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Preface

This Open File results from collaborative work between Saint Mary's University and the Geological Survey of Canada, funded by the Nova Scotia Offshore Energy Technical Research Association (OETR) as part of the Play Fairway Analysis. From new sedimentological logging of conventional core carried out under this program, this report examines the evidence for the lateral continuity of individual lithofacies from two areas with closely spaced cored wells: the Panuke and Venture fields.

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ABSTRACT

Gamma logs and conventional core have been correlated in Upper Jurassic–Lower Cretaceous deltaic successions from closely spaced wells in two areas of the Scotian Basin: around the Panuke and Cohasset fields, and the West Venture-Venture fields. In the Panuke-Cohasset area, the Como P-21, Panuke B-90, Cohasset A-52, Balmoral M-32, and Lawrence D-14 wells, located 3–8 km apart, have been correlated in the upper part of the Missisauga Formation and the Cree Member of the Logan Canyon Formation. In the West Venture-Venture area, the West Olympia O-51, West Venture N-91, West Venture C-62, Venture B-52, and Venture H-22 wells, located 2.5 to 11.5 km apart, have been correlated in the Lower Member of the Missisauga Formation.

This precise correlation of cores is provided by lithologically similar transgressive surfaces in the form of shelf lag deposits or coals. In both areas, they make effective benchmarks with which to correlate equivalent packages above and below these surfaces, but some transgressive surfaces are of limited extent, and may represent delta progradation and subsequent distributary switching rather than regional changes in sea level. Further correlation indicates that major sandstone packets are laterally correlative (15 km in the Panuke–Cohasset area, and up to 27 km in the West Venture–Venture area), but commonly show lateral changes in lithofacies. For example, at the top of the Missisauga Formation tidal channel sandstones bioturbated by *Ophiomorpha* at Panuke B-90 pass laterally into thin-bedded by-passing river-mouth turbidites at Cohasset A-52 and thicker bedded delta-front turbidites at Lawrence D-14, over a distance of 15 km. In the Venture Field, lateral continuity is determined by the margins of incised valleys, however continuous sandstone packages that overly the valleys can be correlated up to 27 km, implying that reservoir connectivity may not be limited by the incised valleys. The application of a standard lithofacies scheme in well correlation provided useful information about reservoir shape and conductivity.

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1.0 Introduction and purpose

On land, lateral correlation of rocks in outcrop is fairly straightforward when long continuous sections of rocks are visible. Correlation between offshore wells is more challenging, as each well yields a vertical slice of limited width through the stratigraphy. Well correlation at a regional scale is based on major basin-wide changes in sediment type controlled by regional sea level changes. Physical rock samples are limited to select intervals of conventional core, typically taken in potential reservoir rock. Core provides detail about depositional environment and reservoir quality not captured at a regional scale and are the fundamental source of data used for reservoir characterization.

In order to compare overlapping core intervals in adjacent wells, core samples can be classified into lithofacies using lithology, sedimentary and biogenic structures. These descriptive facies represent different depositional environments. Lithofacies are used to correlate between adjacent wells and investigate how the paleoenvironment changes laterally.

The purpose of this study is (a) to validate lithofacies interpretations based on sedimentological character and vertical succession (Gould et al., 2010b) by defining the lateral variability of such facies between wells spaced several kilometres apart and (b) to evaluate lateral reservoir extent and connectivity based on correlation between wells of lithofacies in conventional core.

2.0 Study area

The Scotian Basin is a Mesozoic–Cenozoic passive margin basin on the continental margin off Nova Scotia and southwestern Newfoundland (Wade and MacLean, 1990) (Fig. 1). It was formed during the rifting of Pangaea and the opening of the North Atlantic Ocean. The Late Jurassic–Early Cretaceous sand-prone Missisauga and Logan Canyon formations host all the gas reservoirs of the Sable Offshore Energy Project. Detailed stratigraphic nomenclature is summarized by Wade and MacLean (1990).

Two areas of the Scotian Basin have been selected with relatively continuous and overlapping core intervals across several adjacent wells for this study: the Panuke-Cohasset area and the West Venture- Venture area (Fig. 1).

The Panuke-Cohasset area is located 32 to 55 km west of Sable Island (Fig. 1) and contains (from southwest to northeast) the Como P-21, Panuke B-90, Cohasset A-52, Balmoral M-32, and Lawrence D-14 wells, located 3–8 km apart (Fig. 2). Cohasset A-52 and Panuke B-90 have core through the Upper Member of the Missisauga Formation, and the Cree and Naskapi members of the Logan Canyon Formation. Lawrence D-14 and Como P-21 have core in the Upper Member of the Missisauga Formation. Balmoral M-32 has one core in the Cree Member of the Logan Canyon Formation (Fig. 2).

The West Venture-Venture area is 8 to 14 km northeast of Sable Island. It includes (from west to east) the West Olympia O-51, West Venture N-91, West Venture C-62, Venture B-52, and Venture H-22 wells, located 2.5 to 11.5 km apart. Cores through the Lower Member of the Missisauga Formation sample a nearly continuous section at the base of the Missisauga Formation.

3.0 Previous work

3.1 Panuke-Cohasset area

A study by Cummings et al. (2006) focused on a section in the Panuke B-90 well through the top of the Missisauga Formation into the base of the Logan Canyon Formation. Using core samples, well logs, and seismic data, they interpreted the succession as representing a fluvial to marine transition. They focused specifically on the sedimentology of two Panuke reservoir sandstones: the P2 and P3 sandstones, located at the top of the Missisauga Formation, and interpreted them to be shallow marine sandstones that accumulated during transgression (Fig. 3).

3.2 West Venture-Venture area

Cummings and Arnott (2005) interpreted the depositional environments of “Industry Sandstones 8-5” (Mobil Oil, 1983, 1984, 195a, 1985b, 1986) in the lower Missisauga Formation at the West Venture-Venture fields as being an example of a shelf margin delta. They presented a cross section though the Lower Member of the Missisauga Formation showing upward coarsening parasequences, locally cut by channel-form units filled with strongly tidally-influenced estuarine deposits (Fig. 4).

3.3 Lithofacies and parasequences

The lithofacies scheme used in this study (Table 1) was that proposed by Gould et al., (2010b). In this classification system, lithofacies are defined on the basis of the general environmental interpretation and are further subdivided into subfacies to discriminate between different rocks within the same depositional environment.

Lithofacies are organized into three principal types of parasequence: prodelta, shoreface and tidal (Gould et al. 2010b). Overlying transgressive units generally comprise carbonate cemented (usually sideritic) muddy, shelly sandstones and limestones. Tidal parasequences may have a thin unit of supratidal coal or lagoon sediments underlying the trangressive unit.

4.0 Methods

Wireline gamma ray log data was obtained from the Canada Nova Scotia Offshore Petroleum Board's Geoscience Research Centre and from data held under licence by the Geological Survey of Canada (Atlantic). A regional correlation was performed for each area using wireline gamma ray logs to determine overlapping cored intervals. Major stratigraphic picks from MacLean and Wade (1993) were used as a framework for correlation at a regional scale. At a detailed scale, the greatest reliance was placed on correlation of two sedimentary settings. Major transgressive surfaces at the top of parasequences, recognised by an abrupt increase to very high and commonly uniform gamma values, were assumed to be of regional extent. Thick sand packets were also assumed to be laterally correlative. In both cases, care was needed because Cummings and Arnott (2005) have shown that incised paleovalleys may limit the lateral extent of both sandy units and thick fill by tidal muds.

Fifty-seven conventional cores were logged at the Canada Nova Scotia Offshore Petroleum Board's Geoscience Research Centre. Lithofacies were determined using lithology, sedimentary and biogenic structures. Descriptive logs of the Venture B-52 and Venture H-22 wells were produced concurrently with the Gould et al. (2010b) lithofacies study and therefore have been reproduced from that open file. The interpreted lithofacies and depositional environments were used to compare thickness and extent of correlated packages in overlapping cored intervals as well as any changes in depositional environments. Core log summaries showing lithology and sedimentary facies, as well as sample locations and detailed photos locations, and samples for geochemistry and petrography (not used in this study) can be found in Appendix 1.

5.0 Results

5.1 Panuke-Cohasset area

5.1.1 Regional gamma correlation

Many blocky sandstone packages and parasequences can be correlated across the five wells through the Logan Canyon and Missisauga formations (Fig. 2). Confident gamma correlations include a prominent blocky sandstone in the middle of the Upper Member of the Missisauga Formation, the increase to high and uniform gamma at the base of the Naskapi Member of the Logan Canyon Formation, an abrupt change from high to low gamma values at the top Naskapi Member of the Logan Canyon Formation, and similarly stacked funnel, bow, and blocky-shaped gamma packages through the Cree Member of the Logan Canyon Formation (red boxes, Fig. 2).

This regional correlation was used to determine overlapping cored intervals as follows: 1) At the top of the Missisauga to base Logan Canyon Formations: Como P-21 core 1, Panuke B-90 cores 6-8, Cohasset A-52 cores 20-22, and Lawrence D-14 cores 1-2; 2) at the base Cree Member, Logan Canyon Formation: Panuke B-90 cores 1-3 and Cohasset A-52 cores 13-18; and 3) in the middle of the Cree Member, Logan Canyon Formation: Cohasset A-52 cores 10-11 and Balmoral M-32 core 1.

The top of the Missisauga Formation - base Logan Canyon Formation contact is marked by an abrupt lithological change from sandstone to a dominantly shale unit (MacLean and Wade, 1993). This is reflected in the wireline gamma logs by sharp increase in values, and a change in gamma character from serrated and funnel shaped to more consistently high values. The widespread, regional pick for contact across the Panuke-Cohasset area by MacLean and Wade (1993) is reasonable, however in the Como P-21 and Panuke B-90 wells, the pick is complicated by the serrated character of the gamma logs, seen as interbedded shale and sandstone near the contact (Fig. 2). At a detailed scale, an eight metre thick section of lower gamma ray values (blocky in shape in Panuke B-90 and Lawrence D-14, funnel-shaped in Cohasset A-52) is present just below a thick section of high values (Fig. 5). In Cohasset A-52 and Lawrence D-14 this change was picked as the Upper Missisauga Member-Naskapi Member by MacLean and Wade (1993), however in Panuke B-90 and Como-P-21 the contact was picked 30 m and 11 m shallower, respectively. There is a well-defined sharp negative peak seen across all wells within the Naskapi Member. This point was used in Como P-21 as the base Naskapi Member pick, however the gamma character above and below it match those seen in the lower part of the Naskapi Member of the other wells. Based on detailed gamma logs and subsequent core data, we revised Missisauga-Logan Canyon Formation pick in Como P-21 and Panuke B-90 wells.

5.1.2 Top Missisauga Formation-Base Logan Canyon Formation

The deepest cored interval in this section is within Panuke B-90 and Lawrence D-14, where a thick unit of muddy shoreface deposits can be correlated (Fig. 5). Above this unit, the section shallows to muddy tidal flat deposits (Figs. 6B-1, 6B-2, 6B-3) with sandstone beds. In Como P-21 the sandstone beds are thicker and fluvial in origin (Fig. 6A-1), in Panuke B-90 and Lawrence D-14 the beds are thinner, and are interpreted as tidal channel deposits (Figs. 6A-2 and 6A-3). A thin transgressive unit of brown, shelly mudstone is present in Como P-21 and Panuke B-90 (Figs. 6C-1 and 6C-2), but is not seen in Lawrence D-14. Four metres higher is a thicker trangressive unit of completely bioturbated, shelly sandstone, muddier in Como P-21 and Panuke B-90 (Figs 6D-1 and 6D-2) and sandier in Lawrence D-14 (Figs 6D-3). Above this transgressive unit, there is a brief deepening and then the section returns to muddy tidal flat deposits with a similar oyster shell bed present in Como P-21 and Panuke B-90 (Figs 6E-1, 6E-2).

The top of the section thickens in Panuke B-90, Cohasset A-52, and Lawrence D-14. A thick sandstone package, just below the base of the Naskapi Member, varies in depositional environment from tidal estuary in Panuke B-90 (Fig 6F-1), shoreface and river-mouth turbidites in Cohasset A-52 (Fig. 6F-2), and a thick unit of turbidites in Lawrence D-14 (Fig. 6F-3). This sandstone package is absent in Como P-21.

The base of the Naskapi Member of the Logan Canyon Formation interpreted by MacLean and Wade (1993) was revised in Como P-21, Panuke B-90 and Cohasset A-52 based on the previously described gamma ray log character, a transgressive surface seen in core, and a major lithology change from mud to sand. The transgressive surface is seen in Como P-21 (Fig. 6G-1), Panuke B-90 (Fig. 6G-2), and Cohasset A-52 (Fig. 6G-3); it is just above the cored interval in Lawrence D-14.

5.1.3 Base Cree Member, Logan Canyon Formation

The lower part of the Cree Member shows good correlation between Panuke B-90 and Cohasset A-52 wells through a set of repeating prodelta parasequences, with Cohasset A-52 being sandier overall (Fig. 7). Similar shelly beds and intraclast conglomerates are found in both wells indicating transgressive surfaces, in combination with gamma and facies assemblages relatively easy to correlate.

At the base of the Cree Member, the Cohasset A-52 well has a blocky gamma character, while Panuke B-90 shows a more cleaning upward trend (Fig. 7). Lithofacies differ from with prodelta sandstones and mudstones in Panuke B-90 (Fig. 8A-1), to more proximal thick river-mouth turbidite sandstones in Cohasset A-52 (Fig. 8A-2). This parasequence is capped in both wells by a sideritic, intraclast conglomerate (Fig. 8B-1, 8B-2).

Upsection are distal mudstones, partially cored in both wells. The sequence begins to shallow and both wells sample fluvial to fluvial estuarine sandstones (Fig. 8C-1, 8C-2). The top of the parasequence in both wells is marked by a similar bed of oyster and possible trigonid shells (Fig. 8D-1, 8D-2). The shell bed is overlain in both wells by a thick transgressive unit of highly bioturbated sandstone with medium to coarse-grained sand and some shell fragments (Fig. 8E-1, 8E-2).

5.1.4 Middle of the Cree Member, Logan Canyon Formation

There is limited core overlap in the middle of the Cree Member, between Cohasset A-52 and Balmoral M-32 (Fig. 9). Lower in the section, both wells have muddy tidal flat deposits (Fig. 10A-1, 10A-2). Above this, a package of transgressive sediments overlain by shoreface deposits in Balmoral M-32 (Fig. 10B-1, 10C-2) is not seen in Cohasset A-52, where the equivalent package is tidal estuarine sandstones (Fig. 10C-1). Based on the facies succession, Balmoral M-32 seems more distal than Cohasset A-52 and the transgressive package thus seems to have been of limited extent.

5.2 West Venture-Venture Area

5.2.1 Regional gamma correlation

An initial correlation between wells was made using a common set of industry sand packages picked by the operator (Mobil Oil Canada Ltd. 1983, 1984, 1985a, 1985b, 1986) (Fig.

11). In general, we were in agreement with these packages at a regional scale, however at a detailed scale it became apparent that in places these sands were not always equivalent (e.g., Sands 6 and 7, as discussed below). For this study we focused on the relatively continuously cored section at the base of the Missisauga Formation: Cores 2-6 in West Olympia O-51, cores 4-9 in West Venture N-91, cores 5-12 in West Venture C-62, cores 4-5 in Venture B-52, and cores 3-7 in Venture H-22.

5.2.2 Detailed correlations

Through industry sands 8-6, major parasquences have been identified and correlated across the five wells (Fig. 12). For descriptive purposes, they have been named Units A-D from deepest to shallowest. Discontinuous core samples through Venture B-52 limit correlation through this well and the gamma log is used in places. A fault near base of section has removed the lower part of the Missisauga Formation from this well. West Olympia O-51 correlates poorly into the section, perhaps because of its greater distance (11.5 km).

Unit A: Near base of cored section, above the base of the Missisauga Formation, a distinctive coal bed in the West Venture wells marks the top of a parasequence (Fig. 13B-1, 13B-2, 13C-1). The corresponding unit in Venture H-22 is seen as a laminated mudstone within sandstone facies 4g (Fig. 13B-3). The equivalent package in West Olympia O-51 is represented by muddy slump deposits more than 25 m thick (Fig. 13A-1). Slumped units of such thickness are likely present only on a delta front or in deeper water. This section is missing from Venture B-52 section because of a fault.

Unit B: Unit B is very similar to Unit A in facies succession: shoreface deposits passing up from distal to proximal turbidites and capped with tidally influenced fluvial sandstones. A coal bed marks the top of the parasequence in the West Venture wells (Fig. 13D-1, 13D-2) and is absent in Venture H-22, however an overlying bioturbated trangressive unit in West Venture C-62 (Fig. 13E-1) is also present in Venture H-22 (Fig. 13E-2).

Unit C: Facies remain dominantly prodeltaic in West Venture N-91, the gamma log showing a “cleaning upward” pattern similar to that seen in Units A and B (Fig. 12). The corresponding intervals in West Venture C-62 and Venture H-22 lack the thick fluvial sandstone present in West Venture N-91, instead having a mix of shoreface sediments and prodelta turbidites (Fig. 12). Our gamma correlation through Unit C is in disagreement with industry sandstone correlation through top of Sand 7 and base of Sand 6. The gamma log is bow-shaped through Sand 7-U in the West Olympia O-51, West Venture C-62, Venture B-52, Venture H-22 wells. This shape is not seen in West Venture N-91 well, where the log is funnel-shaped (cleaning upward trend). At the top of this section the gamma values sharply increase and is marked by a transgressive surface in all cores (Figs. 13F-1, 13F-2, 13F-3). The core shows a change from sandstone-dominated proximal facies, to mudstone-dominated distal facies. This re-interpretation means that Sand 7-U and 6-L in West Venture N-91 correlate with Sand 7-U in West Venture C-62, Venture B-52, Venture H-22, and the top of Sand 7 in West Olympia O-51 (where no 7-U was picked).

Unit D: Approaching the top of the cored section, lithofacies become tidally dominated in West Venture C-62 and Venture B-52 (Fig. 13G-2), but remain prodeltaic in West Venture N-91 and Venture H-22 (Fig. 13G-1). Delta-front turbidites in industry sand 6 are overlain by estuarine-tidal flat facies in West Venture C-62 and Venture B-52 (Fig. 13H-2, 13H-3, 13I-1, 13I-2), but in West Olympia O-51, West Venture N-91 and Venture H-22 are overlain by more distal prodelta sands and muds, (Fig. 13H-1, 13H-4) suggesting delta lobe switching. The top of this parasequence is marked by a thick package of river-mouth turbidites overlain by fluvial to tidal estuarine sandstones (Figs. 13J-1, 13J-2, 13J-3, 13J-4). This section is uncored in Venture B-52. Similar to Unit C, the industry sand correlation differs from our interpretation. At the base, a blocky-shaped unit of high gamma values is seen in all wells, seen as mud-dominated shoreface to distal turbidites facies. Above this, the gamma becomes more serrated in West Venture N-91 and Venture H-22, and the core shows a mix of sandstone and mudstone lithologies. In West Venture C-62 and Venture H-22, the gamma is consistently low and the core shows river-mouth turbidites becoming estuarine sandstones upsection in core at West Venture C-62. This indicates that Sand 6-M in West Venture N-91 correlates with Sand 6-L in West Venture C-62 and Venture N-91. The tidally-dominated facies succession in West Venture C-62 and Venture B-52 (Sand 6-M and base Sand 6-U) is absent from the other wells. Sand 6-U seems to convincingly correlate across the section.

It should also be noted that because incised valley deposits were given the same industry sand numbers as neighbouring wells, the correlation of these sands through the incised valley-fill sections appears incorrect, which may explain some of the problems using the reservoir sand packages in the initial correlation.

5.2.3 Interpretation of facies successions

The West Venture–Venture section represents repeating vertical successions of mainly prodelta parasquences marked at the top by bioturbated transgressive surfaces or coal beds (seen in West Venture wells). Near the top of the section, tidal parasequence are present in West Venture C-62 and Venture B-52, but are absent in other wells where sequences remain prodeltaic in facies association.

In general most facies assemblages, specifically many sandstone packages, correlate through the 15 km length of the section through the West Venture and Venture fields, however 12 km away at West Olympia the correlation is less clear in the deeper units. The sandstone package at the top of industry sand 6 (Unit D) can be traced across the whole section (27 km)/

6.0 Discussion

6.1 Panuke Cohasset area

Generally, facies in the Panuke–Cohasset area vary from proximal to distal from west to east. Paleoflow directions in fluvial sandstones in the Upper Member of the Missisauga Formation were interpreted to be southwest from architecture of 3-D slices, whereas an incised channel near the top of the Missisauga Formation trends to the southeast (Cummings et al., 2006). River-mouth turbidite sand complexes correlated between wells have lateral dimensions of 15 km in the Como–Panuke–Cohasset–Lawrence transect. This transect is likely almost perpendicular to the regional progradation direction to the south-southeast. The transition at the top of the Missisauga Formation from tidal estuary at Panuke to shoreface and river-mouth turbidites in Cohasset A-52 to thick unit of turbidites in Lawrence D-14 is consistent with the transect being sub-parallel to local paleoflow direction, as is the deeper change from fluvial sandstones at Como P-21 to tidal estuary at Panuke B-90 and Lawrence D-14. The lateral dimensions of the delta-front turbidites is considerable greater than the width of incised valleys in the Venture field (Cummings and Arnott, 2005) suggesting either that there was distributary switching or that the transect is sub-parallel to paleoflow direction.

Transgressive surfaces make effective benchmarks with which to correlate equivalent packages above and below these surfaces, but some transgressive surfaces are of limited extent (Fig. 9). Identifying lithofacies in core samples is a crucial element to detailed correlation and understanding how changes in depositional environments change laterally. Facies changes in combination with the high frequency gamma character are effective at fine-tuning correlations made at a regional scale using principally gamma logs.

6.2 West Venture-Venture area

Cummings and Arnott (2005) interpreted several incised valleys filled with strongly tide-influenced estuarine deposits through the West Venture to Venture section (Fig. 4). Their interpretation shows the valley fills as being narrow, the majority spanning 2.3 km and only one spanning ~8 km based on well spacing in Figure 4 (Cummings and Arnott state that incised valleys are 7-13 km wide). The more detailed facies analyses allowed for some fine-tuning of Cummings and Arnott's interpretation of the West Venture-Venture section, with more focus on the lateral extent and differences of the sand packages. The top of Unit A has a similar 5 m thich fluvial sandstone package 5 m thick in West Venture N-91 and West Venture C-62, and < 1 m thick in Venture H-22. This sandstone has a lateral extent of at least 15 km. The sandstone is underlain by a tidally influenced sandstones and mudstones in West Venture C-62, and river-mouth turbidites in West Venture N-91 and Venture H-22. Thick slump deposits within the equivalent section in West Olympia O-51 represent the delta front. Therefore Unit A represents an oblique proximal to distal transect: Tidal estuarine sands (Venture H-22) to strongly tidally influenced channel deposits (West Venture C-62) to river-mouth turbidites (West Venture N-91) to delta front deposits (West Olympia O-51).

Similarly near the top of Unit B, Cummings and Arnott (2005) interpreted incised valley fill in West Venture C-62 and Venture B-52. Although there is a break in core within this interval at West Venture N-91, the base of core 6 samples a coal bed and underlying medium grained, possibly cross-bedded sandstone that is similar in character to those in West Venture C-62 (Figs. 13D-1, 13D-2). Gamma ray character through the uncored section also matches West Venture C-62, and thus the incised valley fill may to extend to West Venture N-91, however without core samples we cannot confirm this. At Venture H-22, the corresponding succession is composed of fluvial sandstones without a strong tidal influence. Although the top of the succession correlates with West Venture C-62 and West Venture N-91, the lack of tidal signatures within the sandstones indicate that is may not be part of the incised valley sampled at West Venture C-62 and Venture B-52. The similarities between core of the fluvial sandstones to those seen at the top of the Unit B (Facies 4g in all wells) and the low gamma values suggest that a laterally extensive sandstone can be correlated across the section (~15 km). It is 11 m thick in West Venture C-62, 13 m thick in Venture H-22, and possibly 8 m thick at West Venture N-91. No core samples are available between Venture C-62 and Venture H-22 wells to confirm this, but the gamma response in Venture B-52 shows the same decrease and consistently low values seen in the other wells.

6.3 Validation of facies interpretations and evaluation of reservoir connectivity

Lithofacies interpretations of previous workers such as Cummings and Arnott (2005), Cummings et al. (2006) and Gould et al. (2010a, b) were based principally on sedimentological character and vertical succession, although the facies associations (braided fluvial, coastal plain) of Cummings et al. (2006) were based in part on correlation with 3-D seismic. Comparing wells in lateral successions through a transect of closely spaced wells rather than in vertical succession can be effective way to confirm our understanding of lithofacies as a correlation tool.

Transgressive units are present in both regional and localized features. At a regional scale, transgressive units (e.g. coals in the West Venture wells; thick shell beds in the Panuke B-90 and Cohasset A-52 wells) and can be correlated over tens of kilometres. More localized surfaces may vary considerably in thickness and character from adjacent wells (e.g., the muddy, shelly trangressive unit at the top of Balmoral M-32, absent at Cohasset A-52 3 km away; the thick transgressive unit in Como P-21; that in Panuke B-90 is interbedded with more distal facies, and is a singular thin unit at Lawrence D-14). These localized surfaces may represent transgressive abandonment facies at the top of a parasequence formed the through delta lobe and distributary switching. The more regional surfaces (i.e., the top Missisauga Formation in Como P-21, Panuke B-90, and Cohasset A-52; and the top Unit A, B and D in the West Venture-Venture section) are formed as a result of more regional changes in sea level due either to eustatic or tectonic processes. Unit C in the West Venture-Venture cross-section is an example of a parasequence deposited by distributary channel, giving a set of progradational lithofacies absent in adjacent wells. However this parasequence is capped by a regional transgressive surface that extends laterally.

Differences in lithofacies at the top of the Missisauga Formation in the Panuke-Cohasset area reflect the lateral variability of facies and give evidence to the overall paleoenvironment in relation to the transect. Shoreface deposits in Cohasset A-52 (facies 2b) may represent a brief interruption or distributary switching in vigorous river supply, corresponding perhaps to distal turbidites deposits at Lawrence D-14 (facies 0m). Generally the lateral variation from facies 9g at Lawrence D-14 and facies 9s+4o at Cohasset A-52 to mostly facies 4o at Panuke B-90 is consistent with previous interpretation (Gould et al. 2010a; 2010b) that facies 9g occurs in deeper water where there is sufficient accommodation space, whereas facies 9s tends to be a by-passing facies on the proximal delta front. Facies 4o represents tidal channel fill by flooding river that creates turbidites distally, and is reworked by *Ophiomorpha*.

Tidal successions are variable between wells and can be discontinuous. Where good correlation is present, the mudstone-dominant facies seem to maintain a more uniform character laterally (Fig. 6B-1, 6B-2, and 6B-3; Fig. 6E-1, and 6E-2; Fig. 10A-1, and 10A-2). Sandstone units with tidally influenced sections (facies 5) are more inconsistent in their occurrence and facies character between wells. Heterolithic facies 4a correlates well but because of variable sand to mud ratios, reservoir quality of this unit may change laterally. In the West Venture–Venture transect, strongly tidally influenced facies are restricted to incised valleys (i.e., in Units A, B, and D in West Venture C-62 and Venture B-52), however laterally extensive fluvial sandstones (facies 4g) overlie the valley fill and can be correlated across all wells in the section. These sandstones can be correlated in Units A and C over 15 km, suggesting that they represent a regional progradation of the entire fluvial system. A more widespread sandstone at the top of Unit D correlates across the entire section (27 km) and is generally tidal estuarine interbedded with proximal delta front deposits in most wells, however it is recognised as fluvial in West Venture N-91.

Some sandstone packages are laterally continuous, even if depositional environment changes. For example in the top of the section in West Venture-Venture area (~26 km), varying from generally fluvial to tidal estuarine interbedded with turbidites in places. Likewise, thick river-mouth turbidites in Panuke B-90 and Cohasset A-52 in the lower Logan Canyon Formation are continuous over 7.5 km. Where such sands are reservoirs, reservoir connectivity may extend over tens of kilometres laterally, but reservoir quality is likely to be variable. Gould et al. (2010a) found that best porosity was in delta-front turbidites (facies 9g), so that in the Panuke–Cohasset–Lawrence transect, at the top of the Missisauga Formation, reservoir quality would likely decrease from east to west as facies changed from thick river-mouth turbidites to proximal delta-front turbidites to estuarine sandstones. Sandstone reservoirs with strong tidal or fluvial influence may be limited by the extent of incised valleys within which they occur, however thick sandstones overlying these deposits appear to be laterally extensive. Therefore when correlating sandstone packages at a regional scale, defining the sedimentary facies (where core samples are available) becomes an important part of predicting reservoir quality.

7.0 Conclusions

The recognition of facies associations and distinctive vertical successions of parasequences was effective for comparing and correlating across several wells.

Generally, facies in the Panuke–Cohasset area vary from proximal to distal from west to east. This transect is almost perpendicular to the regional progradation direction to the south-south east. The lateral dimensions of the delta-front turbidites is considerably greater than the width of incised valleys in the Venture Field (~15 km) indicating either that there was distributary switching or that the transect is sub-parallel to local paleoflow direction, as suggested by lateral facies changes in the Upper Member of the Missisauga Formation.

The West Venture–Venture section represents a vertical succession of stacked prodelta parasequences capped by trangressive surfaces or coal beds. Detailed facies analyses allowed for some fine-tuning of Cumming and Arnott's (2005) interpretation and extension of the correlation to the West Olympia Field. We are in agreement with Cummings and Arnott's recognition of incised valley deposits, but thick sandstone packages overlying these deposits can be correlated across the section, in places up to 27 km, implying that reservoir connectivity may not be limited by the incised valleys.

Trangressive surfaces and coal beds were mostly regional in scale, therefore proving vital for reliable correlation between wells. Localized surfaces may represent delta progradation and subsequent distributary switching, where the regional may relate to changes in sea level.

Tidal parasequences can be quite variable and therefore are more difficult to correlate than regional sandstone packages. Some sandstone packages are laterally continuous, even if depositional environment changes. In both study areas, thick sandstone packages correlate across the section, 15 km in Panuke–Cohasset, and up to 27 km in West Venture–Venture, with the depositional environment varying from proximal to distal facies. The reservoir quality may therefore not be constant.

Gamma logs are most effective for regional correlation, but since lithology and sedimentary facies change laterally on a scale of 10 km, gamma can only correlate major lithological changes related to sand input or transgressions.

8.0 References

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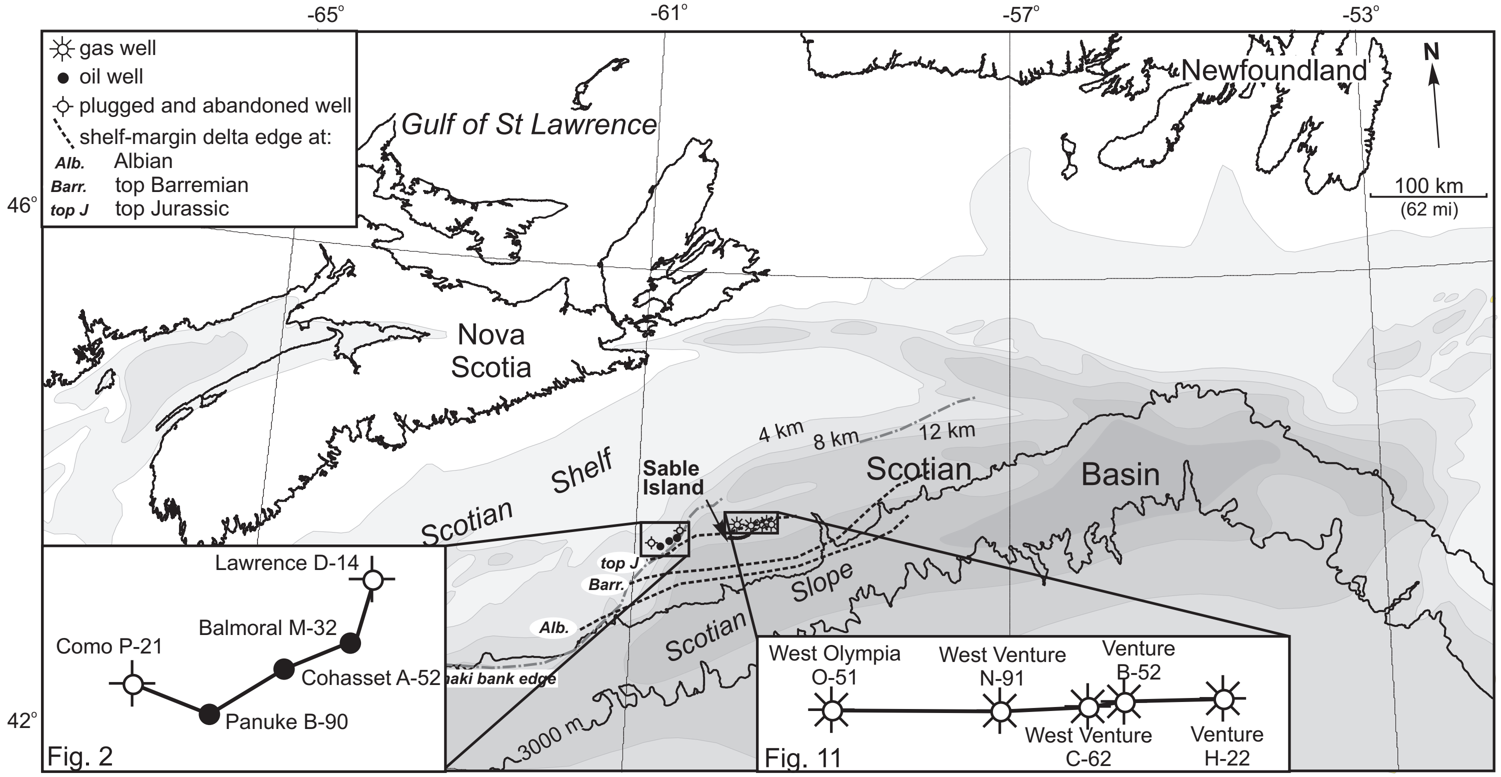


Figure 1: Map of the central Scotian Basin, showing the location of wells used in this study. Isopachs of Mesozoic to Cenozoic sediments in kilometres from MacLean & Wade (1992).

