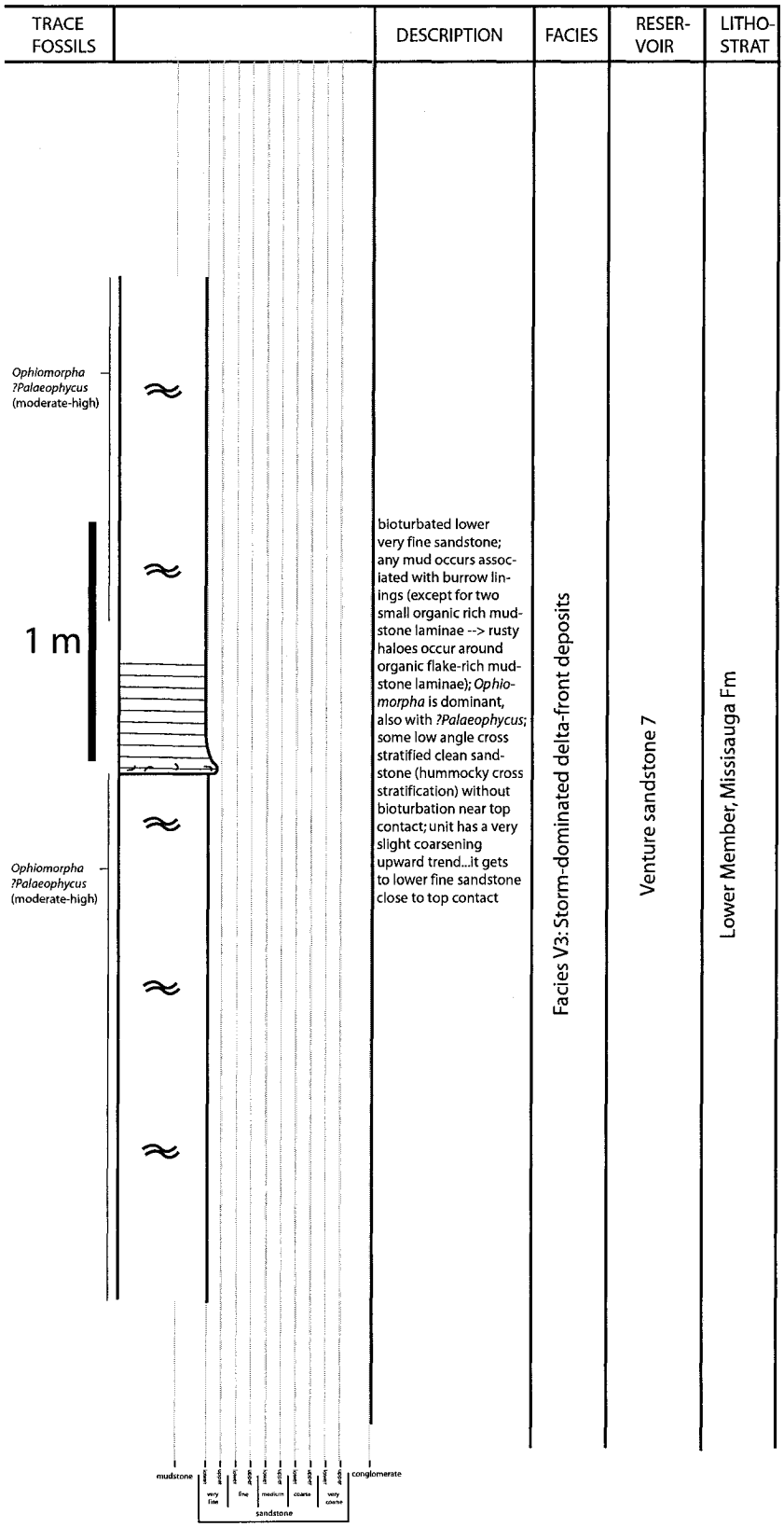
Venture H-22
core 6
boxes 14/24 to 11/24



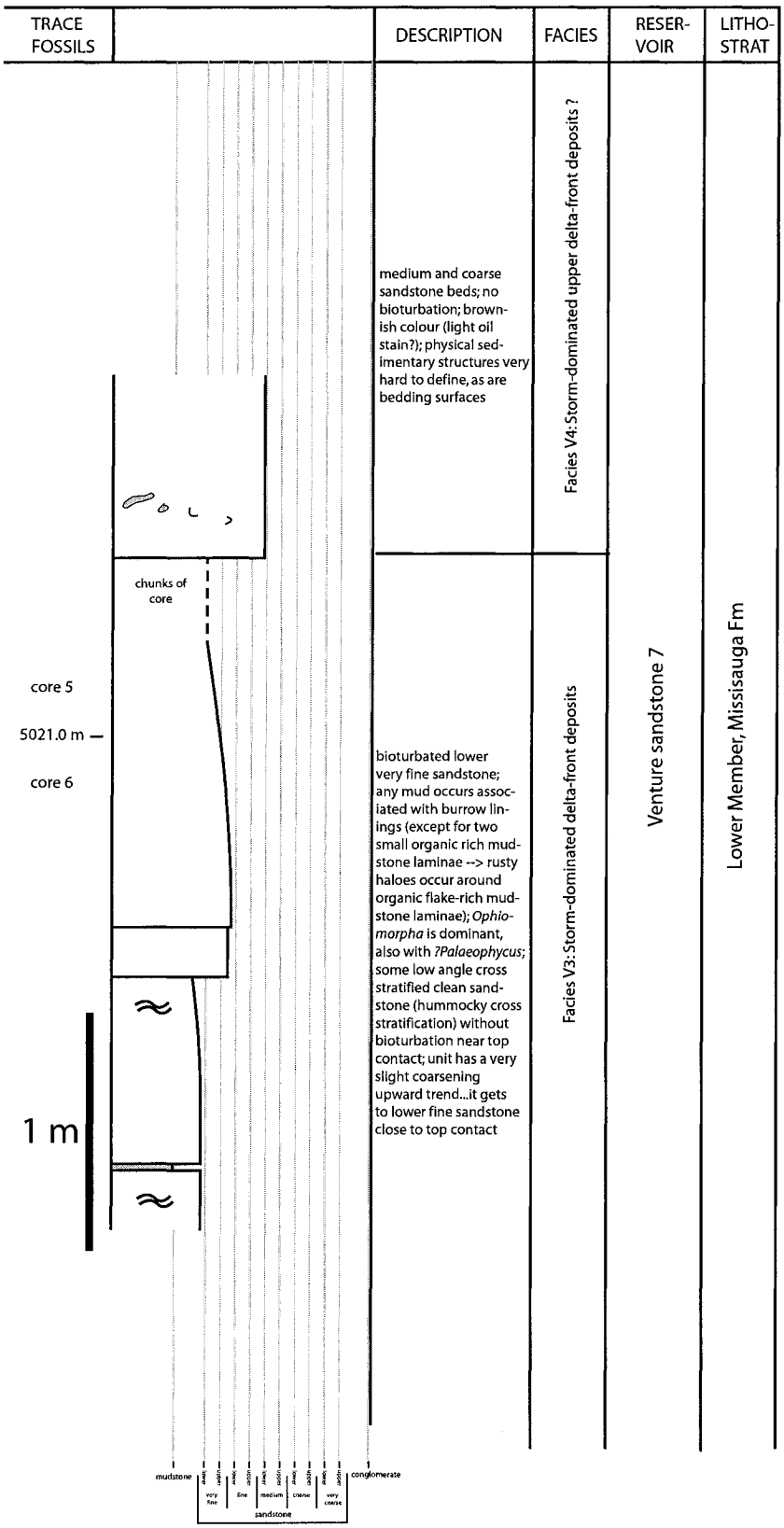
Venture H-22
core 6
boxes 10/24 to 7/24

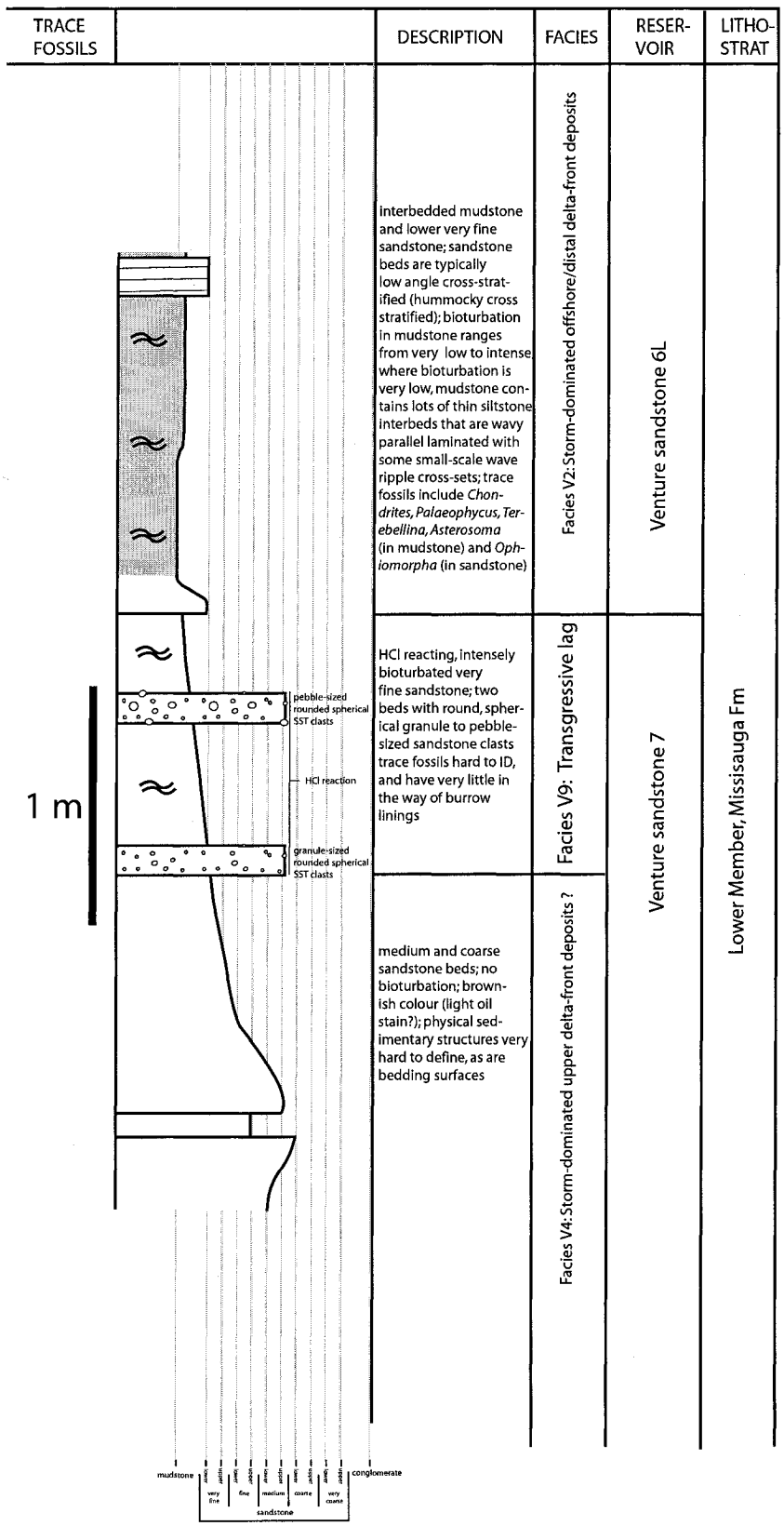


Venture H-22
core 6
boxes 6/24 to 3/24



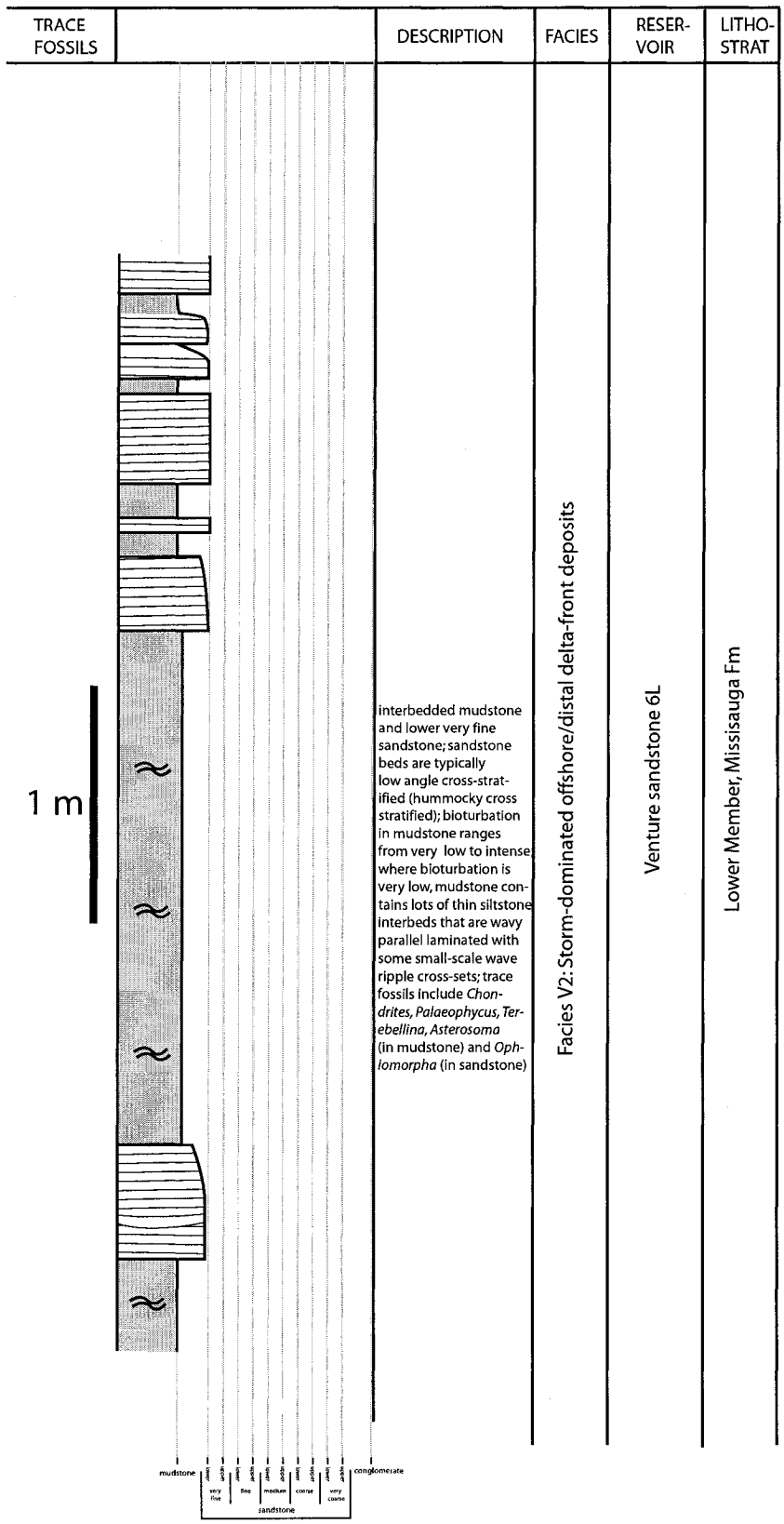
Venture H-22
core 6, box 2/24 to
core 5, box 23/24

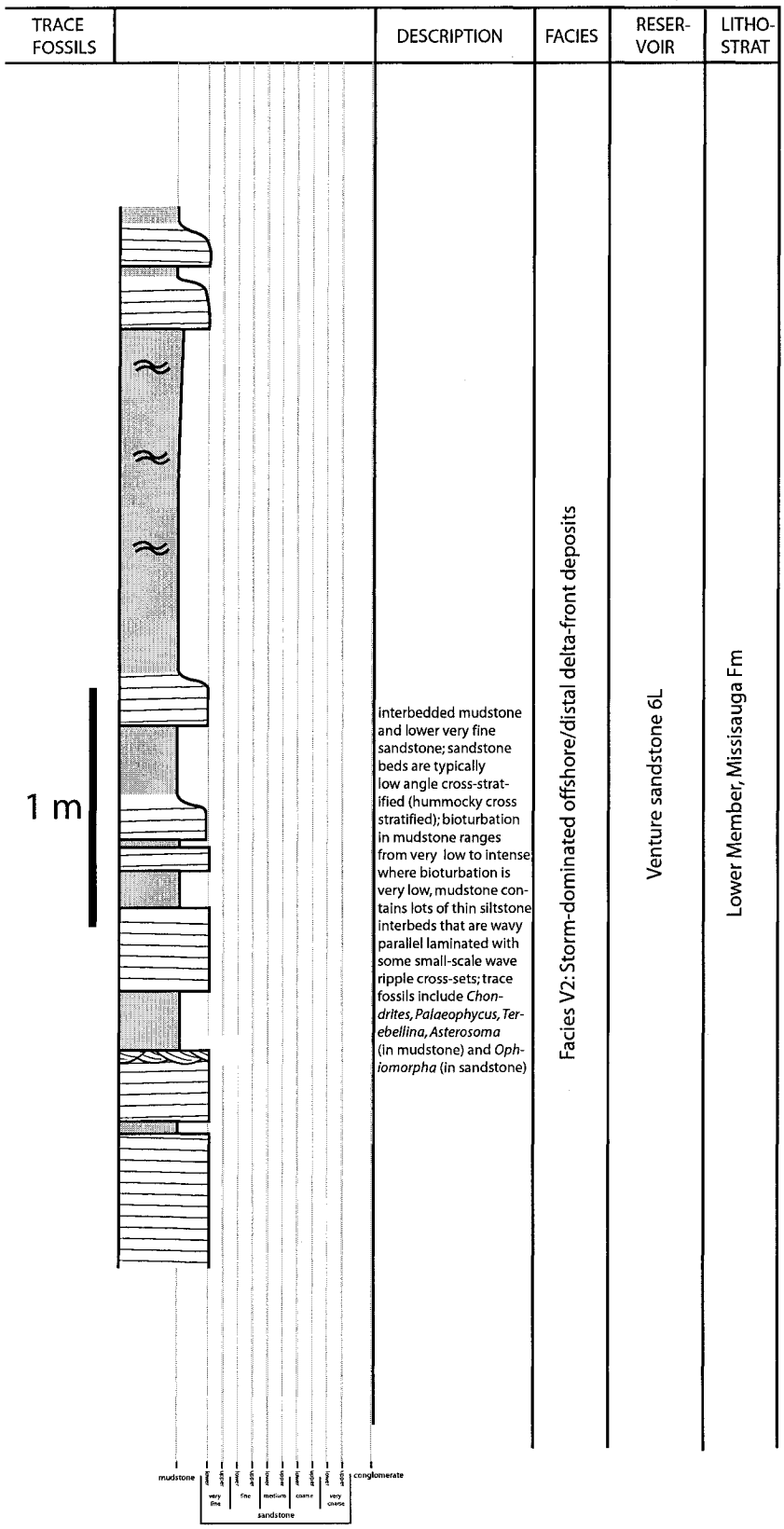




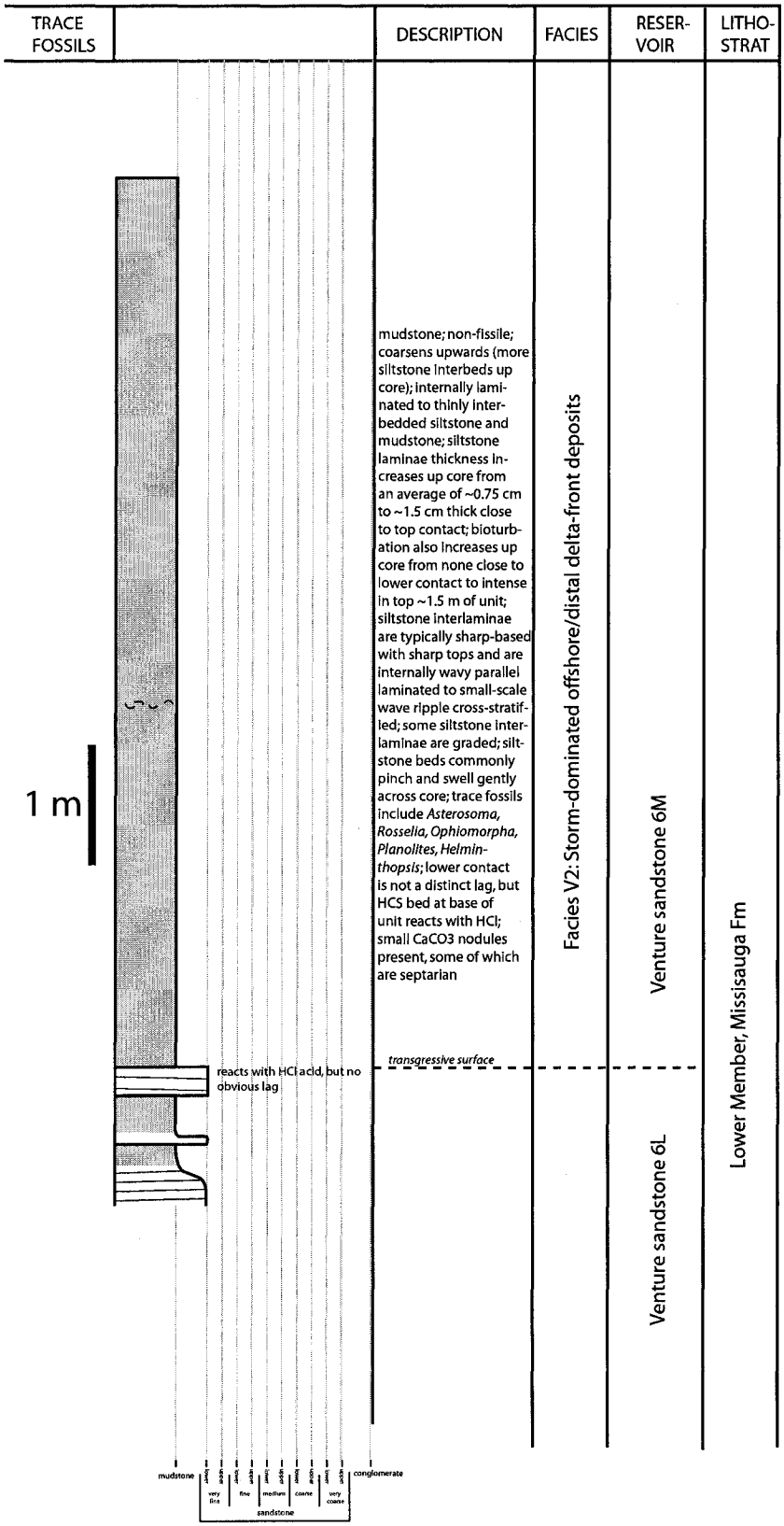
Venture H-22
core 5
boxes 22/24 to 19/24

Venture H-22
core 5
boxes 18/24 to 15/24

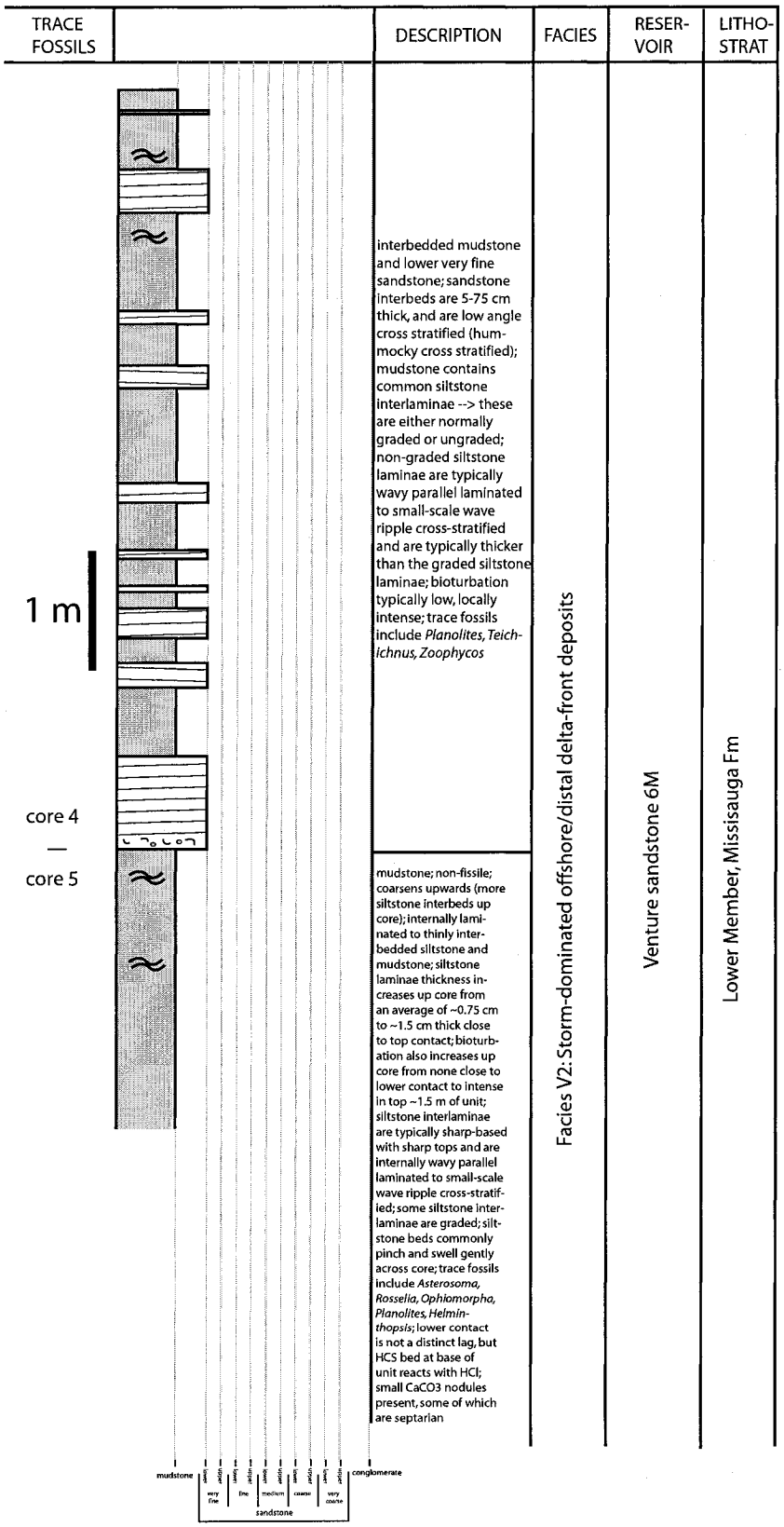




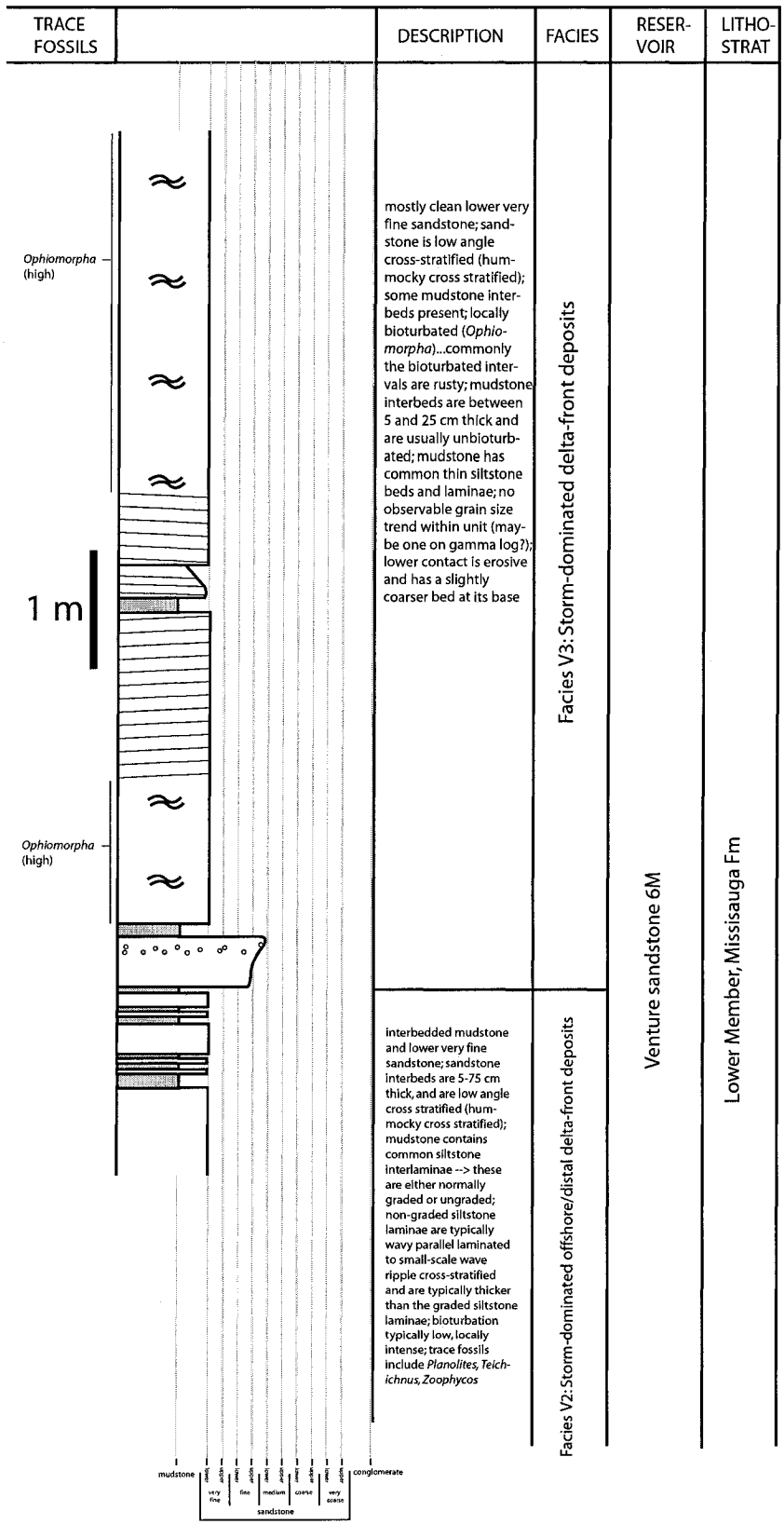
Venture H-22
core 5
boxes 14/24 to 11/24



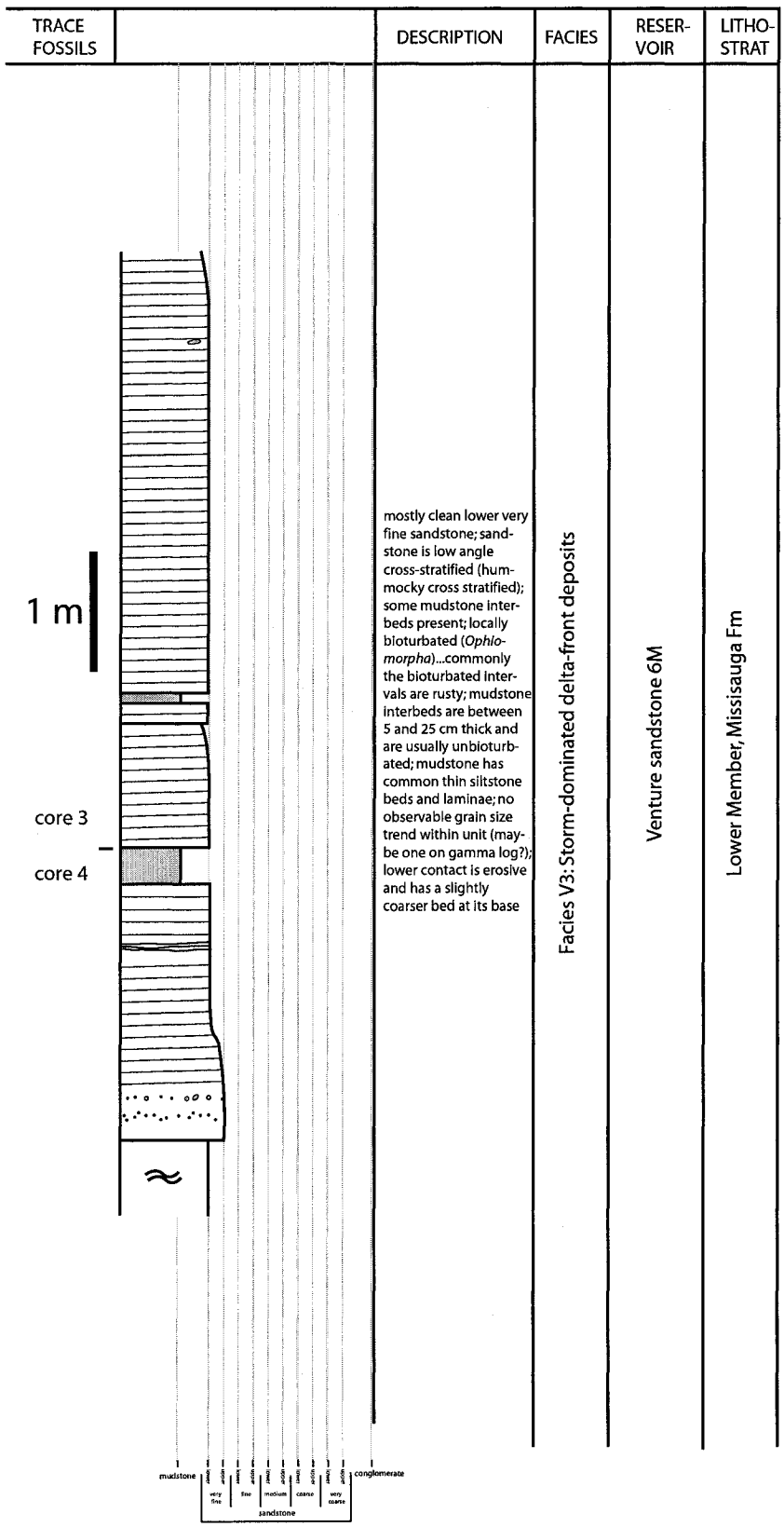
Venture H-22
core 5
boxes 10/24 to 3/24
(note blown up scale)



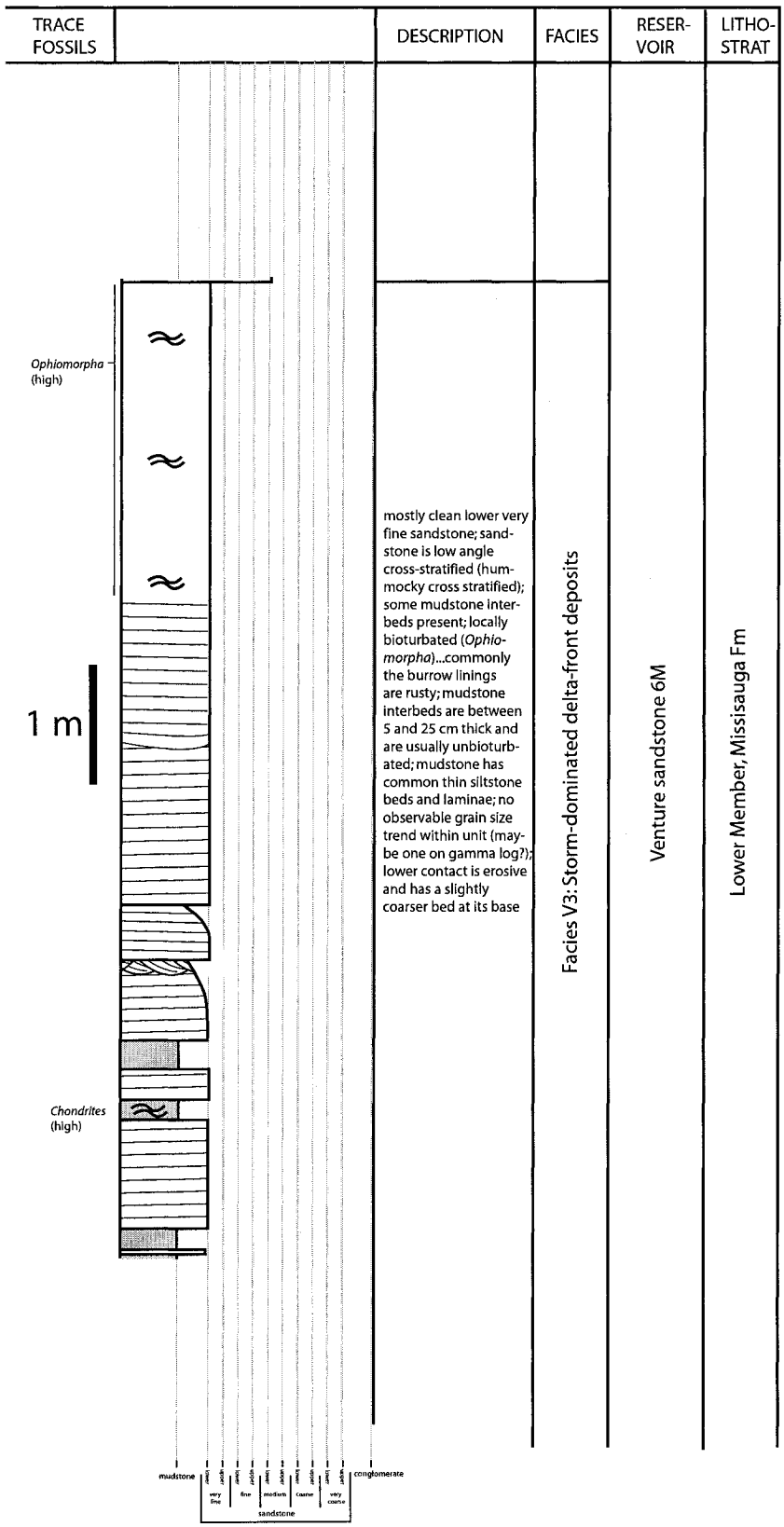
Venture H-22
core 5, box 2/24 to
core 4, box 12/17
note blown up scale



Venture H-22
core 4
boxes 11/17 to 4/17
note blown up scale



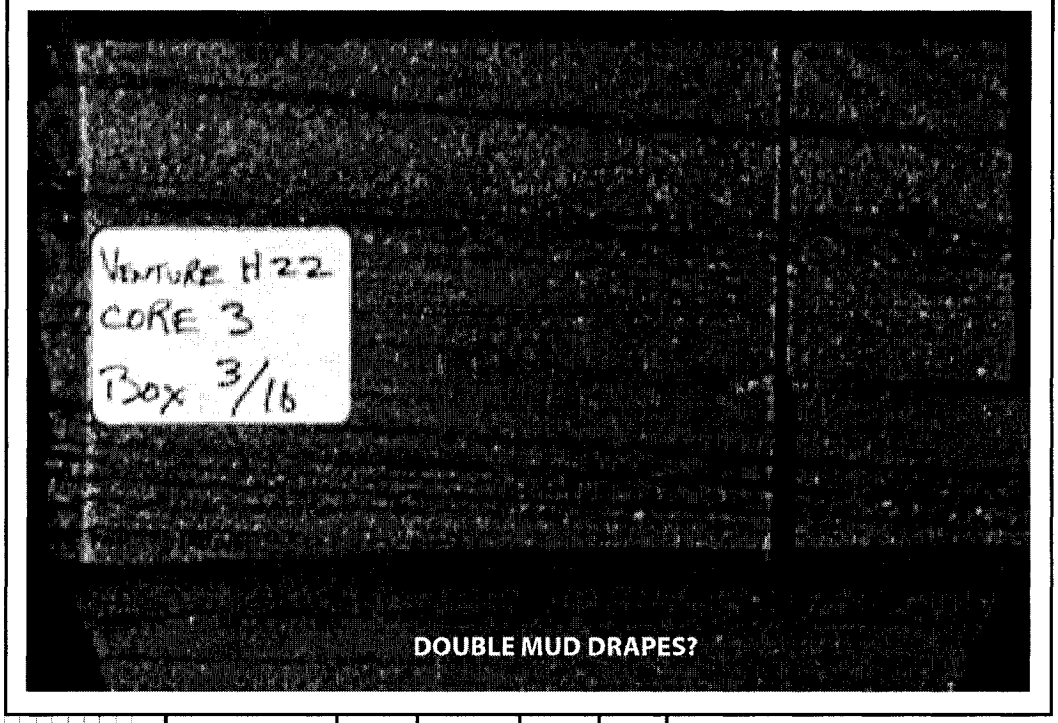
Venture H-22
core 4, box 3/17 to
core 3, box 12/16
note blown up scale

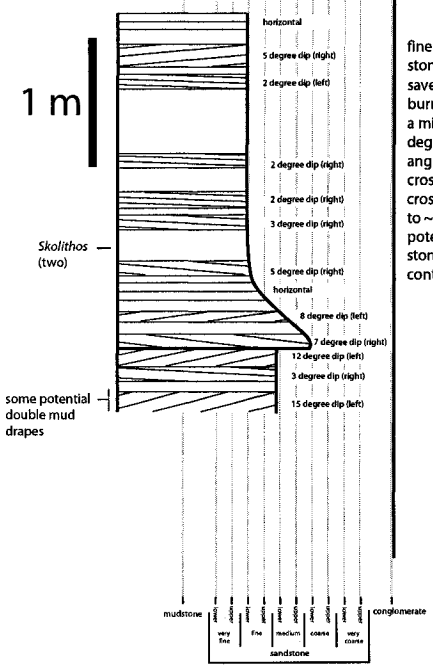


Venture H-22
core 3
boxes 11/16 to 4/16
note blown up scale

TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT

Venture H-22
core 3
boxes 3/16 to 1/16
note blown up scale





fine to medium sandstone; no bioturbation save for two Skolithos burrows; sandstone is a mix of low angle (<10 degrees) and moderate angle (10 to 15 degrees) cross stratified beds; cross-sets are several to ~25 cm thick; some potential double mud stone drapes?; lower contact is sharp

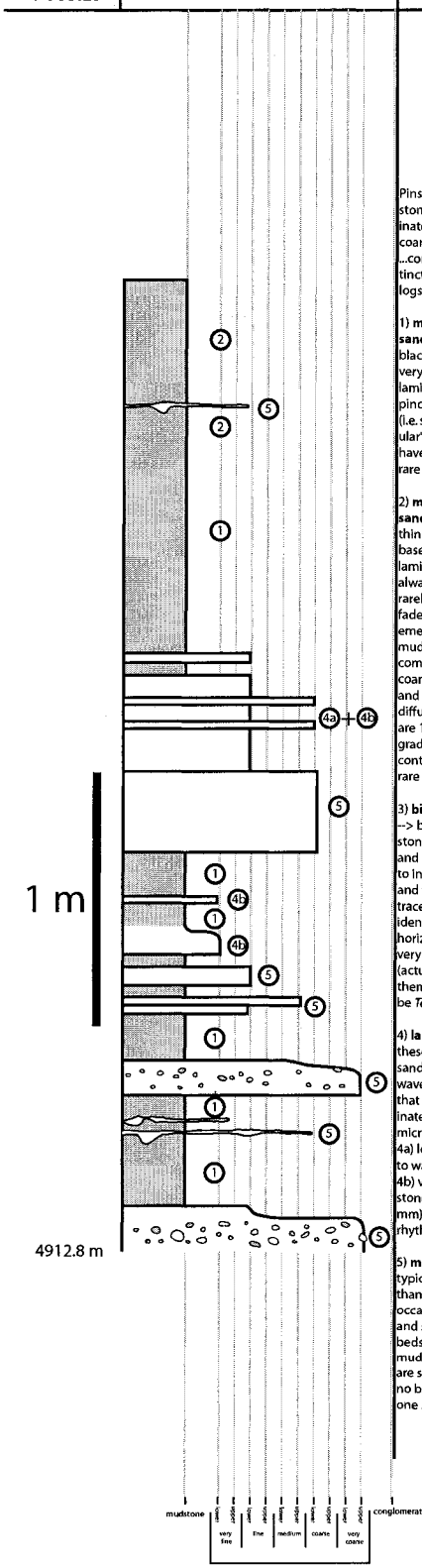
Facies V4: Storm-dominated upper delta-front deposits ?

Venture sandstone 6M

Lower Member, Missisauga Fm

Venture H-22
core 2
boxes 17/17 to 14/17

TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT



Pinstripe laminated mudstone with massive to laminated very fine to very coarse sandstone interbeds ...composed of several distinct subfacies, as notated on logs ...

1) **mudstone with 'sharp' sandstone pinstripes** --> black mudstone; non-fissile; very thin (<1 mm) sandstone laminae that commonly pinch and swell across core (i.e. sometimes get 'lenticular'); sandstone pinstripes have sharp bases and tops; rare syneresis cracks

2) **mudstone w/ 'diffuse' sandstone pinstripes** --> thin (< 1 cm) gradationally-based and topped sandstone laminae common; these always occur in groupings, rarely rhythmic, that fade upwards into and/or emerge upwards from black mudstone (i.e. the groupings commonly thicken and coarsen upwards, then thin and fine-upwards); individual diffuse sandstone pinstripes are 1-10 mm thick, and have gradational upper and lower contacts with mudstone; rare syneresis cracks

3) **bioturbated mudstone** --> bioturbation in the mudstone seems to just 'turn' on and off ... goes from nothing to intensely bioturbated and vice versa rather quickly; trace fossils are quite hard to identify .. seemingly all are horizontal, and many are very *Teichichnus*-looking (actually, the more I look at them, could most of them be *Teichichnus* ?)

