SEDIMENTOLOGY AND STRATIGRAPHY OF THE UPPER NEOPROTEROZOIC FERRYLAND HEAD FORMATION, EASTERN AVALON PENINSULA, NEWFOUNDLAND AND LABRADOR WITH PARTICULAR REFERENCE TO THE SOFT SEDIMENT DEFORMATION STRUCTURES

RODRIGO A. SALA TOLEDO

SEDIMENTOLOGY AND STRATIGRAPHY OF THE UPPER NEOPROTEROZOIC FERRYLAND HEAD FORMATION, EASTERN AVALON PENINSULA, NEWFOUNDLAND AND LABRADOR WITH PARTICULAR REFERENCE TO THE SOFT SEDIMENT DEFORMATION STRUCTURES

by

© Rodrigo A. Sala Toledo BSc. (Honours)

A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of Master of Science

Department of Earth Sciences Faculty of Science
Memorial University
April 2004

St. John's Newfoundland

0-612-99112-1

ABSTRACT

The Ferryland Head Formation of Ediacaran age is exposed along the southeastern coast of the Avalon Peninsula, Newfoundland and Labrador. A detailed sedimentological study was undertaken at Ferryland, its type locality, 72 km south of St. John's, where approximately 500 m of the formation are exposed. The objectives of this study are to establish a stratigraphic and sedimentological framework in order to determine depositional environments and the stratigraphic evolution of the succession and to document the diversity of synsedimentary structures. Three detailed stratigraphic sections, covering approximately 600 m were constructed.

The Ferryland Head Formation consists of interbedded tabular reddish-to-purplish-brown siltstones and buff-to-greenish-grey arenites with minor occurrences of lithic arenites and lithofeldspathic arenites. Grain size varies from silt to medium sand; the mode being fine sand. Five lithofacies including 22 subfacies are defined at Ferryland. Facies 1 comprises siltstone and finer grained sandstones. Facies 2 encompasses silty sandstone. Facies 3 is composed of clean sandstone. Facies 4 and 5 comprise intraformational conglomerates and ash-rich beds respectively. Three facies associations are recognised in the Ferryland Head Formation. Facies association I is interpreted as mouth-bar deposits, facies association II is interpreted as channelised sediments and facies association III is interpreted as overbank deposits. Palaeoflow in the study area is unimodal and south-directed. The depositional environment for the Ferryland Head Formation is interpreted to be a humid fan delta. The abundance of synsedimentary structures in the study area is attributed to rapid deposition, a high water table and probable seismic activity in a tectonically active pull-apart basin.

ACKNOWLEDGEMENTS

First and foremost I have to thank Andy Pulham, my supervisor for making this project possible. He supplied most of the funding and took care of the logistics, which I'm sure were a nightmare. His guidance especially in the field was invaluable. I owe special thanks to Rick Hiscott for his field advice and most importantly very thorough and speedy revisions. I would like to thank Guy Narbonne, Bob Dalrymple for their valuable field advice and Martin Brasier for pointing out the *Arumberia* structures, and Art King and Michael Anderson for the background information. I am very grateful for the financial support from the School of Graduate Studies, the Earth Science Department at Memorial University and Andy Pulham. I am also extremely grateful for all the help from the people at the School of Graduate Studies, the Earth science Main Office, the International student advisor Lillian Beresford and programmer Sonja Knutson for showing me the light when everything seemed hopeless and Ali Aksu and Rick Hiscott for their expedient and efficient way of dealing with my "bumps on the road."

I wish to thank the people of Ferryland for their hospitality. I owe special thanks to Aidan and Diane Costello and Madeline Swain for making me feel at home at the Downs Inn.

A big thank you to all the friends I made in Newfoundland who had to put up with my whining and complaining. Thank you Mark Creighton, Claire Rillie, Maureen Power, Cheryl MacLean, Carley Williams and Irene White. I also wish to thank Jennifer Young and Mark Ferry for all the productive procrastination. Thank you Alex for your understanding and support.

Last but not least, I would like to thank my parents, Raquel Toledo and Antonio Sala and my sister Pamela Sala, for their long distance, unconditional support. I would have never gotten this far without you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF APPENDICES

Chapter 1

INTRODUCTION

1.1. GEOGRAPHY AND STRATIGRAPHY

The Ediacaran (540 – 600Ma) Ferryland Head Formation of the Signal Hill Gorup is exposed at three outcrop localities along the eastern shoreline of the Avalon Peninsula, Newfoundland and Labrador (Figure 1.1). At its type locality, in Ferryland, approximately 500 m of the basal section of the formation are exposed. Cape Broyle and Cape Ballard to the north and south of Ferryland respectively are the other two principal localities where the formation is exposed (Figure 1.2). The only exposures of the upper parts of the Ferryland Head Formation are at Cape Ballard. This study will focus on the exposures at Ferryland Head, Ferryland, located 72 km south of St. John's (Figure 1.1).

