THESIS

FACIES PATTERNS AND DEPOSITIONAL ENVIRONMENTS OF THE *PELTURA SCARABAEOIDES* TRILOBITE BIOZONE SEDIMENTS, UPPER CAMBRIAN ALUM SHALE FORMATION, SOUTHERN SWEDEN

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ABSTRACT

FACIES PATTERNS AND DEPOSITIONAL ENVIRONMENTS OF THE *PELTURA SCARABAEOIDES* TRILOBITE BIOZONE SEDIMENTS, UPPER CAMBRIAN ALUM SHALE FORMATION, SOUTHERN SWEDEN

The Upper Cambrian-age *Peltura Scarabaeoides* Biozone represents 2.2m – 5.94m of the Alum Shale in Västergötland, southern Sweden. The Alum Shale succession has historically been characterized as an accumulation of dark, organic-rich "monotonous" mudstones deposited in an anoxic and tranquil setting. However, the results of this study indicate the contrary and will place the Alum Shale alongside many other high-TOC mudstones that document abundance of benthic life and advective sediment transport.

Description of continuous thin sections at the microscopic-scale enabled the subdivision of the *Peltura scarabaeoides* Biozone into four carbonate and three siliciclastic facies. The entire biozone represents an overall shallowing trend that can be sub-divided into eight medium-scale shallowing-upward cycles consisting of intercalated carbonates and siliciclastic mudstones. These medium-scale cycles can further be sub-divided into numerous small-scale shallowing- and deepening-upward siliciclastic mudstone cycles. Time estimates suggest that long eccentricity explains the eight medium-scale cycles whereas the driver of the small-scale cycles remains unclear.

Along a shelf transect, the proximal sections contain high energy shell debris and pack- to grainstones that grade into carbonate wackestone and mudstones; the distal sections are composed of dark organic-rich shales. All siliciclastic mudstone facies are characterized by abundant bioturbation, with more proximal types being horizontal and larger, and distal ones multidirectional and smaller. All facies also show signs of bed load transport in the form of irregular laminae or ripple structures. Several millimeter-thick slump units are present in the succession, indicating active tectonic movements in the area. The *Peltura scarabaeoides* Biozone therefore exemplarily shows that early in the Phanerozoic the deep shelf environment was already colonized by a variety of organisms burrowing millimeters into the soft substrate. Silt transported from the shoreline by currents reached even the most distal parts of this shelf. Therefore, the Cambrian deep shelves must have already presented an environment similar to later Paleozoic examples with probably dysoxic to oxic, not anoxic conditions controlling the accumulation of high-TOC sediments.

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CHAPTER 1: INTRODUCTION

The Alum Shale Formation in Scandinavia is the most prominent black shale unit of Early Paleozoic age in Western Europe. It is some tens of meters to locally over 100 meters thick, and shows TOC values of up to 17.5% (Andersson et al. 1985; Burchardt et al. 1986). The Alum Shale Formation is a proven excellent source rock that has been considered to be the source for petroleum in Paleozoic rocks located in Scandinavia, Poland, and the Baltic (Pedersen et al. 2007). Recently, the Alum Shale Formation has been intensely studied as a potential unconventional gas reservoir with a test well drilled in Scania, southern Sweden, by Shell (Kuuskraa 2009). Despite its economic importance, however, a sedimentological model for the Alum Shale Formation describing this distinct mudstone unit in detail is still lacking. Thickpenny (1984) described the unit using conventional methods where thin sections of dark, organic-rich mudstones were too thick (i.e. 30 microns opposed to 20 microns) to observe important sedimentologic features. Recent advances in mudstone petrography and sedimentology have allowed for innovative interpretations (i.e. Egenhoff and Fishman, accepted) in mudstones successions that have been described as being monotonous.

This study will focus on two aspects of the Alum Shale Formation important to understanding this particular unit and mudstone systems in general: (1) facies characteristics that distinguish the Alum Shale Formation from other well-studied source rocks and potential unconventional reservoirs, such as a lack of chert and (2) bioturbation gradients across the Alum Shale Formation deep shelf that reflect the evolution of benthic organisms in Late Cambrian offshore and in part slightly oxygen-depleted environments. Based on thin section data this study will show that in contrast to previous models (Thickpenny 1984) and recent geochemical investigations (Gill et al. 2011) the Alum Shale Formation was not deposited in an anoxic, but rather in a dysoxic to oxic environment. As both the proximal carbonate as well as the distal mudstone facies belts are preserved in the Alum Shale succession this study will also enhance our understanding of how carbonates transition into siliciclastic mudstones at the distal end of this temperate-water carbonate ramp, a key aspect generally ignored in facies models of low-inclined carbonate systems (Burchette and Wright 1992).

This study relies on the documentation of two outcrops at Mount Hunneberg and Kinnekulle as well as one drill core from the Tomten quarry, all located in Västergötland, southern Sweden (Figure 1.1). In each of these localities the investigations focus on the *Peltura scarabeoides* trilobite Biozone of the Upper Alum Shale Formation (Figure 1.2). This biozone was chosen because of available outcrops within the Alum Shale of Västergötland that would be aligned along a proximal to distal transect of the Early Paleozoic shelf. This specific stratigraphic interval was sampled continuously covering the entire biozone in the Kakeled locality (2.97m) and the Tomten drill core (5.94m) as well as a part of the biozone in the Mount Hunneberg outcrop (0.68m). This study therefore relies on 170 thin sections, documented in the greatest possible detail, as well as the three measured sections from the field and the drill core.

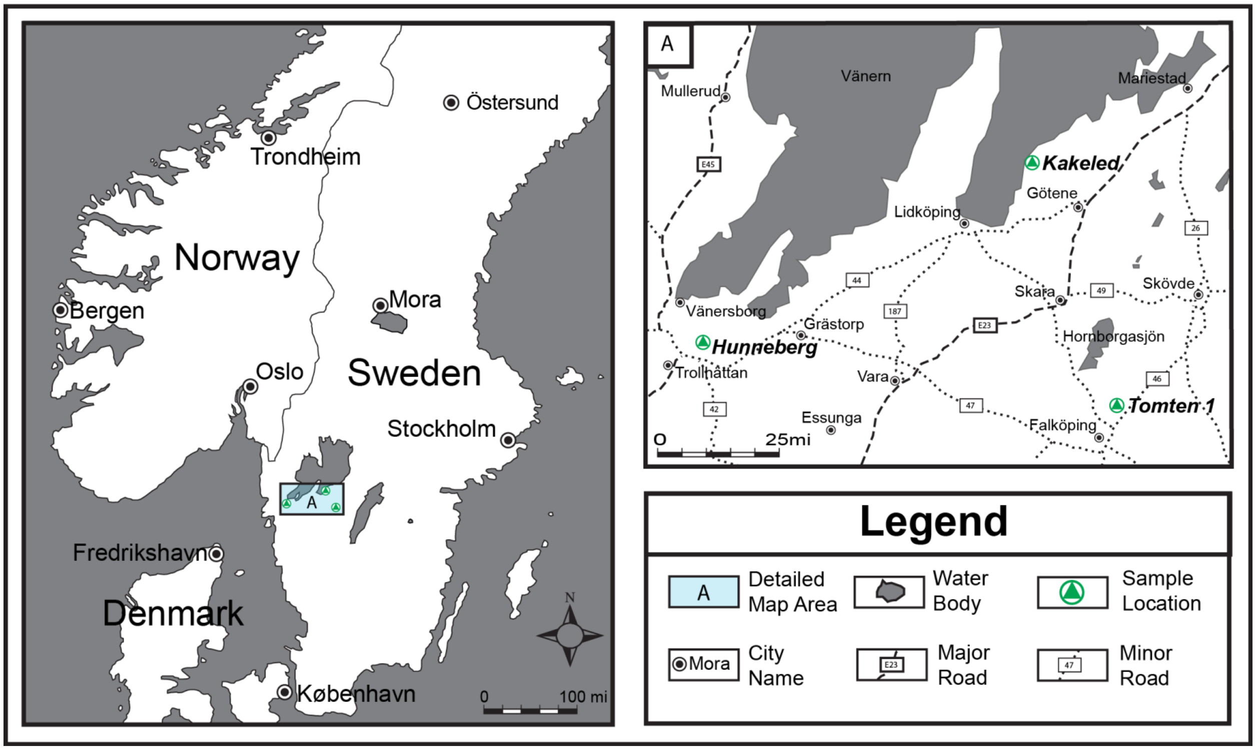

Figure 1.1. Core and outcrop locations within study area.

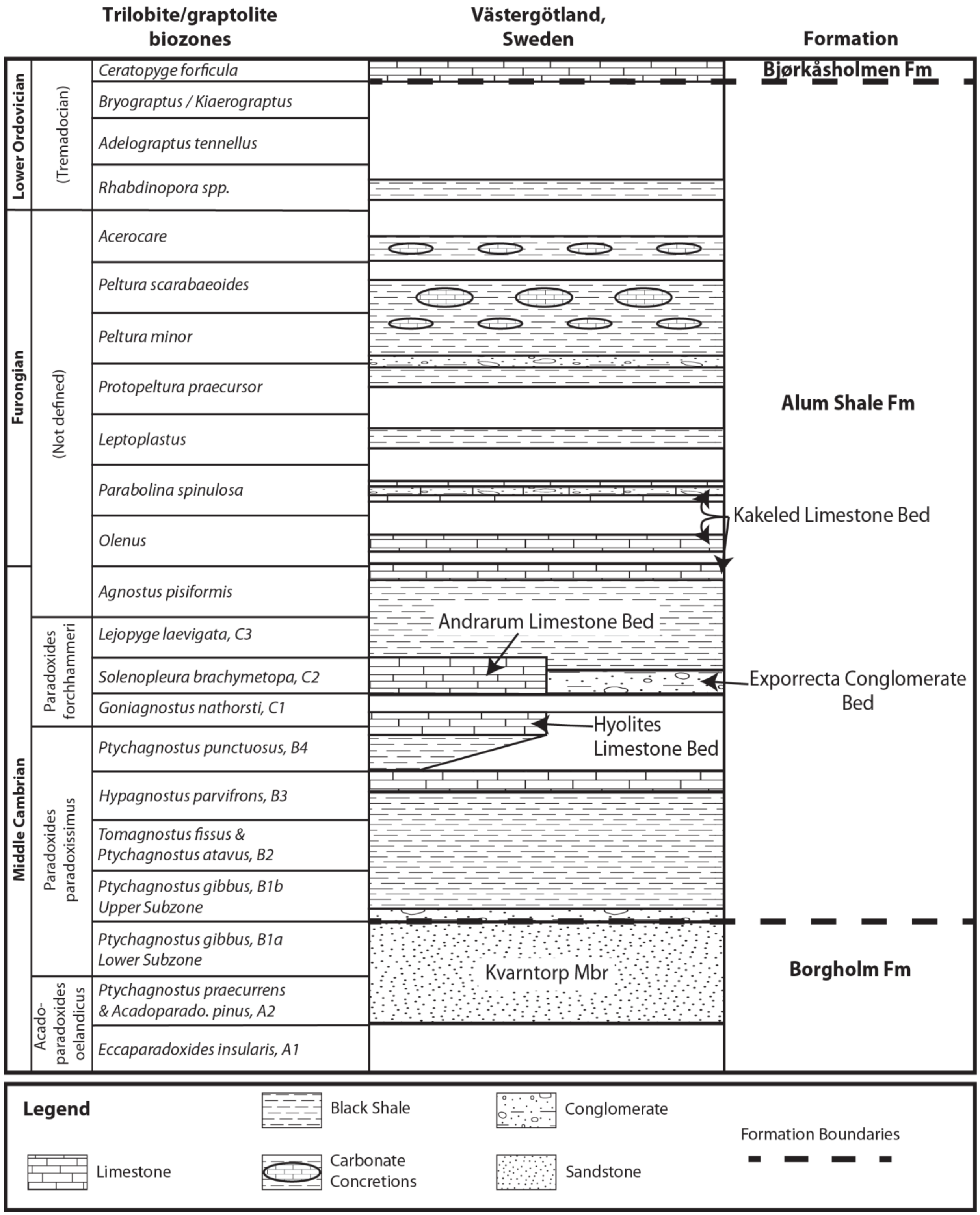

Figure 1.2. Lithostratigraphic and biostratigraphic classification scheme for the Middle Cambrian and Furongian of Västergötland, southern Sweden. (Modified from Nielsen and Schovsbo, 2006).

CHAPTER 2: GEOLOGIC SETTING

During the Lower Paleozoic Scandinavia was located on the southwestern margin of the Baltoscandinavian platform (Grahn & Nolvak, 2007; Hagenfeldt, 1995). Between 510 Ma (Lower and Middle Cambrian) to 480 Ma (Early Mid-Ordovician), Baltica rotated more than 120° counterclockwise and drifted northwards in the southern hemisphere from high to lower paleolatitudes (Cocks and Torsvik, 2005). Västergötland was located between the 40°S-45°S latitude in the Late Cambrian and was covered by a shallow epicontinental sea (Cocks and Torsvik, 2005). Cambrian sediments from this setting, including the Alum Formation, consist primarily of fine-grained siliciclastics deposited on this slowly subsiding shallow shelf facing the Iapetus Ocean to the west and the Tornquist Sea to the south (Thickpenny & Leggett, 1987).

The Alum Formation depositional area extended approximately 2000km in north-south by 800km in east-west direction (Thickpenny, 1984). Today, this black shale unit occurs from the subsurface of Denmark in the south to remnants from Quaternary glacial erosion in the Scania region of southern Sweden to Finnmark in northernmost Norway (Gee, 1987). Water depths at which the Alum was deposited are thought to never have exceeded 200 meters (Thickpenny, 1984). The Upper Cambrian shelf sediments of the Alum Formation are composed of variable amounts of organic matter, terrigenous debris and some carbonates (e.g. Nielson & Schovsbo 2006) with low sedimentation rates of 1.3mm/10^3 years (Thickpenny, 1984).