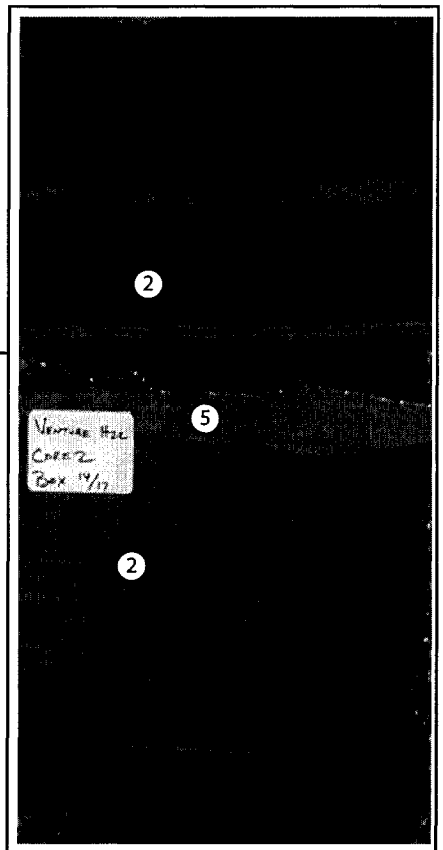
4) **laminated sandstone** --> these come in two types: sandstone beds that look wave influenced, and those that look rhythmically laminated; these are often microfaulted
4a) low angle cross laminated to wavy parallel laminated
4b) very flat thicker sandstone laminae with thin (<1 mm) mudstone interlaminae; rhythmically laminated

5) **massive sandstone** --> typically coarser grained than other sandstone beds; occasionally microfaulted and soft sediment deformed; beds are 1-50 cm thick; rare mud rip ups; lower contacts are sharp, commonly loaded; no bioturbation, except for one *?Arenicolites* burrow

Facies V7: Tide-influenced fluvial deposits

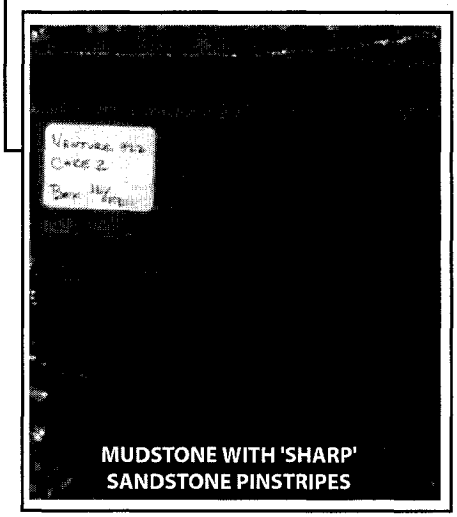
Venture sandstone 5

Lower Member, Missisauga Fm

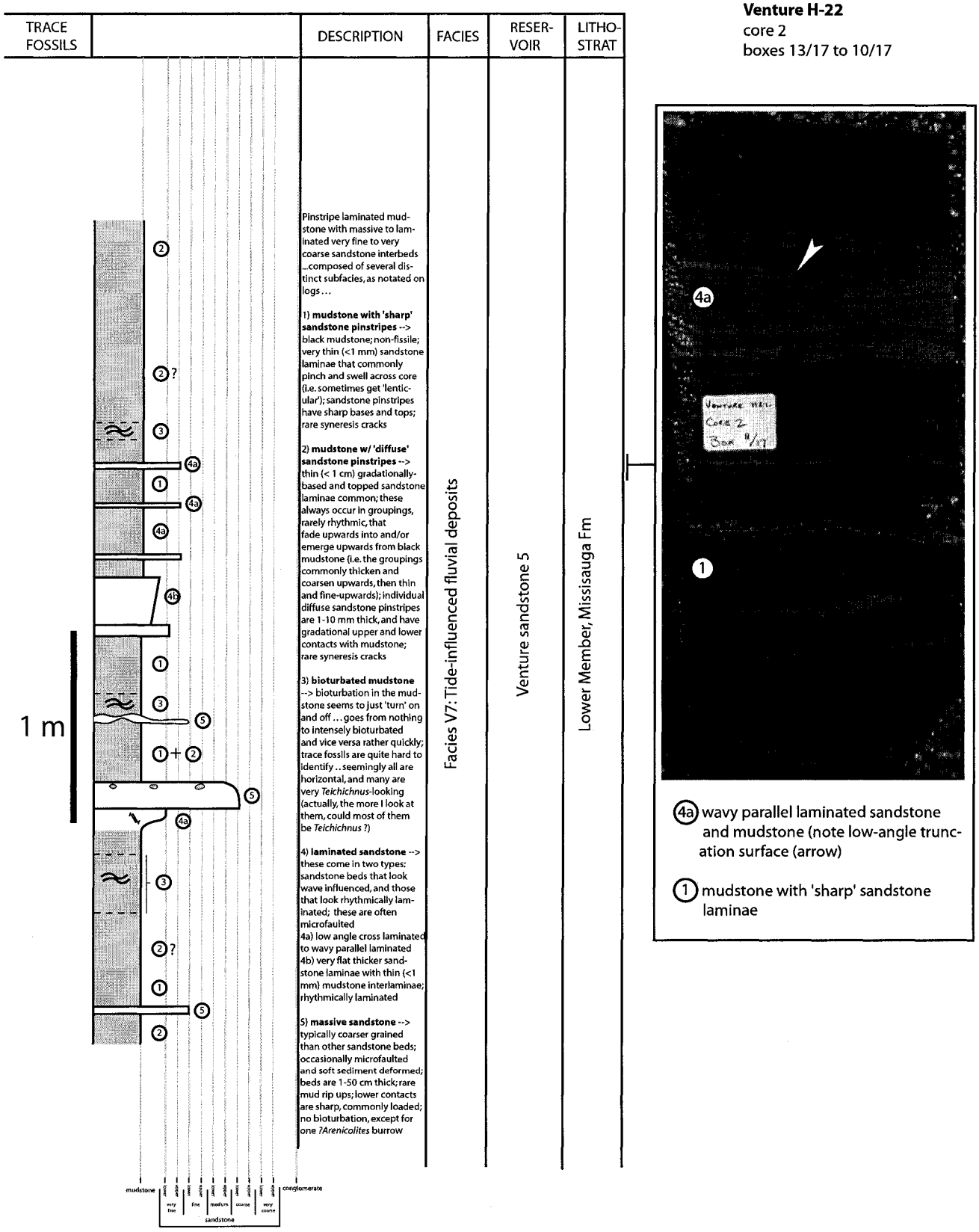


(2) mudstone with 'diffuse' sandstone pinstripes (note rhytmic stratification)

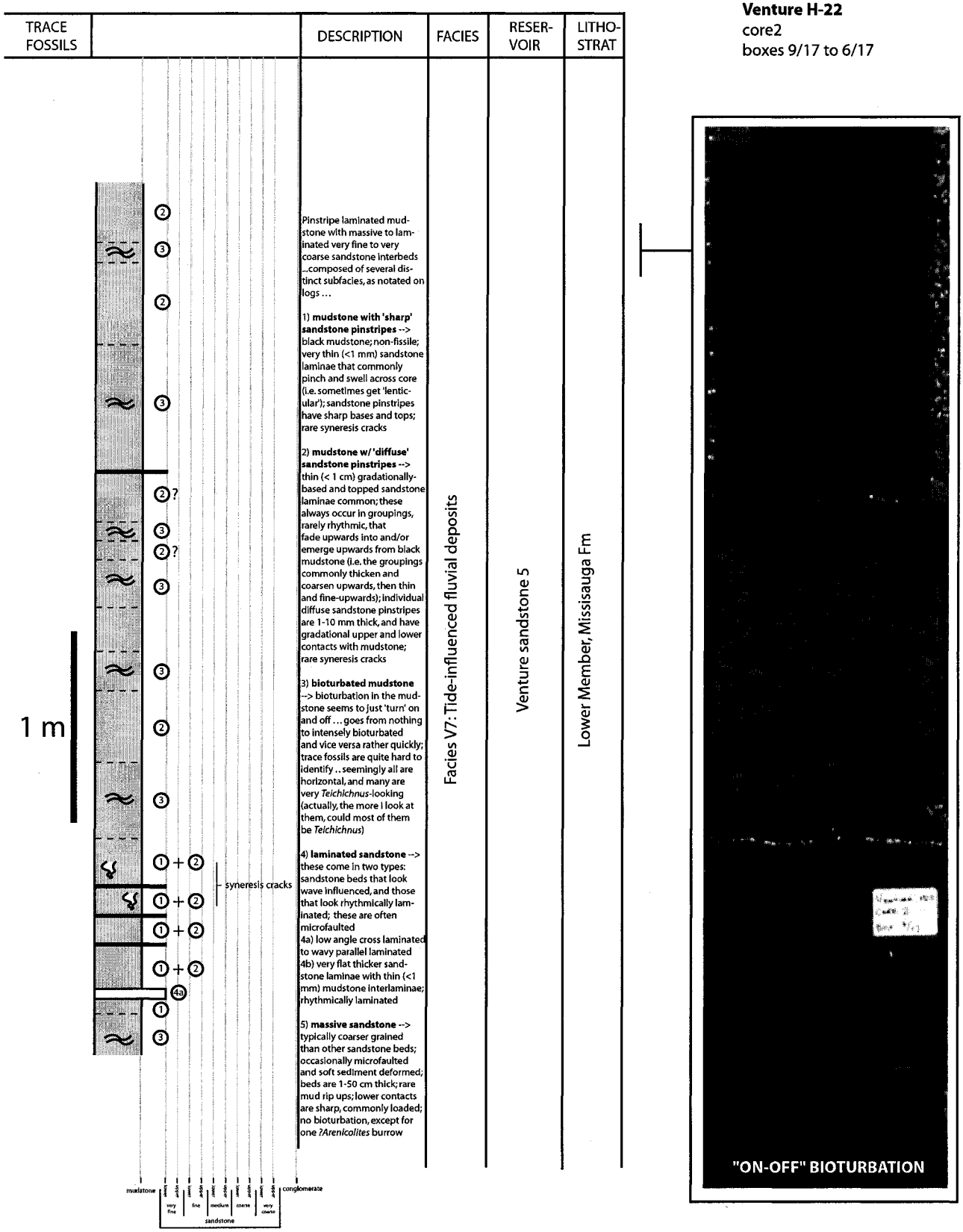
(5) massive sandstone (note loaded lower contact)

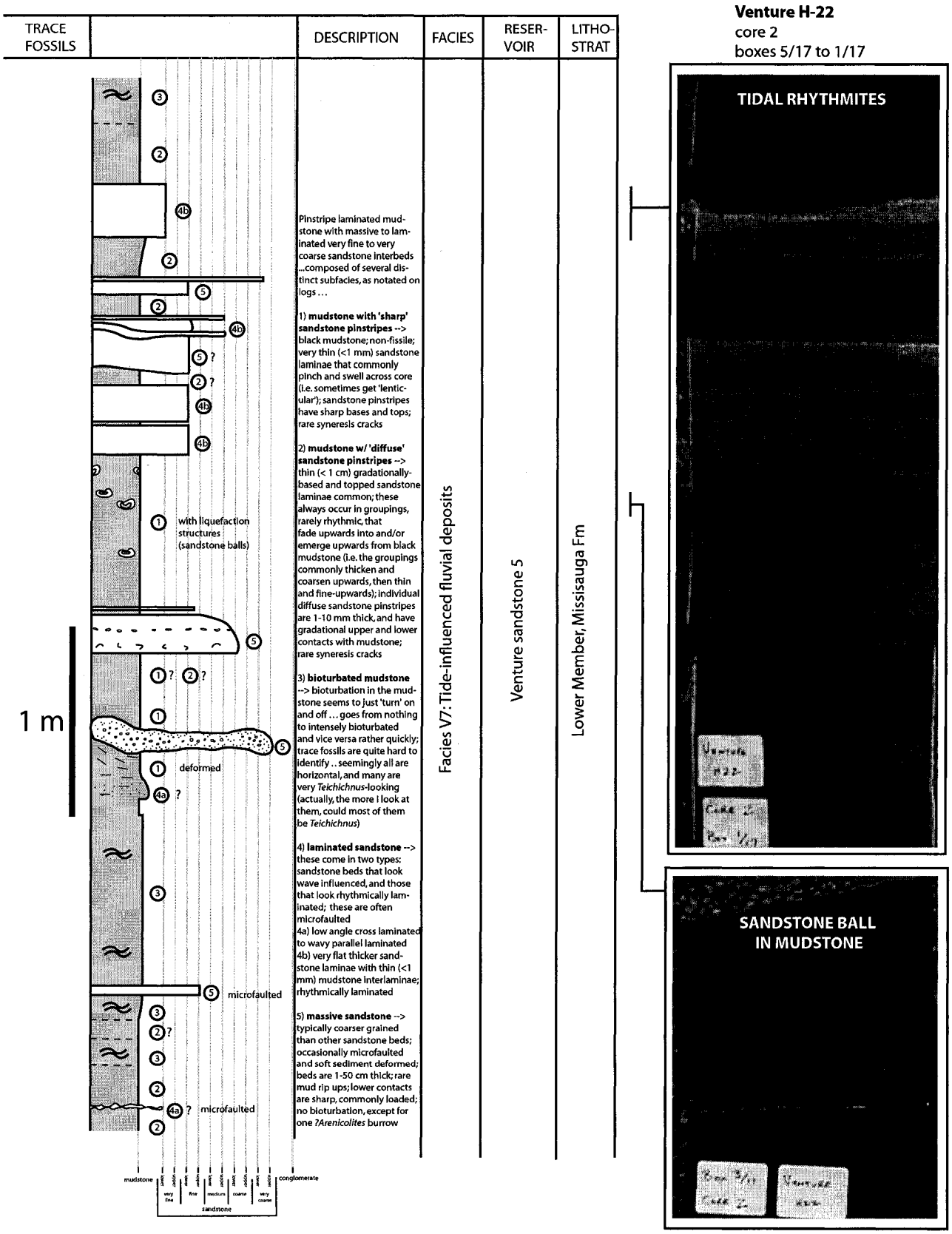


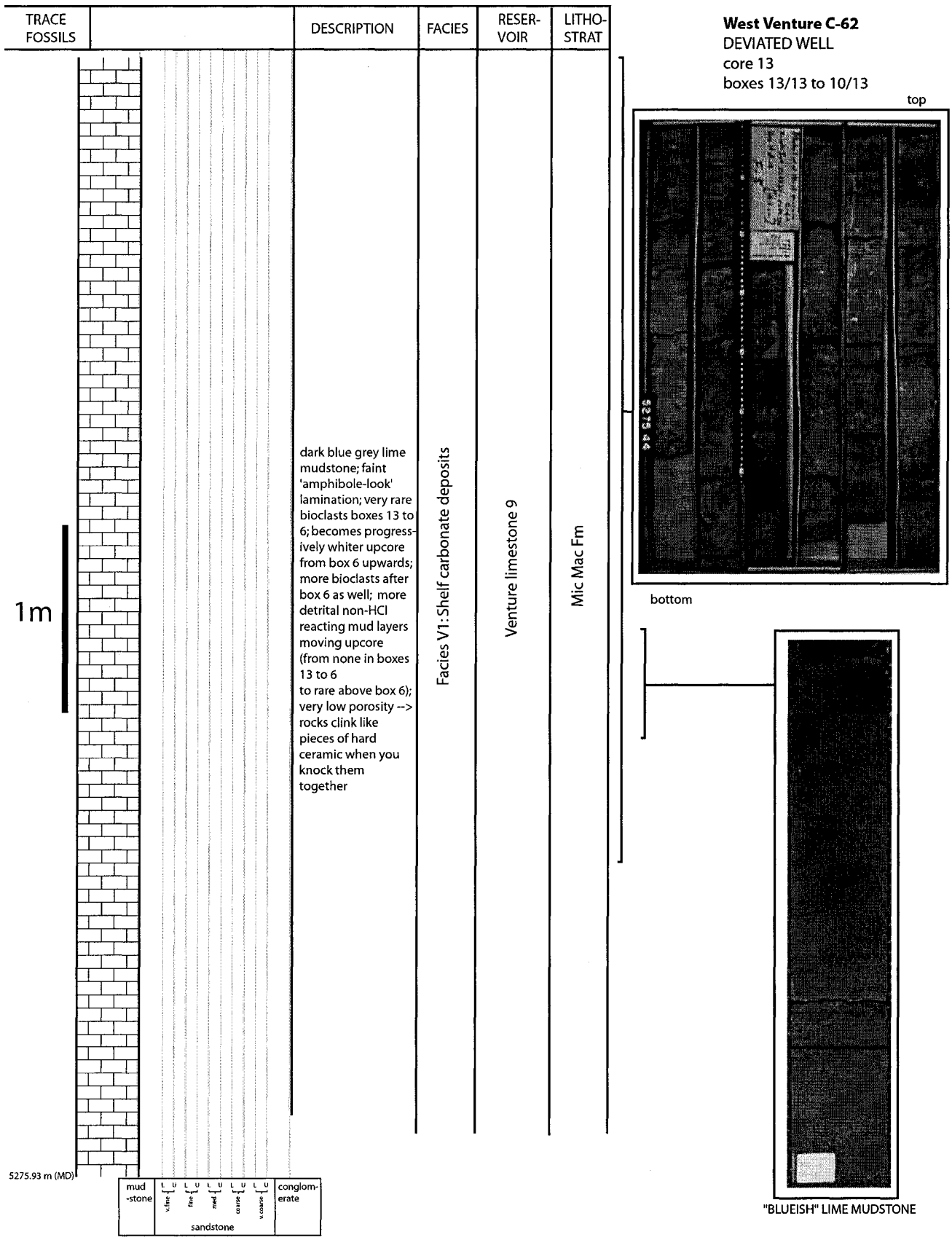
MUDSTONE WITH 'SHARP' SANDSTONE PINSTRIPES


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
1 m
Pinstripe laminated mudstone with massive to laminated very fine to very coarse sandstone interbeds ...composed of several distinct subfacies, as notated on logs...
1) mudstone with 'sharp' sandstone pinstripes --> black mudstone; non-fissile; very thin (<1 mm) sandstone laminae that commonly pinch and swell across core (i.e. sometimes get 'lenticular'); sandstone pinstripes have sharp bases and tops; rare syneresis cracks
2) mudstone w/ 'diffuse' sandstone pinstripes --> thin (< 1 cm) gradationally-based and topped sandstone laminae common; these always occur in groupings, rarely rhythmic, that fade upwards into and/or emerge upwards from black mudstone (i.e. the groupings commonly thicken and coarsen upwards, then thin and fine-upwards); individual diffuse sandstone pinstripes are 1-10 mm thick, and have gradational upper and lower contacts with mudstone; rare syneresis cracks
3) bioturbated mudstone --> bioturbation in the mudstone seems to just 'turn' on and off ... goes from nothing to intensely bioturbated and vice versa rather quickly; trace fossils are quite hard to identify .. seemingly all are horizontal, and many are very Teichichnus-looking (actually, the more I look at them, could most of them be Teichichnus ?)
4) laminated sandstone --> these come in two types: sandstone beds that look wave influenced, and those that look rhythmically laminated; these are often microfaulted
4a) low angle cross laminated to wavy parallel laminated
4b) very flat thicker sandstone laminae with thin (<1 mm) mudstone interlaminae; rhythmically laminated
5) massive sandstone --> typically coarser grained than other sandstone beds; occasionally microfaulted and soft sediment deformed; beds are 1-50 cm thick; rare mud rip ups; lower contacts are sharp, commonly loaded; no bioturbation, except for one ?Arenicolites burrow
Facies V7: Tide-influenced fluvial deposits
Venture sandstone 5
Lower Member, Missisauga Fm
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone
Venture H-22
core 2
boxes 13/17 to 10/17
4a
1
4a wavy parallel laminated sandstone and mudstone (note low-angle truncation surface (arrow)
1 mudstone with 'sharp' sandstone laminae

Venture H-22
core2
boxes 9/17 to 6/17




TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Venture H-22
core 2
boxes 5/17 to 1/17
TIDAL RHYTHMITES
SANDSTONE BALL IN MUDSTONE
1 m
with liquefaction structures (sandstone balls)
deformed
microfaulted
microfaulted
Pinstripe laminated mudstone with massive to laminated very fine to very coarse sandstone interbeds ...composed of several distinct subfacies, as notated on logs ...
1) mudstone with 'sharp' sandstone pinstripes --> black mudstone; non-fissile; very thin (<1 mm) sandstone laminae that commonly pinch and swell across core (i.e. sometimes get 'lenticular'); sandstone pinstripes have sharp bases and tops; rare syneresis cracks
2) mudstone w/ 'diffuse' sandstone pinstripes --> thin (< 1 cm) gradationally-based and topped sandstone laminae common; these always occur in groupings, rarely rhythmic, that fade upwards into and/or emerge upwards from black mudstone (i.e. the groupings commonly thicken and coarsen upwards, then thin and fine-upwards); individual diffuse sandstone pinstripes are 1-10 mm thick, and have gradational upper and lower contacts with mudstone; rare syneresis cracks
3) bioturbated mudstone --> bioturbation in the mudstone seems to just 'turn' on and off ... goes from nothing to intensely bioturbated and vice versa rather quickly; trace fossils are quite hard to identify .. seemingly all are horizontal, and many are very Teichichnus-looking (actually, the more I look at them, could most of them be Teichichnus)
4) laminated sandstone --> these come in two types: sandstone beds that look wave influenced, and those that look rhythmically laminated; these are often microfaulted
4a) low angle cross laminated to wavy parallel laminated
4b) very flat thicker sandstone laminae with thin (<1 mm) mudstone interlaminae; rhythmically laminated
5) massive sandstone --> typically coarser grained than other sandstone beds; occasionally microfaulted and soft sediment deformed; beds are 1-50 cm thick; rare mud rip ups; lower contacts are sharp, commonly loaded; no bioturbation, except for one ?Arenicolites burrow
Facies V7: Tide-influenced fluvial deposits
Venture sandstone 5
Lower Member, Missisauga Fm
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone

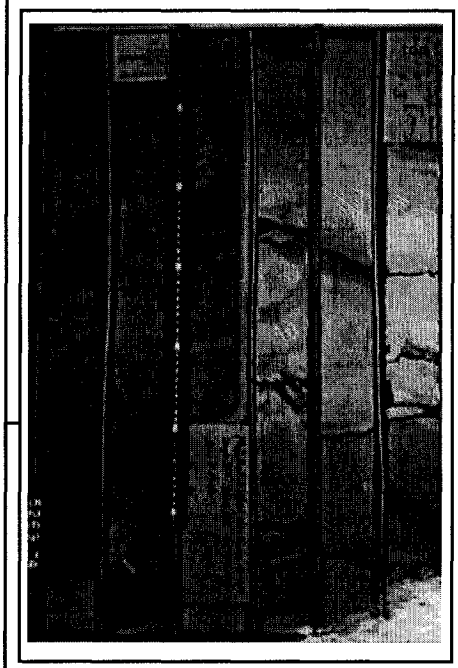

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
1m
dark blue grey lime mudstone; faint 'amphibole-look' lamination; very rare bioclasts boxes 13 to 6; becomes progress-ively whiter upcore from box 6 upwards; more bioclasts after box 6 as well; more detrital non-HCl reacting mud layers moving upcore (from none in boxes 13 to 6 to rare above box 6); very low porosity --> rocks clink like pieces of hard ceramic when you knock them together
Facies V1: Shelf carbonate deposits
Venture limestone 9
Mic Mac Fm
5275.93 m (MD)
mud -stone
v. fine
fine
med
coarse
v. coarse
sandstone
conglom-erate
West Venture C-62
DEVIATED WELL
core 13
boxes 13/13 to 10/13
top
bottom
"BLUEISH" LIME MUDSTONE

TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
		dark blue grey lime mudstone; faint 'amphibole-look' lamination; very rare bioclasts boxes 13 to 6; becomes progress-ively whiter upcore from box 6 upwards; more bioclasts after box 6 as well; more detrital non-HCl reacting mud layers moving upcore (from none in boxes 13 to 6 to rare above box 6); very low porosity --> rocks clink like pieces of hard ceramic when you knock them together	Facies V1: Shelf carbonate deposits	Venture limestone 9	Mic Mac Fm

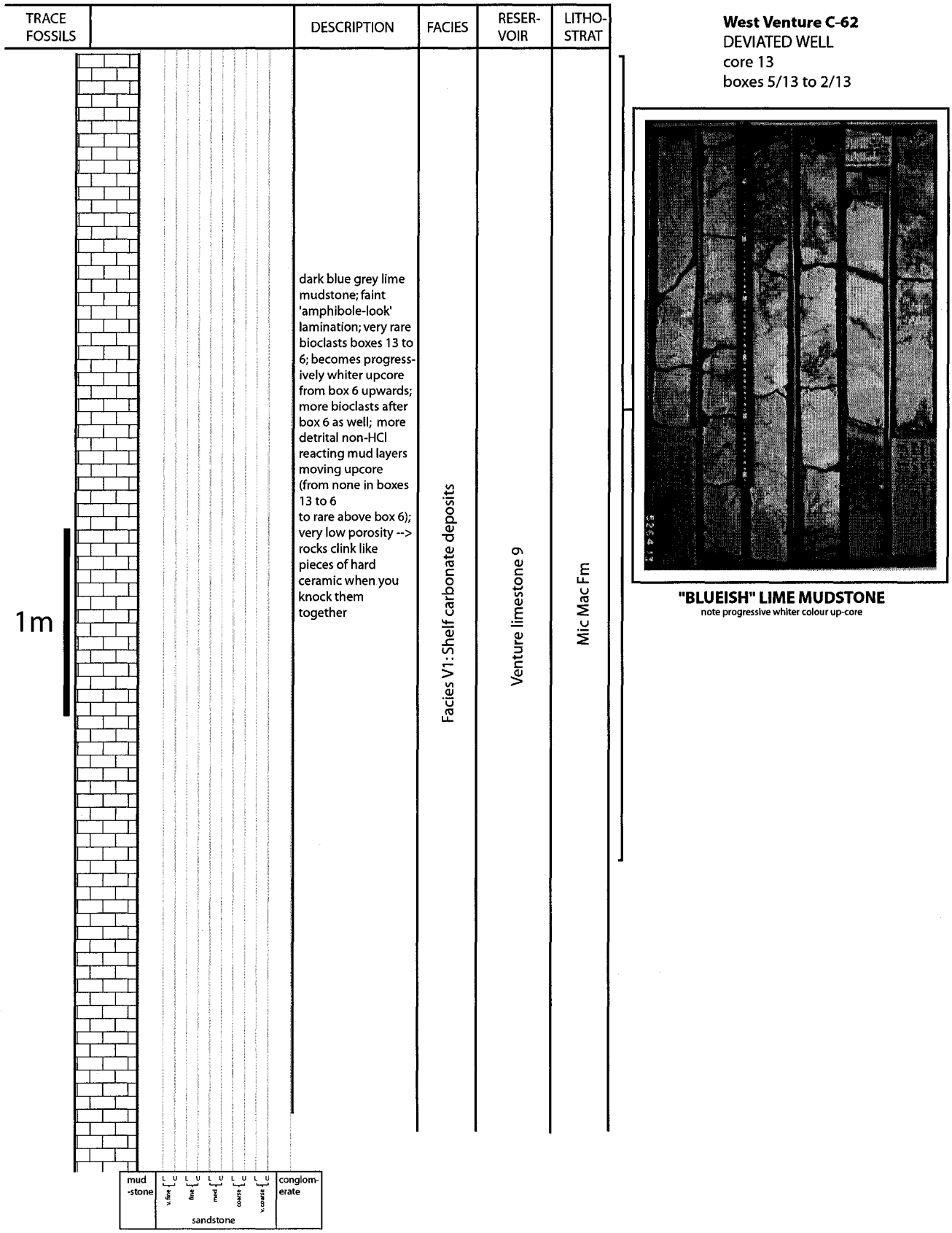
1m

mud -stone | sandstone: v.fine, fine, med, coarse, v.coarse | conglom-erate

West Venture C-62
DEVIATED WELL
core 13
boxes 9/13 to 6/13



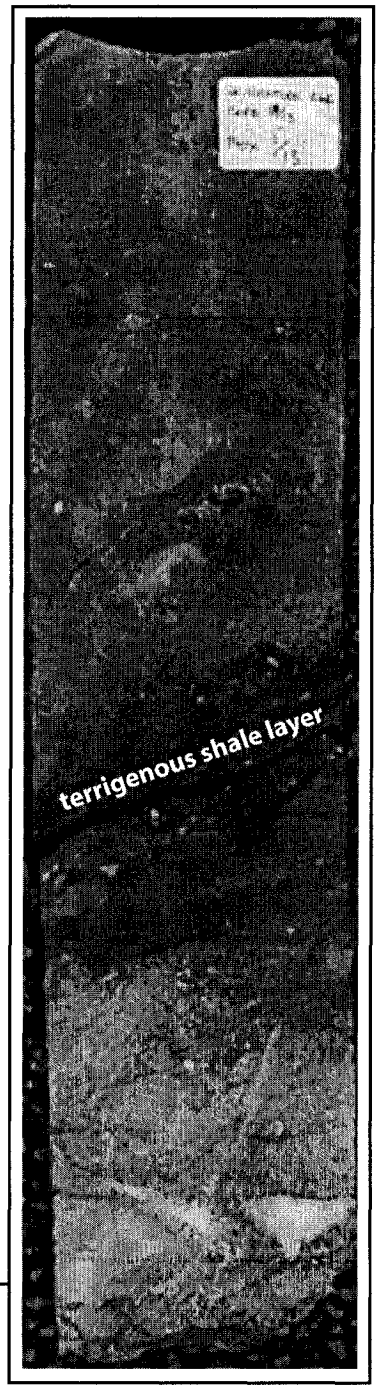
"BLUEISH" LIME MUDSTONE
note progressive whiter colour up-core


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
dark blue grey lime mudstone; faint 'amphibole-look' lamination; very rare bioclasts boxes 13 to 6; becomes progress-ively whiter upcore from box 6 upwards; more bioclasts after box 6 as well; more detrital non-HCl reacting mud layers moving upcore (from none in boxes 13 to 6 to rare above box 6); very low porosity --> rocks clink like pieces of hard ceramic when you knock them together
Facies V1: Shelf carbonate deposits
Venture limestone 9
Mic Mac Fm
1m
mud -stone
v. fine
fine
med
coarse
v. coarse
sandstone
conglom-erate
West Venture C-62
DEVIATED WELL
core 13
boxes 5/13 to 2/13
"BLUEISH" LIME MUDSTONE
note progressive whiter colour up-core

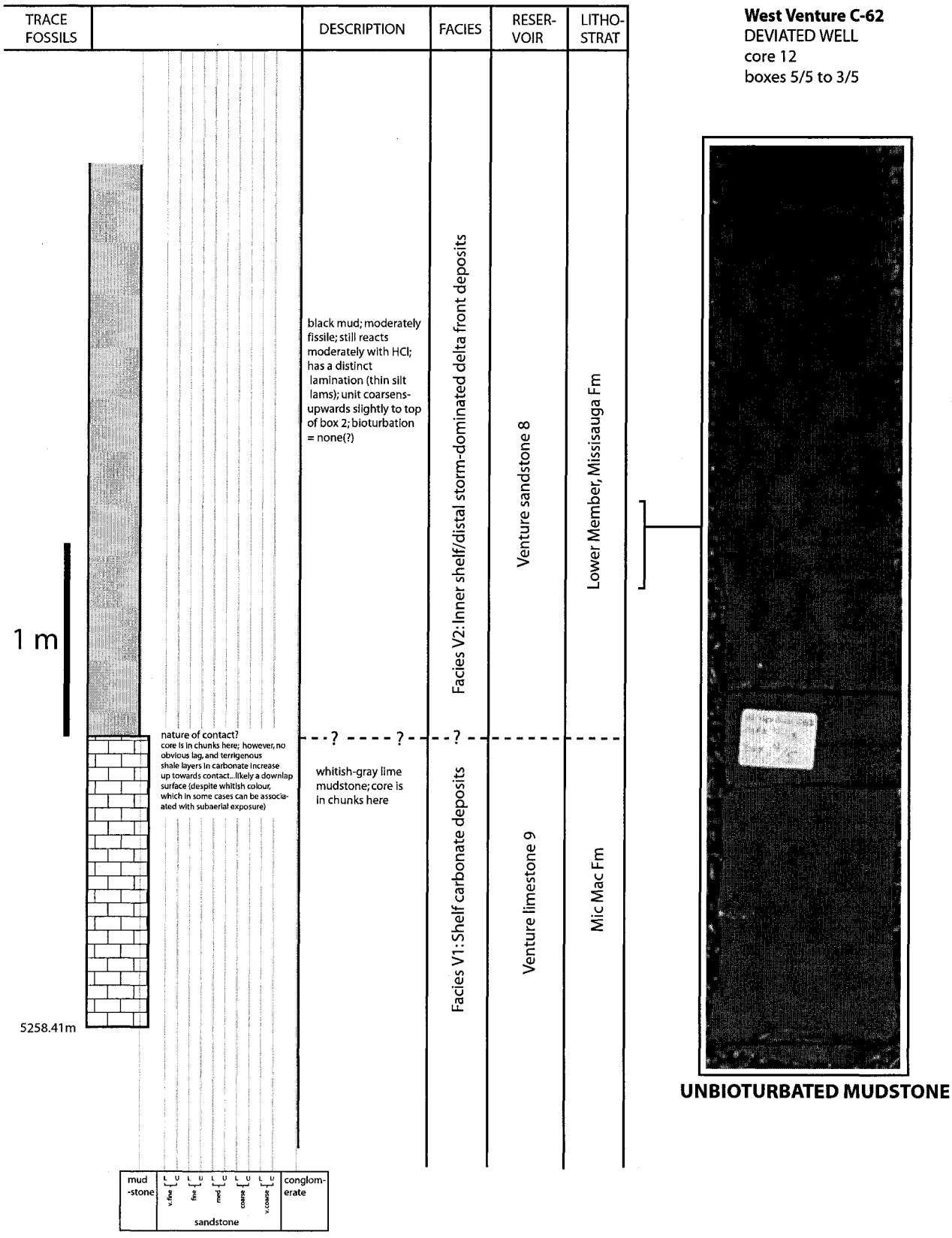
West Venture C-62
DEVIATED WELL
core 13
box 1/13

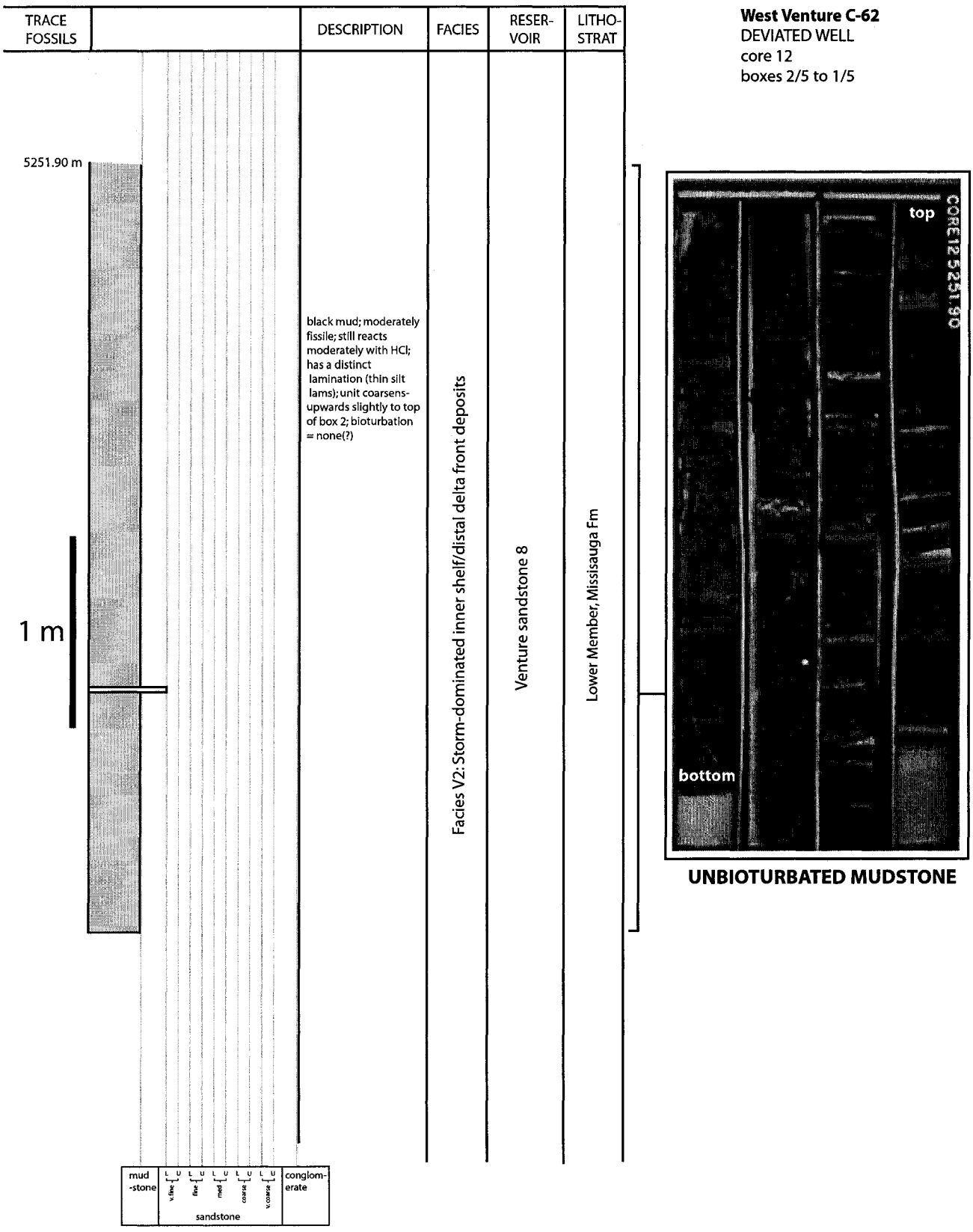
TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
	5258.41 m (MD) 1 m	dark blue grey lime mudstone; faint 'amphibole-look' lamination; very rare bioclasts boxes 13 to 6; becomes progress-ively whiter upcore from box 6 upwards; more bioclasts after box 6 as well; more detrital non-HCl reacting mud layers moving upcore (from none in boxes 13 to 6 to rare above box 6); very low porosity --> rocks clink like pieces of hard ceramic when you knock them together	Facies V1: Shelf carbonate deposits	Venture limestone No. 9	Mic Mac Fm

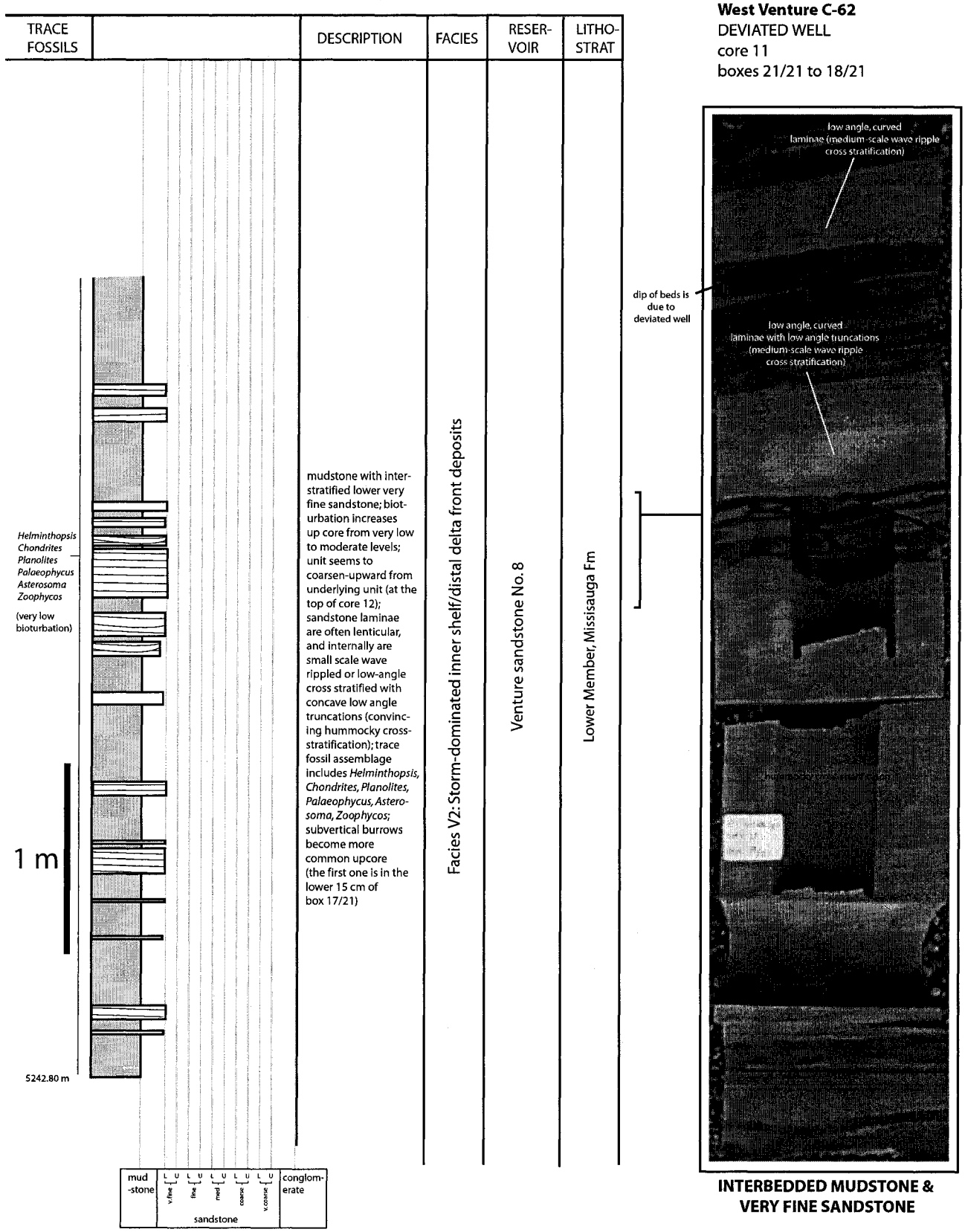
mud -stone | sandstone: v. fine, fine, med, coarse, v. coarse | conglom-erate

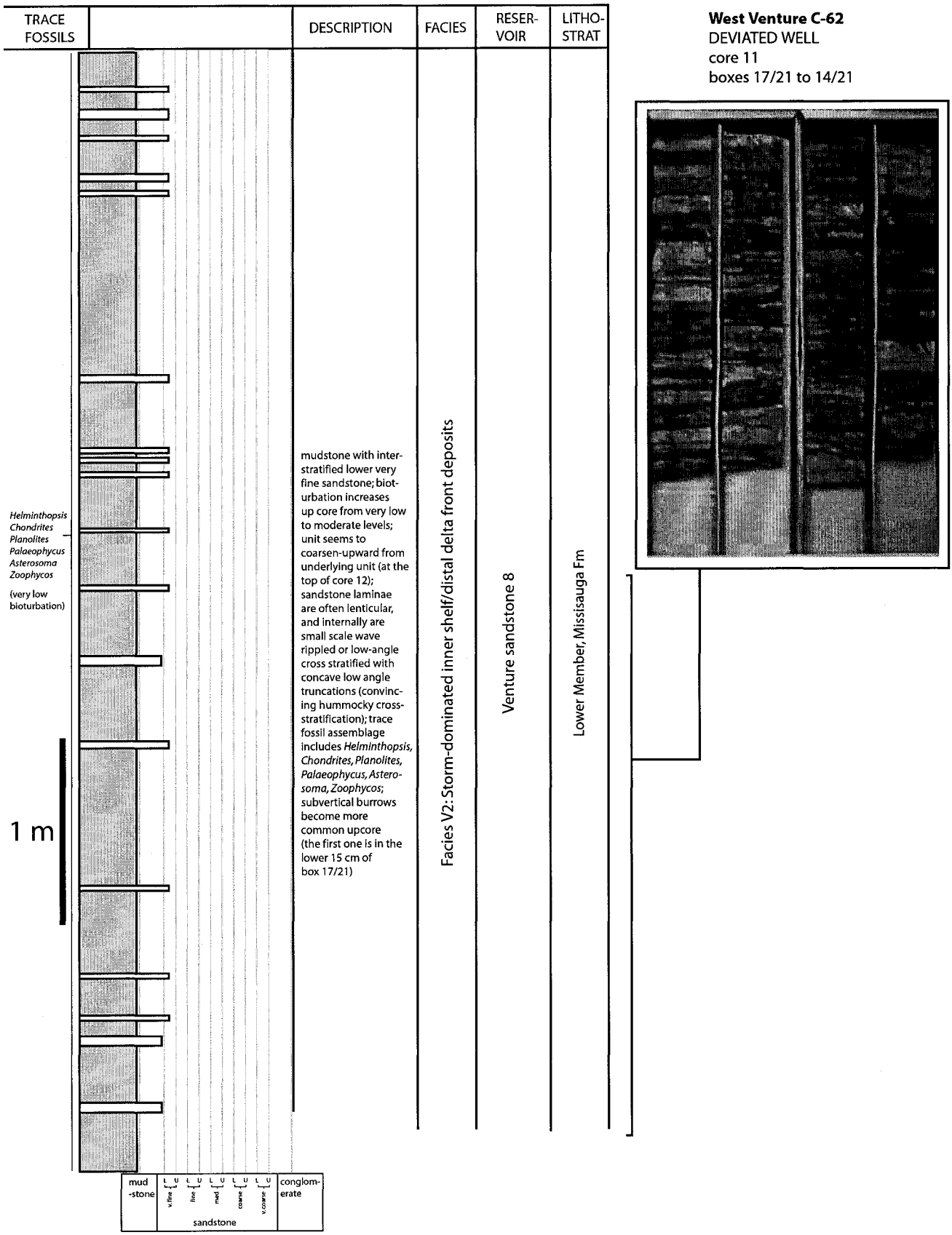


LIME MUDSTONE

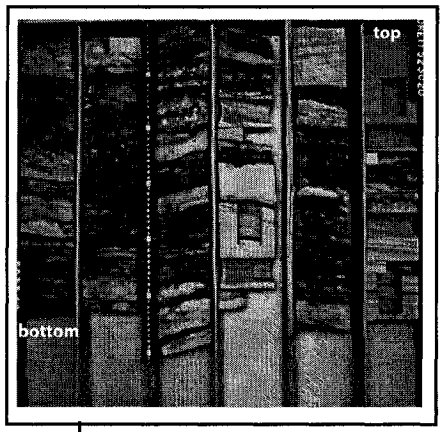

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
West Venture C-62
DEVIATED WELL
core 12
boxes 5/5 to 3/5
1 m
black mud; moderately fissile; still reacts moderately with HCl; has a distinct lamination (thin silt lams); unit coarsens-upwards slightly to top of box 2; bioturbation = none(?)
Facies V2: Inner shelf/distal storm-dominated delta front deposits
Venture sandstone 8
Lower Member, Missisauga Fm
nature of contact?
core is in chunks here; however, no obvious lag, and terrigenous shale layers in carbonate increase up towards contact...likely a downlap surface (despite whitish colour, which in some cases can be associated with subaerial exposure)
? ? ?
whitish-gray lime mudstone; core is in chunks here
Facies V1: Shelf carbonate deposits
Venture limestone 9
Mic Mac Fm
5258.41m
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
UNBIOTURBATED MUDSTONE

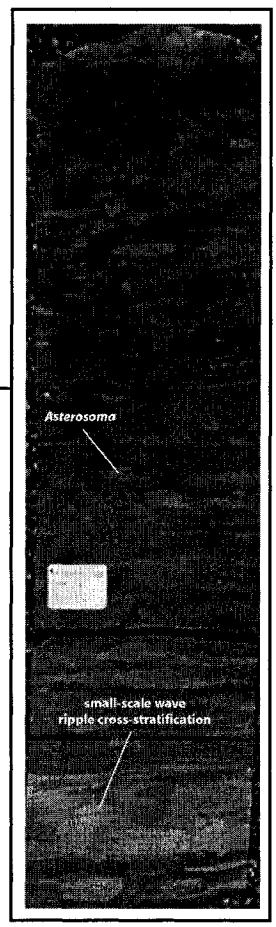

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
5251.90 m
1 m
black mud; moderately fissile; still reacts moderately with HCl; has a distinct lamination (thin silt lams); unit coarsens-upwards slightly to top of box 2; bioturbation = none(?)
Facies V2: Storm-dominated inner shelf/distal delta front deposits
Venture sandstone 8
Lower Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 12
boxes 2/5 to 1/5
top
bottom
CORE12 5251.90
UNBIOTURBATED MUDSTONE

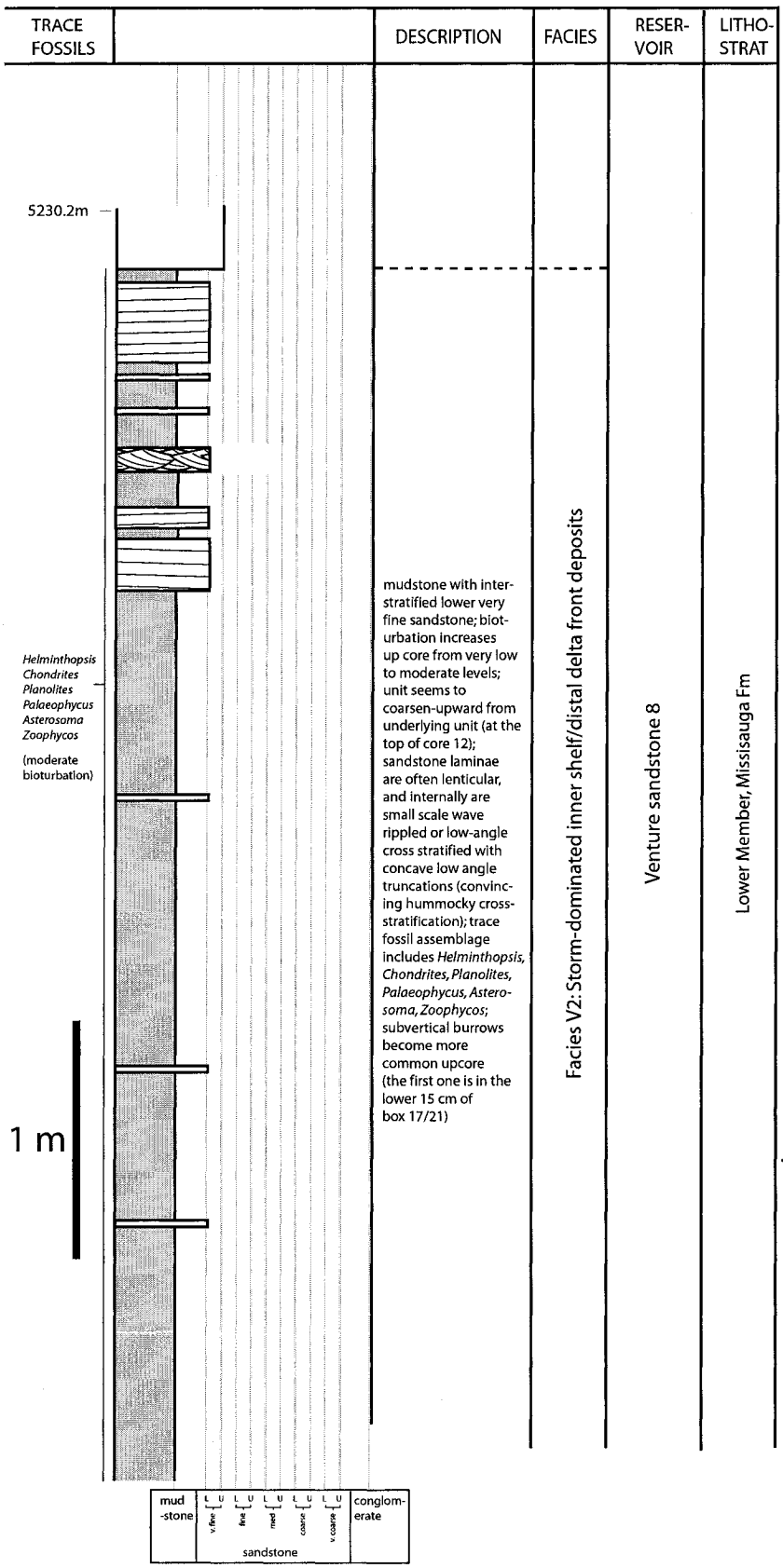

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Helminthopsis
Chondrites
Planolites
Palaeophycus
Asterosoma
Zoophycos
(very low bioturbation)
1 m
5242.80 m
mudstone with inter-stratified lower very fine sandstone; biot-urbation increases up core from very low to moderate levels; unit seems to coarsen-upward from underlying unit (at the top of core 12); sandstone laminae are often lenticular, and internally are small scale wave rippled or low-angle cross stratified with concave low angle truncations (convinc-ing hummocky cross-stratification); trace fossil assemblage includes Helminthopsis, Chondrites, Planolites, Palaeophycus, Astero-soma, Zoophycos; subvertical burrows become more common upcore (the first one is in the lower 15 cm of box 17/21)
Facies V2: Storm-dominated inner shelf/distal delta front deposits
Venture sandstone No.8
Lower Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 11
boxes 21/21 to 18/21
low angle, curved laminae (medium-scale wave ripple cross stratification)
dip of beds is due to deviated well
low angle, curved laminae with low angle truncations (medium)-scale wave ripple cross stratification)
INTERBEDDED MUDSTONE & VERY FINE SANDSTONE