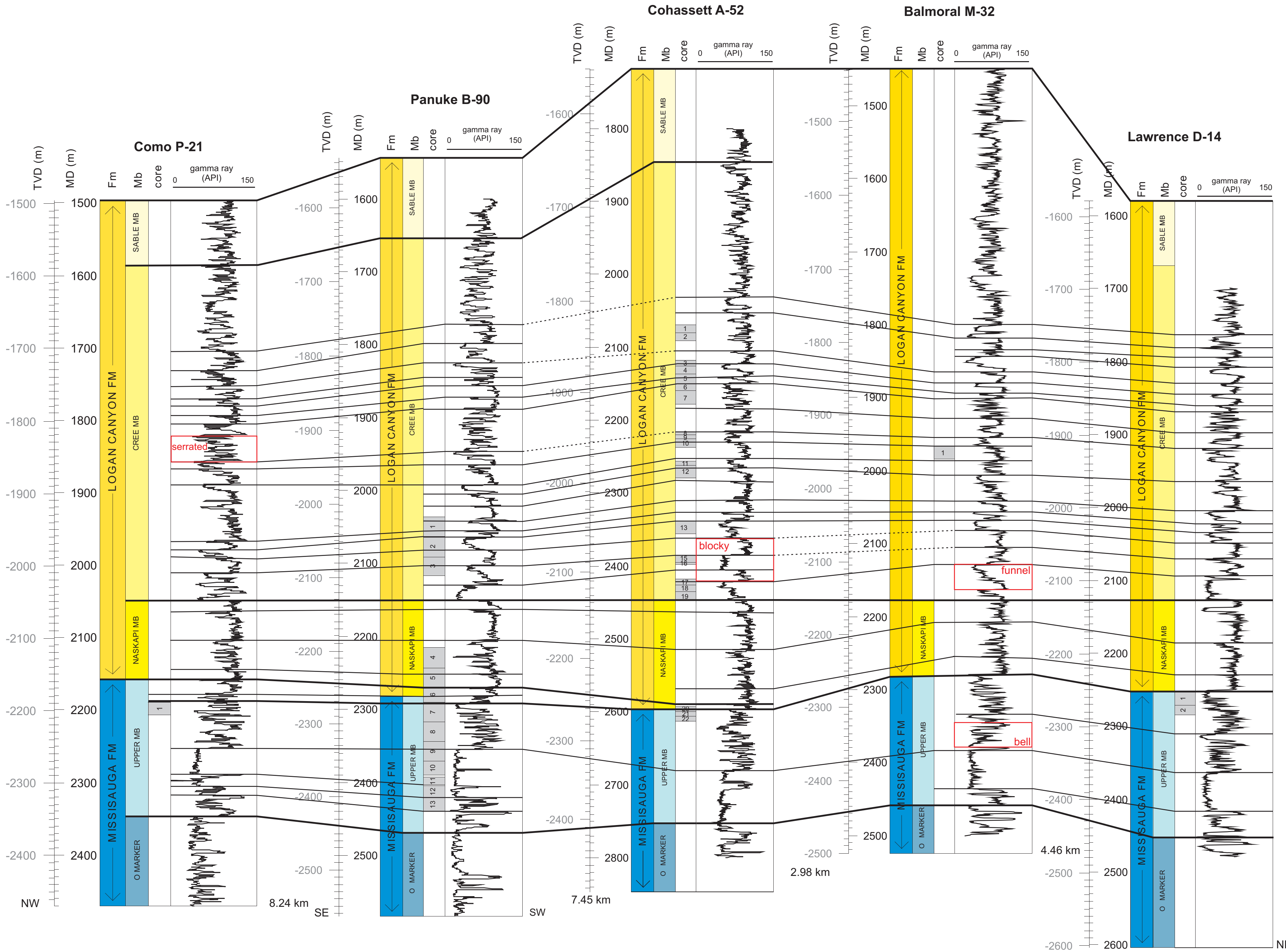


Figure 2: Regional correlation between Como P-21, Panuke B-90, Cohasset A-52, Balmoral M-32, and Lawrence D-14 wells, through the Upper Missisauga and Logan Canyon formations (MacLean and Wade, 1993). Correlation is hung from the top of the Naskapi Member of the Logan Canyon Formation. Core depths are uncorrected to gamma log (TVD = true vertical depth, MD = measured depth). Red boxes are examples of common log shapes used for correlation.

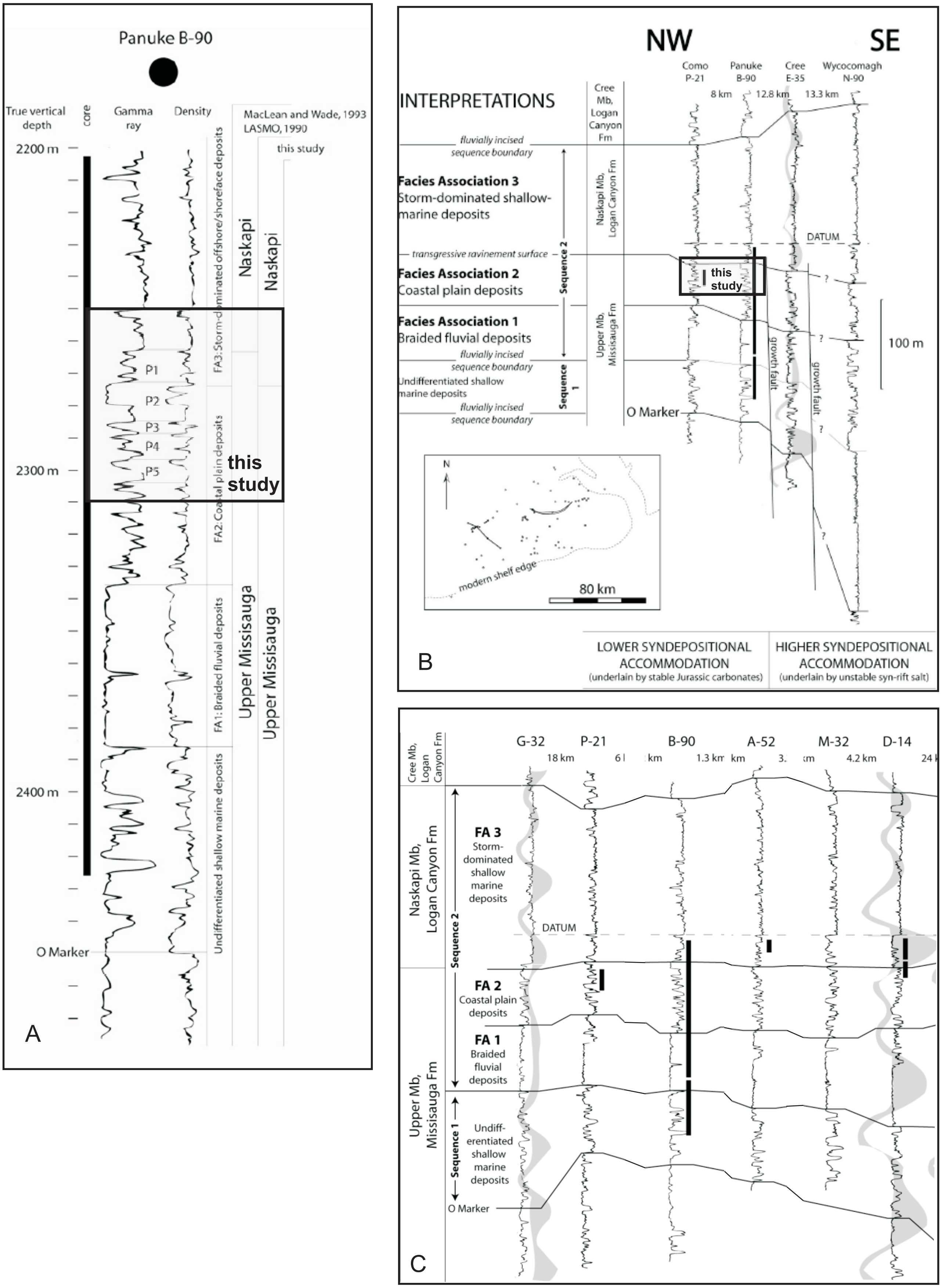


Figure 3: Previous interpretations of the Panuke -Cohasset area by Cummings et al., 2006. Intervals used in this study are indicated. (A) Interpretation of the Upper Missisauga - Naskapi transition in Panuke B-90. (B) Correlation between Como P-21 and Panuke B-90 wells. (C) Correlation between Como P-21, Panuke B-90, Cohasset A-52, Balmoral M-32, and Lawrence D-14 wells.

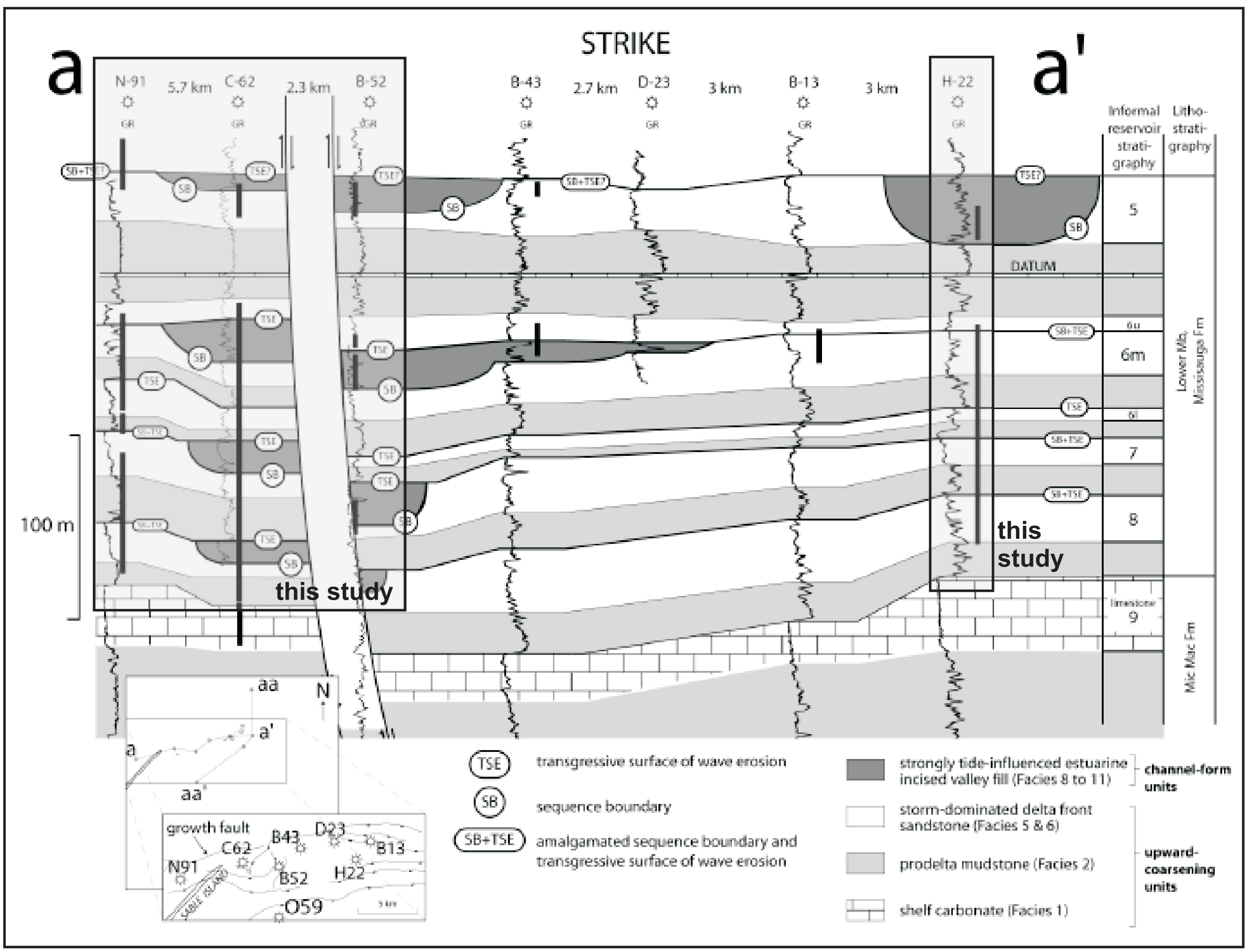


Figure 4: Correlation between the West Venture and Venture fields through the Lower Member of the Missisauga Formation (modified from Cummings and Arnott, 2006) showing the location of wells used in this study.

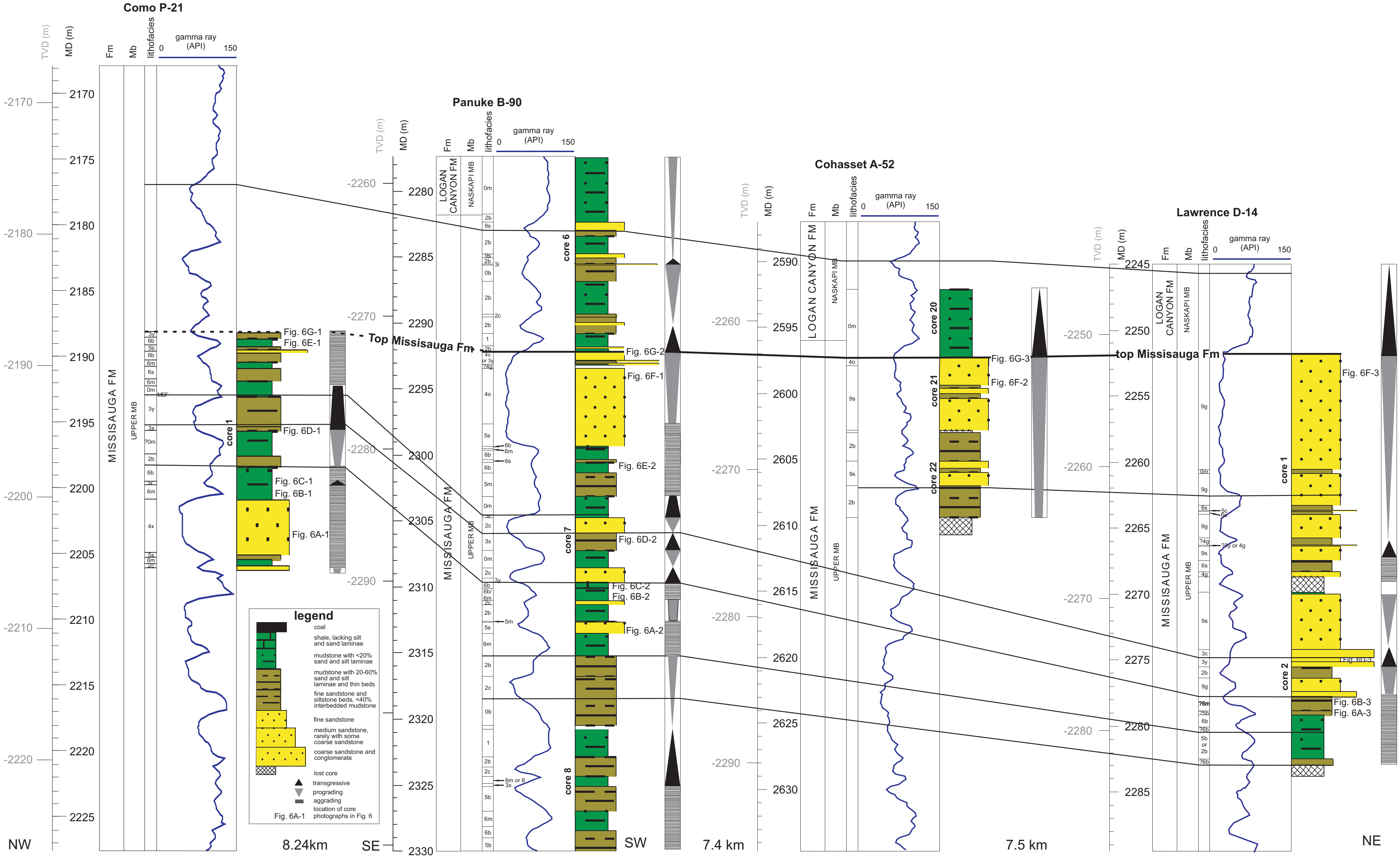


Figure 5: Detailed correlation between the Como P-21, Panuke B-90, Cohasset A-52, and Lawrence D-14 wells, through the top of the Missisauga Formation and the base of the Logan Canyon Formation. Cored intervals have been corrected to well depths by matching core gamma to wireline gamma logs (MD = measured depth, TVD = true vertical depth). Lithofacies are defined in Table 1. Formation and Member picks from McLean and Wade (1993), except the top of the Missisauga Formation in Como P-21, Panuke B-90, and Cohasset A-52, which has been moved 30 m, 11 m and 1.5m deeper, respectively.

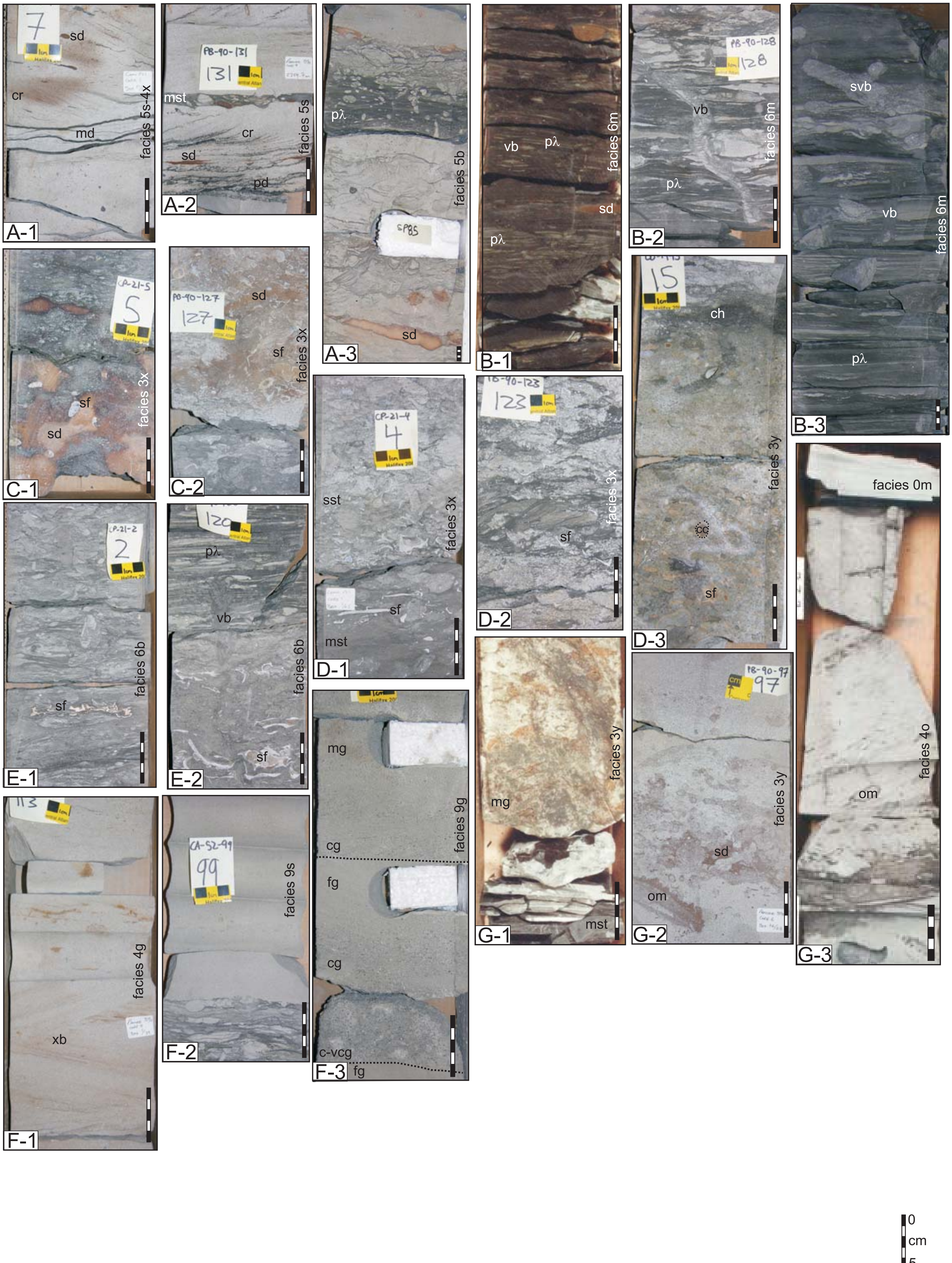

A-1
sd
cr
md
facies 5s-4x
A-2
mst
cr
sd
pd
facies 5s
A-3
pλ
facies 5b
sd
B-1
vb
pλ
facies 6m
sd
pλ
B-2
vb
pλ
facies 6m
B-3
svb
vb
pλ
facies 6m
C-1
sf
sd
facies 3x
C-2
sd
sf
facies 3x
D-1
sst
facies 3x
sf
mst
D-2
facies 3x
sf
D-3
ch
cc
sf
facies 3y
E-1
sf
facies 6b
E-2
pλ
vb
sf
facies 6b
F-1
facies 4g
xb
F-2
facies 9s
F-3
mg
cg
fg
cg
c-vcg
fg
facies 9g
G-1
mg
mst
facies 3y
G-2
sd
om
facies 3y
G-3
facies 0m
om
facies 4o
0
cm
5

Figure 6: Representative core photos of correlated intervals in the Upper Missisauga Formation. (A-1) Fine-grained sandstone with current ripples 'cr', mud drapes 'md', and a few siderite nodules 'sd'. Como P-21. (A-2) Horizontal burrows and siderite concretions 'sd' in 1 cm thick mudstone bed 'mst', within fine-grained sandstone. Sandstone hosts current ripples 'cr' composed of plant detritus 'pd'. Panuke B-90. (A-3) Abundantly bioturbated fine-grained sandstone and mudstone beds. Few sideritized burrows 'sd'. Few preserved silty laminations 'pλ'. Lawrence D-14. (B-1) Mudstone with minor, parallel fine-grained sandstone laminations 'pλ', crosscut by vertical burrows 'vb'. Few siderite patches 'sd'. Como P-21. (B-2) Long vertical burrow 'vb' cross-cutting interlaminated mudstone and sandstone 'pλ'. Panuke B-90. (B-3) Mudstone with minor parallel fine to medium-grained sandstone lamina 'pλ'. Bedding is cut by vertical and subvertical burrows 'vb', 'svb', infilled with medium to coarse-grained sandstone from overlying unit. Lawrence D-14. (C-1) Abundantly bioturbated mudstone with disseminated medium to coarse-grained sand throughout. ?Gastropod shell fragments 'sf' and patchy siderite 'sd'. Como P-21. (C-2) Completely bioturbated, sidertite-stained 'sd', muddy sandstone with common shell fragments 'sf'. Panuke B-90. (D-1) Completely bioturbated, shelly, muddy fine-grained sandstone over mudstone. Few thick ?oyster shell fragments at contact 'sf'. Como P-21. (D-2) Abundantly bioturbated muddy sandstone with coarse-grained sand and thick and thin shell fragments 'sf'. Panuke B-90. (D-3) Pebble and granule conglomerate, with carbonate intraclasts 'cc' and thick shell fragments 'sf'. Thin lens of mudstone has abundant *Chondrities* burrows 'ch'. Lawrence D-14. (E-1) Concentration of oyster shells 'sf' in completely bioturbated sandy mudstone. Como P-21. (E-2) Mudstone with thin fine-grained sandstone laminations ‘pλ’, cut by vertical burrows 'vb', over completely bioturbated sandy mudstone with oyster shell fragments 'sf'. Panuke B-90. (F-1) Cross-bedded 'xb' fine to medium-grained sandstone. Panuke B-90. (F-2) sharp-based, fine-grained sandstone bed over an abundantly bioturbated, sandy mudstone. Cohasset A-52. (F-3) Repeating, very coarse 'cg' grading to fine-grained 'fg' sandstone beds. Lawrence D-14. (G-1) Completely bioturbated, muddy, medium-grained sandstone 'mg', overlying laminated mudstone 'mst'. Como P-21. (G-2) Fine to medium-grained sandstone with siderite-stained burrows 'sd', including *Ophiomorpha* 'om'. Panuke B-90. (G-3) Fine-grained sandstone with faint low to high angle cross-bedding and siderite-stained *Ophiomorpha* burrows 'om'. Cohasset A-52.

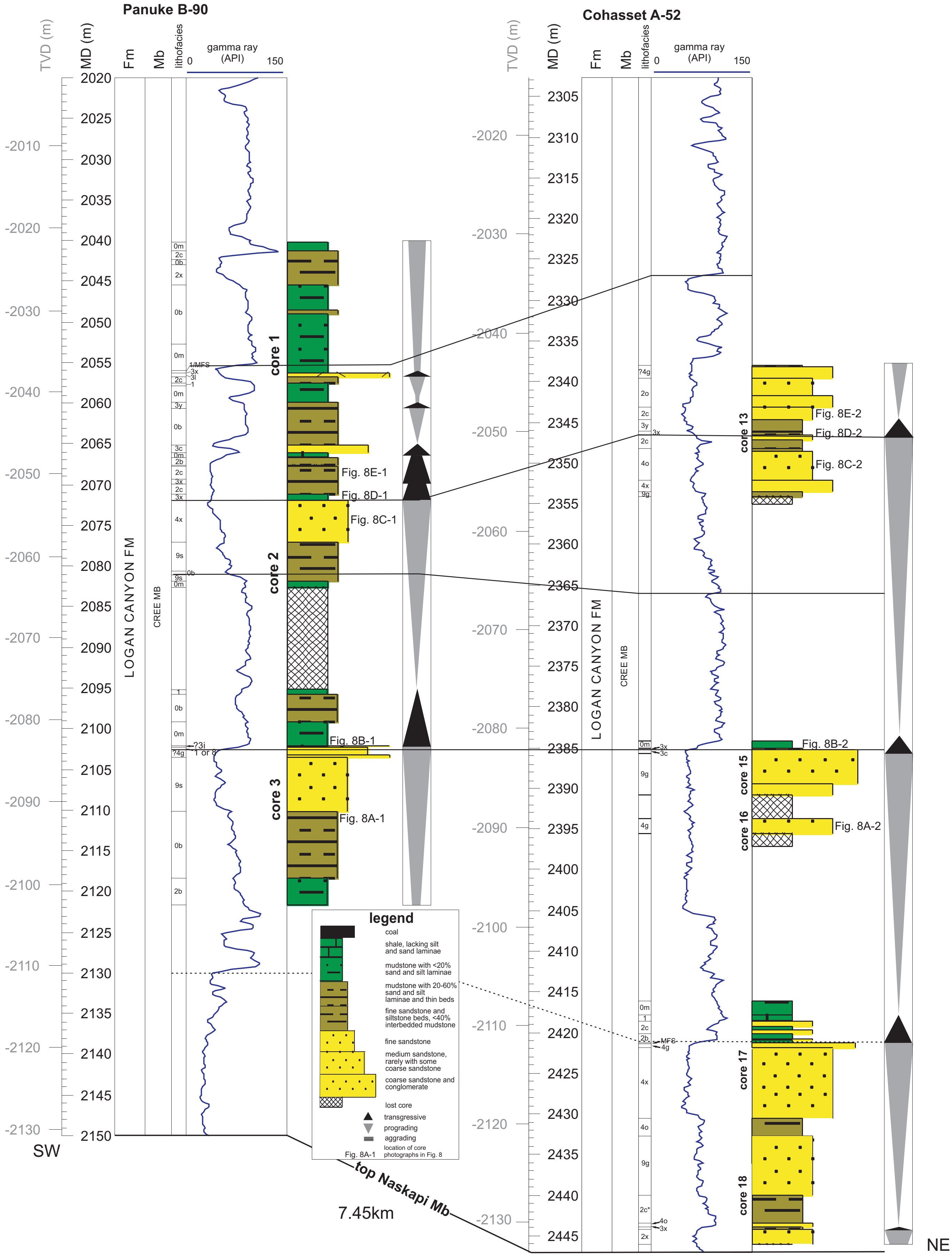
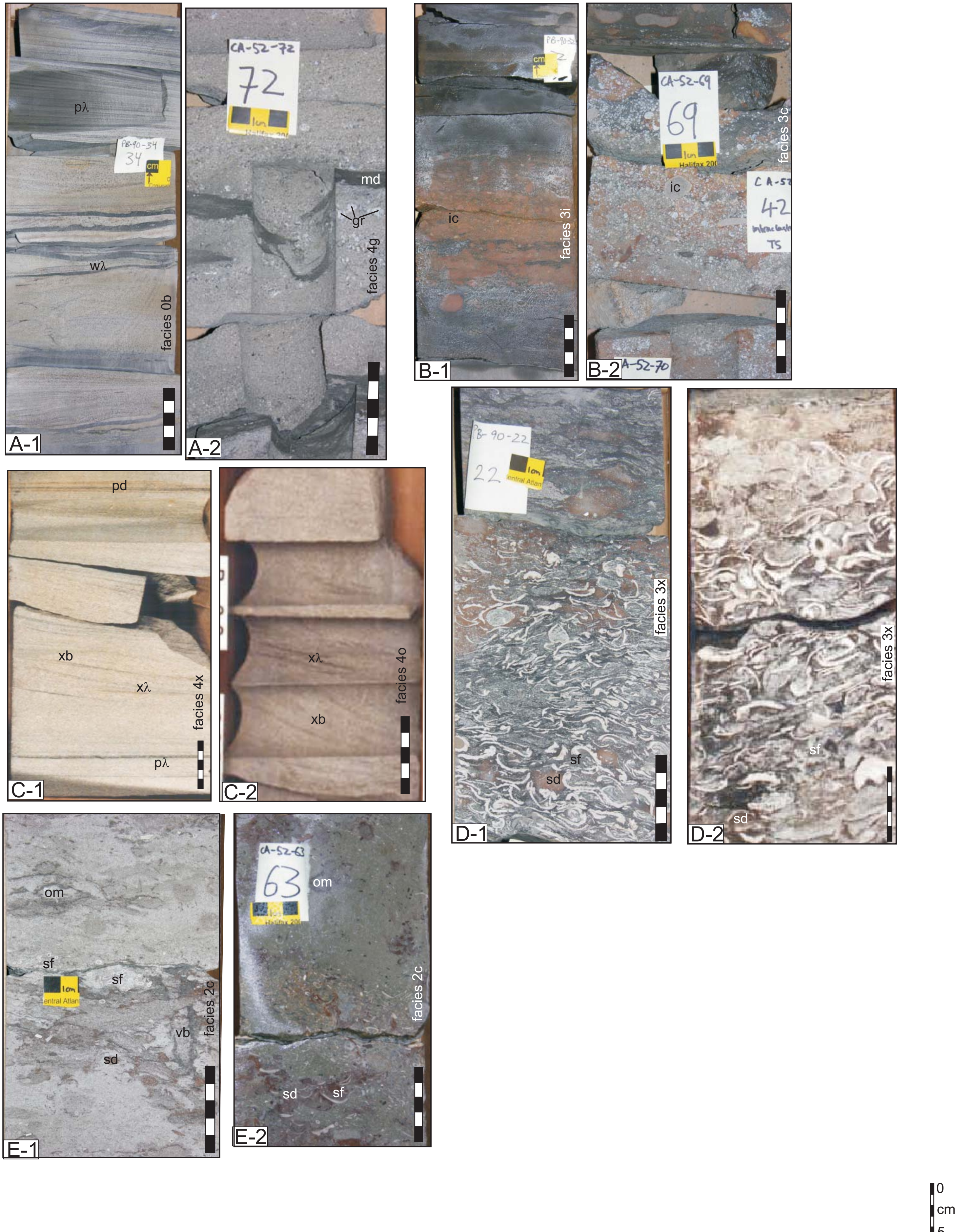


Figure 7: Detailed correlation between the Panuke B-90 and Cohasset A-52 wells, near the base of the Logan Canyon Formation. Cored intervals have been corrected to well depths by matching core gamma to wireline gamma logs (MD = measured depth, TVD = true vertical depth). Lithofacies are defined in Table 1. Formation and Member picks from McLean and Wade (1993).