CHAPTER 3: METHODOLOGY

The data used in this study were obtained from detailed sedimentologic descriptions from two outcrop localities and one shallow core (Figure 1.1). These outcrop and core samples were analyzed with a focus on the upper portion of the Alum Shale, the *Peltura scarabeoides* trilobite Biozone (Figure 1.2). Samples obtained from the outcrop localities at Kinnekulle and Mount Hunneberg in Västergotland, Sweden were taken covering the entire exposed interval. The samples from the Mount Hunneberg outcrop were primarily obtained by cutting slices into the outcrop using an industrial concrete saw. These slices were cut at acute angles mimicking a pie slice. Cutting accordingly allowed the samples to remain in place in the outcrop until a chisel was driven into one of slices with a hammer, thus freeing the sample while keeping it intact and retaining its original stratigraphic order. Samples at Kinnekulle were pried out with a crow-bar and rock hammer in large pieces which were later cut into smaller pieces using an industrial saw. The core samples obtained from the Tomten I core at Lund University, Sweden were continuously slabbed on site using a rock saw to make a cut down the length of the core.

Before cutting, samples were coated in resin to harden the exterior of the sample and prevent breakage. Containers were constructed out of aluminum foil; plastic wrap was placed inside the aluminum foil containers before the sample was placed inside. Resin was then applied on the sample, coating it completely. Once coated, samples were allowed to dry for 24 hours; thereafter the plastic wrap was peeled from the samples. Resin-coated samples were later cut to either 2.5x5 or 5x7.5 centimeter blocks and notched to indicate proper stratigraphic orientation. Carbonate samples were ground to 40 micron thickness, polished on one side, with no coverslip to allow for better viewing of textures. Shale and siltstone samples were ground to 20 micron thickness, polished on one side, with no coverslip to allow for greater visibility of the internal structures and to be viewed in the scanning electron microscope (SEM) equipped with an energy dispersive analyzer of X-rays (EDAX). Before samples were placed into the SEM they were coated with carbon. When organic-rich samples are prepared at standard thickness (30 microns) it is often difficult to observe sedimentary features due to the abundance of detrital particles which are often less than 30 microns in thickness and therefore are masked. Incorporating ultrathin sections (20 micron thickness) allows for the small detrital grains and grain contacts to be distinguished more clearly (Schieber and Zimmerle, 1998).

Multiple criteria were employed while describing these samples with a petrographic microscope at the sub-millimeter scale: lithology, bedding thickness, grain size, degree of roundness of grains, bioturbation index, sedimentary structures and nature of contacts. Internal compositions of critical features were derived from examination using the SEM. Facies, facies associations and stacking patterns were assigned to the measured sections. The core and outcrop sections were hand drafted and later digitized in Adobe Illustrator for further analysis and correlation.

CHAPTER 4: SEDIMENTOLOGY OF THE *PELTURA SCARABAEODIES* BIOZONE WITHIN THE UPPER ALUM SHALE

4.1 Introduction

From detailed microfacies analysis of samples taken from one core and two outcrops, seven different facies are identified (Figure 4.1). Four of these facies are carbonates, while the remaining three are siliciclastic mudstones. All seven facies are described and listed in order from largest to smallest grain sizes.

Two different types of burrows were recognized in the *Peltura scarabaeoides* trilobite Biozone of the Upper Alum Shale (Figure 4.2) and occur in all siliciclastic facies. Multi-directional burrows (Figure 4.2d) measure sub-millimeter (0.02-0.025mm) in diameter and penetrate vertically to sub-vertically up to several millimeters down into the sediment. Multi-directional burrows are back-filled with clay, some quartz and feldspar, and amorphous organic matter (AOM). In places, the backfilled material can be arranged into black, pyritized roundish pellets. *Planolites* burrows (Figures 4.2a, 4.2b and 4.2c) constitute the other frequent and distinct bioturbation feature observed in the Alum Shale rocks. These burrows are arranged parallel to bedding, several tenths of a millimeter in length and lighter in color than the surrounding sediment. The infill of *Planolites* burrows is mostly illite, but fine carbonate and quartz silt occur as smaller components (Figure 4.2c). *Planolites* burrows are depleted in organic matter (Figure 4.2c). In cross section *Planolites*-type burrows can show meandering “in-and-out” patterns along distinct bedding planes.

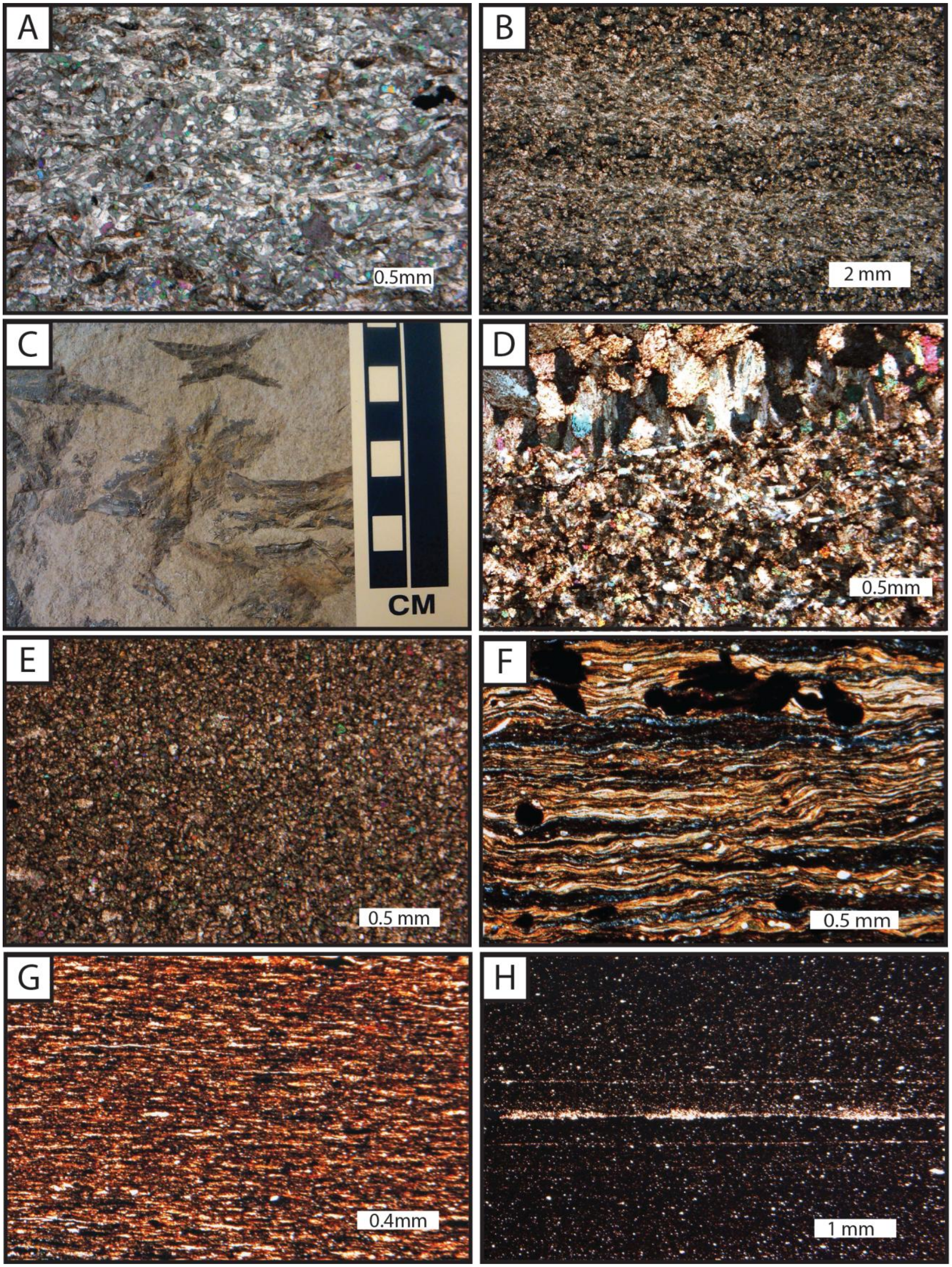
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Figure 4.1. Photos of facies observed in the *Peltura scarabaeoides* Biozone of the Alum Shale. A) Carbonate skeletal grainstone (facies 1) displaying skeletal grains densely packed together and cemented with calcite (Kakeled 2.13m). B) Carbonate wacke-packstone (facies 2). Wacke-packstones occur intercalated in thin layers with carbonate mudstones (Tomten -2.67m). C) Wackestone with barite crystals –exterior surficial view (facies 3). Notice the diagenetic crystal twins and rosettes that form (Kakeled 2.17m). D) Wackestone with barite crystals –interior (facies 3). Shows highly recrystallized nature of the facies, yet fossils are still discernible to characterize this as a wackestone (Kakeled 2.17m). E) Photo of a typical carbonate mudstone (facies 4). Dominance of carbonate mud infers a low-energy environment (Tomten -2.68m). F) Carbonate and phosphate clast mudstone (facies 5) displaying discontinuous laminae consisting of millimeter-thick light-colored carbonate mudstone deficient in organic matter and sub-angular phosphate clasts (Kakeled 0.212m). G) Photo of a massive, rip-up clast mudstone (facies 6). Note the numerous light-colored mud rip-up clasts indicating erosion prior to deposition (Kakaled 1.543m). H) Massive, clay-rich mudstone (facies 7) showing discontinuous silt laminae that thick and thin across the length of a thin section (Tomten -3.824m).

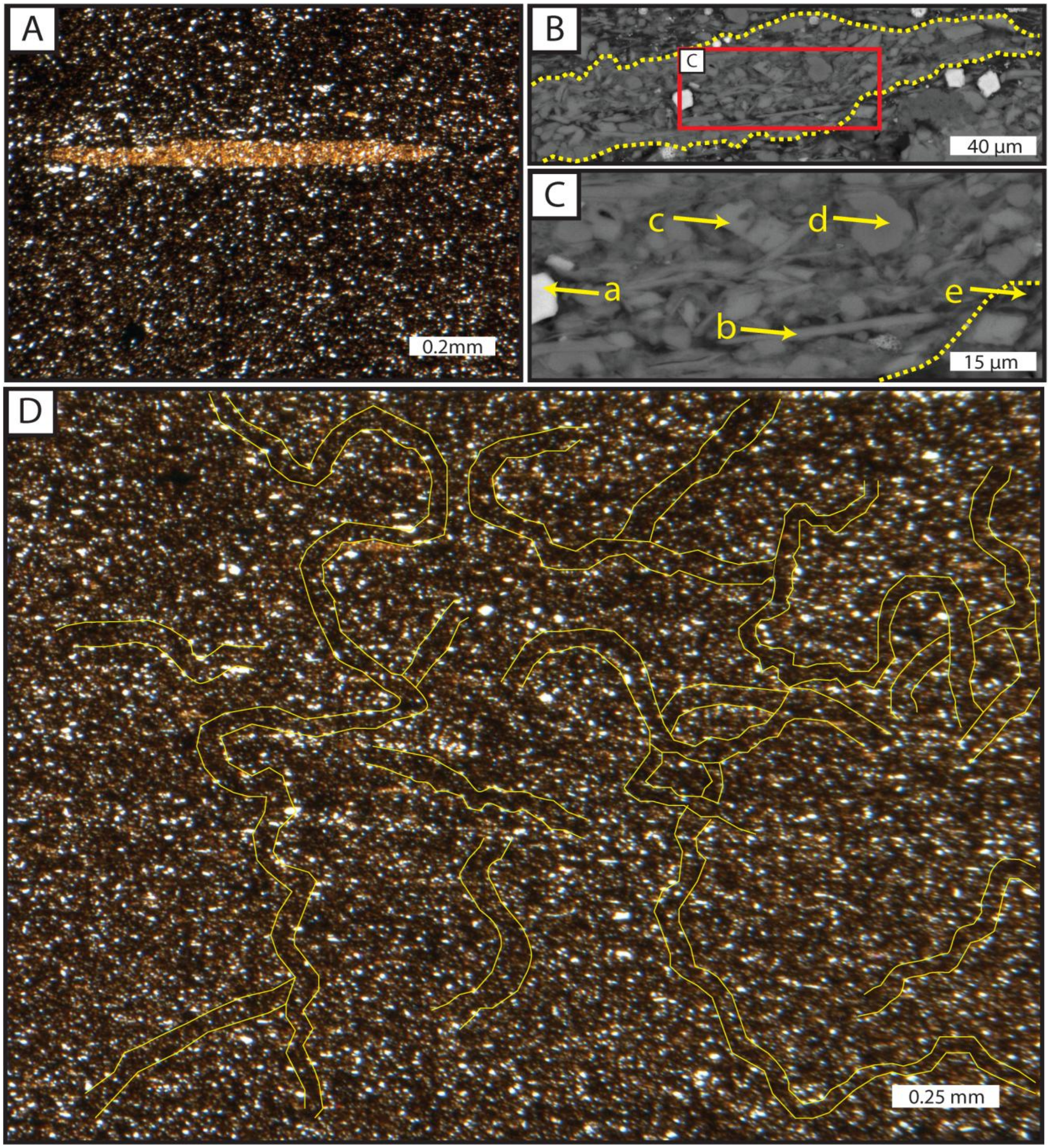

Figure 4.2. Different burrow types observed in the *Peltura scarabaeoides* trilobite Biozone of the Alum Shale. A) Planolites burrow from facies 6 with distinctly lighter color than surrounding matrix (Tomten -3.519m). B) SEM view of *Planolites* burrow (Facies 6, Tomten -3.519m). C) SEM photo of internal composition of *Planolites* burrow a. pyrite, b. illite, c. K-feldspar, d. quartz, e. organic matter; note the smaller amount of organic matter within the burrow compared to matrix outside the burrow which is responsible for its lighter color (Facies 6, Tomten -3.519m). D) Photo of multidirectional burrows in facies 7. Burrow margins outlined in yellow; note that burrow fill does not differ from the surrounding matrix, so it is not depleted in organic matter (Tomten -1.835m).