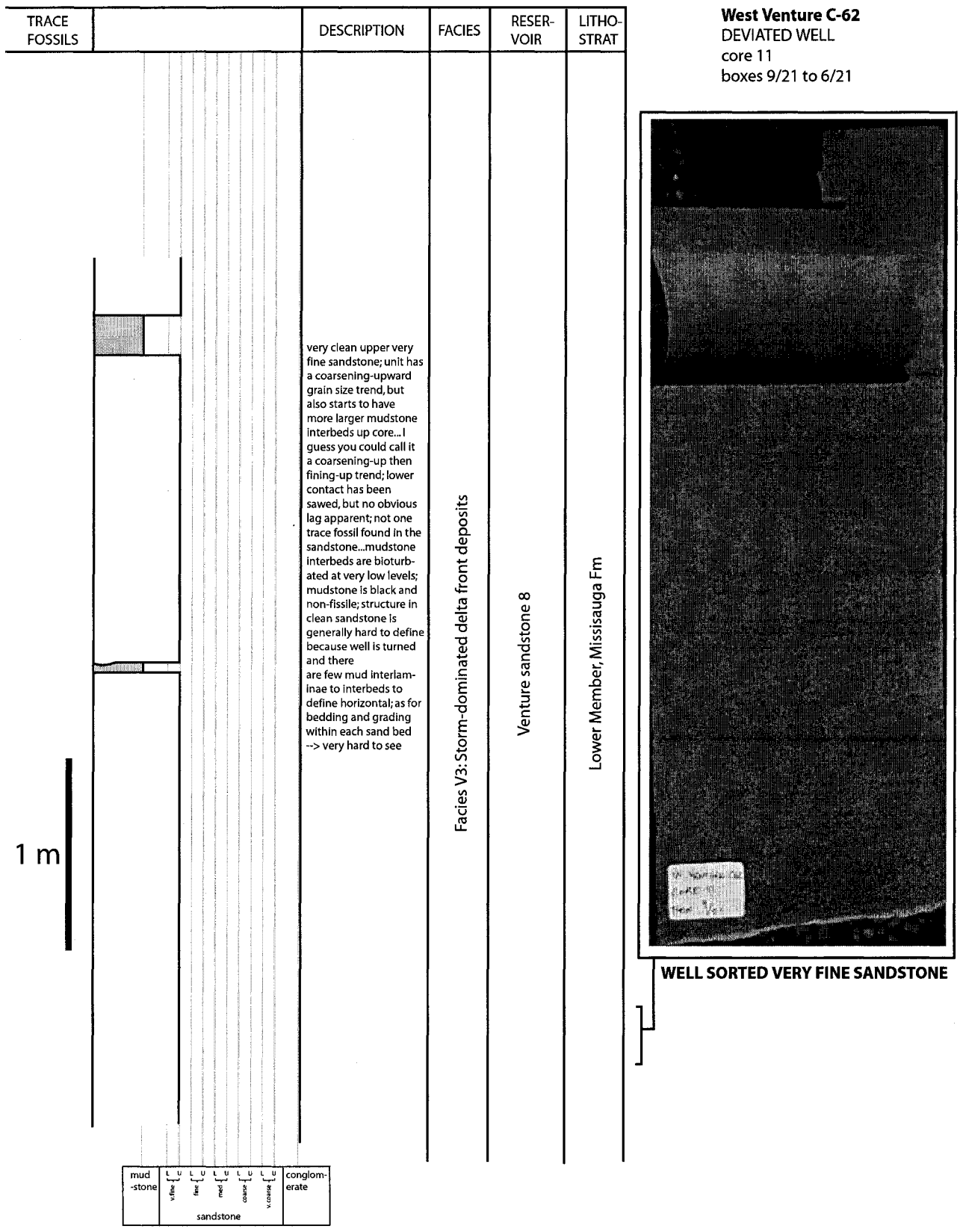

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Helminthopsis
Chondrites
Planolites
Palaeophycus
Asterosoma
Zoophycos
(very low bioturbation)
1 m
mudstone with interstratified lower very fine sandstone; bioturbation increases up core from very low to moderate levels; unit seems to coarsen-upward from underlying unit (at the top of core 12); sandstone laminae are often lenticular, and internally are small scale wave rippled or low-angle cross stratified with concave low angle truncations (convincing hummocky cross-stratification); trace fossil assemblage includes Helminthopsis, Chondrites, Planolites, Palaeophycus, Asterosoma, Zoophycos; subvertical burrows become more common upcore (the first one is in the lower 15 cm of box 17/21)
Facies V2: Storm-dominated inner shelf/distal delta front deposits
Venture sandstone 8
Lower Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 11
boxes 17/21 to 14/21

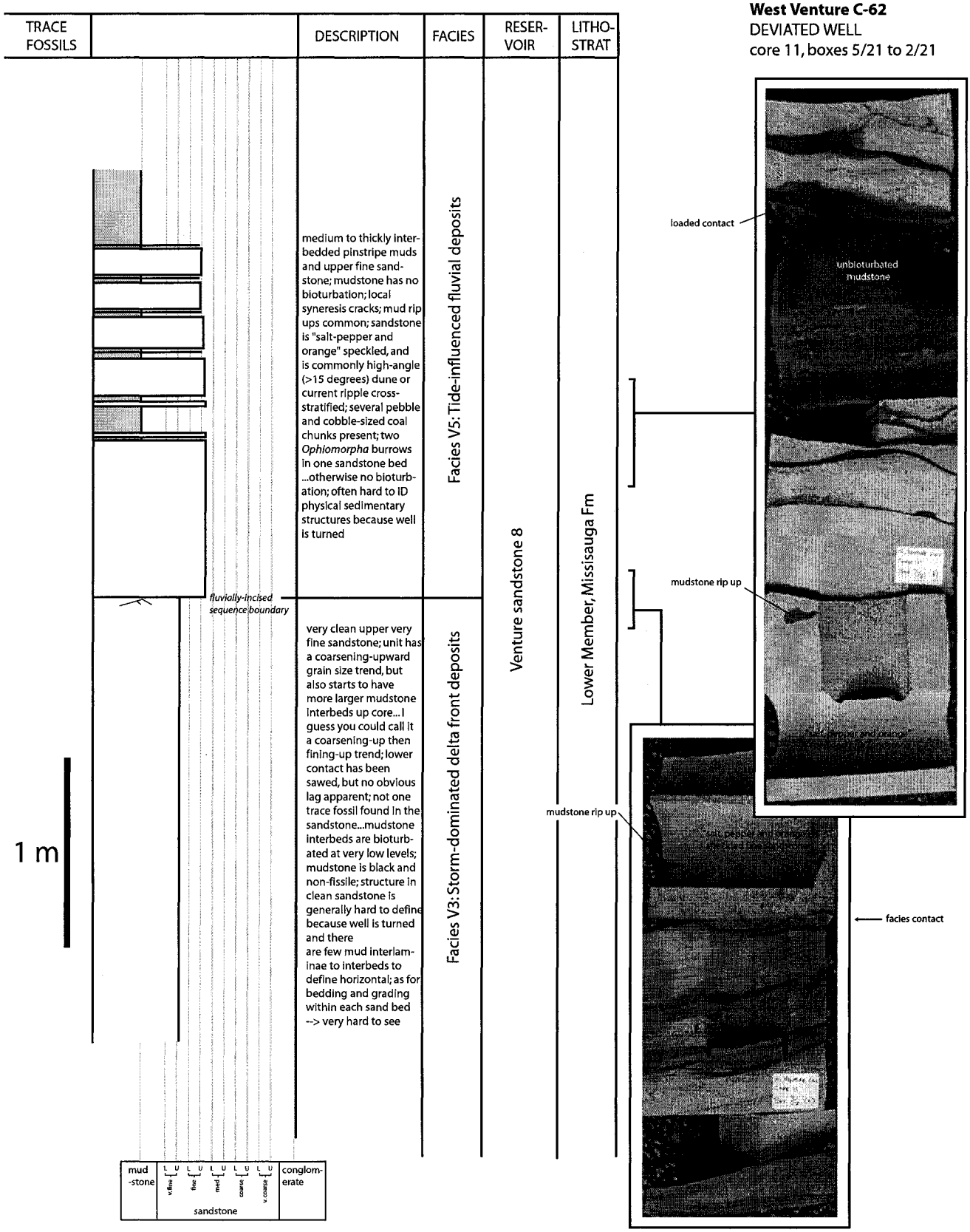
West Venture C-62
DEVIATED WELL
core 11
boxes 13/21 to 10/21

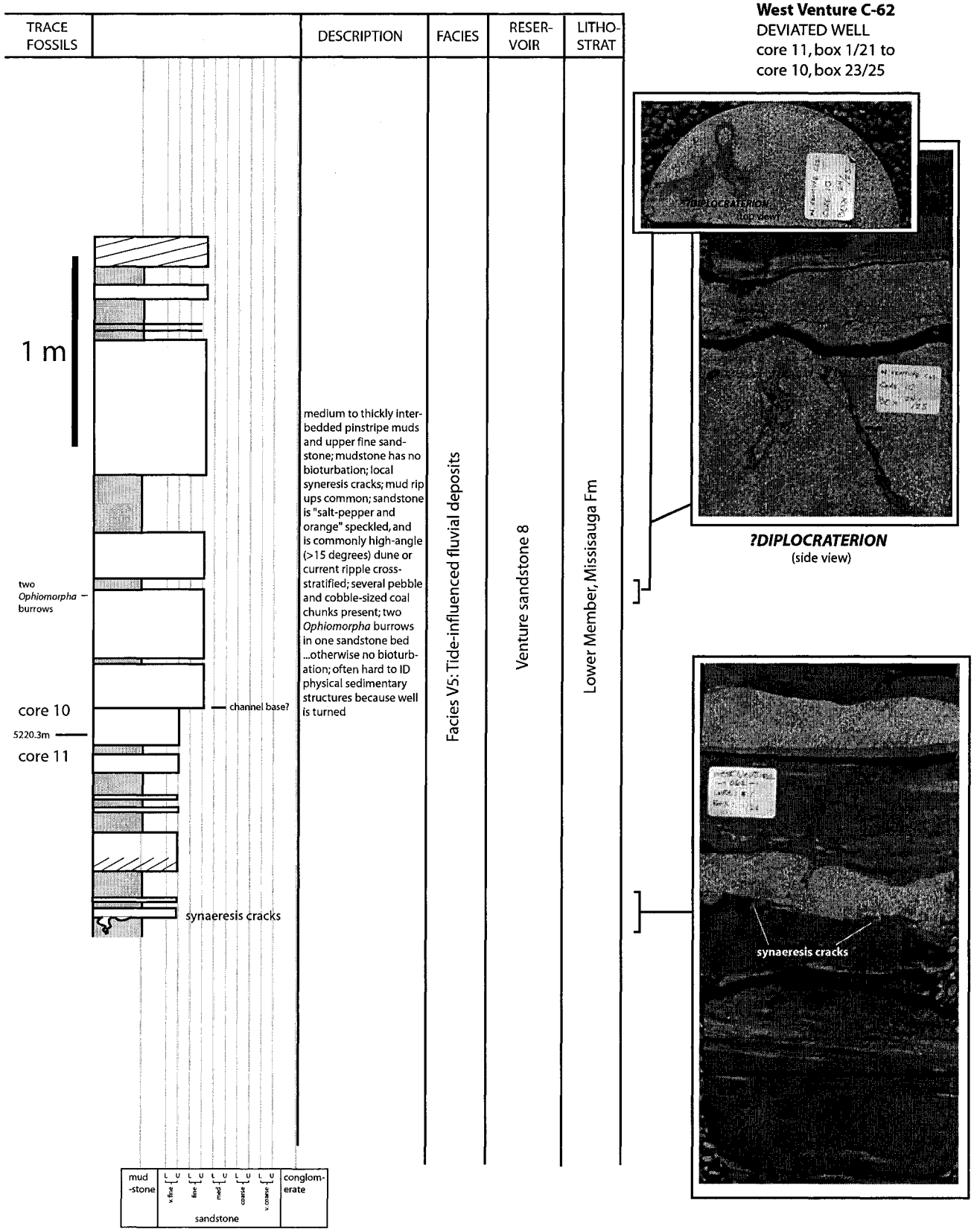


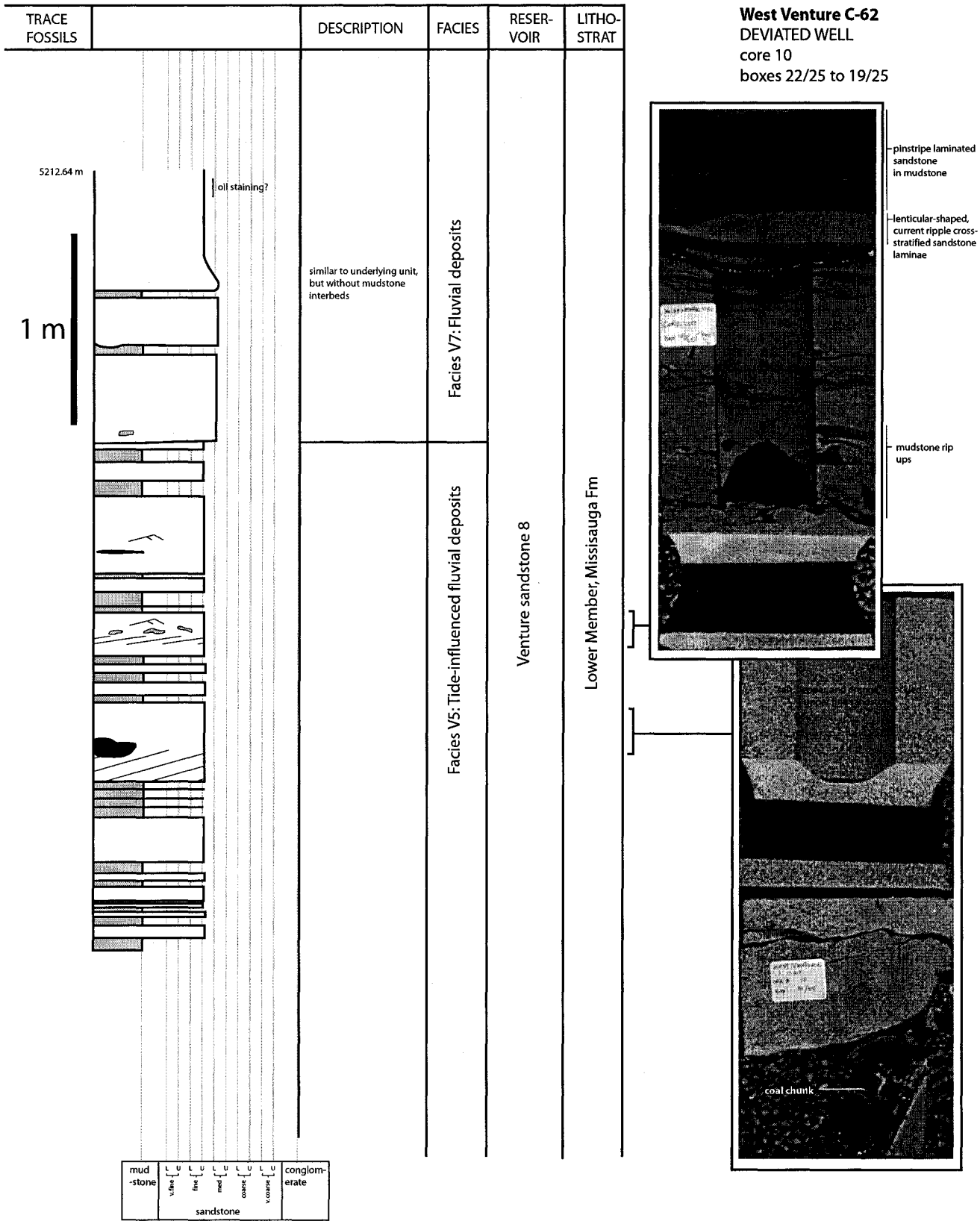


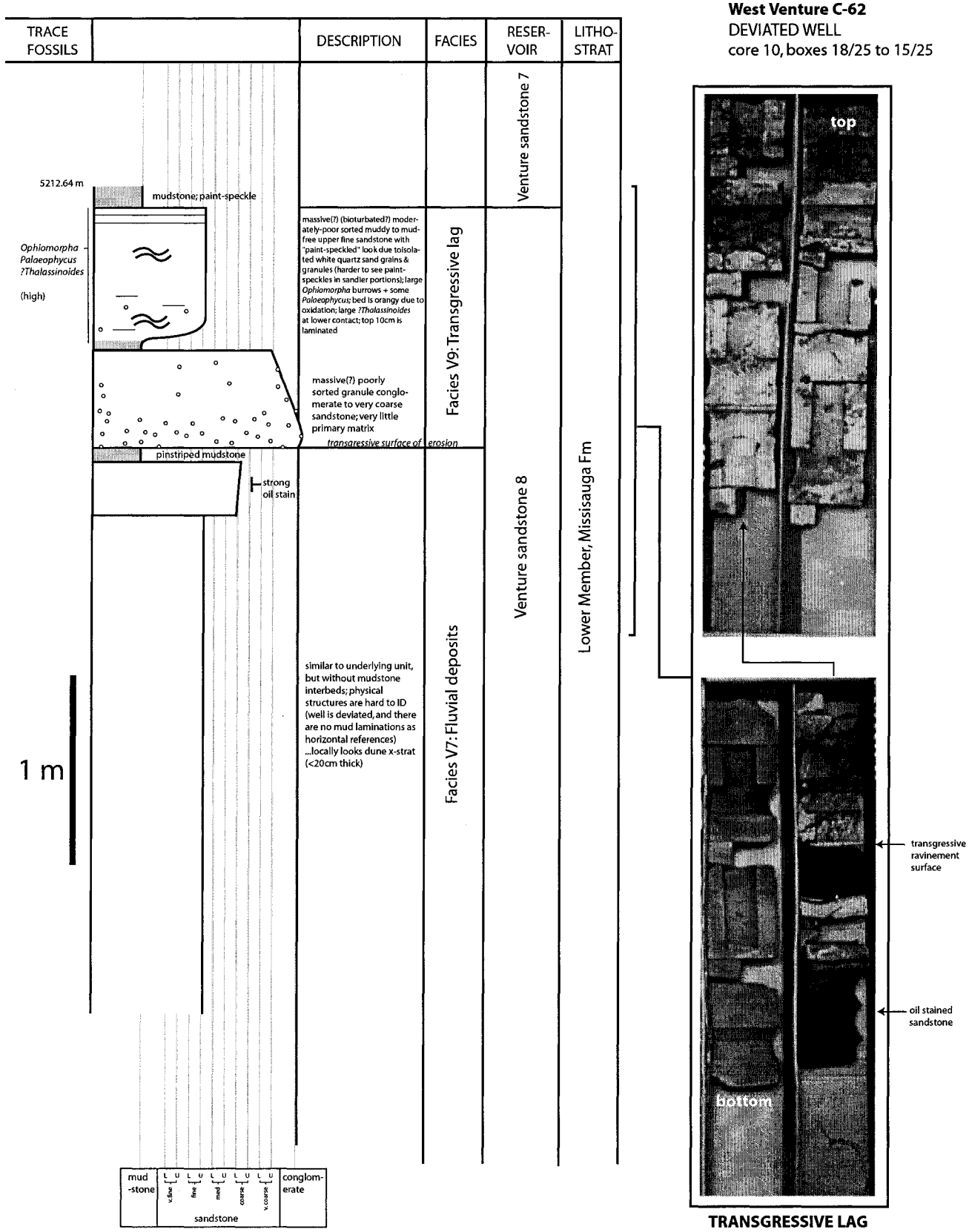



TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
very clean upper very fine sandstone; unit has a coarsening-upward grain size trend, but also starts to have more larger mudstone interbeds up core... I guess you could call it a coarsening-up then fining-up trend; lower contact has been sawed, but no obvious lag apparent; not one trace fossil found in the sandstone...mudstone interbeds are bioturb-ated at very low levels; mudstone is black and non-fissile; structure in clean sandstone is generally hard to define because well is turned and there are few mud interlam-inae to interbeds to define horizontal; as for bedding and grading within each sand bed --> very hard to see
Facies V3: Storm-dominated delta front deposits
Venture sandstone 8
Lower Member, Missisauga Fm
1 m
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 11
boxes 9/21 to 6/21
WELL SORTED VERY FINE SANDSTONE

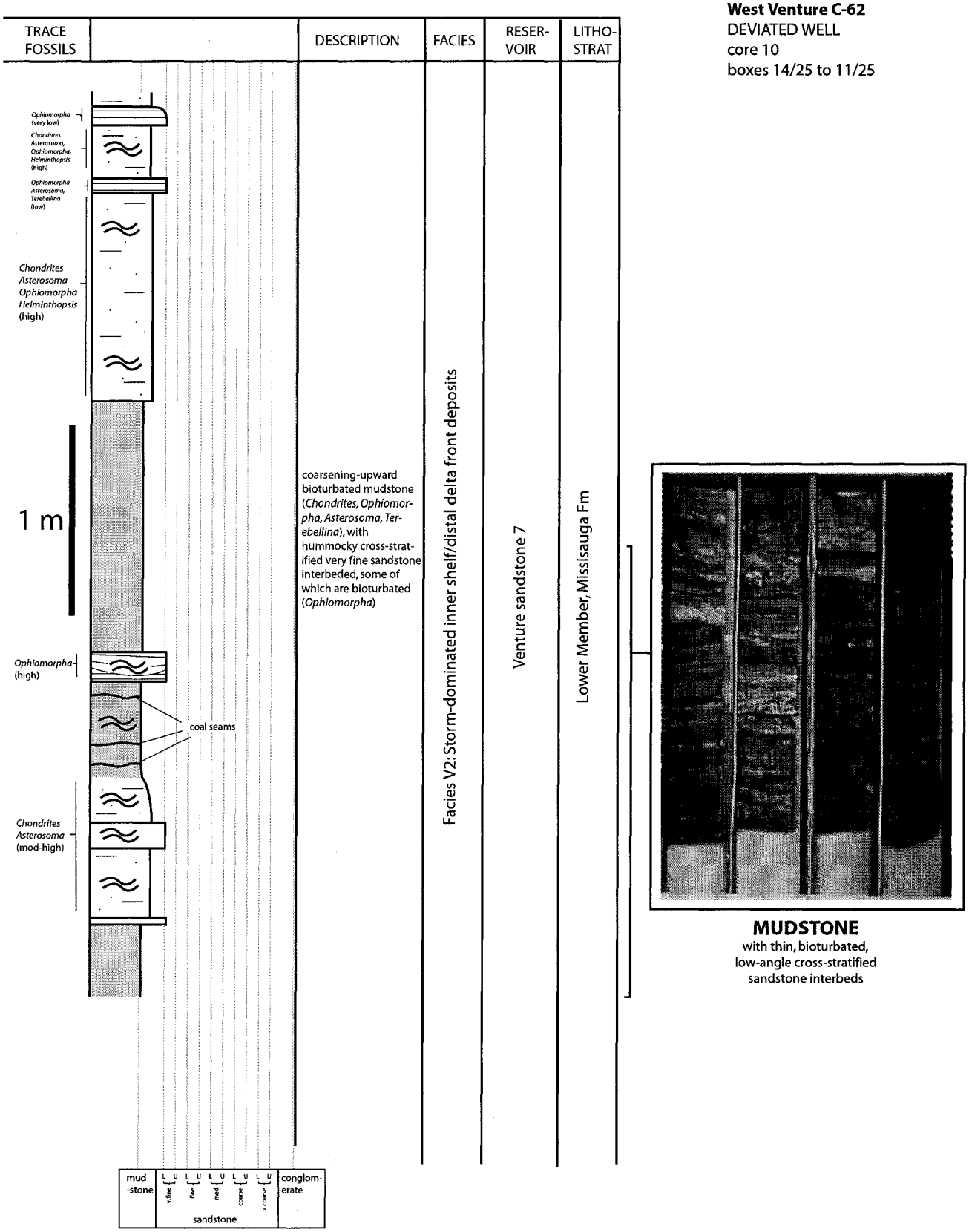

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
West Venture C-62
DEVIATED WELL
core 11, boxes 5/21 to 2/21
medium to thickly interbedded pinstripe muds and upper fine sandstone; mudstone has no bioturbation; local syneresis cracks; mud rip ups common; sandstone is "salt-pepper and orange" speckled, and is commonly high-angle (>15 degrees) dune or current ripple cross-stratified; several pebble and cobble-sized coal chunks present; two Ophiomorpha burrows in one sandstone bed ...otherwise no bioturbation; often hard to ID physical sedimentary structures because well is turned
Facies V5: Tide-influenced fluvial deposits
fluvially-incised sequence boundary
very clean upper very fine sandstone; unit has a coarsening-upward grain size trend, but also starts to have more larger mudstone interbeds up core... I guess you could call it a coarsening-up then fining-up trend; lower contact has been sawed, but no obvious lag apparent; not one trace fossil found in the sandstone...mudstone interbeds are bioturbated at very low levels; mudstone is black and non-fissile; structure in clean sandstone is generally hard to define because well is turned and there are few mud interlaminae to interbeds to define horizontal; as for bedding and grading within each sand bed --> very hard to see
Facies V3: Storm-dominated delta front deposits
Venture sandstone 8
Lower Member, Missisauga Fm
1 m
mud -stone
v. fine
fine
med
coarse
v. coarse
conglom-erate
sandstone
loaded contact
unbioturbated mudstone
mudstone rip up
mudstone rip up
facies contact


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
1 m
two Ophiomorpha burrows
core 10
5220.3m
core 11
channel base?
synaeresis cracks
medium to thickly interbedded pinstripe muds and upper fine sandstone; mudstone has no bioturbation; local syneresis cracks; mud rip ups common; sandstone is "salt-pepper and orange" speckled, and is commonly high-angle (>15 degrees) dune or current ripple cross-stratified; several pebble and cobble-sized coal chunks present; two Ophiomorpha burrows in one sandstone bed ...otherwise no bioturbation; often hard to ID physical sedimentary structures because well is turned
Facies V5: Tide-influenced fluvial deposits
Venture sandstone 8
Lower Member, Missisauga Fm
mud -stone
v. fine
fine
med
coarse
v. coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 11, box 1/21 to
core 10, box 23/25
?DIPLOCRATERION
(side view)
synaeresis cracks


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
5212.64 m
oil staining?
1 m
similar to underlying unit, but without mudstone interbeds
Facies V7: Fluvial deposits
Facies V5: Tide-influenced fluvial deposits
Venture sandstone 8
Lower Member, Missisauga Fm
mud -stone
v. fine
fine
med
coarse
v. coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 10
boxes 22/25 to 19/25
pinstripe laminated sandstone in mudstone
lenticular-shaped, current ripple cross-stratified sandstone laminae
mudstone rip ups
coal chunk

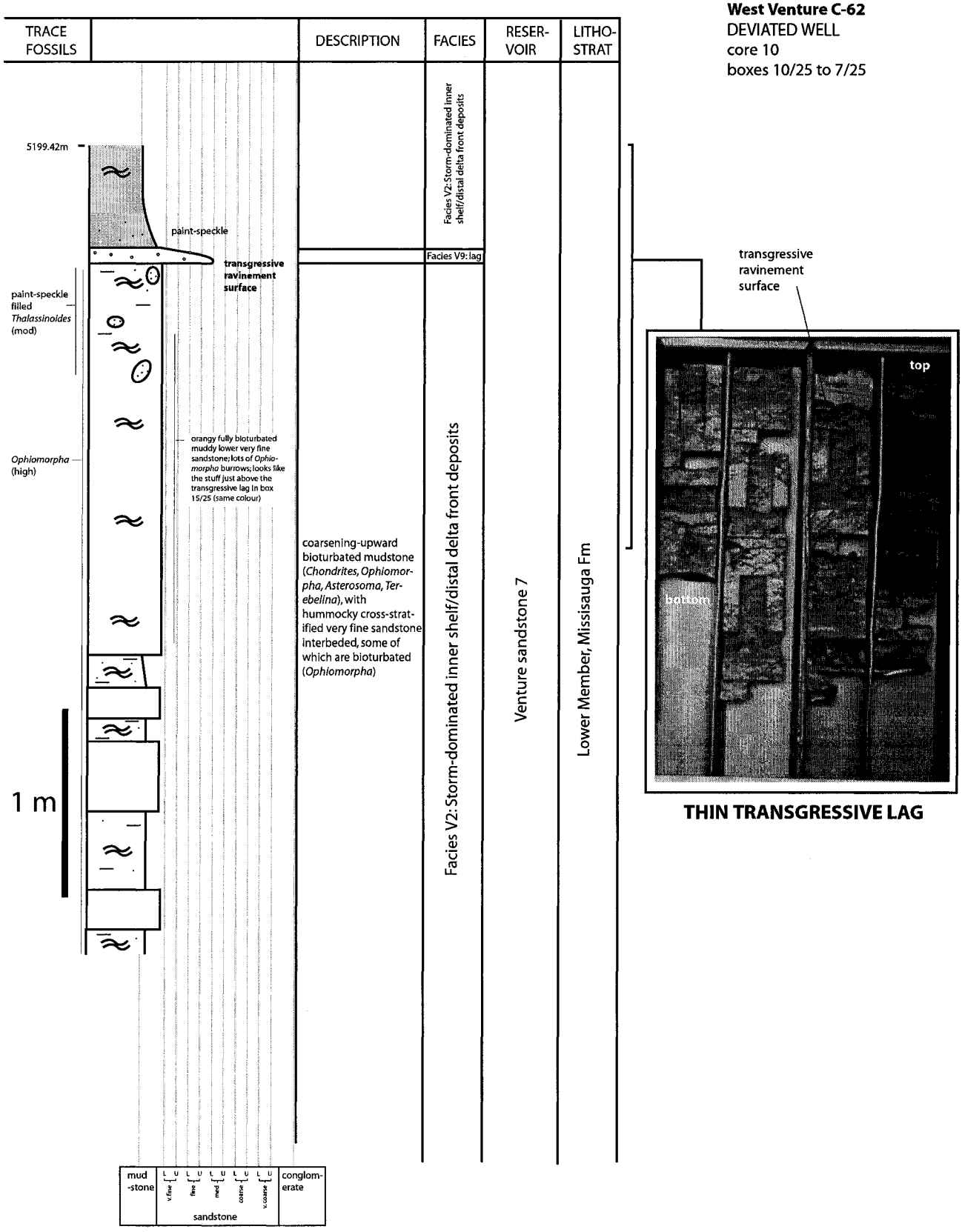

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
5212.64 m
mudstone; paint-speckle
Ophiomorpha
Palaeophycus
?Thalassinoides
(high)
massive(?) (bioturbated?) moderately-poor sorted muddy to mud-free upper fine sandstone with "paint-speckled" look due to isolated white quartz sand grains & granules (harder to see paint-speckles in sandier portions); large Ophiomorpha burrows + some Palaeophycus; bed is orangy due to oxidation; large ?Thalassinoides at lower contact; top 10cm is laminated
Facies V9: Transgressive lag
Venture sandstone 7
massive(?) poorly sorted granule conglomerate to very coarse sandstone; very little primary matrix
transgressive surface of erosion
pinstriped mudstone
strong oil stain
Facies V7: Fluvial deposits
Venture sandstone 8
similar to underlying unit, but without mudstone interbeds; physical structures are hard to ID (well is deviated, and there are no mud laminations as horizontal references) ...locally looks dune x-strat (<20cm thick)
Lower Member, Missisauga Fm
1 m
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 10, boxes 18/25 to 15/25
top
bottom
transgressive ravinement surface
oil stained sandstone
TRANSGRESSIVE LAG

West Venture C-62
DEVIATED WELL
core 10
boxes 14/25 to 11/25

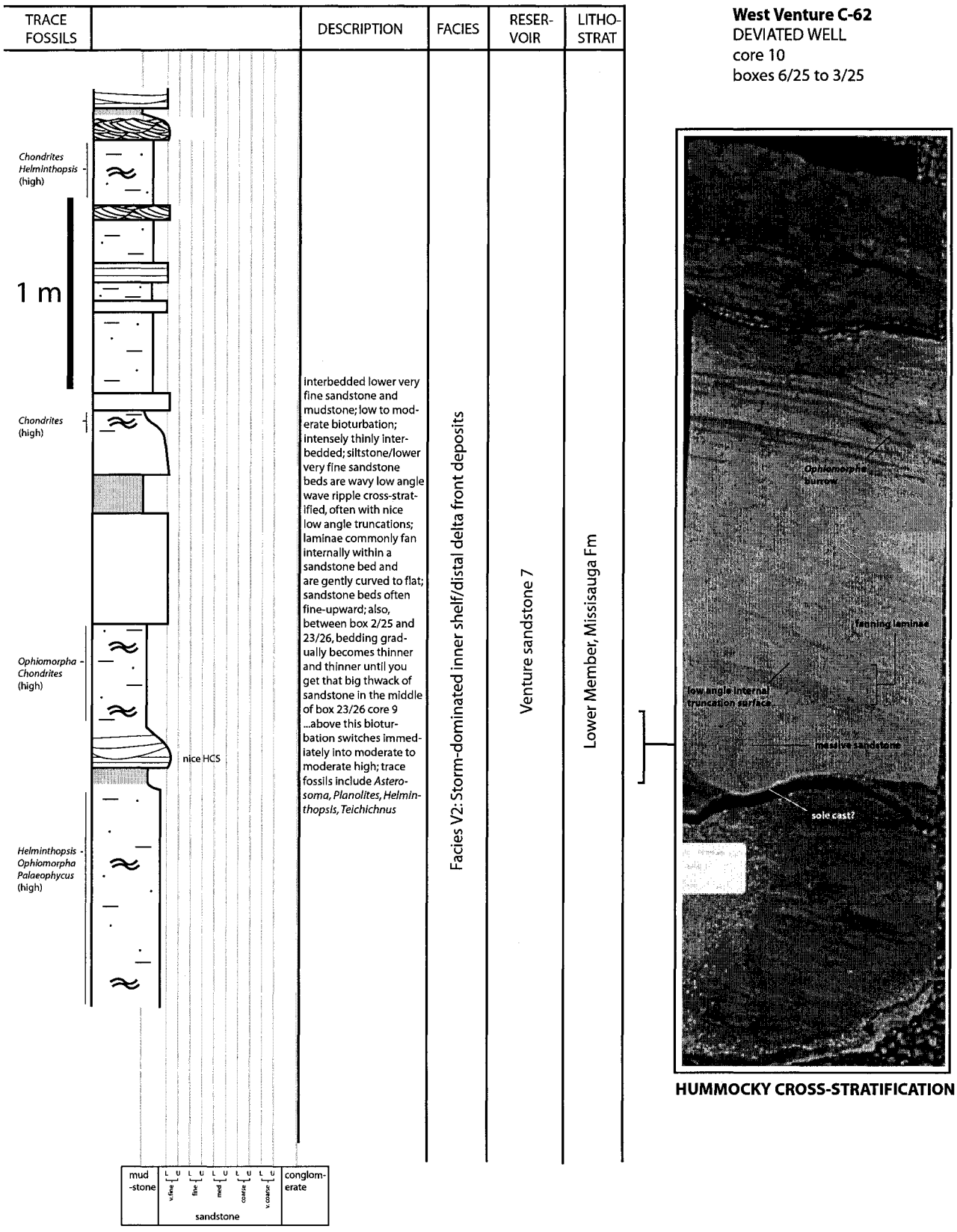


MUDSTONE
with thin, bioturbated, low-angle cross-stratified sandstone interbeds

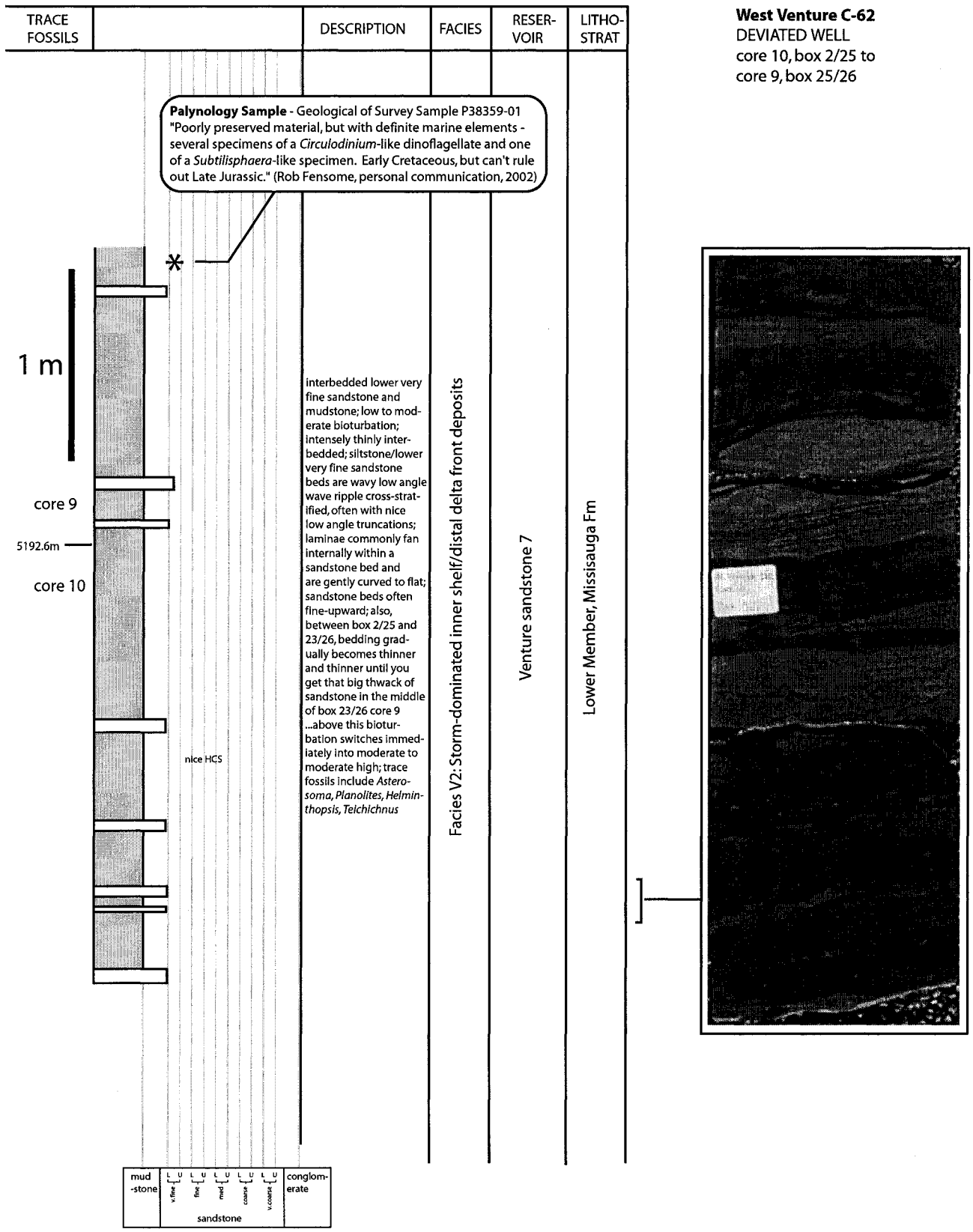
West Venture C-62
DEVIATED WELL
core 10
boxes 10/25 to 7/25



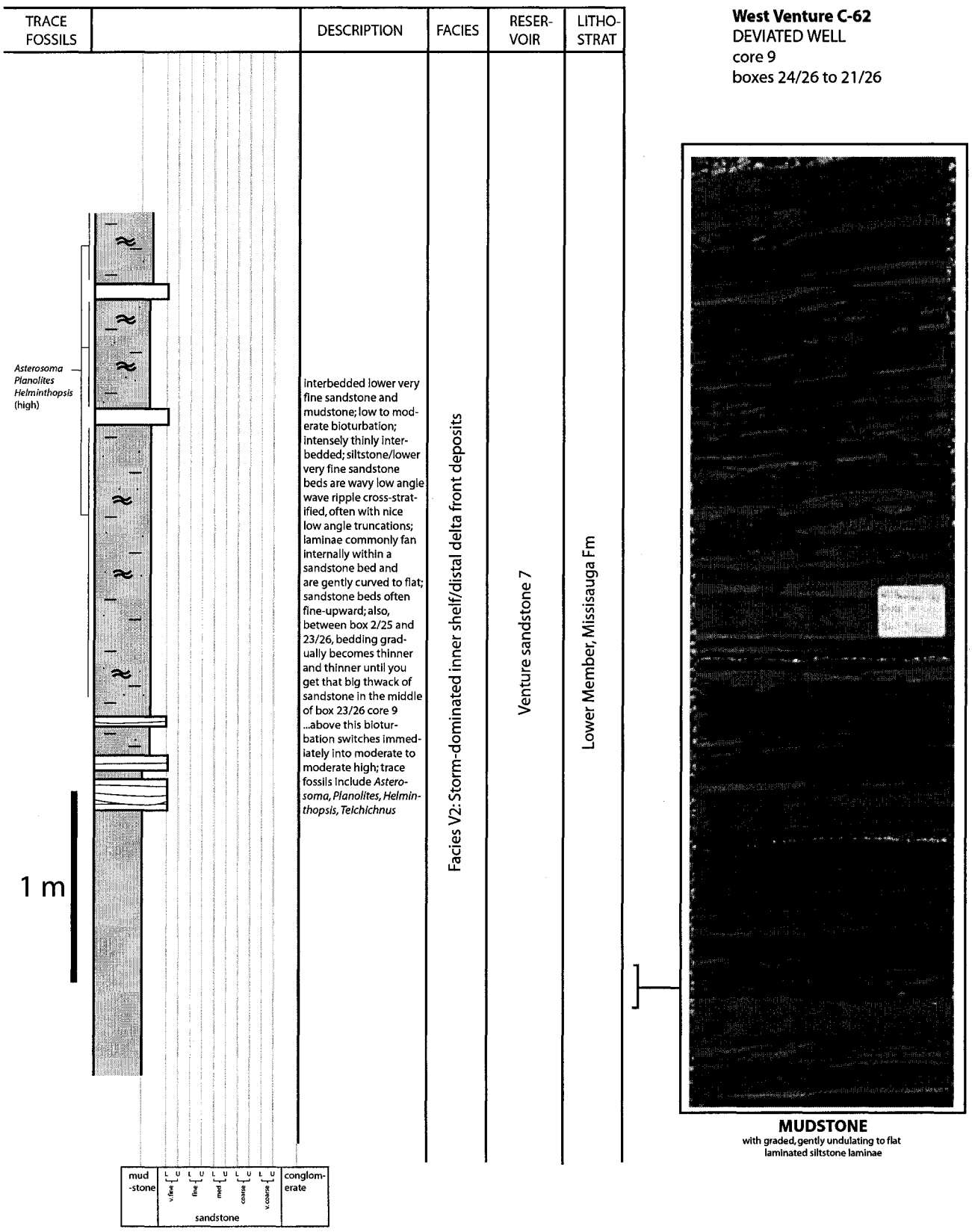
THIN TRANSGRESSIVE LAG


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Chondrites
Helminthopsis
(high)
1 m
Chondrites
(high)
Ophiomorpha
Chondrites
(high)
nice HCS
Helminthopsis
Ophiomorpha
Palaeophycus
(high)
interbedded lower very fine sandstone and mudstone; low to moderate bioturbation; intensely thinly interbedded; siltstone/lower very fine sandstone beds are wavy low angle wave ripple cross-stratified, often with nice low angle truncations; laminae commonly fan internally within a sandstone bed and are gently curved to flat; sandstone beds often fine-upward; also, between box 2/25 and 23/26, bedding gradually becomes thinner and thinner until you get that big thwack of sandstone in the middle of box 23/26 core 9 ...above this bioturbation switches immediately into moderate to moderate high; trace fossils include *Asterosoma, Planolites, Helminthopsis, Teichichnus*
Facies V2: Storm-dominated inner shelf/distal delta front deposits
Venture sandstone 7
Lower Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 10
boxes 6/25 to 3/25
Ophiomorpha burrow
fanning laminae
low angle internal truncation surface
massive sandstone
sole cast?
HUMMOCKY CROSS-STRATIFICATION

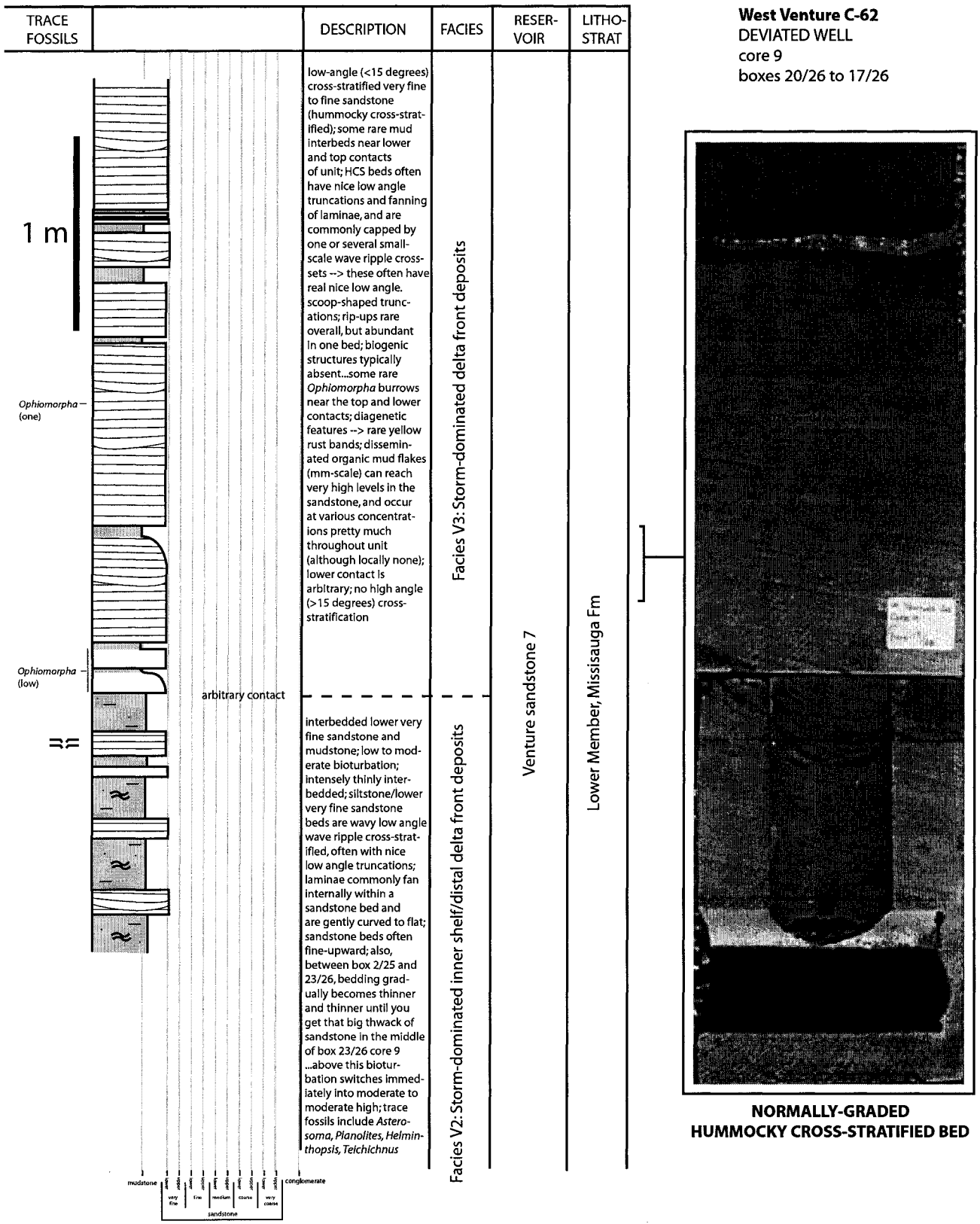
West Venture C-62
DEVIATED WELL
core 10, box 2/25 to
core 9, box 25/26



West Venture C-62
DEVIATED WELL
core 9
boxes 24/26 to 21/26



MUDSTONE
with graded, gently undulating to flat laminated siltstone laminae



West Venture C-62
DEVIATED WELL
core 9
boxes 20/26 to 17/26

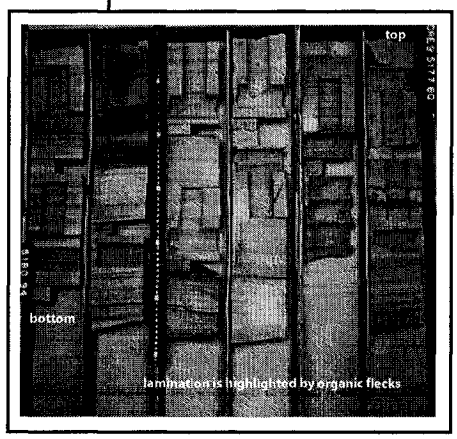
NORMALLY-GRADED HUMMOCKY CROSS-STRATIFIED BED

West Venture C-62
DEVIATED WELL
core 9
boxes 16/26 to 13/26

TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
		low-angle (<15 degrees) cross-stratified very fine to fine sandstone (hummocky cross-stratified); some rare mud interbeds near lower and top contacts of unit; HCS beds often have nice low angle truncations and fanning of laminae, and are commonly capped by one or several small-scale wave ripple cross-sets --> these often have real nice low angle. scoop-shaped truncations; rip-ups rare overall, but abundant in one bed; biogenic structures typically absent...some rare *Ophiomorpha* burrows near the top and lower contacts; diagenetic features --> rare yellow rust bands; disseminated organic mud flakes (mm-scale) can reach very high levels in the sandstone, and occur at various concentrations pretty much throughout unit (although locally none); lower contact is arbitrary; no high angle (>15 degrees) cross-stratification	Facies V2: Storm-dominated inner shelf/distal delta front deposits	Venture sandstone 7	Lower Member, Missisauga Fm

1 m

mud -stone | sandstone: v. fine, fine, med, coarse, v. coarse | conglom-erate



AMALGAMATED HUMMOCKY CROSS-STRATIFIED SANDSTONE BEDS

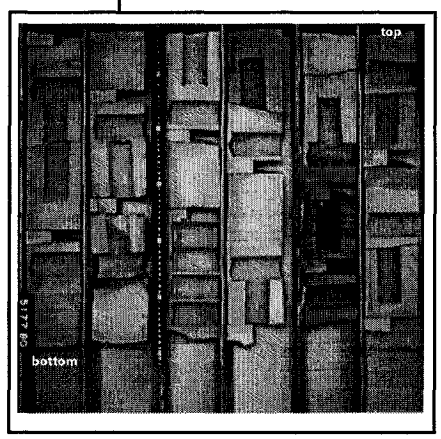
West Venture C-62
DEVIATED WELL
core 9
boxes 12/26 to 9/26

TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
		low-angle (<15 degrees) cross-stratified very fine to fine sandstone (hummocky cross-stratified); some rare mud interbeds near lower and top contacts of unit; HCS beds often have nice low angle truncations and fanning of laminae, and are commonly capped by one or several small-scale wave ripple cross-sets --> these often have real nice low angle. scoop-shaped truncations; rip-ups rare overall, but abundant in one bed; biogenic structures typically absent...some rare *Ophiomorpha* burrows near the top and lower contacts; diagenetic features --> rare yellow rust bands; disseminated organic mud flakes (mm-scale) can reach very high levels in the sandstone, and occur at various concentrations pretty much throughout unit (although locally none); lower contact is arbitrary; no high angle (>15 degrees) cross-stratification	Facies V2: Storm-dominated inner shelf/distal delta front deposits	Venture sandstone 7	Lower Member, Missisauga Fm