A-1
pλ
PB-90-34
34
wλ
facies 0b
A-2
CA-52-72
72
md
gr
facies 4g
B-1
ic
facies 3i
B-2
CA-52-69
69
facies 3c
ic
42
C-1
pd
xb
xλ
pλ
facies 4x
C-2
xλ
xb
facies 4o
D-1
PB-90-22
22
facies 3x
sf
sd
D-2
facies 3x
sf
sd
E-1
om
sf
sf
vb
sd
facies 2c
E-2
CA-52-63
63
om
facies 2c
sd
sf
0
cm
5

Figure 8: Representative core photos of correlated intervals in the base of the Cree Member of the Logan Canyon Formation. (A-1) Sharp-based, fine grained sandstone beds with parallel to wavy mudstone laminations 'pλ', 'wλ'. Panuke B-90. (A-2) Medium-grained sandstone with thick mud drapes 'md' and granules 'gr'. Cohasset A-52. (B-1) Bed of siderite intraclasts 'ic' and coarse-grained sand, within a mudstone unit. Panuke B-90. (B-2) Intraclast conglomerate of carbonate 'ic' and siderite nodules, very coarse-grained sand, and granules. Cohasset A-52. (C-1) Medium-grained, cross-bedded 'xb' sandstone with parallel and cross laminations 'pλ', 'xλ' of plant detritus 'pd'. Panuke B-90. (C-2) Cross bedded 'xb' medium-grained sandstone, with internal cross-laminations 'xλ'. Cohasset A-52. (D-1) Bed of oyster and possible trigonid bivalve shells 'sf' in greenish, medium to coarse-grained sandstone, patchy siderite 'sd'. Panuke B-90. (D-2) Bed of oyster and possible trigonid bivalve shells 'sf' in fine grained sandstone with patchy siderite 'sd'. Cohasset A-52. (E-1) Abundantly bioturbated fine to medium-grained sandstone with mud-lined horizontal and vertical burrows 'vb', a few identified as *Ophiomorpha* 'om'. Some small round shell fragments 'sf' and patchy siderite 'sd'. Panuke B-90. (E-2) Fine-grained sandstone with shell fragments 'sf', patchy siderite 'sd', and a few *Ophiomorpha* burrows 'om'. Cohasset A-52.

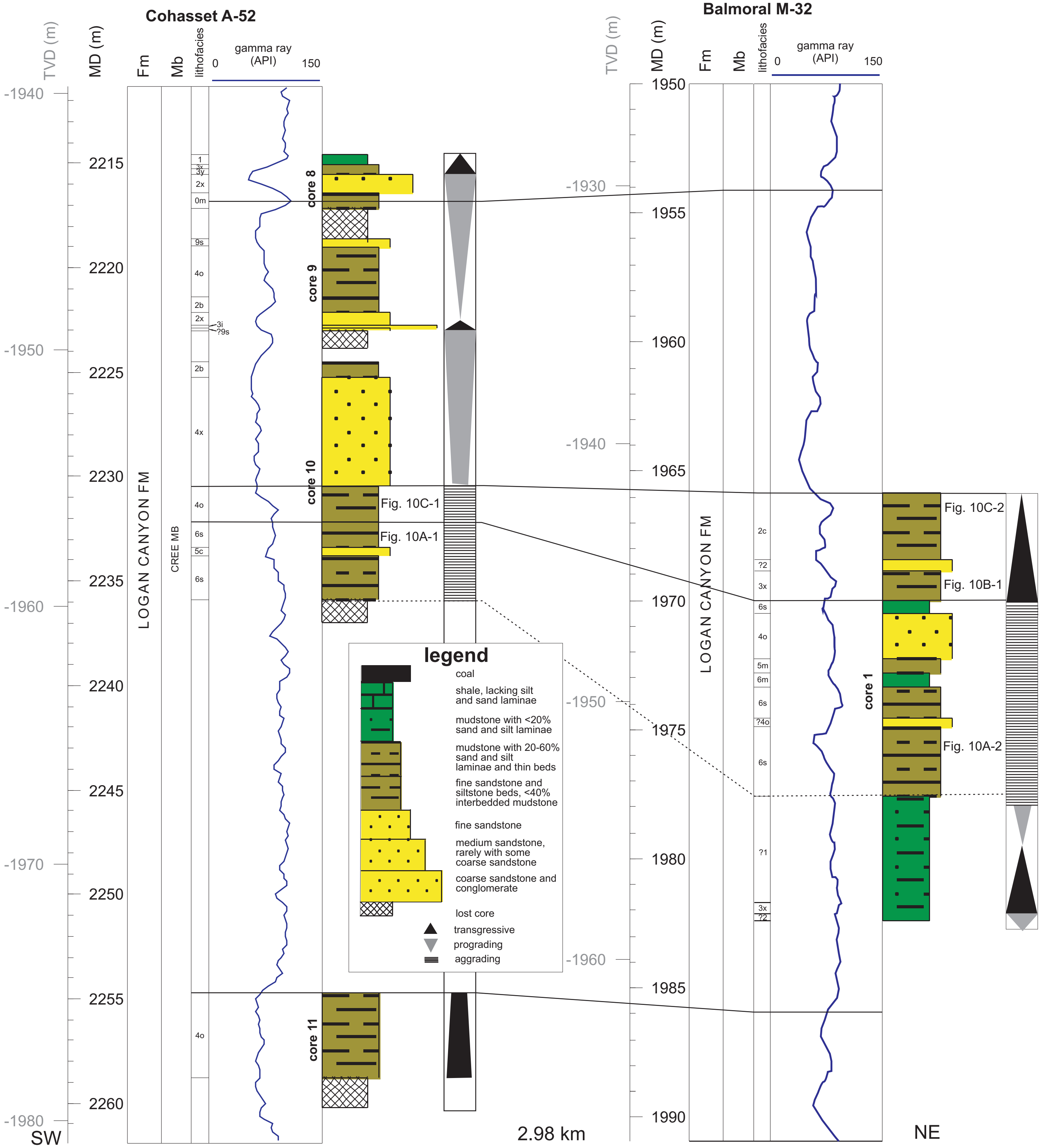
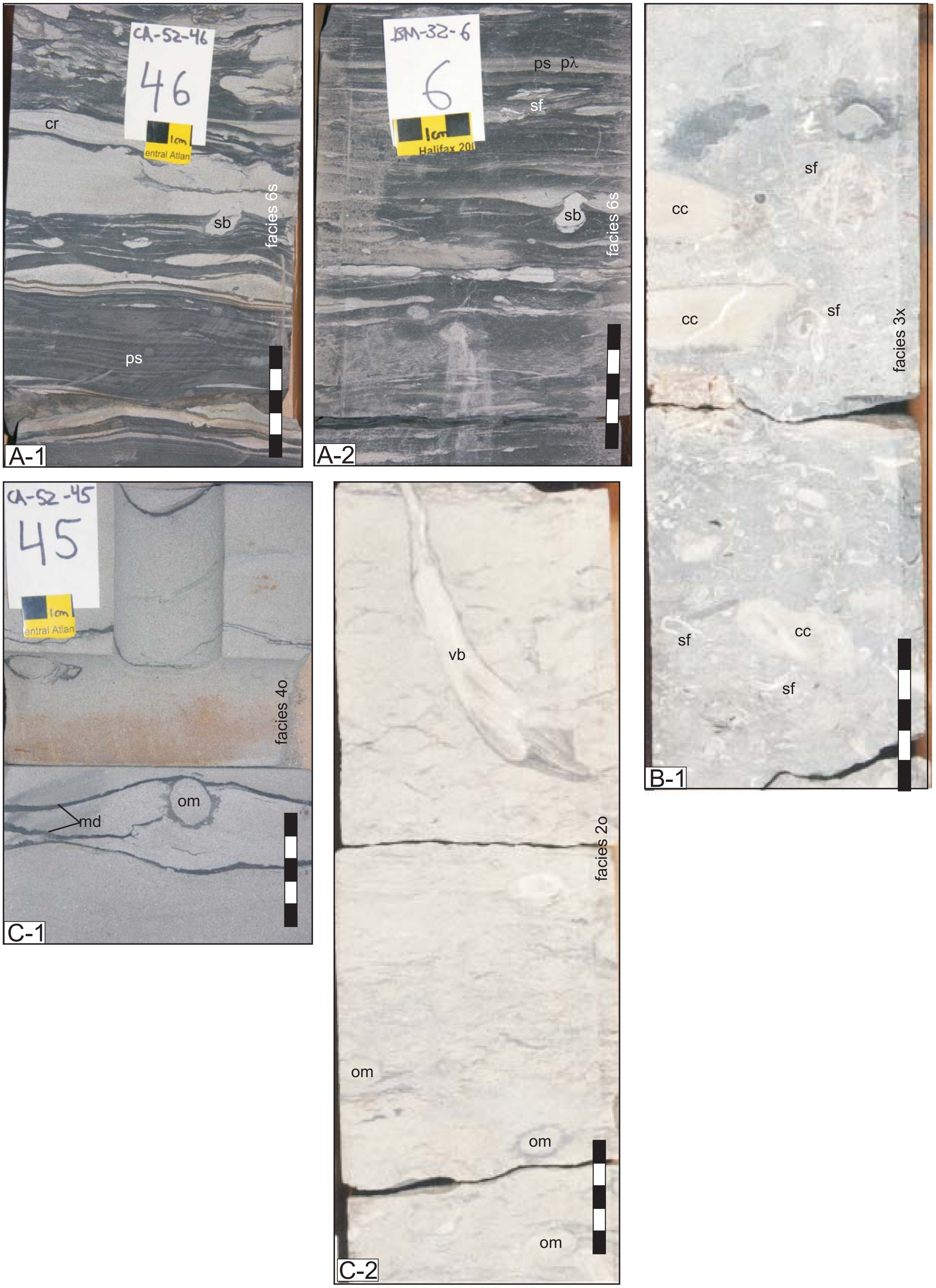


Figure 9: Detailed correlation between the Cohasset A-52 and Balmoral M-32 wells, near the middle of the Logan Canyon Formation. Cored intervals have been corrected to well depths by matching core gamma to wireline gamma logs (MD = measured depth, TVD = true vertical depth). Lithofacies are defined in Table 1. Formation and Member picks from McLean and Wade (1993).



CA-52-46
46
1cm
entral Atlan
cr
sb
facies 6s
ps
A-1
6
1cm
Halifax 200
ps pλ
sf
sb
facies 6s
A-2
sf
cc
cc
sf
facies 3x
sf
cc
sf
B-1
CA-52-45
45
1cm
entral Atlan
facies 4o
om
md
C-1
vb
facies 2o
om
om
om
C-2

0
cm
5

Figure 10: Representative core photos of correlated intervals in the middle of the Cree Member of the Logan Canyon Formation. (A-1) Mudstone with sharp-based, fine-grained sandstone beds, lenticular in shape. Mudstone shows pinstripe alternations of mm-thick silty to very fine-grained sandstone laminations 'ps'. A few subvertical burrows 'sb' and possible current ripples 'cr'. Cohasset A-52. (A-2) Mudstone with graded fine to very fine-grained sandstone laminations, some with mm-sized shell fragments 'sf' and internal pinstripe parallel laminations 'pλ','ps'. A few beds are cut by subvertical burrows 'sb'. Balmoral M-32. (B-1) Abundantly bioturbated, muddy, fine-grained sandstone with common shell fragments 'sf' and patchy carbonate cement 'cc'. Balmoral M-32. (C-1) Fine-grained sandstone with mud drapes 'md' and *Ophiomorpha* burrows 'om'. Cohasset A-52. (C-2) Abundantly bioturbated, muddy, very fine-grained sandstone, with a long mud-lined vertical burrow 'vb', and several horizontal *Ophiomorpha* burrows 'om'. Balmoral M-32.

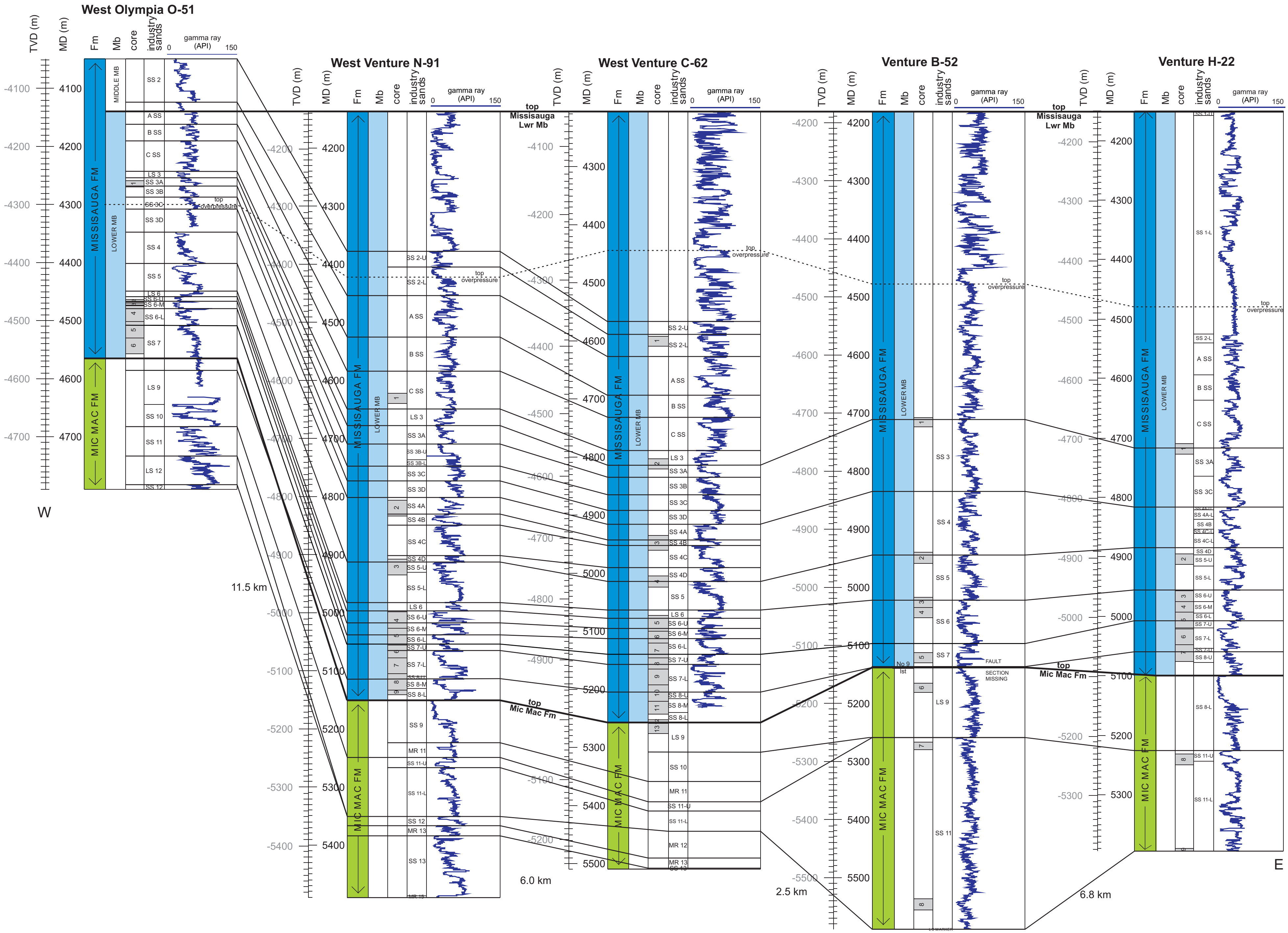


Figure 11: Regional correlation using Industry Sands between West Olympia O-51, West Venture N-91, West Venture C-62, Venture B-52, and Venture H-22 wells, through the Lower Member of theMissisauga Formation. Formation and Member picks are from MacLean and Wade (1993). Core depths are uncorrected to gamma log (MD = measured depth, TVD = true vertical depth).

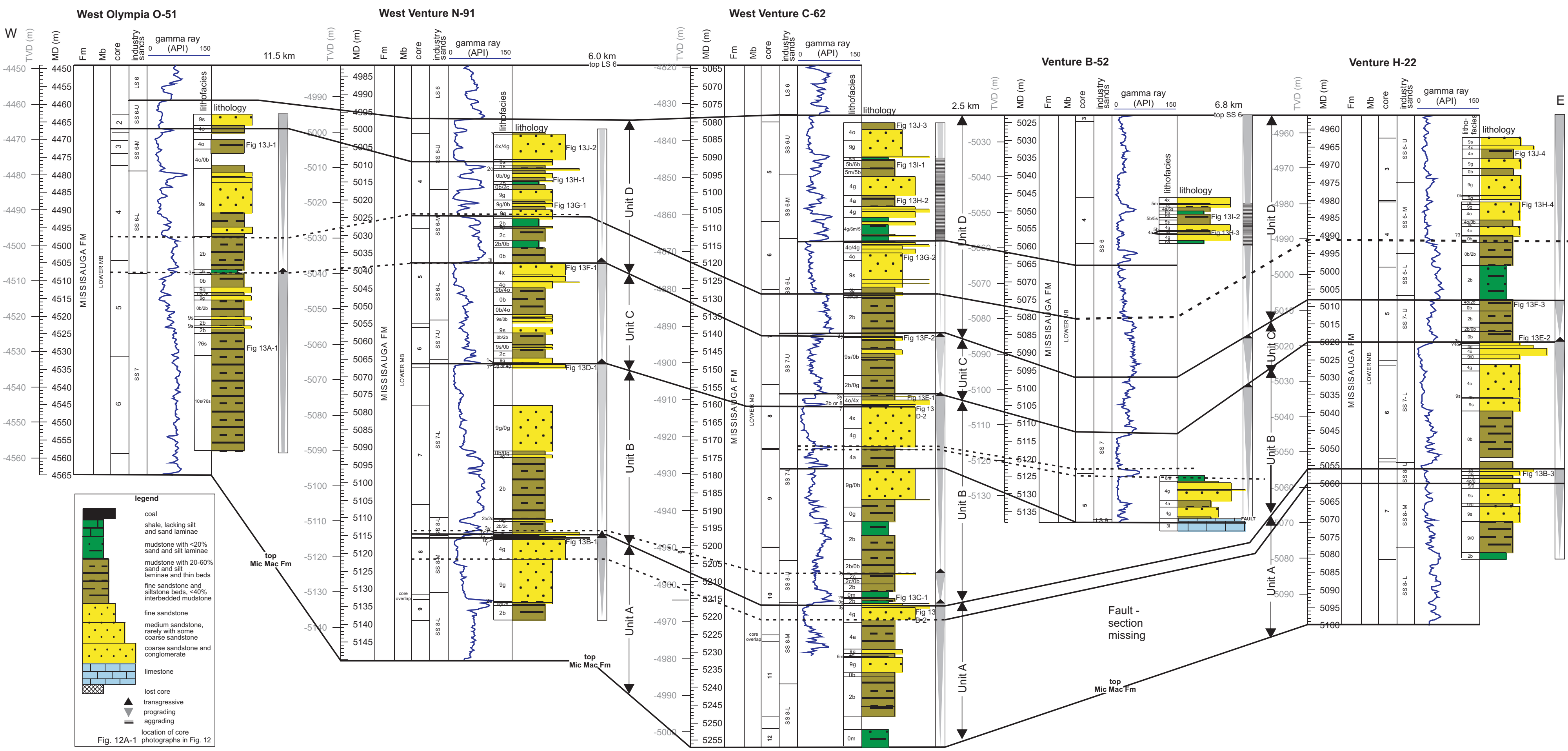
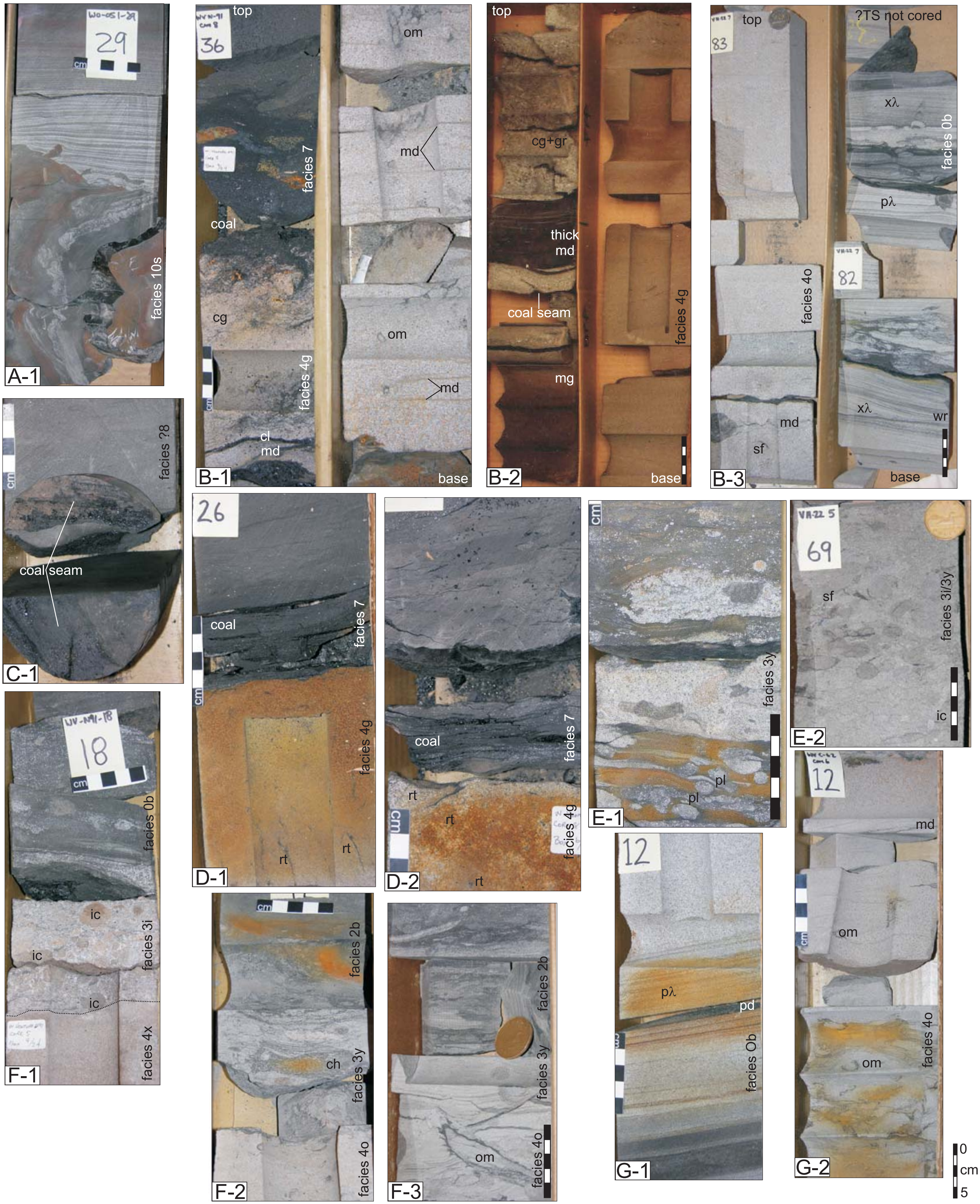


Figure 12: Detailed correlation between West Olympia O-51, West Venture N-91, West Venture C-62, Venture B-52, and Venture H-22 wells through the base of the Missisauga Formation. Cored intervals have been corrected to well depths by matching core gamma to wireline gamma logs. Formation and Member picks from Maclean and Wade (1993); Industry Reservoir Sand picks from Mobil Oil Canada Ltd (1983, 1984, 1985a, 1985b, 1986). (MD = measured depth, TVD = true vertical depth).


A-1
facies 10s
29
cm
B-1
top
36
facies 7
coal
cg
facies 4g
cl
md
om
md
om
md
base
B-2
top
cg+gr
thick
md
coal seam
mg
facies 4g
base
B-3
top
83
facies 4o
md
sf
?TS not cored
xλ
facies 0b
pλ
82
xλ
wr
base
C-1
facies ?8
coal seam
cm
D-1
26
coal
facies 7
facies 4g
rt
rt
cm
D-2
coal
facies 7
rt
rt
facies 4g
rt
cm
E-1
facies 3y
pl
pl
cm
E-2
69
sf
facies 3i/3y
ic
F-1
18
cm
facies 0b
ic
ic
facies 3i
ic
facies 4x
F-2
cm
facies 2b
ch
facies 3y
facies 4o
F-3
facies 2b
facies 3y
om
facies 4o
G-1
12
pλ
pd
facies 0b
G-2
12
md
om
cm
om
facies 4o
0
cm
5

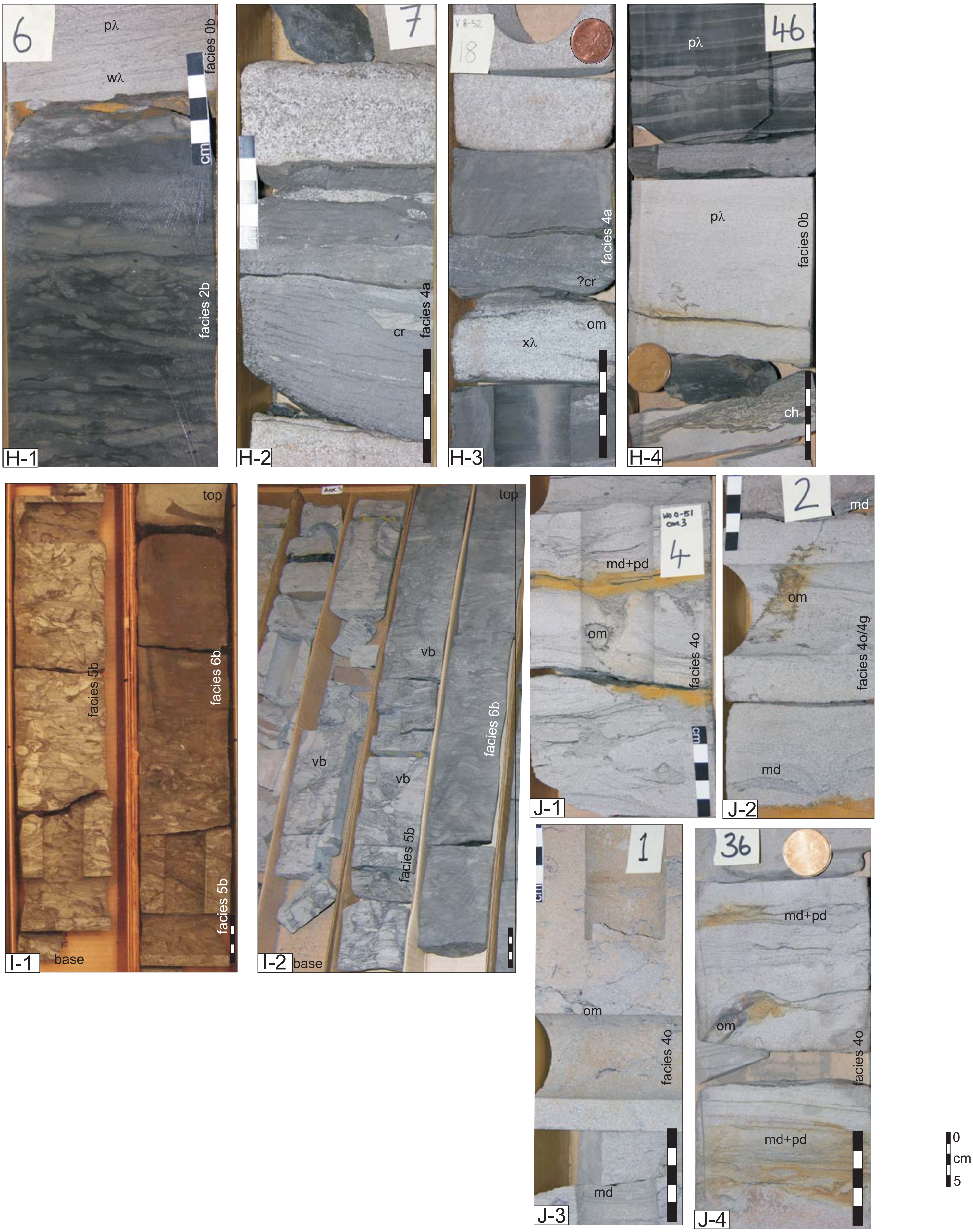

6
pλ
wλ
facies 0b
cm
facies 2b
H-1
7
cr
facies 4a
H-2
V 8-52
18
facies 4a
?cr
om
xλ
H-3
46
pλ
pλ
facies 0b
ch
H-4
top
facies 5b
facies 6b
facies 5b
I-1
base
top
vb
vb
vb
facies 6b
facies 5b
I-2
base
WO 0-51
core 3
4
md+pd
om
facies 4o
cm
J-1
2
md
om
facies 4o/4g
md
J-2
1
om
facies 4o
md
J-3
36
md+pd
om
facies 4o
md+pd
J-4
0
cm
5

Figure 13: Representative core photos of correlated intervals at the base of the Lower Member of the Missisauga Formation. (A-1) Slumped core, folded mudstone and very fine-grained sandstone. West Olympia O-51. (B-1) Thick coal bed overlying coarse-grained sandstone 'cg' with mud drapes 'md' and coal layers 'cl'. West Venture N-91. (B-2) Thick mud drape ‘md’ and thin coal seam between medium-grained sandstone 'mg' and very coarse-grained to granular sandstone 'cg+gr'. West Venture C-62. (B-3) Thin fine-grained sandstone beds, generally massive at base, becoming parallel to cross-laminated 'pλ', 'xλ', with some bed tops bioturbated. Some possible wave-ripples 'wr'. Overlain by medium-grained sandstone with shell fragments 'sf' and a few mud drapes 'md'. Venture H-22. (C-1) Thin coal seam seen on bedding surface of bioturbated coaly mudstone. West Venture C-62. (D-1) Coal bed sharply contacting underlying coarse-grained sandstone, with rootlets 'rt' extending from the coal into the sandstone. West Venture N-91. (D-2) Coal bed with a few lenses of medium-grained sandstone over medium to coarse-grained sandstone. Sandstone has root traces 'rt' extending down from coal. West Venture C-62. (E-l) Bioturbated contact between mudstone and medium to coarse-grained sandstone with possible *Planolities* burrows 'pl'. West Venture C-62. (E-2) Completely bioturbated fine-sandstone with intraclasts 'ic', and mm-sized shell fragments 'sf'. Venture H-22. (F-1) Poorly sorted intraclast 'ic' conglomerate overlain by mudstone with fine to coarse-grained sandstone infilling burrows. West Venture N-91. (F-2) Bioturbated contact between very fine-grained sandstone and mudstone. Mud lens has *Chondrities* 'ch' burrows. West Venture C-62. (G-1) Thin, fine-grained sandstone beds with parallel laminations 'pλ' of mud and phytodetritus 'pd'. West Venture N-91. (G-2) Fine-grained sandstone with *Ophiomorpha* burrows 'om' and thin, discontinuous mud drapes 'md'. West Venture C-62. (H-1) Moderately bioturbated mudstone with silty to very fine-grained sand beds disturbed by bioturbation. Overlain by fine-grained sandstone with parallel to slightly wavy laminations 'pλ', 'wλ'. West Venture N-91. (H-2) Very coarse-grained sandstone beds alternating with mudstone beds. Few current ripples 'cr' preserved in finer sand lenses within mudstone. West Venture C-62. (H-3) Sharp-based, coarse-grained sandstone beds, alternating with mudstone. Some discontinuous very fine-grained sand laminations in mudstone show faint current ripples 'cr'. Sand beds have faint cross laminations 'xλ', and sparse *Ophiomorpha* burrows 'om'. Venture B-52. (H-4) Alternating thin, fine-grained sandstone and mud beds. A thicker sand bed has faint parallel 'pλ'. One mud lens has several *Chondrities* 'ch' burrows. Venture H-22. (I-1) Completely bioturbated muddy sandstone with many mud-lined vertical and subvertical burrows. Transitions up section to a completely bioturbated sandy mudstone. West Venture C-62. (I-2) Abundantly bioturbated very fine-grained sandstone, with common long vertical burrows 'vb'. Becomes gradually muddier upsection. Venture B-52. (J-1) Very fine-grained sandstone with *Ophiomorpha* burrows 'om', mud drapes and plant detritus 'md', 'pd'. West Olympia O-51. (J-2) Fine to medium-grained sandstone with subvertical *Ophiomorpha* burrow 'om', and thin mud drapes 'md'. West Venture N-91. (J-3) Fine-grained sandstone with *Ophiomorpha* burrows 'om' and faint mud drapes 'md'. West Venture C-62. (J-4) Sparsly bioturbated fine-grained sandstone with faint mud drapes 'md', plant detritus 'pd', and *Ophiomorpha* burrows 'om'. Venture H-22.