4.2 Facies description and interpretation

4.2.1 Carbonate Skeletal Grainstone (Facies 1)

Description

This facies consists of centimeter-scale skeletal-type grainstone beds that show an intense recrystallization of complete and fragmented fossils. Most bioclasts (complete and broken) are sub-centimeter in size and consist primarily of brachiopod and trilobite fragments. The fossils are oriented parallel or sub-parallel to bedding. Very little carbonate mud occurs in this facies (less than 1%). Clear, blocky calcite cement fills all porosity between skeletal grains. Less than 1% of the composition consists of round phosphate grains. This facies does not contain any burrows. Contacts can be sharp or gradational with the generally completely recrystallized carbonate beds above and below.

Interpretation

The sandy grain sizes, abundance of fragmented marine fossils, and the lack of mud in this facies suggests deposition in constantly agitated, high-energy, shallow water where fine-grained sediment was winnowed away (Pomar et al., 2002). The parallel orientation of skeletal grains is an indication that no bioturbation was present to disturb the original orientation of the grains. Small amounts of phosphate grains and carbonate mud in this facies likely were brought into voids between skeletal fragments prior to the formation of pore-clogging calcite cement.

4.2.2 Carbonate Wacke-Packstone (Facies 2)

Description

This facies is characterized by tan sub-centimeter to centimeter-scale brachiopod and trilobite-rich wacke-packestone beds that have been partially to mostly recrystallized and are generally observed intercalated with carbonate mudstone beds (Facies 4). Most of the grains in this facies consist of trilobite debris with lesser amounts of brachiopod shells. Calcispheres exist in some places. The bioclasts are commonly between half a millimeter to several millimeters in size. Some rounded phosphate grains occur in non/partially recrystallized packstone beds. The matrix separating the grains and fossils is homogeneous carbonate mud. Grains and fossils are preferentially oriented parallel to bedding. Some of the larger shells show well-developed shelter porosity filled with calcite cement. Contacts within this facies to the underlying units are mostly sharp, while the upper contacts are typically gradational with adjacent overlying facies.

Rarely, centimeter-thick intervals of rounded to subangular, oval to elongated intraclasts occur embedded in a fine-grained, recrystallized carbonate matrix. The intraclasts are several tenths of a millimeter to about one millimeter in diameter and consist of recrystallized carbonate mud with micritized rims. In places, they contain skeletal fragments. The intraclasts are arranged along the bases of millimeter-thick horizontal to sub-horizontal laminae. These laminae can be associated with trilobite and brachiopod debris oriented parallel and at an angle to bedding. Similar to the intraclasts, the bioclasts also show marginal micritic rims. In places, millimeter-sized vugs are present in this facies. They are partially filled with calcite cement and can show remnants of petroleum in their centers.

Interpretation

The environment in which this facies was deposited was likely well oxygenated based on the abundance of intraclasts, fossils and skeletal debris. The wealth of millimeter-sized fragmented fossils points to episodic high-energy conditions. These events, most likely storms, were responsible for preferentially accumulating skeletal material along distinct bedding planes and subsequently creating sharp basal contacts. The calcispheres likely sank down in the water column by suspension, as they are randomly distributed within this facies. Wackestone portions of this facies represent low-energy deposition of carbonate from suspension during the waning of storms and background sedimentation (cf. Aigner, 1985). Phosphate was likely brought in as grains during pulses in depositional energy. While no distinct burrows can be recognized in this facies, the random orientation of elongate fossils within the matrix suggests that burrowing organisms were originally present during and slightly after deposition.

The intraclast-bearing sediments most likely reflect extreme energy conditions during deposition of this facies. High-energy events eroded semi-lithified mud, probably in the near distance, and transported the lithoclasts further offshore, likely downslope. Collision during transport led to the rounding of some of the grains, while others were more resistent, lithified and kept their angular shape because they were not transported far. Their micritized margins indicate that they were most likely not instantly buried after their formation, but were subject to micritization by bacteria and other boring organisms on the seafloor (Flügel, 2004). This indicates that either these intraclasts were re-deposited several times before reaching their site of final sedimentation, or no finer-grained sediment was deposited on top during the same storm event. This event left them uncovered on the sea-floor, thereby allowing small destructional organisms to produce the thin micritic rims. Vugs found within intervals containing intraclasts are likely an artifact of diagenesis.

4.2.3 Wackestone with Barite Crystals (Facies 3)

Description

The wackestone with barite crystals facies consists of partially to completely recrystallized, massive-appearing carbonate mud with approximately 15% of the overall composition being bioclasts. The carbonate mud occurring in this facies tends to be of a light brown to grey color and is therefore significantly lighter than all other mud-containing facies in the *P. scarabaeoides* Biozone of the Alum Shale. Bioclasts occur preferentially in discrete layers, make up approximately 5% of the overall rock volume and are sand-sized. The bioclasts are composed of brachiopods that are oriented parallel or sub-parallel to bedding. The most striking characteristic of this facies is the occurrence of several centimeter-sized idiomorphic barite crystals embedded in the wackestone matrix. The basal contact of this to underlying facies is sharp while the top contact is exposed to surficial weathering and is not preserved.

Interpretation

The overall fine-grained nature of this facies gives merit to a low-energy depositional environment. The bioclasts aligned along bedding planes were likely deposited from episodic high energy events leaving bioclasts to accumulate in thin layers and display sharp basal contacts. The carbonate mud within this facies is relatively light-colored which is generally considered a characteristic of lagoonal carbonates (Flügel, 2004). Its association with the high-energy and very shallow-water grainstones of facies 1 also places these rocks into a shallow-marine, likely a lagoon. The orientation of fossil fragments other than parallel to bedding is most likely the result of diffuse bioturbation of these rocks. The origin of the barite crystals remains unclear; however, it is here assumed that the Ba may have originated from the weathering of granites located on the Baltica peneplain. In this case, the Ba would have entered the system through rivers, shedding their load onto the shallow Swedish shelf. A half-enclosed environment, such as a lagoon, would have helped to concentrate Ba by being trapped in the lagoon after a major storm. The form and size of the crystals suggests growth within the shallow sediment and not on the surface. Alternatively, the original mineralogy may have been dissolved during diagenesis and was then replaced by barite.

4.2.4 Carbonate Mudstone (Facies 4)

Description

This facies consists largely of massive carbonate mudstone with very minimal and only sub-millimeter sized shell fragments that make up less than 5% of the rock volume. These shell fragments are preferentially located toward the base of individual beds and are tenths of a millimeter thick in this facies. Fossil fragments are only preserved as relic “ghost” structures and are strongly re-crystallized. Within individual beds of this facies, however, carbonate mud often appears to show a subtle fining upwards. In places, sub-millimeter to millimeter size laminations are present that exhibit concentrations of fine-grained carbonate silt. Both the upper and lower contacts of this facies are generally sharp. Remnant traces of sub-vertical burrowing structures are present in this facies that extend a few millimeters vertically into the sediment.

Interpretation

This facies represents a low energy environment which is reflected in the dominance of carbonate mud. The recognition of a subtle fining upward trend and concentration of shell fragments at the base of individual beds can be attributed to an overall decrease in energy during deposition. The sub-millimeter to millimeter concentrations of silt-sized fossil fragments are interpreted have originated from relatively high energy events and therefore likely represent lag deposits and the distal expression of storms reworking and sorting fossil fragments. Sharp contacts within this facies are attributed to the abrupt onset or termination of contrasting energy conditions. The absence of lamination in much of this facies was likely caused by intense bioturbation. The abundance of burrows indicates presence of benthic life and therefore sufficiently oxygenated conditions during deposition at the sediment-water interface and within at least the uppermost few millimeters of sediment.

4.2.5 Carbonate and Phosphate Clast Siliciclastic Mudstone (Facies 5)

Description

This facies consists of massive mudstones being intercalated with abundant laminae consisting of silt and sand-sized carbonate, quartz and phosphate grains. These laminae range from half a millimeter to two centimeters in thickness with sand-sized angular phosphate clasts being the coarsest component. In places lee sets of current ripples occur, which consist of sub-angular to sub-rounded silt laminae and intercalated mudstone layers. These ripples are up to seven millimeters high, and their foresets show angles of 10 to 20 degrees with often poorly defined top surfaces. While this facies generally displays an overall massive appearance, both a slight normal and overlying inverse grading can be observed in up to centimeter-thick intervals within the mudstones. In places, this facies also contains laterally discontinuous millimeter-thick laminae consisting of light-colored carbonate mudstone devoid of organic matter. These are arranged in sub-millimeter-thick lenses draping over each other and may represent ripple foresets, or occur intercalated with the siliciclastic mudstones. This facies contains both

Planolites and multidirectional burrows. The abundance of *Planolites* varies becoming more common within the mud-rich portions of this facies. The basal contacts of this facies are generally sharp and often undulatory, while upper contacts are predominantly gradational.

Interpretation

This facies consists of contrasting lithological units representing very different sedimentary environments: the massive mudstones reflect deposition of mostly clay, silt and organic material, either by suspension or bed load transport (cf. Schieber et al. 2007), while the siltstone laminae and the ripples record exclusively bed load transport of near-bottom currents. The massive mudstones represent background sedimentation that was frequently interrupted by pulsess of high energy deposition. The presence of the fine sand-sized phosphate extraclasts also reflect relatively high energy that resulted in the upslope erosion and offshore transport of clasts of reworked phosphatic crusts. Bed load transport led to rounding of grains. Many of the phosphate extraclasts retained their angular form and were most likely transported only relatively short distances. The mudstone ripples consisting of alternating carbonate and siliciclastic fine-grained material reflect different densities of the original grains which resulted in the deposition of compositionally sorted laminae. The clay material most likely traveled as floccules as shown by experiments (Schieber et al. 2007), whereas the silt grains travelled individually. Clay floccules of silt size have a significantly lower density than their quartz counterparts, are separated out by currents, and travel much faster while the quartz silt grains stay behind. Therefore, the co-occurrence of silt and clay laminae either presents slight fluctuations in energy, or just availability of different grain populations during the formation of the ripple sets. The fact that these laminae may be the result of several ripple trains passing through the studied section would also explain the relatively irregular geometries of the foresets observed within the thin section (Figures 5.4e, 5.4f). The light-colored and laterally discontinuous carbonate mudstone laminae forming foresets were likely deposited by the same bed load process creating ripples, but these were derived from the more proximal portion of the basin where the facies are lighter in color and lack organic matter.

The bed load currents depositing ripples and discontinuous laminae in this facies likely also eroded underlying sediment accounting for the shale rip-up clasts and creating sharp and often undulatory basal contacts. Waning stages of energy pulses resulted in normally graded siltstone laminae, while waxing periods of high energy events caused the inverse grading of siltstone laminae.

Abundant *Planolites* and multidirectional burrows in the facies indicate that there was sufficient time between energy pulses to thoroughly colonize the sediment-water interface. These burrows disturbed original sedimentation features and somewhat homogenized the sediment giving its massive appearance. The presence of *Planolites* and multidirectional burrows suggests that the conditions at the sediment-water interface were oxic to dysoxic and not anoxic.

4.2.6 Massive, Rip-up Clast Mudstone (Facies 6)

Description

This facies is characterized by its light brown color, massive texture and varying amounts of “golden”-colored, flattened silt-sized, and horizontally-oriented mudstone clasts. These mudstone clasts can account for upwards of 60% of the overall facies composition. Sub-angular to sub-rounded quartz and carbonate grains are present (less than 5%) as fine to medium silt. Scattered dark brown/burgundy phosphate grains of fine sand size occur in the form of angular clasts, but are rarer than their finer counterparts. In places, the silt grains are arranged in the form of laminae composed of detrital quartz grains that may also contain shell fragments, carbonate grains, and phosphate clasts. They often have undulatory bases and flat tops. Tenths of a millimeter long fragments of elongated AOM are common and arranged parallel to bedding. Also present, but occurring only rarely in this association, are millimeter-thick, grain-supported skeletal beds. This facies is extensively bioturbated by multidirectional burrows and in places the *Planolites* burrows are concentrated along individual surfaces, oriented parallel to overall bedding. The upper and lower boundaries of this mudstone facies can be either sharp or gradational.

Interpretation

The presence of numerous light-colored mud clasts in this facies indicates erosion of mudstone in the form of rip-up clasts nearby, either laterally or up-dip and subsequent deposition during the waning phase of the eroding current. The lighter, "golden" color of the mudstone clasts could be a result of erosion of the mudstone in less AOM-containing and more proximal portions of this ramp environment. However, the color could also have changed from originally dark to lighter as the result of contact with oxygen-rich waters and thereby depleting the mud in organic matter during the transport process. Laboratory experiments showed that silt-sized mudstone rip-up clasts are formed from currents with flow velocities of between 15 and 25 cm/s (Schieber et al. 2010). Similarly strong but nevertheless waning currents likely also transported quartz and phosphate grains into this depositional environment where they formed laterally fairly continuous siltstone laminae of varying thickness. Many of the siltstone layers have been entirely or partly destroyed by bioturbation. However, abundant remnants of siltstone laminae throughout this facies show that originally many more of these laminae must have been present. Therefore, deposition from bed-load processes were likely quite frequent during deposition of this facies and also include the generally oversized phosphate clasts that are often associated with the quartz and carbonate silt grains. However, a portion of the clay-rich matrix, the AOM as well as some of the fine silt grains may well have been deposited as marine snow from suspension similar to modern deep shelf environments (cf. Macquaker et al., 2010). While the source of much of the organic matter remains unclear, some elongate particles resemble cyanobacterial mats growing on the sea-floor (Fedonkin et al., 2007), or planktic algae similarly to Tasmanites occurrences observed in the Woodford Shale (Fishman et al., 2010). The rare occurrence of grain-supported skeletal beds likely represents the distal expression of storms that distributed skeletal material down ramp from skeletal-rich facies belts.