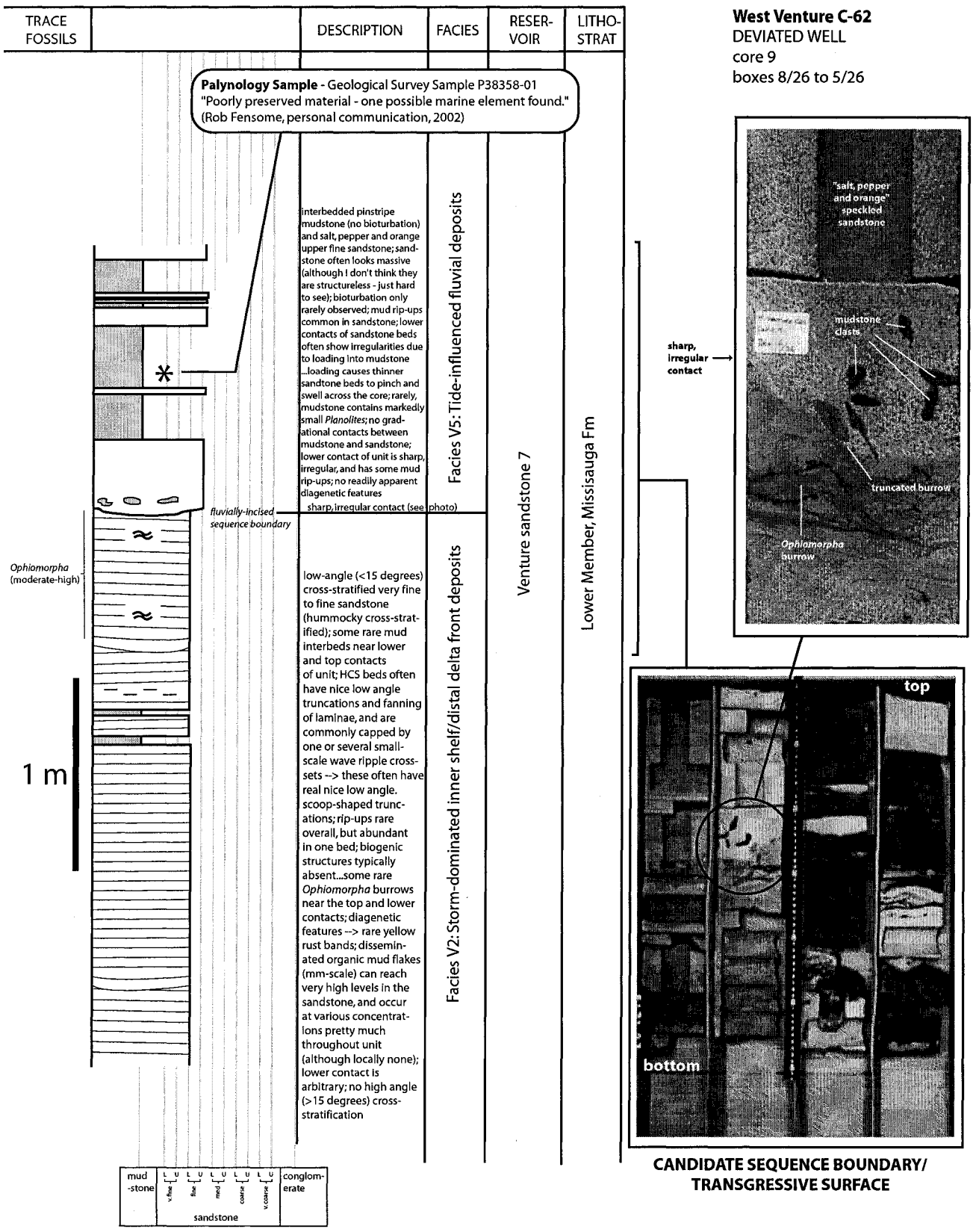
1 m

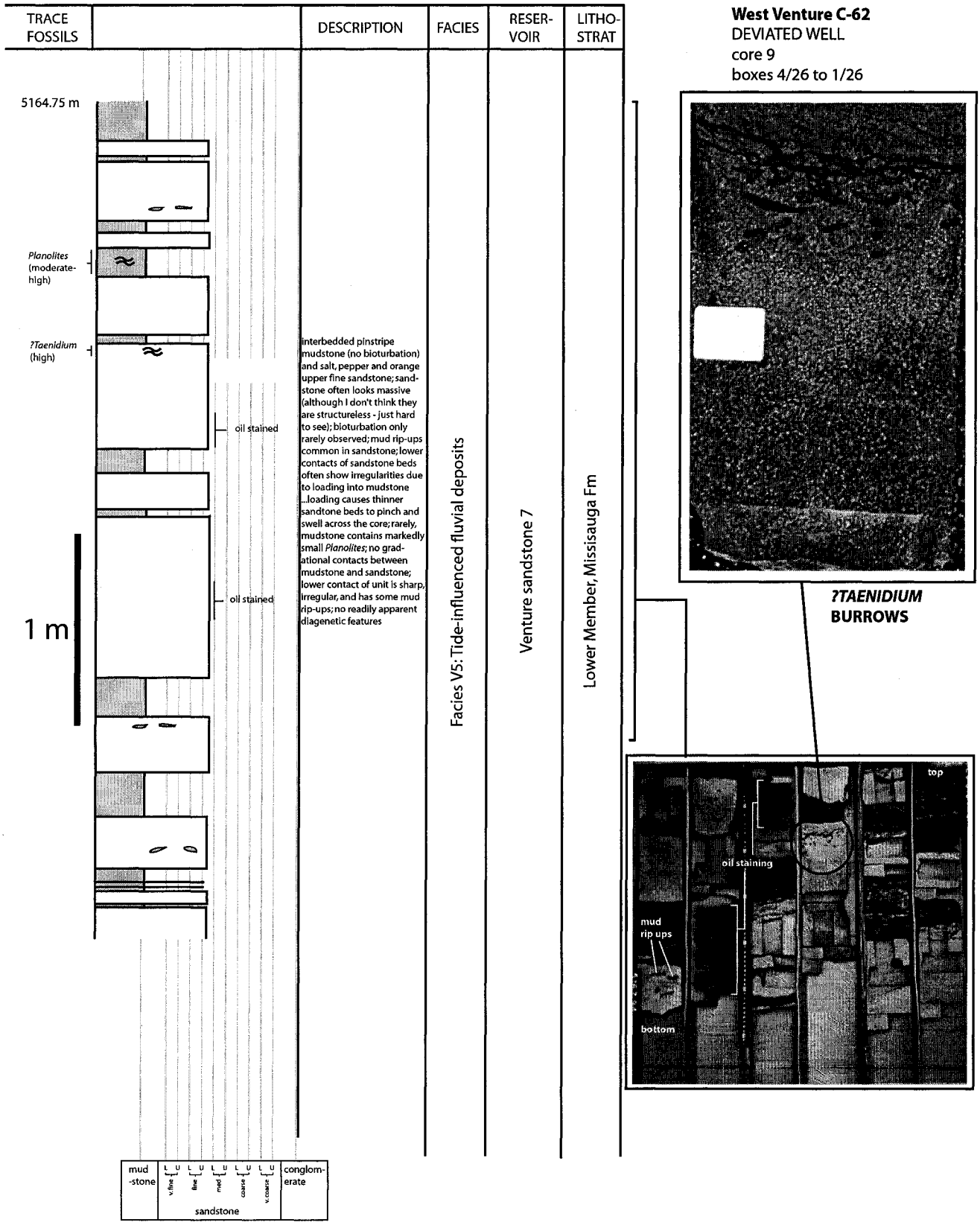
5177.80 m

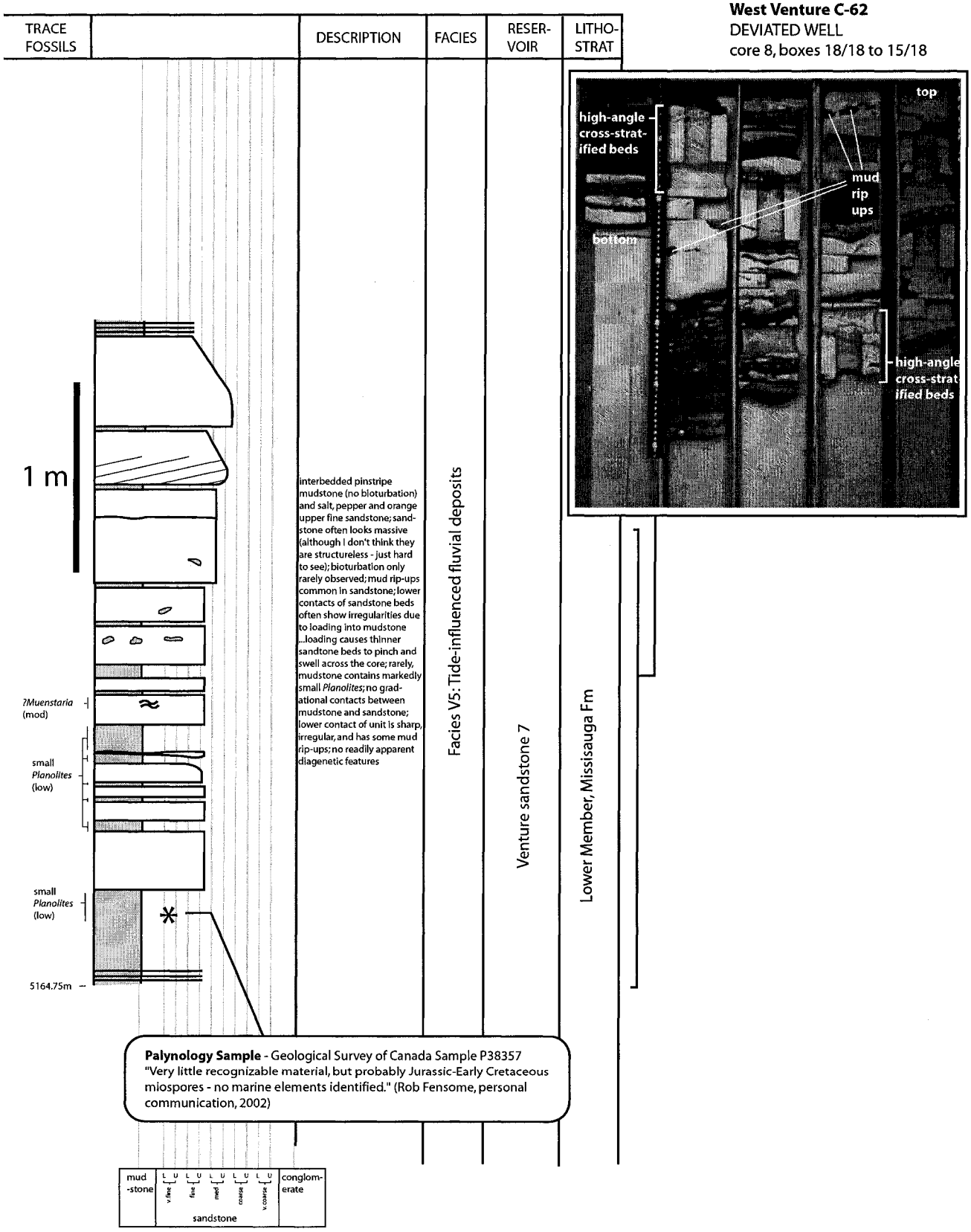
mud -stone | sandstone: v.fine, fine, med, coarse, v.coarse | conglom-erate

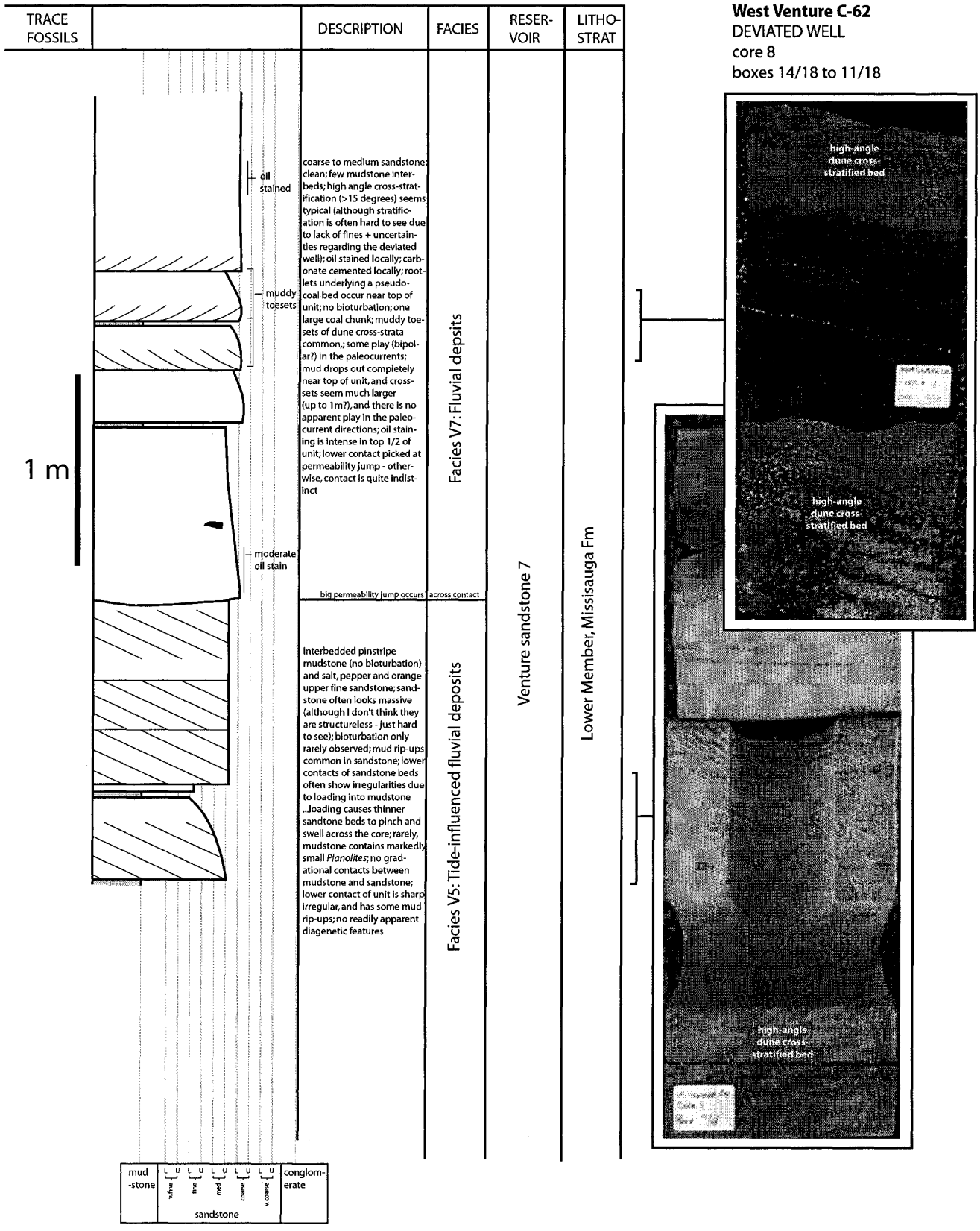


AMALGAMATED HUMMOCKY CROSS-STRATIFIED SANDSTONE BEDS


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Palynology Sample - Geological Survey Sample P38358-01
"Poorly preserved material - one possible marine element found."
(Rob Fensome, personal communication, 2002)
interbedded pinstripe mudstone (no bioturbation) and salt, pepper and orange upper fine sandstone; sandstone often looks massive (although I don't think they are structureless - just hard to see); bioturbation only rarely observed; mud rip-ups common in sandstone; lower contacts of sandstone beds often show irregularities due to loading into mudstone ...loading causes thinner sandtone beds to pinch and swell across the core; rarely, mudstone contains markedly small Planolites; no gradational contacts between mudstone and sandstone; lower contact of unit is sharp, irregular, and has some mud rip-ups; no readily apparent diagenetic features
sharp, irregular contact (see photo)
fluvially-incised sequence boundary
Facies V5: Tide-influenced fluvial deposits
Ophiomorpha (moderate-high)
low-angle (<15 degrees) cross-stratified very fine to fine sandstone (hummocky cross-stratified); some rare mud interbeds near lower and top contacts of unit; HCS beds often have nice low angle truncations and fanning of laminae, and are commonly capped by one or several small-scale wave ripple cross-sets --> these often have real nice low angle. scoop-shaped truncations; rip-ups rare overall, but abundant in one bed; biogenic structures typically absent...some rare Ophiomorpha burrows near the top and lower contacts; diagenetic features --> rare yellow rust bands; disseminated organic mud flakes (mm-scale) can reach very high levels in the sandstone, and occur at various concentrations pretty much throughout unit (although locally none); lower contact is arbitrary; no high angle (>15 degrees) cross-stratification
Facies V2: Storm-dominated inner shelf/distal delta front deposits
Venture sandstone 7
Lower Member, Missisauga Fm
1 m
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 9
boxes 8/26 to 5/26
"salt, pepper and orange" speckled sandstone
mudstone clasts
sharp, irregular contact
truncated burrow
Ophiomorpha burrow
top
bottom
CANDIDATE SEQUENCE BOUNDARY/ TRANSGRESSIVE SURFACE


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
5164.75 m
Planolites (moderate-high)
?Taenidium (high)
oil stained
oil stained
1 m
interbedded pinstripe mudstone (no bioturbation) and salt, pepper and orange upper fine sandstone; sandstone often looks massive (although I don't think they are structureless - just hard to see); bioturbation only rarely observed; mud rip-ups common in sandstone; lower contacts of sandstone beds often show irregularities due to loading into mudstone ...loading causes thinner sandtone beds to pinch and swell across the core; rarely, mudstone contains markedly small Planolites; no gradational contacts between mudstone and sandstone; lower contact of unit is sharp, irregular, and has some mud rip-ups; no readily apparent diagenetic features
Facies V5: Tide-influenced fluvial deposits
Venture sandstone 7
Lower Member, Missisauga Fm
mud -stone
v. fine
fine
med
coarse
v. coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 9
boxes 4/26 to 1/26
?TAENIDIUM BURROWS
top
oil staining
mud rip ups
bottom


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
West Venture C-62
DEVIATED WELL
core 8, boxes 18/18 to 15/18
top
high-angle cross-strat-ified beds
mud rip ups
bottom
high-angle cross-strat-ified beds
1 m
?Muenstaria (mod)
small Planolites (low)
small Planolites (low)
5164.75m
interbedded pinstripe mudstone (no bioturbation) and salt, pepper and orange upper fine sandstone; sandstone often looks massive (although I don't think they are structureless - just hard to see); bioturbation only rarely observed; mud rip-ups common in sandstone; lower contacts of sandstone beds often show irregularities due to loading into mudstone ...loading causes thinner sandtone beds to pinch and swell across the core; rarely, mudstone contains markedly small Planolites; no gradational contacts between mudstone and sandstone; lower contact of unit is sharp, irregular, and has some mud rip-ups; no readily apparent diagenetic features
Facies V5: Tide-influenced fluvial deposits
Venture sandstone 7
Lower Member, Missisauga Fm
Palynology Sample - Geological Survey of Canada Sample P38357
"Very little recognizable material, but probably Jurassic-Early Cretaceous miospores - no marine elements identified." (Rob Fensome, personal communication, 2002)
mud -stone
v.fine
fine
med
coarse
v.coarse
sandstone
conglom-erate



West Venture C-62
DEVIATED WELL
core 8
boxes 14/18 to 11/18

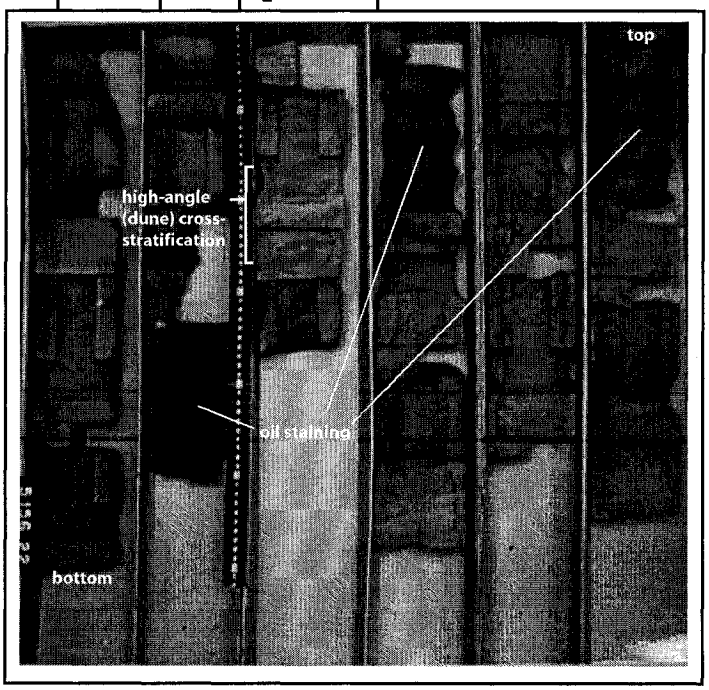
West Venture C-62
DEVIATED WELL
core 8
boxes 10/18 to 7/18

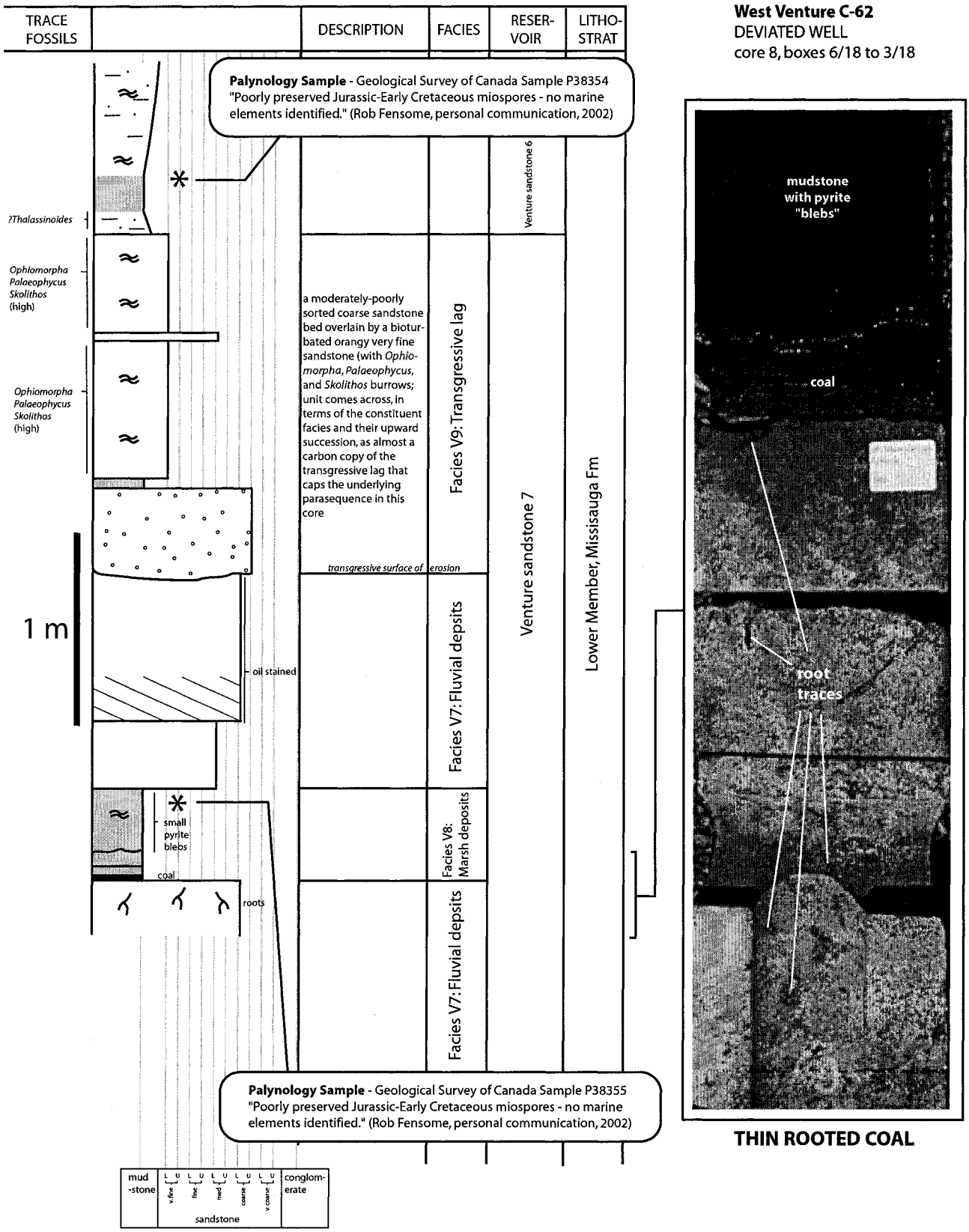
TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
5153.18 m	roots strongly oil stained strongly oil stained	coarse to medium sandstone; clean; few mudstone interbeds; high angle cross-stratification (>15 degrees) seems typical (although stratification is often hard to see due to lack of fines + uncertainties regarding the deviated well); oil stained locally; carbonate cemented locally; rootlets underlying a pseudo-coal bed occur near top of unit; no bioturbation; one large coal chunk; muddy toesets of dune cross-strata common,; some play (bipolar?) in the paleocurrents; mud drops out completely near top of unit, and cross-sets seem much larger (up to 1m?), and there is no apparent play in the paleocurrent directions; oil staining is intense in top 1/2 of unit; lower contact picked at permeability jump - otherwise, contact is quite indistinct	Facies V7: Fluvial depsits	Venture sandstone 7	Lower Member, Missisauga Fm

1 m

mud -stone | sandstone: v.fine, fine, med, coarse, v.coarse (each l–u) | conglom-erate

OIL STAINED COARSE SANDSTONE

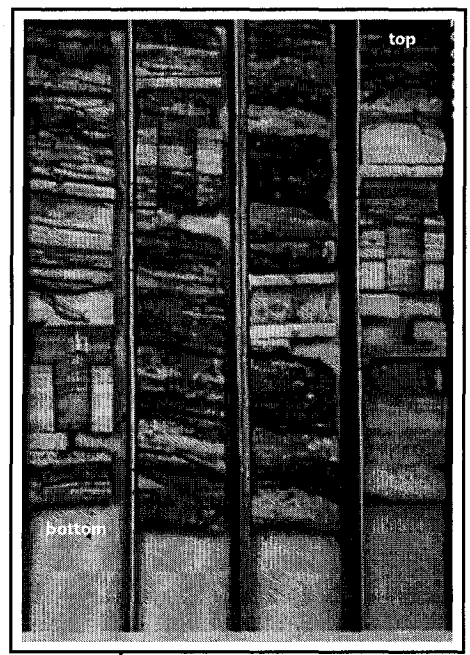




West Venture C-62
DEVIATED WELL
core 8, boxes 6/18 to 3/18

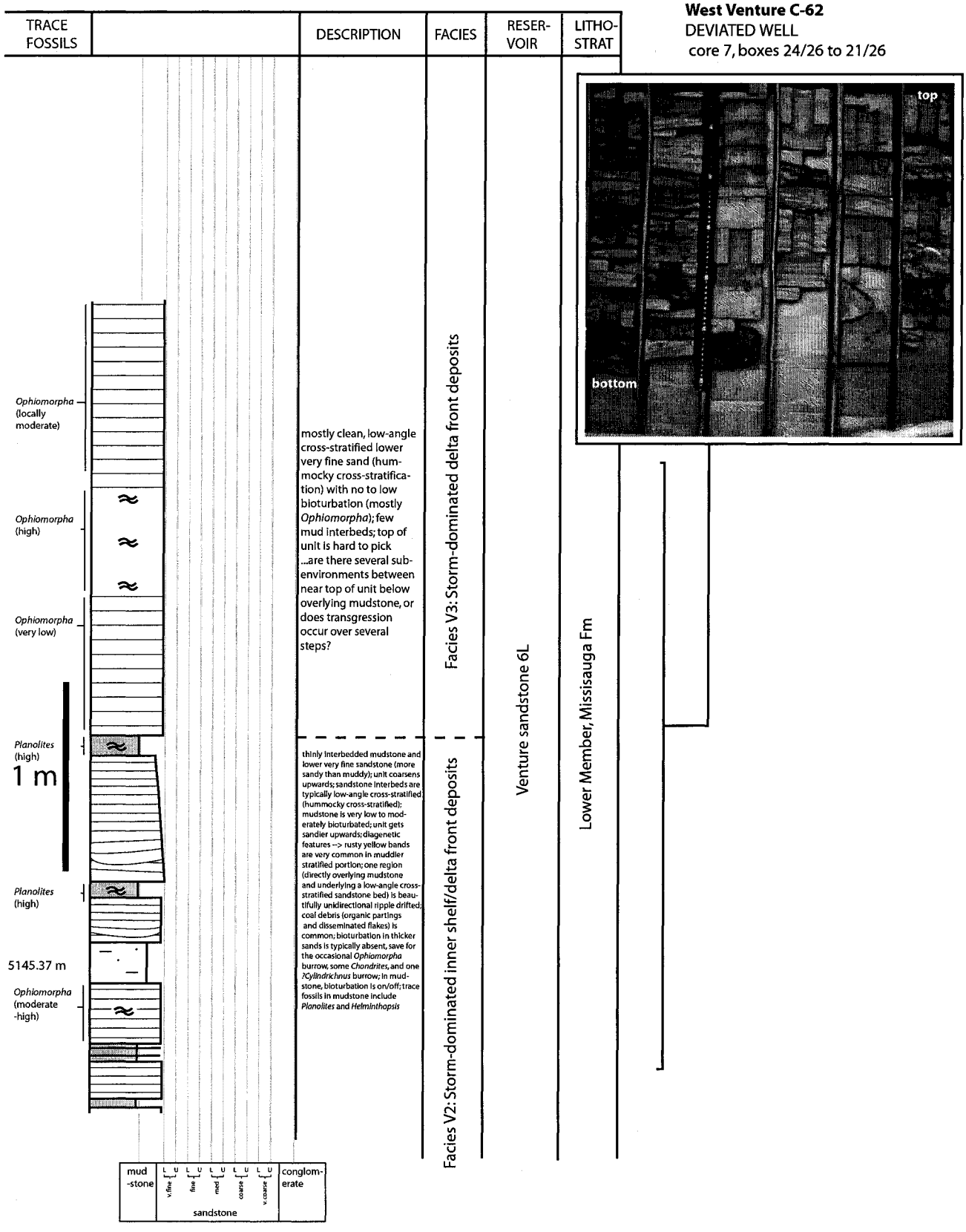
THIN ROOTED COAL

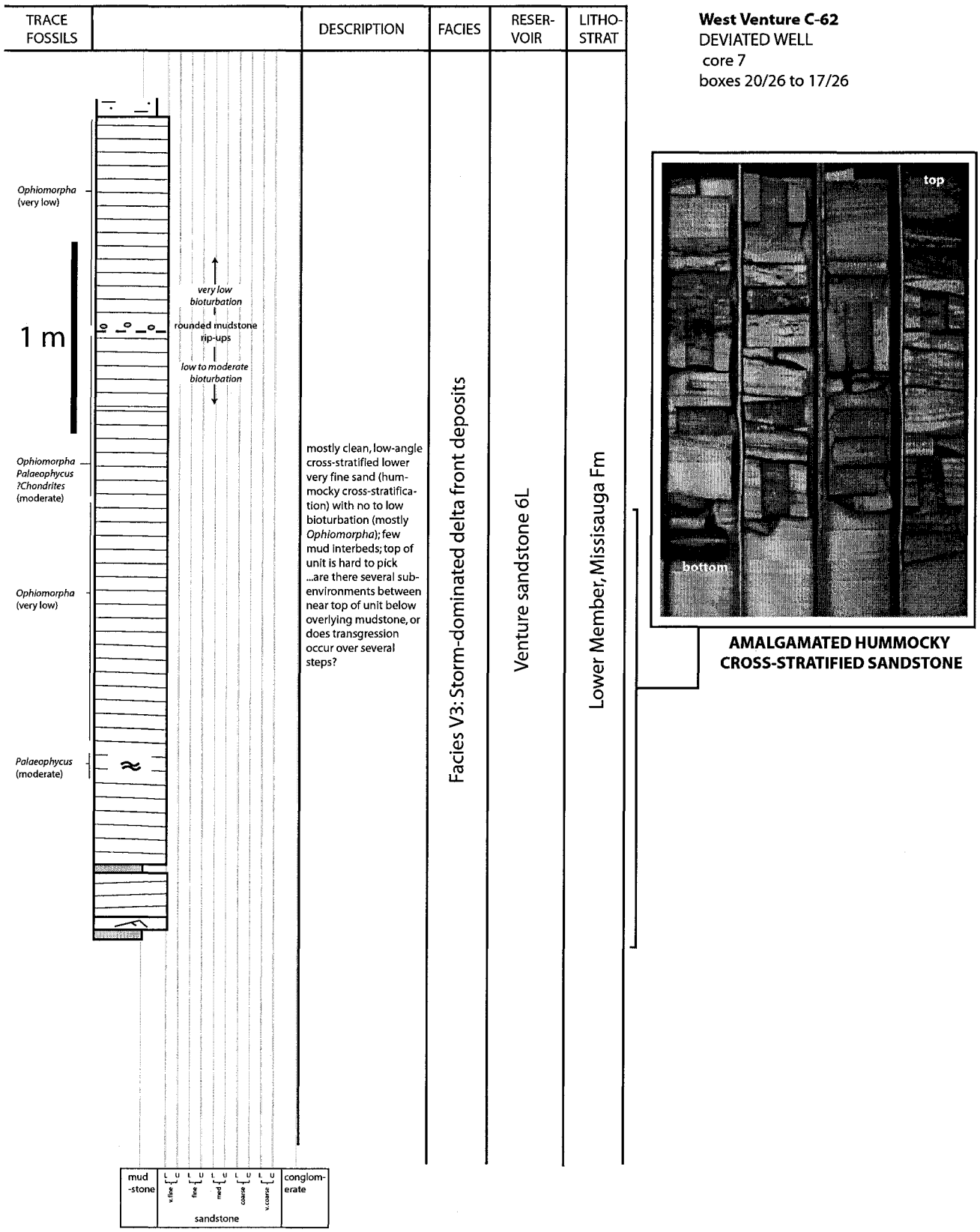
West Venture C-62
DEVIATED WELL
core 8, box 2/18 to
core 7, box 25/26

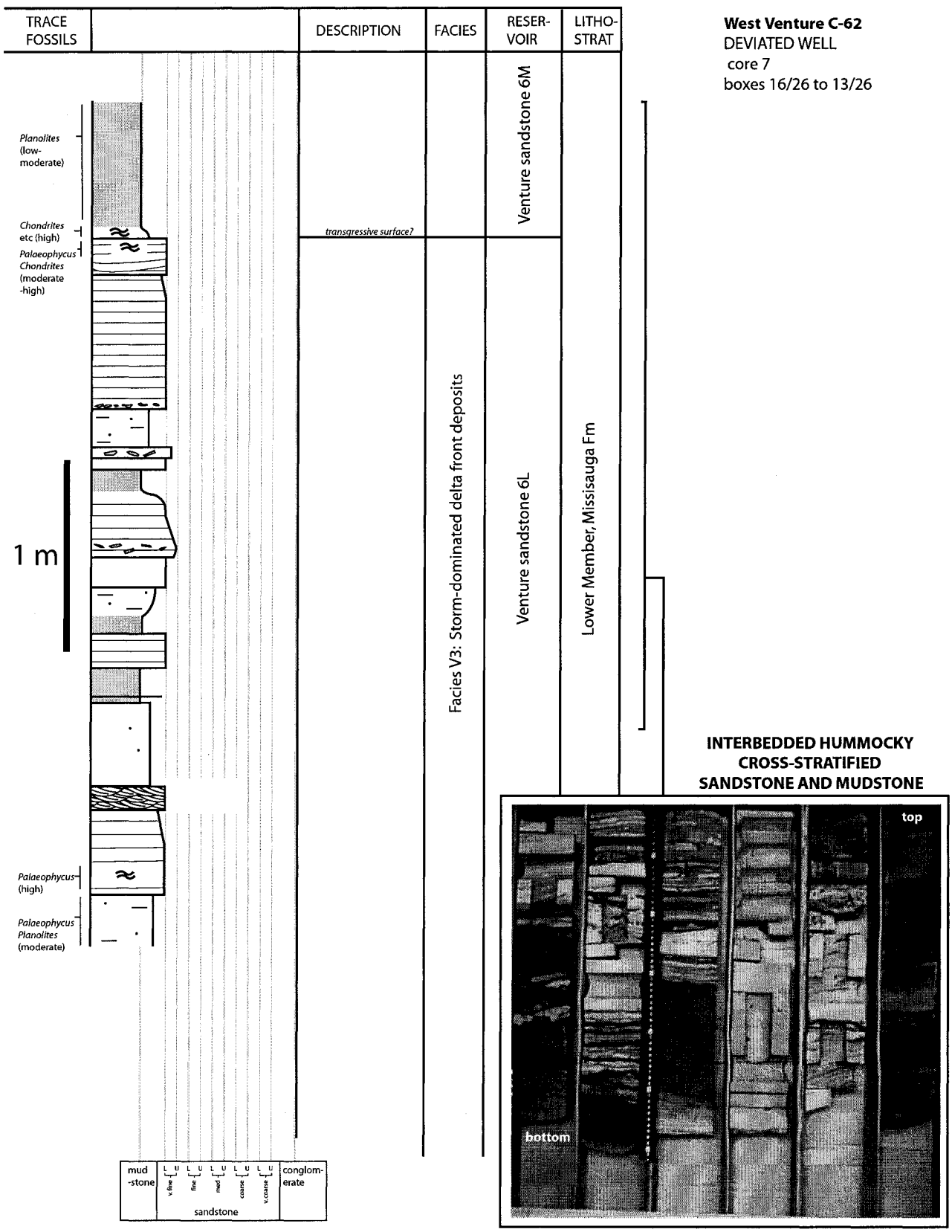


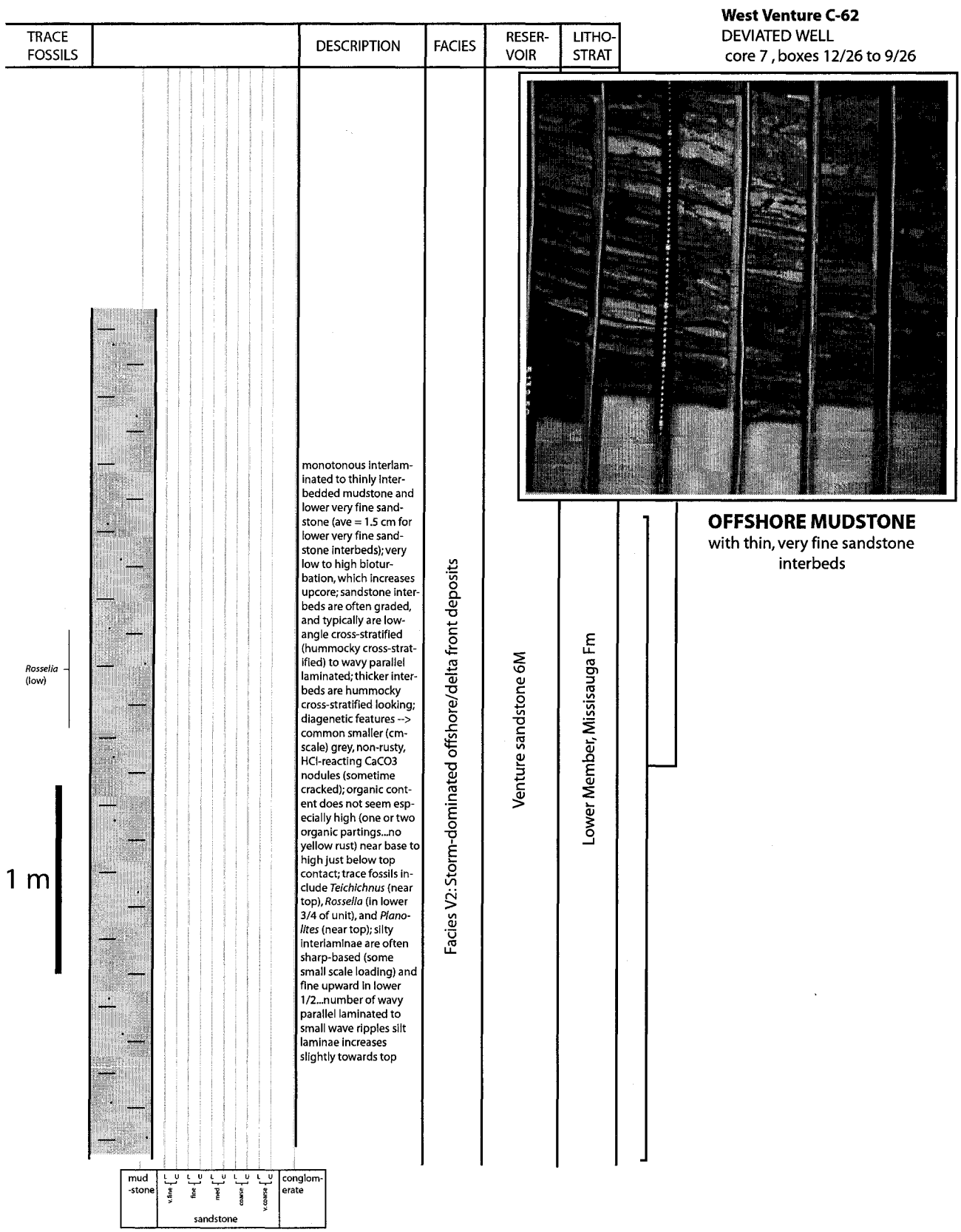
TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
	core 7 5146.55 m core 8 1 m	thinly interbedded mudstone and lower very fine sandstone (more sandy than muddy); unit coarsens upwards; sandstone interbeds are low-angle, long-wavelength cross-stratified (hummocky cross-stratified); mudstone is very low to moderately bioturbated; unit gets sandier upwards; diagenetic features --> rusty yellow bands are very common in muddier stratified portion; one region (directly overlying mudstone and underlying a low angle long wavelength cross-stratified sandstone bed) is beautifully unidirectional ripple drifted; coal debris (organic partings and disseminated flakes are common; bioturbation in thicker sands is typically absent, save for the occasional *Ophiomorpha* burrow, some *Chondrites*, and one *?Cylindrichnus* burrow; In mudstone, bioturbation is on/off; trace fossils in mudstone include *Planolites*, *Helminthopsis*	Facies V2: Storm-dominated inner shelf/delta front deposits	Venture sandstone 6L	Lower Member, Missisauga Fm

mud -stone | sandstone: v.fine, fine, med, coarse, v.coarse | conglom-erate

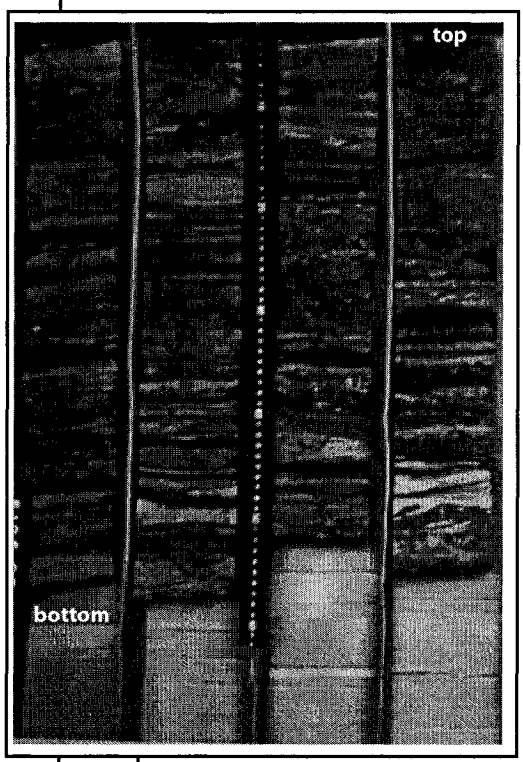

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
West Venture C-62
DEVIATED WELL
core 7, boxes 24/26 to 21/26
top
bottom
Ophiomorpha (locally moderate)
Ophiomorpha (high)
Ophiomorpha (very low)
Planolites (high)
1 m
Planolites (high)
5145.37 m
Ophiomorpha (moderate -high)
mostly clean, low-angle cross-stratified lower very fine sand (hummocky cross-stratification) with no to low bioturbation (mostly Ophiomorpha); few mud interbeds; top of unit is hard to pick ...are there several sub-environments between near top of unit below overlying mudstone, or does transgression occur over several steps?
thinly interbedded mudstone and lower very fine sandstone (more sandy than muddy); unit coarsens upwards; sandstone interbeds are typically low-angle cross-stratified (hummocky cross-stratified); mudstone is very low to moderately bioturbated; unit gets sandier upwards; diagenetic features --> rusty yellow bands are very common in muddier stratified portion; one region (directly overlying mudstone and underlying a low-angle cross-stratified sandstone bed) is beautifully unidirectional ripple drifted; coal debris (organic partings and disseminated flakes) is common; bioturbation in thicker sands is typically absent, save for the occasional Ophiomorpha burrow, some Chondrites, and one ?Cylindrichnus burrow; in mudstone, bioturbation is on/off; trace fossils in mudstone include Planolites and Helminthopsis
Facies V3: Storm-dominated delta front deposits
Facies V2: Storm-dominated inner shelf/delta front deposits
Venture sandstone 6L
Lower Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Ophiomorpha (very low)
1 m
very low bioturbation
rounded mudstone rip-ups
low to moderate bioturbation
Ophiomorpha Palaeophycus ?Chondrites (moderate)
Ophiomorpha (very low)
Palaeophycus (moderate)
mostly clean, low-angle cross-stratified lower very fine sand (hummocky cross-stratification) with no to low bioturbation (mostly Ophiomorpha); few mud interbeds; top of unit is hard to pick ...are there several sub-environments between near top of unit below overlying mudstone, or does transgression occur over several steps?
Facies V3: Storm-dominated delta front deposits
Venture sandstone 6L
Lower Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 7
boxes 20/26 to 17/26
top
bottom
AMALGAMATED HUMMOCKY CROSS-STRATIFIED SANDSTONE


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Planolites (low-moderate)
Chondrites etc (high)
Palaeophycus Chondrites (moderate -high)
Palaeophycus (high)
Palaeophycus Planolites (moderate)
1 m
transgressive surface?
Facies V3: Storm-dominated delta front deposits
Venture sandstone 6M
Venture sandstone 6L
Lower Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
sandstone
conglom-erate
West Venture C-62
DEVIATED WELL
core 7
boxes 16/26 to 13/26
INTERBEDDED HUMMOCKY CROSS-STRATIFIED SANDSTONE AND MUDSTONE
top
bottom


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
West Venture C-62
DEVIATED WELL
core 7 , boxes 12/26 to 9/26
Rosselia (low)
1 m
monotonous interlaminated to thinly interbedded mudstone and lower very fine sandstone (ave = 1.5 cm for lower very fine sandstone interbeds); very low to high bioturbation, which increases upcore; sandstone interbeds are often graded, and typically are low-angle cross-stratified (hummocky cross-stratified) to wavy parallel laminated; thicker interbeds are hummocky cross-stratified looking; diagenetic features --> common smaller (cm-scale) grey, non-rusty, HCl-reacting CaCO3 nodules (sometime cracked); organic content does not seem especially high (one or two organic partings...no yellow rust) near base to high just below top contact; trace fossils include Teichichnus (near top), Rosselia (in lower 3/4 of unit), and Planolites (near top); silty interlaminae are often sharp-based (some small scale loading) and fine upward in lower 1/2...number of wavy parallel laminated to small wave ripples silt laminae increases slightly towards top
Facies V2: Storm-dominated offshore/delta front deposits
Venture sandstone 6M
Lower Member, Missisauga Fm
OFFSHORE MUDSTONE
with thin, very fine sandstone interbeds
mud -stone
v. fine
fine
med
coarse
v. coarse
sandstone
conglom-erate

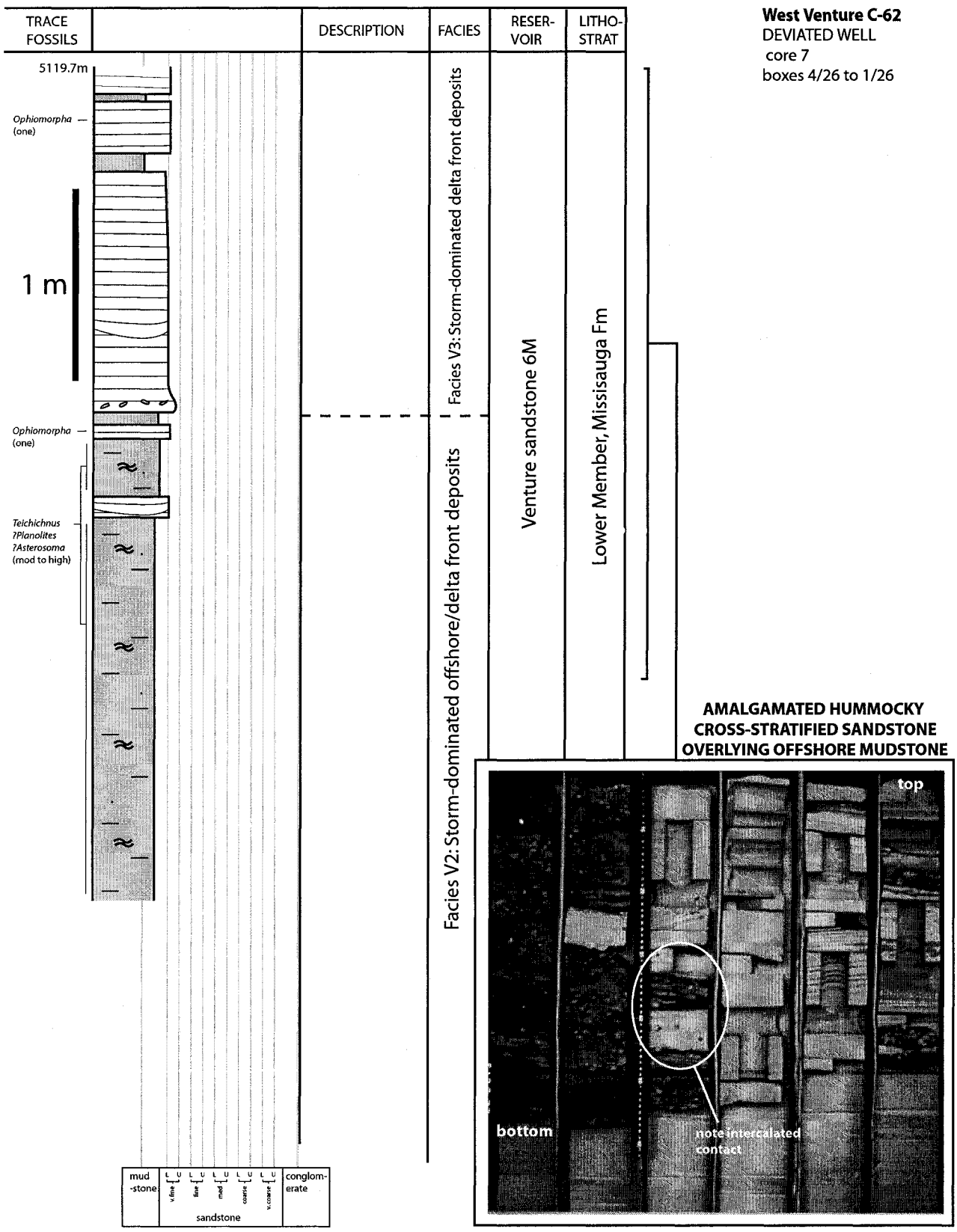
West Venture C-62
DEVIATED WELL
core 7, boxes 8/26 to 5/26