Table 1:Summary of sediment facies description and interpretation.

Facies	Subfacies	Lithology and texture	Primary sedimentary structures	Biogenic structures	General interpretation	Related facies	Notes on diagnostic criteria	Type example	Comparison with others
0	0g	sandstone, generally fine but may reach coarse	medium bedded; laminated or cross laminated, common erosional base; possible wave and current ripples	absent to sparse biot	River mouth to shoreface; prodeltaic turbidites	commonly overlies 1 and 2; may interbed with 9	lacks interbedded mudstone	2395	Gould (S4); Cummings and Arnott (6)
	0b	fine sandstone, siltstone, mudstone (sandstone > mudstone)	sharp, erosive based beds (<25 cm thick) with sltst laminae, interbedded with mst with sltst laminae; some lenticular bedding; parallel and cross laminae; variable sed structures as in Lamb et al, 2008; possible wave and current ripples	sparse to uncommon biot			sandstone:mudstone ratio	1150	Gould (S2b); Cummings and Arnott (3) and (5); Karim, 2008 (0t), (0s) and (0l)
	0m	mudstone, siltstone, very fine sandstone (mudstone >> sandstone)	some sltst or very fine sst laminae; parallel lam, x-lam, lenticular bedding; possible wave and current ripples	uncommon biot			sandstone:mudstone ratio; from 1 by sst; from 1 and 2b by lack of biot	2616	Gould (M1); Cummings et al. (4); Cummings and Arnott (4)
	0a	fine and coarse sandstone, mudstone (sandstone ><mudstone)	alternation of coarse and fine sst beds with interbedded mst; parallel lam, x-lam, lenticular bedding; possible wave and current ripples	absent to sparse biot			mudstone with coarse and fine grained sst	1146	
1		mudstone, <5% fine sandstone or siltstone	thin beds and laminae of parallel fine sst or sltst laminae	abundant to complete biot (*Chondrites* ichnofacies); uncommon thin shelled fossils - echinoderms, ammonites	Shelf	commonly overlies 3 and underlies 2 or 0	from 0 by biot; from 2b by sst; presence of marine shells	4246	
2	2b	mudstone, fine sandstone (10-60%)	destroyed by biot, possible remnants of storm beds with parallel lamination, wave ripples and wave dominated structures	generally moderate to common biot; possible shells, *Cruziana* ichnofacies; may have reworked shell frags at base of preserved beds	Shoreface	interbeds with 0; possibly grades into 3	from 0 by biot; from 1 by higher % of sand; less sst than 2c; diverse trace fossil assemblage; sst beds with possible shell hash at base, interbedded with biot sandy mst	1576	Gould (S4)
	2c	fine sandstone (60-95%), mudstone	destroyed by biot, possible remnants of storm beds with parallel lamination, wave ripples and wave dominated structures	common to complete biot, multiple species; possible shells; *Cruziana* ichnofacies; may have reworked shell frags at base of preserved beds			from 0s by biot; from 2b by sst; diverse trace fossil assemblage; primary structures rarely preserved; reworked shells, preserved structures are wave not current dominated	1383	Cummings and Arnott (14)
	2o	fine sandstone	generally thin to thick massive beds	sparse to moderate biot, horizontal *Ophiomorpha* burrows			like 4o but mud drapes absent	4338	
	2x	fine-rare medium sandstone	cross-bedding (mostly low angle), thin bed sets; rare mud drapes	sparse biot			from 4x because of biot, no mud drapes absent. Coal absent. Biot not *Skolithos* ichnofacies	4130	

Table 1:Summary of sediment facies description and interpretation.

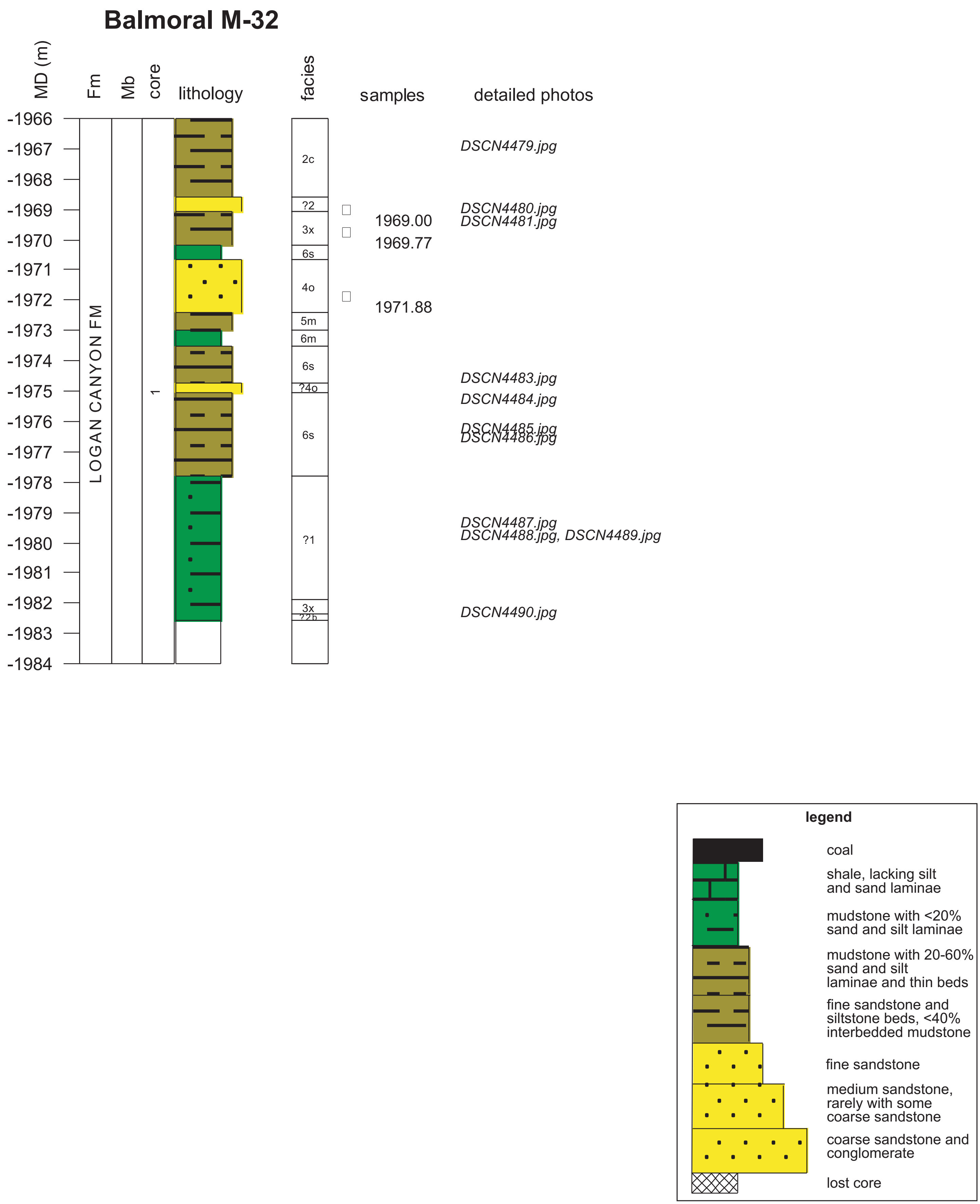
Facies	Subfacies	Lithology and texture	Primary sedimentary structures	Biogenic structures	General interpretation	Related facies	Notes on diagnostic criteria	Type example	Comparison with others
3	3x	sandy mudstone (10-50% sand); granules; poorly sorted; common brown staining due to early siderite	may have intraclasts	moderate to complete biot; thick shells	Condensed unit on shelf, commonly transgressive	commonly overlies 3y	mudstone	4262	Gould (C1)
	3y	muddy sandstone (50-90% sand), granules; poorly sorted; common brown staining due to early siderite	may have intraclasts	moderate to complete biot; thick shells		commonly overlies 3l or an erosion surface	sandstone	4356	Gould (M2); Cummings and Arnott (13)
	3i	intraclast conglomerate; common brown staining due to early siderite	may have intraclasts	may include shells			intraclast cgl	1547	
	3c	lithic conglomerate; common brown staining due to early siderite	may have intraclasts	may include shells			lithic cgl; generally rare	4326	
	3f	firm ground	evidence of strong sed.; commonly associated intraclasts; erosion or incision of underlying sediment	some burrow penetrating firm ground, *Glossifungites*			evidence of firm ground; generally rare	1716	
	3l	bioclastic limestone	parallel lam	abundant shell fragments, possibly in place			bioclastic limestone	3956	Gould (L1); Cummings et al. (7)
	3o	oolitic limestone and sandstone	parallel lam	possible biot			oolitic limestone and sandstone	2572	
4	4o	principally fine sandstone	thin to medium bedded, may be cross-bedded; thin mud drapes	sparse to common biot, *Ophiomorpha* , *Skolithos* ichnofacies	Tidal estuary to fluvial	passes up into 5 or 2	from 5-4 by *Ophiomorpha* burrows; common mud drapes;	4297	Karim, 2008 (4o); Karim, 2008 (4u)
	4a	medium to coarse sandstone (>50%); mudstone	thin sharp-based sst beds (can be >30 cm thick, ave 5-10 cm), interbedded with thin to thick mst drapes. Mst drapes have m-cg lam (simular to 6) may have current ripples	biot absent; coal lam, intraclasts		may be interbedded with 4, 5, 6	from 4g by thick mud drapes with facies 6 character; from 6 by alternating cg sst beds and thick mst drapes	4913	
	4g	medium to coarse sandstone; may have coarse grained lag at base of unit; <5% mst	typically thin-bedded, parallel to low angle; mud drapes	absent to sparse biot			from 4x by presence of mud drapes and possible sparse biot	1098	Gould (S1); Cummings et al. (2); Cummings and Arnott (10, 12)
	4x	medium to coarse sandstone; mudstone intraclasts; may have coarse grained lag at base of unit	thin to thick cross-beds, med to high angle	biot absent; coal intraclasts			from 4g by coarser grainsize, high-angle cross-bedding, lack of mud drapes	2297	Cummings et al. (1)
	4n	mudstone, siltstone, very fine sandstone (sandstone>mudstone)	"tidal bundles" of poorly sorted sand and silt; or well-sorted fine sand, rarely with ripples; mud partings 1-2 mm	biot absent or sparse			more silt and sand than 0m; differs from 0a in lack of coarse sst beds	2622	Cumings and Arnott (2); Karim, 2008 (0n)
5	5m	>75% sandstone, predominantly fine may have medium or coarse grained beds, mudstone	thin bedded; variable mud drapes; mud, slt, and vf sst parallel & x-lam; mud on ripples	variable biot - sparse to moderate, or common to abundant, *Skolithos* ichnofacies; ?plant frags	Mixed flat - intertidal		from 6s by sandstone dominance; from 2 by less biot and dominant subvertical burrows, preservation of primary structures diagnostic of tidal environ.	Panuke B-90 core 8, box 24	Gould (S3); Cummings et al. (5); Cummings and Arnott (7)
	5s	>95% sandstone, generally fine may be medium or coarse grained, minor mudstone	possible thin to med bedded; some x-bedding	sparse to mod biot; shells	Sand flat - intertidal to subtidal	may pass up into 4o	mud drapes and *Ophiomorpha* rare compared to 4o; cross- bedding diagnostic; from 2 by less biot, subvertical burrows dominant, preservation of primary structures diagnostic of tidal environ.	4323	Karim, 2008 (4s)

Table 1:Summary of sediment facies description and interpretation.

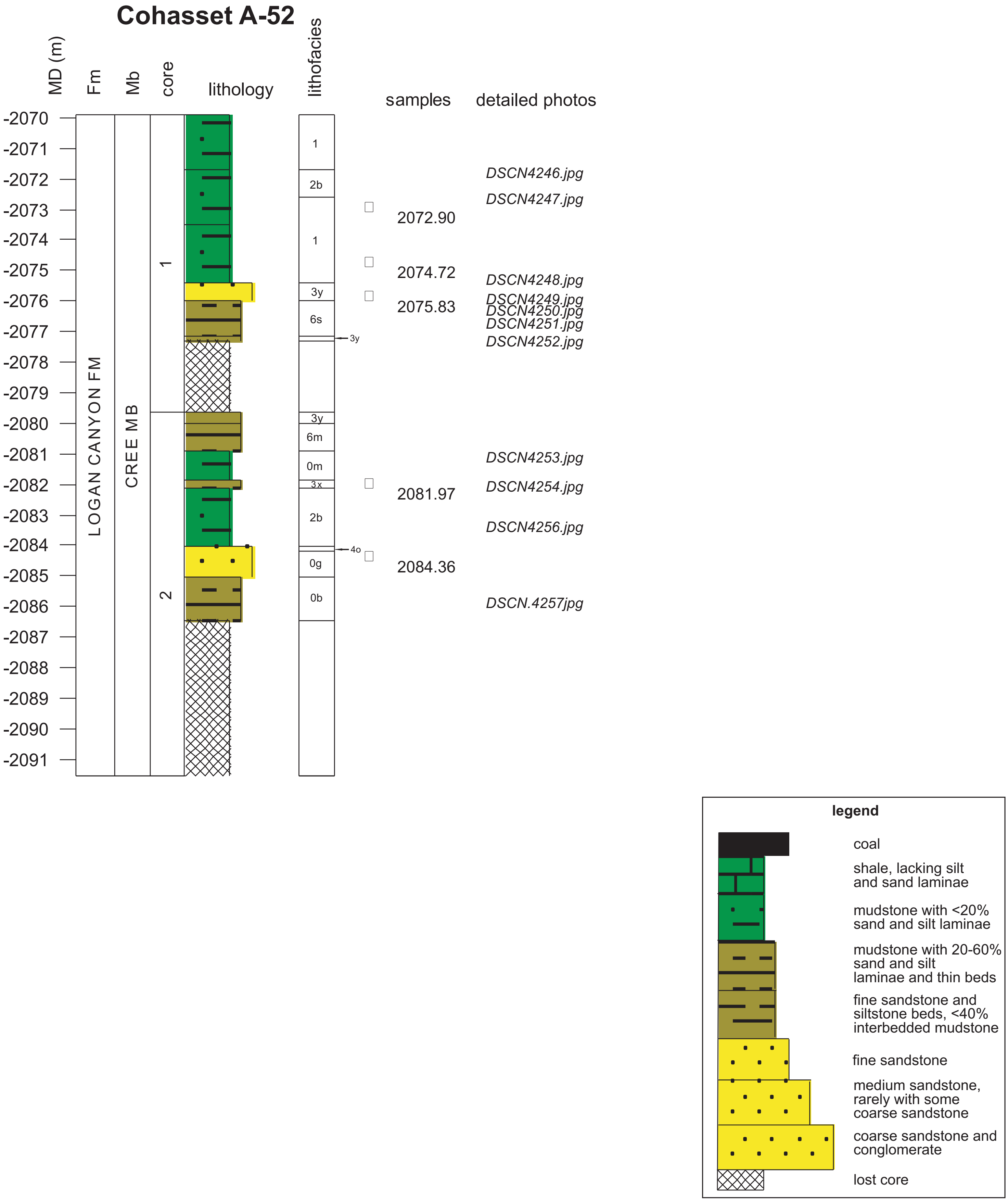
Facies	Subfacies	Lithology and texture	Primary sedimentary structures	Biogenic structures	General interpretation	Related facies	Notes on diagnostic criteria	Type example	Comparison with others
	5b	20-75% sandstone, predominantly fine may have medium or coarse grained beds	destroyed	abundant to complete biot - common large and long subvertical burrows; may have shells	Mixed flat - intertidal	transitional to 2	large subvertical burrows; from 2 by less biot, subvertical burrows dominant, preservation of primary structures some diagenetic of tidal environ.	4334	
	5c	medium sandstone	sharp based, thin beds	absent	Tidal channel - subtidal	within 5/6	thin beds within 5/6	4185	
6	6s	subequal fine sandstone,mudstone; or 60-75% mudstone, fine sandstone; may have minor medium-coarse sandstone, e.g. in burrows	mud dominant sections with wavy or current ripples and mud on ripple lam, interbedded with prominant parallel lam sst and mst (pinstripe-shaped)	small *Skolithos* ichnofacies burrows absent to common; possible plant frags	Mixed flat- intertidal	commonly interbedded with 4, 5, 7, 8	like 0 but with *Skolithos* burrows, current ripples	4299	Cummings et al. (3); Cummings and Arnott (11); Cummings (P4)
	6b	>80% mudstone, minor very fine to fine sandstonemay have minor medium-coarse sandstone, e.g. in burrows	destroyed; rare preserved parallel lam, current ripples	common to complete biot; may have whole or fragments of oyster shells	Mudflat- intertidal		from 5b by mud dominance; oyster shells	4169	
	6m	>95% mudstone, may have minor medium-coarse sandstone	rare discontinuous lam, broken by subvertical to vertical burrowing	biot absent to common, may have burrows (horizontal and subvertical) filled with m-c sst; ?oyster shells	Mudflat- intertidal		from other 5/6 by mudstone dominance	Panuke B-90 core 8 box 28	Cummings (P4)
7		lignite or carbon-rich mud		rootlets beneath	Tidal marsh	may overlie 6	lignite or carbon-rich mud	4188	
8		mudstone, rare siltstone	planar parallel to low angle cross siltstone lam	biot generally absent to sparse, with locally intense biot	Lagoon	interbeds with 5 & 6	1 has fossils and overlies 3, is more biot; 8 interbeds with 5 and 6	4053	Cummings (P3)
9	9g	very coarse to fine sandstone, some graded beds	sharp-based beds, some with erosive structures (sole marks); predominantly massive beds, generally >25cm thick, with minor parallel or cross laminae at top of some beds; possible mud intraclasts	absent to moderate biot at top of beds; plant detritus; possible reworked coastal deposits (shells, sid nodules)	River mouth to prodelta turbidite	commonly interbedded with 0, overlain by 4o	from facies 0 by bed thickness; from 9s by lack of interbedded mudstone	1688	Gould (S2c); Cummings and Arnott (8); Karim, 2008 (4b)
	9s	fine sandstone, minor mudstone, minor interbedded facies 0	sharp-based beds, some with erosive structures (sole marks); generally >25 thick, parallel lamination at base and cross lamination at top; some beds have mud intraclasts near base	moderate biot at top of beds; plant detritus; possible reworked coastal deposits (shells, sid nodules)			from facies 0 by bed thickness	4535	Gould (S2a), Karim 2008 (9m)
10	10f	mudstone to muddy sandstone	destroyed by deformation; secondary structures - massive texture, horizontal foliation	-	Deformed facies	commonly interbedded with 0		Alma K-85 core 3	
	10g	sandstone	destroyed by deformation; secondary structures - liquified beds	-				Alma K-85	
	10s	sandstone, siltstone, mudstone,	mostly destroyed by deformation; secondary structures - sheared and folded beds	variable biot				1466	

Appendix 1

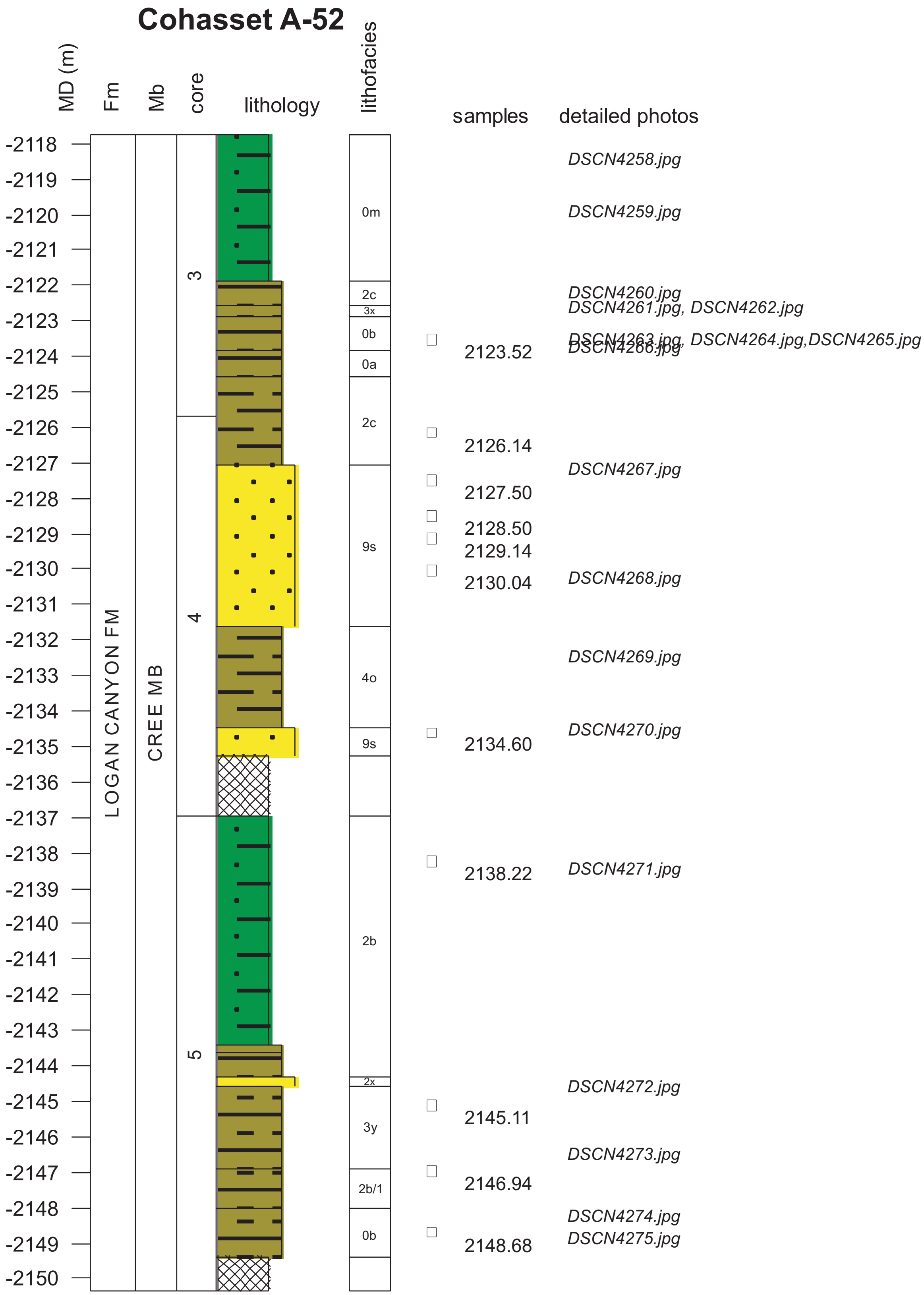
Down core plots with detailed photo and sample locations



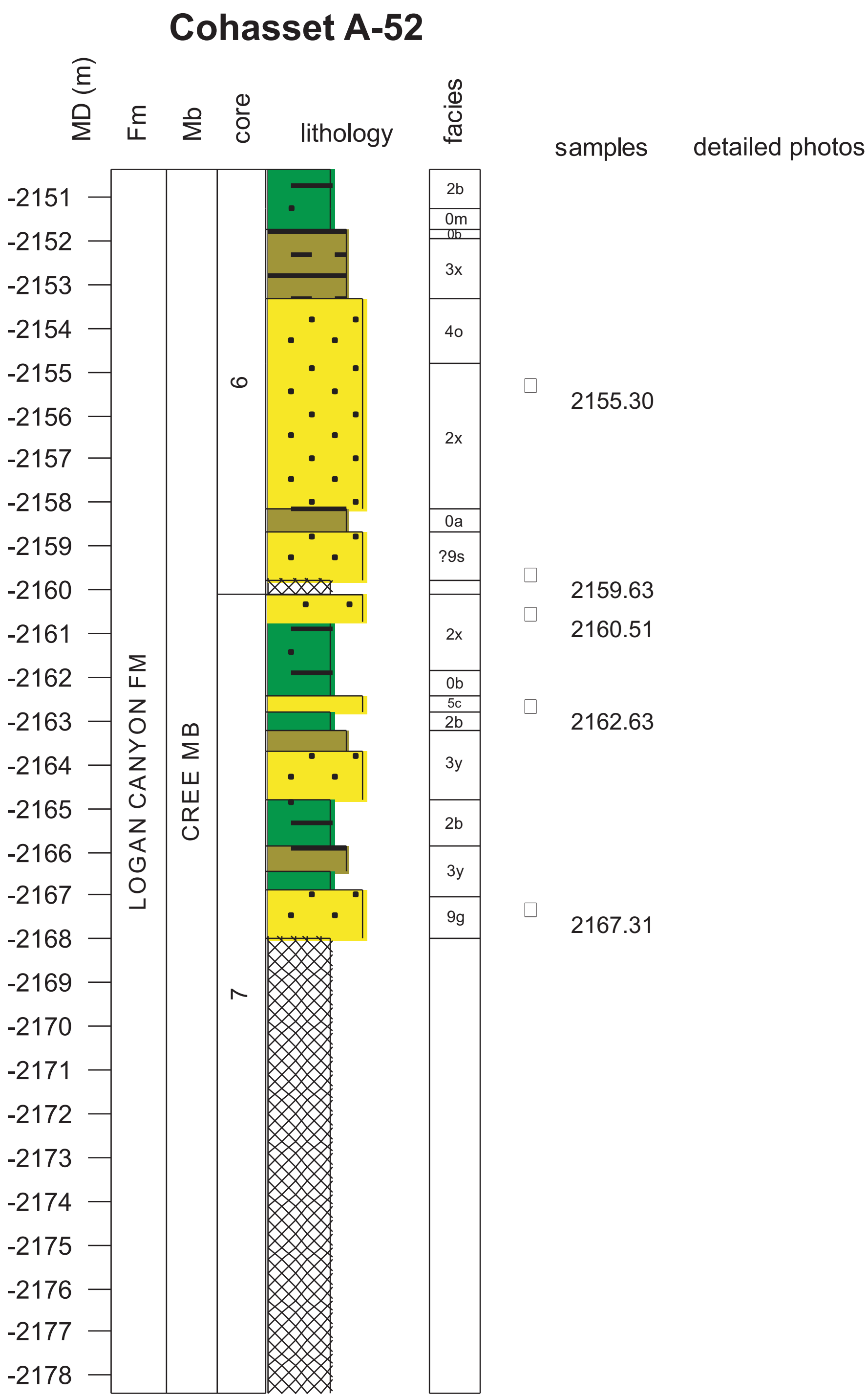
Appendix 1A: Summary log of conventional core 1 from the Balmoral M-32 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



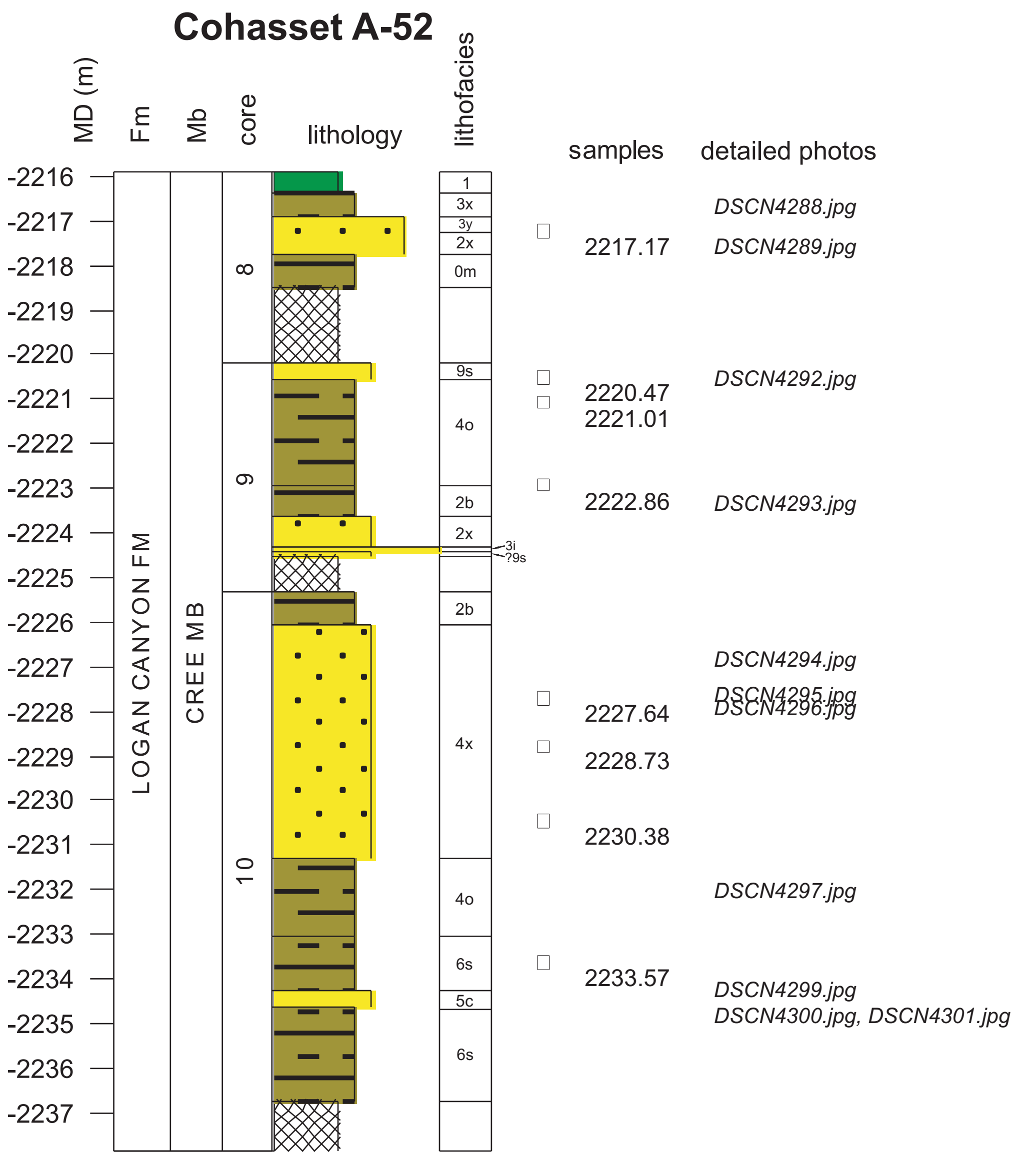
Appendix 1B: Summary log of conventional cores 1-2 from the Cohasset A-52 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