4.2.7 Massive, Clay-rich Mudstone (Facies 7)

Description

This facies consists mostly of massive mudstones made up of clay minerals and amorphous organic matter (AOM) with some scattered silt-sized carbonate and quartz grains as well as occasional rounded phosphate clasts. Locally, these sub-angular to rounded detrital components form distinct millimeter- to mostly sub-millimeter-thick laminae that vary in thickness over the width of the thin section. In places these siltstone laminae consist of only single grains aligned along one bedding plane. However, several tenths of millimeter-thick examples can also show a weakly developed normal grading. The siltstone laminae show sharp, flat or undulatory bases while upper contacts can be either sharp or gradational. Additionally, tenths of millimeter-size distinct particles of organic matter occur that resemble remnants of algae or microbes. This facies sporadically contains slumped intervals and microfaults associated with numerous scattered illite clasts (Figure 5.4a) and fecal pellets (5.4b). The fecal pellets consist of mostly clay-sized grains and slightly elevated organic matter content relative to the surrounding matrix. Both fecal pellets and illite clasts are one to several tens of a millimeter long, elongate in shape and aligned roughly parallel to bedding with some exceptions showing a sub-parallel orientation. Facies 7 is thoroughly bioturbated by multi-directional burrows, and units of this rock type are generally bounded by sharp, well-defined contacts at the base and top, some of them being slightly undulatory. Centimeter-long calcite- and gypsum-filled horizontal fractures are present throughout the massive clay-rich mudstones and become more frequent with increasing silt content in this facies.

Interpretation

The mostly massive character of this facies is likely the result of intense bioturbation, indicated by the presence of abundant multidirectional burrows. This also explains the random distribution of highly varying grain sizes throughout this facies, which originally were likely deposited by either currents of low energy or suspension settling. While any indications of suspension deposition have been destroyed by the burrowing organisms the locally visible alignment of quartz and carbonate silt grains in remnant layers of laterally varying thickness still reflects current transport by bed-load processes. The sharp basal contact of each of these laminae, especially when undulatory shows that prior to deposition some erosion occurred, indicating sedimentation from a waning current. This is in agreement with normal grading observed in some of the siltstone laminae also reflecting decreasing energy conditions during deposition. Coarser grain sizes and the presence of phosphate clasts indicate a more proximal and relatively high energy setting while finer grains and thinner laminae represent more distal and low-energy depositional conditions. Within the “siltier” portions of this facies, the abundance of quartz has caused the facies to become more brittle and is therefore the most likely cause for the presence of horizontal fractures.

The clay particles accounting for the bulk of the matrix, however, could have been deposited by both suspension and bed-load transport (cf. Schieber et al., 2007). The sporadic occurrence of illite clasts within the facies likely represents times of deposition from dominantly suspension settling. The illite clasts are interpreted to have originated from the craton in the form of mica flakes prior to conversion to illite (N. Fishman, personal communication 2011). These illite clasts are possibly eolian in origin and likely descended through the water column as suspension together with mud and marine snow background sedimentation (cf. Macquaker et al., 2010). The illite clasts do not show sorting or any signs of re-working and were therefore likely not transported after their initial deposition on the seabed. In places, fecal pellets were found alongside the illite clasts. Shortly after deposition these pellets could have easily succumbed to destructive forces (i.e. bedload transport or currents), suggesting that this was a low-energy, distal environment. The non-fluorescent organic matter in this facies likely represents AOM remnants of algal mats growing on the sea floor (Fishman et al., 2012).

The abundance of multidirectional burrows indicates that the environment could not have been completely anoxic as it still allowed burrowing even some millimeters deep into the sediment. However, the monospecific assemblage of the burrows does point to stressed and therefore probably dysoxic conditions during deposition of this mudstone facies.

CHAPTER 5: FACIES PATTERNS AND DEPOSITIONAL MODEL

5.1 Lateral and vertical facies distribution

The seven different facies found within the *Peltura scarabaeoides* Biozone of the Upper Alum Shale display a distinctive stratigraphic and/or geographic position. Both the carbonate skeletal grainstones (Facies 1) and wackestone with barite crystals (Facies 3) occur exclusively at the Kakeled outcrop. The wackestone with barite crystals (Facies 3) is found in the uppermost position of the *Peltura scarabaeoides* Biozone, while carbonate skeletal grainstones (Facies 1) occur in the upper half meter of the section. The carbonate mud- (Facies 4) to wackestones intercalated with packstones (Facies 2) are observed at all outcrop localities in the study area and are most commonly found in the section at Kakeled and Hunneberg, but are less common in the Tomten section. Carbonate and phosphate clast siliciclastic mudstones (Facies 5) exclusively occur in the Kakeled section lying in close stratigraphic proximity to the carbonates. Massive, rip-up clast mudstones (Facies 6) are found in the sections at all three localities, but these mudstones are more common at the Kakeled outcrop while the massive, clay-rich mudstones (Facies 7) are found to be the dominant siliciclastic mudstones within the Hunneberg and Tomten sections.

The overall facies architecture of the *Peltura scarabaeoides* Biozone is well represented at Tomten and Kakeled. Unfortunately, the section at Mt. Hunneberg has undergone severe diagenesis so that detailed facies trends are obscured and difficult to delineate, therefore only the Tomten and Kakeled localities will be described in detail. The successions at Tomten and Kakeled show three orders of cycles that vary depending on each locality (1) an overall trend reflected by a well pronounced coarsening-upward interval as expressed especially well in the

Tomten core; this trend encompasses the entire biozone and is equivalent to a sediment stack of between 2.16m (Kakeled) and 5.94m (Tomten); (2) medium-scale cyclicity represented by carbonates and intercalated siliciclastic mudstones; these cycles are a decimeter to half a meter thick and well developed in all three investigated localities; and (3) small-scale cyclicity comprising of several centimeters thick and well defined coarsening and fining-upward mudstone successions.

Generally, the medium-scale cycles consist of decimeter-thick coarsening-upward siliciclastic mudstones topped by decimeter-thick carbonate beds. These are well represented in the section from the Kakeled locality (Figure 5.1). Internally at Kakeled, the siliciclastic mudstone units show an arrangement of rip-up clast mudstones (Facies 6) at the base grading into carbonate and phosphate clast siliciclastic mudstones (Facies 5) with an abrupt contact to the overlying carbonates. The typical medium-scale cycle in the Tomten core (Figure 5.1) consists of clay-dominated mudstones (Facies 7) overlain by mudstones with rip-up clasts (Facies 6), which are then in turn overlain by carbonates. The internal architecture of the carbonates typically consists of centimeter-scale, mud-rich lithologies (i.e. carbonate mudstone of Facies 4), intercalated with millimeter to up to a few centimeters thick wacke-packstones (Facies 2) or skeletal grainstones (Facies 1). Eight complete carbonate and siliciclastic mudstone medium-scale cycles are clearly expressed in the Kakeled core, while only four were found at Tomten. Within the basal portion of the overall succession at Tomten, the medium-scale cycles are often lacking the carbonate units that define the top of the complete cycle, resulting in the amalgamation of thicker siliciclastic mudstones units.

Small-scale cyclicity is reflected in coarsening upward siliciclastic mudstones some millimeters to a few centimeters thick. The typical small-scale cycle is best developed in the

Tomten core where it contains a basal portion represented by clay-rich mudstones of facies 7 that grades upwards into rip-up clast mudstones of facies 6 (Figure 5.2). Within the mud rip-up clast mudstones (Facies 6), progressively more silt laminae are present near the top of the cycle. This "typical" small-scale cycle from the Tomten section is similarily observed in the Kakeled section (Figure 5.1). However, the small-scale cycles at Kakeled are expressed as mudstones with few rip-up clasts (facies 6) that grade into mudstones with significantly more rip up clasts upsection and typically show siltstone laminae at the top. Also, some of the small-scale cycles in Kakeled are topped by "higher" energy mudstones containing ripples, numerous phosphate clasts or mud drapes (Facies 5). Although coarsening-upward packages form the dominant pattern of the small-scale cyclicity, fining-upward packages are also present, especially in the Tomten succession. The fining-upward packages show the same facies as the small-scale coarsening-upward cycle, but in reverse order, and are typically one or two centimeters thick.

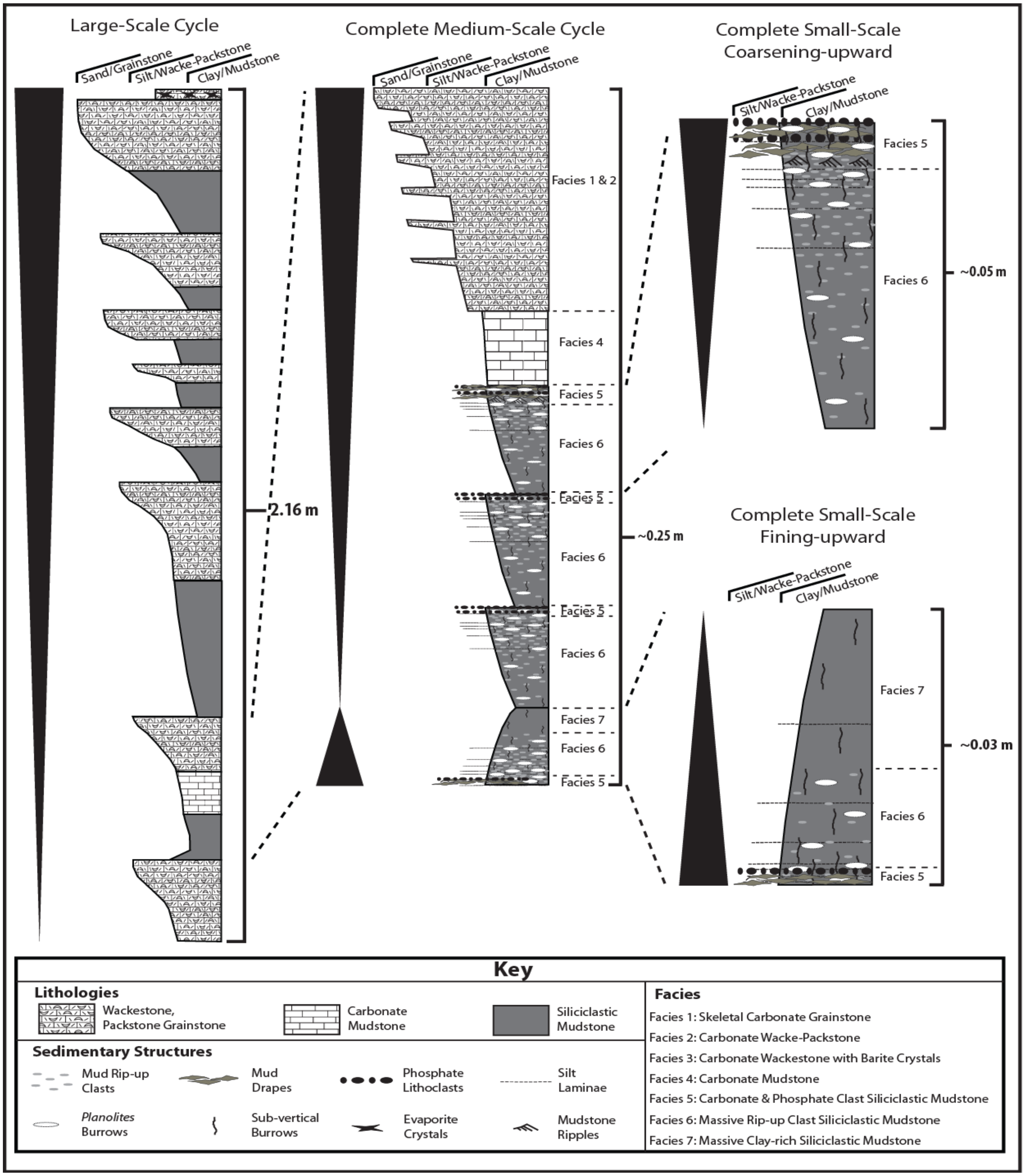

Figure 5.1. The three different orders of cyclicity observed within the *Peltura scarabaeoides* Biozone of the Alum Shale at the Kakeled locality. A large-scale cycle is represented by the overall *Peltura scarabaeoides* Biozone, which encompasses a coarsening-upward trend and increasing abundance in carbonate beds stratigraphically higher in the biozone. Medium-scale cycles are generally represented by intercalated carbonate and siliciclastic mudstone packages. Small-scale cyclicity is generally represented by cm-scale packages of coarsening or fining-upward siliciclastic mudstones of facies 5 and 6.