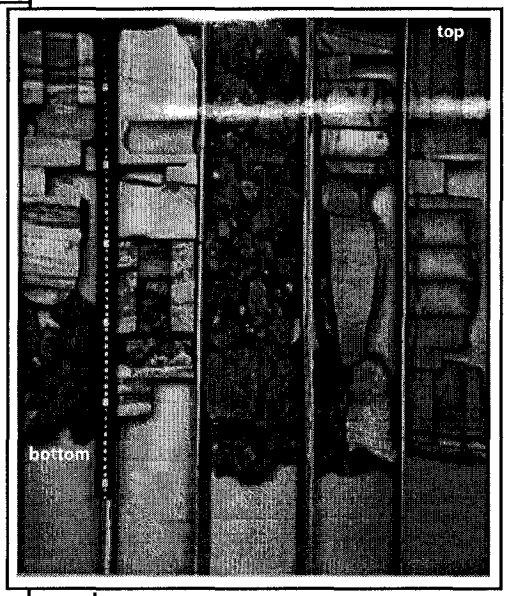
OFFSHORE MUDSTONE
with thin, very fine sandstone interbeds

TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
Planolites etc? (moderate to high) *Rosselia* (low) *Rosselia* (two)	1 m	although at this point the general apearence of the unit is similar to the description below, there seems now to be less gradation in the top contacts of the silt and lower very fine sandstone interbeds --> top contacts are now either gradational or sharp; mudstone overlying the siltstone or very fine sandstone interbeds is either wavy parallel laminated or nicely small-scale wave ripple cross-stratified...the siltstone interbeds are also more distinctly low-angle and wavy than they are below	Facies V2: Storm-dominated offshore/delta front deposits	Venture sandstone 6M	Lower Member, Missisauga Fm

mud -stone | sandstone: v. fine, fine, med, coarse, v. coarse | conglom-erate


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
5119.7m
Ophiomorpha (one)
1 m
Ophiomorpha (one)
Teichichnus ?Planolites ?Asterosoma (mod to high)
Facies V3: Storm-dominated delta front deposits
Facies V2: Storm-dominated offshore/delta front deposits
Venture sandstone 6M
Lower Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 7
boxes 4/26 to 1/26
AMALGAMATED HUMMOCKY CROSS-STRATIFIED SANDSTONE OVERLYING OFFSHORE MUDSTONE
top
bottom
note intercalated contact

West Venture C-62
DEVIATED WELL
core 6, boxes 18/18 to 15/18



TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
		monotonous (amalgamated) very well sorted lower fine sandstone; no bioturbation until top ~1 m, then *Ophiomorpha* come in along with light orangy colour (as opposed to the buff grey colour of most of unit); when mud particles highlight laminae, they tend to be organic flakes; diagenetic features --> yellow rust present near lower and upper contacts, but not in the middle of the unit --> here sandstone is very clean and unbioturbated; sandstone is typically monotonous beige-grey, except near top contact where they get a little salt-pepper and orangish (seems to be associated with occurrence of slightly coarser material); organic partings common close to top contact in association with yellow rust; no obvious high angle stratification/uni-ripples/reversing paleocurrents etc.	Facies V3: Storm-dominated delta front deposits	Venture sandstone 6M	Lower Member, Missisauga Fm

1 m

dirty chunks of core

Ophiomorpha
Palaeophycus
etc?
(high)

dirty chunks of core

5119.70 m

mud -stone | v.fine | fine | med | coarse | v.coarse | conglom-erate

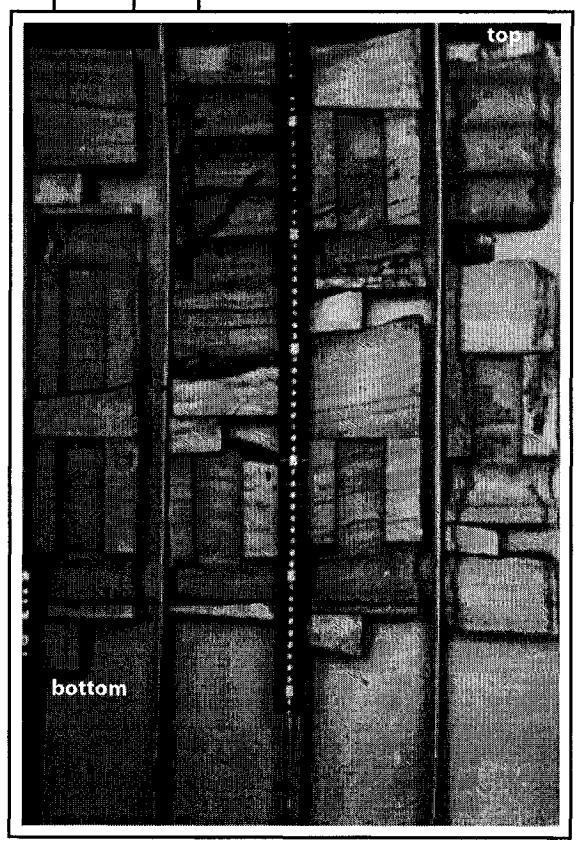
sandstone

West Venture C-62
DEVIATED WELL
core 6
boxes 14/18 to 11/18

TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
	stratification hard to see	monotonous (amalgamated) very well sorted lower fine sandstone; no bioturbation until top ~1 m, then Ophiomorpha come in along with light orangy colour (as opposed to the buff grey colour of most of unit); when mud particles highlight laminae, they tend to be organic flakes; diagenetic features --> yellow rust present near lower and upper contacts, but not in the middle of the unit --> here sandstone is very clean and unbioturbated; sandstone is typically monotonous beige-grey, except near top contact where they get a little salt-pepper and orangish (seems to be associated with occurrence of slightly coarser material); organic partings common close to top contact in association with yellow rust; no obvious high angle stratification/uni-ripples/reversing paleo-currents etc.	Facies V3: Storm-dominated delta front deposits	Venture sandstone 6M	Lower Member, Missisauga Fm

1 m

mud -stone | sandstone: v.fine, fine, med, coarse, v.coarse | conglom-erate



West Venture C-62
DEVIATED WELL
core 6, boxes 10/18 to 7/18

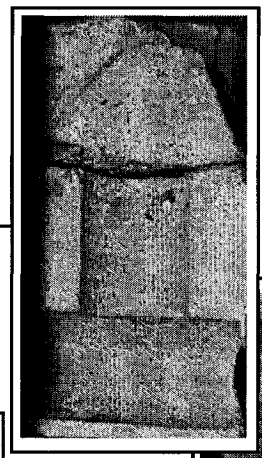
TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
		hard to tell what this is; several coarse grained sandstone beds which seem to fine up slightly; a few Ophiomorpha burrows here and there; rounded mud rip-ups common at the base of beds; stratification never gets to obviously high-angle, except one bed at base of unit composed of two nice small scale dune cross-sets that are apparently bipolar (tidal influence?); some stuff in here which looks wave influenced; the combined presence of coarse sandstone, bipolar dune cross-sets, mud drapes, finer sandstone with wave-influenced structures, and stratigraphic position suggests a fluctuating energy level in an environment subjected to both waves and unidirectional currents; colouration of sandstone is in places "salt, pepper and orange" (like sands in overlying unit) and in places buff (like underlying unit)	? Facies V4: Upper delta front deposits ?	Venture sandstone 6M	Lower Member, Missisauga Fm
		monotonous (amalgamated) very well sorted lower fine sandstone; no bioturbation until top ~1 m, then Ophiomorpha come in along with light orangy colour (as opposed to the buff grey colour of most of unit); when mud particles highlight laminae, they tend to be organic flakes; diagenetic features --> yellow rust present near lower and upper contacts, but not in the middle of the unit --> here sandstone is very clean and unbioturbated; sandstone is typically monotonous beige-grey, except near top contact where they get a little salt-pepper and orangish (seems to be associated with occurrence of slightly coarser material); organic partings common close to top contact in association with yellow rust; no obvious high angle stratification/uni-ripples/reversing paleocurrents etc.	Facies V3: Storm-dominated delta front deposits		

Ophiomorpha (low -moderate)

1 m

Ophiomorpha (low to moderate)

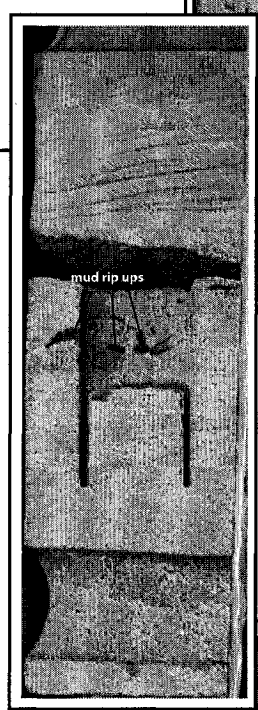
mud -stone | sandstone: v.fine (L U), fine (L U), med (L U), coarse (L U), v.coarse (L U) | conglom-erate



"salt, pepper and orange" speckled sandstone (similar to sandstone in overlying unit)

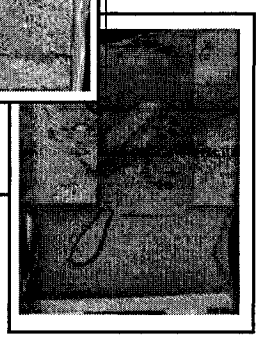
***OPHIOMORPHA* BURROWS**





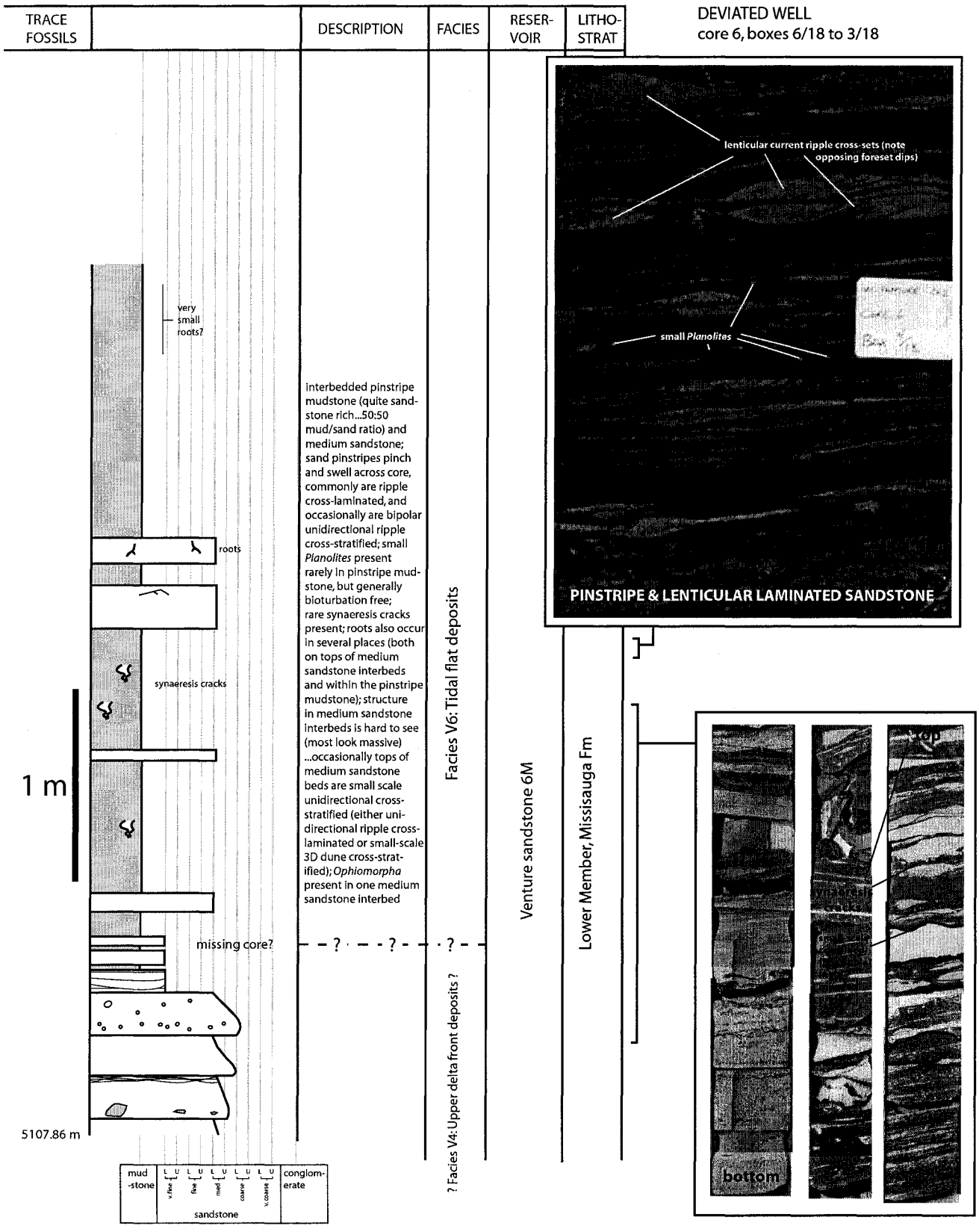
buff grey sandstone (similar to sandstone in underlying unit)

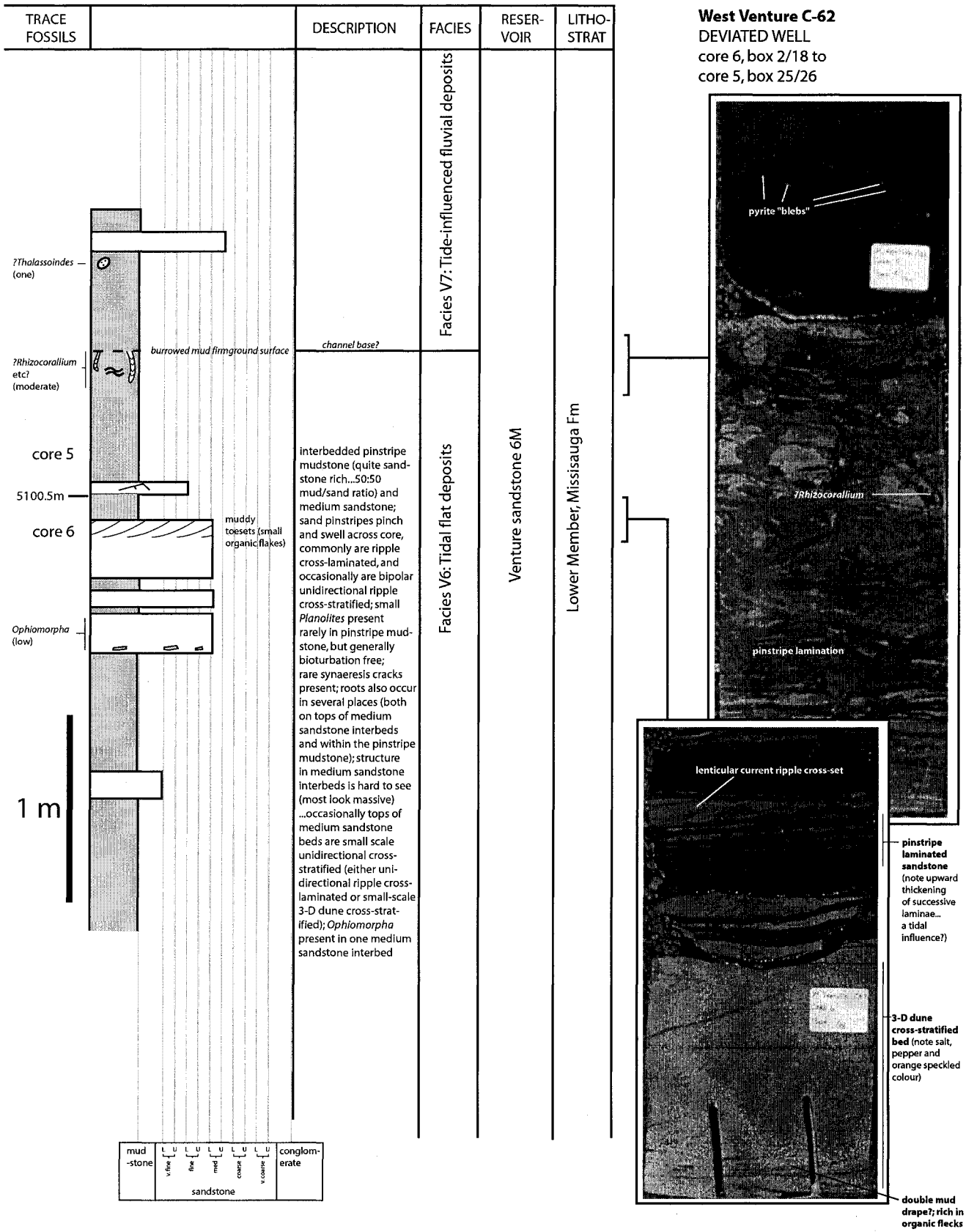
"salt, pepper and orange" speckled sandstone (similar to sandstone in overlying unit)

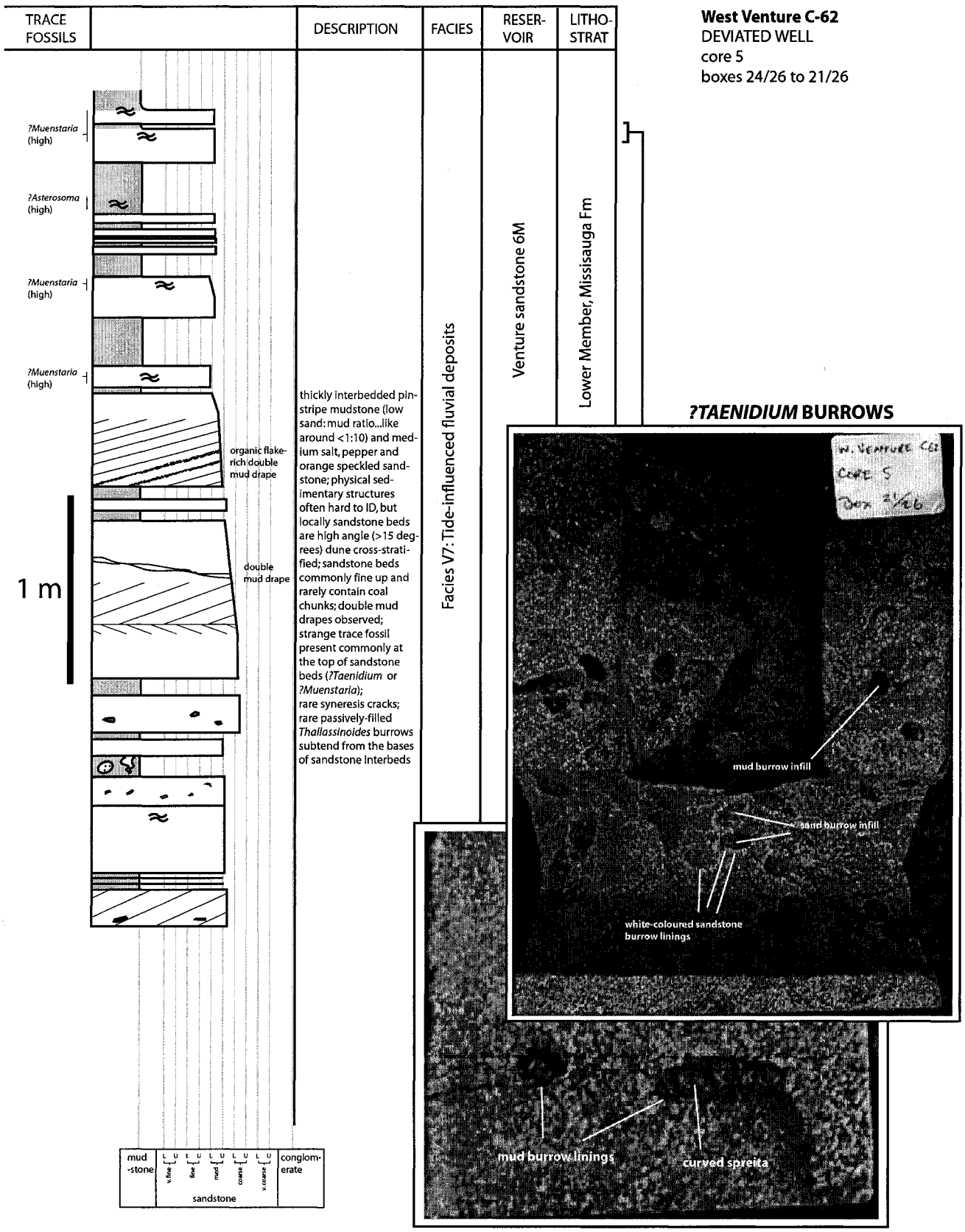


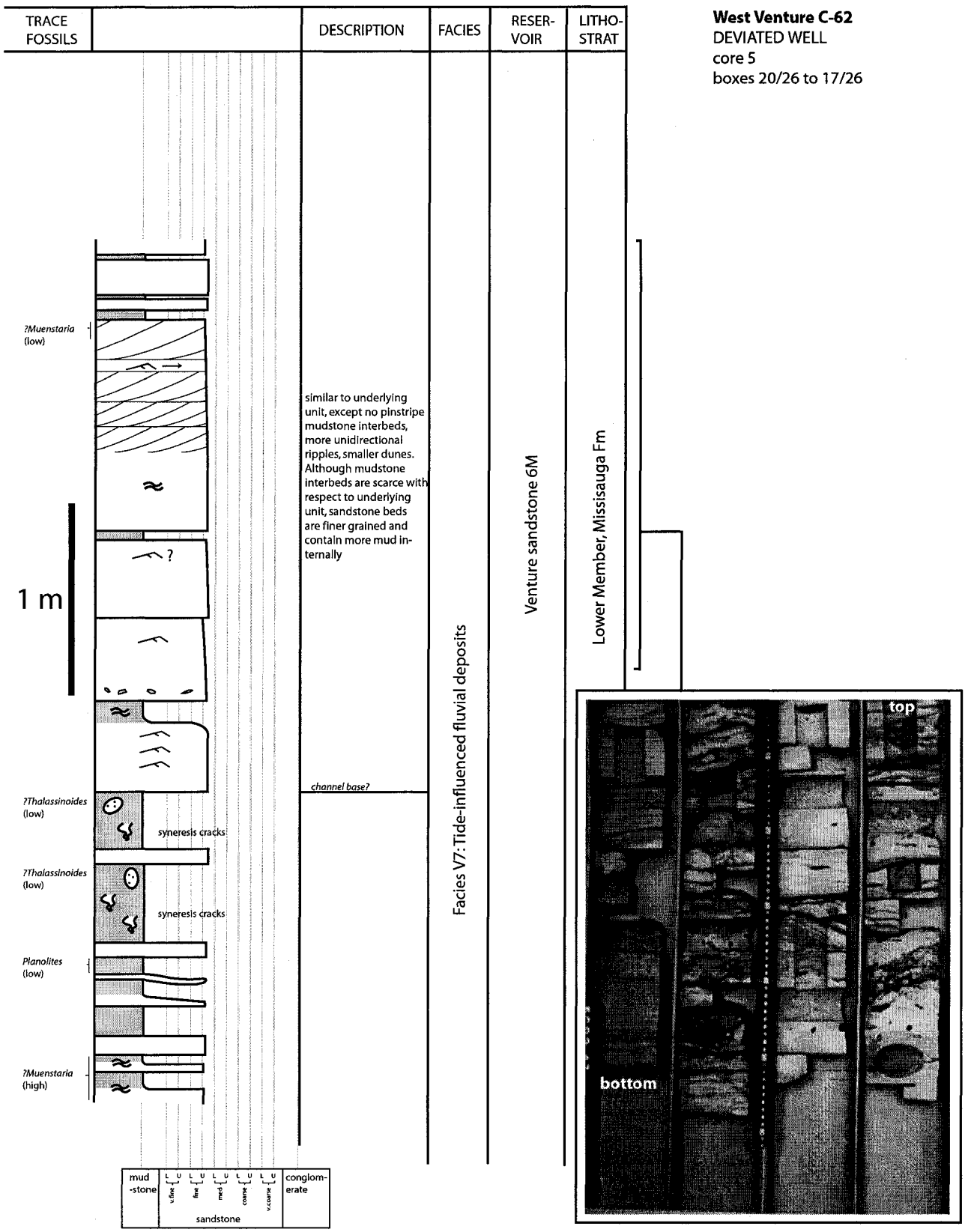
***OPHIOMORPHA* BURROWS**

West Venture C-62
DEVIATED WELL
core 6, boxes 6/18 to 3/18

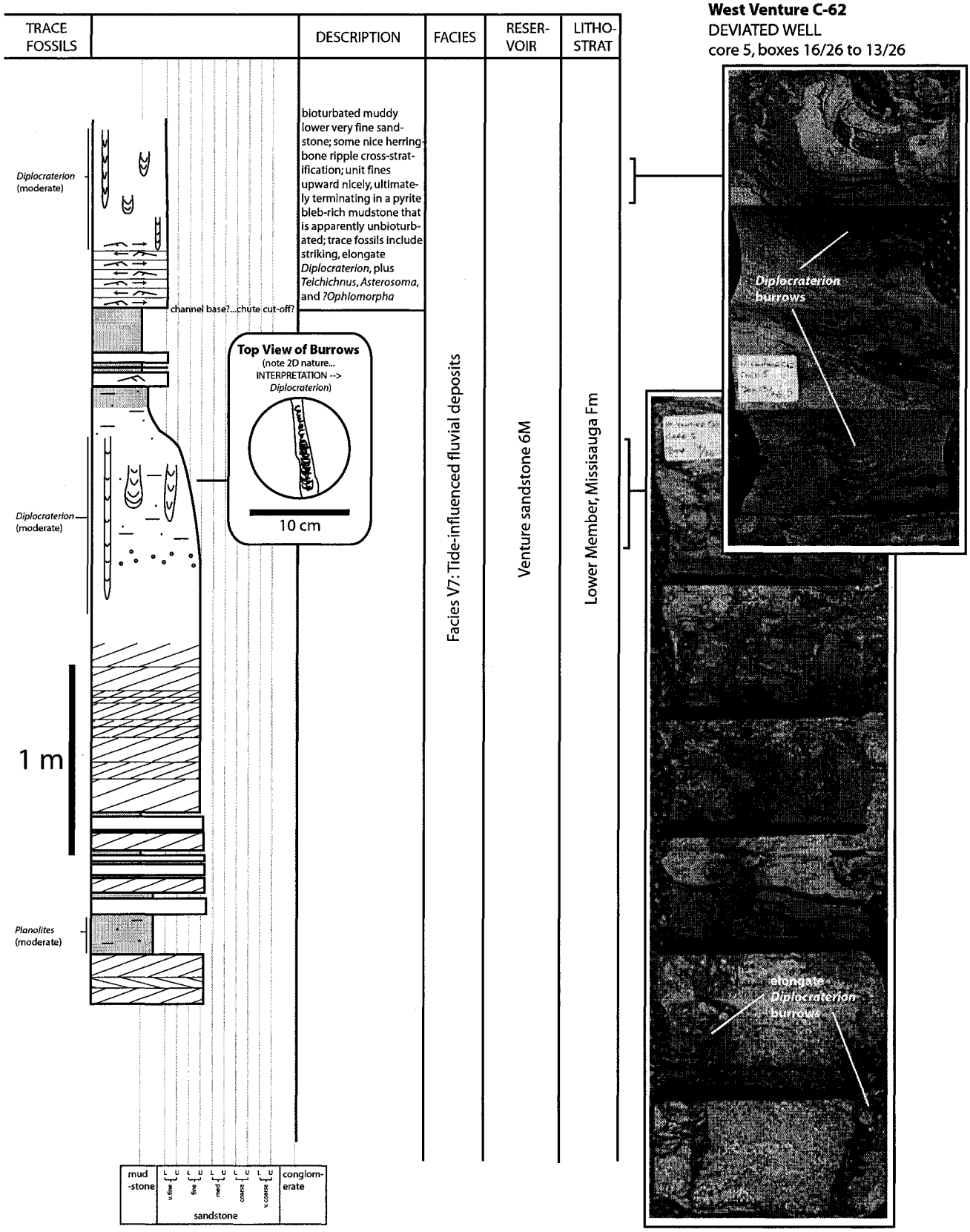



TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
?Thalassoindes (one)
?Rhizocorallium etc? (moderate)
Ophiomorpha (low)
burrowed mud firmground surface
channel base?
core 5
5100.5m
core 6
1 m
muddy toesets (small organic flakes)
interbedded pinstripe mudstone (quite sandstone rich...50:50 mud/sand ratio) and medium sandstone; sand pinstripes pinch and swell across core, commonly are ripple cross-laminated, and occasionally are bipolar unidirectional ripple cross-stratified; small Planolites present rarely in pinstripe mudstone, but generally bioturbation free; rare synaeresis cracks present; roots also occur in several places (both on tops of medium sandstone interbeds and within the pinstripe mudstone); structure in medium sandstone interbeds is hard to see (most look massive) ...occasionally tops of medium sandstone beds are small scale unidirectional cross-stratified (either uni-directional ripple cross-laminated or small-scale 3-D dune cross-stratified); Ophiomorpha present in one medium sandstone interbed
Facies V7: Tide-influenced fluvial deposits
Facies V6: Tidal flat deposits
Venture sandstone 6M
Lower Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
sandstone
conglom-erate
West Venture C-62
DEVIATED WELL
core 6, box 2/18 to
core 5, box 25/26
pyrite "blebs"
?Rhizocorallium
pinstripe lamination
lenticular current ripple cross-set
pinstripe laminated sandstone (note upward thickening of successive laminae... a tidal influence?)
3-D dune cross-stratified bed (note salt, pepper and orange speckled colour)
double mud drape?; rich in organic flecks

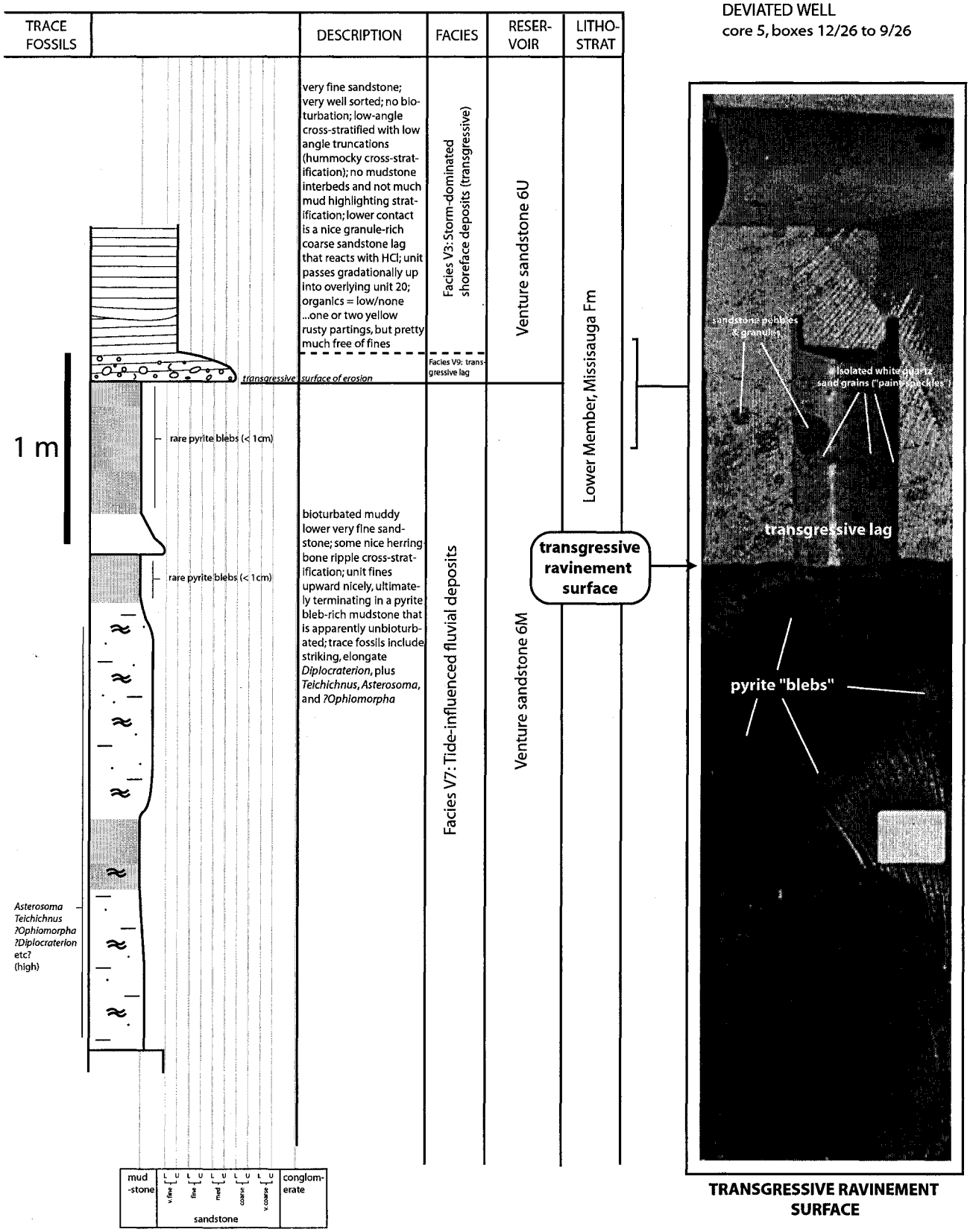

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
?Muenstaria (high)
?Asterosoma (high)
?Muenstaria (high)
?Muenstaria (high)
organic flake-rich double mud drape
double mud drape
1 m
thickly interbedded pin-stripe mudstone (low sand: mud ratio...like around <1:10) and medium salt, pepper and orange speckled sandstone; physical sedimentary structures often hard to ID, but locally sandstone beds are high angle (>15 degrees) dune cross-stratified; sandstone beds commonly fine up and rarely contain coal chunks; double mud drapes observed; strange trace fossil present commonly at the top of sandstone beds (?Taenidium or ?Muenstaria); rare syneresis cracks; rare passively-filled Thallassinoides burrows subtend from the bases of sandstone interbeds
Facies V7: Tide-influenced fluvial deposits
Venture sandstone 6M
Lower Member, Missisauga Fm
mud -stone
v. fine
fine
med
coarse
v. coarse
conglom-erate
sandstone
West Venture C-62
DEVIATED WELL
core 5
boxes 24/26 to 21/26
?TAENIDIUM BURROWS
mud burrow infill
sand burrow infill
white-coloured sandstone burrow linings
mud burrow linings
curved spreita



West Venture C-62
DEVIATED WELL
core 5
boxes 20/26 to 17/26

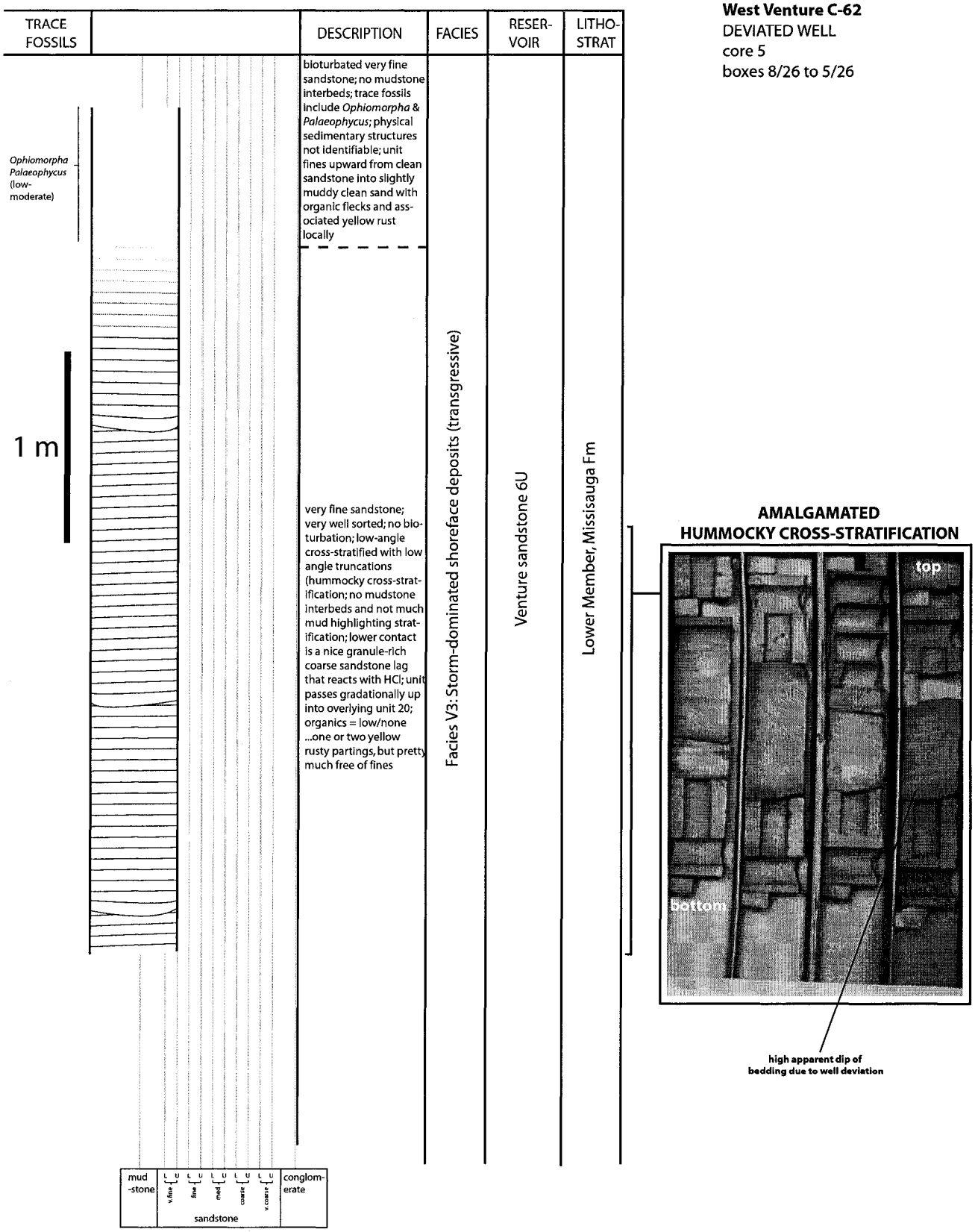

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
bioturbated muddy lower very fine sandstone; some nice herringbone ripple cross-stratification; unit fines upward nicely, ultimately terminating in a pyrite bleb-rich mudstone that is apparently unbioturbated; trace fossils include striking, elongate Diplocraterion, plus Teichichnus, Asterosoma, and ?Ophiomorpha
Diplocraterion (moderate)
channel base?...chute cut-off?
Top View of Burrows
(note 2D nature...
INTERPRETATION --> Diplocraterion)
10 cm
Diplocraterion (moderate)
1 m
Planolites (moderate)
Facies V7: Tide-influenced fluvial deposits
Venture sandstone 6M
Lower Member, Missisauga Fm
mud -stone
v.fine
fine
med
coarse
v.coarse
sandstone
conglom-erate
West Venture C-62
DEVIATED WELL
core 5, boxes 16/26 to 13/26
Diplocraterion burrows
elongate Diplocraterion burrows

West Venture C-62
DEVIATED WELL
core 5, boxes 12/26 to 9/26



TRANSGRESSIVE RAVINEMENT SURFACE

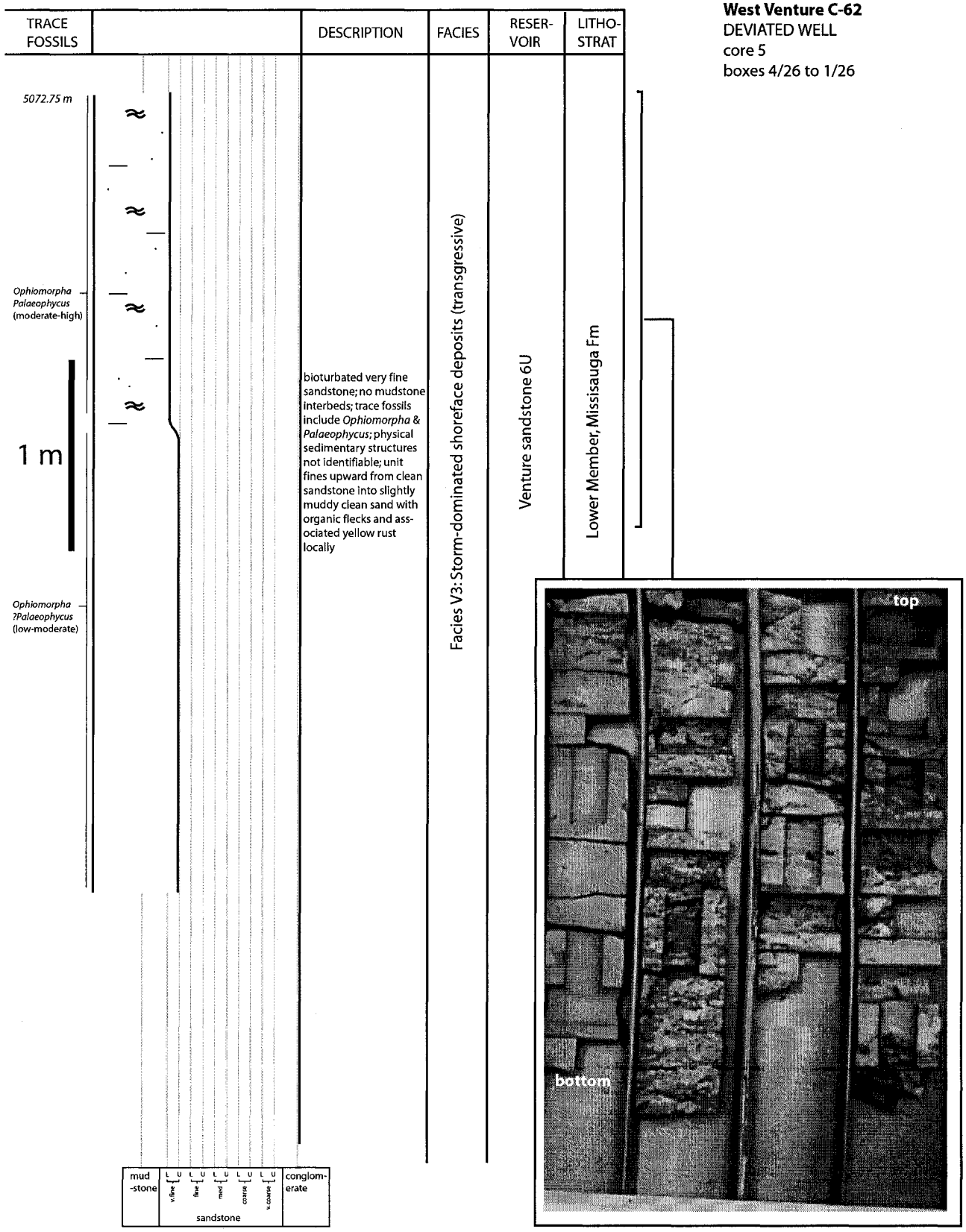
West Venture C-62
DEVIATED WELL
core 5
boxes 8/26 to 5/26



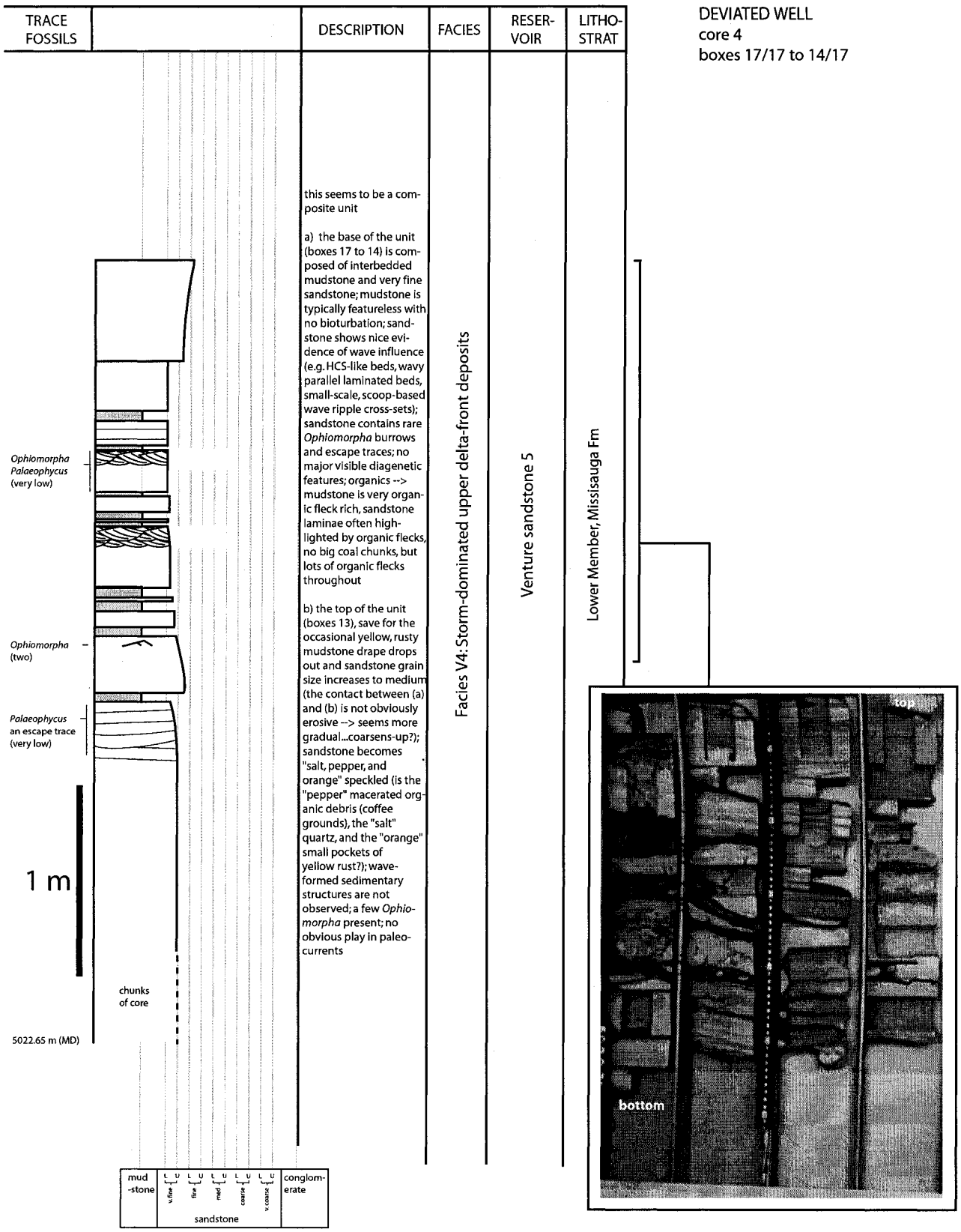
AMALGAMATED HUMMOCKY CROSS-STRATIFICATION

high apparent dip of bedding due to well deviation

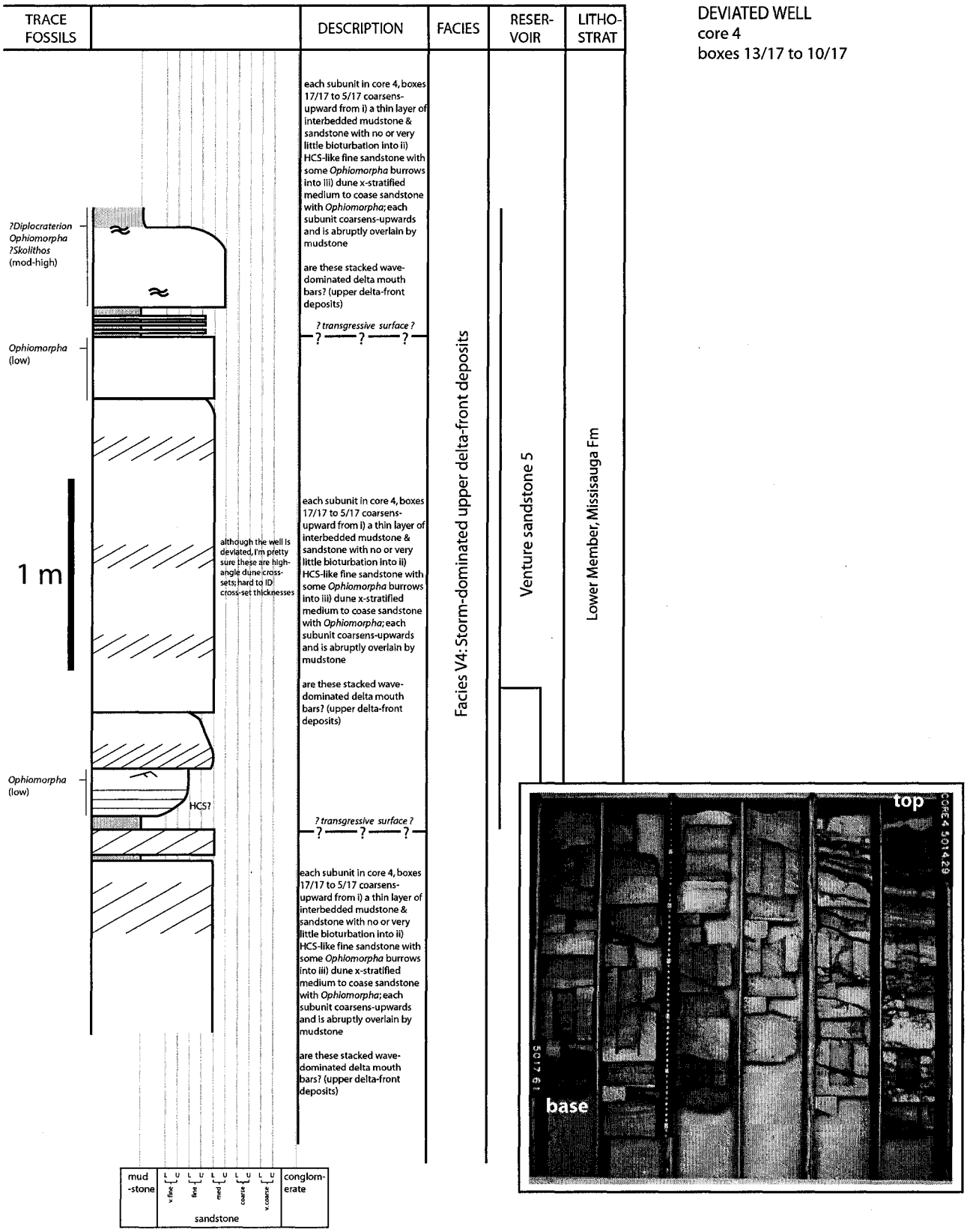
West Venture C-62
DEVIATED WELL
core 5
boxes 4/26 to 1/26



