THESIS

SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENT OF THE MIDDLE ORDOVICIAN BLACK COVE AND AMERICAN TICKLE FORMATIONS – WESTERN NEWFOUNDLAND

Submitted by

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ABSTRACT

SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENT OF THE MIDDLE ORDOVICIAN BLACK COVE AND AMERICAN TICKLE FORMATIONS – WESTERN NEWFOUNDLAND

The Middle Ordovician (Darriwilian) Black Cove (*Nicholsonograptus fasciculatus* biozone) and overlying American Tickle Formations (*Pterograptus elegans* biozone) represent the lower portion of the Goose Tickle Group located in western Newfoundland. The succession consists of a total of seven lithofacies, four siliciclastic and three carbonate that are grouped into three distinct facies associations. Facies association 1 (FA1) contains intercalations of clay-rich mudstones (Facies A) with silt-bearing, clay-rich mudstones (Facies B) and in places, foresets of alternating siltstone and clay-rich laminae (Facies C). Facies association 2 (FA2) consists of rocks within FA1 and localized massive, silt-to-sandstones (Facies D). Facies association 3 (FA3) is characterized by carbonate mud-to-wackestones (Facies E), laminated and massive, peloidal, skeletal packstones (Facies F), and skeletal grainstones (Facies G).

Each of the three facies associations is interpreted to represent a distinct position on a proximal to distal transect of a shelf that faced the proto-Atlantic. Bedload transport processes are present throughout the succession and are indicated by sedimentary structures such as ripples, planar laminations, mudstone rip-up clasts and lenticular siltstone laminae. These high-energy event deposits likely represent episodically occurring storms and are intercalated into fine-grained fair-weather sediments (Facies A, C, and E).

The Black Cove and American Tickle Formations as a whole show an overall shallowing-upward trend that is subdivided into four coarsening-upward parasequences marked by carbonates

(FA3) directly overlying fine-grained siliciclastic mudstones (FA1 and FA2). Each of these parasequences is interpreted to represent a lowstand unit attributed to a sea level fall. A comparison with time-equivalent lowstands worldwide suggests that at least two of these lowstands are most likely tectonically-induced. The presence of characteristic shelf sediments showing easily recognized sea level fluctuations, and the absence of turbidites within the Black Cove and American Tickle Formations suggests that these units reflect deposition in a distal shelf environment and not on a lower slope or within a basin as previously suggested.

Phycosiphon incertum fecal strings and local *Planolites isp.* ichnofossils are abundant in the carbonate and fine-grained siliciclastic mudstone facies, providing evidence of dysoxic rather than anoxic conditions during deposition of the Black Cove and American Tickle Formations, allowing benthic burrowing organisms to flourish.

ACKNOWLEDGMENTS

I sincerely thank my advisor, Dr. Sven O. Egenhoff for his continuous interest, encouragement, and generous advice throughout the entirety of this study. His exhibited patience and support has shaped me not only academically and professionally, but personally as well. Many thanks are also attributed to Dr. Jörg Maletz of Free University Berlin. Dr. Maletz accompanied Dr. Egenhoff and I during my fieldwork session in western Newfoundland where he served as an invaluable resource for regional geology and local geography. Dr. Maletz also served as an esteemed reference regarding graptolite biostratigraphy and paleontological questions.

I am very grateful for my committee members, Dr. Sven Egenhoff, Dr. Judy Hannah, Dr. Thomas Borch, and Dr. Ronald Hill who provided me with invaluable manuscript editing, constructive criticism, and advice. I would also like to thank Heather Lowers and Adam Boehlke from the United States Geological Survey (USGS) for their assistance in obtaining access to SEM and XRD analyses. Lastly, I would like to acknowledge Sharon Gale for all of her administrative and scheduling assistance as well as the Colorado State University Warner College of Natural Resources Business Office especially Heather Ihde and Carl Davis who have been instrumental in aiding financial obligations that have arisen throughout the study.

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CHAPTER 1 INTRODUCTION

Clay-rich, fine-grained rocks are by far the most important sediment type on Earth (Potter et al. 2005) accounting for over 60% of sedimentary strata. These mudstones and shales occur in a wide range of environments from fluvial to deep marine (Rine and Ginsburg, 1985). They are most abundant and economically important, however, in what was traditionally interpreted as overall quiescent water settings with deposition mainly from suspension settling processes (Potter et al., 2005). Fine-grained rocks accumulating under such circumstances often contain large amounts of organic matter making them source rocks for hydrocarbons, and in recent years also direct targets for oil and gas production from unconventional plays (Aplin and Macquaker, 2010). In order to make predictions on the internal makeup of fine-grained reservoirs, a detailed understanding of mudstone deposition is necessary. The processes forming fine-grained rock successions, however, are not yet fully explored and understood (Macquaker et al., 2010). Their typically massive character in outcrop and core, and the fine scale of sedimentary structures visible only in ultra-thin sections (Schieber, 1998), has hampered detailed description of many depositional features, current indicators (e.g., ripples in muds (Schieber et al. 2007) and the importance of marine snow sedimentation in building mudstone successions (Macquaker et al., 2010) have been recognized only recently. As a consequence, many fine-grained rock successions worldwide lack a detailed description that recognizes small-scale depositional structures that allow reconstruction of their depositional history. One of the prime examples is a package of fine-grained rocks comprising the Black Cove and American Tickle Formations (Figure 1.1) in western Newfoundland (Klappa et al., 1980; Stenzel et al., 1990), a succession of mudstones incorporated into Appalachian nappes (Lavoie, 2003). As their bases and tops are commonly not well exposed or show tectonic contacts, they occur isolated and in part removed from their original sedimentological context, making an unequivocal characterization of their depositional environment challenging. The Black Cove Formation is further believed to be one of the potential source rocks within the Ordovician succession in Newfoundland that most likely added hydrocarbons to producing units within this Early Paleozoic carbonate platform and slope succession (Williams and Burden, 1992).

This study will therefore focus on two aspects of the Black Cove and American Tickle Formations: (1) a mudstone facies study in order to reconstruct sedimentary processes that influenced deposition of these two units based on detailed observations of small-scale sedimentary structures, and (2) a depositional model for these two units distinguishing a possible slope versus platform origin, thereby aiding Ordovician paleogeographical reconstructions for Newfoundland. The study is based on four sections measured in the field in western Newfoundland (Figures 1.2 and 1.3), and a total of 67 thin sections focusing on the siliciclastic mudstones, but also incorporating the associated carbonates and coarser-grained siliciclastic units.

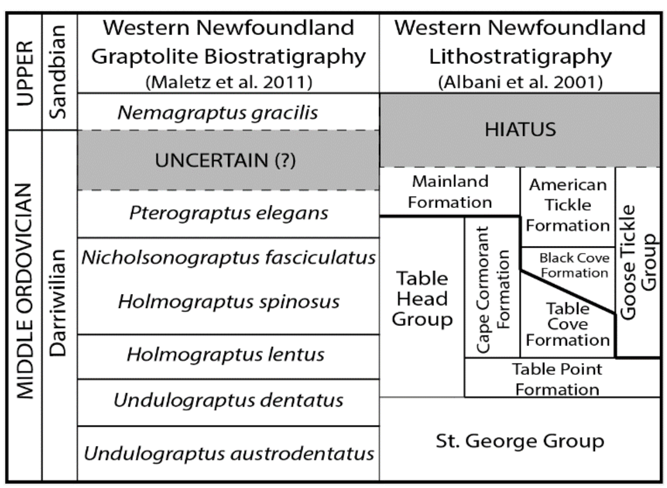

Figure 1.1. Correlation of lithostratigraphic units in the Upper Darriwilian of Western Newfoundland (Canada) with graptolite biostratigraphy. Grey boxes indicate lithostratigraphic hiatuses in the successions or lack of graptolite faunas in these intervals (Modified from Albani et al., 2001 and Maletz et al., 2011).

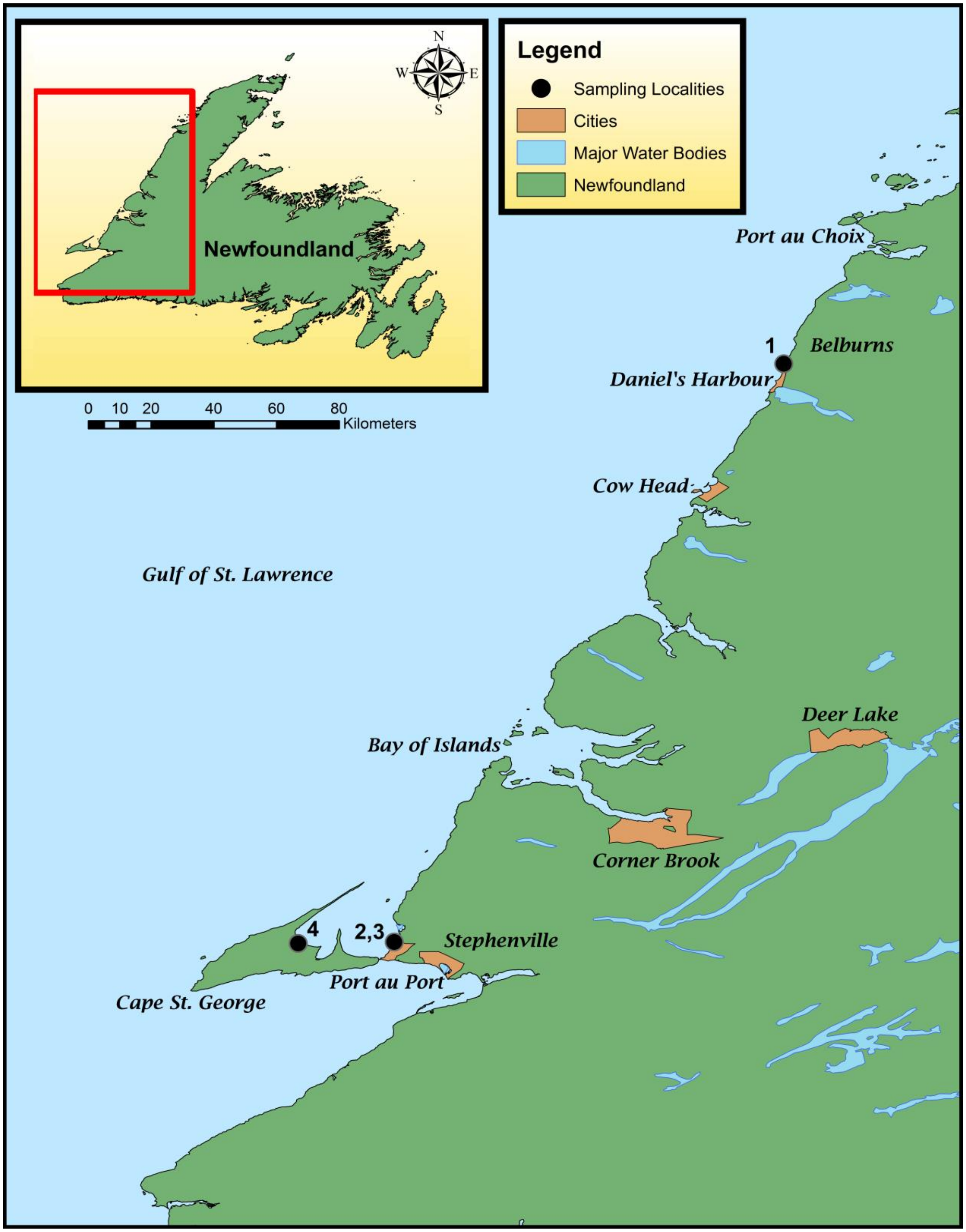

Figure 1.2. Outcrop sampling locality map of western Newfoundland. Numbers correspond to the four areas of sample collection: 1. Spudgels Cove – Intertidal Platform (approximately 5 km north of Daniel's Harbour), 2. Black Cove – Low Cliff Exposure (approximately 2.5 km north of the isthmus between the town of Port au Port and the Port au Port Peninsula), 3. Oil Tank Platform (approximately 0.6 km north along the coast from Black Cove), 4. West Bay Center Quarry (approximately 25.6 km west of the isthmus between the town of Port au Port and the Port au Port Peninsula along Route 463).

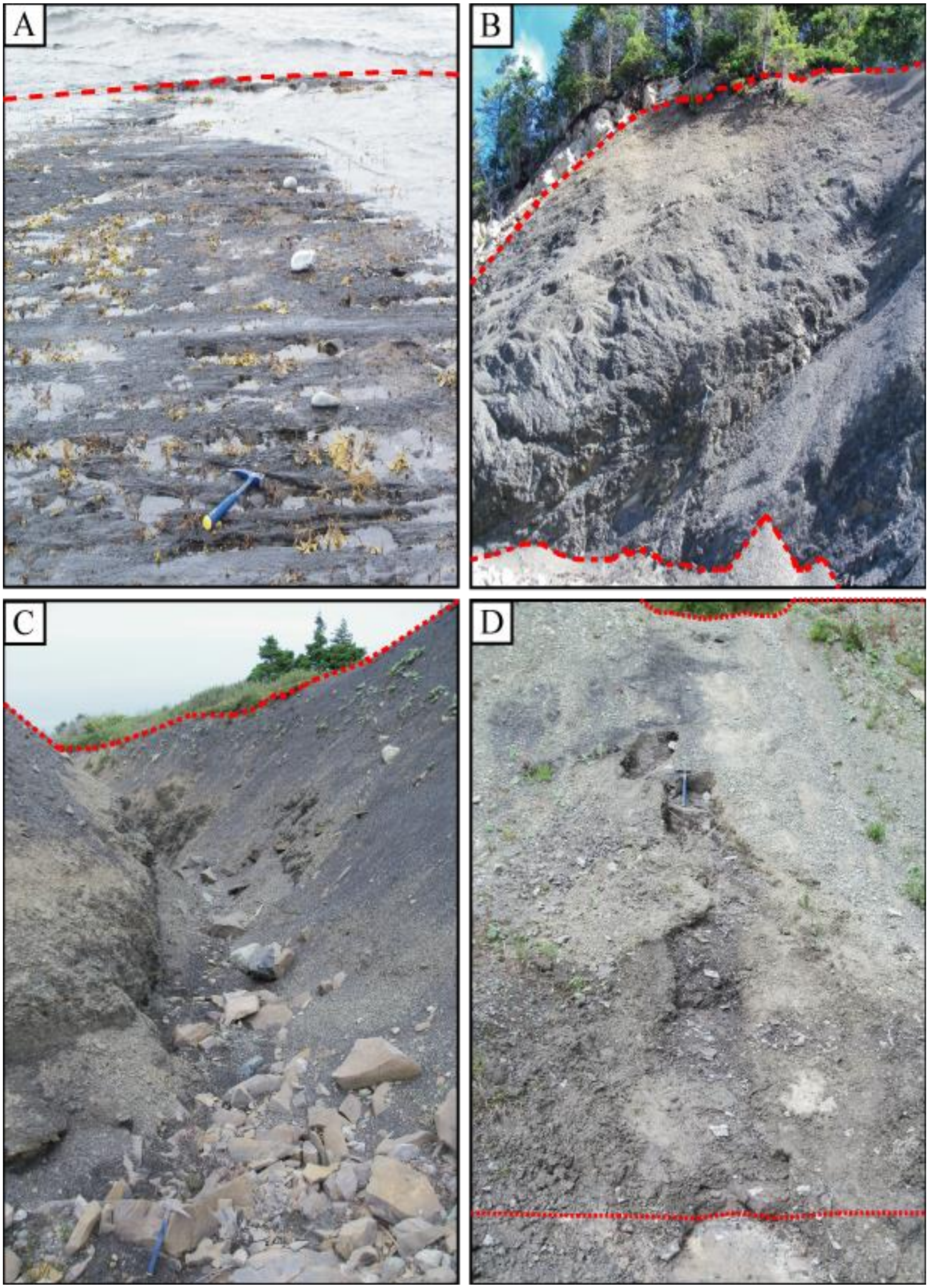

Figure 1.3. Photographs of measured sections attributed to each of the localities illustrated in Figure 1.2. Red lines indicate the extent of the stratigraphic sections. A) Spudgels Cove Locality – American Tickle Formation. B) Black Cove Type Locality – Black Cove Formation. C) Oil Tank Platform – Upper American Tickle Formation. D) West Bay Center Quarry – Black Cove Formation.

CHAPTER 2: GEOLOGIC SETTING

In the Ordovician, western Newfoundland was located at the southeastern edge of the Appalachian margin of North America (Laurentia), which was oriented approximately east-west between 10° and 20°S paleolatitude (Figure 2.1) (Van der Voo, 1988). In North America, Newfoundland represents the northeastern-most extension of the Appalachian mountain system and the eastern extension of the Canadian Appalachians. Subdivided into five tectonic-stratigraphic zones, (from East to West - Meguma, Avalon, Gander, Dunnage, and Humber) this extension of the Canadian Appalachians reflects both sides of the Late Proterozoic-Early Paleozoic Iapetus Ocean (Albani et al., 2001; Williams, 1979). Western Newfoundland is incorporated into the Humber zone, the westernmost of these broad domains recording the initiation and destruction of a Cambro-Ordovician passive continental margin (Botsford, 1987; Stenzel et al., 1990; Stevens, 1970; Williams, 1979). This margin preserves an autochthonous platform and foreland basin succession divided into the Labrador, Port au Port, St. George, Table Head and Goose Tickle Groups (Williams et al., 1996). Succeeding these autochthonous sediments are overlying Taconic allochthons characterized by imbricated thrust slices of passive margin slope and rise facies (e.g. formed in adjacent deep-water environments) time equivalent to the shelf and foreland basin succession (Stenzel, 1991; Williams et al., 1996).