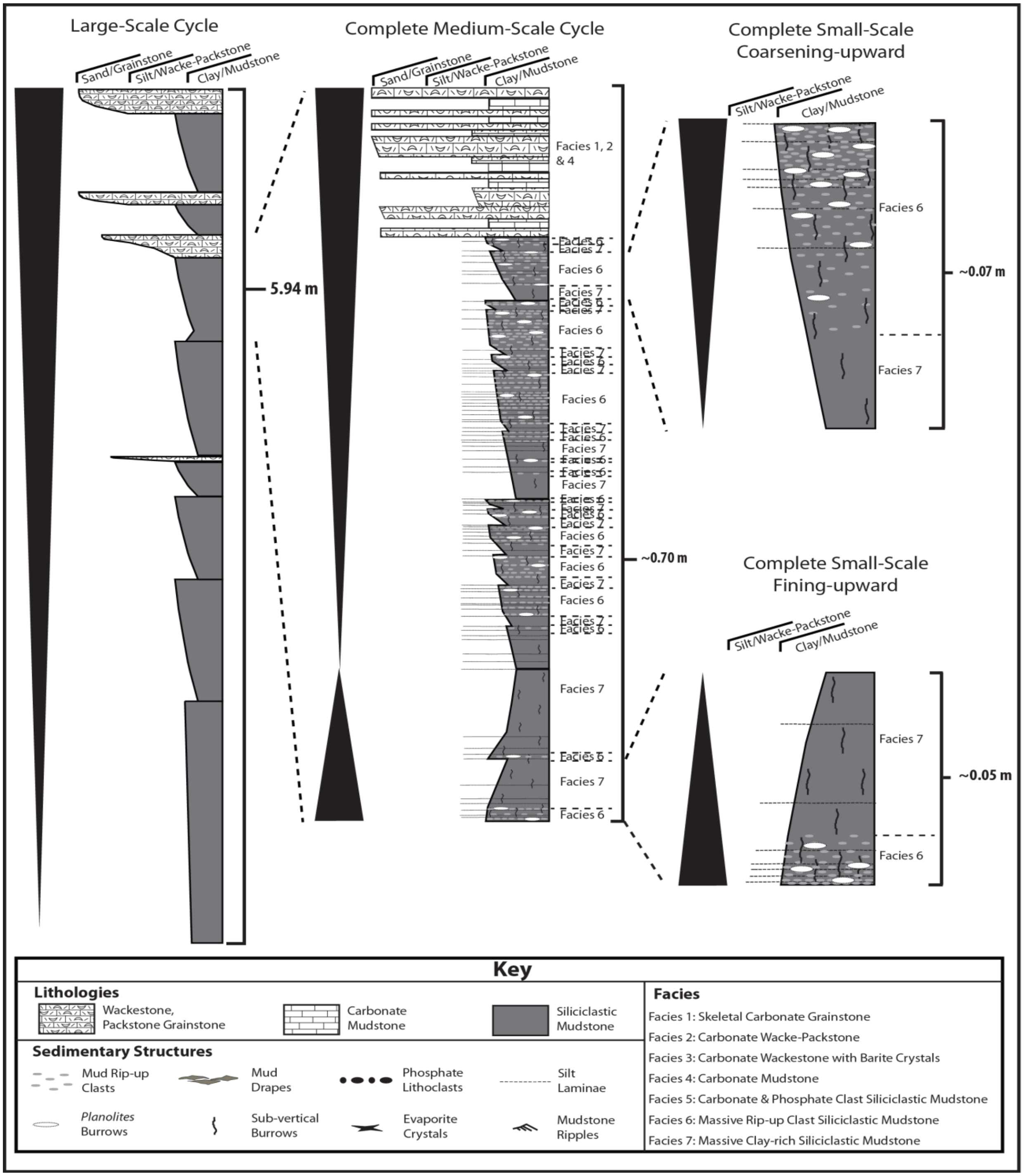

Figure 5.2. Cyclicity observed within the Tomten 1 core. Large-scale cyclicity is represented by an overall coarsening-upward trend encompasses the entire *Peltura scarabaeoides* Biozone. A "perfect' medium-scale cycle is composed of siliciclastic mudstones at the base and topped by ramp carbonates, but note in Tomten some of the cycles are missing the ramp carbonate representing the termination of the cycle, whereby a "thicker" accumulation of rip-up clast mudstones (facies 6) indicate the termination of the cycle. Small-scale cyclicity in Tomten is represented by mm- to cm-scale coarsening- or fining-upward siliciclastic mudstones of facies 6 and 7.

5.2 Depositional model

Based on the depositional energy indicated by grain size, depositional structures, and the amount of carbonate and/or siliciclastic mud the relative position of each of the Alum Shale facies (as defined in chapter 4) can be reconstructed from a proximal to distal transect (Figure 5.3) of this Upper Cambrian shelf system. This lateral relationship of facies is also well reflected in the vertical arrangement of facies within the medium-scale cycles which show a successive shallowing of the depositional environment from low-energy siliciclastic mudstones at the base to higher-energy carbonate sediments at the top.

Within the Alum Shale of the *Peltura scarabaeoides* Biozone the carbonate skeletal grainstones (facies 1) represent sedimentation in the highest energy setting based on the overall large grain size of the shells and shell fragments, and the absence of carbonate mud. These sediments were deposited in constantly agitated water above normal wave base, most likely very close to the beach in a shoreface environment. The carbonate wacke- to packstones of facies 2, often closely associated with facies 1 grainstones, reflect varying energy regimes with episodic high-energy pulses resulting in packstone sedimentation, and low-energy fair-weather conditions leading to the deposition of mostly carbonate mud and some shells from organisms inhabiting the sea floor. These sediments therefore record deposition below normal, but above storm wave base in a proximal offshore environment, but still in relative proximity to the coast. In facies 2 carbonate wacke- to packstones, the thick storm packstone beds represent relatively proximal, and the thin, millimeter-thick packstone layers distal storm beds. Even further distally, the wacke- to packstones of facies 2 grade into carbonate mudstones of facies 4. This facies belt is located at a significant distance from the coastline and too distally to be significantly affected by storm events. While thin storm layers of bioclastic debris may have been originally present intense bioturbation in this area has completely dispersed the grains and distributed them randomly in the fine-grained carbonate matrix. At the distal end of the carbonate mudstone facies belt, the transition occurs to the basinal siliciclastic mudstone facies.

The coarsest siliciclastic mudstone facies reflecting the highest amount of energy is represented by the carbonate and phosphate clast mudstones (facies 5). These sediments form a facies belt adjacent to the carbonate mudstones of facies 4 recording mostly fair-weather sedimentation represented by the massive siliciclastic mudstones, and intercalated event deposition during storms reflected by the laminae of carbonate and phosphate clasts. Even though bioturbation intensity is high in this setting, it is not strong enough to completely mix the coarse shell and grain lags with the fine-grained siliciclastic matrix dominating deposition within this facies belt. The intensity of storm deposition and the resulting thickness and expression of event beds, however, further decreasing down ramp is reflected in the massive rip-up clast mudstones (facies 6) representing the facies belt located distally of the carbonate and phosphate clast mudstones (facies 5). In this environment, fair-weather deposition is still reflected in the massive mudstones, but high-energy events are exclusively represented by mudstone rip-up clasts embedded in a shale-rich matrix. The overall lower density and smaller size of the mudstone clasts compared to the phosphate and carbonate clasts observed in the adjacent carbonate and phosphate clast mudstone facies places these storm sediments in a more distal position than their coarse-grained counterparts. The mudstone clasts characterizing these storm deposits most likely originated from the more proximal mudstone facies by erosion into the sea bed and subsequent downslope and/or lateral sediment transport. The same process may also have been responsible for accumulating shell and other grain-rich material along the erosion surfaces underlying the phosphate and carbonate lags of facies 5. The most distal facies is represented by the massive clay-rich mudstones of facies 7. The fine grain size of these sediments indicates that they were deposited probably predominantly under quiet water conditions. If currents influenced deposition, e.g. in the form of bed load transport of mud floccules (cf. Macquaker et al. 2010), then these currents had already deposited all the coarser load upslope, and most likely represent the furthest distal expression of storm-induced currents.

In general, all the facies follow a trend with depositional energy decreasing from a proximal ramp carbonate to a basinal siliciclastic mudstone setting. The only exception to this trend are the carbonate wackestones with barite crystals of facies 3 that are always associated with facies 1 carbonate grainstones. Their association with exclusively high-energy sediments makes it therefore probable that the carbonate wackestones with barite crystals were deposited close to a high-energy setting, most likely a lagoon with the grainstones forming adjacent high-energy shoals protecting the lagoon on the seaward side. While the barite crystals are most likely entirely diagenetic they may represent a replacement of gypsum crystals originally grown within the sediment, a feature common in sabkha settings adjacent to lagoons in arid environments (Wilson 1975). However, the lagoon would have needed to be entirely exposed for evaporite crystals to grow, and in this case the gypsum pseudomorphs would represent the exposure stage of the lagoon during a continued sea-level fall after the lagoonal sediments had been deposited.

Bioturbations are ubiquitous in sediments of all facies belts indicating that living conditions must have been favorable for organisms along the entire length of the of the Alum Shale shelf transect. The diversity of traces, however, shows a distinct trend within the mudstones from two types of burrows in proximal to only one species in the most distal facies belt. This decrease in trace fossil diversity most likely reflects a decrease in oxygen levels as also observed on modern shelves (Diaz and Rosenberg, 1995; Levin, 2003; Levin and Gage, 1998; Wu, 2002).

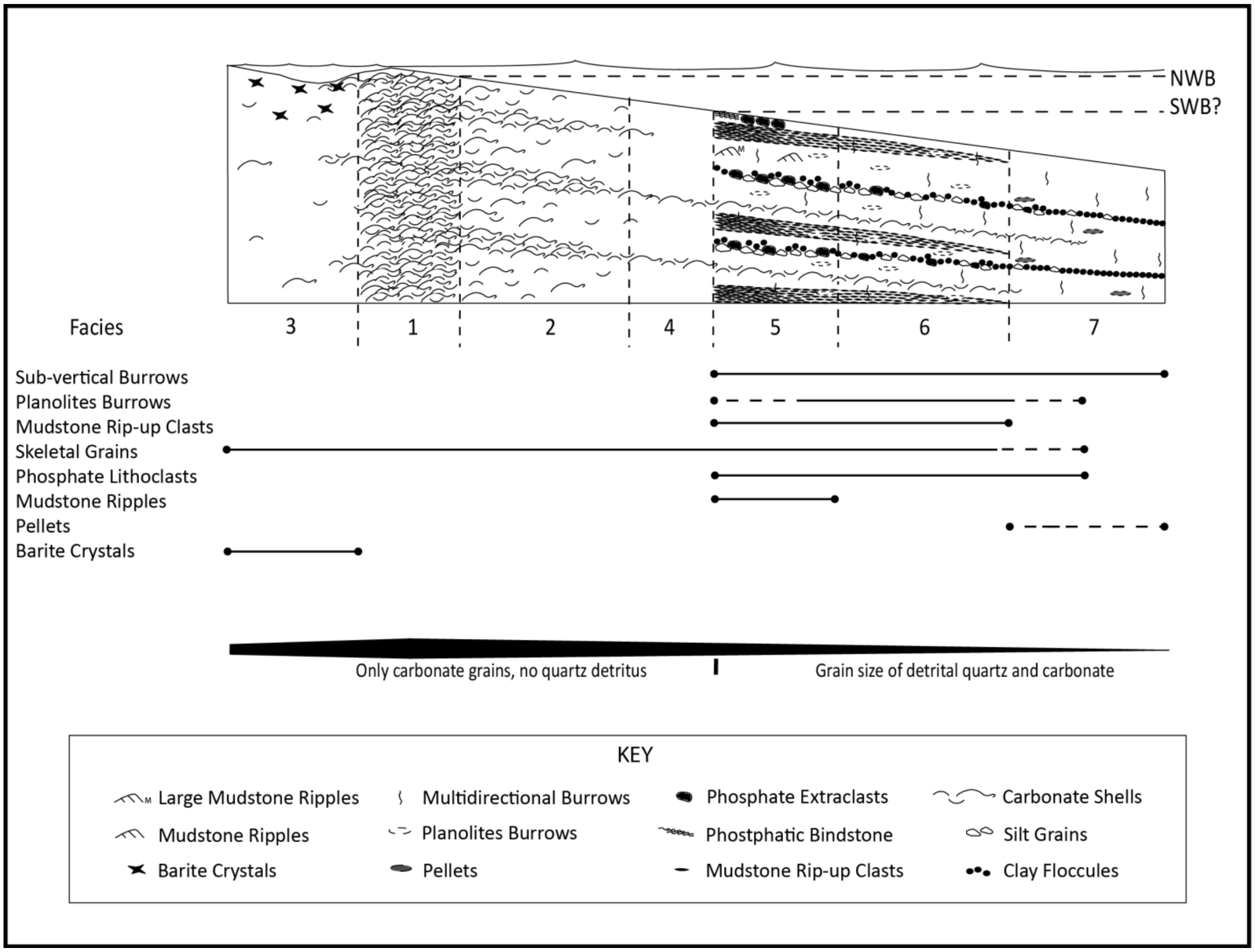

Figure 5.3. Depositional model for the *Peltura scarabaeoides* Biozone.