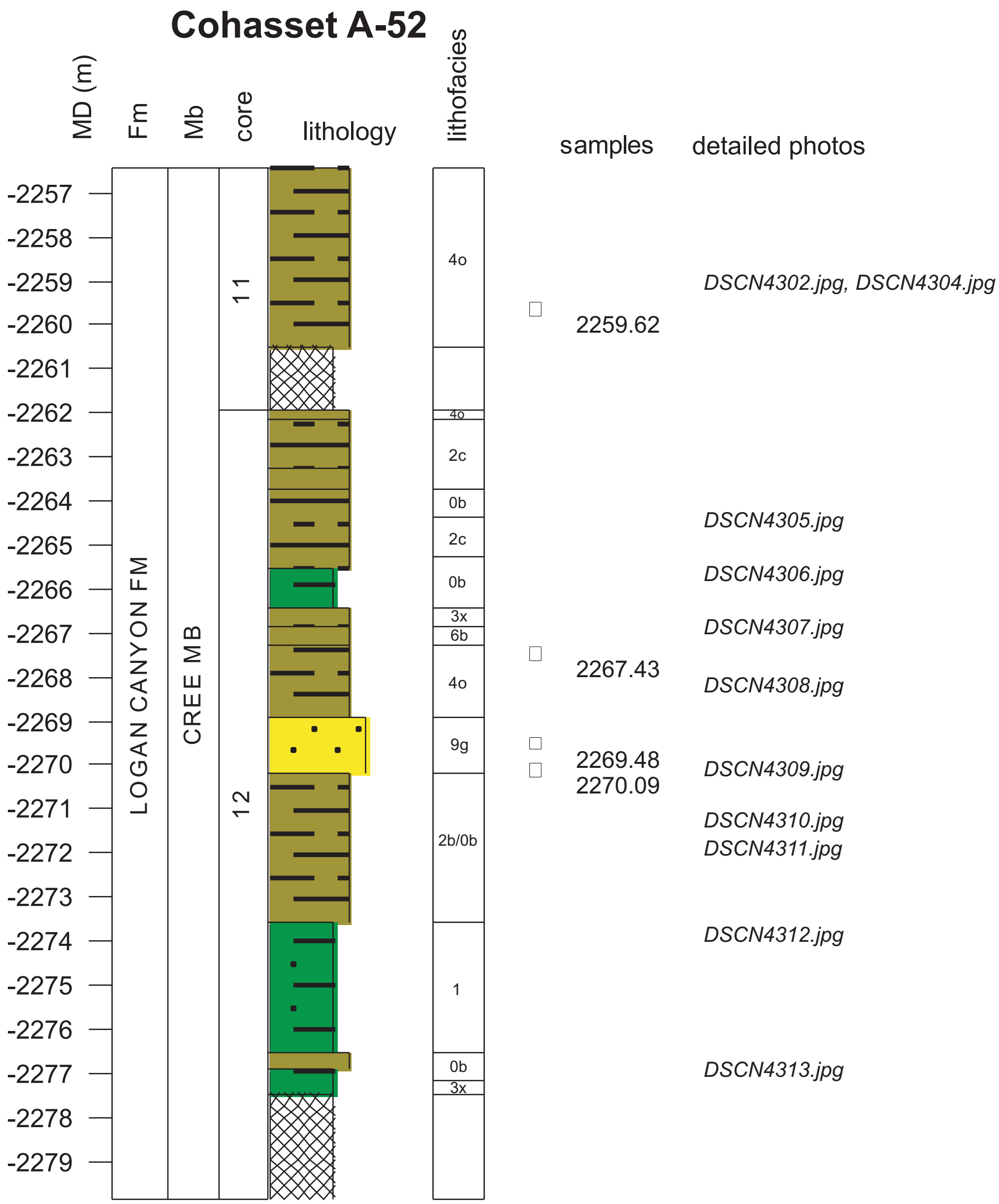
Appendix 1B (con't): Summary log of conventional core 3-5 from the Cohasset A-52 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



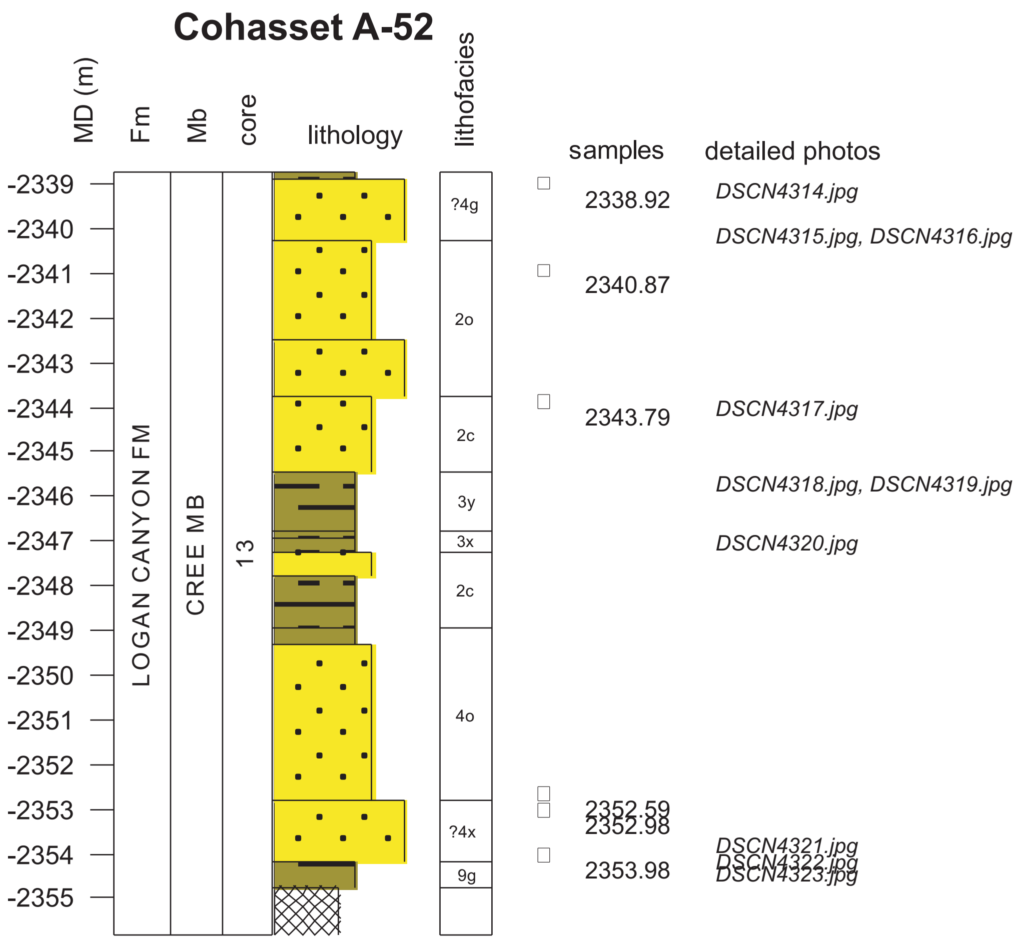
Appendix 1B (con't): Summary log of conventional core 6-7 from the Cohasset A-52 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



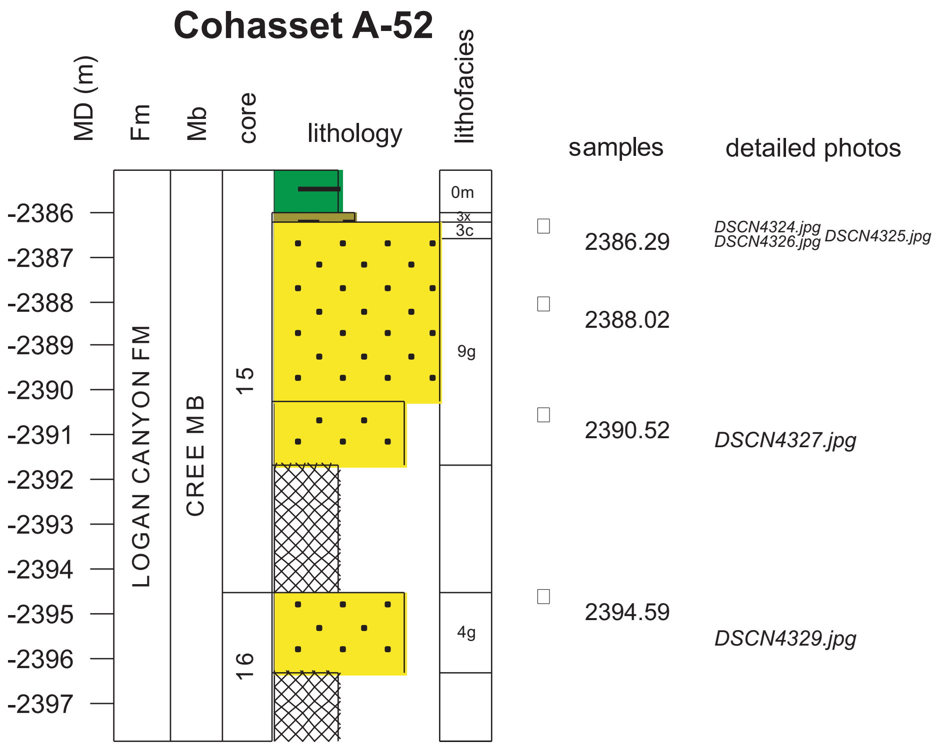
Appendix 1B (con't): Summary log of conventional core 8-10 from the Cohasset A-52 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



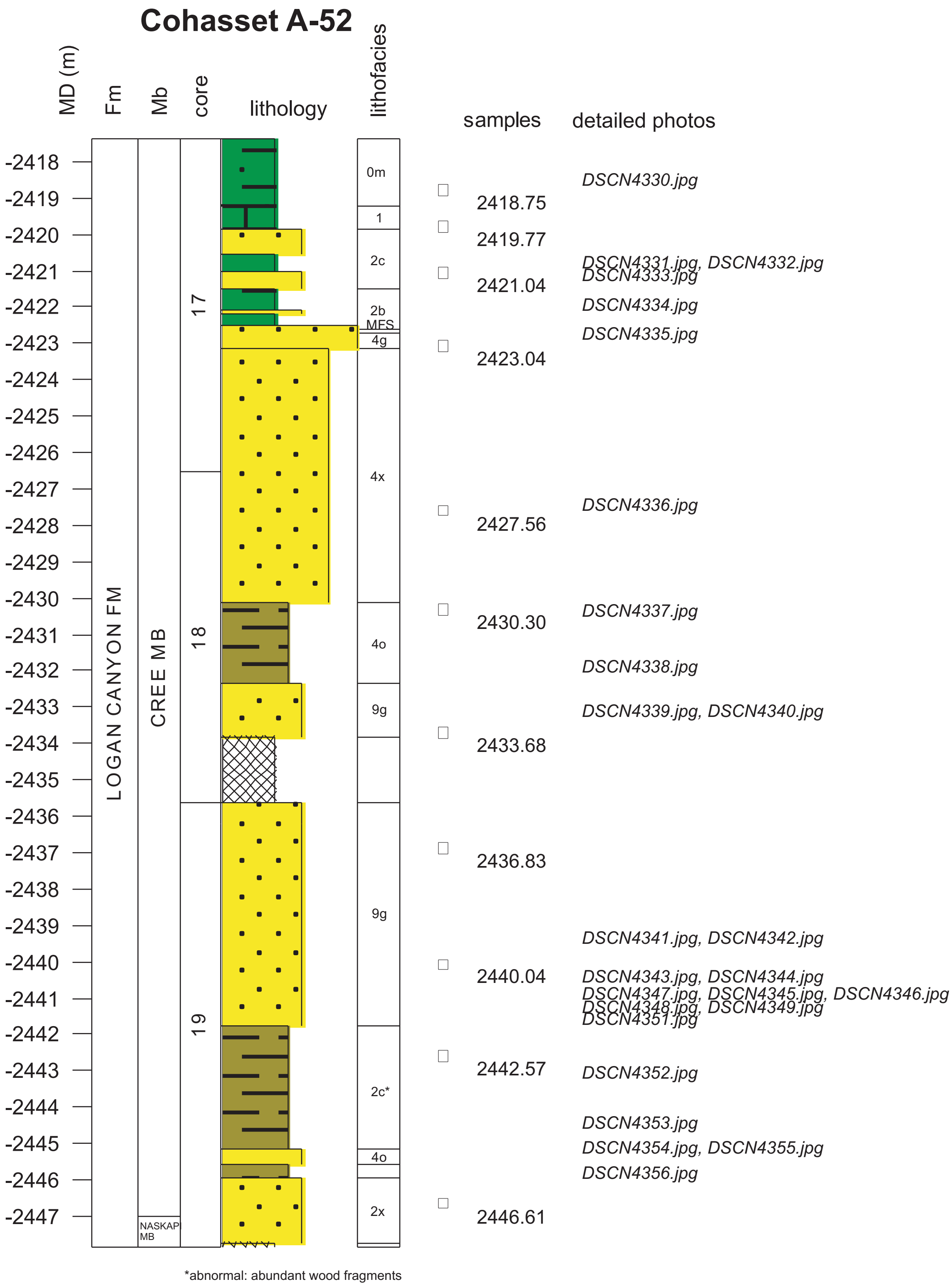
Appendix 1B (con't): Summary log of conventional core 11-12 from the Cohasset A-52 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



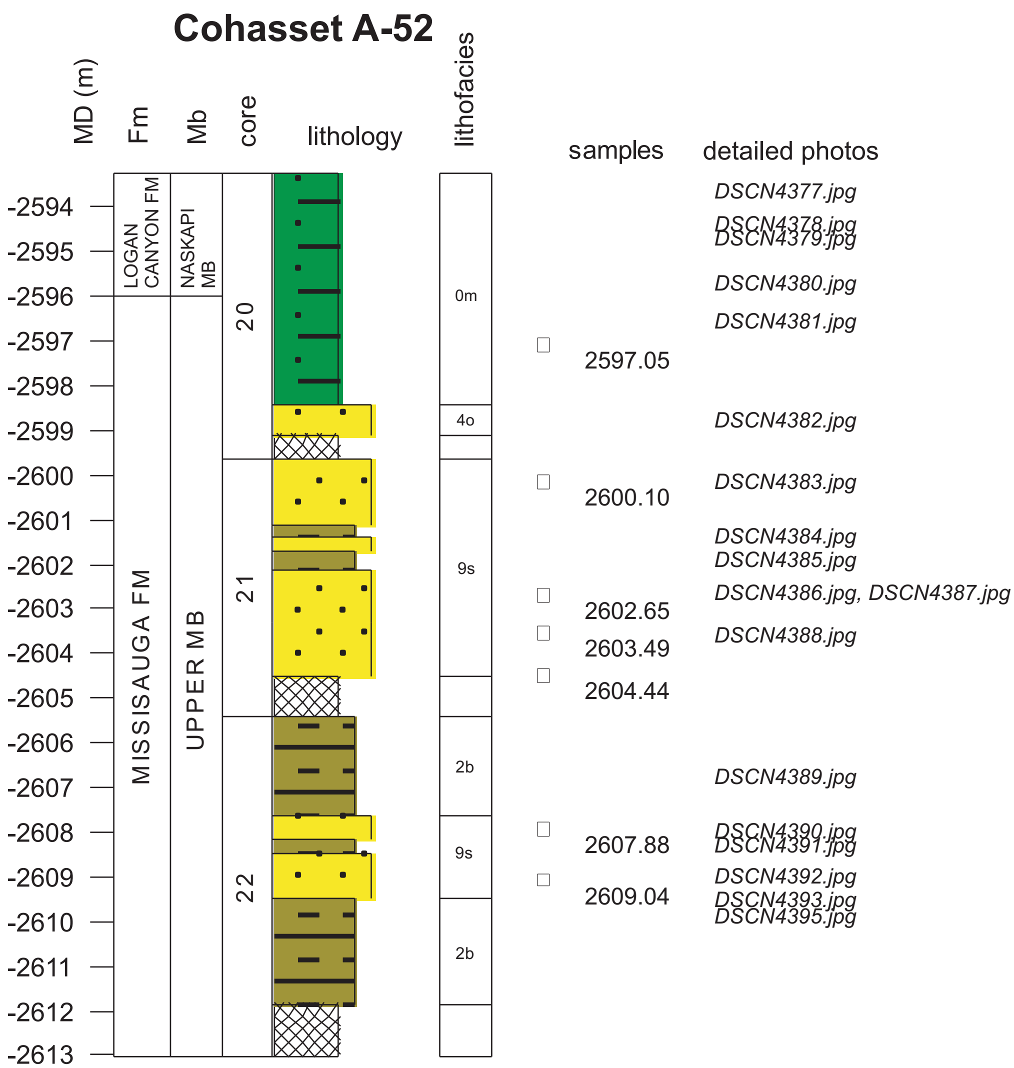
Appendix 1B (con't): Summary log of conventional core 13 from the Cohasset A-52 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



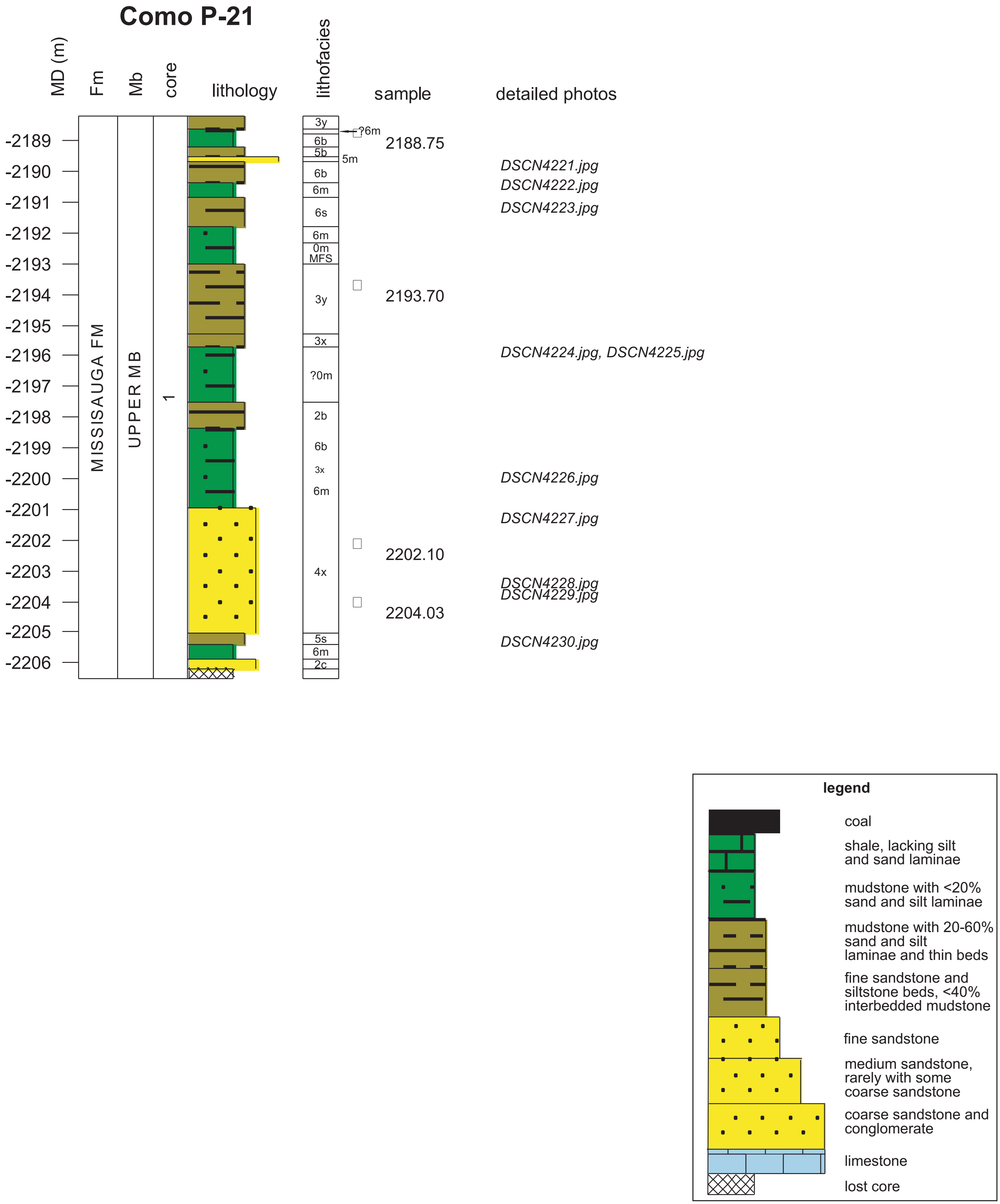
Appendix 1B (con't): Summary log of conventional core 15-16 from the Cohasset A-52 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



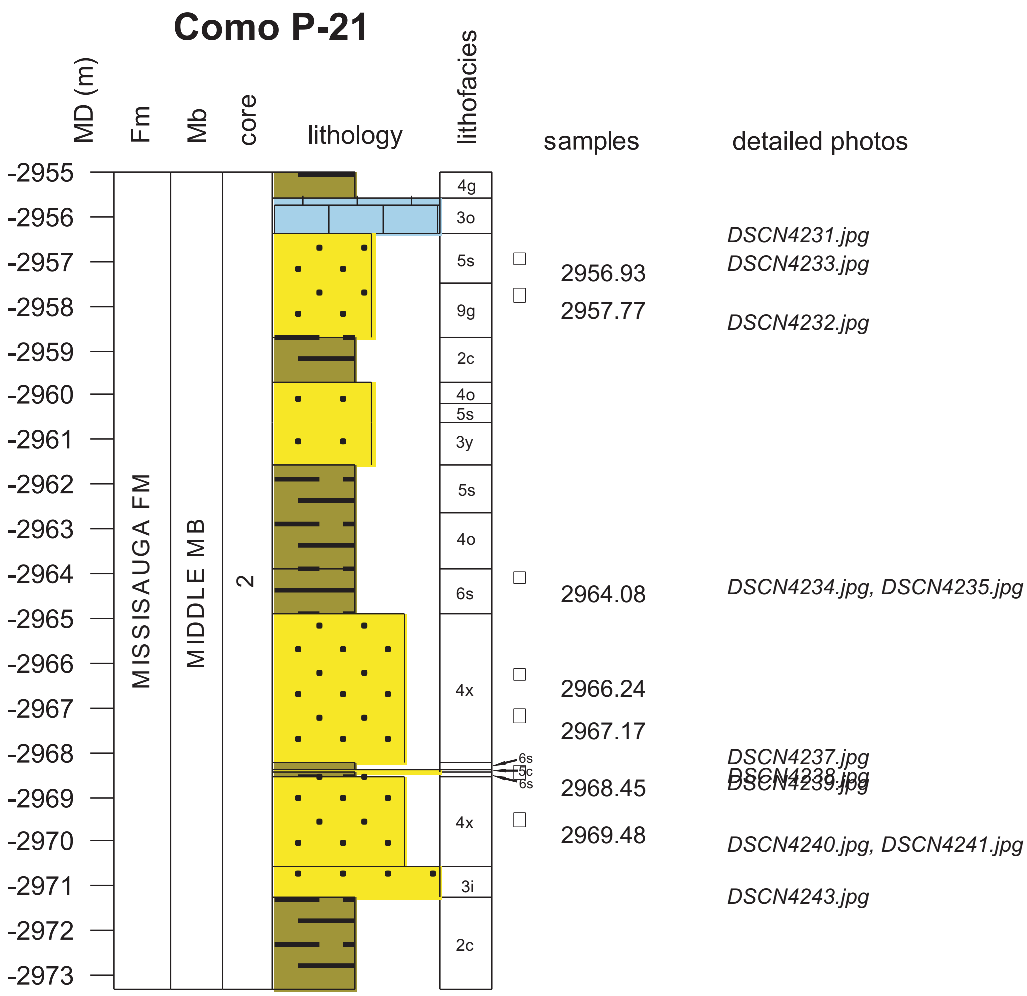
Appendix 1B (con't): Summary log of conventional core 17-19 from the Cohasset A-52 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



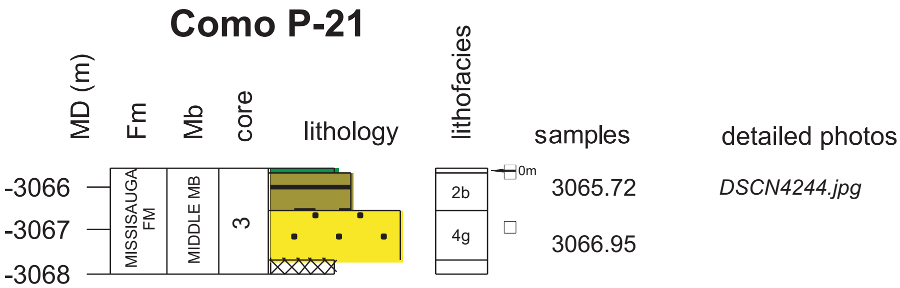
Appendix 1B (con't): Summary log of conventional core 20-22 from the Cohasset A-52 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



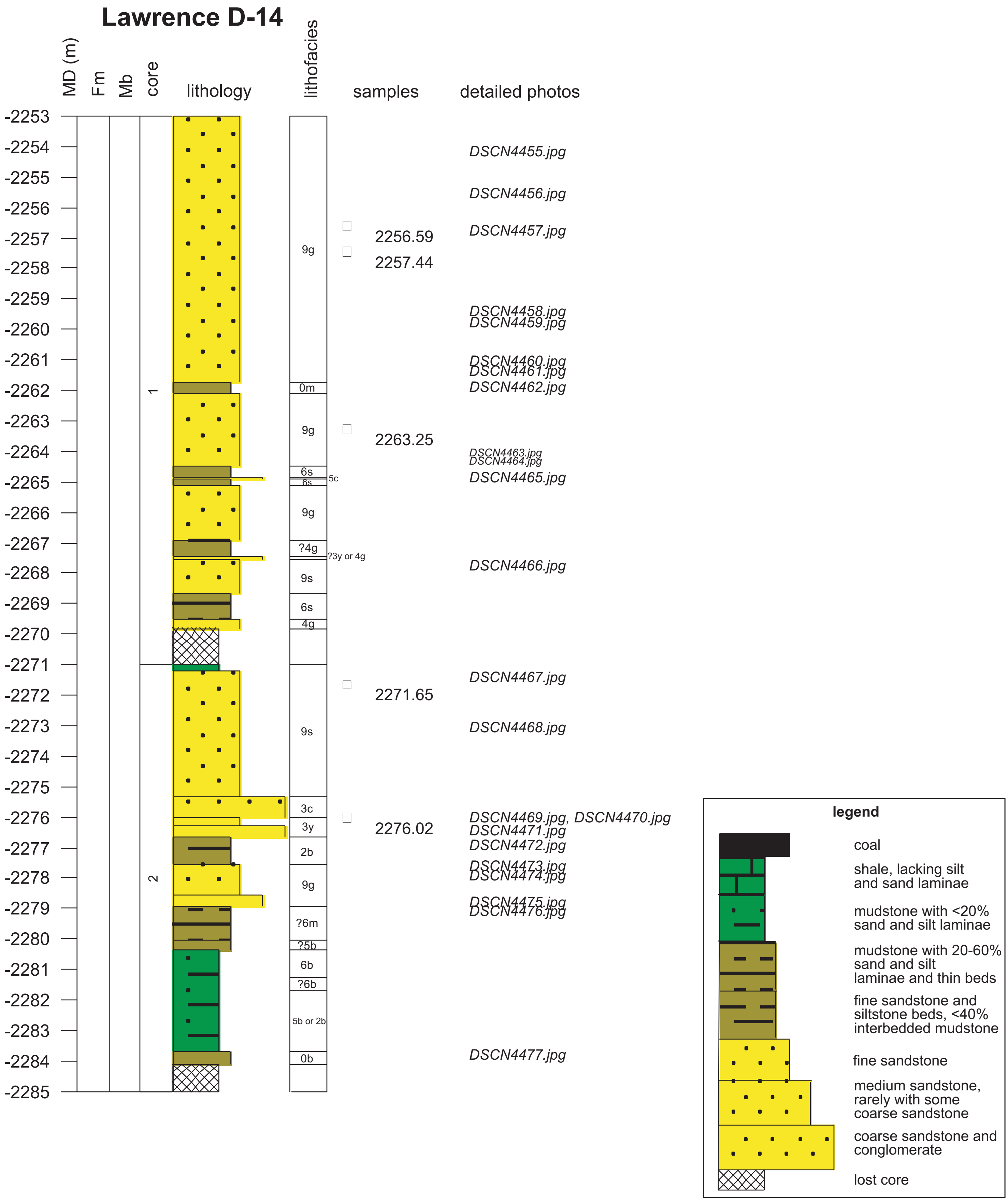
Appendix 1C: Summary log of conventional core 1 from the Como P-21 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



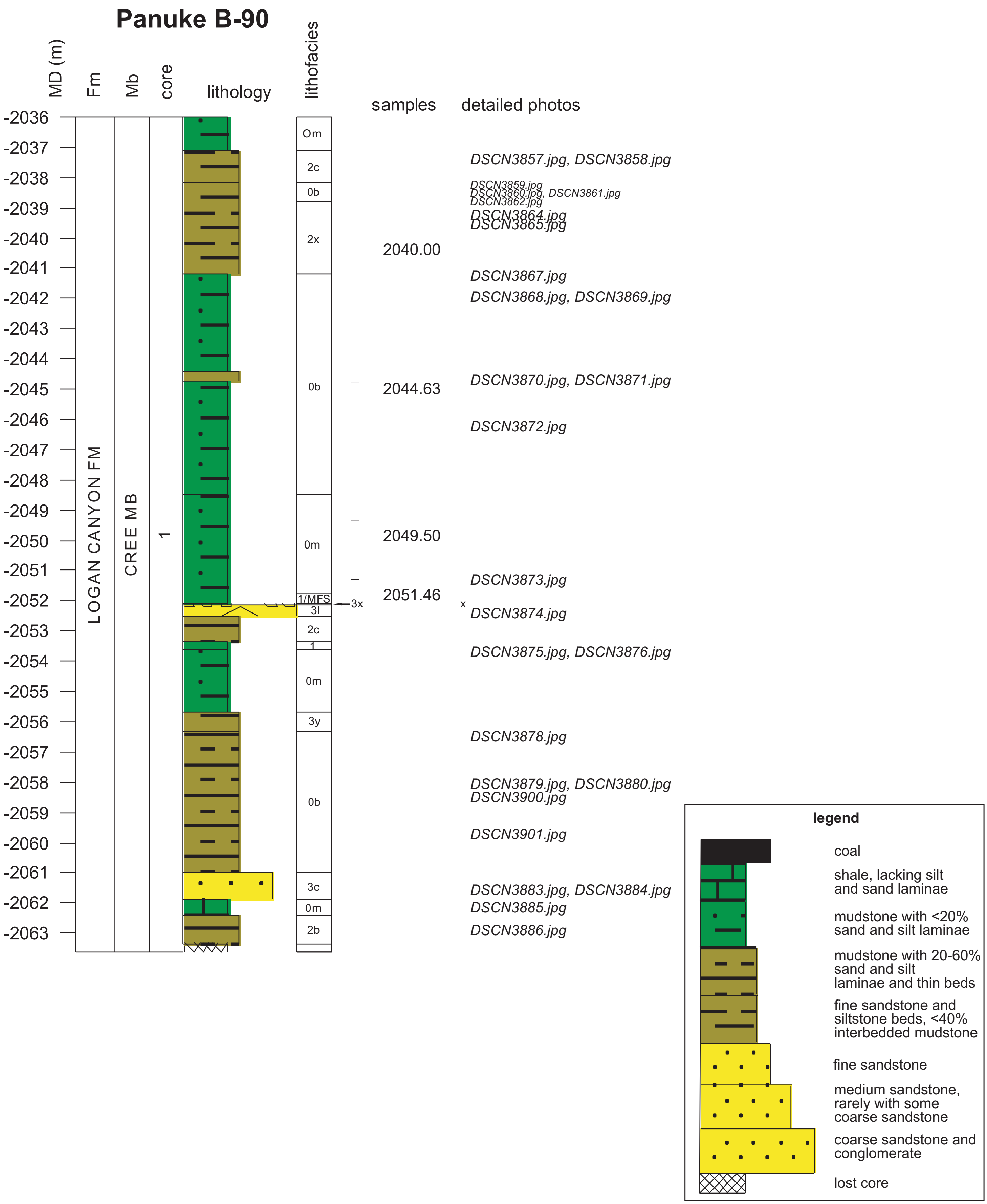
Appendix 1C (con't): Summary log of conventional core 2 from the Como P-21 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