Autochthonous strata unconformably overlies Grenvillian crystalline basement. They are represented by the dominantly siliciclastic rift sequence (Early Cambrian Labrador Group) and a series of upward shoaling carbonate cycles known as the Port au Port (Middle to Late Cambrian) and St. George Groups (Early Ordovician) (Albani et al., 2001; Cooper et al., 2001; Stenzel, 1991; Stockmal et al., 1995). Overlying these stable platform sediments is a foreland basin succession attributed to the Taconian Orogeny, represented by deepening-upward carbonates of the Table Head Group and the clastic sedimentary rocks of the Goose Tickle Group (Stenzel et al., 1990; Stockmal et al., 1995). A local unconformity separating these successions (St. George Unconformity) is the result of a collapsed platform due to extensional faulting within a westward migrating forebulge across the continental margin associated with Taconian plate subduction and encroachment of an arc-trench system located offshore to the east (Jacobi, 1981; Knight et al., 1991; Stockmal et al., 1995; Waldron et al., 1993).

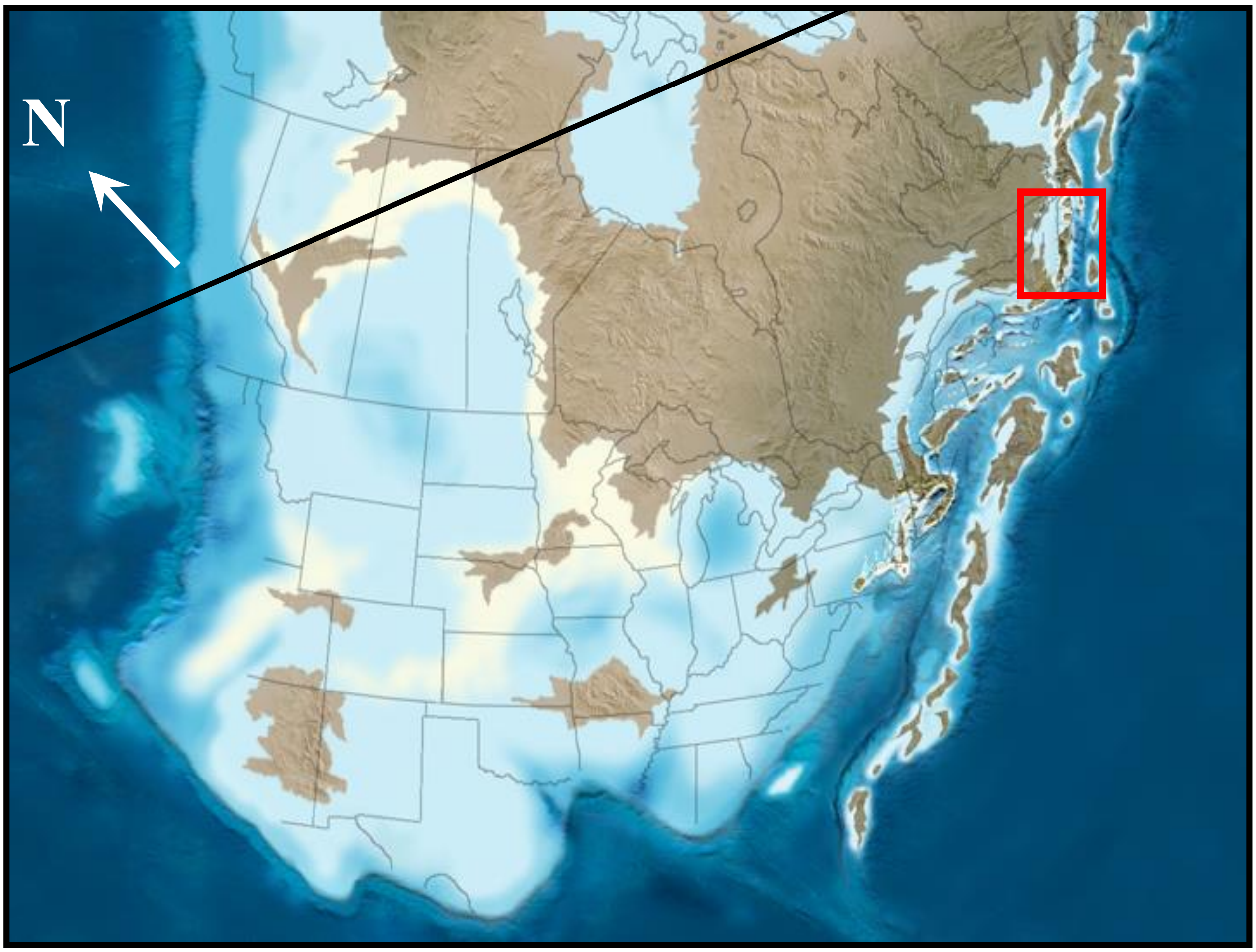

Figure 2.1. Middle Ordovician (470 Ma) Paleogeography of North America. Red box indicates approximate location of Western Newfoundland and black line indicates approximate location of the equator (Modified from Ron Blakey, Colorado Plateau Geosystems, Inc., 2012; Scotese and McKerrow, 1990).

As the foreland basin evolved during early phases of the Taconian Orogeny, rapid facies changes formed regionally discontinuous lithologic units that indicate the strong influence of tectonics on sedimentation (Stenzel et al., 1990). Overthrusting and obduction of westerly migrating allochthons stimulated tectonic loading and differential subsidence of the platform during deposition of the Table Head Group (Stockmal et al., 2004; Williams et al., 1996). The lower part of the this group, the Table Point Formation, consists of shallow marine carbonates deposited following uplift, subaerial erosion and inundation of the broken platform (Albani et al., 2001; Stockmal et al., 2004; Waldron et al., 1993). The carbonates of the lower Table Head Group are overlain diachronously by deeper water slope and basinal sediments of the Upper Table Head Group (Table Cove and Cape Cormorant Formations) (Klappa et al., 1980; Stenzel et al., 1990). The character of these units suggests continued faulting and slope instability as fragmentation and collapse of the broken platform developed (Fowler et al., 1995; Stenzel et al., 1990). Deposited on top of the Table Head Group are easterly-derived siliciclastic flysch of the Goose Tickle Group (Fowler et al., 1995). As blocks of the platform drowned, Black Cove Formation mudstones (Lower Goose Tickle Group) are interpreted to have accumulated directly on platformal carbonates (Stenzel et al., 1991). Interbedded mudstone, siltstone, limestone, and conglomerates interpreted as flysch deposits of the American Tickle Formation, overlie the Black Cove Formation, while turbidites of the Mainland or Lower Head Formations were uplifted, eroded, and shed west along thrust sheets ahead of advancing allochthons into the foreland basin (Albani et al., 2001; Fowler et al., 1995; Stenzel et al., 1990; Stockmal, 1995; Waldron et al., 1993).

CHAPTER 3: METHODOLOGY

The sedimentological analysis of this study stems from observations, descriptions, and interpretations from 4 outcrop localities along the coast of Western Newfoundland. These outcrop exposures were measured and sampled with a focus on the Black Cove Formation and locally, the overlying American Tickle Formation of the lower Goose Tickle Group. Fresh samples were collected at each of the localities at intervals ranging from 0.5m to 1.5m with some intermixed discontinuous sampling in part due to the localized erosion of the Black Cove Formation. At specific localities (e.g. West Bay Center Quarry) shallow voids were excavated in order to acquire appropriate samples. Once the samples were collected, they were correctly labeled and marked for accurate stratigraphic orientation.

Samples collected underwent preparation at the Colorado State University Sedimentology Laboratory for microscopic (thin section) analysis. Preparation included impregnation of each sample with epoxy resin prior to the cutting phase. Samples were cut using a traditional rock saw to manageable sizes allowing for easier manipulation during ultra-thin section (~20μm) preparation. According to Schieber, (1998), ultra-thin sections are most desirable when analyzing fine grained sediments such as mudstones, because the detrital particles are typically smaller than the standard 30μm thin section. This difference allows for enhanced observation of minute sedimentological structures. Thin sections were also infused with blue epoxy for porosity determination, left uncovered, and diamond polished. These attributes allow for clearer observations under both a stereo petrographic microscope (Nikon SMZ1500) and a scanning electron microscope.

Petrographic analyses on each of the ultra-thin sections were carried out using polarized light microscopy to determine sedimentological features on a sub-millimeter scale. These features (including lithology, grain size distribution and sedimentary structures) allow for facies association descriptions and interpretations to be made and applied to the overall mudstone dominated succession. In order to determine more precise details and textures (10^{-4} to 10^{-5} m scale) in some of the ultra-thin sections, scanning electron microscopy (SEM) was conducted. With the aid and collaboration of the United States Geological Survey (USGS) in Denver, Colorado, specific ultra-thin sections were coated in carbon and analyzed using a Quatra 450 FEG scanning electron microscope equipped with energy-dispersive X-ray spectroscopy (EDS). The utilization of SEM and EDS technology supplements observations and interpretations that were conducted from conventional ultra-thin section petrographic analyses by providing detailed imagery and reinforcing elemental analysis of very fine grained particles.

CHAPTER 4: SEDIMENTOLOGY

4.1 Introduction

The underlying focus of this study reflects sedimentological observations based on both a macroscopic and microscopic approach of four localities along the coast of western Newfoundland. Presented herein are observations, descriptions and interpretations of 4 measured sections and 67 ultra-thin sections through the Black Cove and American Tickle interval at these localities (Figure 4.1). Detailed illustrations of these sections are located in Appendix I.

Petrographic observations of the Black Cove and American Tickle Formations define the subdivision of seven facies that are grouped into three facies associations (Table 4.1). These facies are comprised of four siliciclastic (Figure 4.2) and three carbonate facies (Figure 4.3). Facies nomenclature follows a scheme slightly modified from Macquaker and Adams (2003) for mudstones and the Dunham (1962) classification (scheme) for carbonates. In this format a siliciclastic rock that contains 50-90% of a component is described as being "rich" in that material, and one containing 10-50% is described as "bearing" that constituent (Macquaker and Adams, 2003).

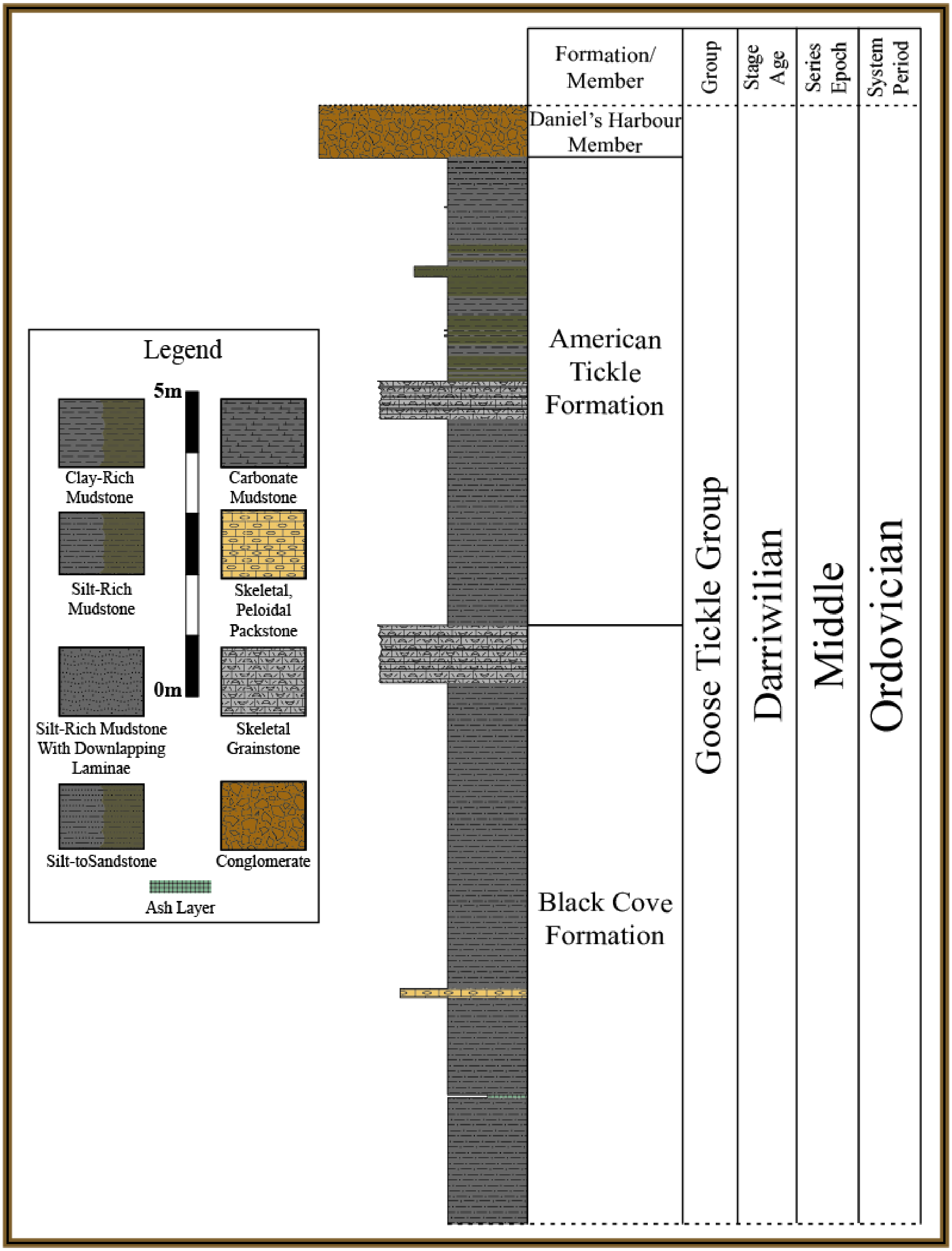

Figure 4.1. Idealized stratigraphic column of the measured Black Cove and American Tickle Formations at the oil tank locality.

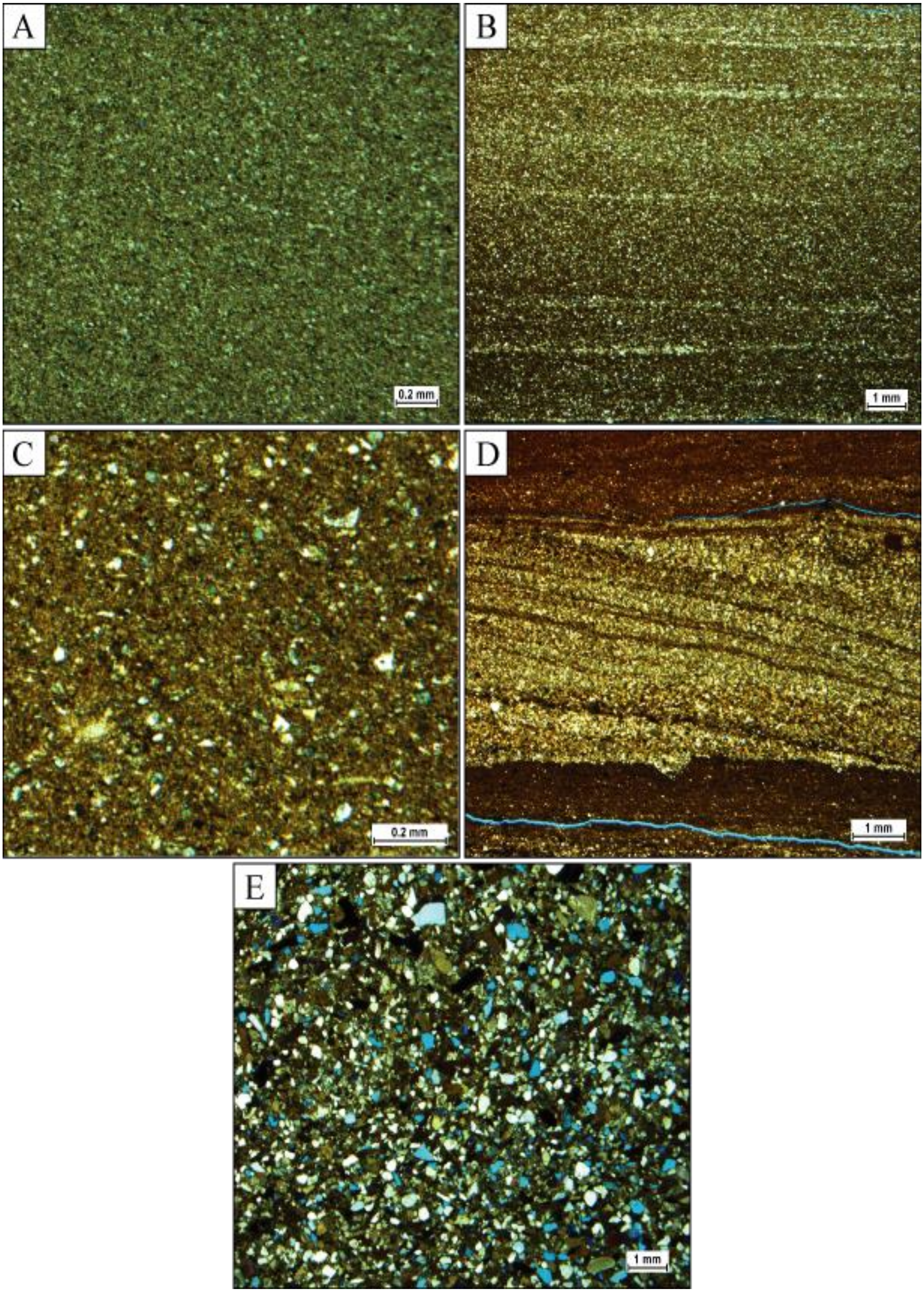
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Figure 4.2. Ultra-thin section natural light photographs of four siliciclastic facies observed in the Black Cove and American Tickle Formations of Western Newfoundland. A) Massive appearance of Clay-Rich Mudstone (Facies A). B) Laminated appearance of Silt-Bearing, Clay-Rich Mudstone (Facies B). C) Massive appearance of Silt-Bearing, Clay-Rich Mudstone (Facies B). D) Silt-Rich Mudstone with Downlapping Laminae (Facies C). E) Massive Silt-to-Sandstone (Facies D).