1.2. REGIONAL GEOLOGY

1.2.1. Introduction to the Avalon Zone Geology and Regional Palaeogeography

The Avalon Zone is a tectonostratigraphic subdivision of Appalachian orogen (Williams and King, 1979) which is one of many peri-Gondwanan terranes (O'Brien et al., 1983; O'Brien et al., 1996; Murphy et al., 2001). This terrane is interpreted to have formed as a volcanic arc along the margins of Neoproterozoic Gondwana called Avalonia (Murphy et al., 2001). Rocks within the Avalon Zone of Newfoundland can be correlated with rocks in Cape Breton, eastern New Brunswick, eastern Massachusetts, the Carolinas, the British Caledonides, the Hercynides of France and Iberia and the northern and western margins of the West African Shield (Murphy et al., 2001; McNamara, 2001;

Morris, 1989; Myrow 1995). The Avalon Zone as a whole can be subdivided into three smaller geographic zones (Myrow, 1995; Morris, 1989): the eastern, central and western zones. The Ferryland Head Formation is situated within the eastern Avalon Zone.

Several authors place Avalonia along the margin of Neoproterozoic Gondwana (Nance and Murphy, 1996; Keppie and Dostal, 1998; Nance et al., 2002). However, establishing a precise latitude and palaeogeographic location for Avalonia with respect to other Neoproterozoic cratons is problematic and uncertainties are primarily due to sparse paleomagnetic data (Morris, 1989; Myrow and Kaufman, 1999). In the basal part of the Avalon stratigraphy, the Harbour Main Group palaeomagnetic data indicate a low palaeolatitude, *circa* 20–30 degrees north or south (Morris, 1989). In younger stratigraphy on the Avalon Peninsula (the Marystown Group), equivalent data suggest depositional palaeolatitudes of $34°+8°/-7°$ (McNamarra, 2001). Dalziel (1997) places Avalonia at high latitudes (between 30° and 60°) in the late Neoproterozoic. Myrow and Landing (1992) suggest a high latitude location based on the lack of carbonate platforms in the stratigraphy.

Terminal Neoproterozoic climates are similarly problematic to model. There is evidence of at least two glacial episodes, the oldest being the Rapitan-Sturtian glaciation (approximately 750–700 Ma) and the youngest being the Marinoan-Varanger-Ice Brook glaciation (approximately 600–590 Ma) (Young, 1995; Kaufman, et al.,1997). The latter is sometimes separated into two discrete glaciations. The second of which is sometimes referred to as the Gaskiers glaciation, after