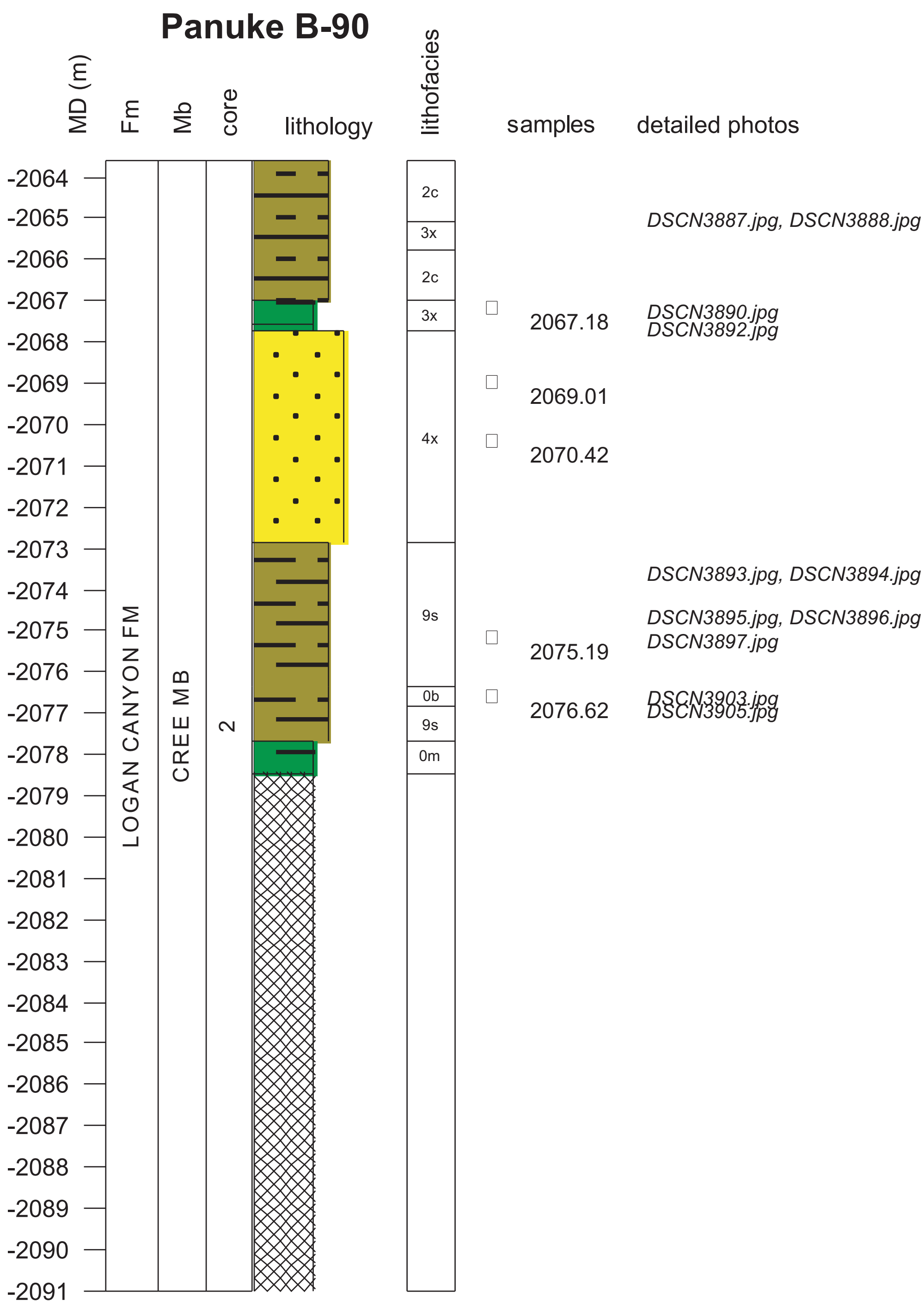
Appendix 1C (con't): Summary log of conventional core 3 from the Como P-21 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



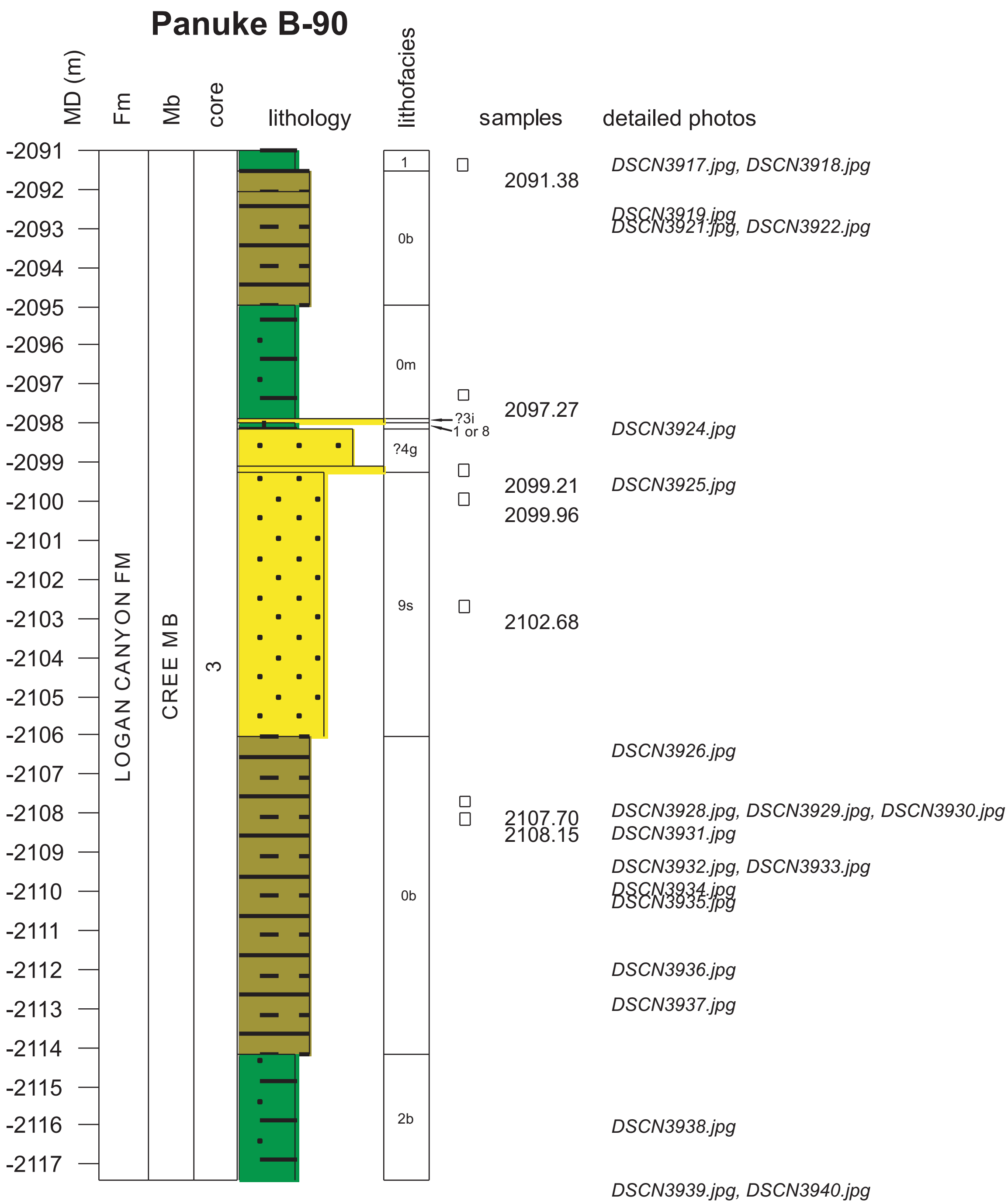
Appendix 1D: Summary log of conventional core 1 and 2, from the Lawrence D-14 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



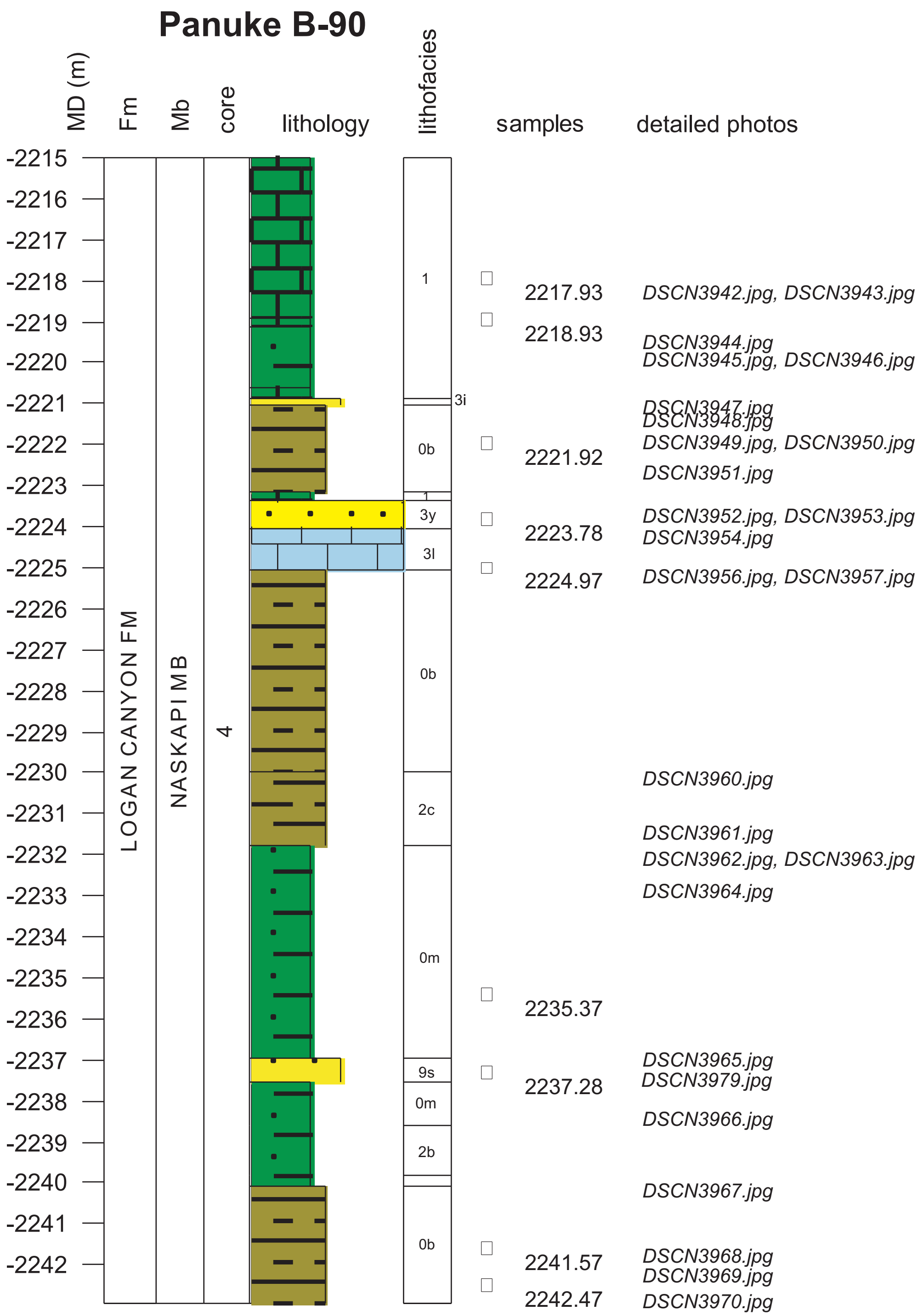
Appendix 1E: Summary log of conventional core 1, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



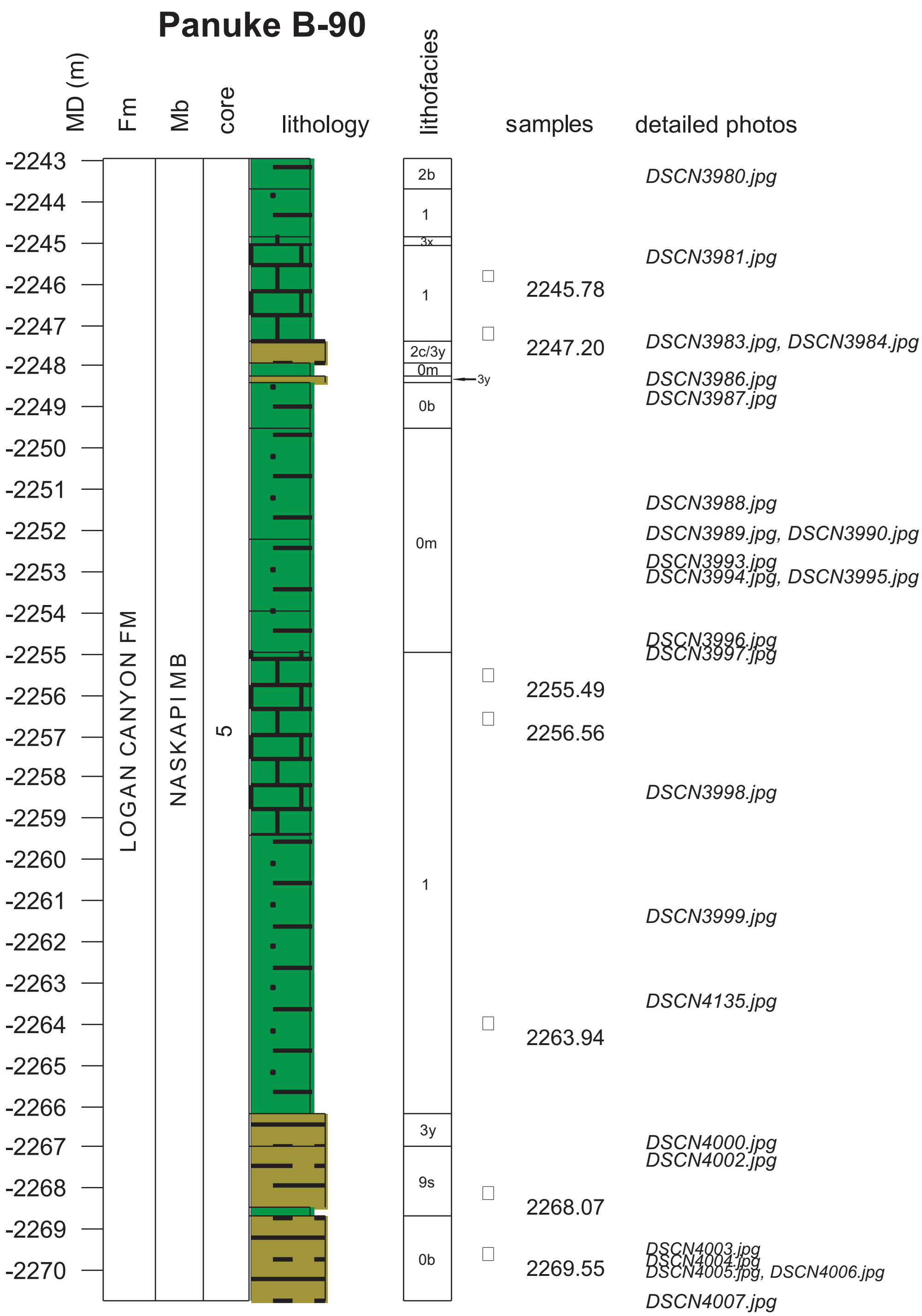
Appendix 1E (con't): Summary log of conventional core 2, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



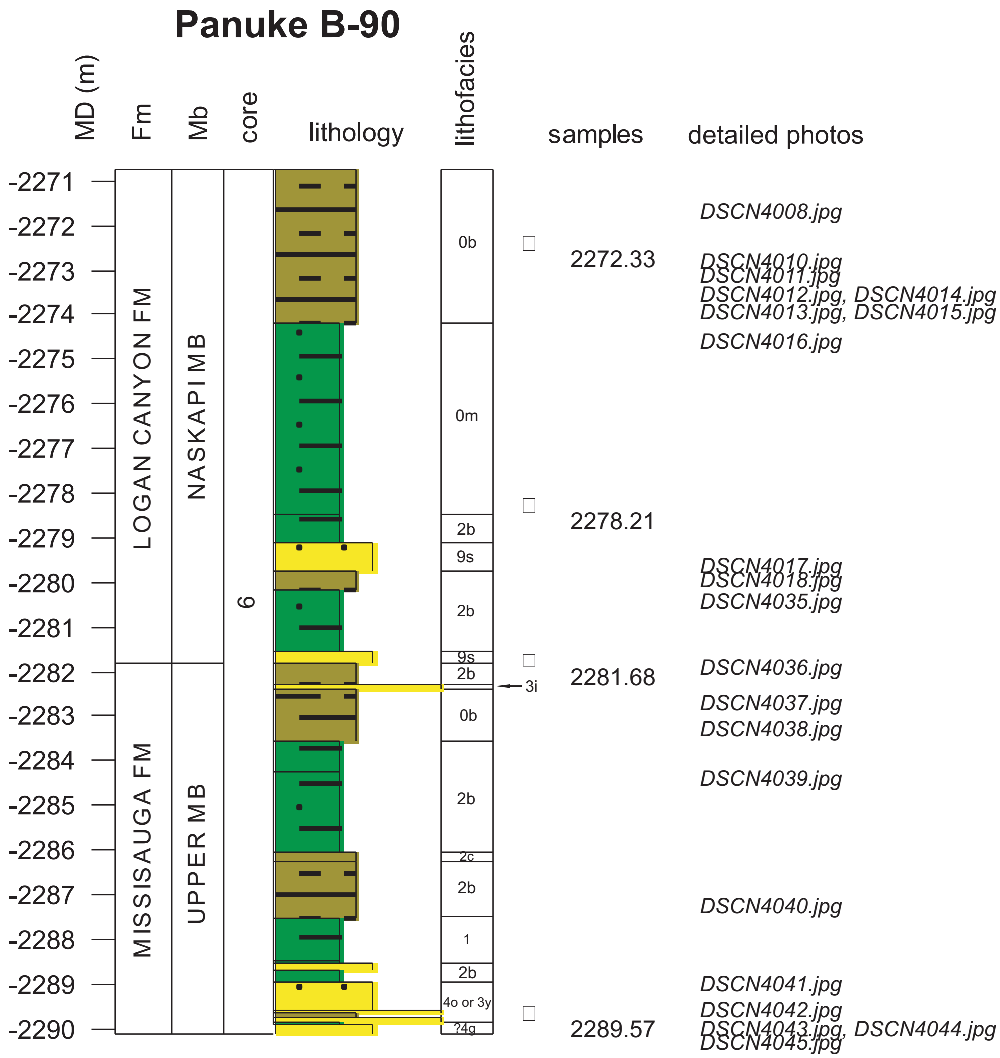
Appendix 1E (con't): Summary log of conventional core 3, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



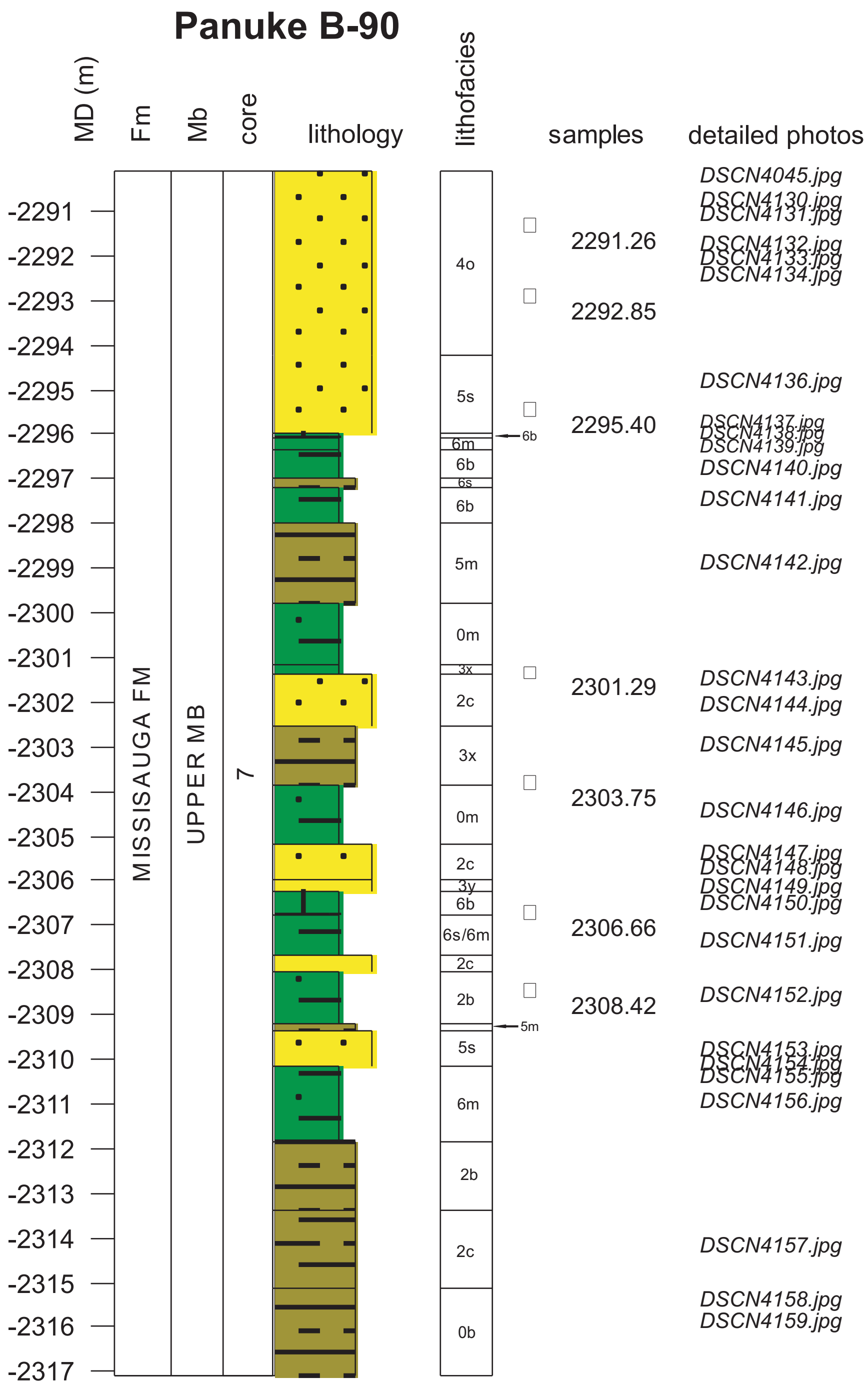
Appendix 1E (con't): Summary log of conventional core 4, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



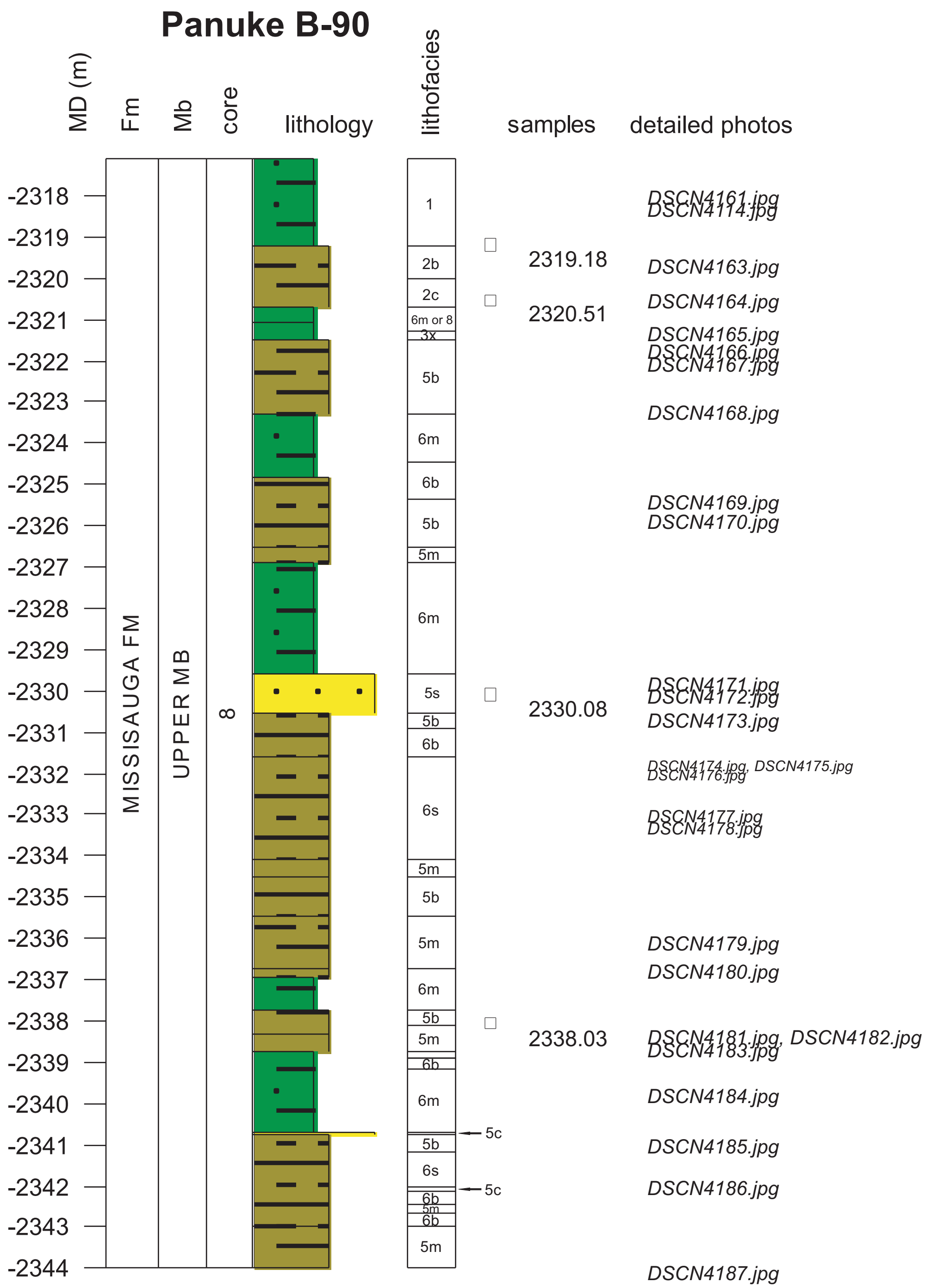
Appendix 1E (con't): Summary log of conventional core 5, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



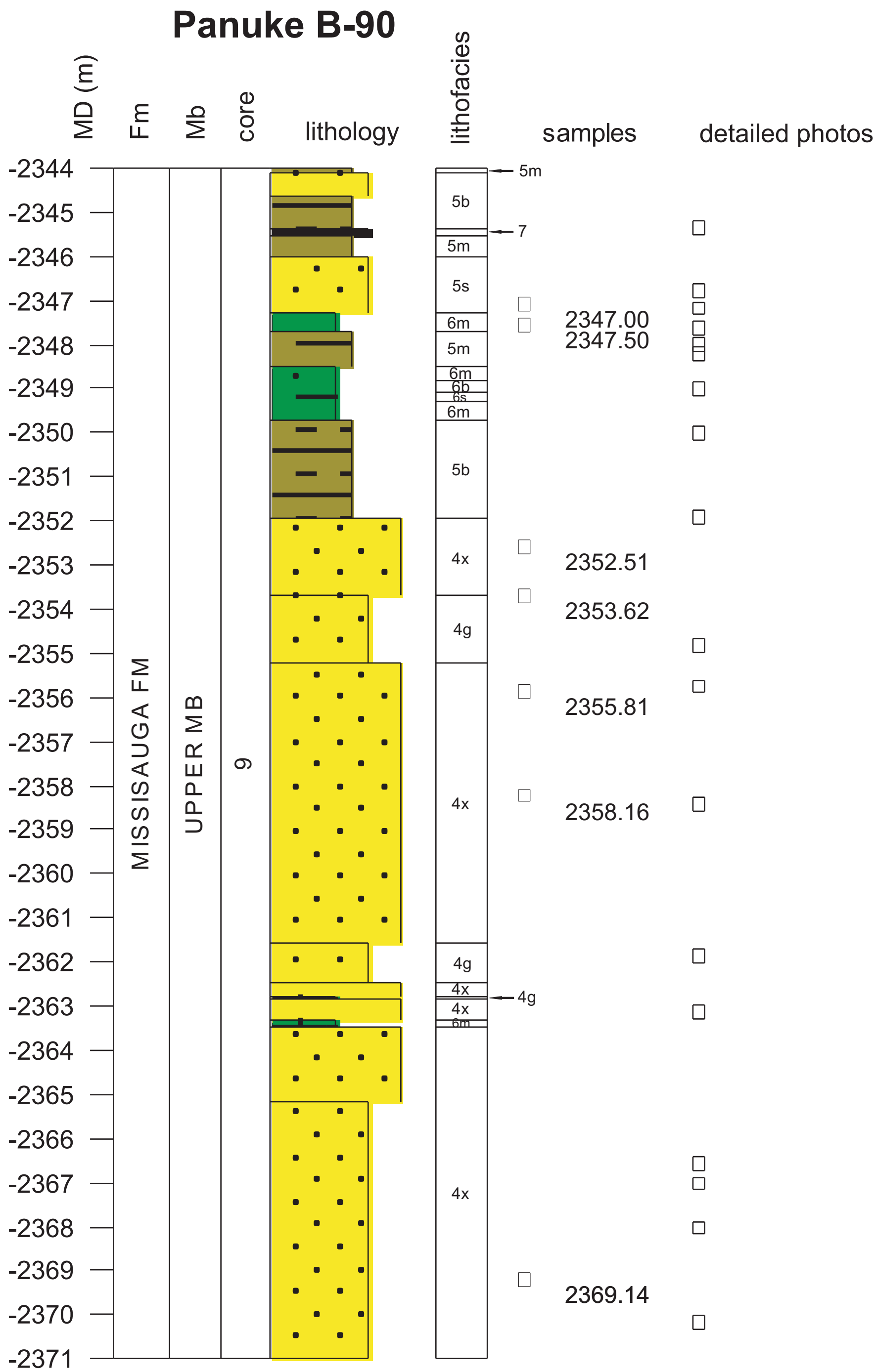
Appendix 1E (con't): Summary log of conventional core 6, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



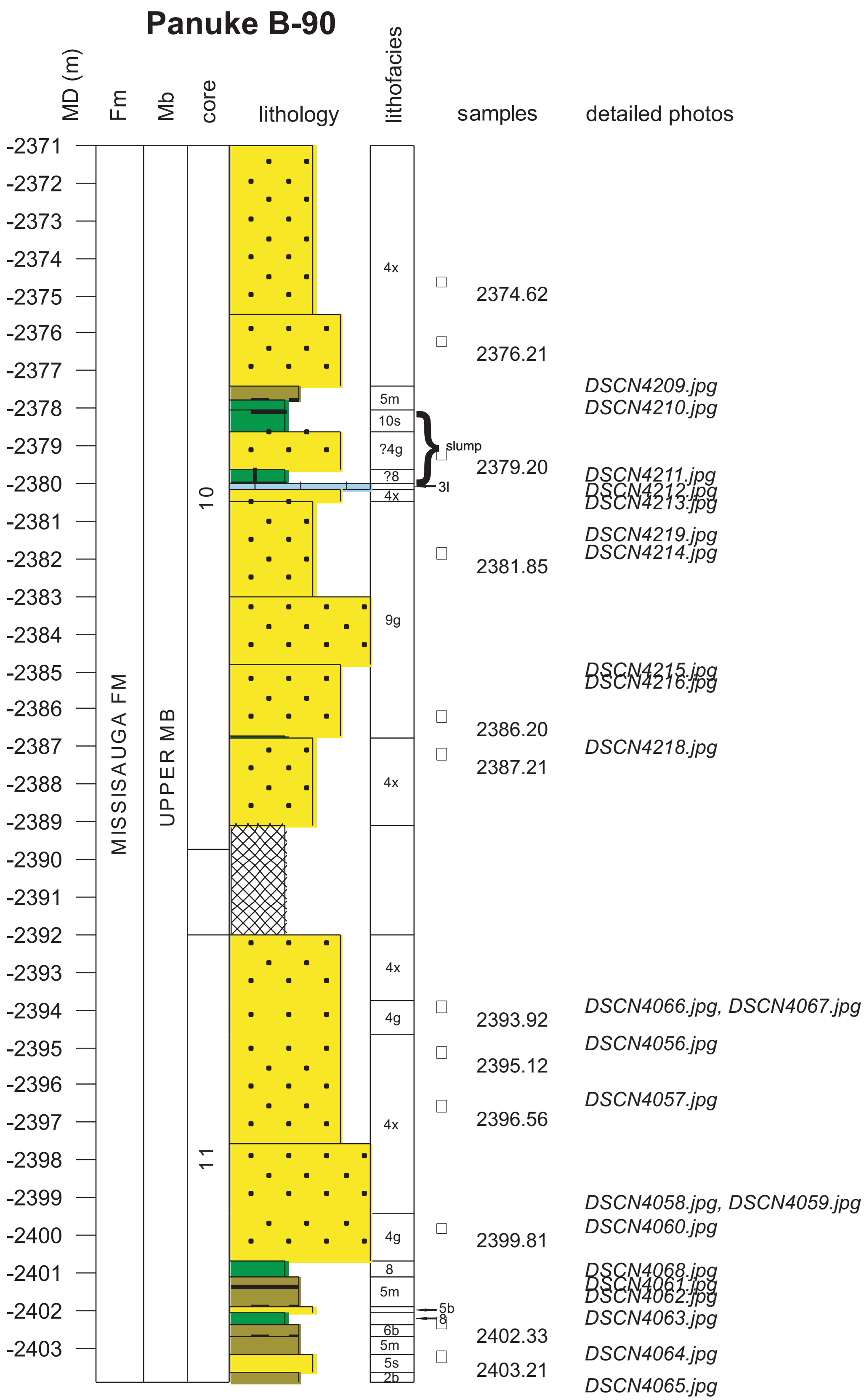
Appendix 1E (con't): Summary log of conventional core 7, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