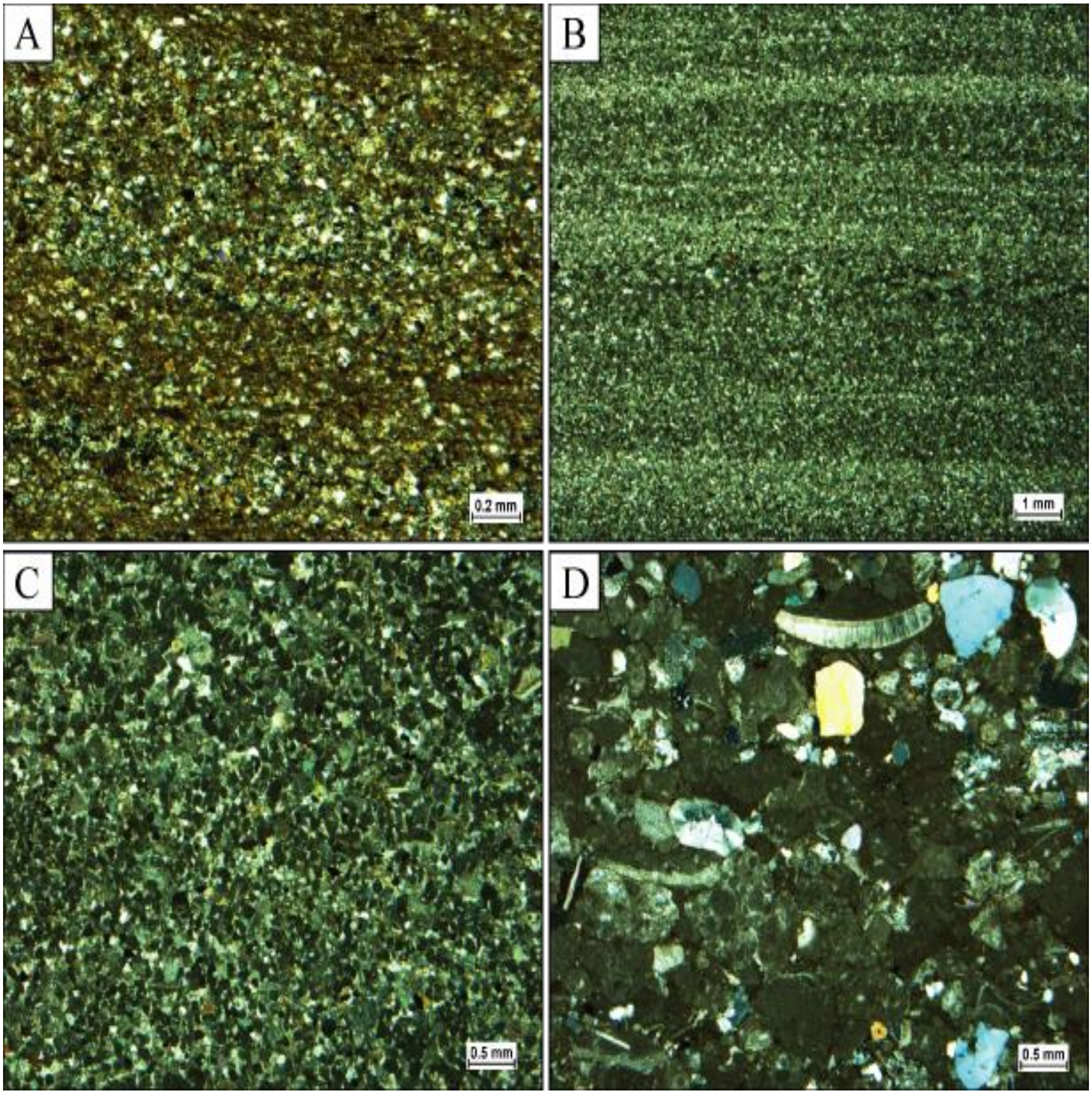

Figure 4.3. Ultra-thin section natural light photographs of three carbonate facies observed in the Black Cove and American Tickle Formations of Western Newfoundland. A) Massive, Carbonate Mud-To-Wackestone (Facies E). B) Laminated Appearance of Ripple-bedded, Peloidal, Skeletal Packstone (Facies F). C) Massive Appearance of Ripple-bedded, Peloidal, Skeletal Packstone (Facies F). D) Massive, Skeletal Grainstone (Facies G).

Table 4.1. Summary table of sedimentologic attributes of facies A-G identified in the Black Cove and American Tickle Formations, western Newfoundland.

Lithofacies Name	Facies Assoc.	Description	Interpretation
Laminated and Massive, Clay-Rich Mudstone (Facies A)	1 & 2	Dark grey/black color in outcrop, layers up to 14.0mm thick in ultra-thin section. Matrix-supported fabric, clay minerals, 0-10% randomly dispersed fine to very-fine silt-sized quartz and carbonate grains (Figure 4.2a). Localized evenly thick (sub-millimeter) laminae, distinct upper and lower boundaries, can have lenticular shape. *Phycosiphon incertum* abundant, displaces detrital quartz and carbonate grains, cross-cut laminae locally.	Either suspension settling (Macquaker and Bohacs, 2007) or bedload transport (Schieber et al., 2007) of clay aggregates and marine snow particles (Macquaker et al., 2010); siltstone laminae of laterally varying thickness; facies homogenized by abundant burrowing (*Phycosiphon incertum*).
Laminated and Massive, Silt-Bearing, Clay-Rich Mudstones (Facies B)	1 & 2	Dark grey/black color in outcrop, layers up to 20.0mm thick in ultra-thin section. Clay matrix-supported fabric (Figure 4.5), containing silt-sized detrital quartz, calcite, and dolomite grains. Clay clasts oriented parallel to bedding, disseminated with higher concentrations in layers (Figure 4.4a). Remnant, sub-mm, siltstone laminae (Figure 4.2b), exhibit parallel/irregular geometries, display sharp contacts, locally gradational. Isolated *Planolites isp.* (Figure 4.4b) only in laminated portion. *Phycosiphon incertum* (Figure 4.4c) cross-cut laminae.	Lenticular siltstone laminae indicate deposition through bedload transport; clay clasts represent erosion and re-deposition of muddy substrate through currents; abundant siltstone laminae reflect high amount of detrital input. Moderate burrow diversity (*Phycosiphon incertum* and *Planolites isp.*) likely reflect dysoxic conditions.
Silt-Rich Mudstone with Downlapping Laminae (Facies C)	1 & 2	Dark grey/black color in outcrop; two compositionally alternating downlapping laminae (Figure 4.2d); layers (up to 0.01m in length) of silt-sized quartz and carbonate grains (0.10-to-0.90mm thick), intercalated clay particles (0.08-to-0.20mm thick). *Phycosiphon incertum* locally cross-cut laminae.	Downlapping laminae represent foresets formed by bottom currents (likely unidirectional). Intercalation of two types of laminae evidences fluctuating energy conditions (Schieber, 1998) and/or two separate grain populations (Schieber, 2007).
Massive, Silt-to-Sandstone (Facies D)	2	Dark grey to black/green color in outcrop, beds ranging from 0.07-to-0.15m thick. Massive appearance (Figure 4.2e); silt to fine-grained sand-sized detrital quartz (60-80%), feldspar (0-15%), and clay particles (5-15%). Localized calcite and dolomite constituents and clay rip-up clasts (Figure 4.4d). *Phycosiphon incertum* locally present.	Rip-up clasts evidence erosion by high-energy currents, likely storms; massive appearance reflects rapid deposition and/or liquefaction, suspension of clay particles; localized homogenization by burrowing (*Phycosiphon incertum*).

Massive Carbonate Mud-to-Wackestone (Facies E)	3	Dark grey/black color in outcrop, beds up to 0.105m thick. Massive carbonate mud (80-90%), silt-sized detrital quartz and carbonate grains (0-10%). Recrystalized randomly dispersed bioclastics, preserved "ghost" structures (Figure 4.3a). 80% dolomite replacement of carbonate mud. *Phycosiphon incertum* displaces detritus and skeletal fragments.	Likely fluctuating energy conditions with carbonate mud deposited from either suspension or bedload (Schieber, 2012), quartz and carbonate grains form in part during high-energy events, e.g. storms; dolomite represents diagenetic replacement.
Peloidal, Skeletal Packstone with Downlapping Laminae (Facies F)	3	Light grey and tan color in outcrop, beds up to 0.21m thick. Laminated (Figure 4.3b) and massive (Figure 4.3c) appearance composed of peloids, recrystalized bioclastic debris, detrital quartz, and diagenetically altered dolomite sucrosic matrix. Laminations (0.20-to-1.00mm thick) consist of peloid-rich; peloid-poor layers. Locally, oversteepened foresets (up to 45° to horizontal).	Bedload transport of grains (ripple foresets, planar laminations); carbonate mud deposition from suspension or bedload (Schieber, 2012). Oversteepened foresets reflect synsedimentary deformation; massive variety most likely reflects constant energy conditions.
Skeletal Grainstone (Facies G)	3	Light grey color in outcrop, beds up to 0.30m thick. Carbonate aggregates, peloid and bioclastic lithoclasts, 10-15% sand-sized quartz and plagioclase grains (Figure 4.3d). Skeletal fragments, crinoid ossicles, brachiopod remnants, and lithoclasts of *Girvanella* algae. Blocky calcite and dolomite cements. Diagenetic suturing connects cemented grains, aggregates and lithoclasts.	Coarse silt-to-sand-sized detritus and bioclastic material reflect high-energy currents capable of transporting coarse material; massive appearance reflecting constant energy conditions.

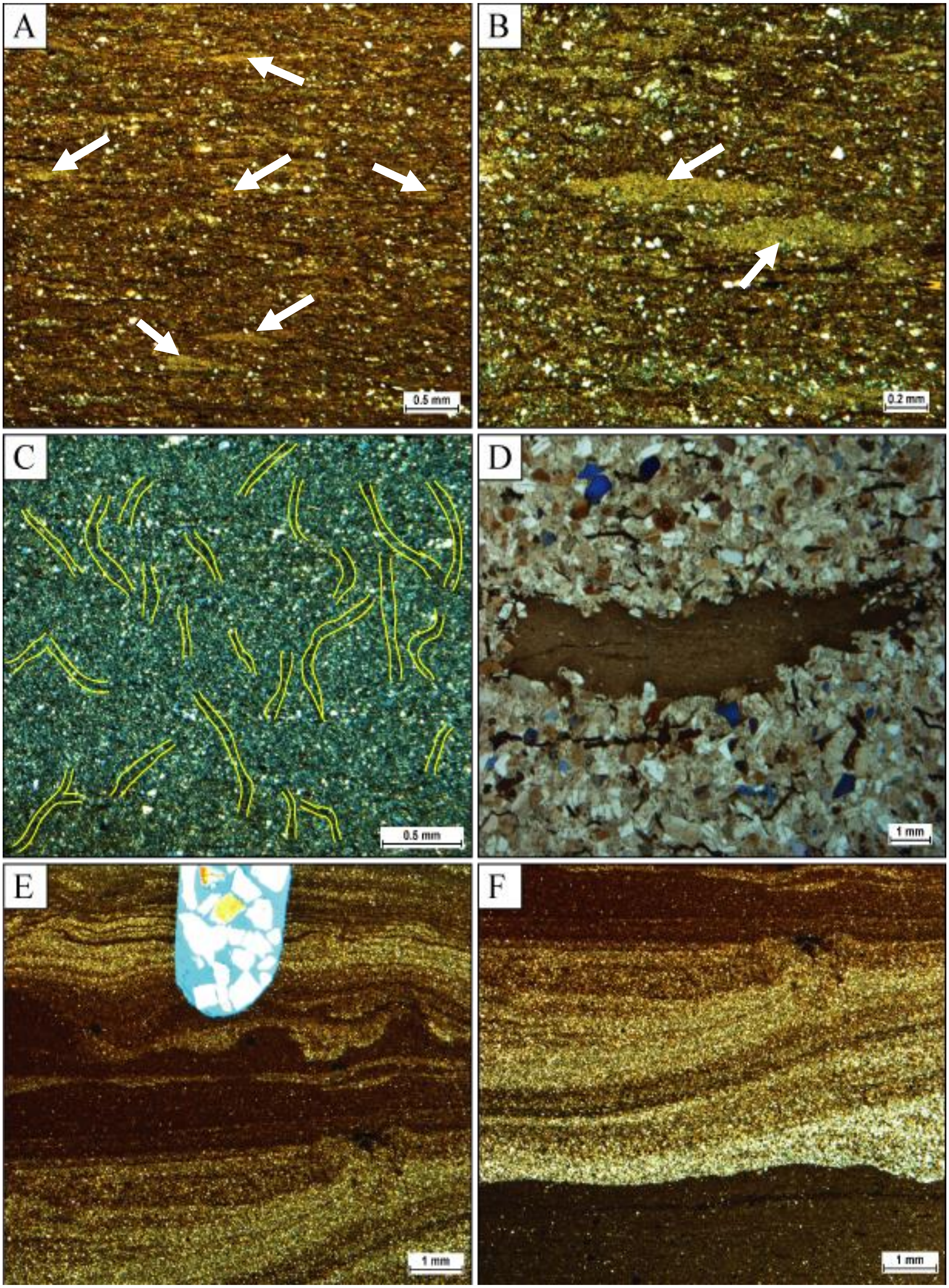
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Figure 4.4. Ultra-thin section natural and polarized (photograph C) light photographs of siliciclastic sedimentary features observed in the Black Cove and American Tickle Formations of Western Newfoundland. The letter after each description indicates corresponding facies letter. A) Light brown clay clasts (indicated with white arrows) oriented parallel to bedding within the laminated and massive silt-bearing, clay-rich mudstone facies (B). B) *Planolites isp.* Ichnofossils (indicated with white arrows) oriented parallel to bedding within the laminated and massive silt-bearing, clay-rich mudstone facies (B). C) *Phycosiphon incertum* fecal strings (outlined in yellow) throughout the laminated and massive silt-bearing, clay-rich mudstone facies (B). D) Mudstone rip-up clast within the massive, silt-to-sandstone facies (D). E) Load/flame soft sediment deformation structures within the silt-bearing, clay-rich mudstone and silt-rich mudstone with downlapping laminae facies (B and C). F) Soft sediment deformation water escape structure within the silt-bearing, clay-rich mudstone and silt-rich mudstone with downlapping laminae facies (B and C).