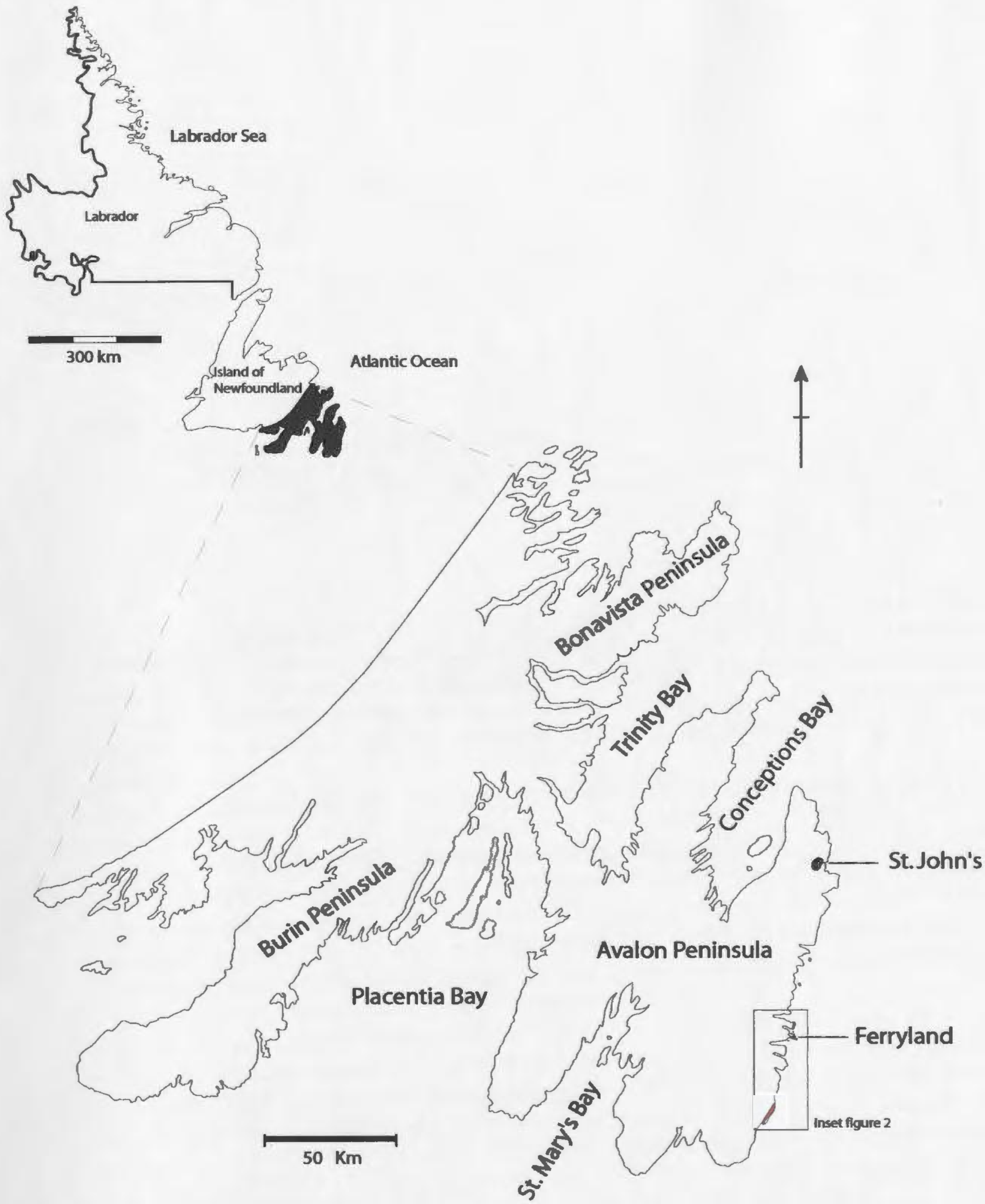


Figure 1.1. Location map showing the Avalon Zone of the Island of Newfoundland and the outcrop locations for the Ferryland Head Formation.