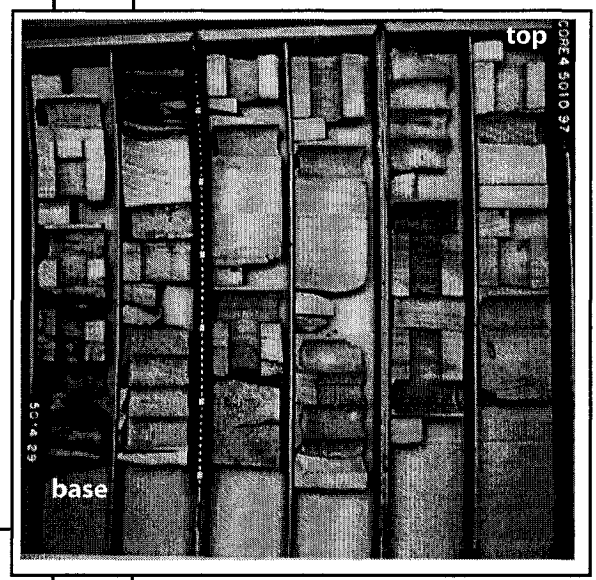
West Venture C-62
DEVIATED WELL
core 4
boxes 17/17 to 14/17

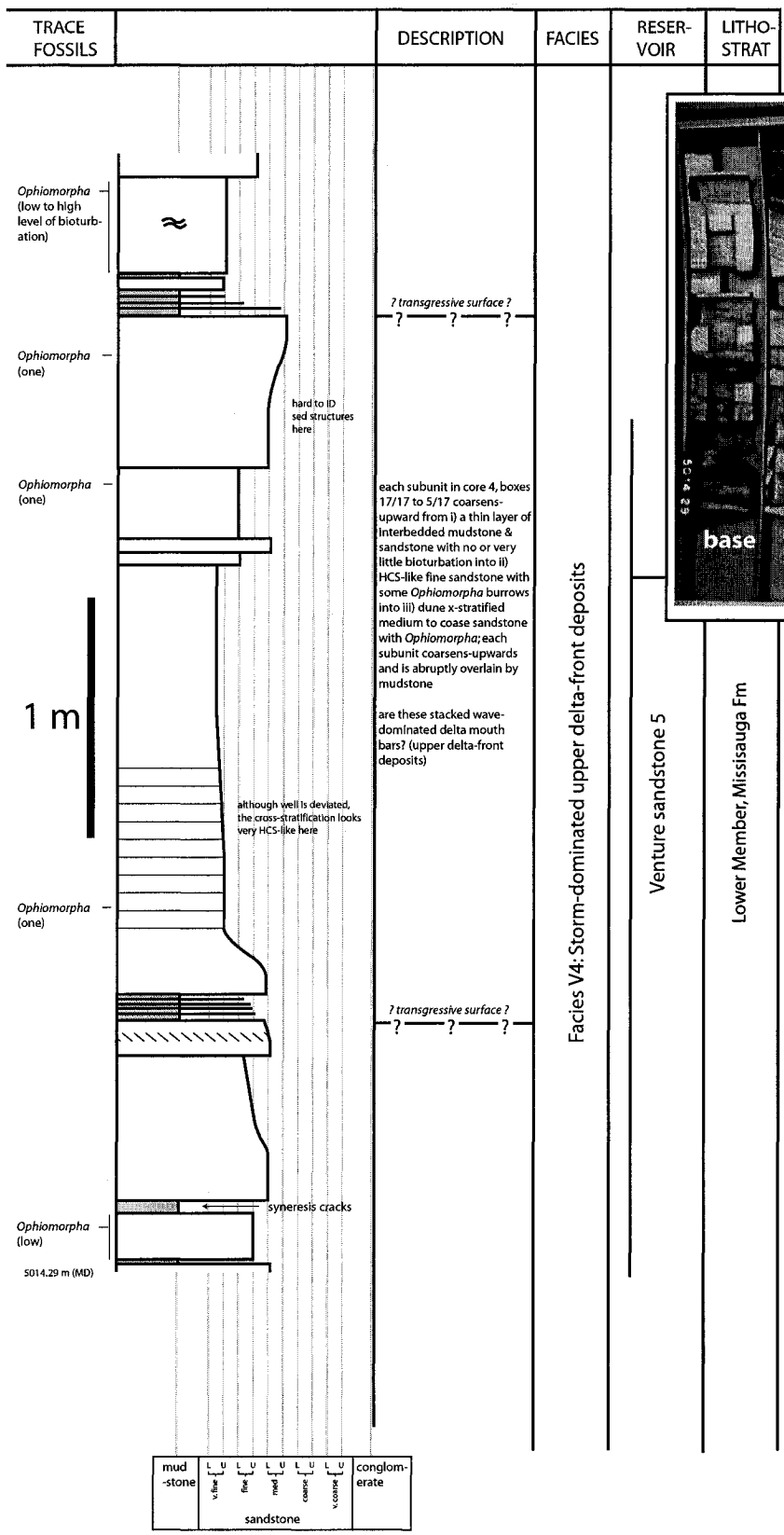


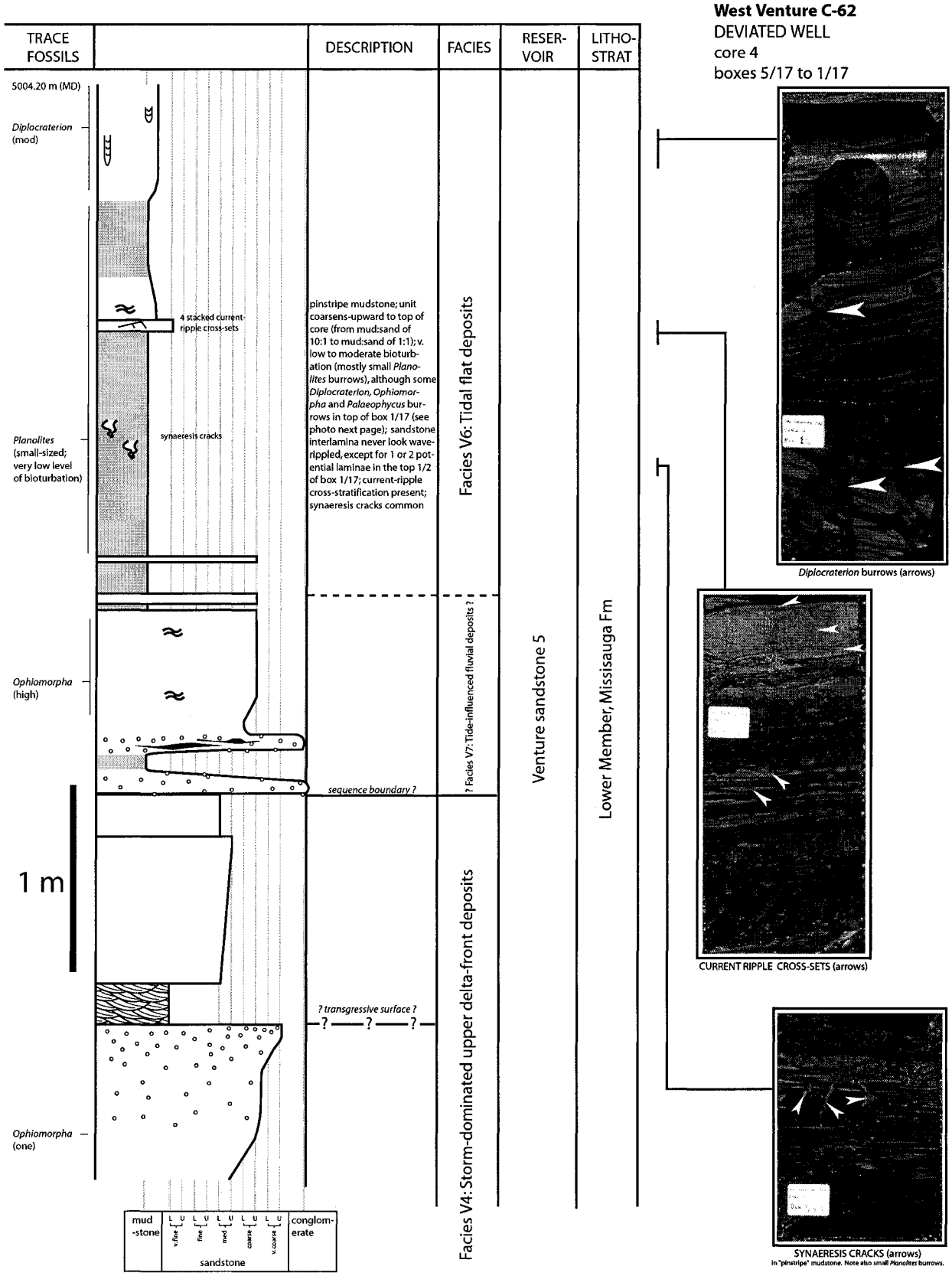
West Venture C-62
DEVIATED WELL
core 4
boxes 13/17 to 10/17



West Venture C-62
DEVIATED WELL
core 4
boxes 9/17 to 6/17

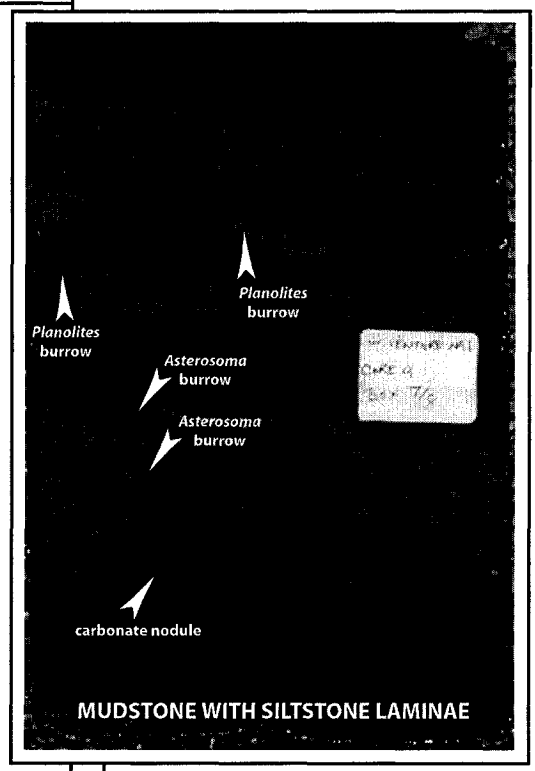





West Venture C-62
DEVIATED WELL
core 4
boxes 5/17 to 1/17
TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
5004.20 m (MD)
Diplocraterion (mod)
Planolites (small-sized; very low level of bioturbation)
Ophiomorpha (high)
Ophiomorpha (one)
4 stacked current-ripple cross-sets
synaeresis cracks
pinstripe mudstone; unit coarsens-upward to top of core (from mud:sand of 10:1 to mud:sand of 1:1); v. low to moderate bioturbation (mostly small Planolites burrows), although some Diplocraterion, Ophiomorpha and Palaeophycus burrows in top of box 1/17 (see photo next page); sandstone interlamina never look wave-rippled, except for 1 or 2 potential laminae in the top 1/2 of box 1/17; current-ripple cross-stratification present; synaeresis cracks common
sequence boundary ?
? transgressive surface ?
? — ? — ?
Facies V6: Tidal flat deposits
? Facies V7: Tide-influenced fluvial deposits ?
Facies V4: Storm-dominated upper delta-front deposits
Venture sandstone 5
Lower Member, Missisauga Fm
1 m
mud -stone
v.fine
fine
med
coarse
v.coarse
sandstone
conglom-erate
Diplocraterion burrows (arrows)
CURRENT RIPPLE CROSS-SETS (arrows)
SYNAERESIS CRACKS (arrows)
in "pinstripe" mudstone. Note also small Planolites burrows.

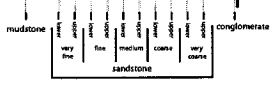
West Venture N-91
core 9
boxes 8/8 to 5/8

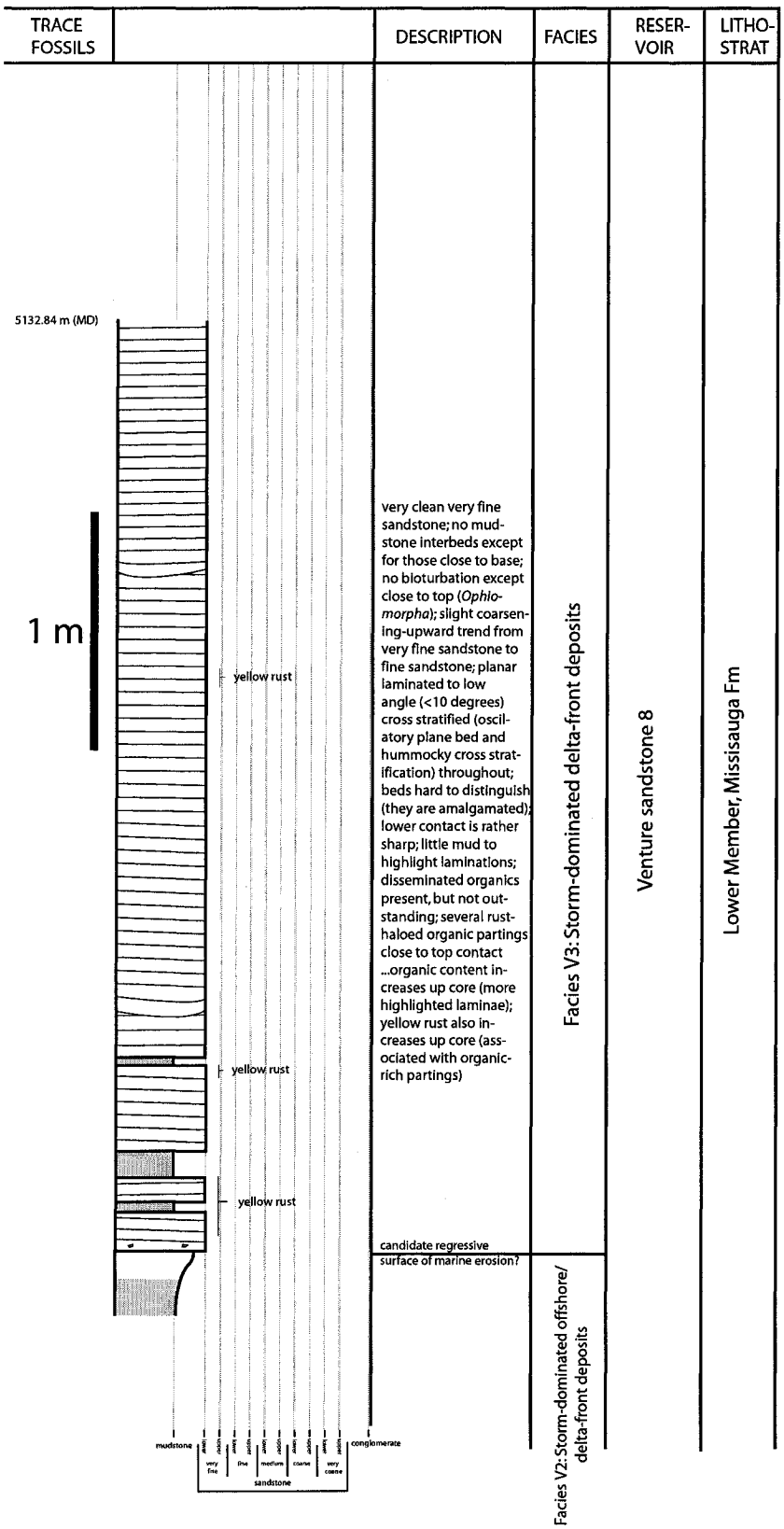
TRACE FOSSILS		DESCRIPTION	FACIES	RESER-VOIR	LITHO-STRAT
		laminated mudstone and siltstone; non-fissile; bioturbation is moderate throughout; rare small CaCO3 nodules; lamination on average is ~1 cm to <1 cm; siltstone laminae are sharp-based, and either grade upwards into mudstone or have sharp top contacts; internally siltstone laminae are flat laminated to low angle cross-laminated (oscillatory plane bed or hummocky cross stratified); trace fossils include *Planolites, Zoophycos, Asterosoma*; no interbeds thicker than 2.5 cm...most interlams are siltstone, not very fine sandstone; organic content (coal chunks and small flakes) not obviously high (there is little yellow rust and very few coal partings)	Facies V2: Storm-dominated offshore/delta-front deposits	Venture sandstone 8	Lower Member, Missisauga Fm



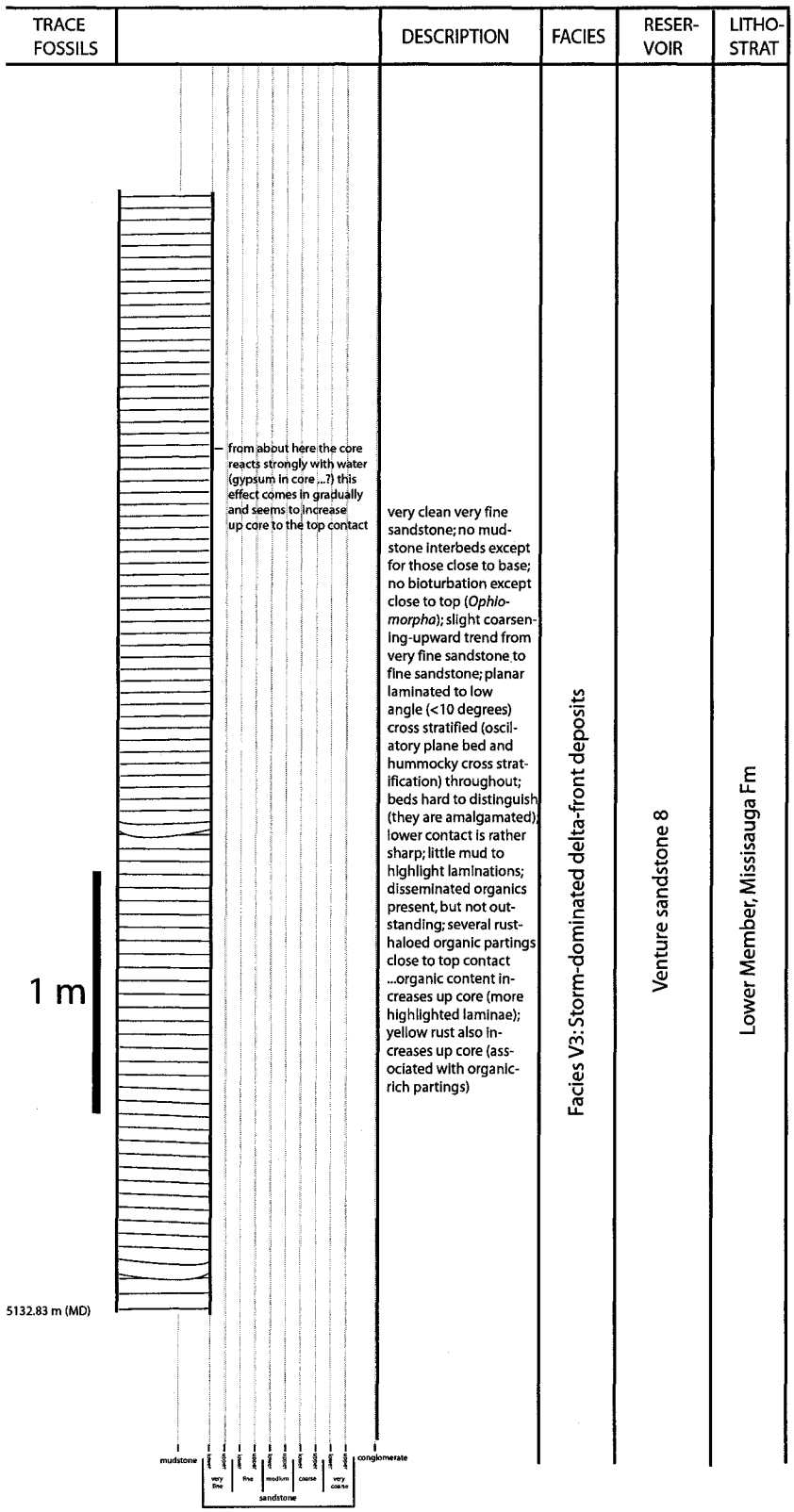
1 m

5141.84 m (MD)

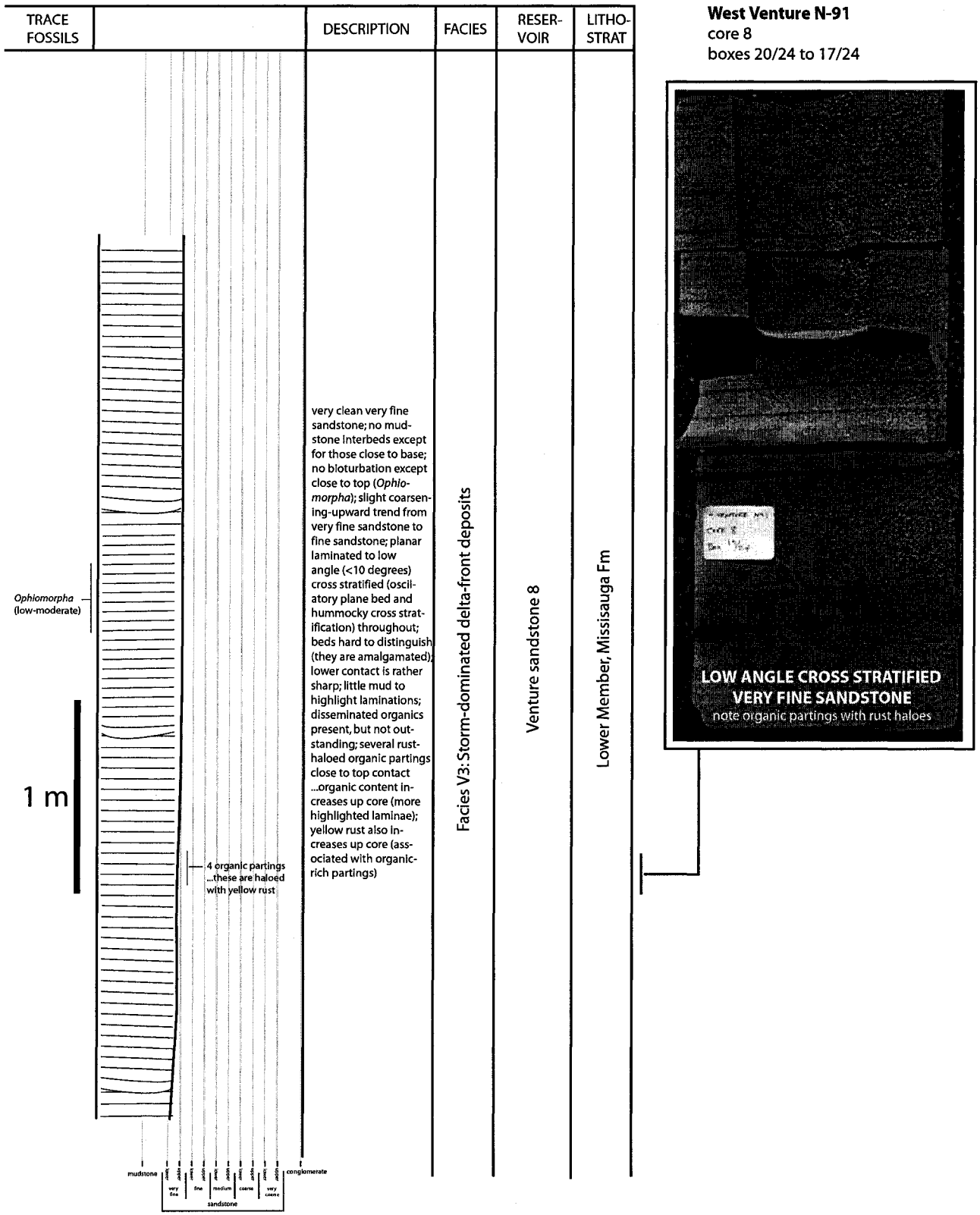


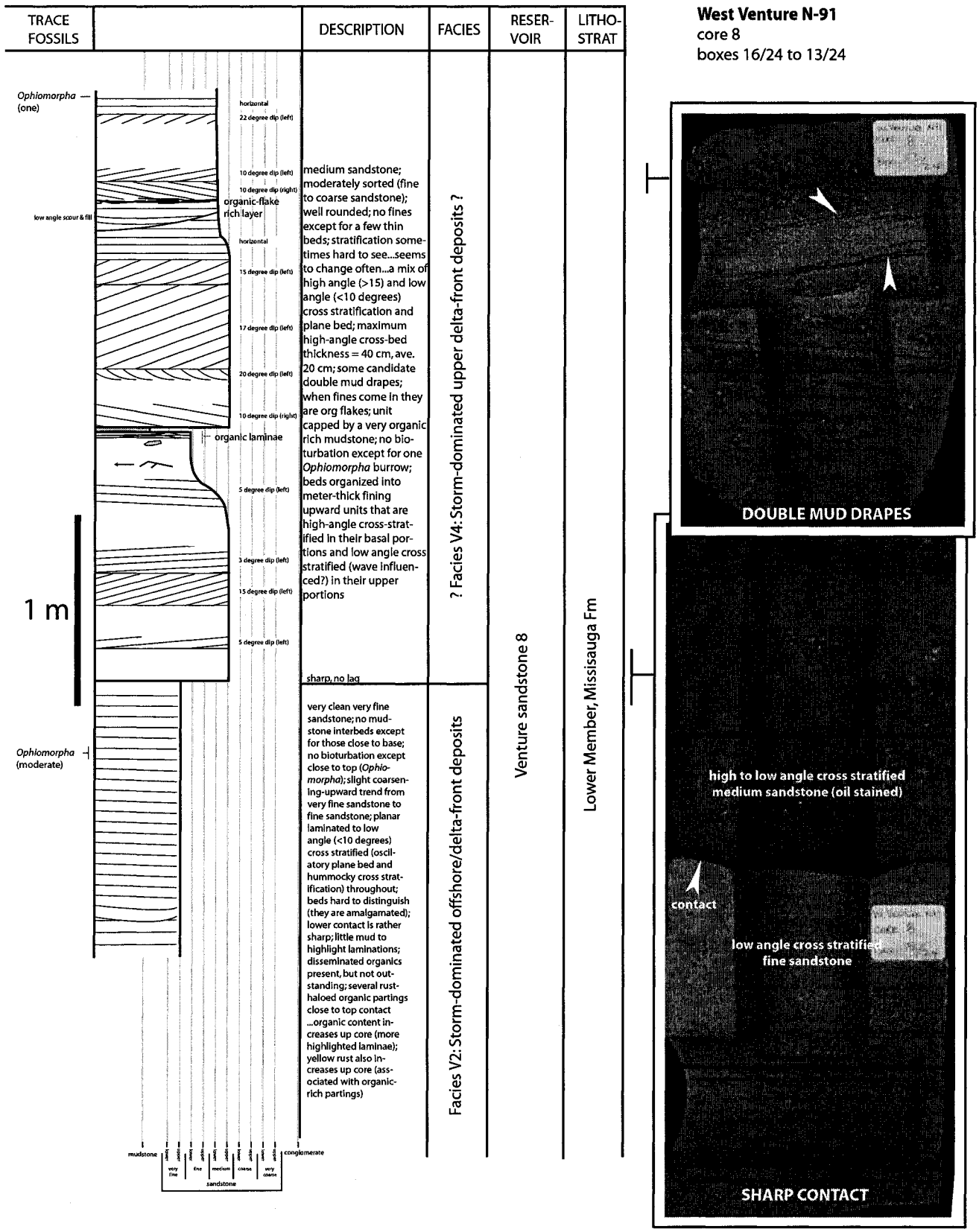


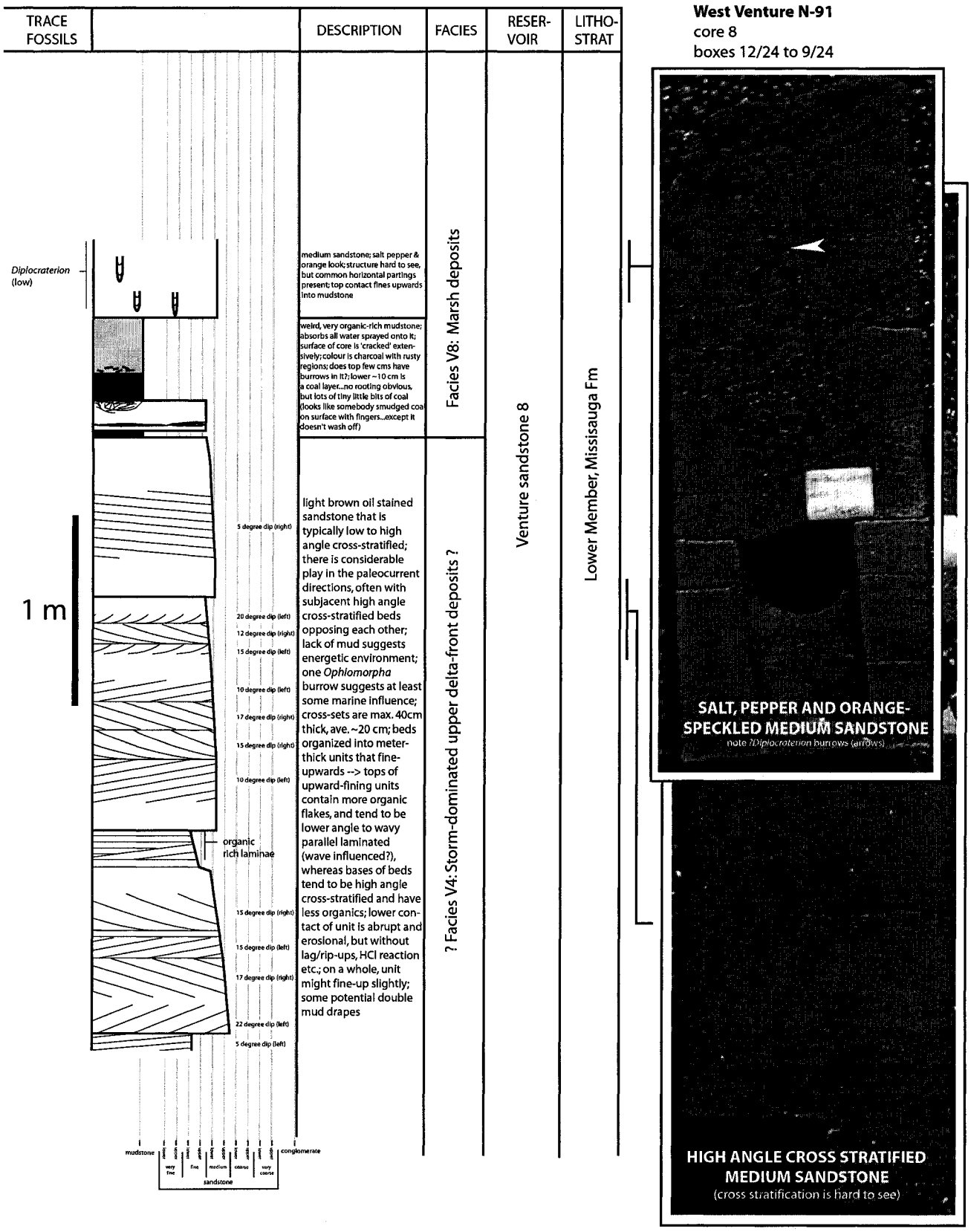
West Venture N-91
core 9
boxes 4/8 to 1/8



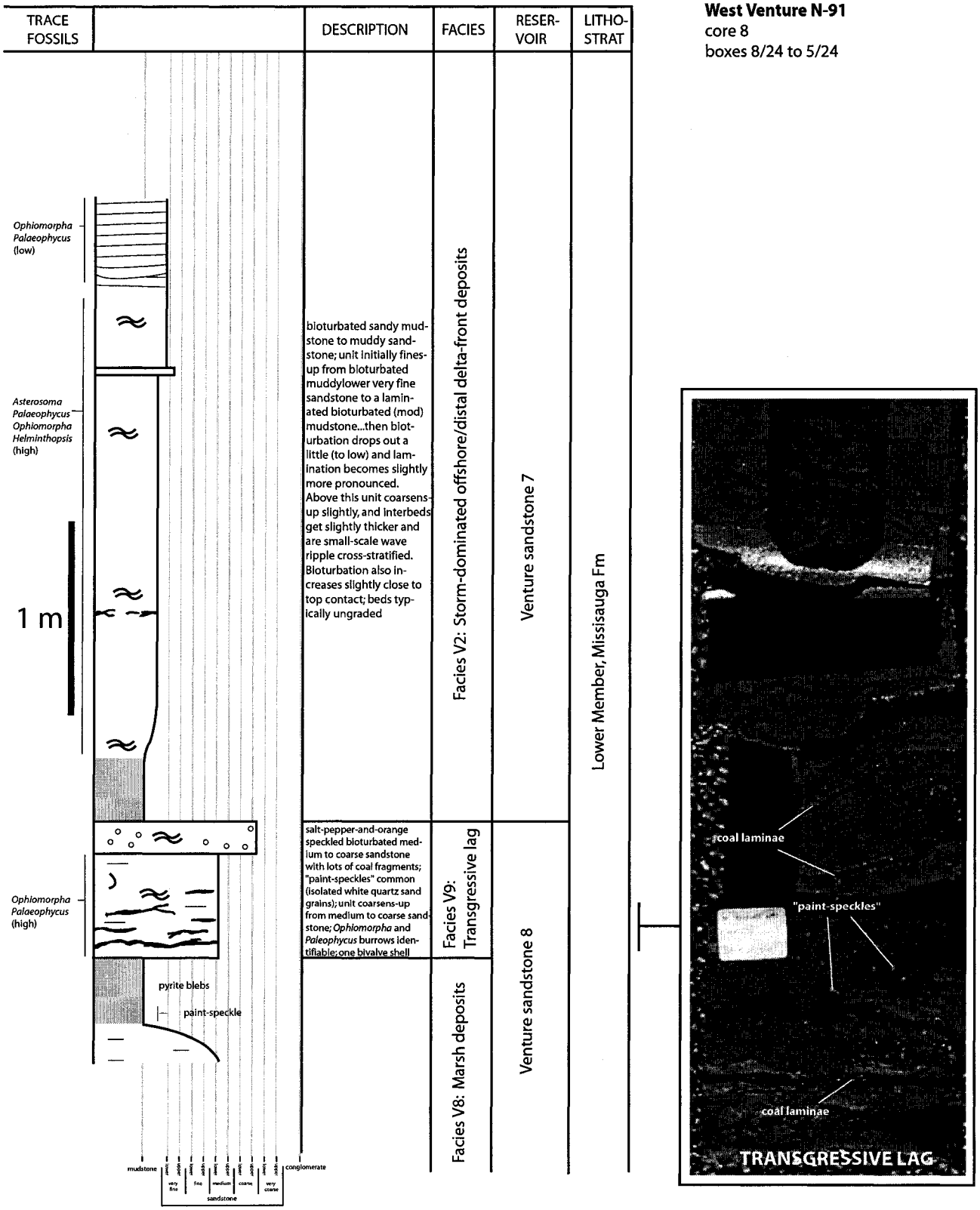
West Venture N-91
core 8
boxes 24/24 to 21/24


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
Ophiomorpha (low-moderate)
1 m
4 organic partings ...these are haloed with yellow rust
very clean very fine sandstone; no mudstone interbeds except for those close to base; no bioturbation except close to top (Ophiomorpha); slight coarsening-upward trend from very fine sandstone to fine sandstone; planar laminated to low angle (<10 degrees) cross stratified (oscillatory plane bed and hummocky cross stratification) throughout; beds hard to distinguish (they are amalgamated); lower contact is rather sharp; little mud to highlight laminations; disseminated organics present, but not outstanding; several rust-haloed organic partings close to top contact ...organic content increases up core (more highlighted laminae); yellow rust also increases up core (associated with organic-rich partings)
Facies V3: Storm-dominated delta-front deposits
Venture sandstone 8
Lower Member, Missisauga Fm
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone
West Venture N-91
core 8
boxes 20/24 to 17/24
LOW ANGLE CROSS STRATIFIED VERY FINE SANDSTONE
note organic partings with rust haloes

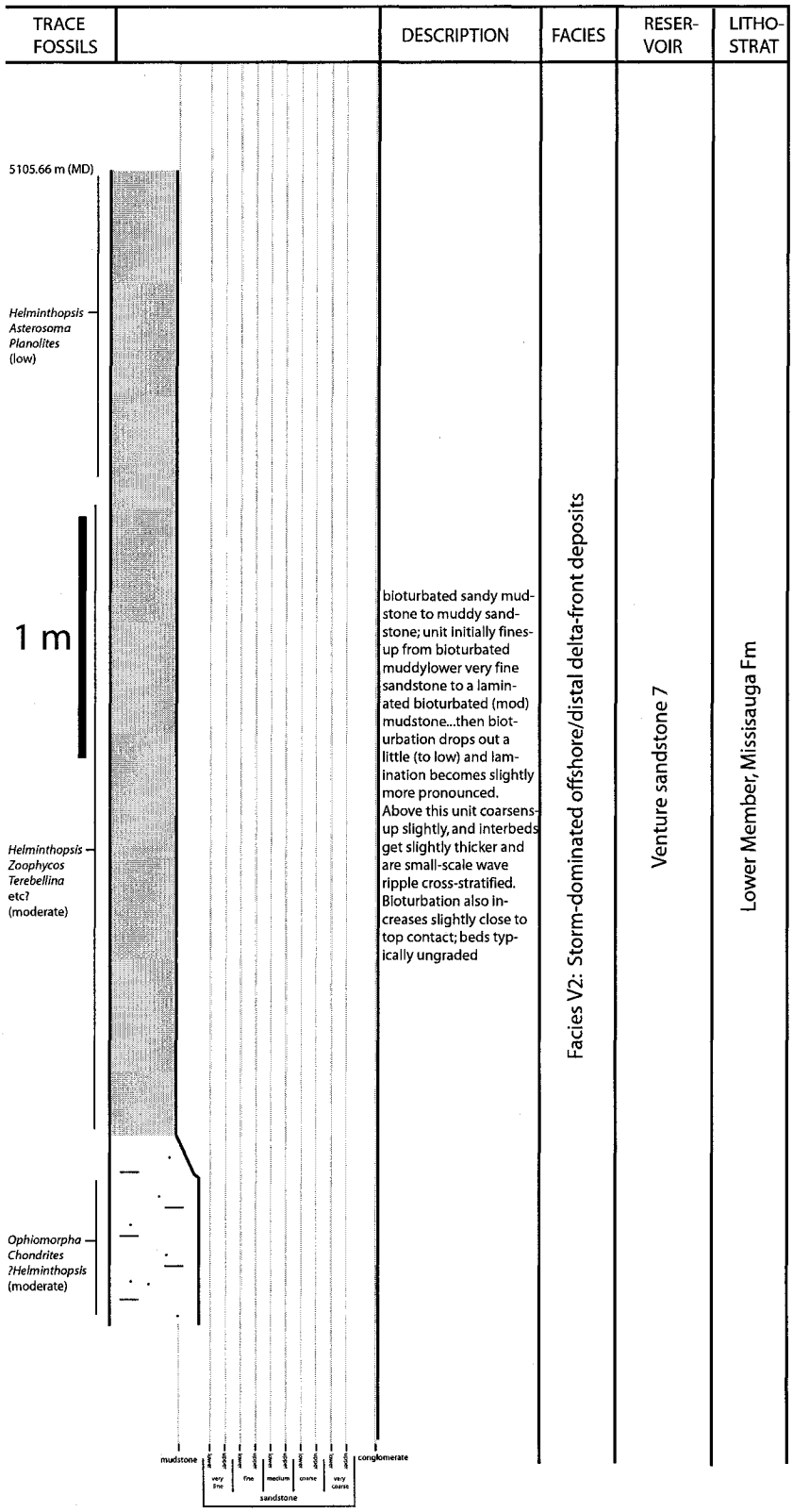

TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
West Venture N-91
core 8
boxes 16/24 to 13/24
Ophiomorpha (one)
horizontal
22 degree dip (left)
10 degree dip (left)
10 degree dip (right)
organic-flake rich layer
low angle scour & fill
horizontal
15 degree dip (left)
17 degree dip (left)
20 degree dip (left)
10 degree dip (right)
organic laminae
5 degree dip (left)
3 degree dip (left)
15 degree dip (left)
5 degree dip (left)
1 m
Ophiomorpha (moderate)
medium sandstone; moderately sorted (fine to coarse sandstone); well rounded; no fines except for a few thin beds; stratification sometimes hard to see...seems to change often...a mix of high angle (>15) and low angle (<10 degrees) cross stratification and plane bed; maximum high-angle cross-bed thickness = 40 cm, ave. 20 cm; some candidate double mud drapes; when fines come in they are org flakes; unit capped by a very organic rich mudstone; no bioturbation except for one Ophiomorpha burrow; beds organized into meter-thick fining upward units that are high-angle cross-stratified in their basal portions and low angle cross stratified (wave influenced?) in their upper portions
? Facies V4: Storm-dominated upper delta-front deposits ?
sharp, no lag
very clean very fine sandstone; no mudstone interbeds except for those close to base; no bioturbation except close to top (Ophiomorpha); slight coarsening-upward trend from very fine sandstone to fine sandstone; planar laminated to low angle (<10 degrees) cross stratified (oscillatory plane bed and hummocky cross stratification) throughout; beds hard to distinguish (they are amalgamated); lower contact is rather sharp; little mud to highlight laminations; disseminated organics present, but not outstanding; several rust-haloed organic partings close to top contact ...organic content increases up core (more highlighted laminae); yellow rust also increases up core (associated with organic-rich partings)
Facies V2: Storm-dominated offshore/delta-front deposits
Venture sandstone 8
Lower Member, Missisauga Fm
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone
DOUBLE MUD DRAPES
high to low angle cross stratified medium sandstone (oil stained)
contact
low angle cross stratified fine sandstone
SHARP CONTACT


TRACE FOSSILS
DESCRIPTION
FACIES
RESER-VOIR
LITHO-STRAT
West Venture N-91
core 8
boxes 12/24 to 9/24
Diplocraterion (low)
medium sandstone; salt pepper & orange look; structure hard to see, but common horizontal partings present; top contact fines upwards into mudstone
weird, very organic-rich mudstone; absorbs all water sprayed onto it; surface of core is 'cracked' extensively; colour is charcoal with rusty regions; does top few cms have burrows in it?; lower ~10 cm is a coal layer...no rooting obvious, but lots of tiny little bits of coal (looks like somebody smudged coal on surface with fingers...except it doesn't wash off)
Facies V8: Marsh deposits
1 m
5 degree dip (right)
20 degree dip (left)
12 degree dip (right)
15 degree dip (left)
10 degree dip (left)
17 degree dip (right)
15 degree dip (right)
10 degree dip (left)
organic rich laminae
15 degree dip (right)
15 degree dip (left)
17 degree dip (right)
22 degree dip (left)
5 degree dip (left)
light brown oil stained sandstone that is typically low to high angle cross-stratified; there is considerable play in the paleocurrent directions, often with subjacent high angle cross-stratified beds opposing each other; lack of mud suggests energetic environment; one Ophiomorpha burrow suggests at least some marine influence; cross-sets are max. 40cm thick, ave. ~20 cm; beds organized into meter-thick units that fine-upwards --> tops of upward-fining units contain more organic flakes, and tend to be lower angle to wavy parallel laminated (wave influenced?), whereas bases of beds tend to be high angle cross-stratified and have less organics; lower contact of unit is abrupt and erosional, but without lag/rip-ups, HCl reaction etc.; on a whole, unit might fine-up slightly; some potential double mud drapes
? Facies V4: Storm-dominated upper delta-front deposits ?
Venture sandstone 8
Lower Member, Missisauga Fm
mudstone
very fine
fine
medium
coarse
very coarse
conglomerate
sandstone
SALT, PEPPER AND ORANGE-SPECKLED MEDIUM SANDSTONE
note Diplocraterion burrows (arrows)
HIGH ANGLE CROSS STRATIFIED MEDIUM SANDSTONE
(cross stratification is hard to see)

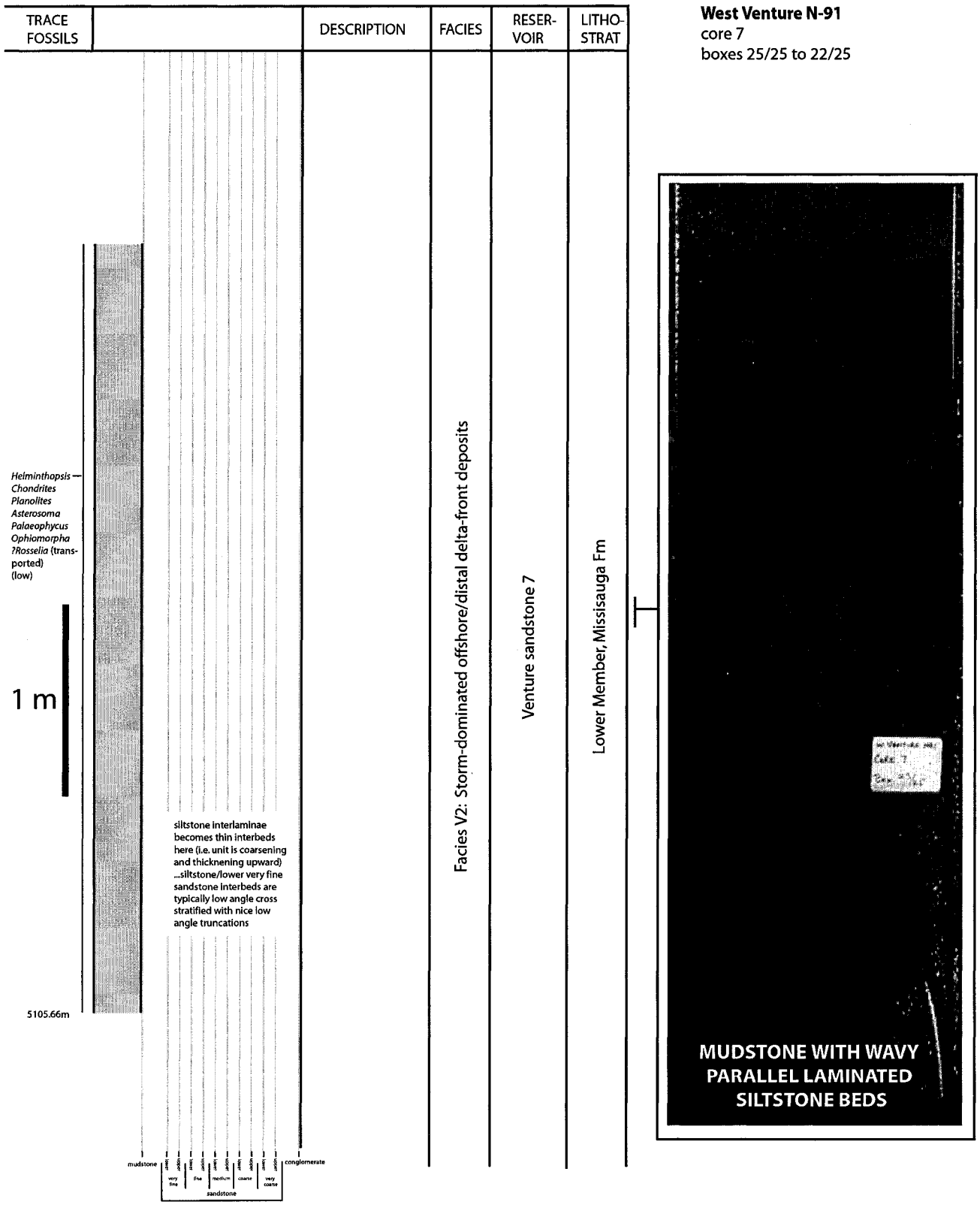
West Venture N-91
core 8
boxes 8/24 to 5/24