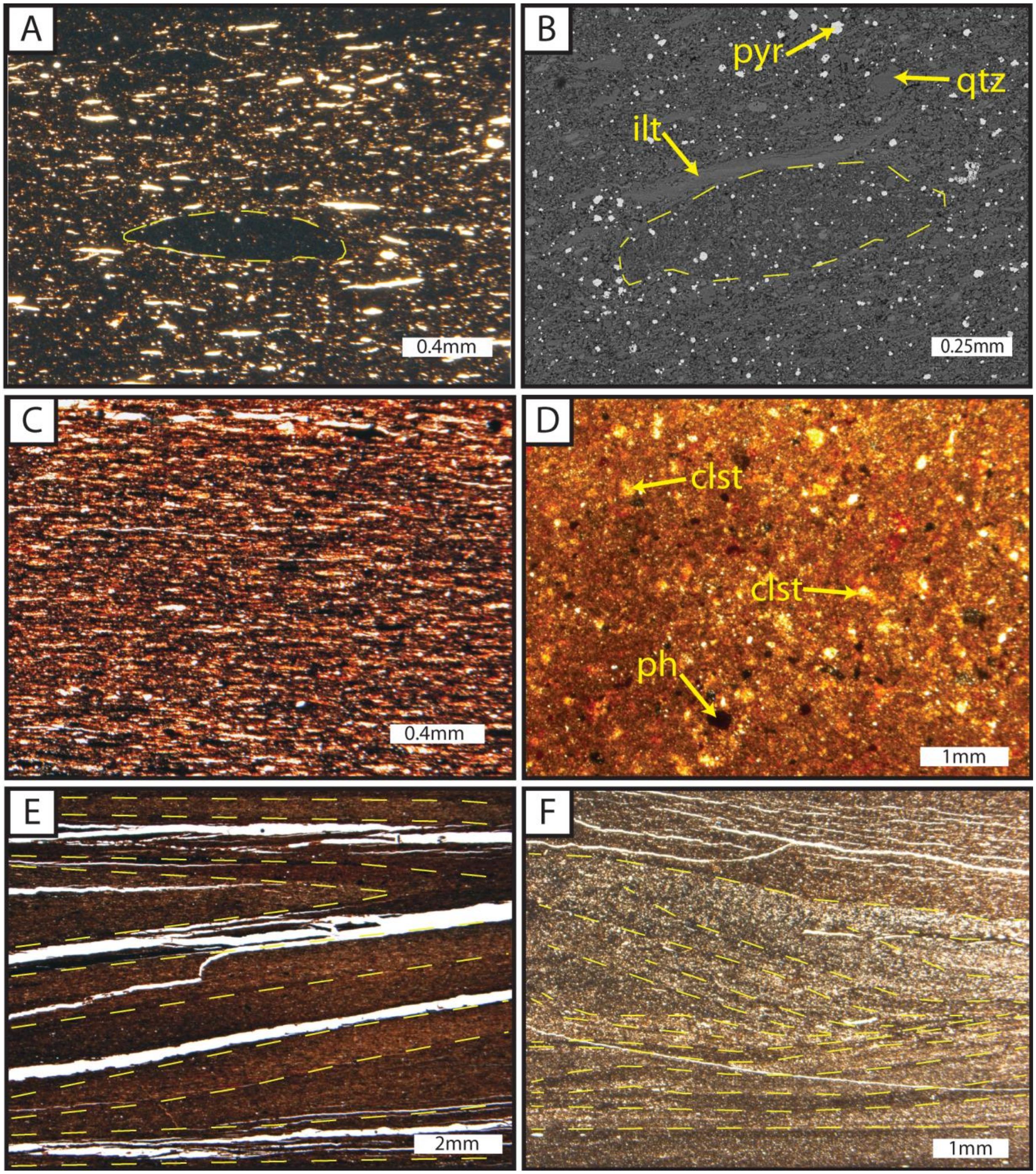

Figure 5.4. Different sedimentary features found within the *Peltura scarabaeoides* Biozone of the Alum Shale. A) Pellet (outlined in yellow) of facies 7 (Tomten -2.11m). Notice the abundance of illite clasts (white). B) SEM photo of a pellet (outlined in yellow); ilt= illite, pyr = pyrite, qtz = quartz. (Tomten -2.11m). C) Mud rip-up clasts –vertical slice (Kakeled 1.510m). D) Mud rip-up clasts –horizontal slice; clst = mud rip-up clast, ph = phosphate (Kakeled 1.393m). E) Large mudstone ripple (Kakeled 1.980m). Laminae outlined in yellow dashes. F) Small mudstone ripple with laminae outlined in yellow dashes (Tomten -2.162m).

CHAPTER 6: DISCUSSION

6.1 Sediment transport and deposition on the Alum Shale shelf

The depositional model presented in this study differs significantly from previous interpretations of Alum Shale sedimentology (e.g. Thickpenny 1984) and other classical source rock depositional models (Didyk et al., 1978). One key aspect is the proposed dominance of bed-load transport processes responsible for sedimentation of many of the facies characterizing this black shale unit in contrast to the previous belief that the siliciclastic muds accumulated in a tranquil environment through suspension. According to the model presented herein (Figure 5.3) and observed sedimentary structures (Figure 5.4), bed load transport mechanisms played a role in distributing sediment from shallow regions to more distal portions of the shelf, most likely during storms. Interestingly, these transport mechanisms occur in both the most proximal siliciclastic mudstone setting (facies 5) showing mudstone ripples and clay rip-up clasts, as well as in the most distal portion of the shelf (facies 7) containing silt laminae of laterally irregular thickness. These facies and their associated sedimentary structures clearly show the effects of bed load transport along the entire depositional profile of the Alum Shale. Surprisingly however, little evidence supports deposition of Alum Shale sediments from suspension. No facies clearly shows blanket-like geometries that can be unequivocally assigned to suspension sedimentation in an absolutely tranquil environment. Nevertheless, recent deep shelf environments do experience long times of no or little water movement which should have been the case for the Cambrian Alum Shale shelf as well (Thickpenny, 1984). Most likely, the bioturbation ubiquitous in all facies preferentially destroyed the suspension laminae as they originated from slower sedimentation rates allowing benthic organisms more time for homogenization. Suspension-laminae are most likely very fine-grained and therefore do not stand out in compositionally dark, clay-dominated sediments in contrast to event beds. Evidence for suspension could therefore be generally hard to detect on deep shelves characterized by abundant burrowing organisms even though it may have been a ubiquitous and frequent process.

The event beds often contain either quartz and/or carbonate grains, mud rip-up clasts or skeletal fragments and are often still recognizable in thin section despite the heavy bioturbation, similar to other storm beds in well-oxygenated shelf sediments (e.g. Aigner 1985; Myrow 1992). Event layers in the Alum Shale show a unique compositional distribution pattern based on geographic location. In the Tomten and Kakeled sections, quartz grains of silt size are absent in the carbonate beds interpreted as the more proximal setting, but present in the siliciclastic mudstones representing the distal part of the shelf. This distribution pattern is most likely the expression of isolated entry points for siliciclastic material combined with the lack of relief on the Baltic microcontinent during Late Cambrian times (c.f. Cocks and Torsvik, 2005). The absence of an elevated hinterland inhibited input of much erosional debris from land to mix with the proximal carbonates as it only entered the shelf in very few locations. Nevertheless, the siliciclastic detritus that was eroded from the Baltica peneplain was brought onto the shelf by rivers, very likely mostly in the Estonian portion of the basin (Artyushkow et al., 2000). Geostrophic currents, mostly induced by storms, seem to have distributed the quartz silt laterally and preferentially supplied it to the deep shelf leaving out most of the shoreface areas and shallow offshore portions along the Baltica coast.

6.2 Synsedimentary Tectonics

The Alum Shale Formation has been thought to have been deposited in a tectonically quiescent setting (Buchardt et al., 1998; Hagenfeldt, 1997; Thickpenny and Leggett, 1987). This was based on the overall regular laminated appearance of the Alum Shale siliciclastic mudstones reflecting a tranquil deep shelf environment. However, the shales exposed in the Tomten 1 core show numerous small-scale slumps, water-escape structures, and synsedimentary microfaulting (Figure 6.1). These features occur not only in the deep shelf mudstones, but also within the associated ramp carbonates (e.g. in the Tomten core at 1.72m, as well as in Kakeled at 2.29m). The inclination of the depositional environment is thought to be well below 1°, which is characteristic of epicontinental settings (cf. Lindström, 1971) and therefore not high enough to overcome the internal shear strength to initiate slumping and create synsedimentary microfaults by mass sliding (cf. Potter et al., 2005). It is therefore most likely that these deformational features were triggered by synsedimentary tectonic activity that affected the study area during deposition of the *Peltura scarabaeoides* Biozone. The Late Cambrian Scandinavian shelf was therefore not entirely tectonically quiet as previously assumed, but was as active as its Lower Ordovician counterpart (Egenhoff et al., 2010) and most likely characterized by some degree of tectonic movements. These movements are most likely related to either the closure of the Iapetus Ocean towards the northwest (Greiling and Garfunkel, 2007), or the subduction of the Rheic Ocean separating Baltica from Avalonia (Beier et al., 2000).

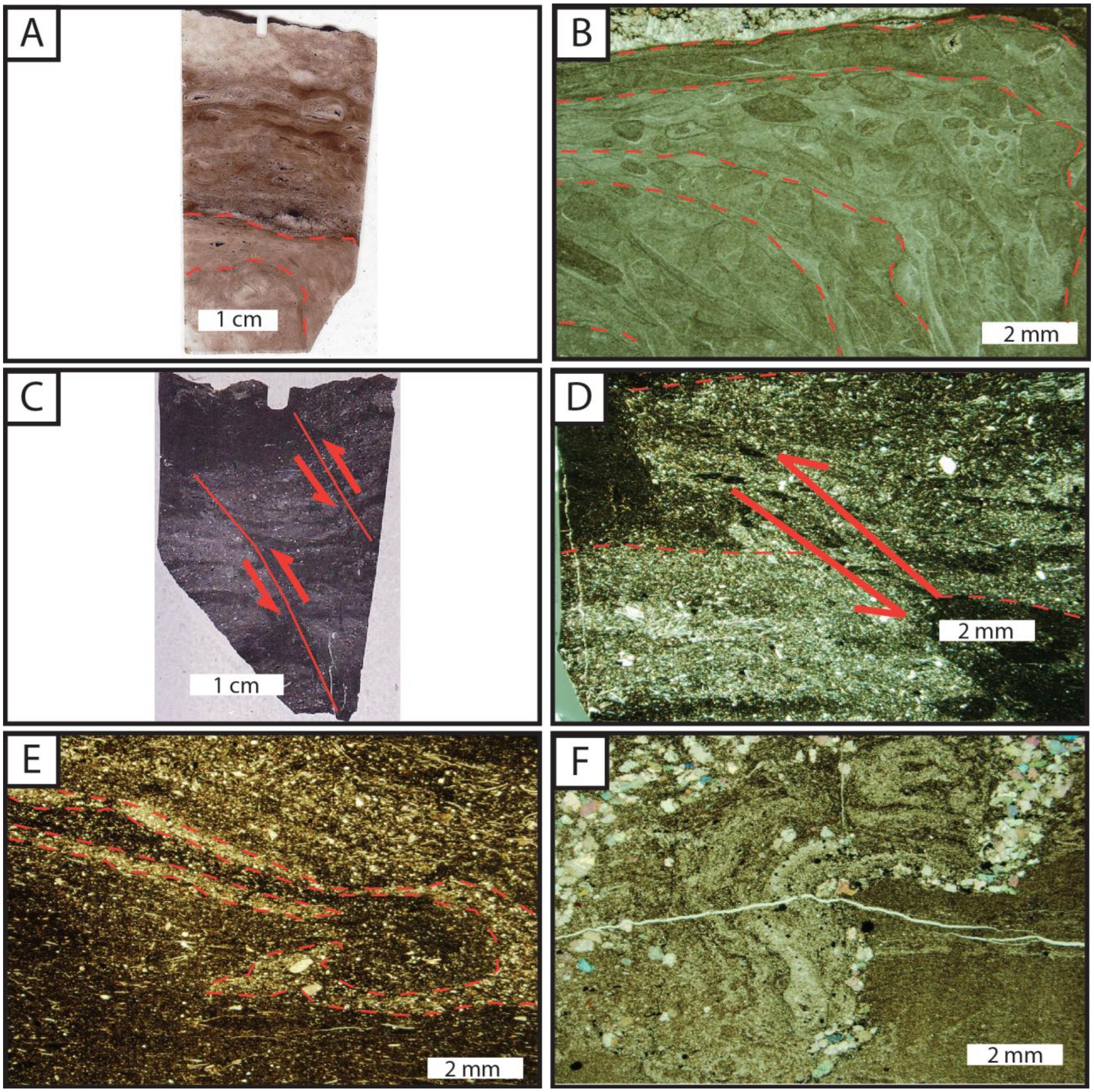

Figure 6.1. Synsedimentary deformation features observed in the *Peltura scarabaedoides* Biozone. A) Plain view of slumped intraclast carbonate packstone (Tomten -2.29m). Primary slump feature is outlined in red. B) Close-up view of (A) (Tomten -2.29m). C) Plain view of a microfaulted siliciclastic mudstone of facies 7 with numerous illite clasts (Tomten -2.37m). Reverse fault block movement directions are indicated by red arrows. D) A close-up views of the reverse microfaulted mudstone in (C) (Tomten -2.37m). E) Rollover slump within skeletal lag deposit. Red outline enhances the outline of rollover (Tomten -2.42m). F) Water-escape structure in a carbonate mudstone. Notice the abundance of precipitated calcite within the structure (Tomten -1.57m).

6.3 Bioturbations and Anoxia

Throughout the entire siliciclastic mudstone succession in the *Peltura scarabaeoides* Biozone, bioturbations are abundant in every facies type. This continuous presence of bioturbations at and near (within a few millimeters of) the sediment water interface reveals that the Alum Shale mudstones were most likely deposited during oxic to dysoxic conditions with at least sufficient oxygen for adapted organisms to survive and thrive. This contrasts with previous studies (Thickpenny, 1984; Gill et al., 2011) where the Alum Shale was envisioned as being deposited under largely anoxic or even in part euxinic conditions. However, an oxygen gradient is reflected in the diversity of burrows down ramp where the more proximal mudstones (facies 5 and 6) show two trace fossil types throughout, while the most distal portion of the shelf (facies 7) is characterized by only one burrow type. This general pattern has also been observed in the lower Mississippian Upper Bakken Shale (Egenhoff and Fishman, accepted) and was similarly interpreted to reflect a decrease in oxygen gradient down ramp.

This decrease in oxygen levels down ramp, as noted for the Alum Shale, is therefore not a phenomenon observed solely in this Cambrian system, but seemingly common also in younger mudstone environments. As it is likely observed throughout the Paleozoic (Egenhoff and Fishman, accepted) and Mesozoic siliciclastic mudstone successions (Maquaker and Gawthorpe, 1993), the decrease in oxygenation down ramp most likely represents an unwavering occurrence and is probably not caused by currents capable of a short-term oxygen increase by supplying it to an otherwise dysoxic to anoxic environment (e.g. Gill et al. 2011).