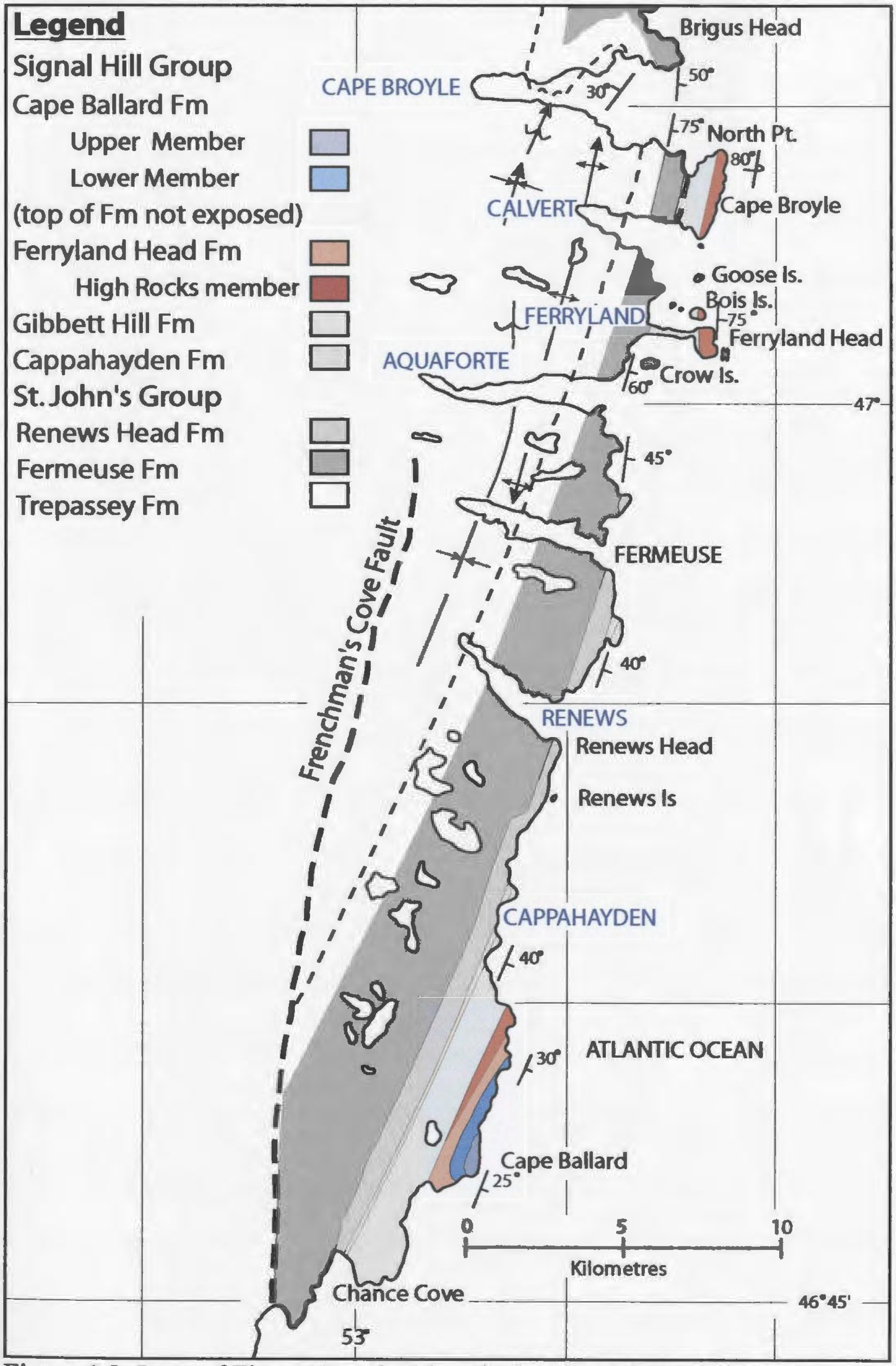


Figure 1.2. Inset of Figure 1.1. showing the local geology of the eastern Avalon Peninsula (Modified from King et al., 1988).

the Gaskiers Formation in Newfoundland and Labrador (Bowring et al., 2003). During the latest Ediacaran, global climate was non- glacial with warm, arid mid- lower latitudes and temperate, humid high latitudes with some evidence for warm humid climate in southern higher latitudes (Chumakov, 2003). So called "greenhouse" conditions, with little or no polar ice, were established by early Cambrian times (Veevers, 1990; Tucker, 1992).

1.2.2. Local Stratigraphy

The entire Precambrian sedimentary succession of the Avalon Peninsula is over 9 km thick and comprises four stratigraphic units. From oldest to youngest, these units are the Harbour Main Group, Conception Group, St. John's Group and the Signal Hill Group (Table I). The Ferryland Head Formation comprises part of the Signal Hill Group.

The Harbour Main Group consists of over 1500 m of volcanic and volcaniclastic deposits that comprise the base of the exposed Precambrian sedimentary succession (Williams and King, 1979). The base of the Harbour Main Group is not exposed and it is unconformably overlain by the Conception Group. U-Pb zircon dates of $606 ^{+3.7}_{-2.9}$ Ma in an ash flow tuff and $622.6 ^{+2.3}_{-2.0}$ Ma in a rhyolite (Krogh et al., 1988) provide an age control for the Harbour Main Group. Overall, this group consists of red, pink and grey silicic tuffs, aggregates, pink to red rhyolites, welded tuffs and massive dark green to purplish basalts. The Harbour Main Group is interpreted to be mainly terrestrial in origin but some subaqueous volcanism is suggested by local pillow lavas (O'Brien and King, 1982; O'Brien et al., 1983; King, 1990).

The Conception Group is subdivided into five formations (Table 1) and is the thickest interval of Precambrian sediments exceeding 4000 m in thickness. It is exposed throughout the Avalon Peninsula and comprises mainly grey to green siliceous turbiditic sandstones of volcanic provenance. The sedimentary rocks are medium to very thick bedded. The succession is punctuated by ash beds and airfall tuffs and is interpreted as being deposited in deep basinal to slope environment in a volcanically active setting (Williams and King, 1979; Narbonne et al., 2001, 2002).