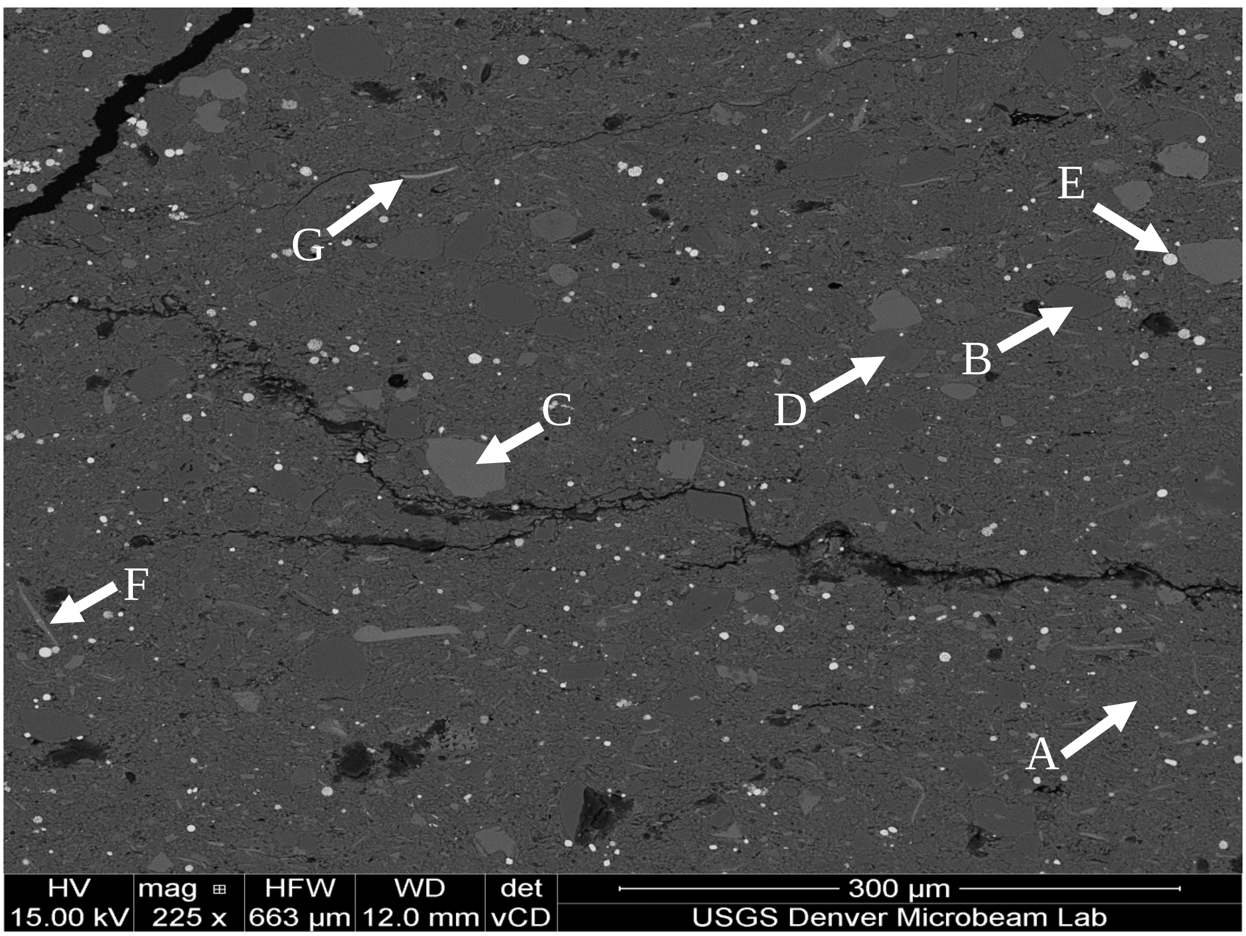

Figure 4.5. High contrast (VCD) SEM image of the silt-bearing, clay-rich mudstone (Facies B) within the Black Cove Formation (*Nicholsonograptus fasciculatus* biozone) at the oil tank locality. The fine matrix represents predominantly clay minerals (A) while the larger sub-rounded grains represent quartz (B), calcite (C), and dolomite (D). Small rounded white grains represent pyrite (E) and the more platy grains represent biotite (F) and apatite (G).

4.2 Facies Association Descriptions

The Black Cove and overlying American Tickle Formations of the Middle Ordovician Goose Tickle Group contain three distinct facies associations. Individual facies (Table 4.1) are grouped into three associations based on their co-occurrence within the measured sections. The facies associations are described in detail below.

4.2.1 Facies Association 1

Facies association 1 (FA1) consists predominantly of laminated and massive silt-bearing, clay-rich mudstones (Facies B). This facies association forms relatively homogenous units that are up to 6.0m thick. The laminated and massive silt-bearing clay-rich mudstones (Facies B) can occur with foresets of alternating siltstone and clay-rich laminae (Facies C) and massive mudstones (Facies A), which are intercalated as several cm-thick beds in irregular intervals about every several decimeters. Clay clasts, organo-mineralic components ("marine-snow particles", Macquaker et al., 2010), and fine-to-medium-grained silt-sized quartz, calcite and dolomite are the main grain types in this facies association. Grains generally occur randomly distributed within the clay-rich matrix. Some of the silt grains show local accumulations in distinct lenticular laminae, while others are continuous and of equal thickness over the width of a thin section (Facies B). Where preserved, the continuous and discontinuous silt laminae range from 0.1-to-1.5mm in thickness. The stratigraphic upper and lower contacts of these laminae regularly exhibit sharp contacts with the surrounding sediment, but locally can appear gradational and erosional. Synsedimentary deformation occurs in this facies association; it is readily visible however, only in contrasting lithologies. In places, flame (Figure 4.4e) and water escape (Figure 4.4f) structures are discernible, where dense foresets of siltstone and mudstone laminae (Facies C) overlie less-dense silt-bearing, clay-rich mudstones (Facies B). Common skeletal components include graptolites, phyllocarids, and small inarticulate brachiopods (see Whittinton and Kindle, 1963;

Morris and Kay, 1966). FA1 sediments are entirely bioturbated with *Phycosiphon incertum* fecal strings (James MacEachern, personal communication to Sven Egenhoff, November 2012), whereas *Planolites isp.* ichnofossils are only locally preserved.

4.2.2 Facies Association 2

Facies association 2 (FA2) is comprised of 0.07-to-0.15m thick beds of silt-to-fine-grained sandstones (Facies D) intercalated with rocks within FA1 silt-bearing clay-rich mudstones (Facies B), stacked foresets of siltstone and clay-rich laminae (Facies C), and massive mudstones (Facies A). The main grain types include medium to coarse-grained silt to fine-grained sand-sized detrital quartz, feldspar (mostly plagioclase), calcite, dolomite, and clay particles. All grains generally occur randomly distributed within a clay matrix, exhibiting poor-to-moderate sorting, and displaying angular-to-sub-rounded shapes. Localized mudstone rip-up clasts occur within FA2, found within coarse-grained silt and fine-grained sand dominated facies (Facies D) as well as associated silt-bearing clay-rich mudstones (Facies B). *Phycosiphon incertum* fecal strings are only preserved in fine-grained, silt-bearing lithologies of facies association 2.

4.2.3 Facies Association 3

Facies Association 3 (FA3) encompasses three carbonate facies: massive, carbonate mud-to-wackestones (Facies E), laminated and massive, peloidal, skeletal packstones (Facies F), and skeletal grainstones (Facies G). Present in only the southern three localities (Black Cove, oil tank section, and West Bay Center), FA3 outcrops in 0.10-to-0.30m thick beds composed of peloids, recrystalized bioclastic debris, and detrital quartz, with lithoclasts, aggregate grains, and carbonate mud occurring only locally. Rocks within this facies association are either massive or characterized by millimeter-thick laminations. These laminations consist of alternating peloid-rich and peloid-poor layers (0.20-to-1.00mm in thickness) with rare oversteepened foresets. While most siliciclastic detritus is silt-sized, specific intervals can contain up to 10-15% sand-sized quartz and plagioclase grains. In other areas, diagenetic suturing connects cemented grains, lithoclasts, and aggregates.

4.3 Facies Architecture

The lower Goose Tickle Group is subdivided into two units exhibiting stratigraphic disparity. The stratigraphically lower unit, the Black Cove Formation (BCF), defines the *Nicholsonograptus fasciculatus* graptolitic biozone (Maletz et al., 2011). Represented in only the three southern localities (from south to north - Black Cove, the oil tank section, and West Bay Center), the *Nicholsonograptus fasciculatus* biozone records an overall coarsening-upward trend that is broken up into two smaller-scale coarsening upward units (cyclicity annotated within the correlated overview (Figure 4.4) and illustrated stratigraphic sections (in the Appendix). These small-scale intervals range in thickness from approximately 3.5-to-8.0m and are comprised of predominantly laminated and massive, silt-bearing, clay-rich mudstones (FA1) punctuated by centimeter-laminated, and massive peloidal, skeletal packstones and skeletal grainstones with rare intercalations of carbonate mud-to-wackestones (FA3). Aerially, detrital silt-sized quartz and calcite grains increase in size (from fine-to-medium-sized silt to coarse-sized silt) and abundance due west from Black Cove and the oil tank section to West Bay Center. Conversely, carbonate grains within intercalated carbonate beds of FA3 decrease in size from peloidal, skeletal packstones at Black Cove and the oil tank localities to massive, carbonate mud-to-wackestones present within the West Bay Center stratigraphic section. Stratigraphically, there is compositional variation as dolomite decreases in percentage up-section, while siliciclastic silt increases in abundance up-section.

Overlying the dark grey/black Black Cove Formation and *Nicholsonograptus fasciculatus* biozone is the green/grey American Tickle Formation defining the *Pterograptus elegans* biozone (Maletz, et al., 2011). It is arranged into thick stacks of mudstones (FA1), localized intervals of co-occurring mudstones and silt-to-sandstones (FA2), and some intercalated carbonate beds (FA3). The transitional color change between formations and biozones signifies the localized increased presence of carbonate constituents towards upper parts of the succession. Existing in only three of the four localities (the oil tank section, West Bay Center, and Spudgels Cove) the American Tickle Formation records an overall coarsening-upward trend that is broken into one or two localized smaller-scale coarsening upward units. These small-scale units range in thickness from approximately 5.5-to-8.0m and reflect geographic trends of lithologic discontinuity between stratigraphic sections (e.g. increased detrital siliciclastic grains in the north). The oil tank section represents the thickest continuous interval within the *Pterograptus elegans* biozone. The small-scale coarsening upward intervals are characterized by siliciclastic mudstones and foresets of alternating siltstone and clay-rich laminae (present in both FA1 and FA2) that are locally intercalated with silt-to-sandstones (FA2), and overlain by skeletal grainstones (FA3). These are capped by the Daniel's Harbour Member, characterized by massive limestone-lithoclast conglomerates (Stenzel et al., 1990). The American Tickle Formation at West Bay Center is composed entirely of FA1 mudstones with minute millimeter-to-centimeter thick intercalated layers of siltstone. It represents an abrupt change in facies/sharp transition from mudstones to conglomerate. The northernmost locality, (Spudgels Cove) is characterized by clay-rich mudstones containing abundant intercalations of foresets with alternating siltstone and mudstone laminae (FA1 and FA2) overlain by centimeter thick beds of co-occurring massive, silt-to-sandstone and mudstone (FA2). The concentration of these facies at Spudgels Cove reflects the aerial trend of increased abundance and size of detrital silt -sized components (primarily quartz) in relation to the southern localities (West Bay Center, oil tank section, and Black Cove).

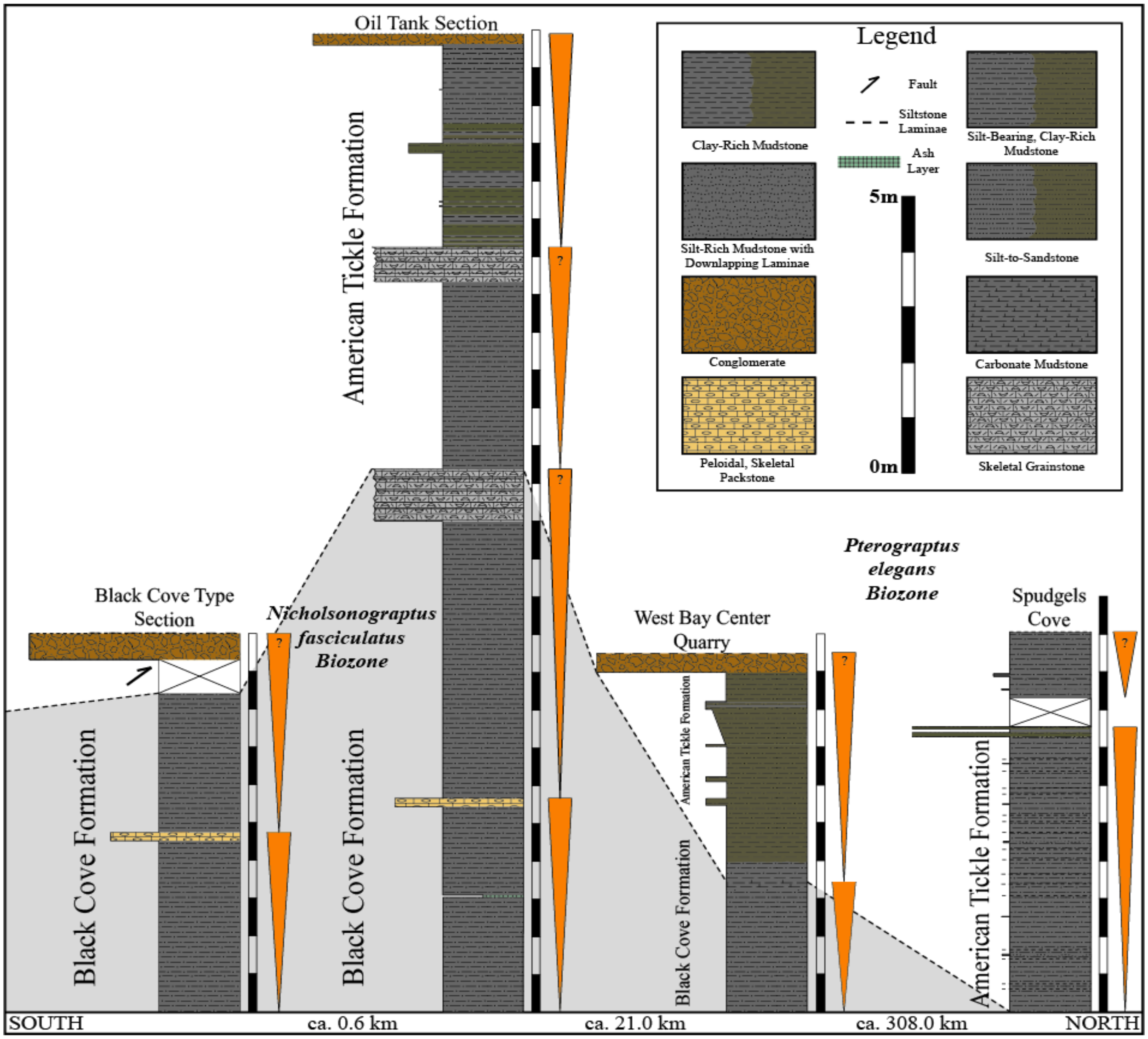

Figure 4.4. Stacking patterns and graptolite biostratigraphic overview of the western Newfoundland stratigraphic sections. Orange arrows denote overall grain size distributions. Question marks (?) symbolize approximate grain size trends as data from these intervals are sparse.

4.4 Facies Association Interpretations

The three facies associations, which characterize the Black Cove and American Tickle Formations record sedimentation during both high-energy and low-energy episodes. Present throughout facies association 1 (FA1) and facies association 2 (FA2), the silt-bearing, clay-rich mudstones (Facies B) are the most common facies type within the Newfoundland succession. These rocks contain an abundance of clay clasts and laterally irregular siltstone laminae indicating deposition through bedload processes. The sub-millimeter-sized clay clasts are often oriented parallel to bedding and distributed in higher concentrations within discrete layers, suggesting episodic high-energy events capable of eroding and re-depositing the muddy substrate. Bedload transport is further evidenced through the presence of remnant and irregular siltstone laminae. The sub-millimeter thick laminae are comprised of primarily silt-sized quartz and calcite grains reflecting high amounts of detrital input via high-energy currents from more proximal portions on the shelf.

Intercalated within the silt-bearing, clay-rich mudstones (Facies B) are localized clay-rich mudstones (Facies A), likely representing either suspension settling and/or bedload transport, as well as silt-rich mudstones with downlapping laminae (Facies C – see below). In places, the clay-rich mudstones (Facies A) contain very fine-grained, evenly thick mudstone laminae representing quiescent periods of clay particle suspension (Macquaker and Bohacs, 2007). In contrast, deposition of this facies could also be attributed to bedload transport through the migration of mudstone ripples (Schieber et al., 2007; Schieber and Southard, 2009), clay aggregates, and marine snow particles (Macquaker et al., 2010). Distinguishing between these depositional processes is made difficult in part because of bioturbation. *Phycosiphon incertum* fecal strings and isolated *Planolites isp.* are present in each of the facies associations, and are easily observed in fine-grained mudstones. The abundant burrowing and subsequent homogenization of sediment has destroyed the presence of any original primary structures that may have existed. This is not only true for the massive, clay-rich mudstones (Facies A), but can also be seen with *Phycosiphon incertum* cross-cutting laminae in the silt-bearing, clay-rich mudstones (Facies B) and silt-rich mudstones with downlapping laminae (Facies C). Facies C represents ripple foresets composed of alternating siltstone and mudstone laminae formed by bottom (likely, unidirectional) currents, which evidences fluctuating energy conditions (Schieber, 1998) and/or two separate grain populations (Schieber, 2007).

The massive silt-to-sandstones (Facies D) that occur within FA2 consist of predominantly coarse detritus indicating deposition from high-energy currents capable of transporting coarse silt-to-fine-grained sand-sized material. The detrital grains exhibit angular-to-sub-rounded shapes and a poor-to-moderate sorting suggesting that sediment was transported a moderate distance from its provenance. Localized rip-up clasts of associated siliciclastic mudstones (FA1) evidence erosion by high-energy currents, likely storms. The overall massive appearance may be attributed to the homogenization of the sediment by abundant burrowing (e.g. *Phycosiphon incertum*); trace fossils, however, are only visible in the silt-sized portion of this facies. Therefore, the massive appearance of the predominantly fine-grained sandstones reflects either rapid deposition and/or liquefaction.