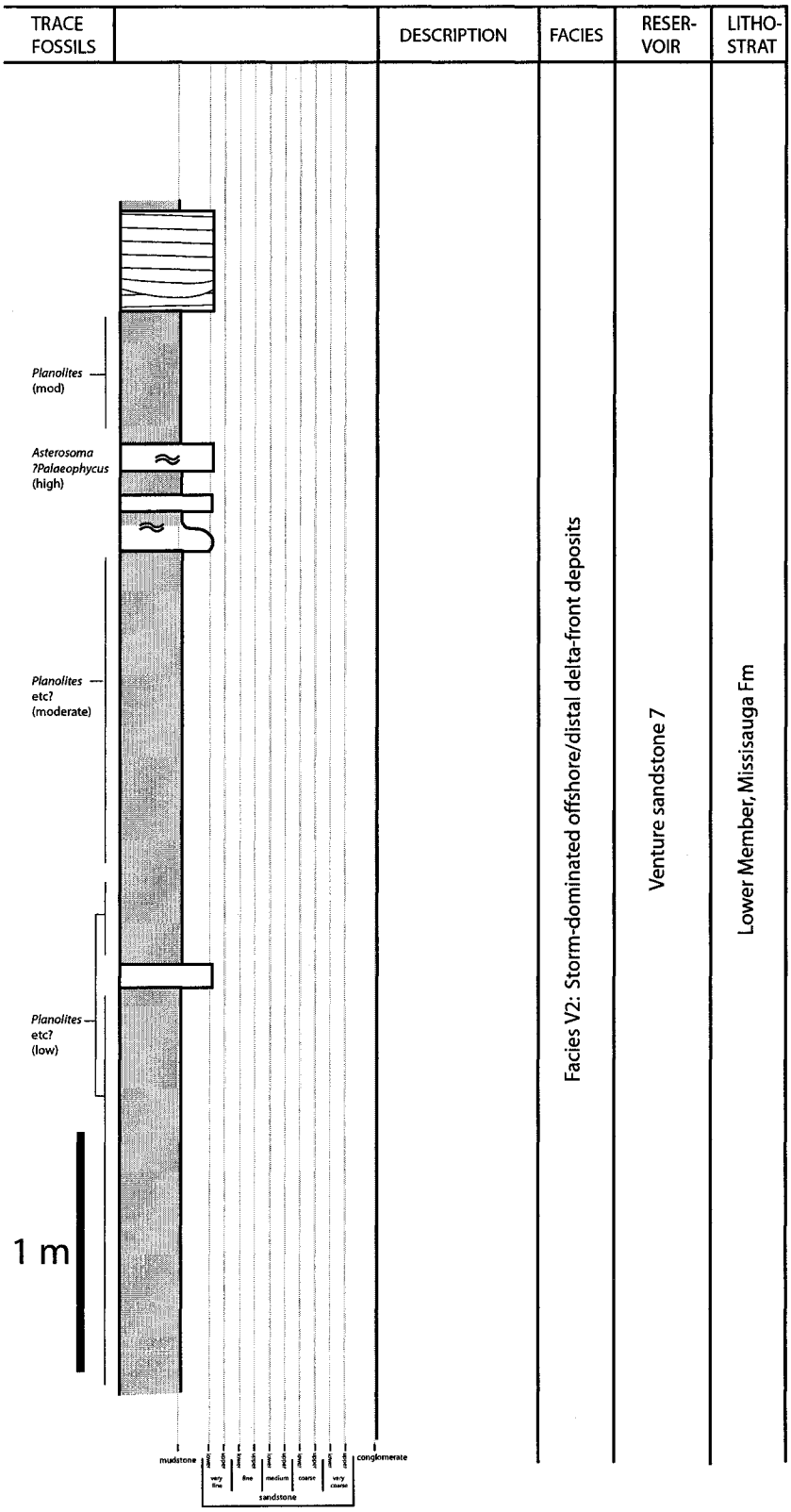


West Venture N-91
core 8
boxes 4/8 to 1/8

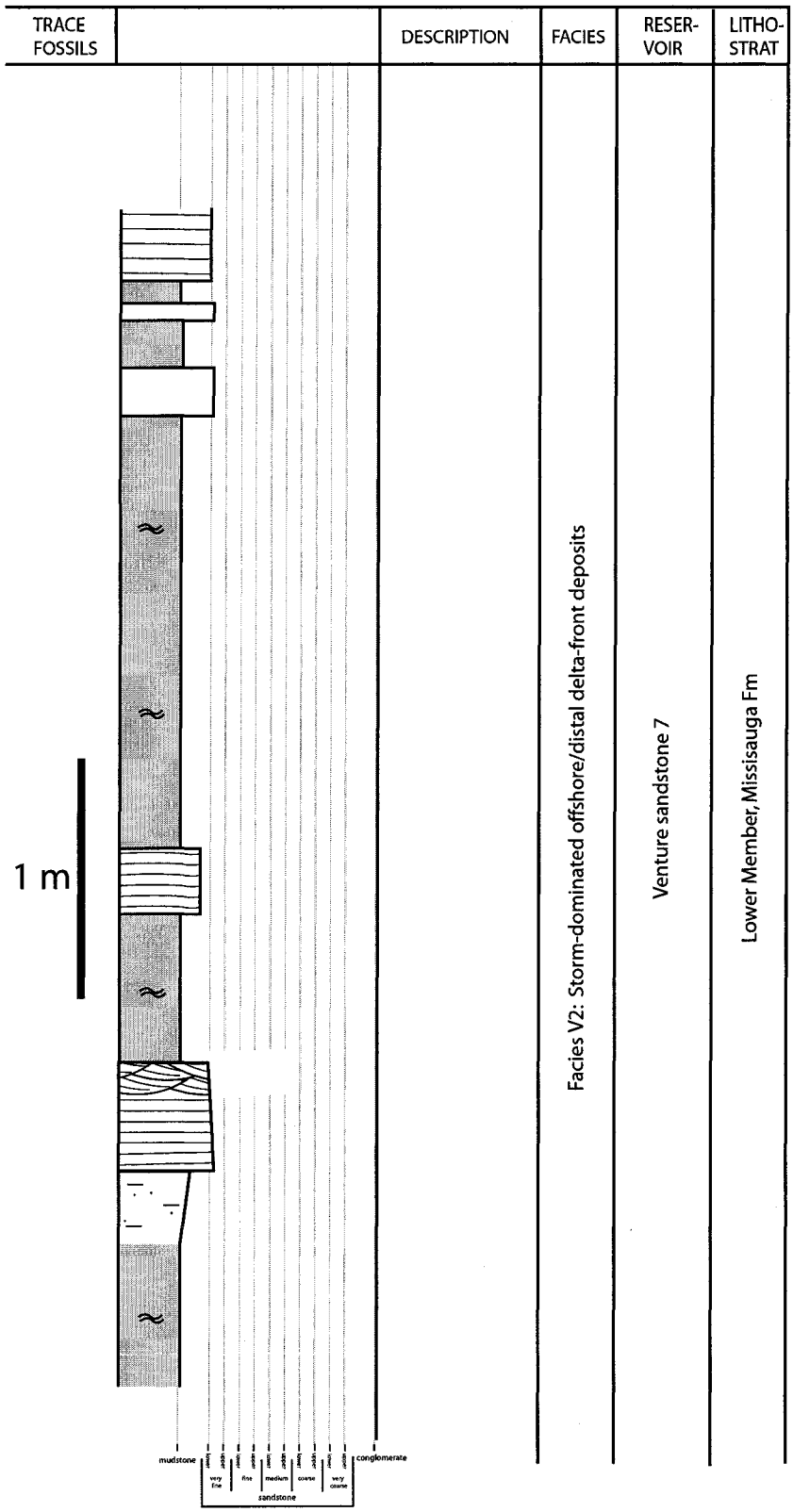


West Venture N-91
core 7
boxes 25/25 to 22/25

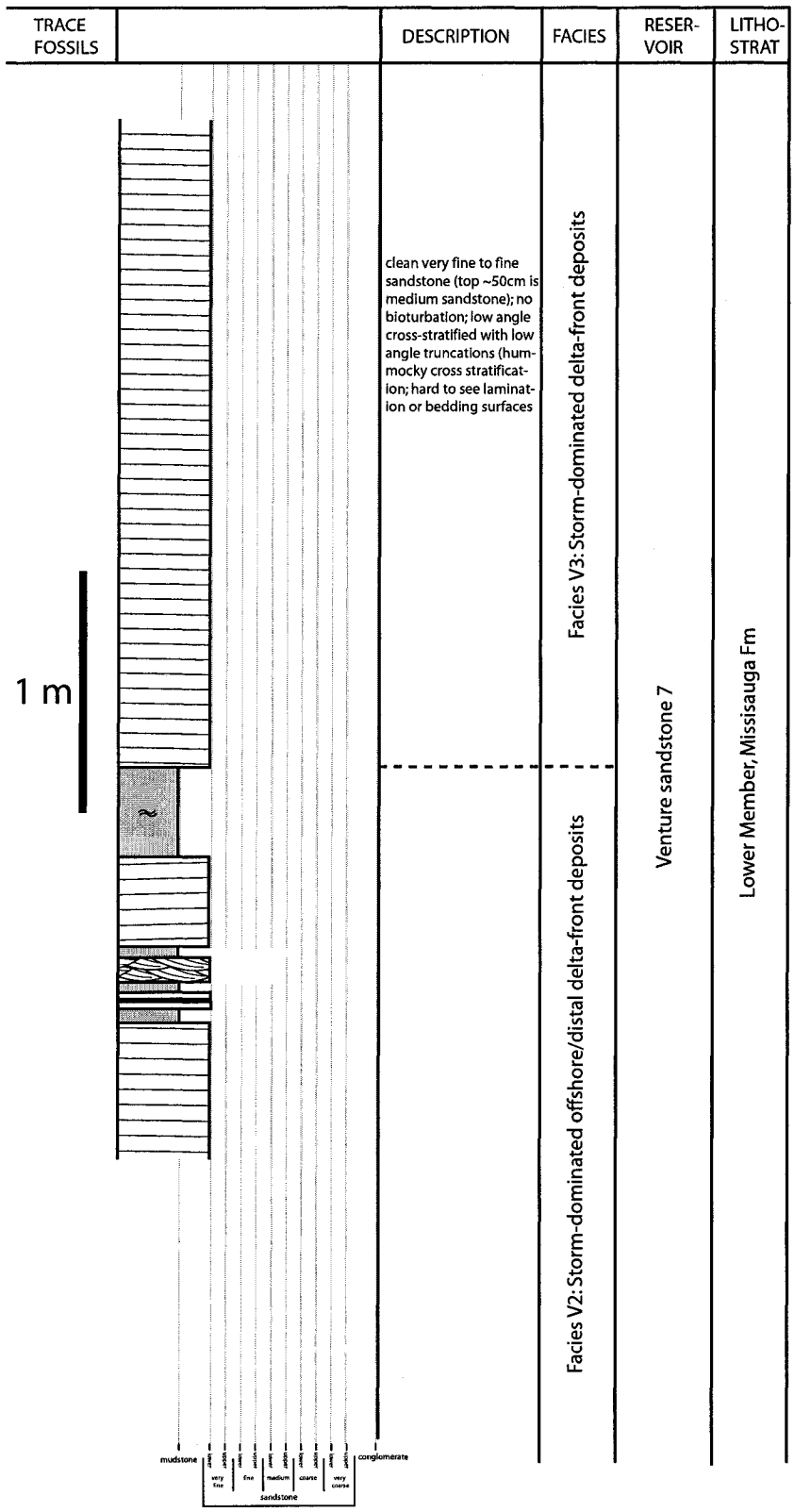




West Venture N-91
core 7
boxes 21/25 to 18/25

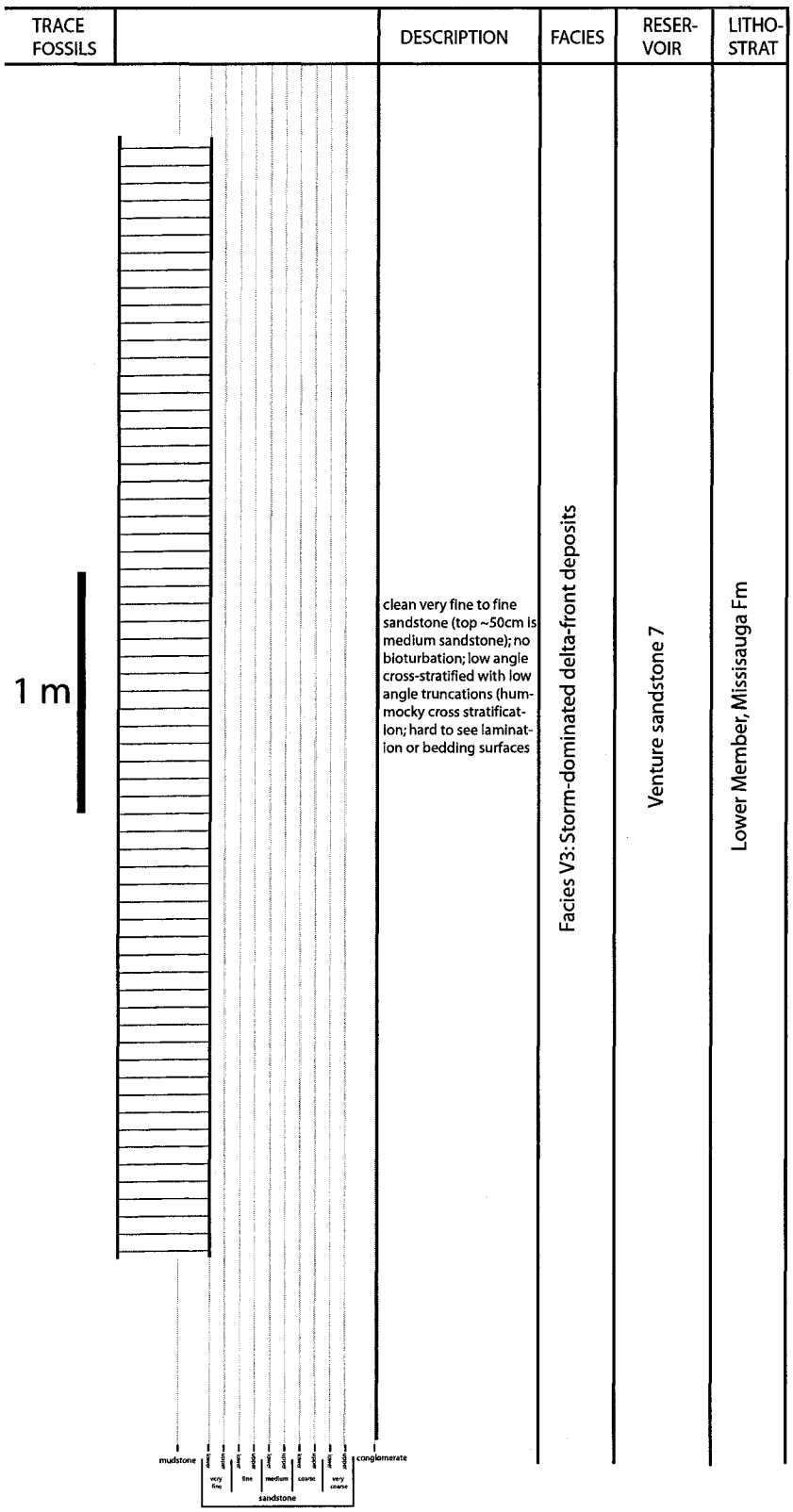


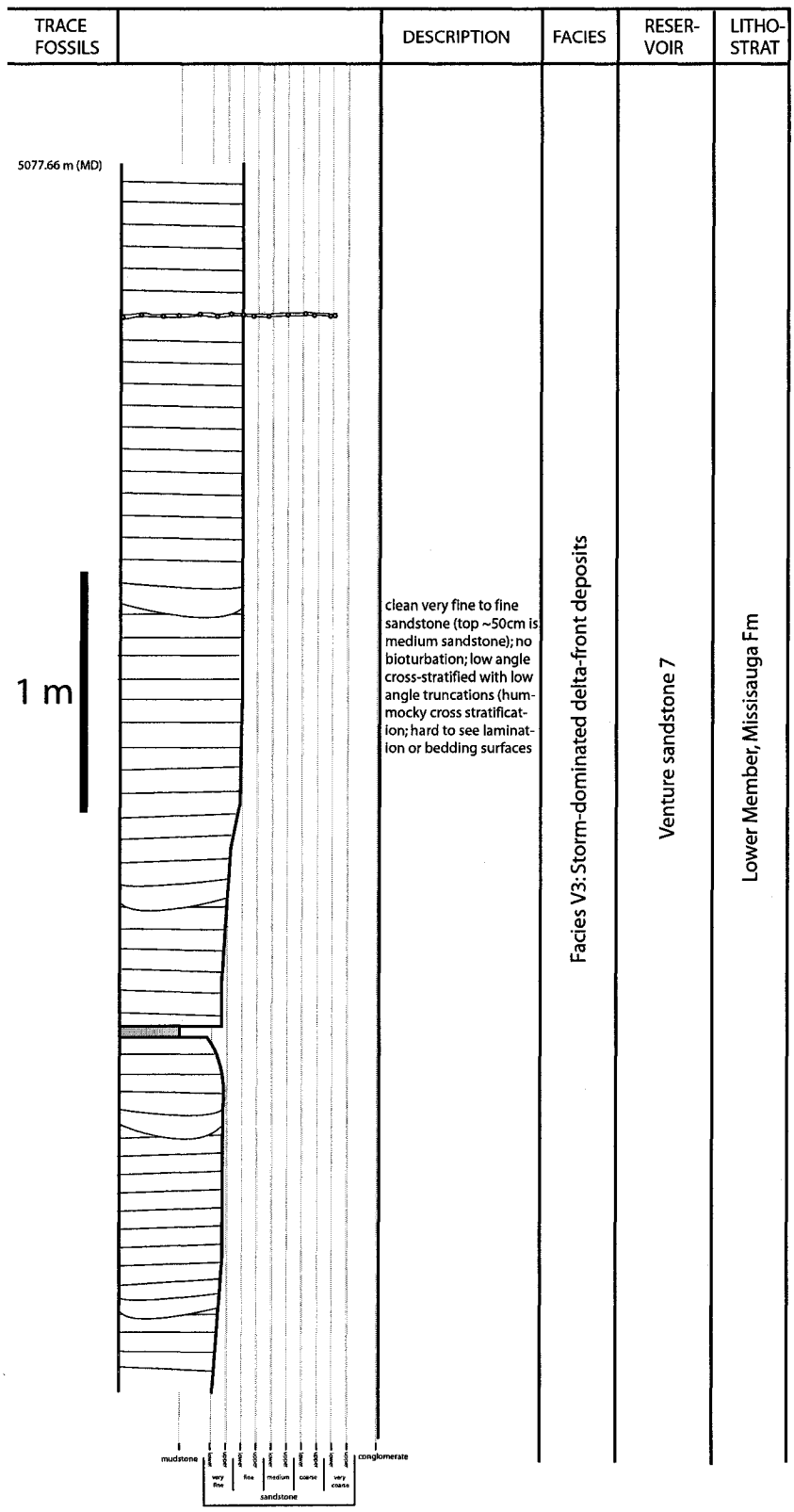
West Venture N-91
core 7
boxes 17/25 to 14/25



West Venture N-91
core 7
boxes 13/25 to 10/25

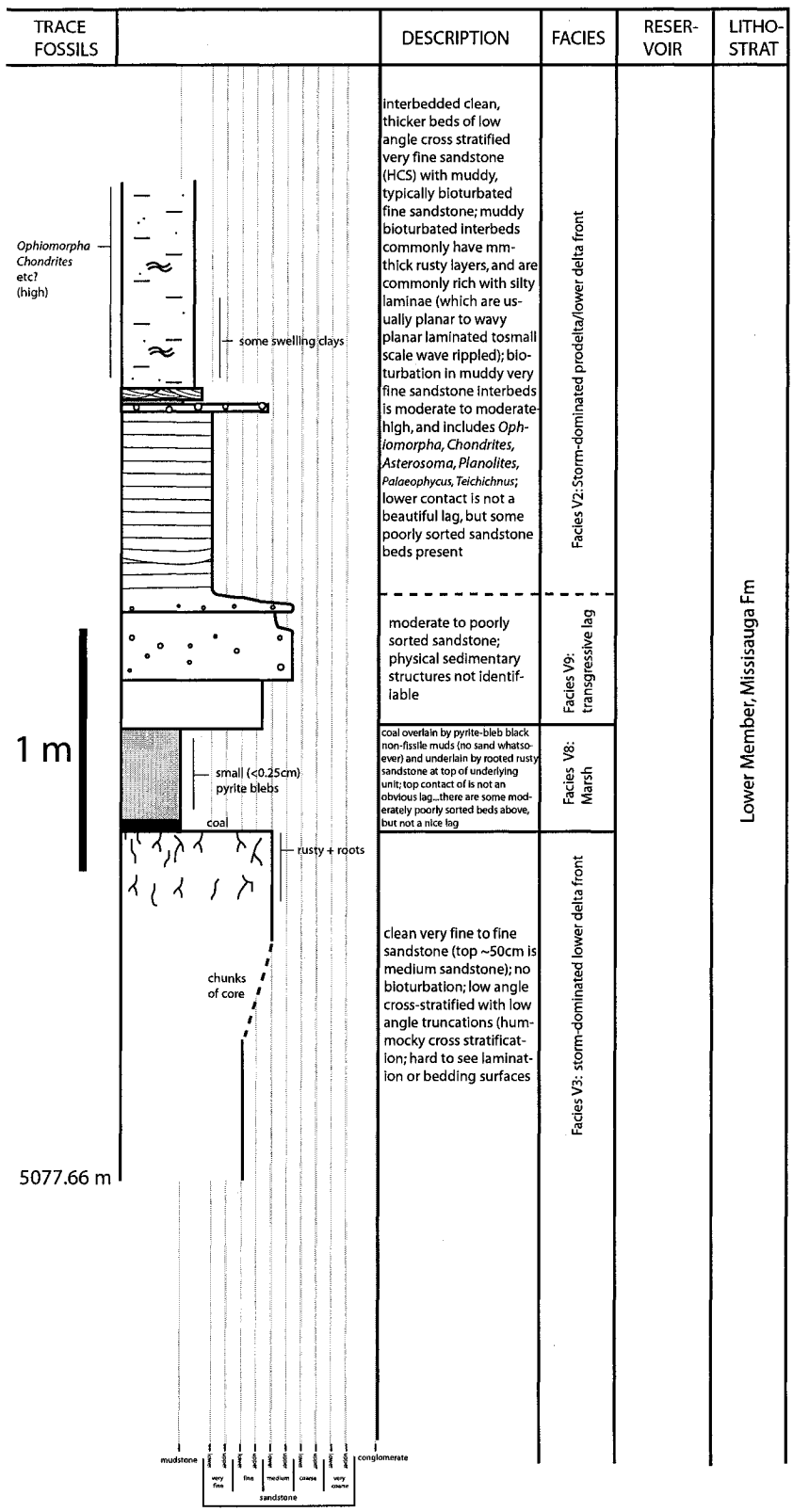
West Venture N-91
core 7
boxes 9/25 to 6/25

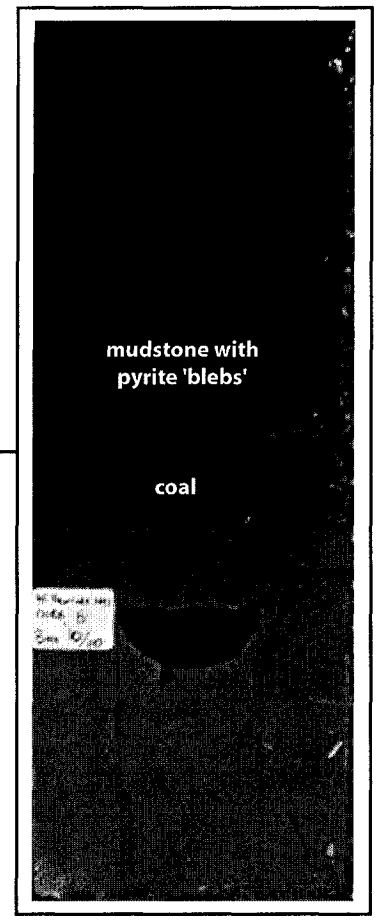




West Venture N-91
core 7
boxes 5/25 to 1/25

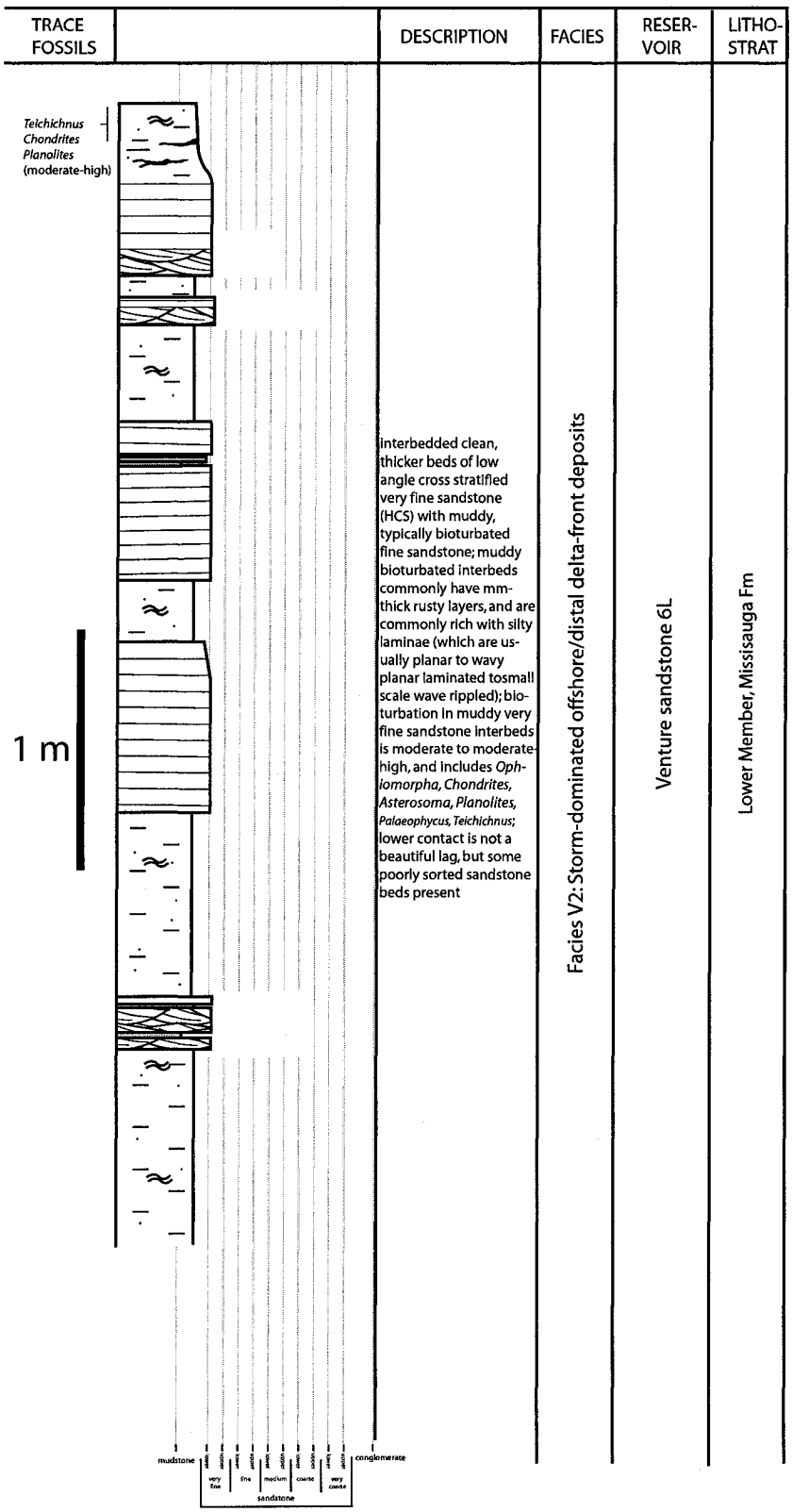
West Venture N-91
core 6
boxes 10/10 to 8/10



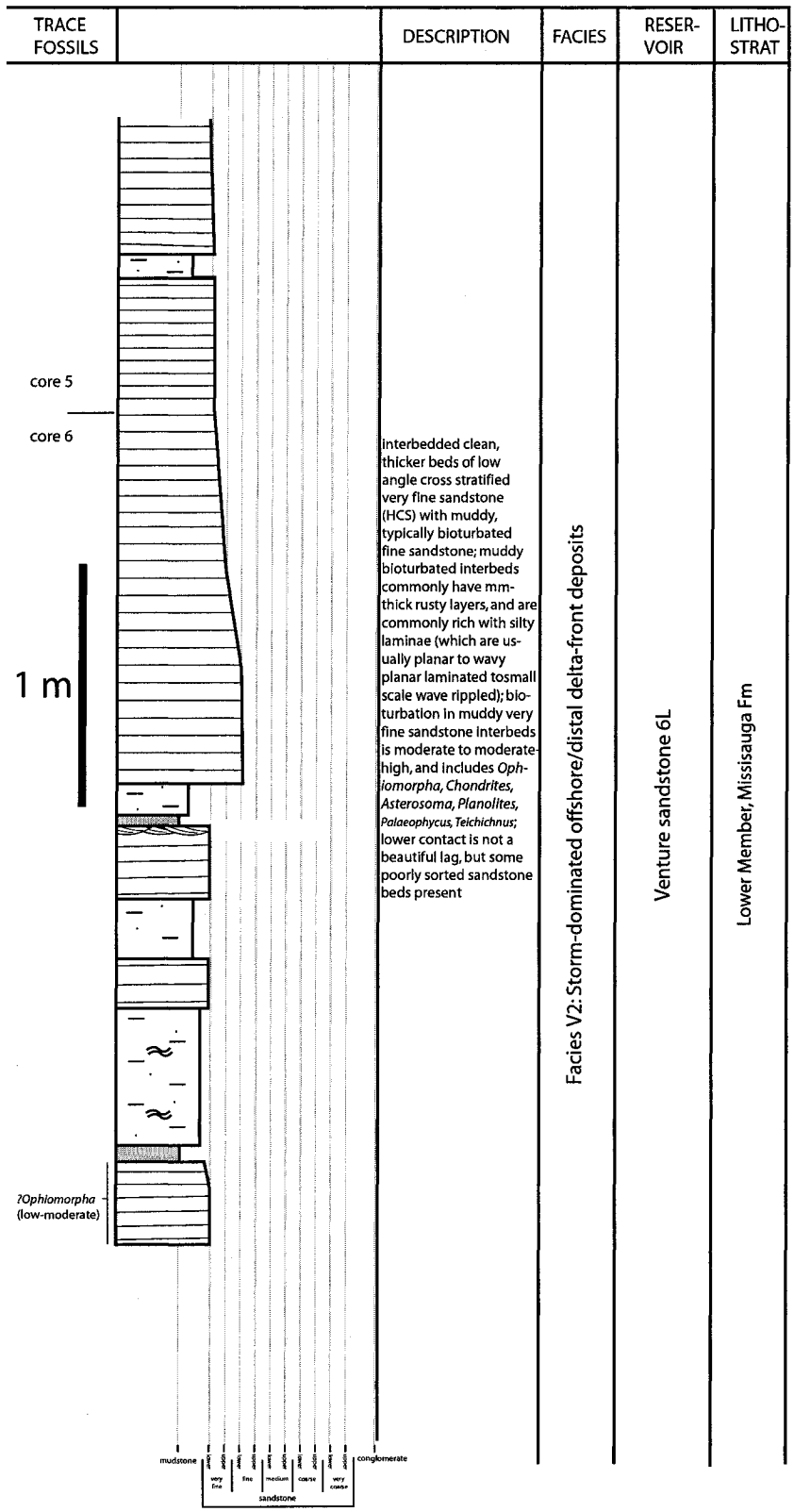


ROOTED COAL

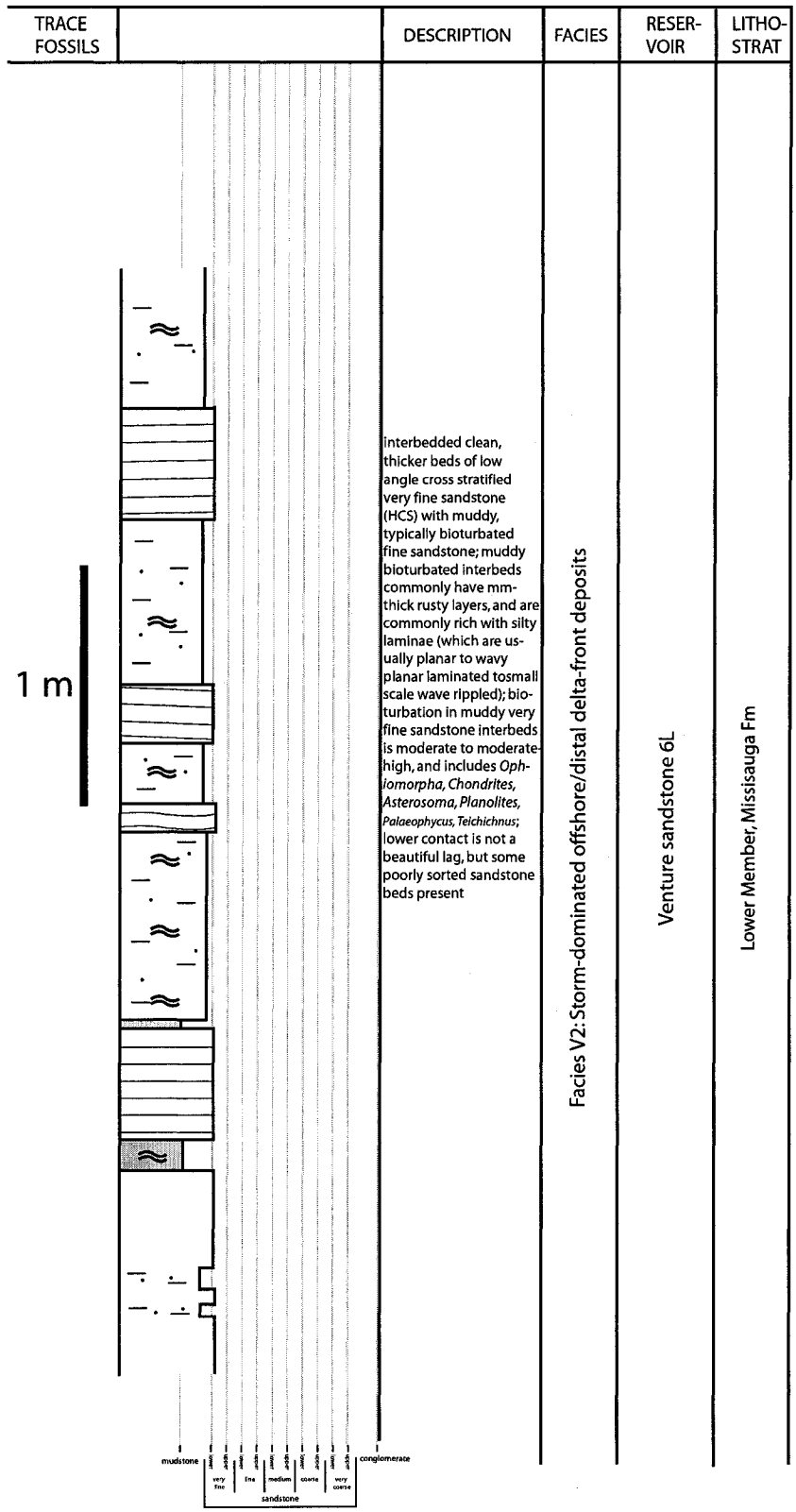
West Venture N-91
core 6
boxes 7/10 to 4/10



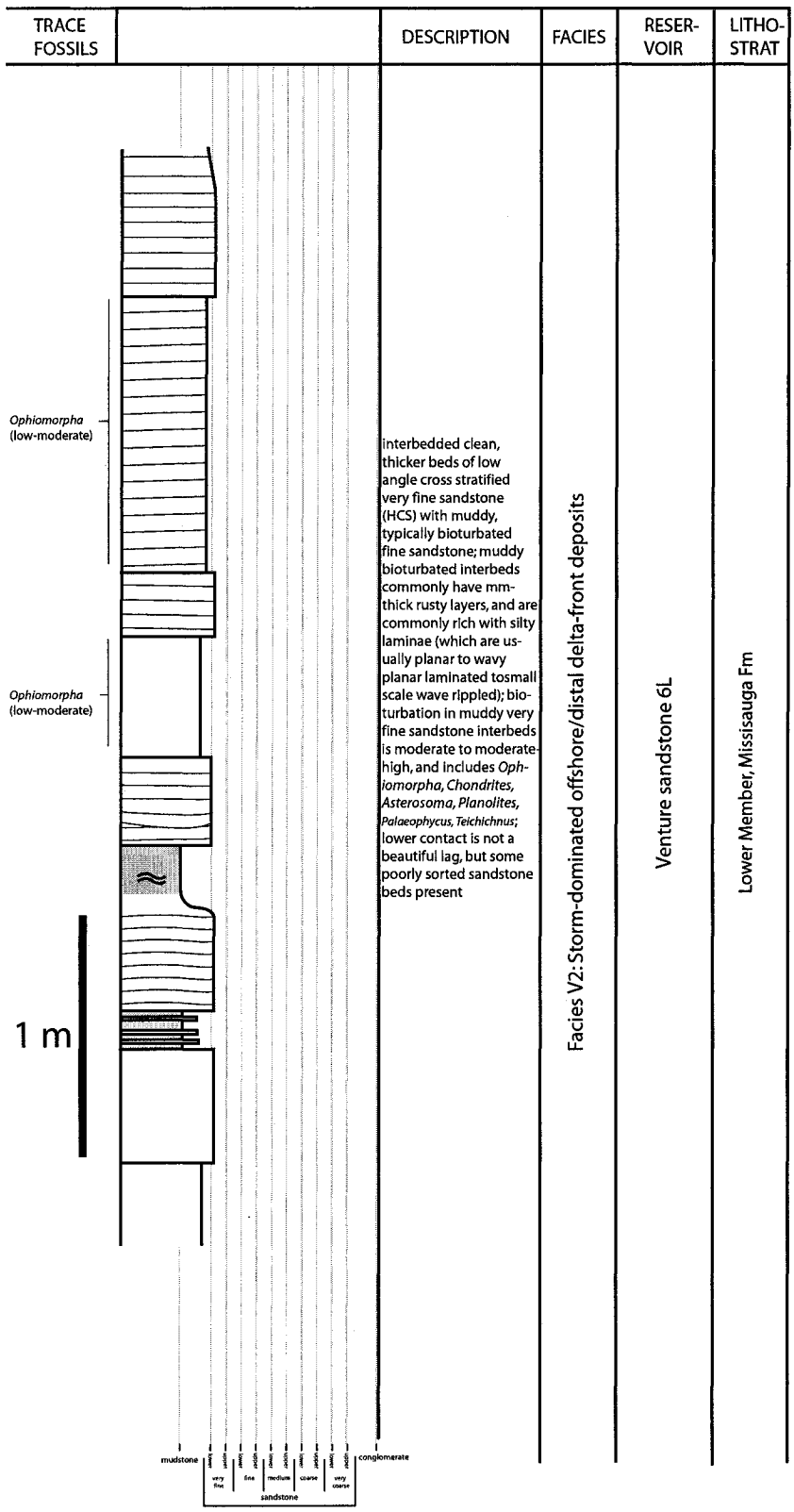
West Venture N-91
core 6, box 3/10 to
core 5, box 24/24



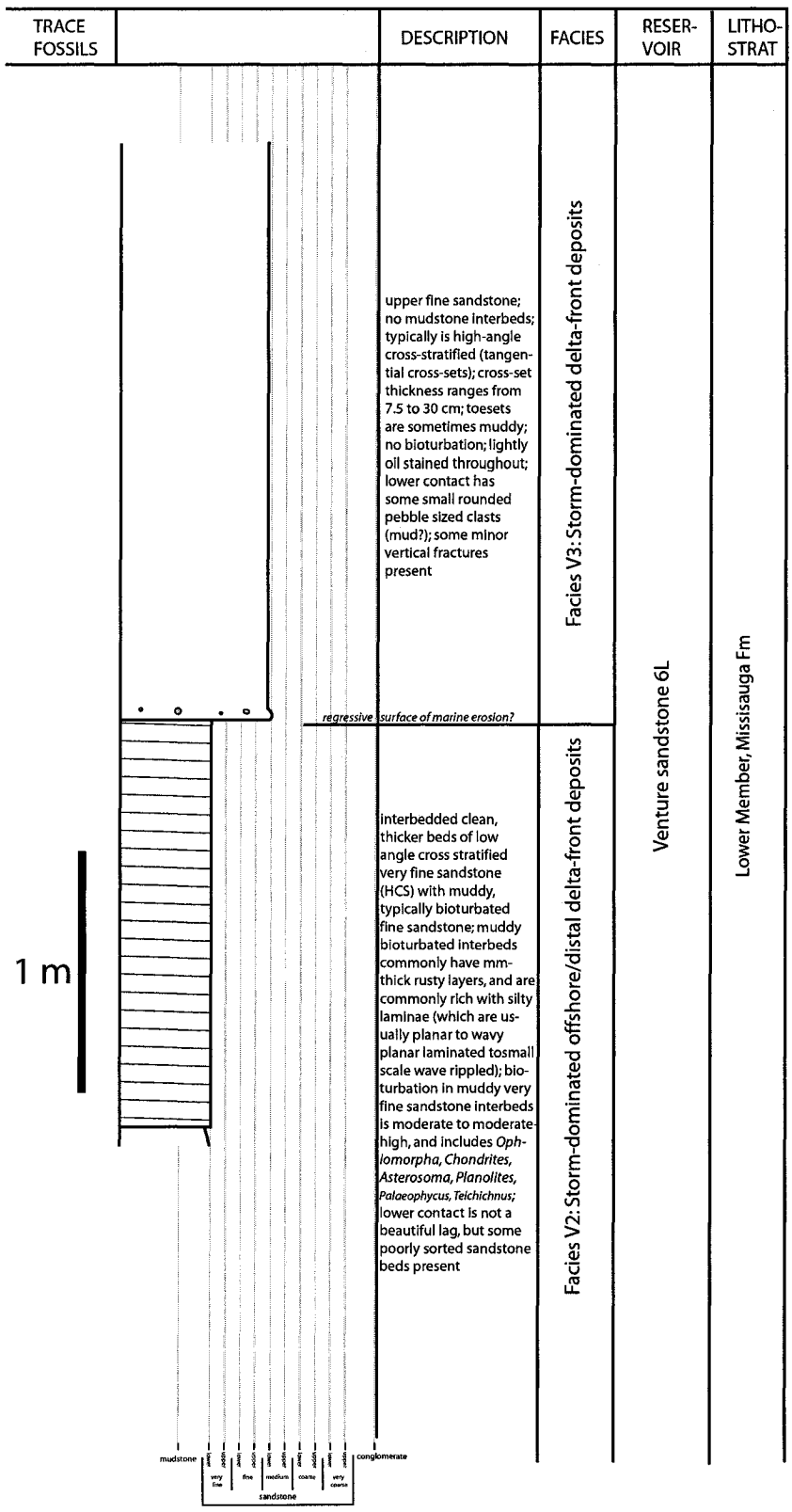
West Venture N-91
core 5
boxes 23/24 to 20/24



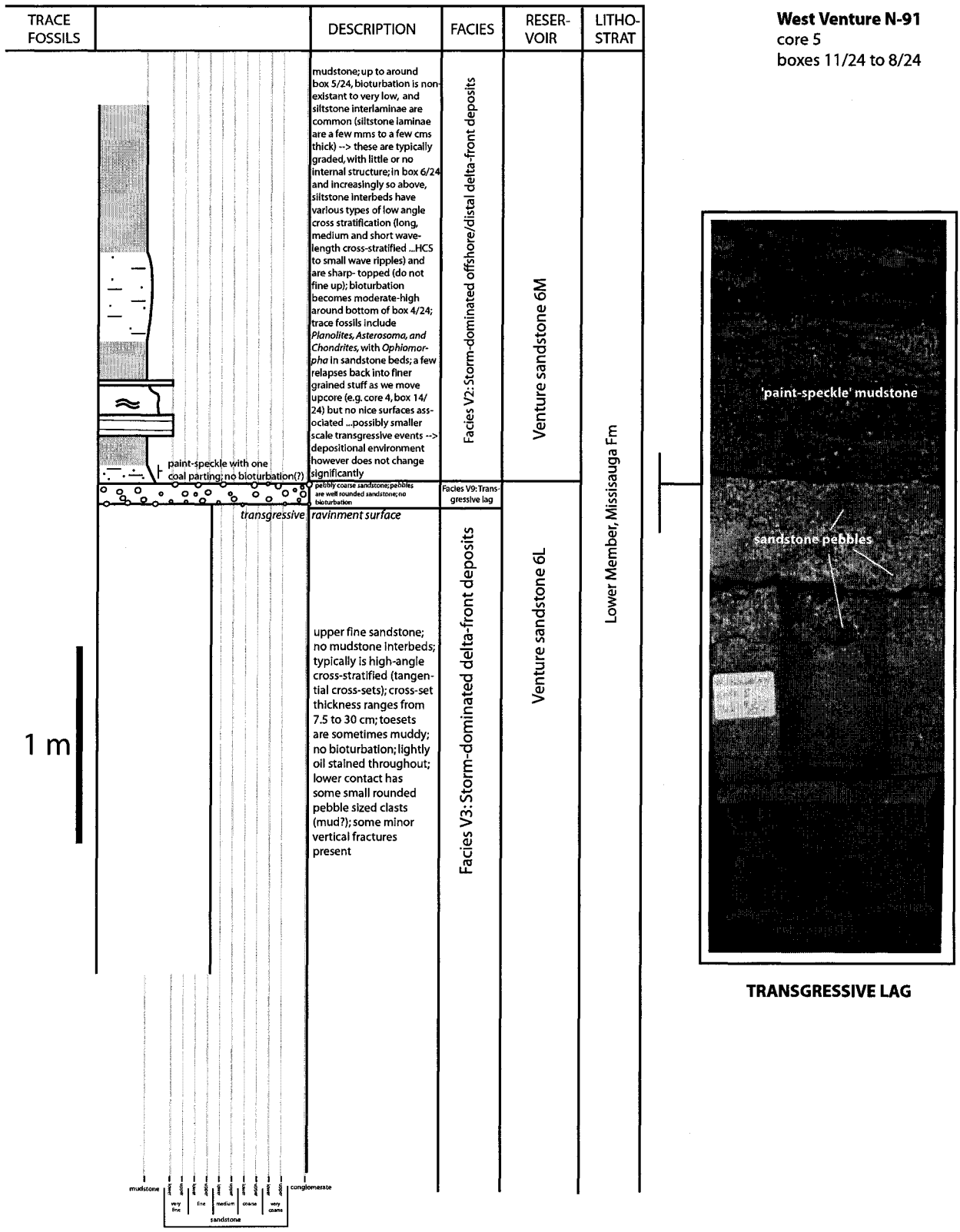
West Venture N-91
core 5
boxes 19/24 to 16/24



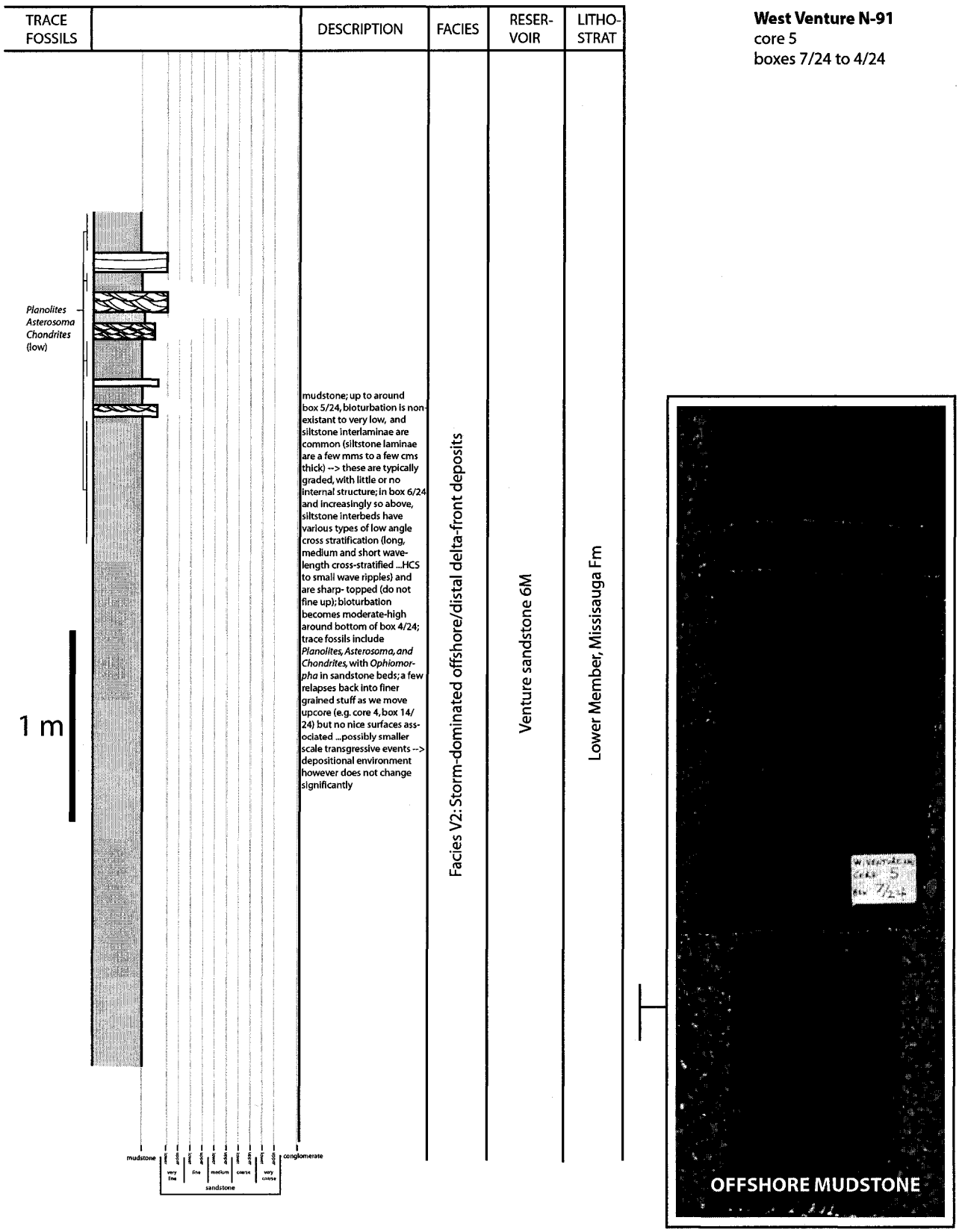
West Venture N-91
core 5
boxes 15/24 to 12/24



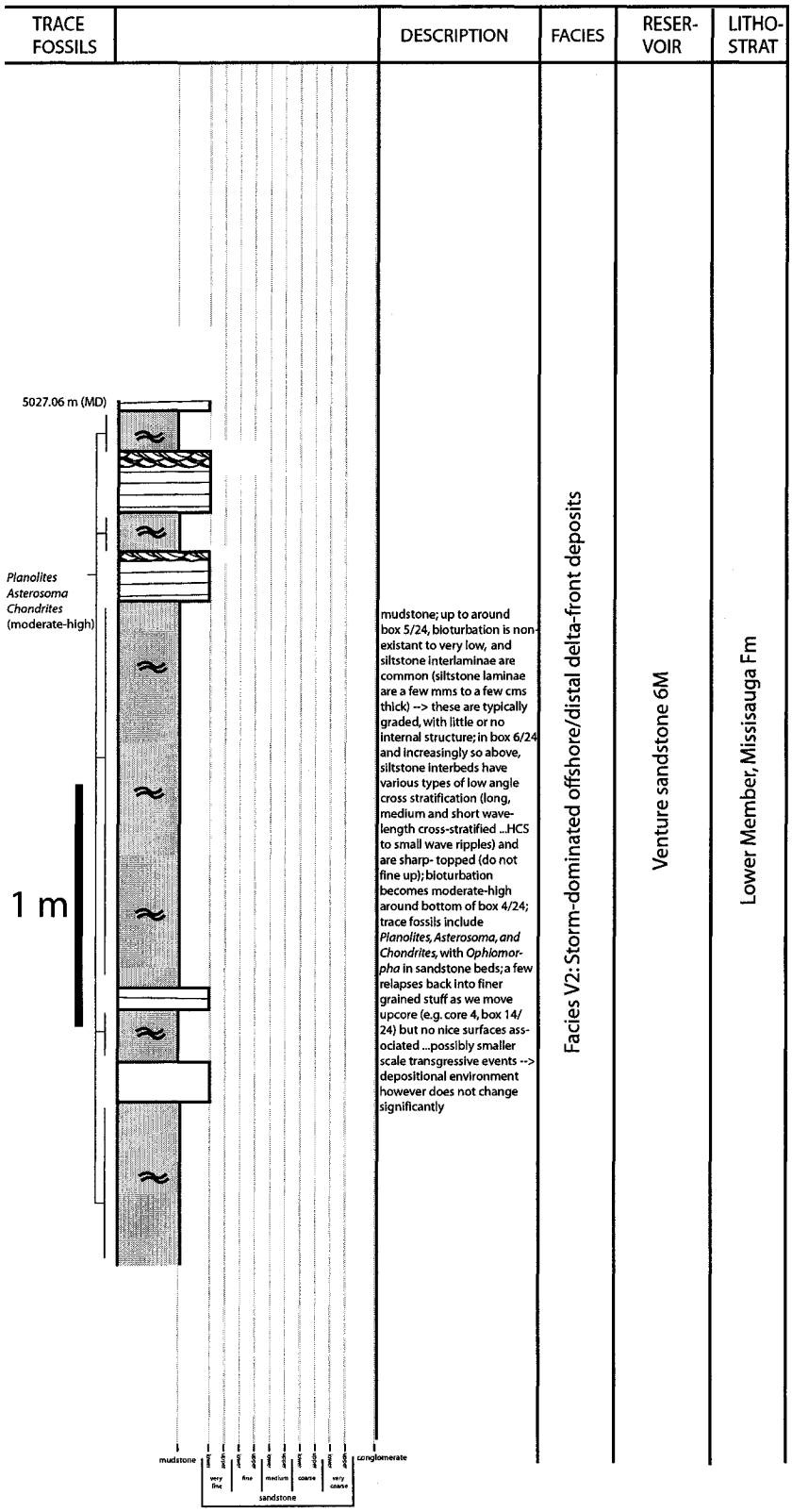
West Venture N-91
core 5
boxes 11/24 to 8/24