The St. John's Group comprises three formations (Table 1) and conformably overlies the Conception Group. It consists mainly of grey to black fissile mudstones and grey to buff fine-grained sandstones with gradational contacts and has a thickness of approximately 2000 m (Williams and King, 1979). Large-scale slump structures are present throughout the St. John's Group and ash beds and tuffs are sparse (Narbonne et al. 2001). An overall shallowing-upwards of palaeoenvironments in the St. John's Group has been interpreted as representing the deposition of a prograding slope (King et al., 1988a, 1988b).

The Signal Hill Group caps the exposed Precambrian stratigraphy of the Avalon Peninsula and it approaches 1500 m in thickness. Four mappable units of formational status comprise the Signal Hill group. These are, from oldest to youngest, the Gibbett Hill, Quidi Vidi, Cuckold and Blackhead formations in the St. John's area, and the Cappahayden, Gibbett Hill, Ferryland Head and Cape Ballard formations in the study area (Table 1).

The Ferryland Head Formation conformably overlies the Gibbett Hill Formation and is conformably overlain, where exposed, by the Cape Ballard Formation. The lower boundary of the Ferryland Head Formation is a lithostratigraphic surface marked by the first appearance of red sandstone in the Signal Hill Group stratigraphy (Williams and King, 1979). The overall sedimentary succession of the Ferryland Head Formation is characterised by upward coarsening in grain size and upward increase in bed thickness. There are generally finer and thinner beds in the lower and southernmost areas and coarser thicker beds in the stratigraphically higher areas and northern areas.

1.2.3. Tectonism, Structure and Metamorphism

The Harbour Main, Conception, St. John's and Signal Hill Groups define elongate NNE-SSW trending structural domes and basins. Provenance of the Signal Hill Group sediments, that partially comprise the Ferryland Head Formation, was from late Vendian uplift north of the present Bonavista and Avalon peninsulas. This uplift was related to the ongoing late Precambrian Avalonian Orogeny. The rocks were later deformed and slightly metamorphosed during the mid Palaeozoic Acadian Orogeny (King, 1990). A two-phase tectonic evolution of Avalonia has been proposed by Murphy et al. (1999). The first tectonic phase (Phase I, *circa* 630-590 Ma) entailed arc-related volcanism and associated sedimentation due to northwest-directed, oblique subduction resulting in left lateral strike slip movement (Narbonne et al., 2001). The second tectonic phase (Phase II, *circa* 590-540 Ma), which began as subduction of a spreading centre, caused reversal of strike-slip motion with time and ultimately an inversion of some of the basins. A modern analogue is considered to be the basins of southwestern U.S.A. and northwestern Mexico (Murphy, 1999). Narbonne et al. (2001) proposed that the boundary between the two phases can be drawn where sedimentation styles change within the St. Johns Group. The provenance of sediment in strata below the Trepassey Formation in the St. John's Group (Table 1) ranges from the south to the west. The upper part of the St John's Group and the Signal Hill Group, have a northerly source of sediment (Narbonne et al., 2001).

1.3. <u>SUMMARY OF PREVIOUS WORK IN THE FERRYLAND HEAD FORMATION</u>

The rocks of the Avalon Peninsula were first studied by J. B. Jukes in 1839 and 1840. He used the name Signal Hill Sandstone to describe the red and grey Precambrian sandstones in the eastern Avalon Peninsula. Buddington (1919) proposed the name Signal Hill Series for these rocks. Rose (1950) mapped the Ferryland Head Formation as red sandstone and conglomerates and considered them to correspond to the Signal Hill Formation. In 1952, Rose defined these rocks as the lower and middle members of the Signal Hill Formation. Singh carried out a petrological study of the Signal Hill and Blackhead formations in 1969.

Williams and King (1979) redefined the stratigraphy of the eastern Avalon creating the Signal Hill Group encompassing the Ferryland Head Formation. The Ferryland Head Formation was later defined as a sandy facies of the Quidi Vidi and Cuckold formations that occur in the St John's Area (King, 1980; King et al. 1988a, 1988b). The stratigraphy exposed at Ferryland Head was designated the type section of the Ferryland Head Formation. The lower boundary of the Ferryland Head Formation

Table I. Proterozoic stratigraphy of the Avalon Peninsula (Modified from Williams and King, 1979 and Narbonne *et al.* 2002).