The carbonate facies grouped within facies association 3 (FA3) likely reflect fluctuating energy conditions. Localized carbonate mudstone was deposited from either intermittent fair-weather suspension settling or bed-load processes (Schieber, 2012). The peloidal, skeletal packstones (Facies F) and skeletal grainstones (Facies G) throughout the Black Cove and American Tickle Formations represent episodic sedimentation from high-energy events, likely storms. Deposition of Facies F was dominated by the bedload transport of grains indicated by ripple bedding and planar laminations observed within the peloidal, skeletal packstones (Facies F). The massive appearance of skeletal grainstones (Facies G) reflects constant high-energy conditions able to transport coarse detritus and bioclastic material on the shelf. Dolomite (up to 80%) is interpreted to have replaced carbonate mud (Facies E).

CHAPTER 5: DEPOSITIONAL ENVIRONMENT

5.1 Depositional Model

Figure 5.1 schematically summarizes a depositional model for the Middle Ordovician Black Cove and American Tickle Formations. The strata record the distal, low-energy portion of a shelf system within a foreland basin carbonate platform located on the North American continental margin during initial stages of the Taconian Orogeny (Stenzel et al., 1990; Stockmal et al., 1995). Variations in depositional energy reflected within individual facies and characterized by factors such as lithology and grain size distribution, allow the depositional environment to be subdivided into three distinct facies associations representing a proximal to distal transect of this Middle Ordovician sedimentary system. Composed of predominantly siliciclastic mudstones (FA1 and FA2), the facies associations exhibit abrupt lithologic changes where centimeter-thick beds of silt-to-fine-grained sandstones (FA2) and carbonates (FA3) directly overlie FA1 sediments. These facies changes represent episodes of high-energy events such as storms that transported more proximal carbonate and coarse-grained sediments basinward and deposited them as intercalations within distal siliciclastic-rich mudstones.

Facies association 3 (FA3), occurring episodically throughout the Black Cove (*Nicholsonograptus fasciculatus* biozone) and American Tickle Formations (*Pterograptus elegans* biozone), represents the most proximal of the three facies belts. It is characterized in places, by massive carbonate mud-to-wackestones (Facies E), peloidal, skeletal packstones with downlapping laminae (Facies F), and skeletal grainstones (Facies G) reflecting fluctuating energy conditions within the succession. The overall large grain sizes of carbonate aggregates, bioclastic material, and peloids (Facies F and G) represent deposition under moderately-high-to-high-energy conditions capable of transporting coarse silt-to-fine-grained sand-sized material. The intercalated fine-grained limestones containing peloids and skeletal debris, however, may reflect two different sources, especially for the fine-grained portion of the sediment: (1) the carbonate mud may have originated either in place by the destruction of larger grains such as shells and other biogenic components (Matthews, 1966), or (2) it may have originated in a lagoon-like setting in shallow water similar to the recent Bahamas, and was transported offshore during storms (Flügel, 2004). High-energy conditions that also indicate storm deposition of these sediments are still reflected in a possible lagoonal origin of some of the grains, e.g. the peloids (Gischler, 2010; Neumann and Land, 1975; Scholle and Ulmer-Scholle, 2003), as well as primary sedimentary structures such as ripples and planar laminations indicative of deposition from currents or waves. The localized presence of massive carbonate mud-to-wackestone facies (Facies E) overlying fine-grained siliciclastics attests to either suspension settling of carbonate mud during low-energy fair-weather conditions and/or bedload transport processes (Schieber, 2012). Low-energy, quiet water conditions are also inferred for dolomite, replacing up to 80% of the pore spaces within the packstones and thought to originally represent carbonate mud.

The passage from FA3 to FA2 marks the basinward transition from carbonate sedimentation into adjacent, mostly fine-grained siliciclastic facies. The most proximal of these siliciclastic facies occurs locally within the American Tickle Formation (*Pterograptus elegans* biozone) and consists of compositionally and texturally immature massive silt-to-sandstones (Facies D). Facies D consists of primarily detrital quartz, feldspar, and phyllosilicate minerals, which suggests provenance from geologically complex basement sources such as nearby topographic highs, exposed hinterland, and/or advancing allochthons. Erosion of these sources led to transportation and deposition of this type of coarse-grained detritus under high-energy conditions. This is indicated by centimeter thick silt-to-sandstone beds containing siliciclastic mudstone (FA1) rip-up clasts. The occurrence of silt-to-sandstone beds at irregular intervals within fine-grained mudstones suggests that high-energy currents were likely episodic in nature and therefore likely storms. Further basinward, the distal portion of FA2 exhibits a decrease in depositional energy reflected in the absence of silt-to-sandstones (Facies D) and marks the transition to primarily FA1 sediments: silt-bearing, clay-rich mudstones (Facies B), localized foresets of alternating siltstone and clay-rich laminae (Facies C), and clay-rich mudstones (Facies A). A decrease in depositional energy (distally) may also be reflected in hydrodynamic sorting, where clay minerals are being transported as silt and sand-sized clay floccules that require a similar energy regime to be suspended and transported (Schieber et al., 2007). These clay floccules are capable of being deposited slightly further basinward because they are less dense than similar sized quartz, feldspar and carbonate grains. The presence of irregular lenticular siltstone laminae and clay clasts within facies B indicates that high-energy events (e.g. storms) were capable of eroding and re-dispersing mud as well as episodically depositing coarse silt-sized grains in this distal shelf setting. Locally, intermittent fair-weather sedimentation is observed through evenly thick, sub-millimeter laminae of clay-rich mudstone. *Phycosiphon incertum* and isolated *Planolites isp.* are pervasive throughout all of the fine-grained facies within each of the facies associations. This indicates suitable living conditions even during fair-weather conditions on this Middle Ordovician shelf.

The facies within the Newfoundland succession show four distinct meter-thick coarsening-upward units that are interpreted to represent four cycles of relative sea level change with the coarsest portion reflecting the lowest position of sea level (Plint, 1988). The succession as a whole also follows a general shallowing trend with successively coarser-grained and more proximal facies occurring towards its top. This indicates that the area of deposition was undergoing a shallowing trend with the coastline successively prograding towards the basin during deposition of the Black Cove and American Tickle Formations.

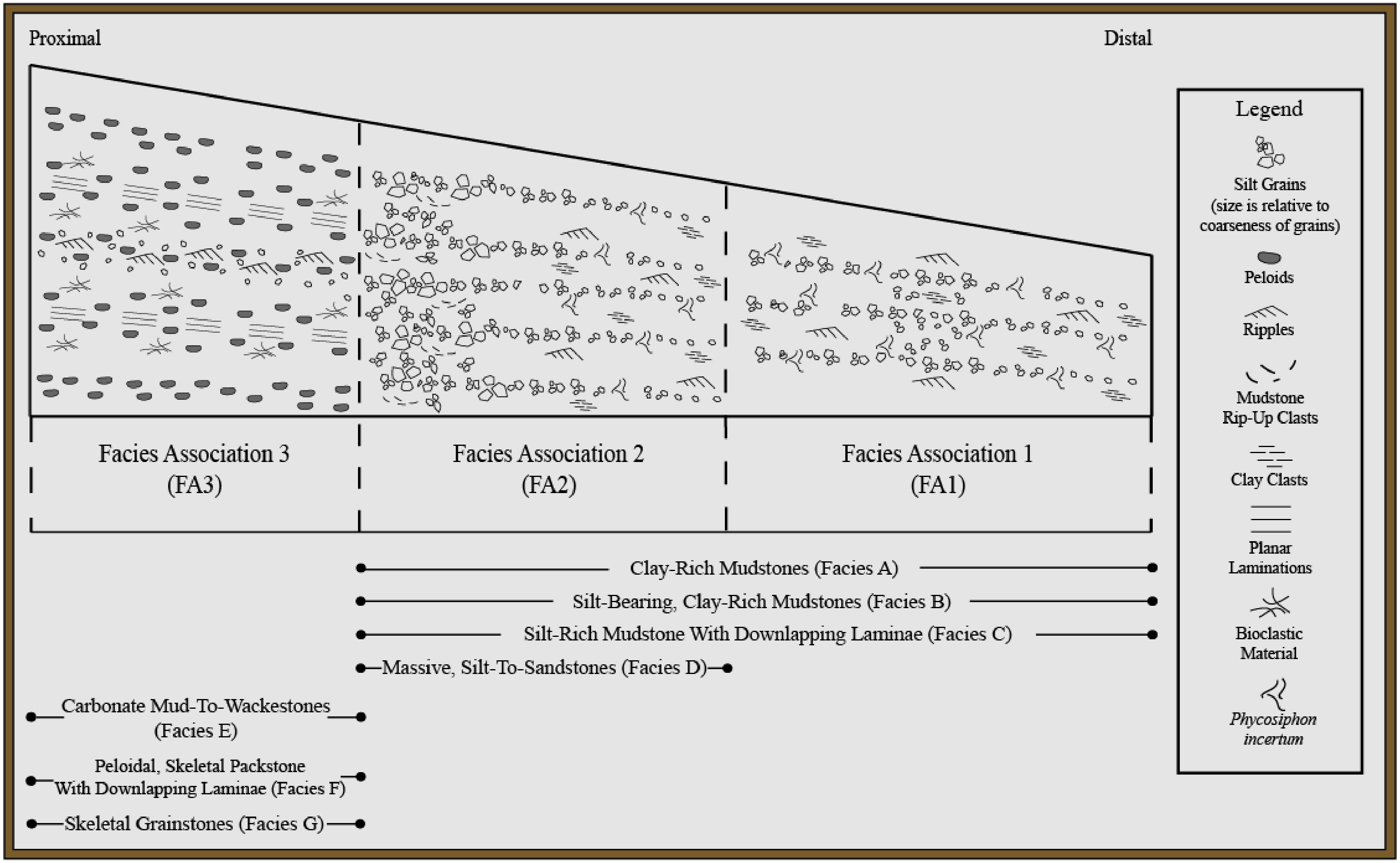

Figure 5.1. Depositional Model for the Lower Goose Tickle Group Black Cove (*Nicholsonograptus fasciculatus* Biozone) and American Tickle Formation (*Pterograptus elegans* Biozone).

CHAPTER 6: DISCUSSION

6.1 Black Cove and American Tickle Deposition

Both the Black Cove and the American Tickle Formations are described as being deposited on a slope of a carbonate platform or a basinal setting, most likely because the surrounding exposures of similar age have been interpreted to represent this setting (e.g. Cape Cormorant Formation in the Mainland section (Stenzel et al., 1990). Nevertheless, clear sedimentological evidence for a slope setting are missing in both stratigraphic units: slopes should either show their inclination through an abundance of synsedimentary slump structures (Mcllreath and James, 1978), and are normally characterized by significant percentages of turbidite deposits (Walker, 1976), none of which holds true for either the Black Cove or the American Tickle Formation. Slope deposits generally have large thicknesses such as the Mainland Formation (Waldron et al., 2012), which is in part time-equivalent to both the Black Cove and the American Tickle Formations (Maletz et al. 2011), but this does not hold true for the two units under study as they are thin in any of the studied locations. The Black Cove and the American Tickle Formations show distinct facies variations that are interpreted as reflecting changes in relative sea level, with carbonate shallow-water deposits representing exclusively lowstands and are otherwise absent from the succession. Such a stratigraphic setup shows well-defined sea level changes, which would also not be typical for slope or basin deposits but characterize both units in any of the four studied locations. Both units overlie interbedded shallow-water limestones intercalated with black shales (Table Cove Formation) that record a gradual deepening of the environment, which also points to the Black cove and American Tickle Formations being a platform setting rather than a slope or basinal environment. This platform setting was most likely (as suggested in the present manuscript), a deep shelf environment mostly located below storm wave base as indicated by abundant storm beds intercalated into bioturbated fair-weather sediments. It was still heavily influenced by sea level fluctuations showing pure carbonate deposition during lowstands and therefore probably not located at significant water depth, most likely around 50 to 100 meters.

6.2 Extensional vs. Compressional Tectonic Regime

Stenzel (1991), and Williams et al. (1996) suggested that the Black Cove and overlying American Tickle Formations were originally deposited in an extensional tectonic setting. According to this model, elevated zones represent horst structures, and the Black Cove and American Tickle Formations would represent the sediments in depressions between these elevated blocks (James et al., 1979; James et al., 1989; Klappa et al., 1980, Stenzel, 1991; Williams et al., 1996). While this model does explain the successively higher clastic input into the two formations, its general setting does not fit the proposed onset of compression within this Ordovician foreland basin. According to Waldren et al., (2012), Early Ordovician compressional movements that significantly predate the formation of the Black Cove and American Tickle Formations generally characterized the basin. It is therefore more likely that the elevated zones envisioned to supply clastic detritus to the basin were formed by compression and not, as claimed by Stenzel (1991) and Williams et al. (1996), within an extensional setting.

6.3 Synsedimentary Tectonics

Synsedimentary deformation structures are not very common in the Black Cove and American Tickle Formations. The sedimentary structures that do occur are flame, water-escape, ball-and pillow-structures, slumps and load casts. Most of these structures occur when mudstones of varying composition are overlain by higher-density and less water-rich sand- and siltstones (Figure 4.3e and f). Flame structures and associated load casts can originate from both tectonic movements and high sedimentation rates (Dzulynski and Walton, 1965; Kelling and Walton, 1957). However, the latter is unlikely as the Black Cove Formation is not unusually thick in comparison with other environments such as the Cape Cormorant Formation in Mainland section from where no synsedimentary deformation structures have been reported so far (cf. Maletz et al. 2011). The ball-and-pillow structures (Figure 6.1c), though miniscule, are generally attributed to earthquakes and therefore with local tectonic activity (Hildebrandt and Egenhoff, 2007; Nichols et al., 1994). These movements most likely were also responsible for the slumps observed in some of the silt-to-sandstone units (Facies D; Figure 6.1a and b).

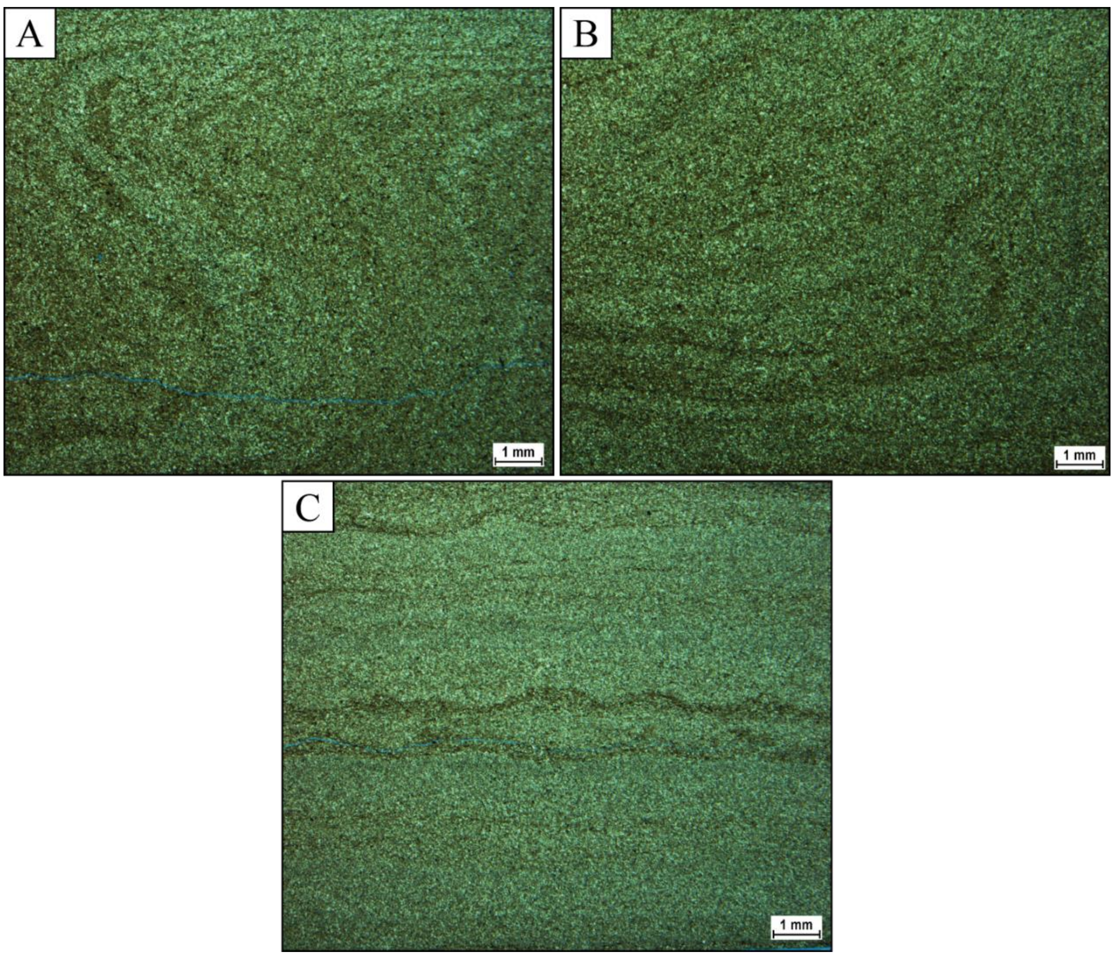

Figure 6.1. Ultra-thin section natural light photographs of synsedimentary features observed in the Black Cove and American Tickle Formations of Western Newfoundland. A and B) Slumping. B) Ball-and-pillow structures.