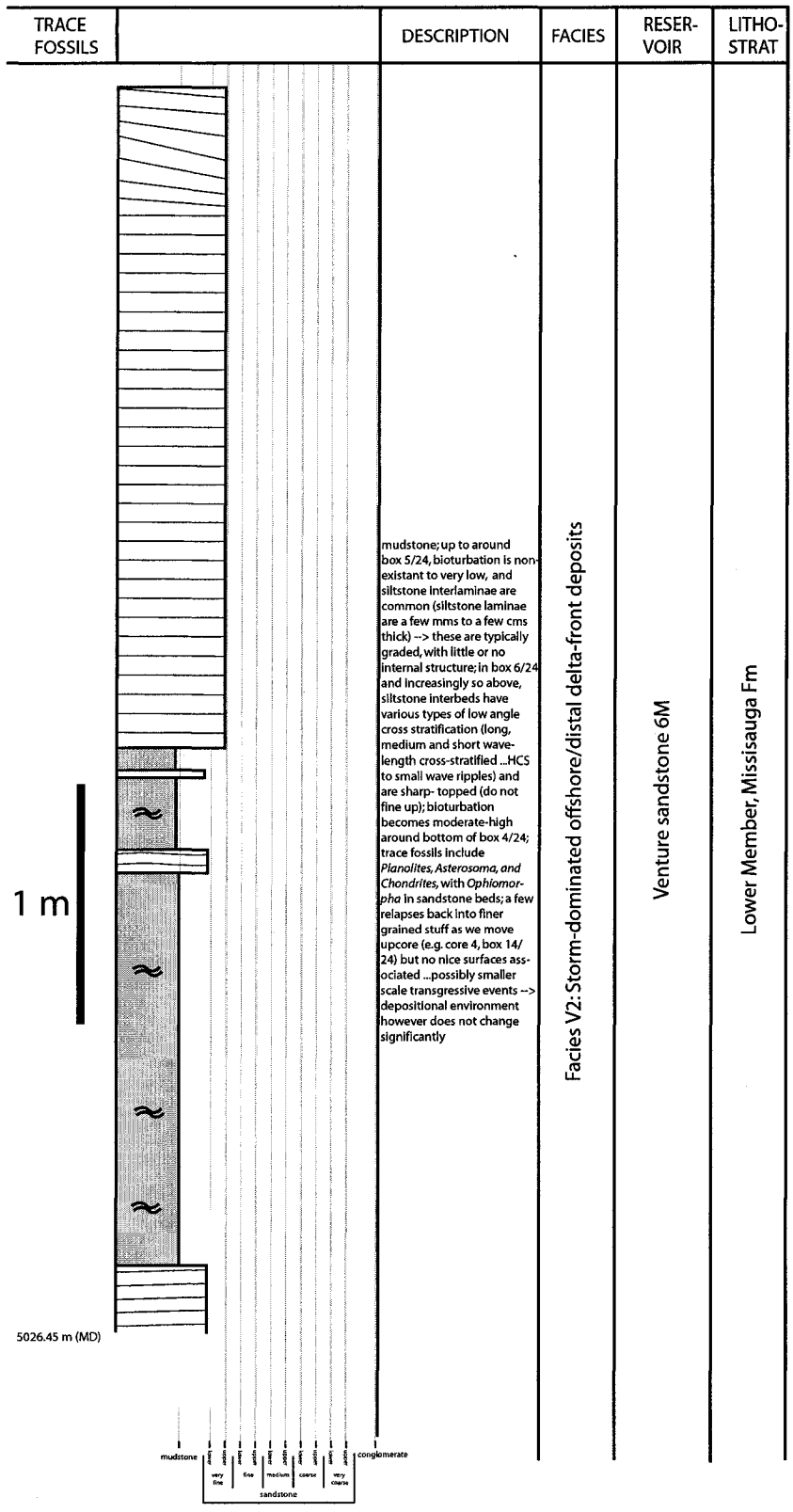
West Venture N-91
core 5
boxes 7/24 to 4/24



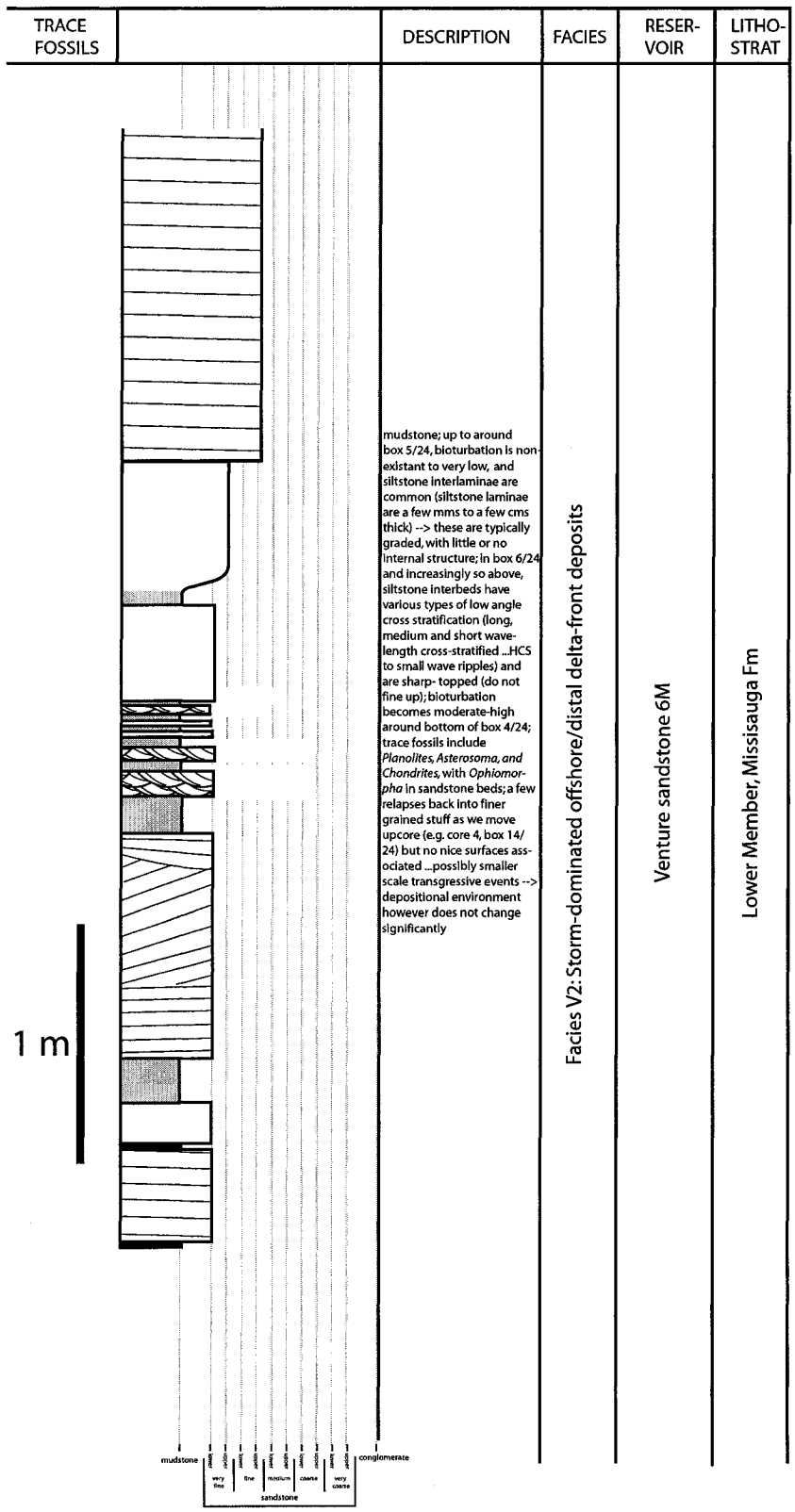
West Venture N-91
core 5
boxes 3/24 to 1/24



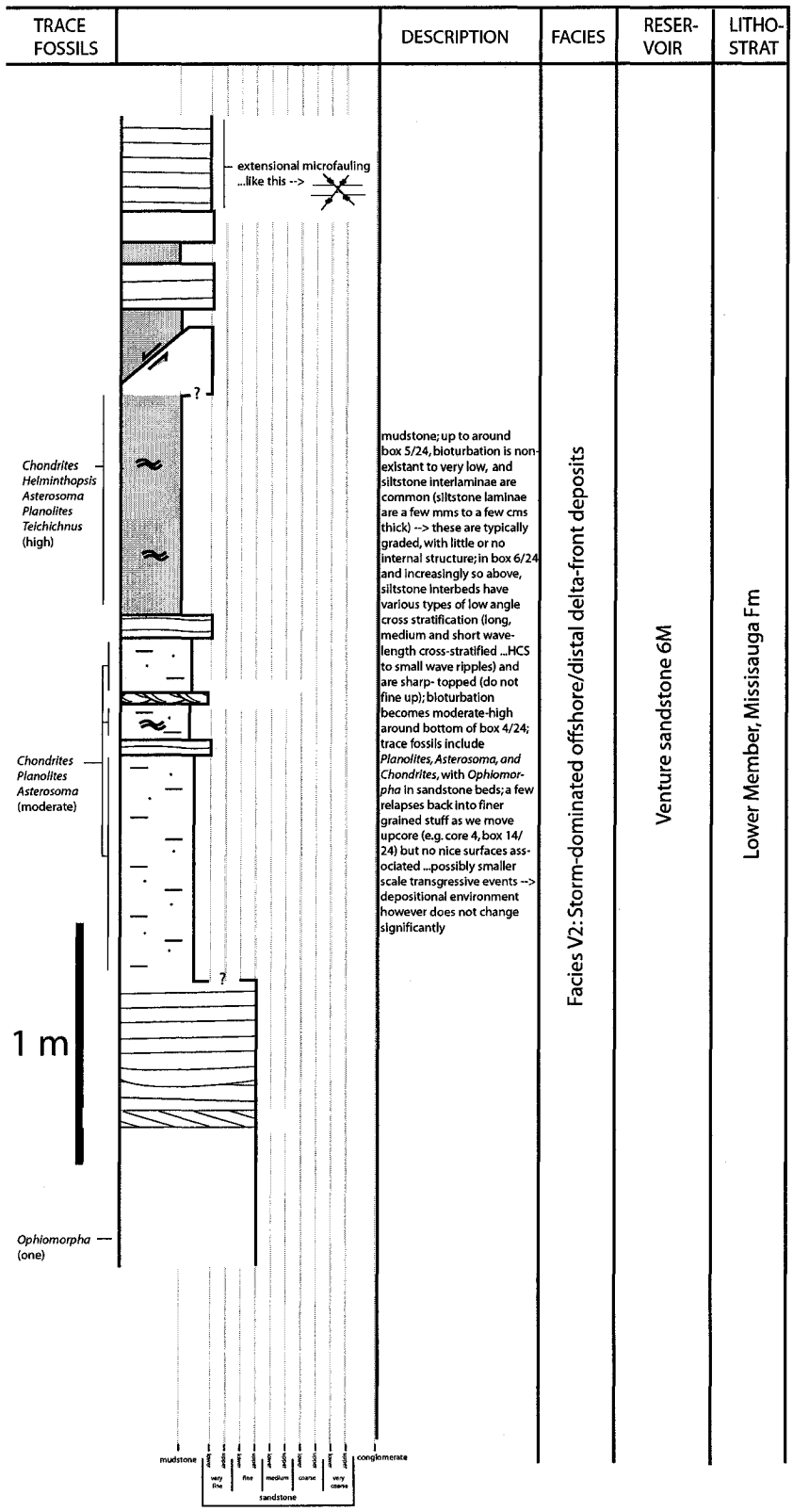
West Venture N-91
core 4
boxes 24/24 to 20/24

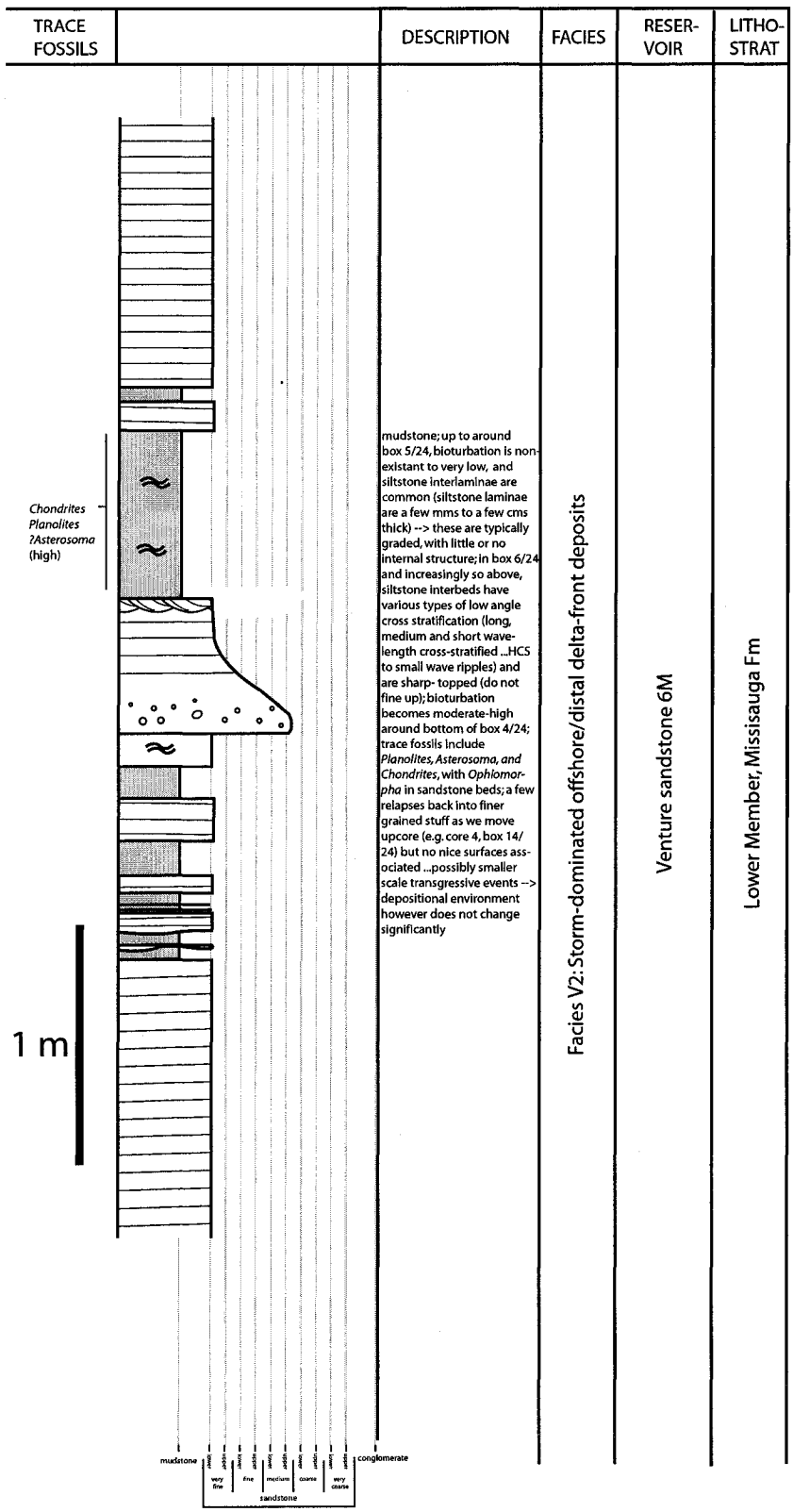


West Venture N-91
core 4
boxes 19/24 to 16/24



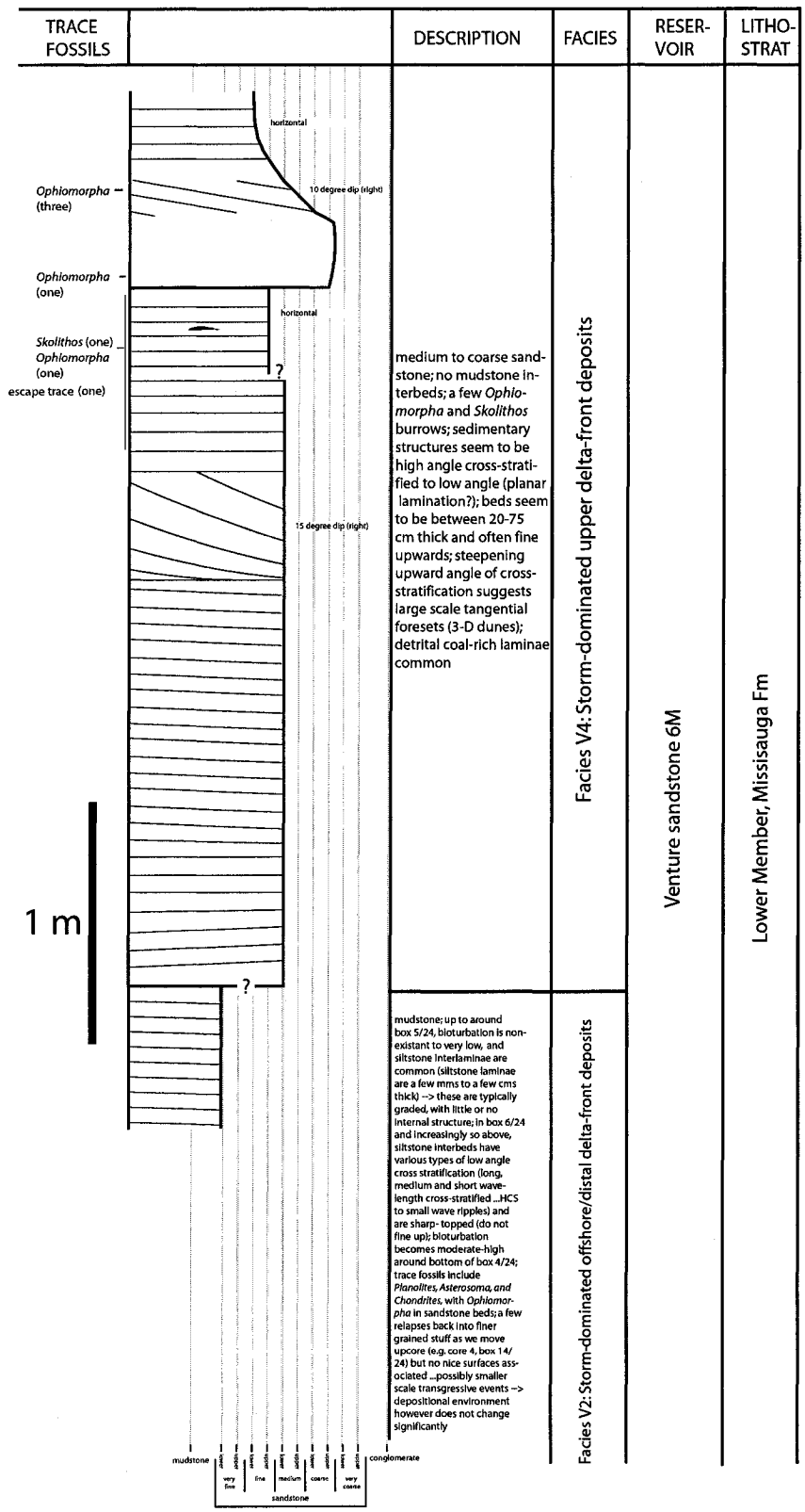
West Venture N-91
core 4
boxes 15/24 to 12/24



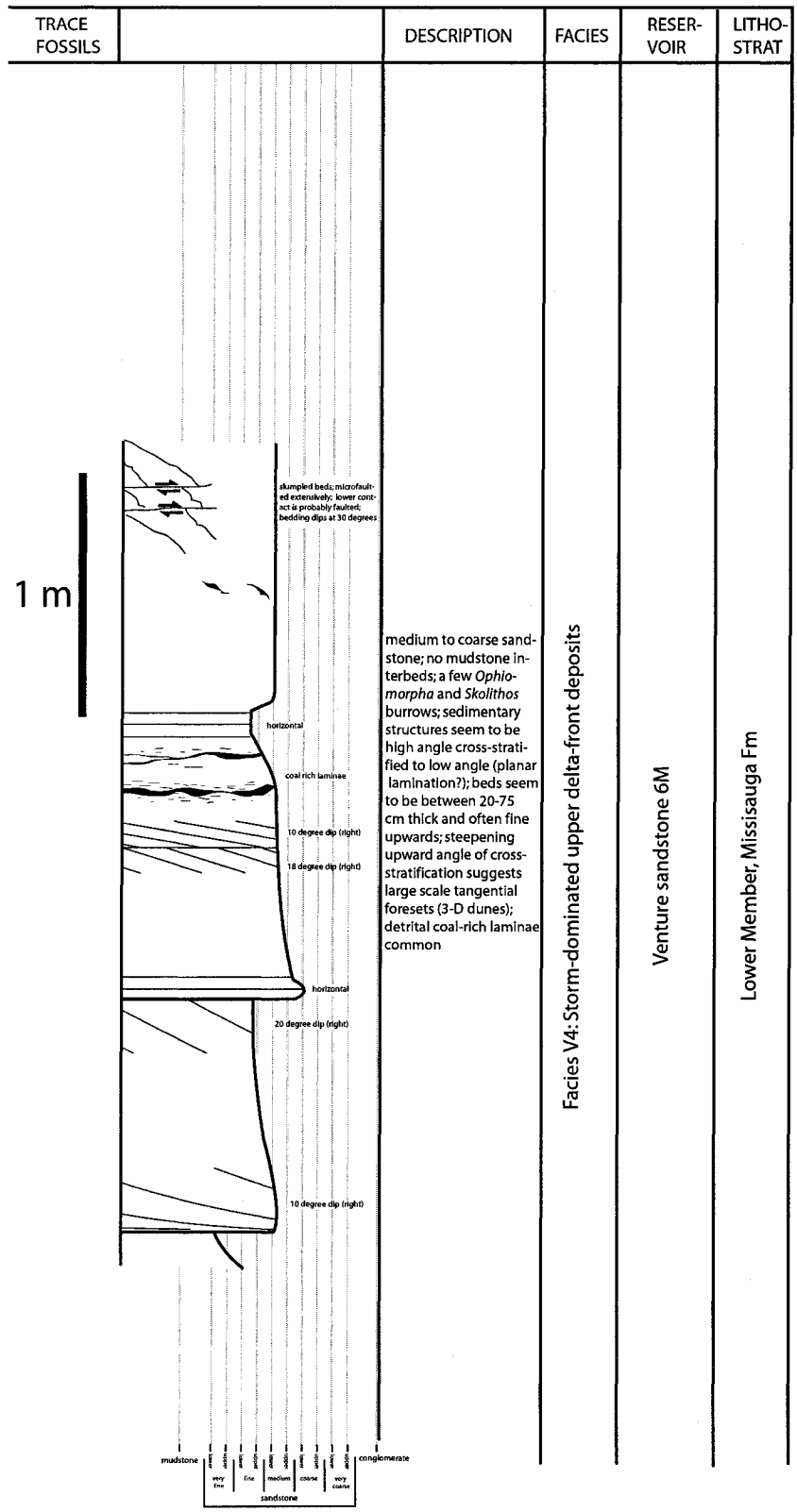


West Venture N-91
core 4
boxes 11/24 to 8/24

West Venture N-91
core 4
boxes7/24 to 4/24



West Venture N-91
core 4
boxes 3/24 to 1/24



APPENDIX 2: DETAILED FACIES ANALYSIS, GLENELG & ALMA FIELDS

Alma Field (Upper Missisauga) – Facies analysis

At Alma, the Missisauga sandstone package is relatively thin (~268 m; MacLean and Wade, 1993) and young (Barremian to Aptian; Lentin, 1987; late Hauterivian to Barremian, Jason Crux, personal communication, 2004), suggesting that sand did not reach Alma until the final stages of Missisauga shelf margin outbuilding (see Figure 5.14). Because of its age, the sandstone package at Alma is assumed correlative with the Upper Member of the Missisauga Formation, and is therefore referred to here as the "Upper Missisauga" (as opposed to "Missisauga"; see MacLean and Wade, 1993).

Core coverage of the Alma reservoirs is reasonably good (see Figure 5.14). Upper Missisauga sandstone at Alma is commonly intensely bioturbated. Upper Missisauga mudstone at Alma is typically rich in nannofossils (Gunnilla Gard, personal communication, 2001; Jason Crux, personal communication, 2004) and contains abundant disseminated organic matter and small shell fragments locally (gastropod, mollusc, scaphopod, echinoid, and ammonite). Soft-sediment deformation features are relatively common at Alma compared to more proximally located fields (*e.g.*, Panuke). Five facies have been identified from core, as described below (see also Appendix 1, table 1).

Alma facies A1. Mudstone

Facies A1 mudstone is commonly fissile and/or friable and is moderately rich in siderite nodules. Bioturbation is absent or very minimal, and includes *Teichichnus, Planolites, Asterosoma, Helminthopsis, Chondrites, Zoophycos, ?Arenicolites, Palaeophycus, Terebellina.* Where, present, burrows are commonly large. Cm-scale

shells and shell fragments (echinoid, gastropod, ammonite, bivalve) and disseminated organic matter are common on beddings surfaces. Microfaults are present locally. Thin (<1 mm), short (1 to 6 cm), light-coloured, vertical to subvertical "streaks" barren of organic particles are rarely present in particularly organic-rich intervals (they look like vertical "knife scratches" on the core; see p. 369). Although pipe-like in cross-section, the "streaks" are commonly sheet-like when viewed from above.

Interpretation. Offshore mudstone

Facies A1 is interpreted to be mudstone deposited in an open marine environment below storm-weather wave base. Specialized feeding traces such as *Zoophycos* and *Asterosoma* and presence of ammonite shells and echinoid plates suggest that fully marine conditions existed during deposition. Thin, vertical, organic-free sheet-like "streaks" are interpreted to be pillar structures formed by fluidization (*e.g.*, Druitt, 1995; Middleton *et al.*, 2003). (Pillar structures, despite their name, are commonly sheet-like; *cf.* Middleton *et al.*, 2003). The presence of pillar structures is suggests that of episodic rapid deposition of mud from suspension occurred.

Alma facies A2. Interbedded mudstone and very fine sandstone

Strata of Facies A2 gradationally overlie Facies A1, and consist of mudstone with rare to very common very fine sandstone beds that are on average <10 cm and at maximum 50 cm thick. Bioturbation in mudstone is generally low, and includes *Asterosoma, Planolites, Teichichnus, Zoophycos,* and *?Cylindrichnus*. Sandstone beds are typically planar laminated, low-angle (<10°) cross-stratified, or rarely small-scale (<5

cm) high-angle (>15°) cross-stratified. High-angle cross-sets are typically flat-based, overlie planar laminated sandstone, and climb at low angles (<5 degrees). Sandstone beds contain rare escape traces and *Ophiomorpha* burrows. Weakly to highly deformed heterolithic units several centimeters to several meters thick occur locally within Facies A2.

Interpretation: Storm-influenced lower shoreface (delta front?) deposits

Facies A2 is interpreted to have been deposited in an open marine, storm-influenced delta front (or possibly lower shoreface) between storm and fairweather wave base. Facies A2 is similar to storm-dominated lower shoreface deposits in adjacent fields such as Panuke in that it contains low-angle cross-stratified beds interpreted to be hummocky cross-stratified sandstone, whose presence suggests deposition under the influence of large, long-period storm waves (Southard *et al.*, 1990; Arnott and Southard, 1990). However, Facies A2 also contains planar laminated sandstone beds (<20 cm thick) that grade upwards into small-scale (<5 cm), climbing, high-angle cross-strata interpreted to be climbing current ripples. Planar laminated beds with overlying current ripples are interpreted to be turbidity current deposits (Bouma T_{bc} units) that evolved either from hyperpycnal river outflows (*e.g.*, Johnson *et al.*, 2001; Wright *et al.*, 2001), updip slope failures (*e.g.*, Piper *et al.*, 1988), or storm-generated sediment-laiden downwelling flows (*e.g.*, Morton, 1981). Deformed units are interpreted to be mass movement deposits. The presence of turbidite and mass movement deposits may be an indication of deposition onto a high-gradient seafloor near or basinward of the shelf edge,

because the low-gradient seafloor typical of continental shelves (<0.1°) theoretically hinders turbidity current ignition (Pantin, 1979, 1983; Parker, 1982).

Alma facies A3. Upward-coarsening sandstone

Facies A3 is only cored in one location (the A "sand" in Alma F-67). It consists of very fine to medium sandstone that coarsens upward. Bioturbation ranges from low to intense, and includes *Ophiomorpha Palaeophycus, Helminthopsis, Planolites, Skolithos, Teichichnus, Zoophycos, Asterosoma, ?Thalassinoides, ?Conichnus* and *?Diplocraterion.* Burrows are typically large and thick-walled. Wispy mud laminae (<3 mm) are common at spacings of ~5 to 50 cm. Bedding planes delineated by wispy mud laminae gradually increase upward in dip from 0° to ~25° (Fig. 12). Pore-filling patches of carbonate-cement between 10 and 300 cm are present locally. Where not obscured by bioturbation, sandstone beds are either planar laminated, low-angle (<10°) cross-stratified, or medium-scale (10-20 cm) high-angle cross-stratified. Facies A3 sandstone either gradationally or sharply overlies Facies A1 mudstone.

Interpretation: Unstressed shoreface deposits

Intense bioturbation and large, thick-walled burrows common to Facies A3 suggest deposition in a fully marine, ecologically-unstressed environment. Upward gradation from offshore mudstone (Facies A1) and the upward-coarsening trend suggests that energy increased during deposition, likely as a result of progressive shoaling. These features are consistent with deposition in an ecologically unstressed shoreface setting. However, although ripple and dune clinoforms commonly dip at 25°, shoreface and delta-

front clinoforms rarely dip more than 5°, even at the shelf margin (Porebski and Steel, 2003; Donnovan, 2003). Significant relief may have existed on the seafloor across the master Alma growth fault, which caused steeply-dipping Gilbert-style foresets to form[1]. (Note: Relief can be significant across growth faults that intersect the seafloor. For example, at the modern shelf-margin offshore of the Orinoco River delta, growth-fault scarps have up to ~45 m relief (Sydow *et al.*, 2003)). However, this interpretation must be considered preliminary until tested against additional data.

Alma facies A4. Poorly sorted sandstone

Strata of Facies A4 are always poorly-sorted and commonly contain small, isolated quartz sand grains and granules. (These resemble white "paint-speckles" on the core.) Bioturbation is typically intense, and includes *Ophiomorpha*, *Planolites*, *?Asterosoma*, *?Thalassinoides*, and *Helminthopsis*. Sedimentary structures are rarely preserved. The basal contact of Facies A4 is either sharp or bioturbated. Bivalve, scaphopod, and gastropod shell fragments are common. Facies A4 commonly reacts strongly to hydrochloric acid.

Interpretation: Wave-ravinement lag deposits

Facies A4 is interpreted to have formed by wave ravinement during shoreface retreat (*e.g.*, Fisher, 1961). Intense bioturbation and the high-diversity of traces suggest a fully marine environment. This facies, with its abundant "paint-speckles", strong reaction to hydrochloric acid, and common shell fragments, is arguably the most

[1] The A "sand", unlike the underlying B and C "sands", thins southwestward from Alma F-67 to Alma K-85, suggesting movement on the master Alma growth fault occurred during or prior to deposition of the Facies A3.

omnipresent and distinctive siliciclastic facies within the Missisauga Formation in the Sable Subbasin.

Alma facies A5: Upward-fining sandstone

Facies A5, which consists of poorly-sorted, muddy coarse to very fine sandstone, was only observed at one interval in Alma F-67 (the top of the A "sand"). Bedding is generally unidentifiable because of intense bioturbation, with large *Ophiomorpha* and *Palaeophycus* traces predominating (many traces are unidentifiable because of the intensity of bioturbation). Facies A5 forms a ~20 m-thick, upward-fining unit that overlies several decimeters of coarse sandstone interpreted to be transgressive lag (Facies A4). Dm- to m-thick patches of pore-filling carbonate cement are present locally. Shell fragments and isolated coarse quartz sand grains and granules ("paint-speckles" - maximum 3 mm) are abundant near the base, and decrease in abundance upward; they are not longer present ~10 m above the base of the unit. The level of bioturbation decreases in the top several meters of Facies A5. Here, bedding is visible, and sandstone beds are parallel laminated to low-angle (<10°) cross-laminated and contain thin mudstone interlaminae. Facies A5 grades upward into interbedded mudstone and very fine sandstone of the Naskapi Member interpreted to be inner shelf to lower shoreface deposits (Facies A2).

Interpretation: Transgressive shelf sandstone

Facies A5 is interpreted to have been deposited in a shallow marine shoreface environment during transgression and shoreface retreat. The high-density/high-diversity

Skolithos-type trace fossil suggests deposition in an unstressed, fully marine setting (*e.g.,* Pemberton *et al.*, 2002). The stratigraphic position of Facies A5 above sharp-based lag deposits (Facies A4) and below lower shoreface mudstone and sandstone (Facies A2) suggests deposition during transgressive shoreface retreat (*e.g.,* Fischer, 1961). Carbonate cementation and abundant shell fragments are features common in transgressive shelf sandstones (*e.g.,* Penland *et al.*, 1988; Snedden and Dalrymple, 1999; Molgat and Arnott, 2001; Posamentier, 2002).

Glenelg Field (Upper Missisauga) – Facies analysis

At Glenelg, the Missisauga Formation (*sensu* MacLean and Wade, 1993) forms a thick (up to 1.3 km), upward-coarsening succession that overlies monotonous Verrill Canyon shale, and is in turn overlain by ~80 to 300 m of Naskapi shale (see Figure 5.18). Cores partially sample the uppermost ~400 m of the Missisauga Formation. Biostratigraphic data indicate that this relatively sandstone-rich interval is Hauterivian to Barremian (Ascoli, 1990; MacLean and Wade, 1993), suggesting that sand arrived roughly coevally at Glenelg and Alma during the final stages of Missisauga shelf-margin outbuilding[2]. The O Marker, which is present at the base of the Upper Missisauga throughout the proximal Sable Subbasin, has a patchy distribution in the Glenelg wells (MacLean and Wade, 1993) and was not identifiable in seismic data (Welsink *et al.*, 1989; Wade, 1991; MacLean and Wade, 1993). Six facies have been identified from core, as described below (see also Appendix 1, table 2).

Glenelg facies G1: Mudstone with low-angle (<10°) cross-stratified sandstone interbeds and rare rhythmites

Facies G1 consists of mudstone with rare to common well-sorted very fine sandstone interbeds. Beds are organized into upward-coarsening units that are tens-of-meters thick. Bioturbation in mudstone is typically very low, with *Planolites*, *Teichichnus*, *Terebellina,* and *Asterosoma.* Sandstone interbeds contain rare *Ophiomorpha* burrows, are 1 to ~50 cm thick, and are typically horizontally-laminated or low-angle (<10°) wavy to planar cross-stratified with low-angle internal truncation surfaces locally. Sandstone beds are rarely normally graded, and are rarely capped by

[2] Sand located below the Upper Missisauga at Glenelg may be slope turbidite deposits – see later

one or more thin (<3 cm), scoop-based, high-angle (>15°) cross-sets interpreted to be small wave ripples (see Boersma, 1970; de Raaf *et al.*, 1977). Rarely, sandstone beds are composed of thin (<3 cm) flat-based high-angle (>15°) cross-sets interpreted to be current ripples. Sandstone beds are commonly deformed, and can be extensively sheared and "microfaulted". Disseminated organic particles are common. Internally, some of the sandstone and mudstone beds are rhythmically laminated.

Interpretation: Storm- and tide-influenced prodelta deposits

Facies G1 is interpreted to have been deposited in a gravitationally unstable prodelta environment that was influenced by both storm wave and tidal processes. Microfaults, thin sheared layers, and tilted beds suggest rotation and downslope translation of prodelta strata (*e.g.* Coleman and Prior, 1982). Current ripple cross-stratified sandstone and normally-graded horizontally-laminated sandstone beds are interpreted to be delta-front/prodelta turbidites. Storm wave influence is inferred based on the presence of sandstone beds which contain gently fanning laminae and low angle concave truncations, two features commonly associated with stratification formed by large, storm-generated hummocky bedforms (*e.g.* Campbell, 1967; Harms *et al.*, 1975; Southard *et al.*, 1990; Arnott and Southard, 1990; Dumas, 2004). Despite the apparent storm wave influence, rarely-observed mudstone-sandstone rhythmites imply that a cyclical forcing mechanism also episodically controlled sedimentation. Although repetitive mudstone-sandstone laminae are ubiquitous in the stratigraphic record and can form by many different mechanisms, the rhythmic nature and thickening-thinning trends exhibited by laminae in Facies G1 are most reasonably interpreted as being tidal in

origin. Although most commonly associated with tide-dominated fluvial and estuarine settings (*e.g.* Rahmani, 1988; Smith *et al.*, 1990; Dalrymple *et al.*, 1991; Li *et al.*, 2000), tidal rhythmites have also been observed to form in modern delta-front and prodelta settings (*e.g.* Jaeger and Nittrouer, 1995; Kuehl *et al.*, 1996).

Glenelg facies G2: Rhythmically interlaminated mudstone and sandstone

Facies G2 consists of rhythmically laminated intervals (maximum 2 m thick) that grade in and out of mudstone. Internally, the rhythmically laminated intervals consist of thin (<1 mm to ~1 cm), rhythmically alternating layers of mudstone and siltstone to lower fine sandstone. Rhythmic laminae typically form successions that thicken and thin progressively. Contacts between rhythmic sandstone and mudstone laminae are typically gradational. Also, although flat, rhythmic laminae typically dip between 1 to 15°. Rarely, the bases of sandstone laminae are loaded. Bioturbation is absent in Facies G2, and disseminated coal flecks are abundant. Athough the base of Facies G2 was not observed in core, log data suggests that Facies G2 gradationally overlies prodelta mudstone (Facies G1).

Interpretation: Tidal rhythmites (delta front?)

Facies G2 rhythmites are interpreted to be tidal in origin. The thickening and thinning of Facies G2 rhythmites, a commonly feature of tidal rhythmites, likely resulted from variation of the magnitude of daily tides (which are caused by the Earth rotating through high and low tides) over the course of a lunar month, in which the moon shifts from syzygy, where tide-raising forces are greatest (spring tides), to quadrature, where

tide raising forces are at a minimum (neap tides). Attempts to reconstruct the dominant governing tidal periodicity (*e.g.* Kvale *et al.*, 1998) have proven unsuccessful, likely due to the short length and sporadic distribution of rhythmically laminated intervals (maximum 42 mudstone-sandstone couplets in one rhythmically laminated interval).

Given the abundance of disseminated coal flecks, Facies G2 was likely deposited close to a terrestrial organic source in a coastal plain setting. Furthermore, given that the rhythmites commonly dip between 1 and 15°, it is likely that they were deposited by lateral point bar accretion, a process that is very common in channelized tide-dominated coastal environments (Dalrymple *et al.*, 2003)[3]. Also, lack of evidence of significant wave action suggests deposition in a relatively sheltered setting (Archer, 1998; Li et al, 2000). Taking all of these observations into consideration, Facies G2 might logically be interpreted as being a tide-influenced subtidal to intertidal fluvial point-bar (*e.g.*, Rahmani, 1988; Dalrymple *et al.*, 1991) or intertidal mud flat deposit (*e.g.* Dalrymple *et al.*, 1991). However, this seems improbable given the stratigraphic position of Facies G2, which, based on log data, appears to gradationally overlie tide-influenced prodelta mudstone (Facies G1) and is in turn erosively overlain by tide-influence fluvial deposits (Facies G3). Although more commonly observed in mudflat and tidally influenced fluvial deposits in modern depositional environments (an observational bias?), tidal rhythmites, as previously mentioned, have also been reported in prodeltaic and delta front deposits (*e.g.* Smith *et al.*, 1990; Williams, 1991; Jaeger and Nittrouer, 1995; Kuehl *et al.*, 1996; Miller and Eriksson, 1997). Furthermore, unlike wave-dominated environments, deep, submerged tidal channels and ridges commonly extend basinward of

[3] Although apparently absent, erosive basal channel contacts are perhaps simply cryptic mudstone on mudstone contacts, which can form if fluid muds accumulate in channel thalwegs (*e.g.* Dalrymple *et al.*, 2003).

the subaerial coastal plain onto tide-dominated delta fronts and shelves (*e.g.*, Dalrymple *et al.*, 2003; Allison *et al.*, 2003; Willis and Gabel, 2003). As such, Facies G2 rhythmites are interpreted to have been deposited in a sheltered, channelized, tide-dominated delta front setting.

Glenelg facies G3: High-angle (>15°) cross-stratified sandstone with thick mudstone interbeds and rare rhythmites

Facies G3 consists of thickly interbedded mudstone (~25%) and very coarse to medium grained, honey brown-coloured sandstone (~75%). Sandstone beds range in thickness from 1 to 70 cm (average ~20 cm) and are commonly composed of one or more high-angle (>15°) cross-sets. Rarely, bipolar cross-stratification is observed. Pebble-sized coal fragments and mudstone intraclasts are common in sandstone beds. Double mud-drapes are present locally. Rare *Skolithos*, *Diplocraterion* and *Ophiomorpha* burrows were observed. Coal flecks commonly highlight lamination in sandstone beds.

Mudstone beds are several centimeters to several decimeters thick. Bioturbation in mudstone is typically absent, although rare, small *Planolites* were observed. Pebble-sized coal clasts and thin, organic-rich laminae are common. Laminae composed of medium grained sandstone are present locally in mudstone beds. Rarely, mudstone and fine sandstone laminae form rhythmically layered intervals in which laminae progressively thicken and then thin. Strata of Facies G3 are commonly organized into sharp-based, upward-fining units that are 6 to 10 m thick. The level of bioturbation commonly increases near the top of upward-fining units.

Interpretation: Tidally influenced fluvial channel fills

Facies G3 is interpreted to be a strongly influenced both by fluvial and tidal currents. The presence of abundant disseminated coal debris suggests deposition close to a terrestrial organic source. High-angle (>15°) sandstone cross sets are interpreted to have been deposited by dune bedforms migrating and aggrading under unidirectional flow (*e.g.* Leclair and Bridge, 2001). Rhythmic stratification, bipolar cross stratification, and abundance of mudstone suggest deposition in a tidally influenced environment (Nio and Yang, 1991). Furthermore, low diversity trace fossil assemblage and presence of diminutive traces suggest that the depositional environment was stressed, and perhaps brackish (Pemberton *et al.*, 2002).

Sharp-based, upward-fining units indicate upward decreasing depositional energy, and are interpreted to be channel fill deposits. The upward increase in the level of bioturbation may suggest that marine incursion commonly accompanied the final stages of channel filling. Assuming that upward-fining units and dune cross-strata scale to flow depth (*e.g.*, Leclair and Bridge, 2001; Bridge and Tye, 2000), channels were likely ~6 to 10 m deep. This suggests that deposition occurred in larger tide-influenced distributary channels (*e.g.*, Gastaldo, 1995; Dalrymple *et al.*, 2003) as opposed to small tidal channels that drain tidal flats (*e.g.*, Barwis, 1978; Fenies, and Faugères, 1998). Also, given the abundance of thick mudstone beds, some of which are interbedded with the coarsest sandstone at the base of upward-fining units, it is possible (likely?) that fluid muds may have resided alongside coarse sand patches at the base of channels (*e.g.*, Dalrymple *et al.*, 2003; Dalrymple and Choi, 2003). (Arguably, this facies could be referred to as fluvially influenced tidal channel deposits).

Glenelg facies G4: Upward-fining mudstone with thin rooted coal beds

Facies G4 consists of organic-rich mudstone with thin (<25 cm) rooted coal layers. Bioturbation increases upwards. Trace fossils were difficult to identify, but *Teichichnus* burrows were observed locally. Mudstone containing oyster shells is present above a rooted in one upward-fining succession observed. Facies G4 gradationally overlies interbedded mudstone and sandstone interpreted to be tidally influenced fluvial deposits (Facies G3) or low-angle cross-stratified sandstone interpreted to be upper shoreface/beach deposits (Facies G6 – see below).

Interpretation: Transgressive abandonment deposits

Strata of Facies G4 are interpreted to have been deposited in a lagoonal to marsh environments during transgressive abandonment of either tidally influenced coastal plain channels (Facies G3) or wave-dominated strandplains (Facies G5). Together, the upward increase in mudstone, bioturbation, and shell content is suggestive of progressive inundation.

Glenelg facies G5: Sharp-based sandstone with Ophiomorpha burrows

Facies G5 is composed of moderately-sorted to moderately-well sorted brownish coarse sandstone. *Ophiomorpha* burrows, although rare, occur throughout. Stratification is typically not visible, although rare, high-angle (>15°) cross-sets (~15 cm thick) are visible locally. Several pebble-sized coal clasts are present. Facies G5 erosively overlies organic-rich mudstone (Facies G4).

Interpretation: Tidal inlet fill?

Based primarily on its stratigraphic position above coastal plain deposits (Facies G4) and below marine deposits (Facies G6), Facies G5 is interpreted to be a tidal inlet fill. The sharp-base, evidence of marine influence (*Ophiomorpha* burrows), and rare unidirectional current indicators (high-angle dune cross-strata) are consistent with this interpretation.

Glenelg facies G6: Upward-coarsening mudstone with low-angle (<10°) cross-stratified sandstone interbeds

Strata of Facies G6 form upward-coarsening units that pass upwards from mudstone with rare to common low-angle (<10°) cross stratified very fine sandstone interbeds into well-sorted low-angle cross-stratified fine sandstone with rare high-angle (>15°) cross-stratified beds. Bioturbation in mudstone is typically low, with *Planolites*, *Asterosoma*, *Zoophycos*, *Teichichnus*, *Terebellina,* and *Rosselia.* Rare *Ophiomorpha, Cylindrichnus Chondrites* and *Palaeophycus* burrows are present in sandstone. Facies G7 overlies poorly sorted sandstone interpreted to be transgressive lag (Facies G6).

Interpretation: Storm-dominated shoreface and offshore deposits

Facies G6 is interpreted to have been deposited in a storm-dominated shoreface environment. Mudstone-rich portions of Facies G6 are very similar to Facies G1 prodelta deposits, but lack rhythmically laminated zones. Low angle (<10°) cross stratification in sandstone interbeds is interpreted to be hummocky cross-stratification formed under the influence of large, long-period storm waves (*e.g.*, Southard *et al.*, 1990; Arnott and

Southard, 1990; Dumas, 2004). Because long-period waves require sufficient distance (fetch), depth, and travel time to form (Barnett and Wilkerson, 1967), the presence of hummocky cross-stratification suggests that Facies G6 was deposited in a large and unrestricted basin. Mudstone at the base of upward-coarsening units, which contains hummocky cross-stratified fine sandstone interbeds, is interpreted to have been deposited in a lower shoreface to offshore setting. High-angle cross-stratification present near the top of some of the upward-coarsening units is interpreted to have been deposited either by asymmetric wave ripples or unidirectional-dominated dunes in the upper shoreface.

Glenelg facies G7: Poorly sorted, sharp-based sandstone

Facies G7 forms thin units (<1 m) composed of poorly sorted, white-coloured sandstone. Bioturbation is locally intense, and *Ophiomorpha* burrows are typically predominant. Sedimentary structures are typically not visible. Coal debris and oyster shell fragments are common, and the facies commonly reacts strongly with dilute hydrochloric acid. Isolated, white-coloured quartz coarse sand grains and granules ("paint-speckles") occur throughout. Typically, Facies G7 erosively overlies organic-rich mudstone interpreted to be coastal plain deposits (Facies G4). Unlined, sandstone-filled *Thalassinoides* commonly penetrate down from Facies G4 into underlying organic-rich mudstone.

Interpretation: Transgressive lag deposits

Facies G7 is interpreted to have formed by wave reworking of the shallow seafloor during relative sea-level rise and shoreface retreat (*e.g.*, Fischer, 1961; Demarest

and Kraft, 1987; Bhattacharya, 1993; Abbott, 1998; Snedden and Dalrymple, 1999; Hwang and Heller, 2002; Cattaneo and Steel, 2002). Burrowed mud firmground surfaces, which commonly occur at the base of Facies G7, are interpreted to be transgressive wave ravinement surfaces formed by the landward passage of the high-energy shoreface overtop of the coastal plain. Transgressive ravinement commonly erodes thick successions of previously deposited sediment (*e.g.*, 10-20 m), exhumes mud firmgrounds, and then abruptly superimposes shallow marine sandstone on coastal plain deposits (Fischer, 1961; Suter and Berryhill, 1985; Demarest and Kraft, 1987; Bhattacharya, 1993; Abbott, 1998; Snedden and Dalrymple, 1999; Hwang and Heller, 2002; Pemberton *et al.*, 2002; Cattaneo and Steel, 2002).