Era (Period)	Group thickness (m)	Formation thickness (m)	Lithology
Neoproterozoic (Ediacaran)	Signal Hill > 1450	Cape Ballard >260	Upper part: thick bedded, buff weathering, grey sandstone and quartz granule conglomerate. Lower part: grey to purple shale and grey siltstone.
		Ferryland Head 500	Thin to medium-bedded buff to greenish grey sandstone and red siltstone. Red, wavy bedded sandstone and siltstone (High Rocks Member) at base
		Gibbett Hill 760	Thick bedded, light grey sandstone, thin bedded, dark grey sandstone and siltstone, calcareous sandstone ellipsoids locally present.
		Cappahayden 175	Laminated, fissile, light grey siltstone
	Local erosional disconformity		
	St. John's 1950	Renews Head 300	Thin, lenticular bedded, dark grey sandstone and minor shale.
		Fermeuse 1400	Grey to dark grey and black shale, thin lenses of buff weathering sandstone and siltstone.
		Trepassey 250	Medium-to-thin-bedded, graded grey sandstone and shale.
	Conception >4000	Mistaken Point 400	Medium bedded grey to pink sandstone, green, purple and red shale, and minor tuff.
		Briscal 100-1200	Thick bedded grey sandstone, green to grey argillite, red sandstone and arkose, locally grey thin bedded siliceous siltstone and shale.
		Drook 1500	White weathering, green, grey, buff and locally red to purple argillaceous chert, siliceous siltstone, sandstone, silicified tuff, locally thick sandstone with shale, siltstone and minor purple argillite.
		Gaskiers 250-300	Grey diamictite, intercalated rhythmites of mudstone siltstone and sandstone with dropstones and conglomerate
		Mall Bay >800	Green siliceous siltstone and argillite, grey sandstone, black green and purple argillite and chert, tuffaceous sandstone, green siliceous tuff and agglomerate, white quartzose sandstone and minor limestone
	Fault contact with Harbour Main Group		
	Harbour Main >1500		Red pink and grey silicic tuff agglomerate, pink to red rhyolite and welded tuff; massive dark green to purplish basalt

was then defined as the first appearance of red-coloured beds (Williams and King, 1969). Red-coloured sandstones and siltstones define the High Rocks Member of Ferryland Head Formation.

The rocks present at Ferryland are indistinguishable from stratigraphically younger grey rocks, except for their colouration (Williams and King, 1979). The environment of deposition of the Ferryland Head Formation has been interpreted as the distal facies of a braided river alluvial plain (Singh, 1969; Williams and King, 1979; King, 1988; King, 1990 and Narbonne et al., 2002) and as delta front to delta plain (Narbonne et al., 2001). No detailed sedimentological study of the Ferryland Head Formation has been undertaken or published prior to the new research presented in this study.

1.4. RESEARCH OBJECTIVES AND METHODOLOGY

This thesis has two main objectives.

The first one is to establish a detailed sedimentological and stratigraphic framework of the Ferryland Head Formation in order to determine the depositional environments and stratigraphic evolution of the unit. This will aid in the understanding of the overall depositional history of the Avalonian sedimentary succession.

The second objective is to describe and interpret the diversity of synsedimentary deformation structures present in the Ferryland Head Formation, within their sedimentological context and to produce an atlas of the more important synsedimentary structures that have been recognised.

The principal method of analysis was a field-based description of the Ferryland Head Formation. Sedimentological data, including bedding relationships, bedding thicknesses, sedimentary structures, textures, sediment colouration and palaeocurrent indicators were recorded. Field sketches were made and digital and 35mm photographs were collected of the important sedimentary and stratigraphic features of the formation.

A Canadian Stratigraphic grain-size-comparison chart was used for grain size description. Microsoft Excel spread sheets were used to calculate mean, mode and median thicknesses of facies association occurrences. StereoNett version 2.02 was used to plot the rose diagrammes illustrating palaeoflow in chapter 4. Three stratigraphic columns, covering approximately 600 m of exposed section in the study area, were constructed. A facies analysis was then undertaken based on all the field measurements and descriptions and by analogy to published models of the origins of sedimentary structures (Reineck and Singh, 1980; Allen, 1982a,b; Collinson and Thompson, 1982).

Chapters 3, 4 and 5 describe and interpret the sedimentology and stratigraphy of the Ferryland Head Formation. Chapter 5 also provides an "atlas" description of the syn-sedimentary deformation structures in the Ferryland Head Formation. Chapter 6 proposes a variety of depositional models that might reasonably fit the sedimentary and stratigraphic observations and then selects a preferred depositional setting. Chapter 7 delivers the major conclusions of the research, some implications and a description of potential future work that could be undertaken. The following Chapter 2 reviews the evidence for late Precambrian flora and fauna and provides an important context for the sedimentological analysis of the Ferryland Head Formation.