It was observed in this study that *Planolites* burrows occurring in more proximal reaches of the shelf consume and considerably deplete the sediment of organic matter. In contrast, multidirectional burrows do not seem to deplete sediment of organic matter and the burrows are in places back-filled with pyritized pellets. Therefore burrowing fauna of the multidirectional-type in the *Peltura scarabaeoides* Biozone are less efficient at consuming and digesting organic matter than the *Planolites*-producing organisms.

6.4 Alum Cyclicity

Based on sedimentation accumulation rates calculated by Thickpenny (1987), approximately 5 million years are represented by the *Peltura scarabaeoides*, *Peltura minor* and *Protopeltura praecursor* Biozones. The *Peltura scarabaeoides* portion of this succession in Västergötland represents a little more than half of the sediment stack encompassing the entire 5 million years, therefore this specific biozone can roughly be expected to represent 2.5 million years. Our study shows that the *Peltura scarabaeoides* Biozone is characterized by an overall shallowing trend that is especially well expressed in both the Kakeled and the Tomten sections. This shallowing trend most likely represents only a portion of a larger-scale second order cycle with its upper limb reflecting a loss of overall accommodation space. This second order cycle is subdivided into up to eight medium-scale cycles recognized in the arrangement of proximal versus distal facies in the study areas. This means that on average each of these medium-scale cycles represent 312,500 years which is less than the 400,000 years generally taken up by long eccentricity (Berger, 1978). However, the precision of the trilobite Biozones is not extremely accurate, so a slightly longer duration of the *Peltura scarabaeoides* Biozone based on trilobite distribution patterns is still plausible, in turn lengthening the time encompassed for each medium-scale cycle. In addition, evidence of erosion prior to lithification exists within the studied succession as seen in abundance of mud rip-up clasts. These were formed by currents that removed portions of the overall sediment stack prior to their deposition thereby further reducing the amount of sediment represented now by the medium-scale cycles. It is therefore assumed herein that the medium-scale cycles probably represent long eccentricity fluctuations, as these are very abundant especially in Paleozoic marine successions (Haq and Shutter, 2008).

CHAPTER 7: CONCLUSIONS

While previous workers (i.e. Thickpenny, 1984; Gill et al. 2011) concluded that the Alum shale was deposited in a quiet and anoxic setting, the findings of this study indicate the contrary. Continuous thin section coverage throughout the entire *Peltura scarabaeoides* Biozone at Kakeled and portions of the trilobite biozone at Tomten and Hunneberg have revealed that the Alum Shale shows a range of facies representing a transect from proximal carbonate to distal siliciclastic mudstone environments, locally including a lagoonal setting with diagenetic barite crystals. Sedimentary structures such as mud rip-up clasts, mudstone ripples and discontinuous silt laminae were found throughout the trilobite biozone demonstrating that bed load processes were actively contributing to mud dispersal on the shelf and suspension was not the only contributor throughout upper Alum shale deposition. Furthermore, numerous slumps and microfaults were found signifying that the Alum was not always tranquil and at least a small degree of synsedimentary tectonic activity had occurred. A bioturbation gradient exists within the siliciclastic basinal portion of the Alum Shale shelf. It shows that more diverse burrowing fauna occurs in more proximal parts of the shelf while in the most distal shelf environment (within clay-rich mudstones) only one burrow type occurs. The fact that burrows are present in all shale samples indicates that anoxic conditions did not prevail and were perhaps the exception to what was likely a dysoxic setting where burrowing fauna could endure.

Three different orders of cyclicity were observed occurring in the *Peltura scarabaeoides* Biozone: (1) an overall coarsening-upward 2^{nd} order cycle lasting 2.5 m.y. that shows a loss in accommodation space near the upper limb of the cycle; (2) up to eight medium-scale 4^{th} order cycles of intercalated siliciclastic mudstones with carbonates equating to each cycle being 312,500 years in length and likely being formed by eccentricital forces influencing sea level fluctuations; (3) numerous well defined small-scale (<1cm-5cm thick) coarsening- and fining-upward siliciclastic mudstone cycles.

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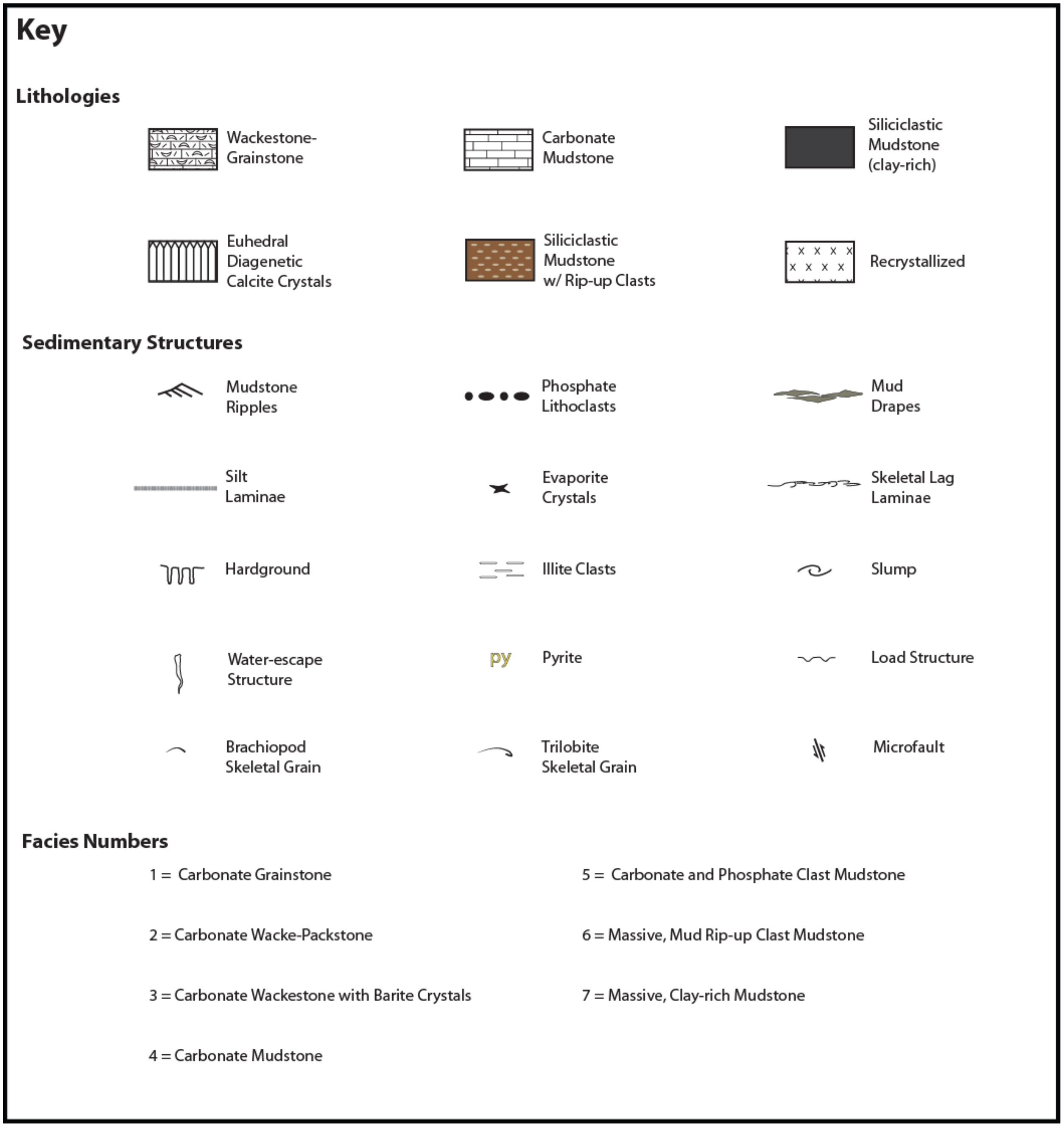
APPENDIX I

Legend applies to all figures within the following appendices.



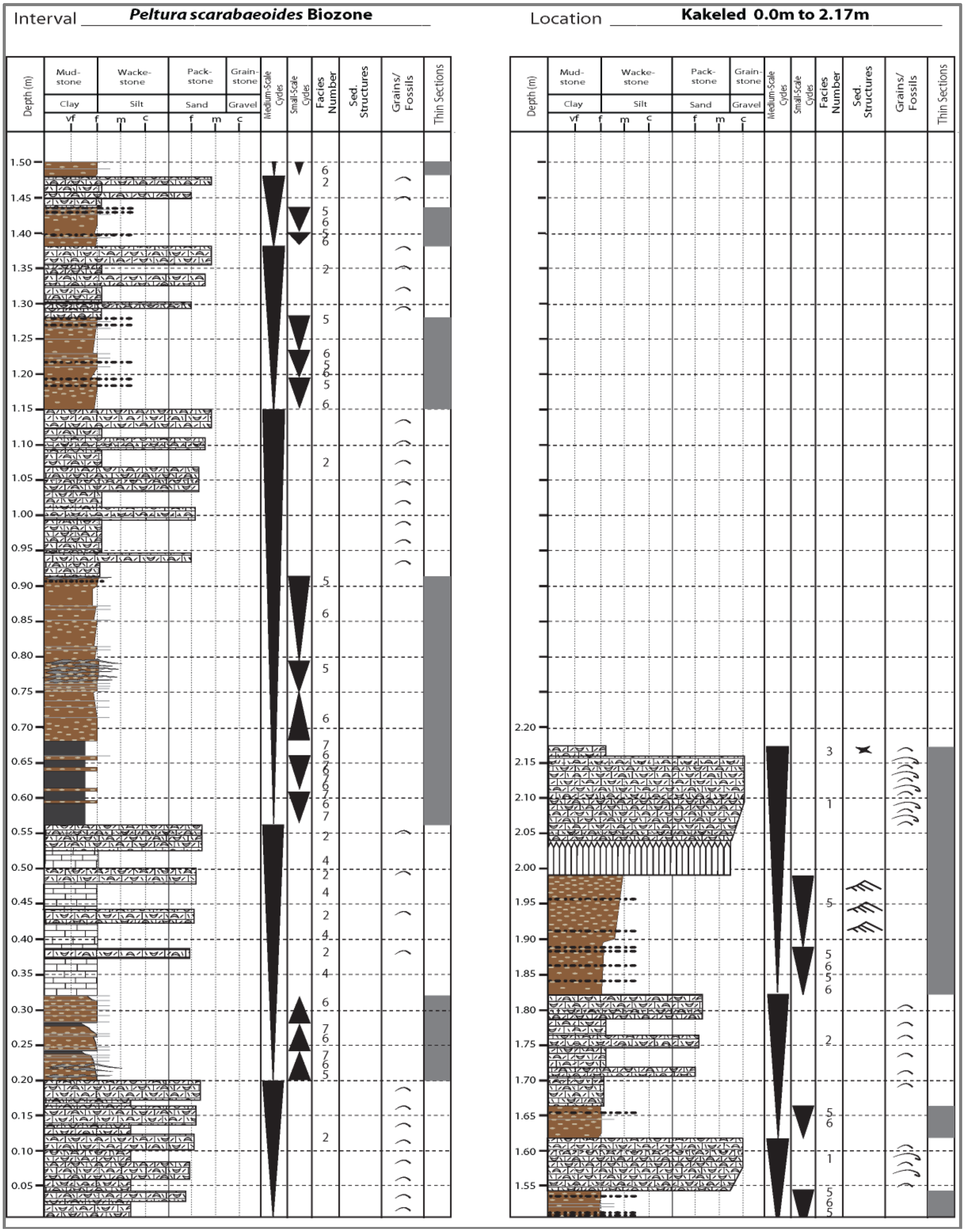


Figure A1.1 Stratigraphic description of *Peltura scarabaeoides* Biozone at the Kakeled outcrop.