6.4 Sea Level Fluctuations

The two studied formations including the overlying Daniel's Harbour Conglomerate show four coarsening-upward units, ranging in thickness from 3.5-8.0m, that are interpreted as reflecting lowstands of relative sea level during deposition on this Ordovician shelf. According to Posamentier et al., (1992), such lowstand units are interpreted to represent forced regressions characterized by a sharp contact of coarser proximal sediments (Facies D, E, F, G) abruptly overlying distal marine deposits without significant coarsening. The time frame of these four lowstand units, each mirroring one distinct sea level fluctuation, encompasses the central portion of the Darriwilian (Middle Ordovician) even though the exact age, especially of the upper succession boundary remains problematic (cf. Maletz et al. 2011). Haq and Schutter (2008), however, show only two fluctuations of sea level for the same stratigraphic interval (Figure 6 .2) based on data from tectonically quiescent areas around the world. While their approach is hampered by e.g. the lack of error bars (Miall, 1992) it still indicates that the Newfoundland succession was most likely subject to two more relative sea level changes than time-equivalent successions worldwide. Therefore, at least two of the sea level changes observed in the Newfoundland successions were most likely controlled by factors other than eustasy. In a tectonically active basin like the study area during the Ordovician, tectonics likely exerted another important control on relative sea level changes. The abrupt deepening observed at the top of the 4 Newfoundland sequences may have been caused by subsidence due to tectonic influences (e.g. crustal loading) of cratonward propagating thrust packages (Beaumont, 1981; Price, 1973). Tectonic influence on deposition is also indicated by the overall sedimentological trend, which is shallowing in the Newfoundland sections whereas it is deepening in tectonically quiet areas worldwide (Haq and Schutter 2008).

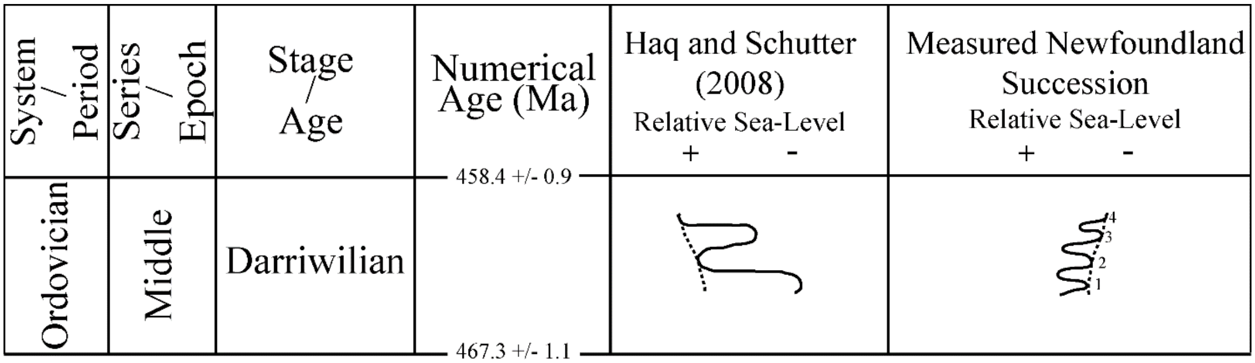

Figure 6.2. Relative sea-level curves for the Newfoundland succession (right), and Haq and Schutter (2008) (left). According to Haq and Schutter (2008), the solid lines represent 3rd order sea-level fluctuations and indicate short-term trends, while the dashed lines represent overall 2nd order changes in sea-level and indicate long-term trends. The Black Cove and American Tickle Formations show four distinctive 3rd order lowstands annotated with numbers from 1-4 and an overall drop in relative sea-level. In contrast, Haq and Schutter (2008), observed only two 3rd order lowstands and record an overall 2nd order sea-level rise over the studied interval. Numerical ages from Gradstein et al., 2012.

6.5 Anoxia

The Black Cove Formation sediments have been interpreted by Stenzel et al. (1990) to represent an overall anoxic environment without benthic life. This interpretation is likely based on its black character indicating richness in organic matter, which was thought to be exclusively possible under anoxic conditions (Deuser, 1975; Richards, 1965). However, the ubiquity of *Phycosiphon incertum* fecal strings throughout the succession makes a complete anoxic setting for the deposition of the Black Cove sediments unlikely. These fecal strings originating from benthic organisms burrowing at least some millimeters into the sediment indicate that bottom waters must have been at least dysoxic during most of Black Cove Formation's depositional history (cf. Egenhoff and Fishman, accepted). The low diversity of fecal strings, however, indicates that dysoxic were more likely than anoxic conditions at the sediment-water interface and a few millimeters into the sediment as indicated by the burrowing depth of *Phycosiphon incertum*.

CHAPTER 7: CONCLUSIONS

(1) The Middle Ordovician Black Cove (*Nicholsonograptus fasciculatus* biozone) and American Tickle (*Pterograptus elegans* biozone) Formations contain seven facies, four siliciclastic and three carbonate, that can be grouped into three different sedimentary facies associations. Facies association 1 (FA1) consists of laminated and massive, clay-rich mudstones (Facies A), laminated and massive, silt-bearing, clay-rich mudstones (Facies B), and silt-rich mudstone with downlapping laminae (Facies C). Facies association 2 (FA2) is comprised of (rocks within FA1) as well as massive, silt-to sandstones (Facies D). Facies association 3 (FA3) is made up of massive, carbonate mud-to-wackestones (Facies E), peloidal, skeletal packstones with downlapping laminae (Facies F), and skeletal grainstones (Facies G).

(2) Sedimentary structures such as ripple foresets, planar laminations, mudstone rip-up clasts and lenticular siltstone laminae are abundant throughout the three facies associations within the Newfoundland succession. Their presence demonstrates that the predominant sediment dispersal mechanism for the deposition of the Black Cove and American Tickle Formations was bedload transport, likely from high-energy events, such as storms. Intermittent fair-weather sedimentation is also observed through evenly thick, (sub-millimeter) laminae of fine-grained mudstones, suggesting that suspension settling processes occurred during quiescent periods between high-energy events.

(3) The range of facies observed in this study represents deposition on the distal reaches of an Ordovician shelf system, opposing previous interpretations of a lower slope and/or basin environment. Three facies associations form distinctive zones characterizing different energy positions along a proximal to distal transect. Moderately-high to high-energy (proximal) sediments are grouped into facies association 3 (FA3) and consist of peloidal, skeletal packstones (Facies F)

and skeletal grainstones (Facies G) with localized carbonate mud-to-wackestones (Facies E) reflecting low-energy deposition. The basinward shift from FA3 to facies association 2 (FA2), marks the transition from carbonate sedimentation into adjacent, mostly fine-grained siliciclastic facies. The most proximal of these siliciclastic facies are the silt-to-sandstones (Facies D), which occur in the central part of the sedimentary system and are associated with rocks of facies association 1 (FA1). Further basinward, the distal portion of FA2 exhibits a decrease in depositional energy reflected in the absence of silt-to-sandstones (Facies D) and marks the transition to primarily FA1 sediments: clay-rich mudstones (Facies A), silt-bearing, clay-rich mudstones (Facies B), and localized foresets of alternating siltstone and clay-rich laminae (Facies C). These low-energy sediments reflect the most distal part of the Ordovician shelf system but still remain periodically influenced by high-energy currents, likely storms.

(4) The carbonate and siliciclastic facies within the studied formations indicates a depositional environment that was at least partially favorable for burrowing organisms. No recognizable bioturbation gradient is identified within the succession, however, the presence of *Phycosiphon incertum* fecal strings and localized *Planolites isp.* suggests that the Black Cove and American Tickle depositional environment was not continuously anoxic as previously believed, but must have been dominantly oxic to dysoxic allowing for some adapted benthic organisms to thrive with anoxic events, if they occurred, representing the exception.

(5) Throughout the Newfoundland succession, the facies and facies associations characterizing the Black Cove and American Tickle Formations record an overall shallowing of the environment with successively coarser-grained and more proximal facies occurring towards its top. Four lowstand units comprise the overall succession and are attributed to the lowering of relative sea level. In comparison, Haq and Schutter (2008) recognized only two fluctuations of sea

level during the same stratigraphic interval encompassing the Middle Darriwilian. Therefore, it is likely that mostly tectonics and not only eustasy controlled sea level changes within the investigated interval.

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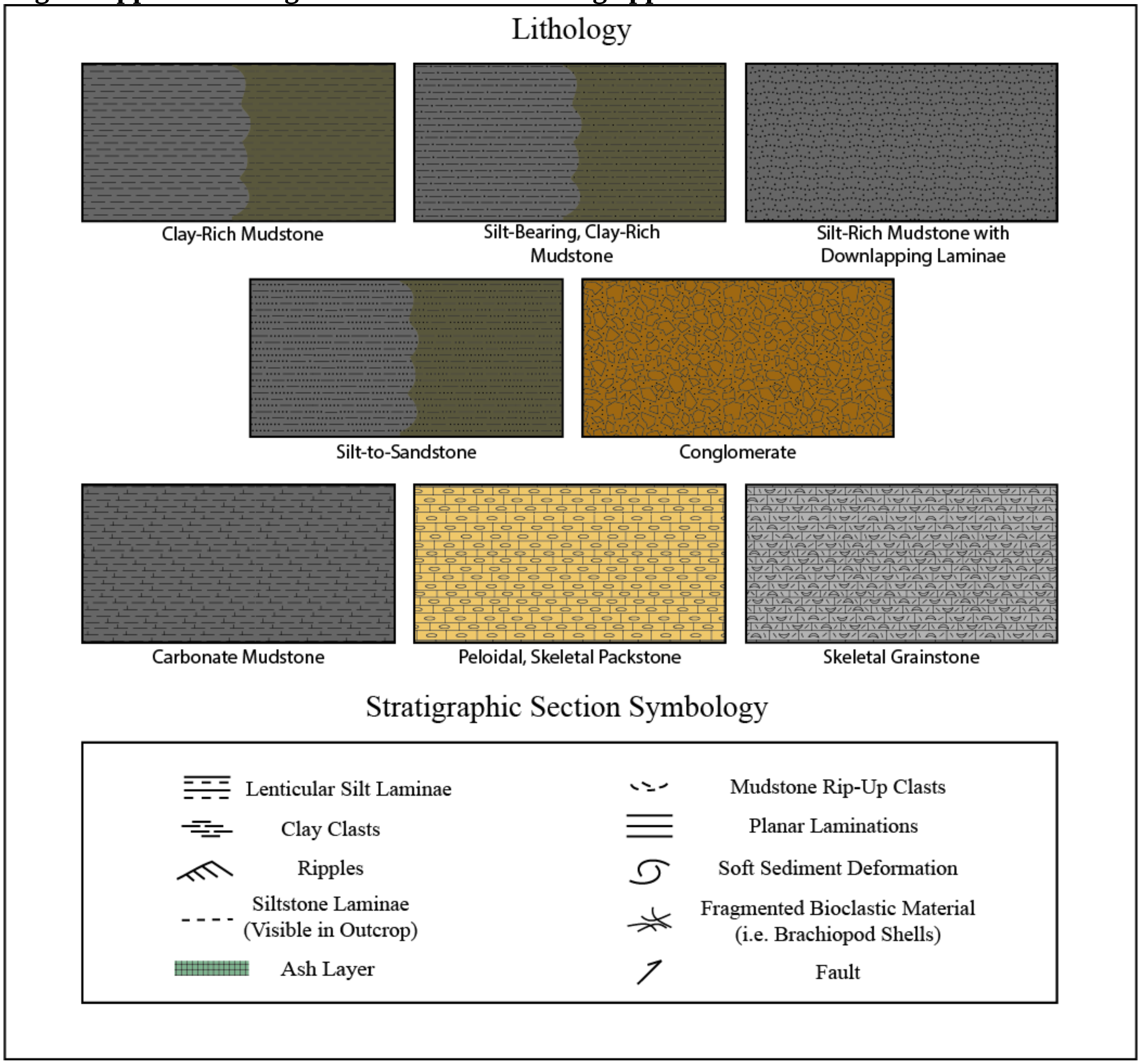
APPENDIX I

Legend applies to all figures within the following appendices.



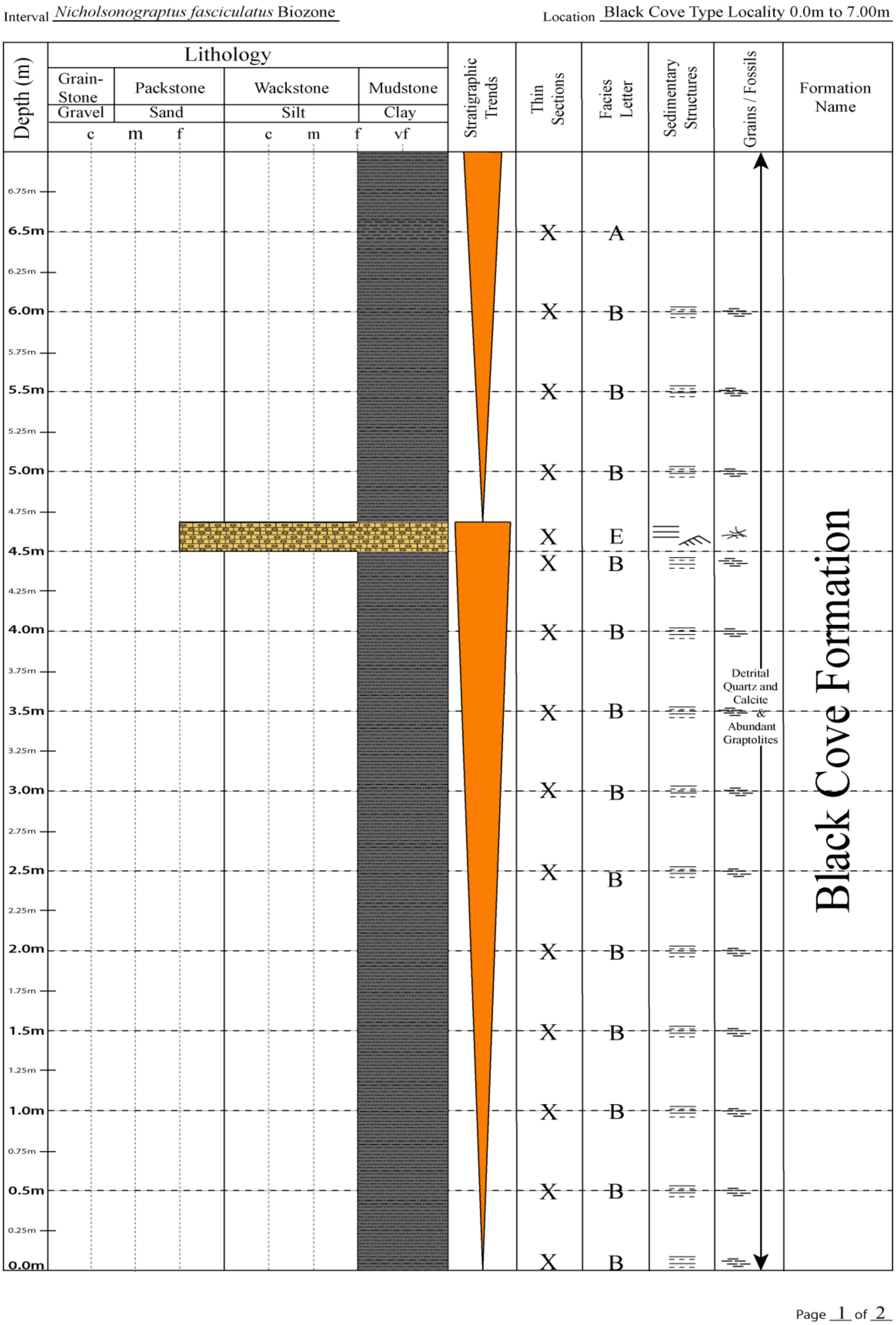


Figure A1.1. Stratigraphic description of the *Nicholsonograptus fasciculatus* biozone at the Black Cove Locality (1 of 2).