Chapter 2

BIOGENIC STRUCTURES AND THE LATE PRECAMBRIAN

2.1. LATE PRECAMBRIAN FLORA AND FAUNA: A BRIEF REVIEW

Late Neoproterozoic fossils are known from the all continents except Antarctica. Most notable localities are in the White Sea region in northeastern Europe, southern Ukraine, southwestern U.K., Finnmark, Norway, Ediacara, South Australia, central Australia, Namibia, southwestern Africa, Northern and Southern China, southwestern and eastern U.S.A., the Wernecke and Mackenzie Mountains in Northwestern Canada and the Avalon Zone of Newfoundland and Labrador. Late Precambrian fossil assemblages occur as impressions and body fossils as well as trace fossils.

Simple horizontal traces have been reported from rocks as early as the Mesoproterozoic (Seilacher et al., 1998). Palaeoproterozoic traces however, after been interpreted as such, are consistently reinterpreted as inorganic sedimentary structures (Bergström, 1990; Hofmann, 1971) or have been incorrectly dated (Fedonkin and Runnegar, 1992). Pre-Ediacaran age trace fossils are limited to simple, unbranched traces assigned to the ichnogenus *Planolites*, and are rare (Crimes, 1994; Droser et al., 2002). Trace fossils diversified and became abundant worldwide in the mid Cryogenian, *circa* 700 Ma (Fedonkin, 1994; Crimes, 1994).

Crimes (1994), lists *Planolites* isp. as the only known Riphean (1600 Ma–700 Ma) trace fossil. Varengerian (600–610 Ma) traces amount to 4 ichnogenera and 35 ichnogenera worldwide for his "Ediacarian biozone" and 66 ichnogenera for the "pre-trilobite Cambrian".

Late Neoproterozoic trace fossils have been reported from various localities in Northwestern Canada (Narbonne and Hofmann, 1987; Hofmann et al., 1990; Narbonne and Aitken, 1990; Hofmann et al., 1991). *Planolites montanus* is known from the Sheepbed Formation and *Aulichnites* isp., *Helminthoida* isp., *Neonerites* isp., *Palaeophycus tubularis*, *Planolites montanus*, *Torrowangea rosei* and a knotted burrow structure are known from the Blueflower Formation in the Windemere Supergroup Northwest Territories of Canada (Narbonne and Aitken, 1990).

The serial fossils *Palaepascichnus*, *Intrites*, *Neonerites renarius* and *Yelovichnus* have been reported from the Fermeuse Formation in the study area, in association with the body fossil *Aspidella terranovica*, but are interpreted to be body fossils rather than trace fossils (Gehling et al., 2000) of probable algal origin (Jensen, 2003). No trace fossils are known from the Neoproterozoic of the Avalon Peninsula, Newfoundland and Labrador.

2.2. BIOGENIC STRUCTURES IN THE LATE PRECAMBRIAN STATIGRAPHY OF THE AVALON PENINSULA

No Ediacaran-type fossils have been found to date in the Signal Hill Group, even though taphonomic conditions are comparable to fossiliferous strata of similar age (Narbonne et al., 2001, 2002). Ediacara-type fossils and trace fossils are well known from similar strata in the Northwest Territories, Canada (MacNaughton and Narbonne, 1999). The only known fossils in the Signal Hill Group come from the lower St. John's Group, specifically, sphaeromorph acritarchs from the Cappahayden Formation and lower Gibbet

Hill Formation (Hofmann and King, 1979). A few algal mat textures can be observed on bedding surfaces of the Ferryland Head Formation.

Ediacaran body fossils (Figure 2.1) are common within the upper Conception Group and lower St. John's Group (Gehling et al., 2000; Misra, 1969, 1971, 1981; Anderson and Morris, 1982; Landing et al., 1989). The latest occurrence of Ediacara-type fossils in the Avalon stratigraphy is in the Fermeuse Formation (Figure 2.2). *Aspidella* is the most common fossil, occurring in densities up to 4000/m^2. *Hiemalora, Triforillonia,* poorly preserved fronds, *Palaeopascichnus* , *Intrites* and *Yelovichnus* are also present, but rare (Gehling at al., 2000).