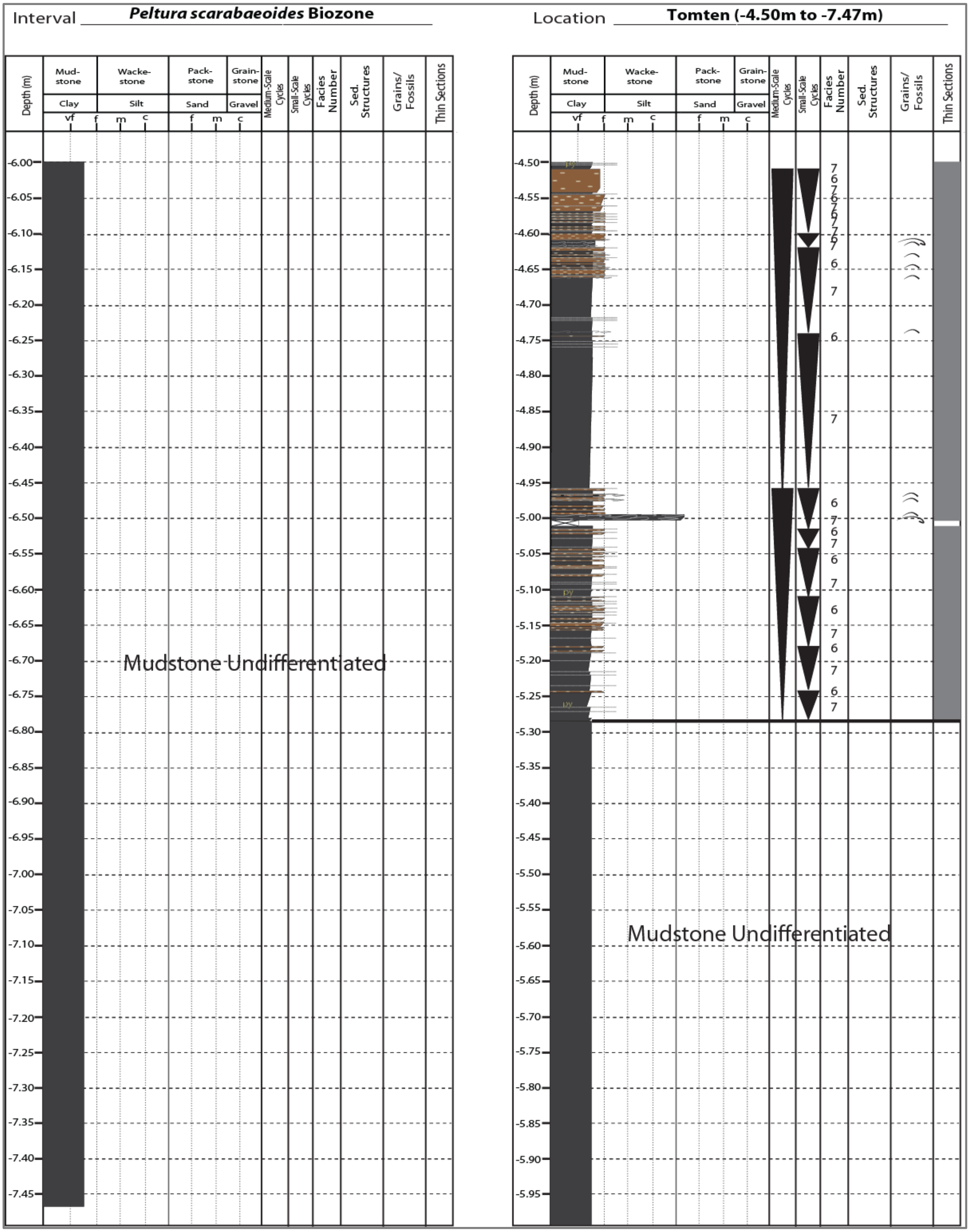


Figure A1.2. Stratigraphic description of *Peltura scarabaeoides* Biozone in the Tomten 1 core.

Interval ***Peltura scarabaeoides* Biozone** Location **Tomten (-1.53m to -4.50m)**

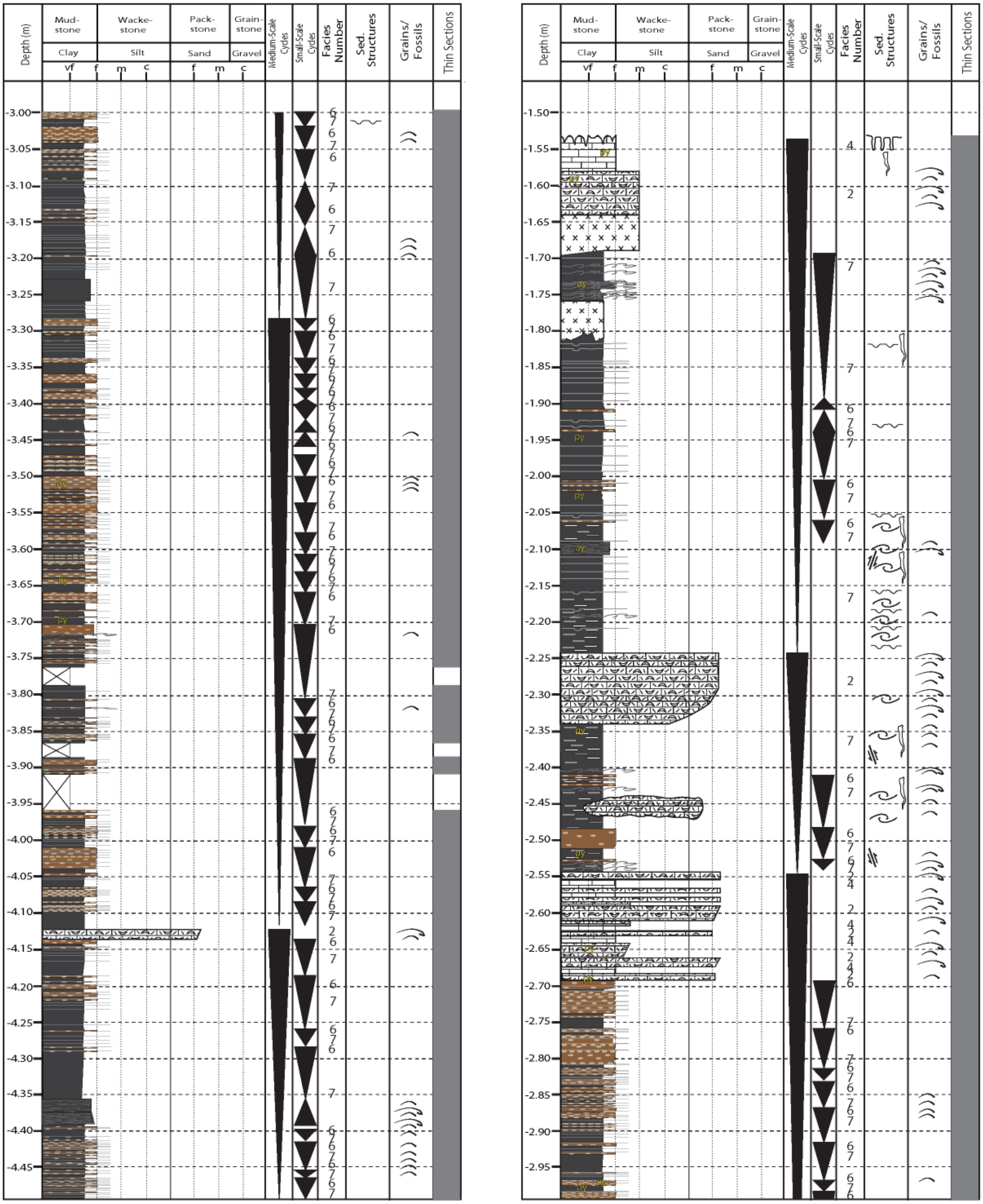


Figure A1.3. Stratigraphic description of *Peltura scarabaeoides* Biozone in the Tomten 1 core.

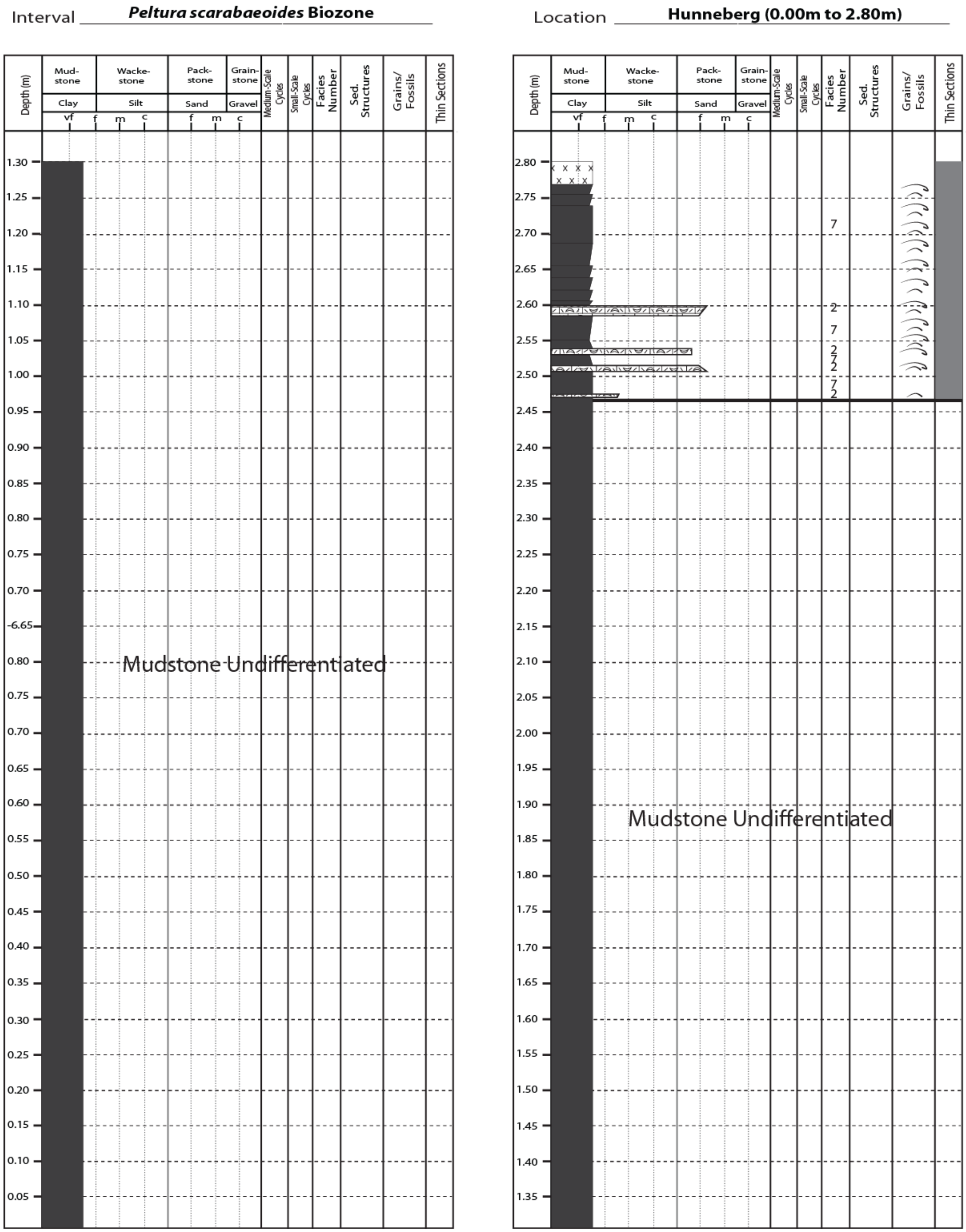


Figure A1.4 Stratigraphic description of *Peltura scarabaeoides* Biozone at the Mt. Hunneberg outcrop.

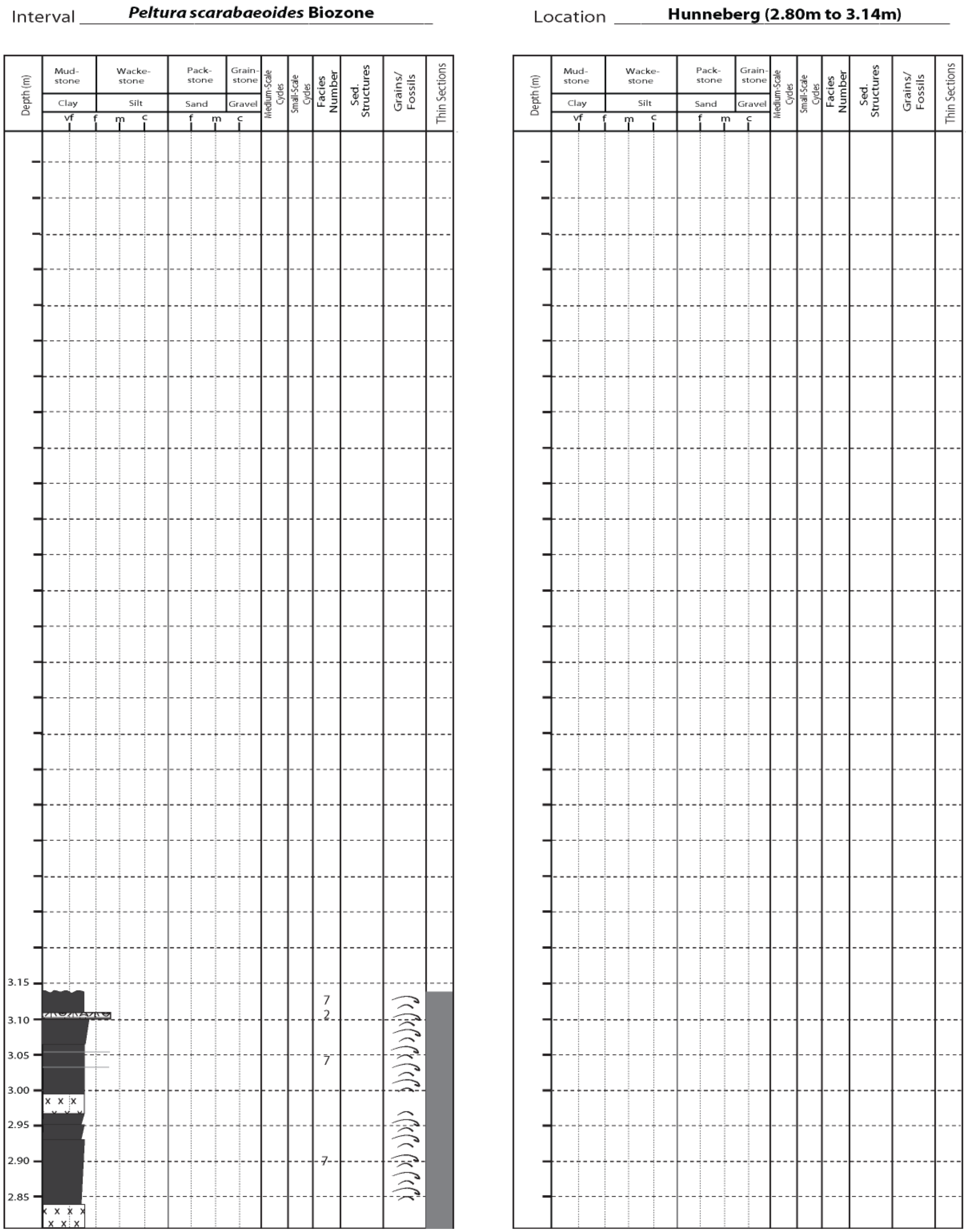


Figure A1.5 Stratigraphic description of *Peltura scarabaeoides* Biozone at the Mt. Hunneberg outcrop.