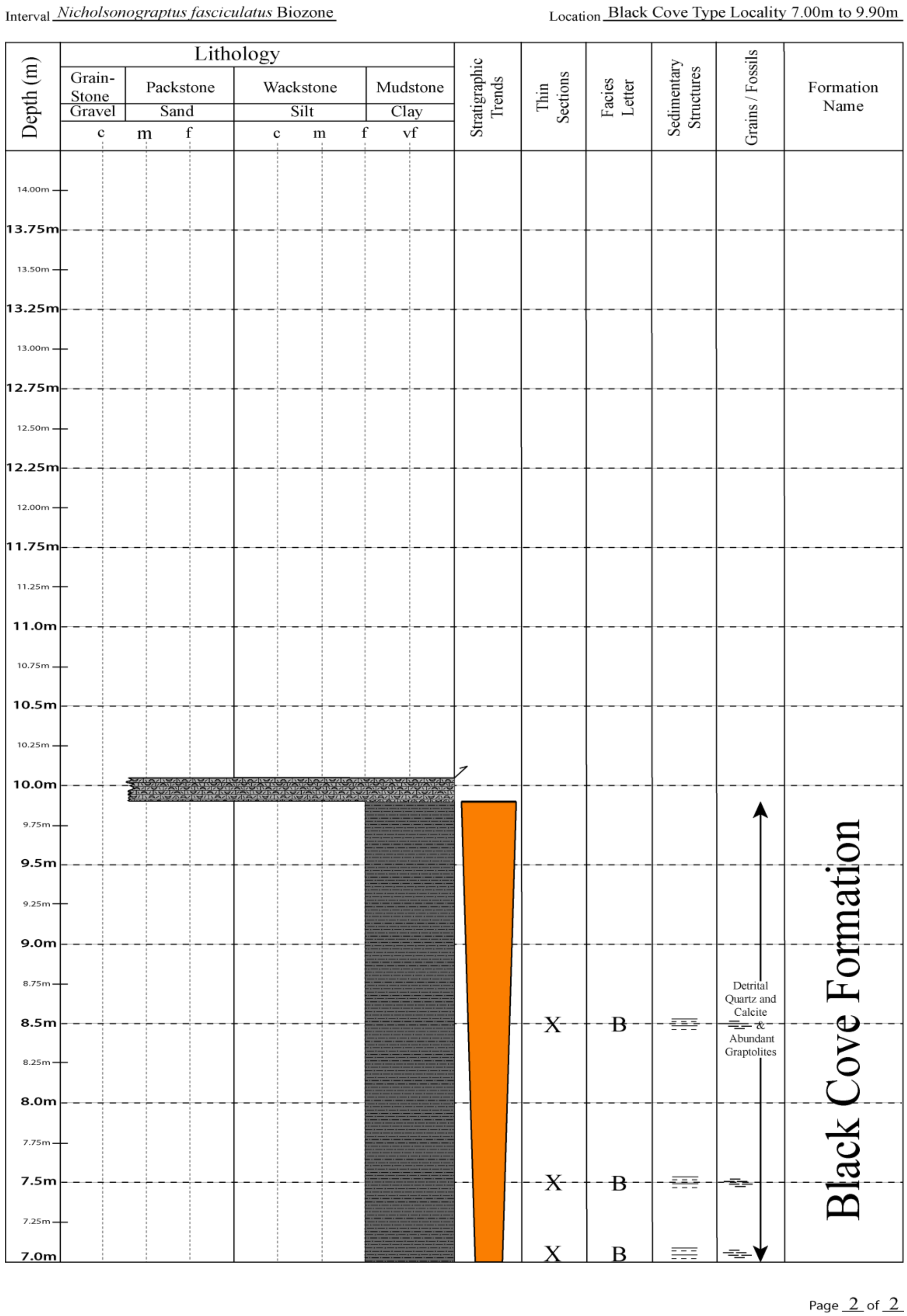


Figure A1.2. Stratigraphic description of the *Nicholsonograptus fasciculatus* biozone (Black Cove Formation) at the Black Cove Locality (2 of 2).

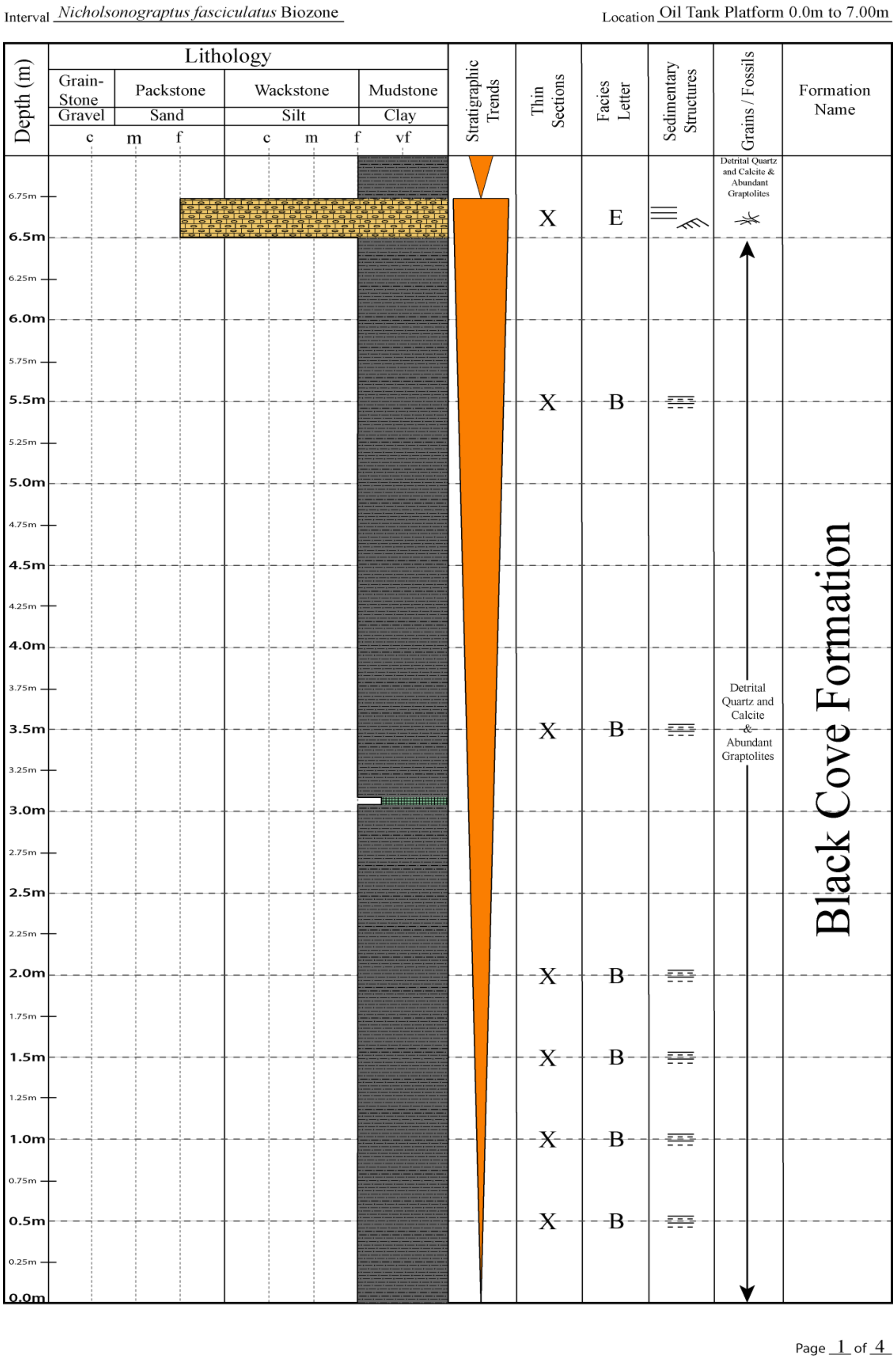


Figure A1.3. Stratigraphic description of the *Nicholsonograptus fasciculatus* biozone (Black Cove Formation) at the Oil Tank Section Locality (1 of 4).

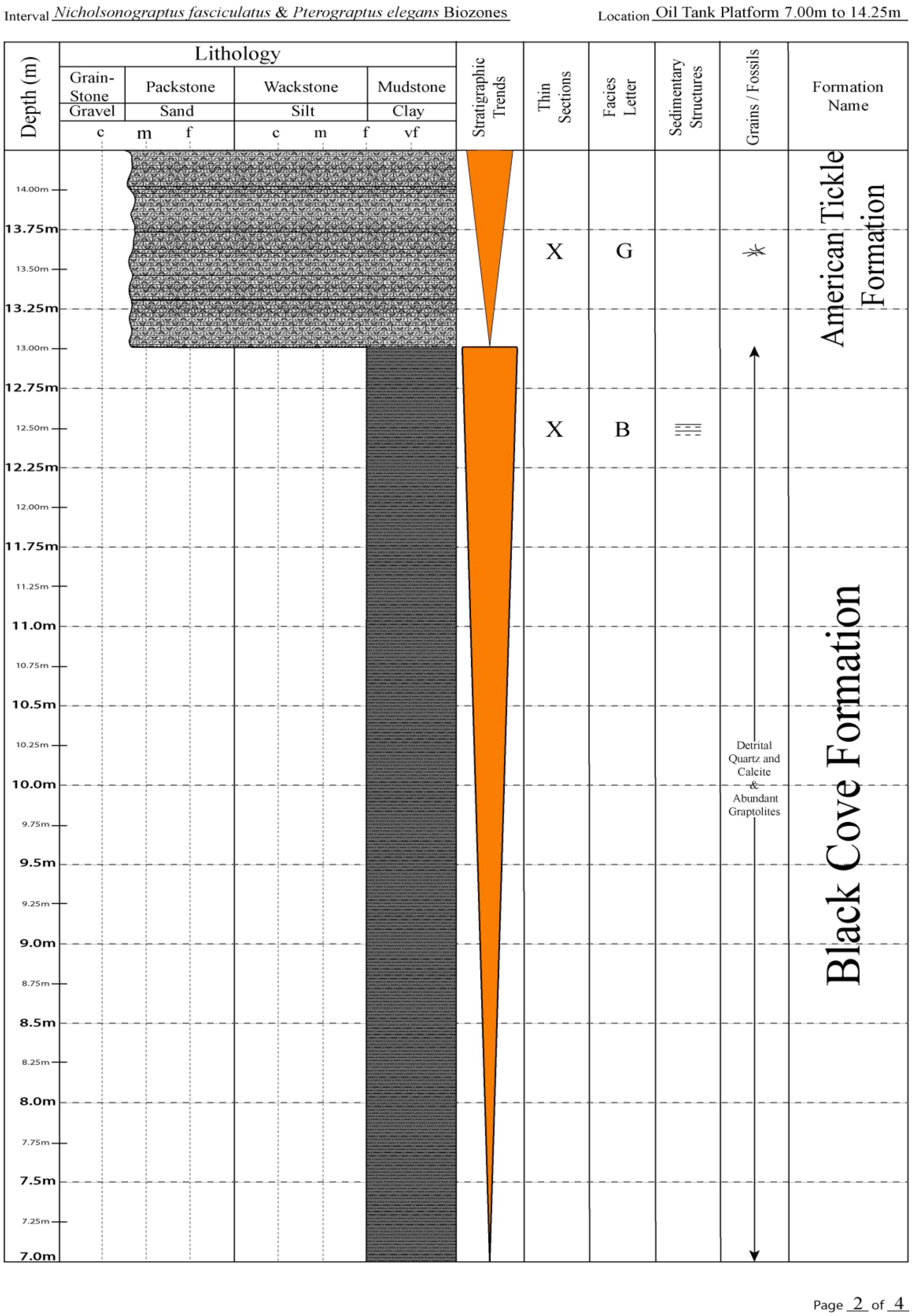


Figure A1.4. Stratigraphic description of the *Nicholsonograptus fasciculatus* (Black Cove Formation) and overlying *Pterograptus elegans* (American Tickle Formation) biozones at the Oil Tank Section Locality (2 of 4).

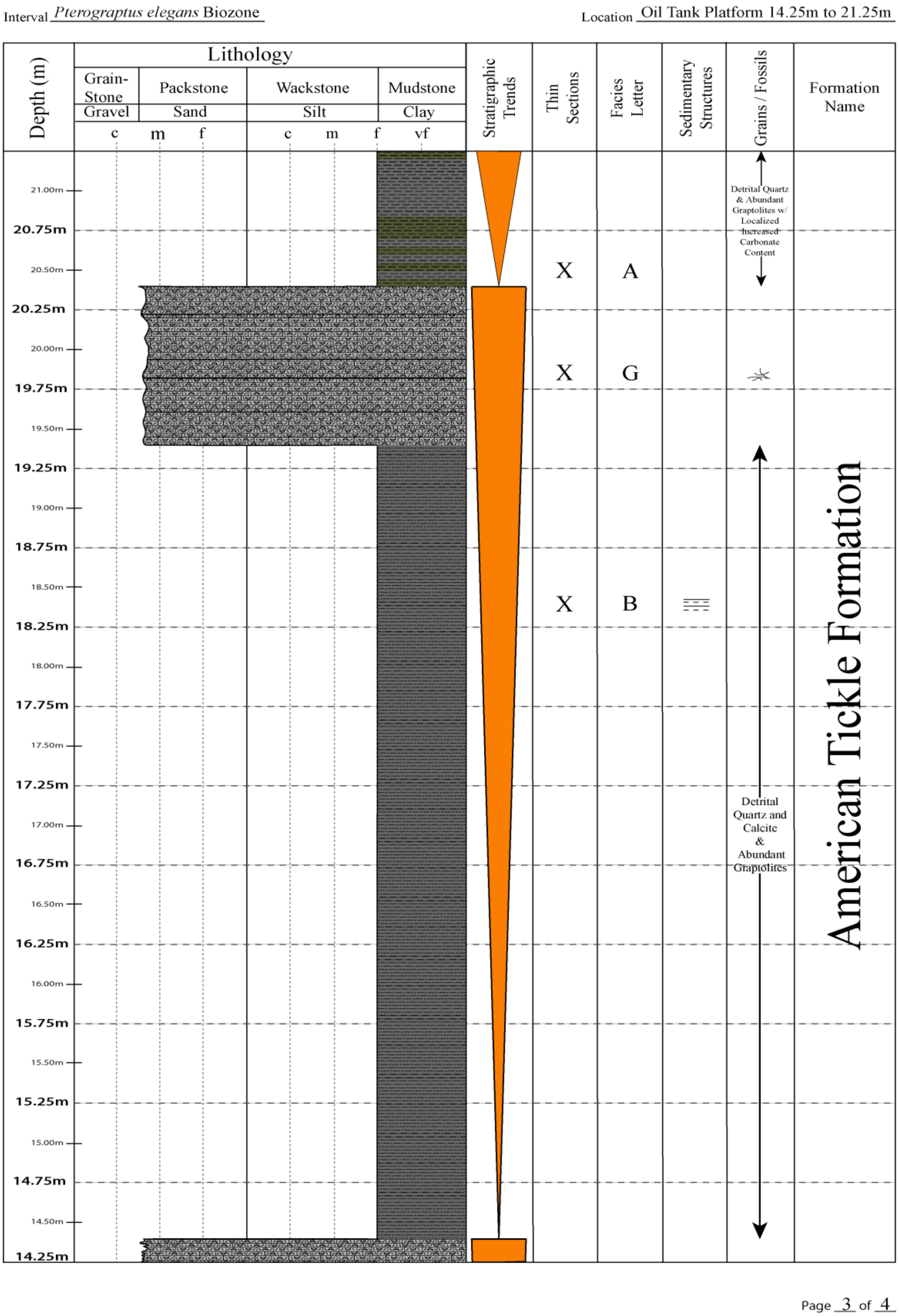


Figure A1.5. Stratigraphic description of the *Pterograptus elegans* (American Tickle Formation) biozone at the Oil Tank Section Locality (3 of 4).

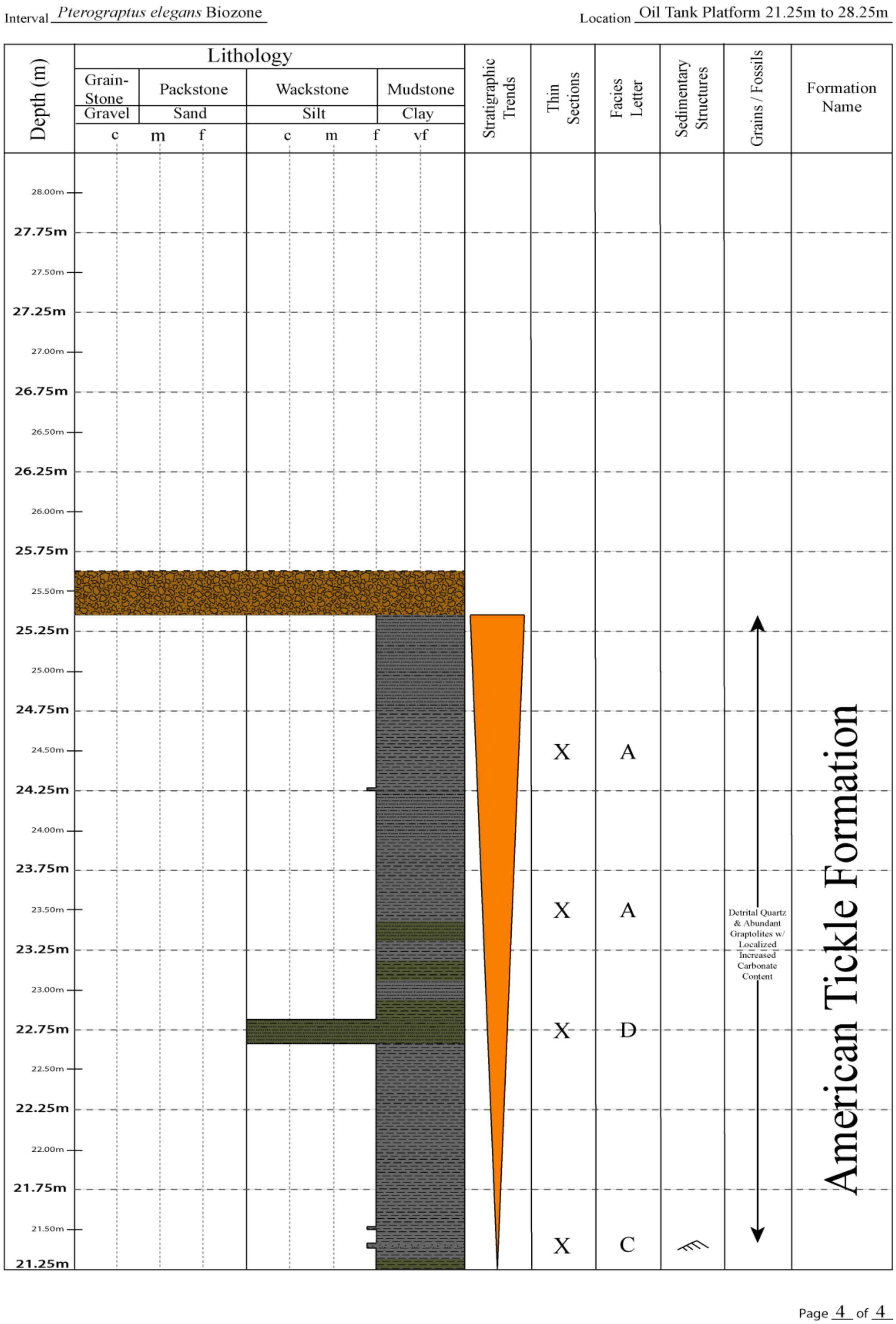


Figure A1.6. Stratigraphic description of the *Pterograptus elegans* (American Tickle Formation) biozone at the Oil Tank Section Locality (4 of 4).