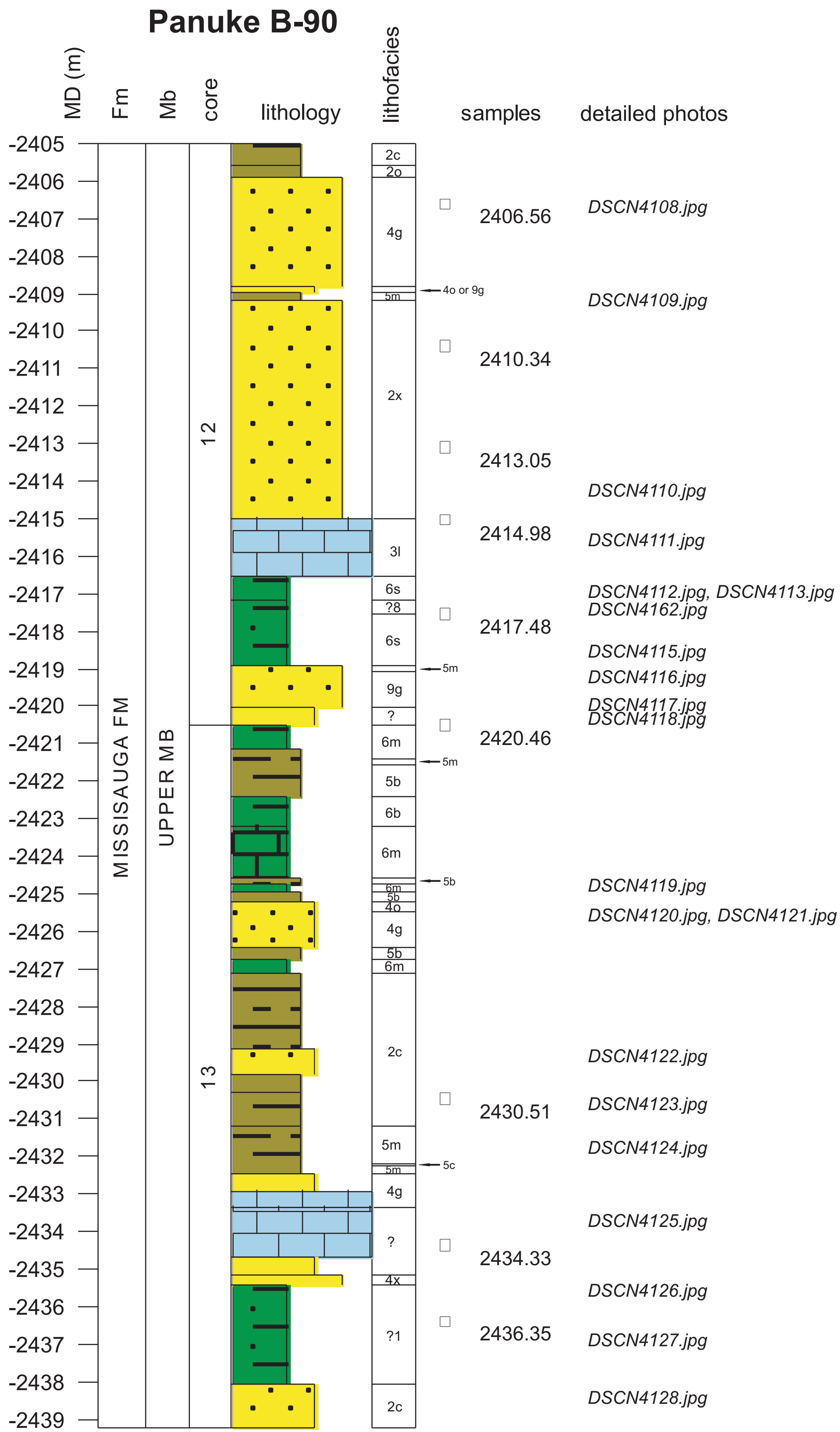
Appendix 1E (con't): Summary log of conventional core 8, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



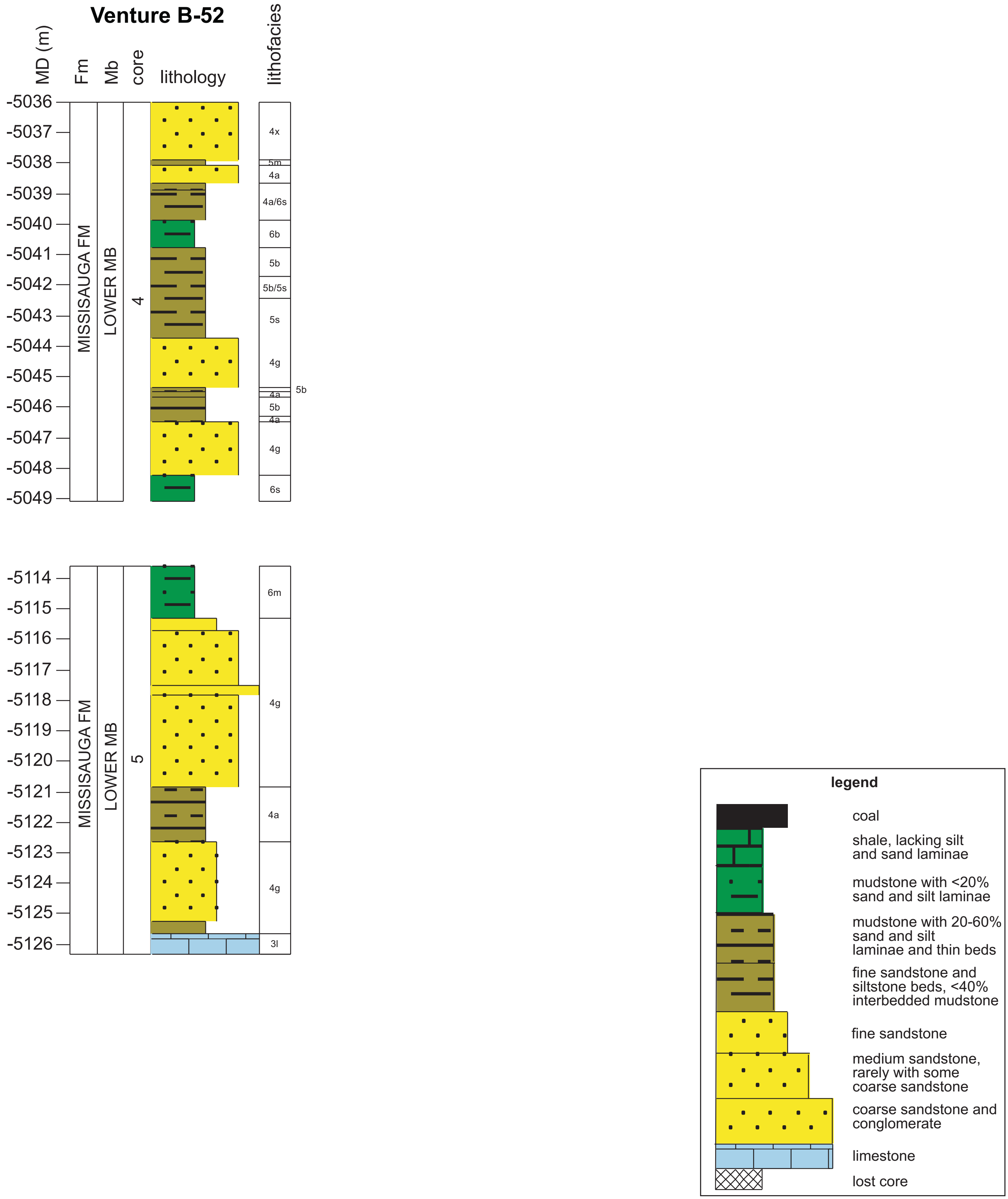
Appendix 1E (con't): Summary log of conventional core 9, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



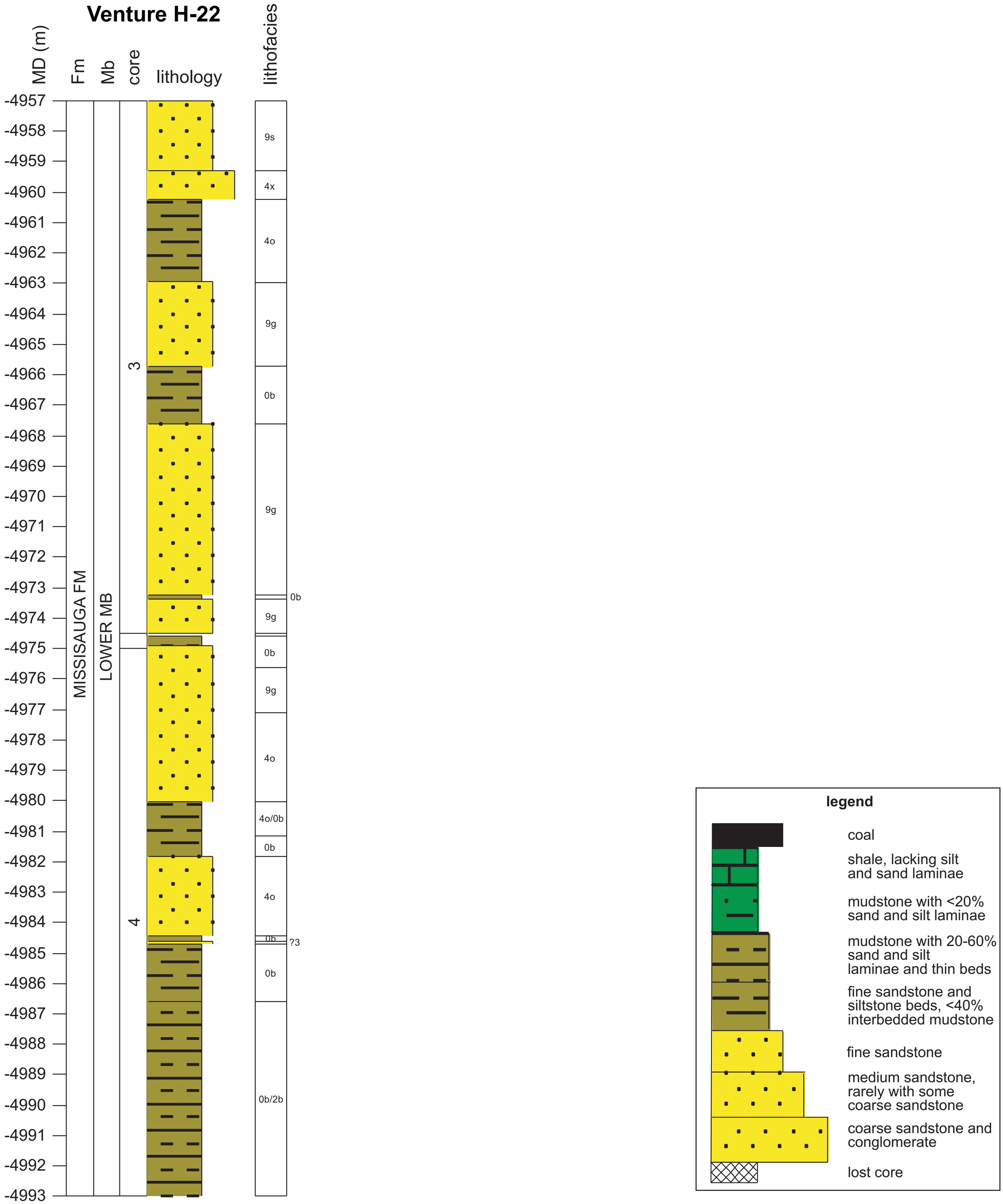
Appendix 1E (con't): Summary log of conventional core 10 and 11, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



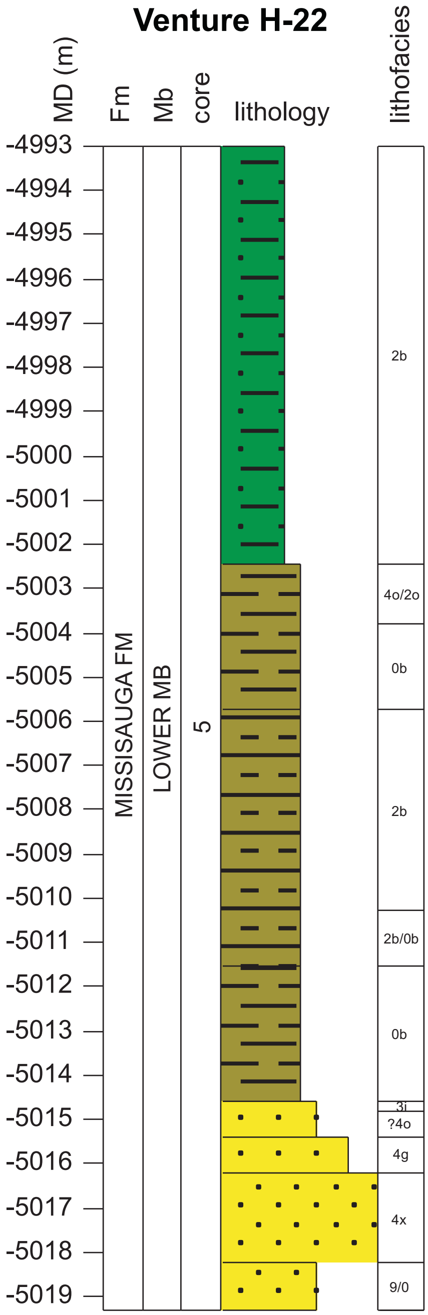
Appendix 1E (con't): Summary log of conventional core 12 and 13, from the Panuke B-90 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



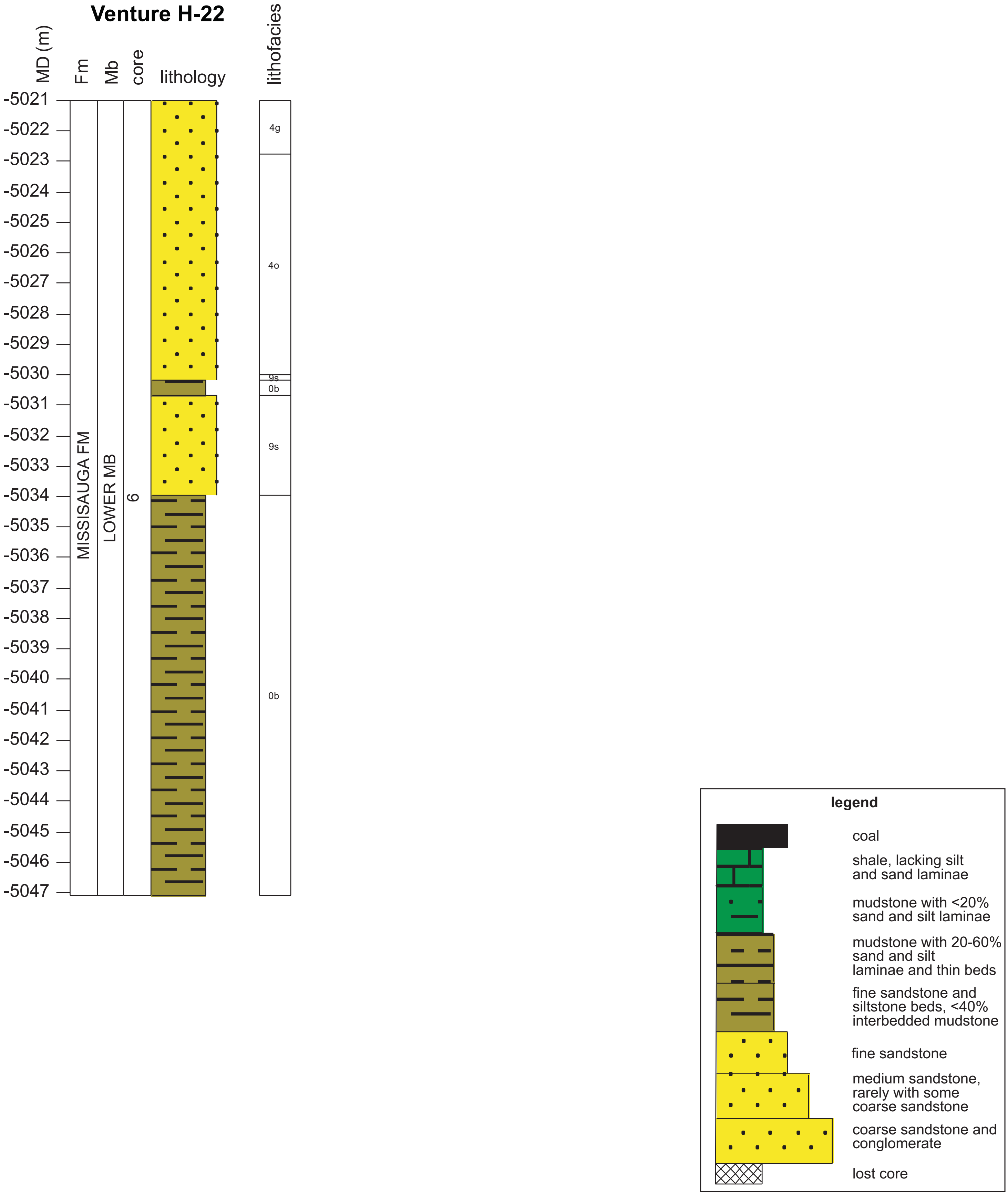
Appendix 1F: Summary log of conventional cores 4-5 from the Venture B-52 well modified from Gould et al., 2010 (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



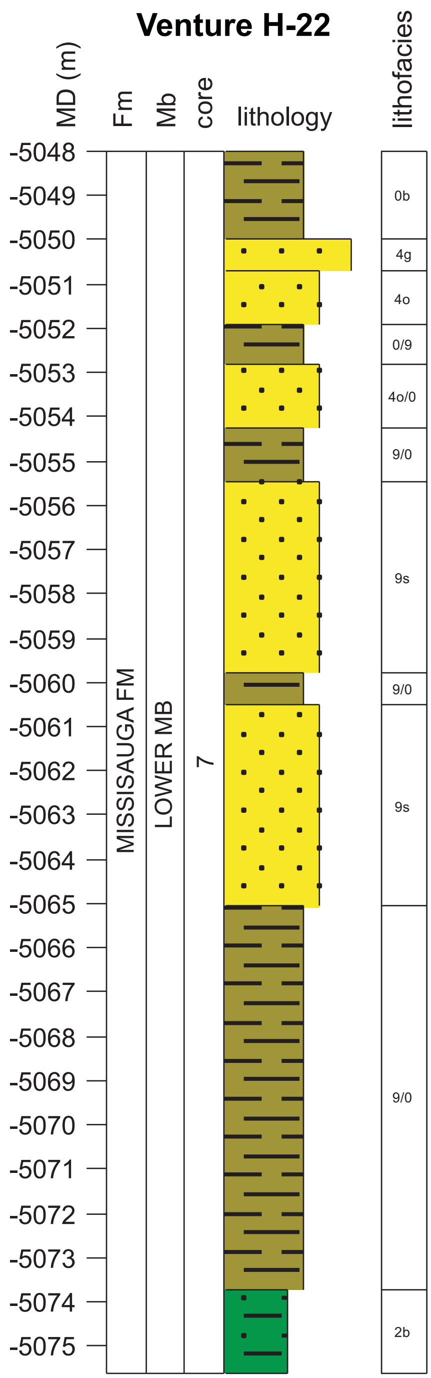
Appendix 1G: Summary log of conventional core 3 and 4 from the Venture H-22 well modified from Gould et al., 2010 (MD = measured depth) Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



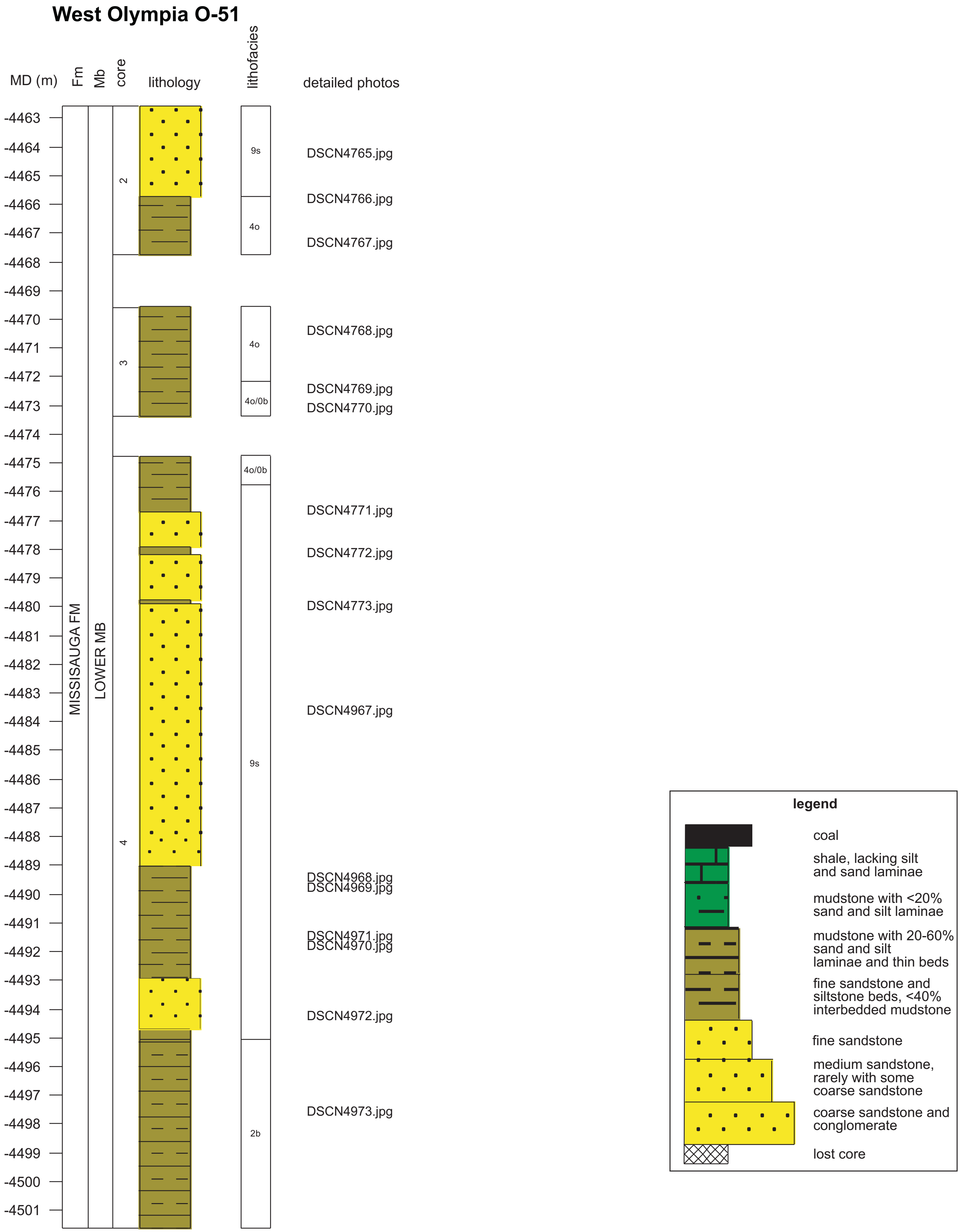
Appendix 1G (con't): Summary log of conventional core 5 from the Venture H-22 well modified from Gould et al., 2010 (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



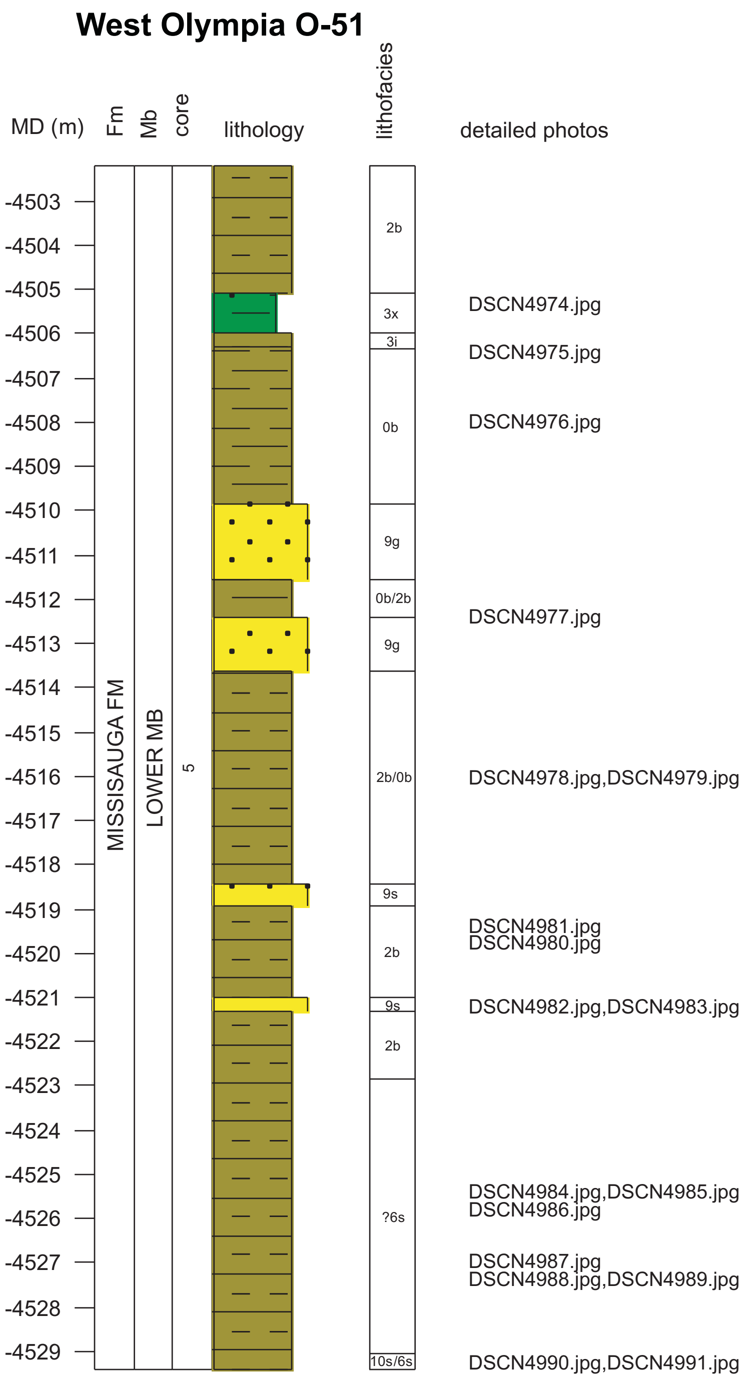
Appendix 1G (con't): Summary log of conventional core 6 from the Venture H-22 well modified from Gould et al., 2010 (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



Appendix 1G (con't): Summary log of conventional core 7 from the Venture H-22 well modified from Gould et al., 2010 (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).

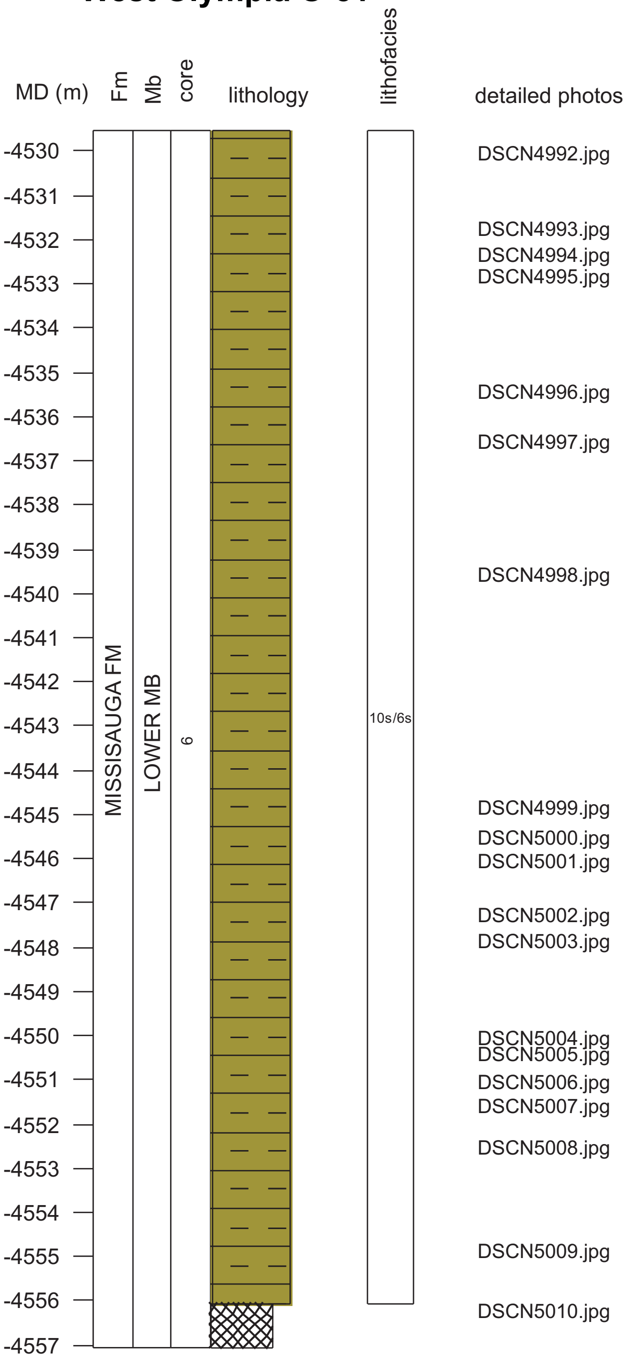


Appendix 1H: Summary log of conventional core 2-4 from the West Olympia O-51 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Memberpicks from MacLean and Wade (1993).

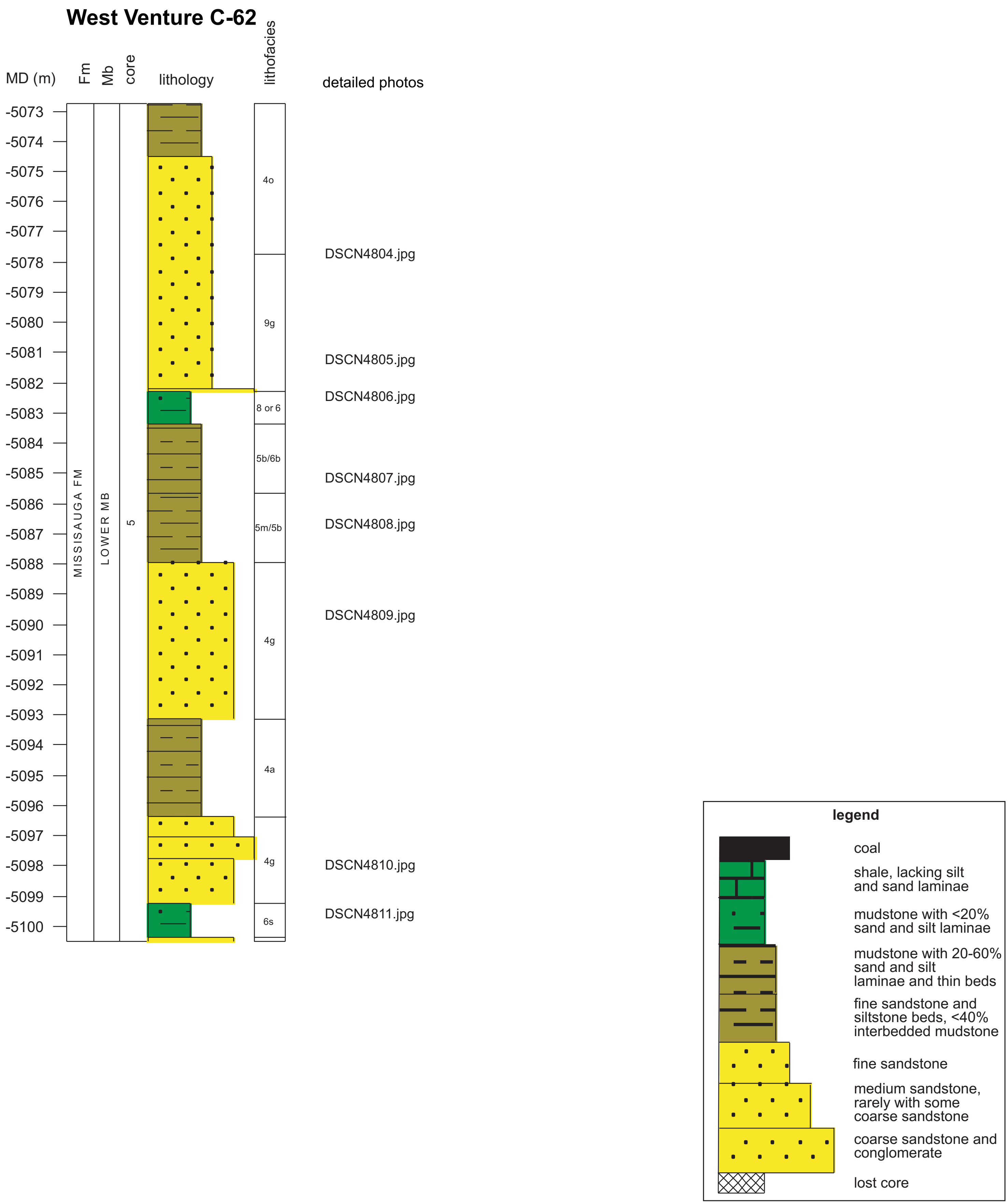


Appendix 1H (con't): Summary log of conventional core 5 from the West Olympia O-51 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Memberpicks from MacLean and Wade (1993).

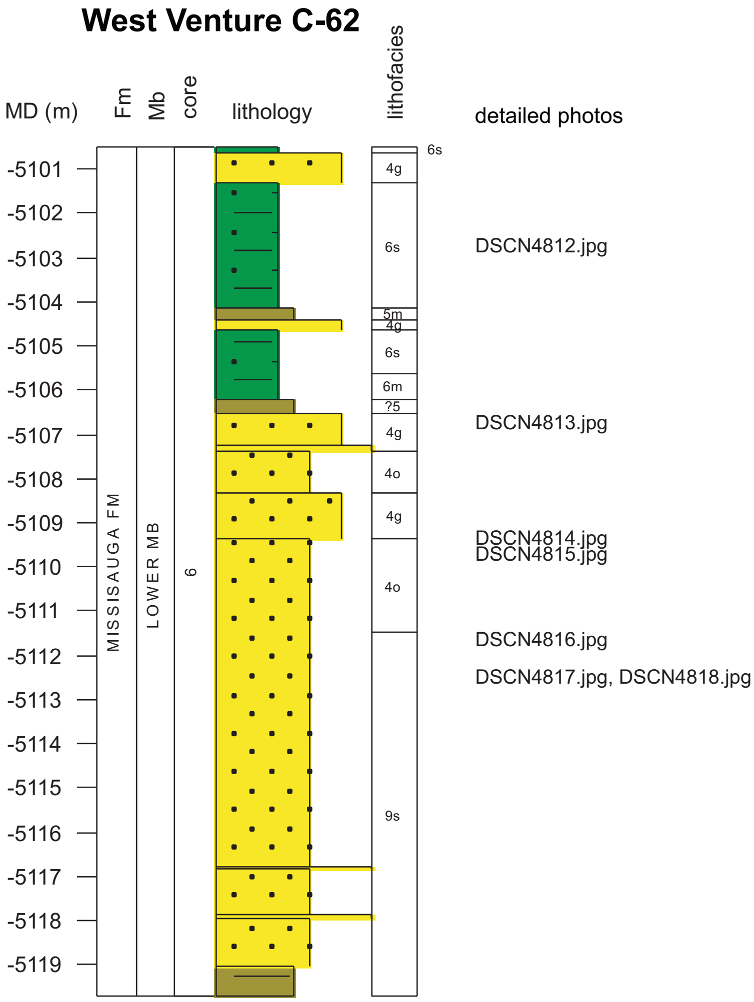
West Olympia O-51



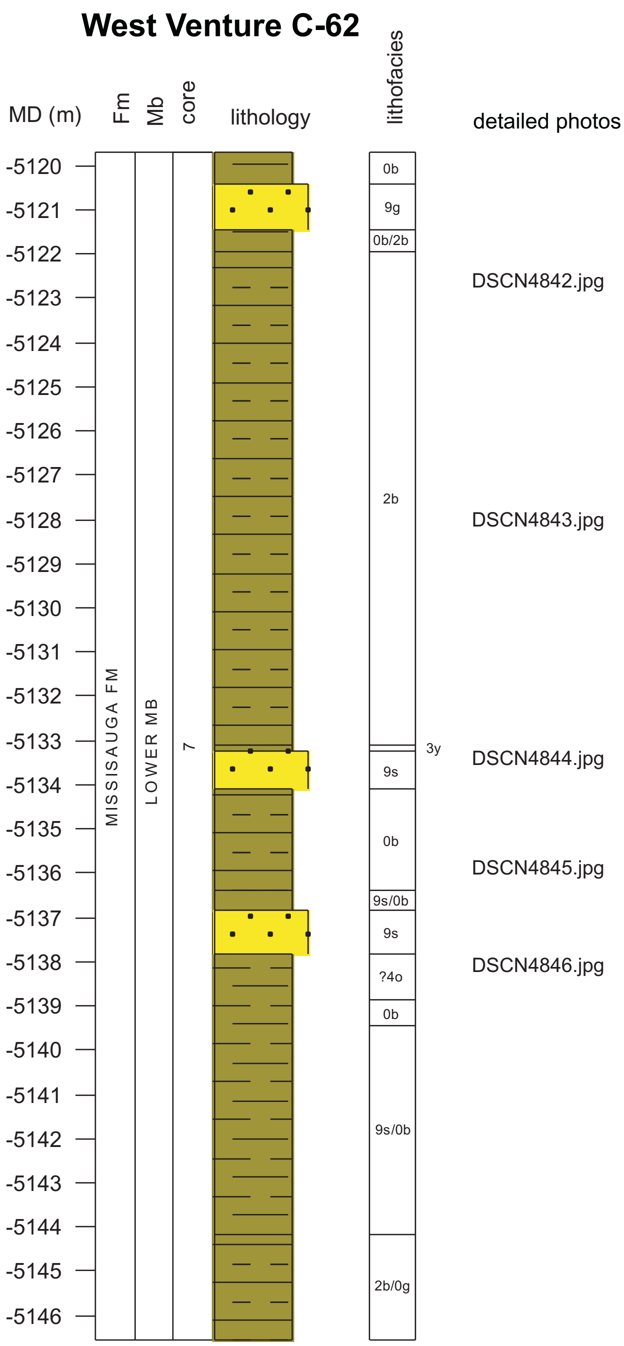
Appendix 1H (con't): Summary log of conventional core 6 from the West Olympia O-51 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Memberpicks from MacLean and Wade (1993).



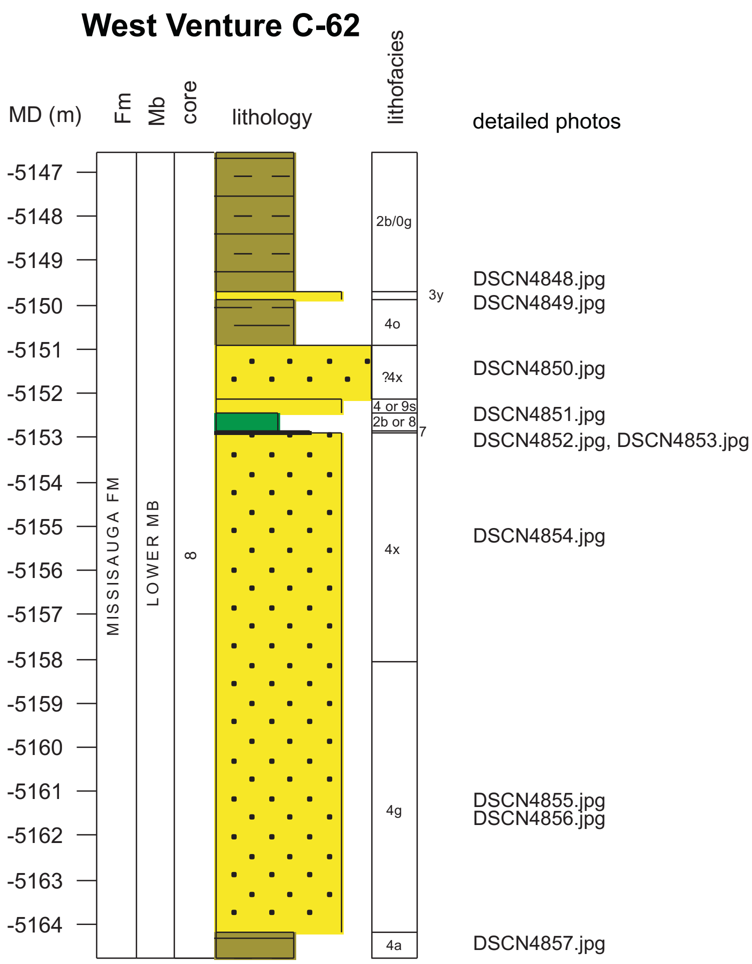
Appendix 1I: Summary log of conventional core 5 from the West Venture C-62 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



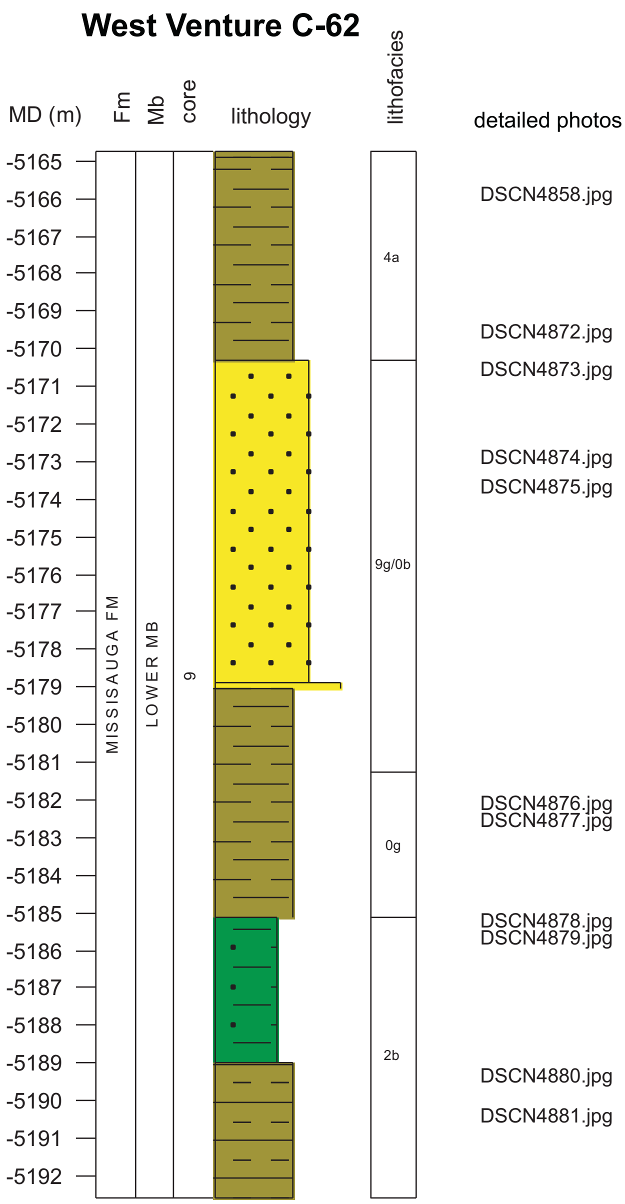
Appendix 1I (con't): Summary log of conventional core 6 from the West Venture C-62 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



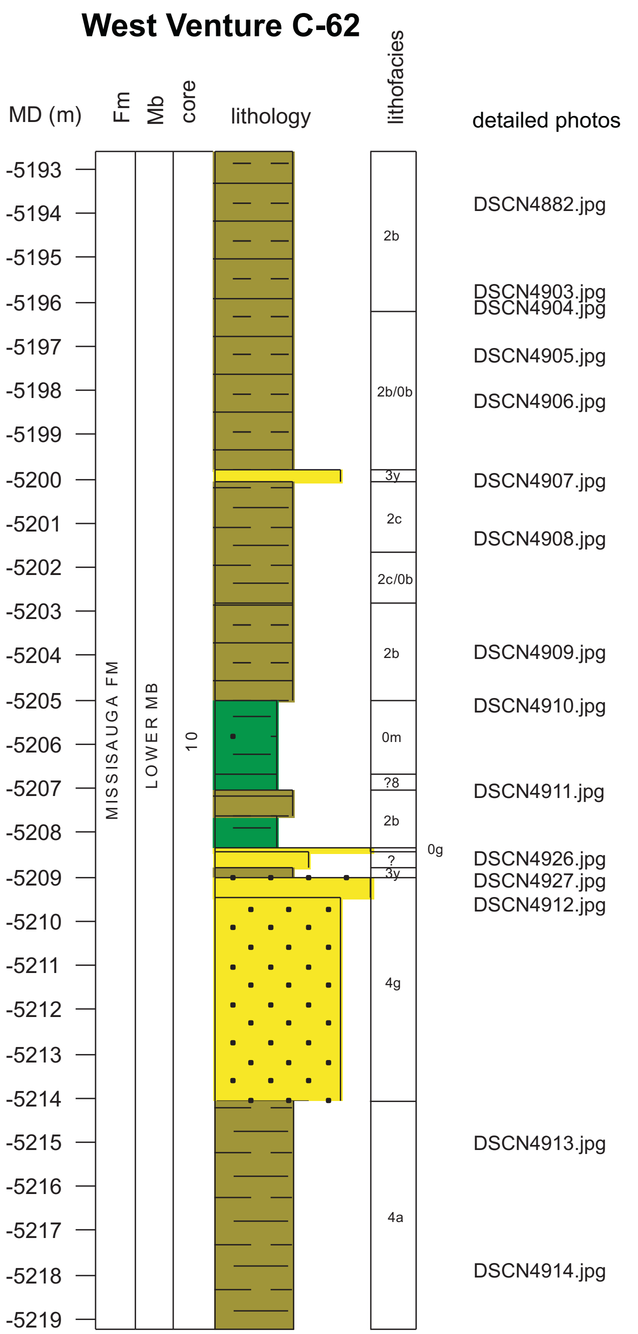
Appendix 1I (con't): Summary log of conventional core 7 from the West Venture C-62 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



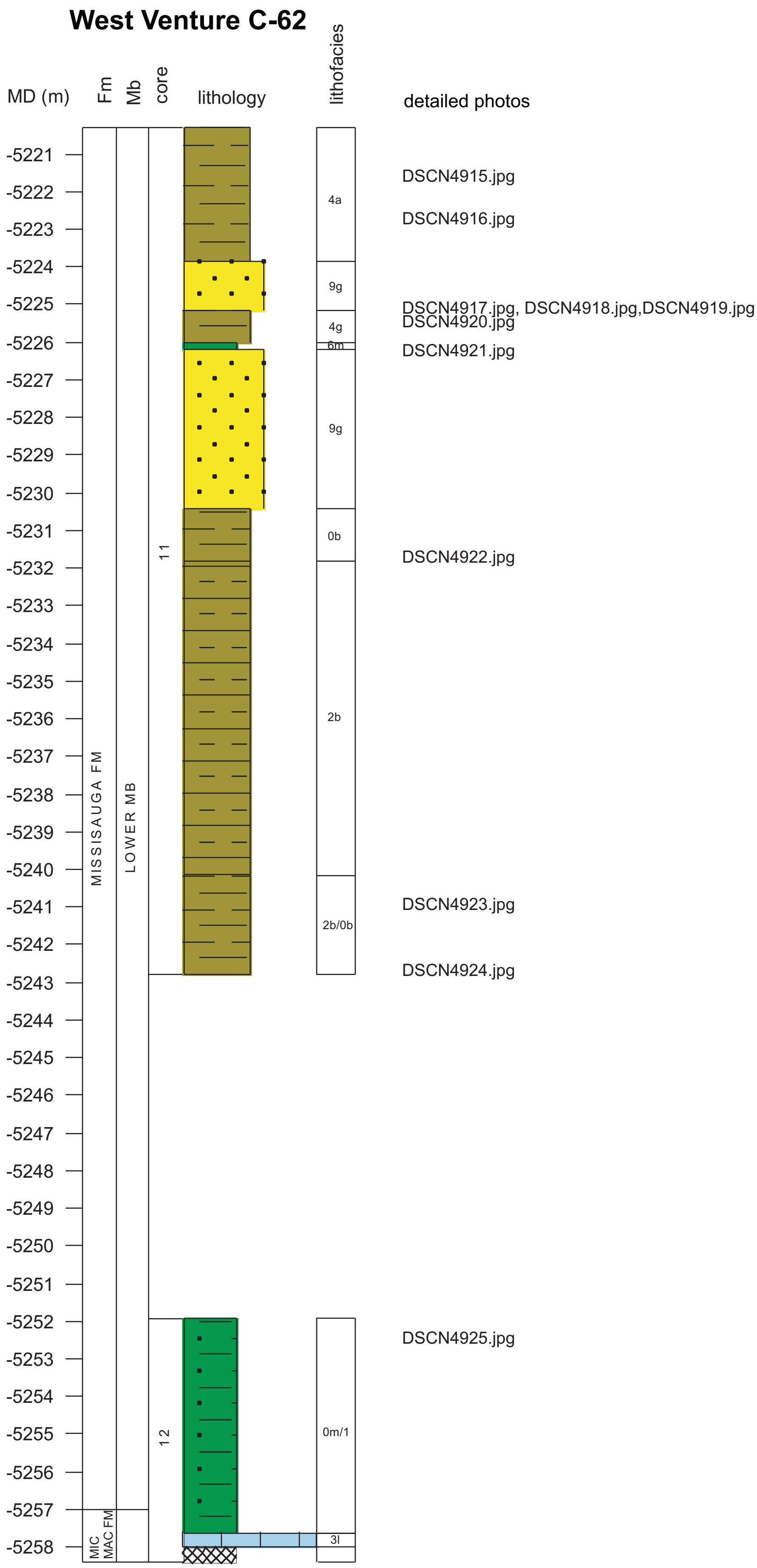
Appendix 1I (con't): Summary log of conventional core 8 from the West Venture C-62 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



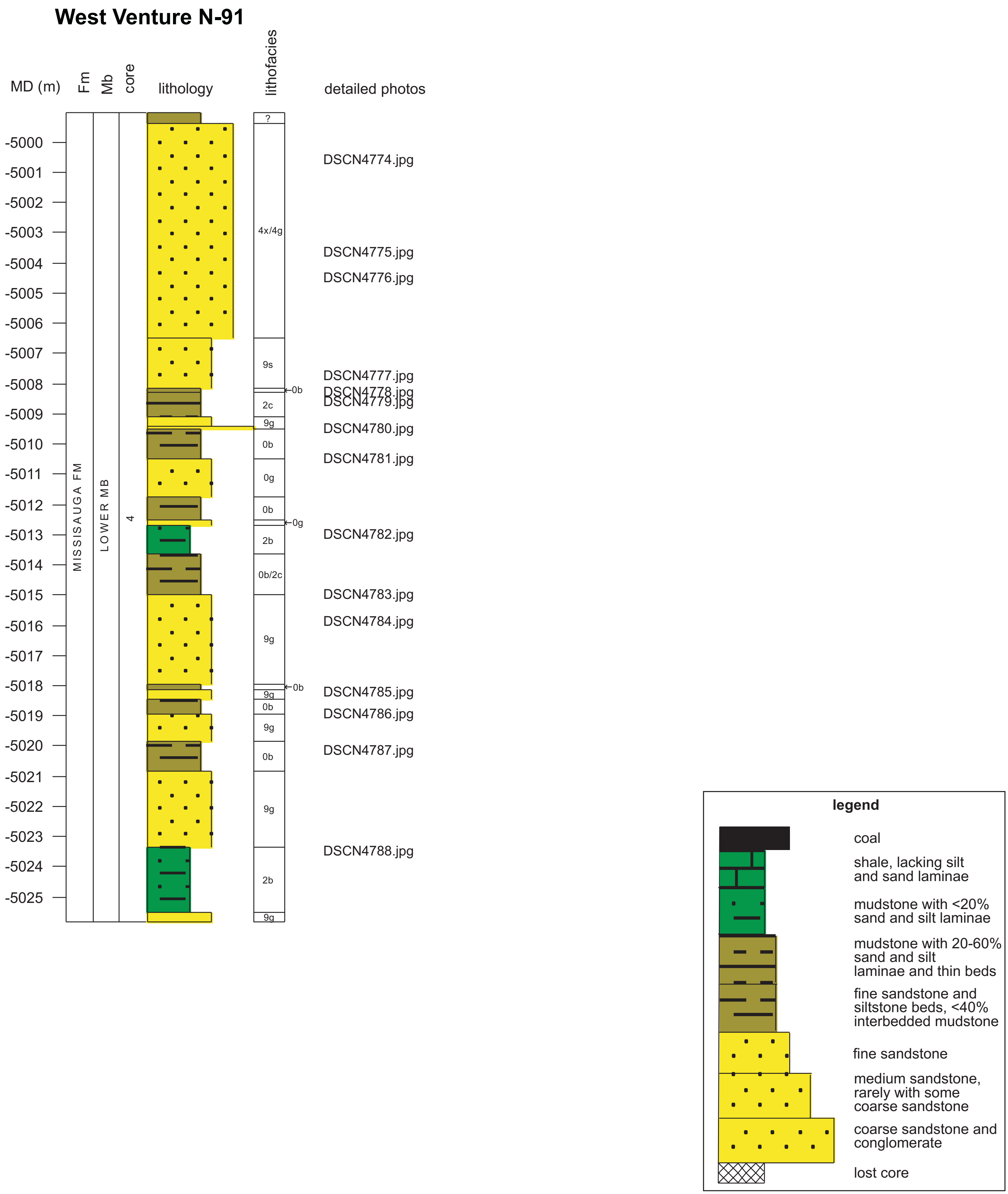
Appendix 1I (con't): Summary log of conventional core 9 from the West Venture C-62 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



Appendix 1I (con't): Summary log of conventional core 10 from the West Venture C-62 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).

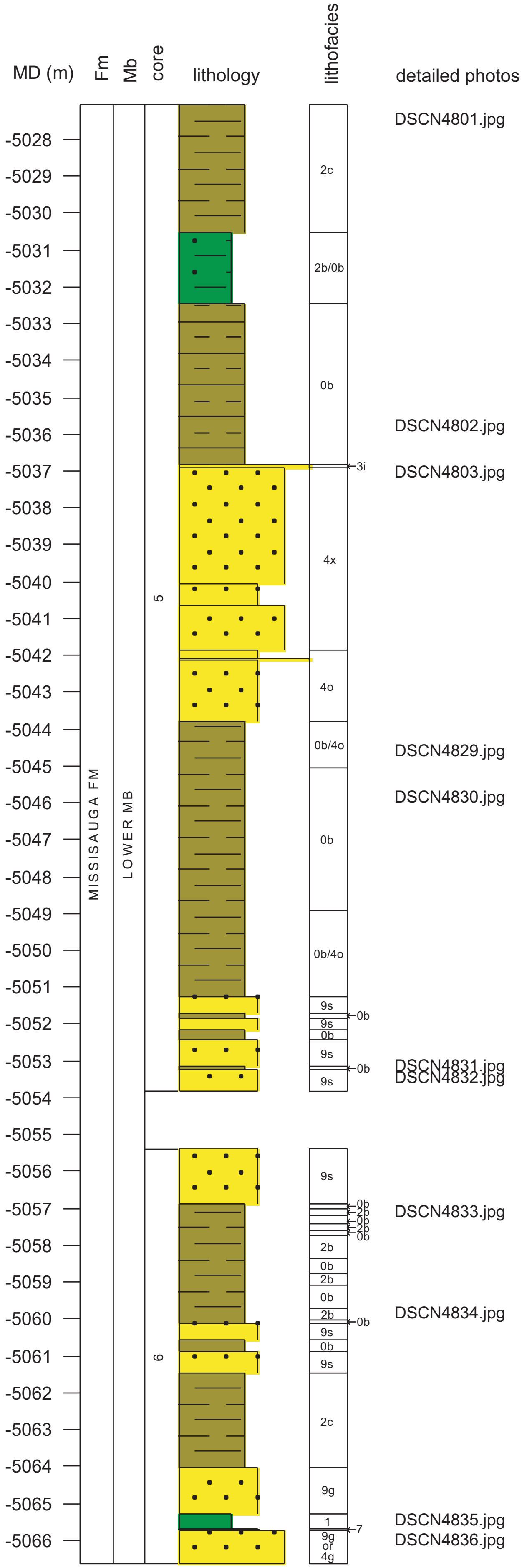


Appendix 1I (con't): Summary log of conventional core 11 and 12 from the West Venture C-62 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).



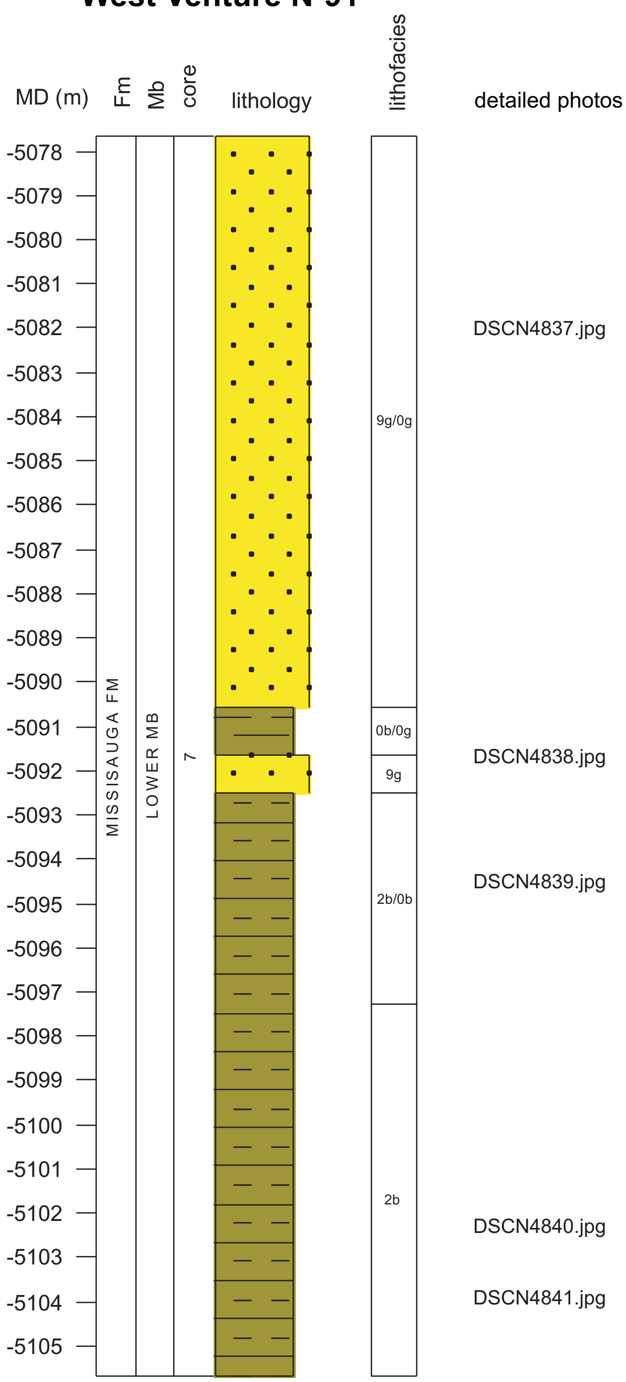
Appendix 1J: Summary log of conventional core 4 from the West Venture N-91 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).

West Venture N-91



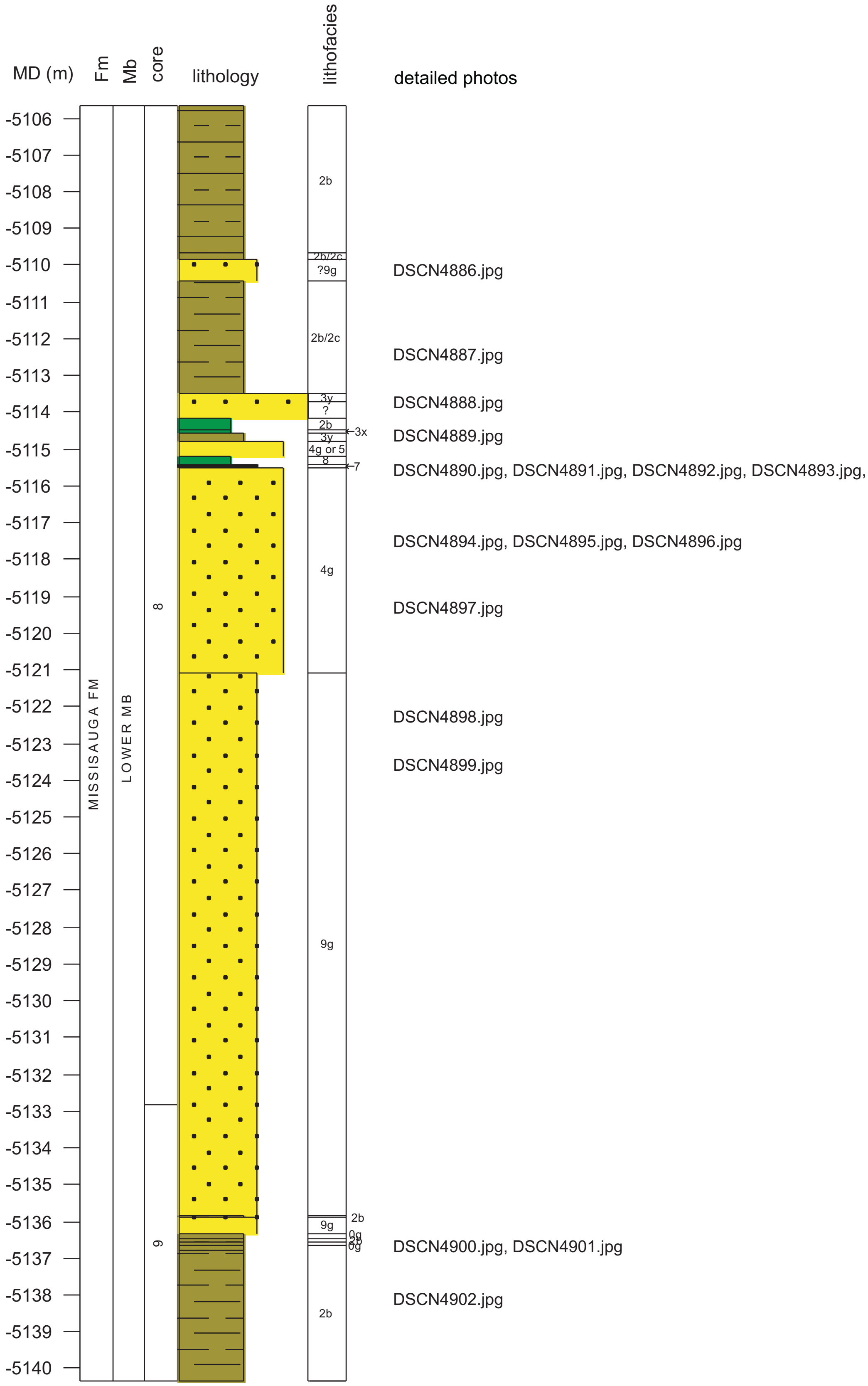
Appendix 1J (con't): Summary log of conventional cores 5-6 from the West Venture N-91 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).

West Venture N-91



Appendix 1J (con't): Summary log of conventional core 7 from the West Venture N-91 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).

West Venture N-91



Appendix 1J (con't): Summary log of conventional cores 8-9 from the West Venture N-91 well (MD = measured depth). Lithofacies are defined in Table 1. Formation and Member picks from MacLean and Wade (1993).