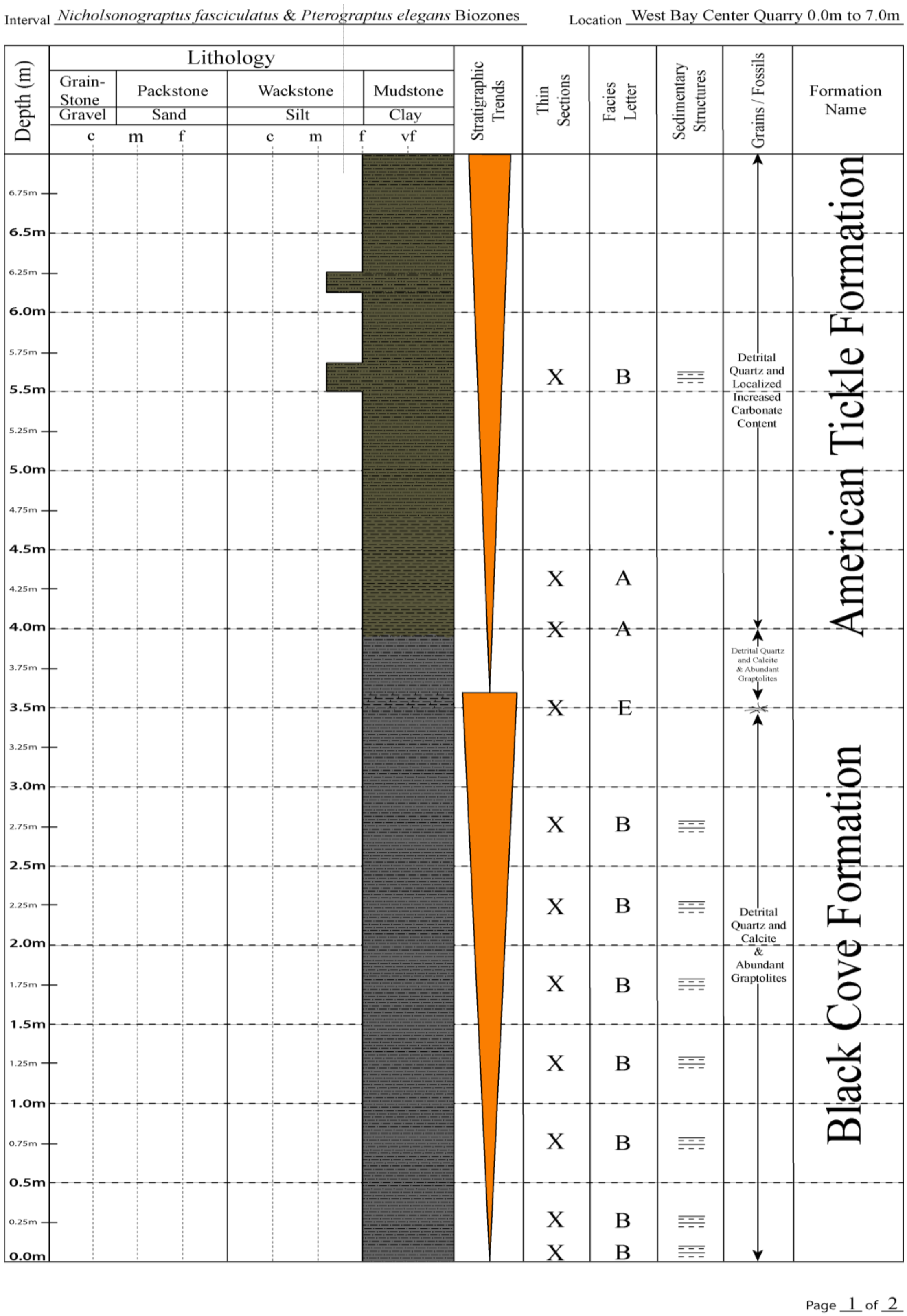


Figure A1.7. Stratigraphic description of the *Nicholsonograptus fasciculatus* (Black Cove Formation) and overlying *Pterograptus elegans* (American Tickle Formation) biozones at the West Bay Center Quarry Locality (1 of 2).

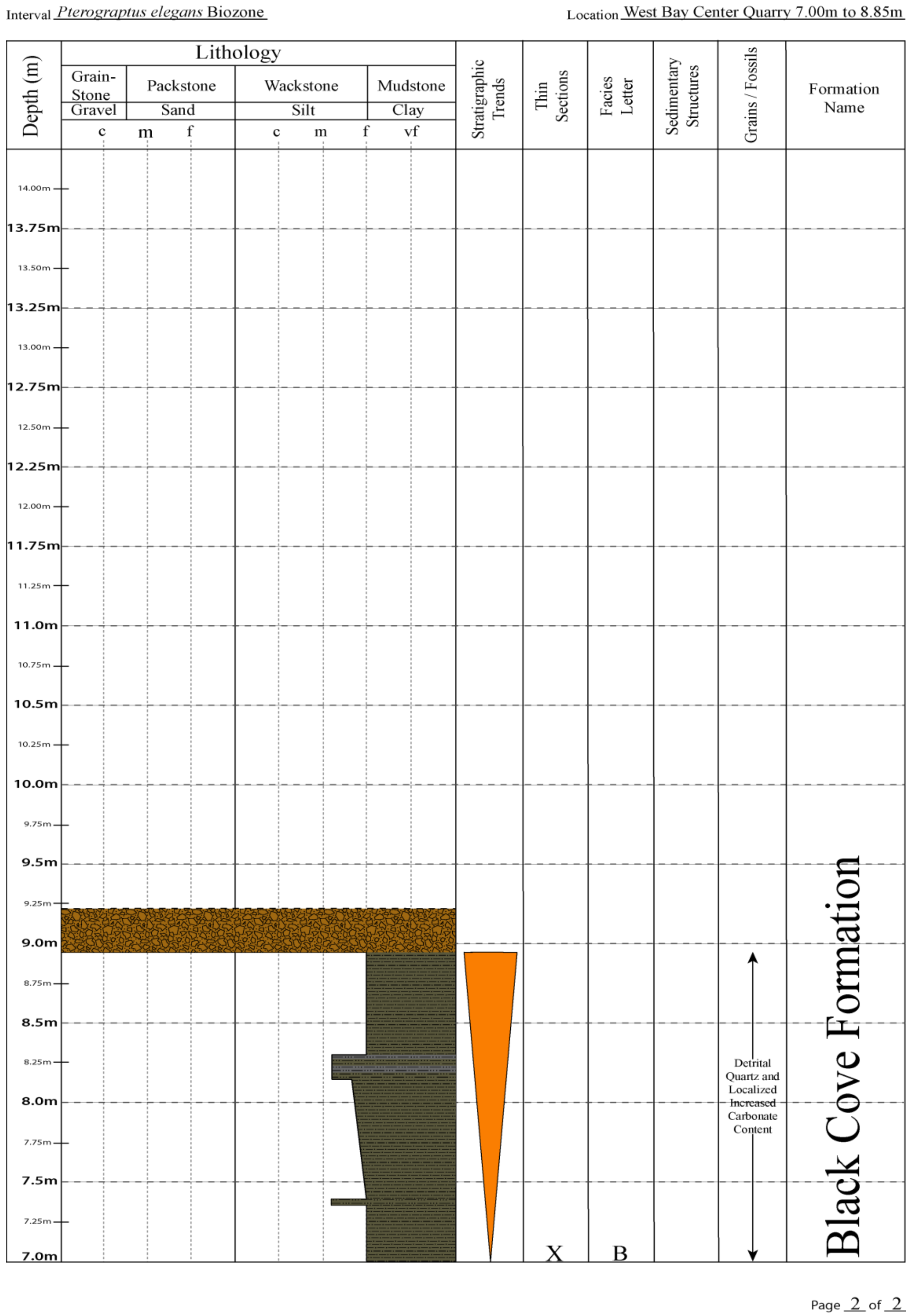


Figure A1.8. Stratigraphic description of the *Nicholsonograptus fasciculatus* (Black Cove Formation) and overlying *Pterograptus elegans* (American Tickle Formation) biozones at the West Bay Center Quarry Locality (2 of 2).

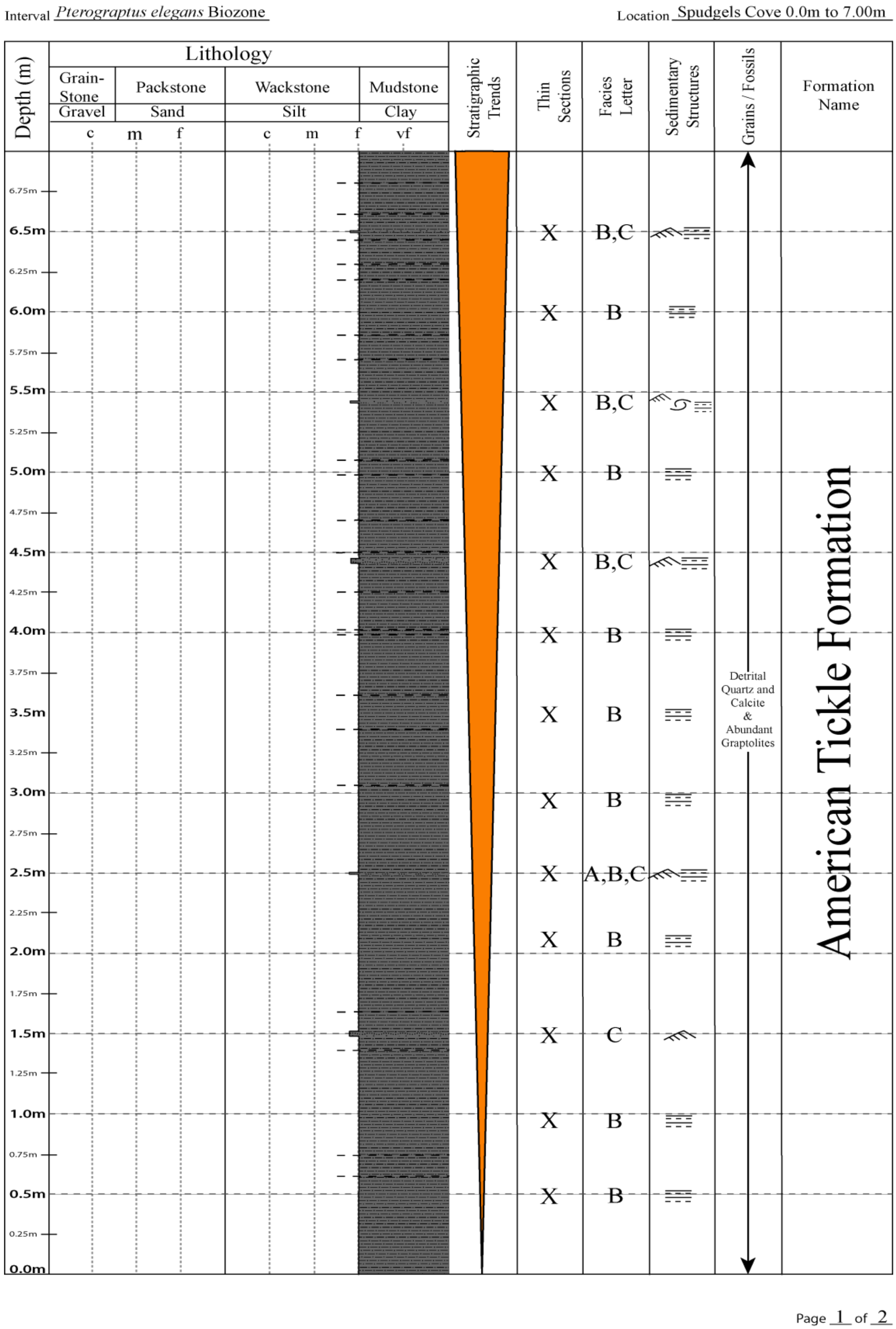


Figure A1.9. Stratigraphic description of the *Pterograptus elegans* (American Tickle Formation) biozone at the Spudgels Cove Locality (1 of 2).

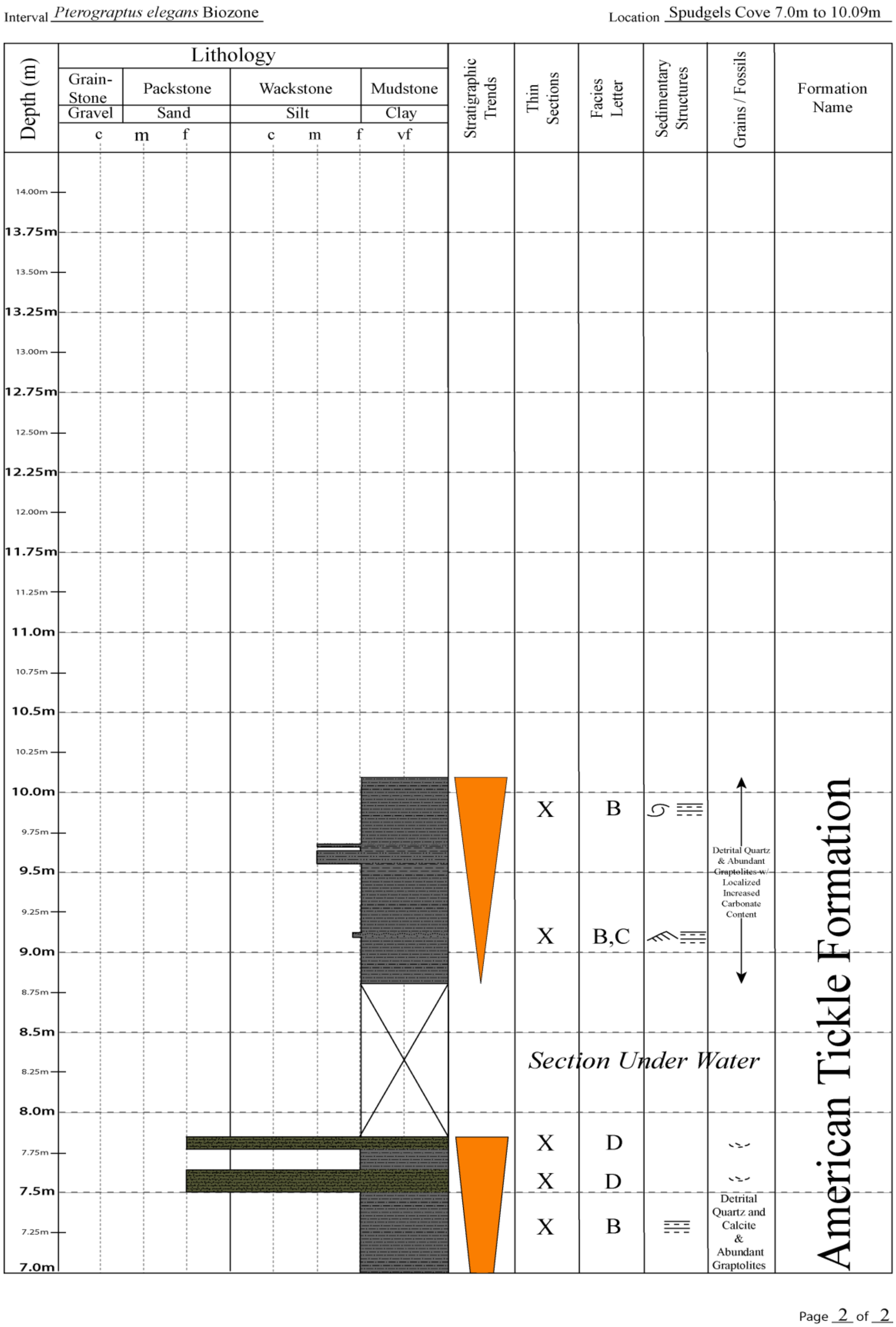


Figure A1.10. Stratigraphic description of the *Pterograptus elegans* (American Tickle Formation) biozones at the Spudgels Cove Locality (2 of 2).