Trace fossils have never been described in all of the Avalon Neoproterozoic stratigraphy. Reasons for their absence are most likely explained by environmental factors, such as terrestrial conditions and other depositional settings unfavourable to Neoproterozoic life. However, in the Ferryland Head Formation there are abundant soft sediment deformation structures that offer intriguing possibilities of potential biogenic origins (Figure 2.3). The absence of any evidence for Ediacaran communities in the Ferryland Head Formation, despite their presence in underlying formations, strongly limits the likelihood of flora or fauna being involved in the formation of any of the sedimentary structures observed. Therefore a hypothesis that all the Ferryland Head Formation sedimentary structures are the products of abiogenic, and possibly chemical, processes is a reasonable assumption. A thorough description of the soft sediment deformation structures in the Ferryland Head Formation could provide a very useful context for improved understanding of other sedimentary successions that have a mixture of biogenic and physical sedimentary structures.

An analysis of the sedimentary facies and depositional setting of the Ferryland Head Formation is presented in the following chapters. The array of sedimentary structures are interpreted in their context and ranked according to the mode and clarity of their genesis. A discussion of the physical origins of the Ferryland Head Formation soft sediment deformation structures is undertaken and analogue value to other investigations proposed.

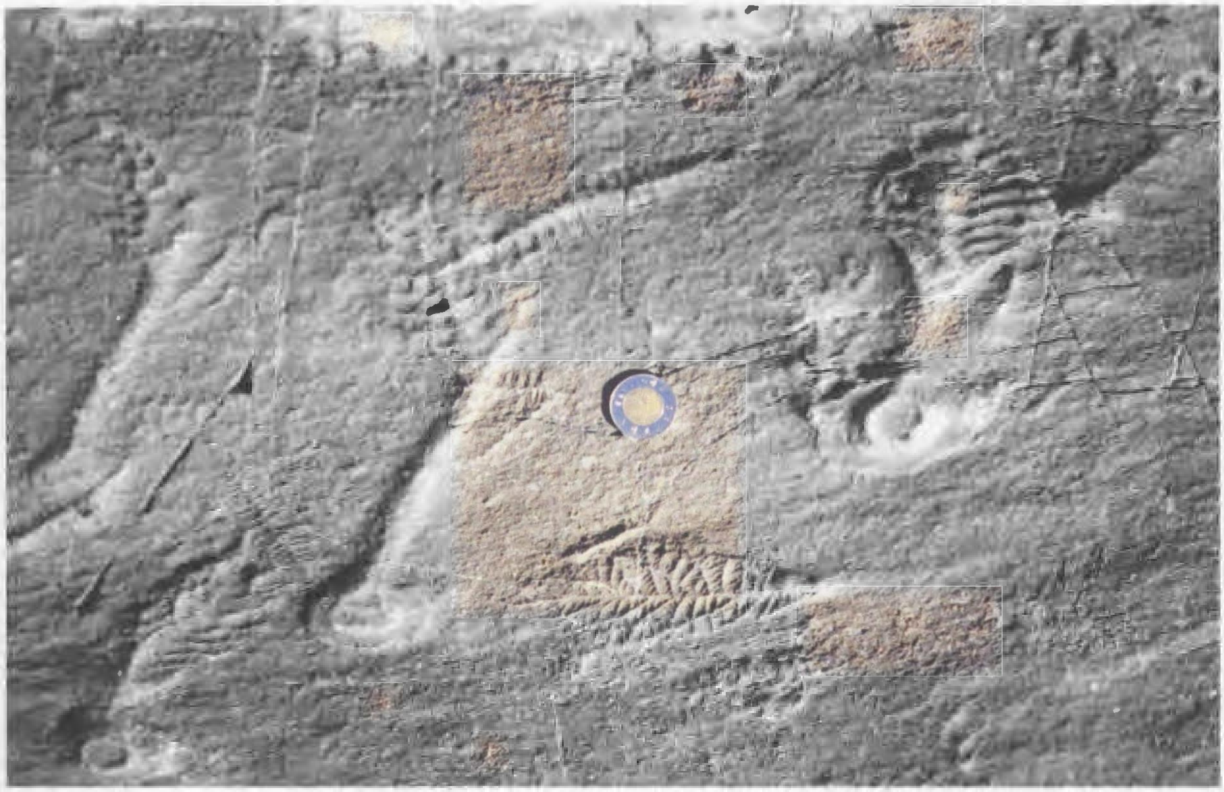


Figure 2.1. Ediacara- type body Fossils from the upper Mistaken Point Formation, Mistaken Point. Canadian Twonie for scale (28 mm diameter).

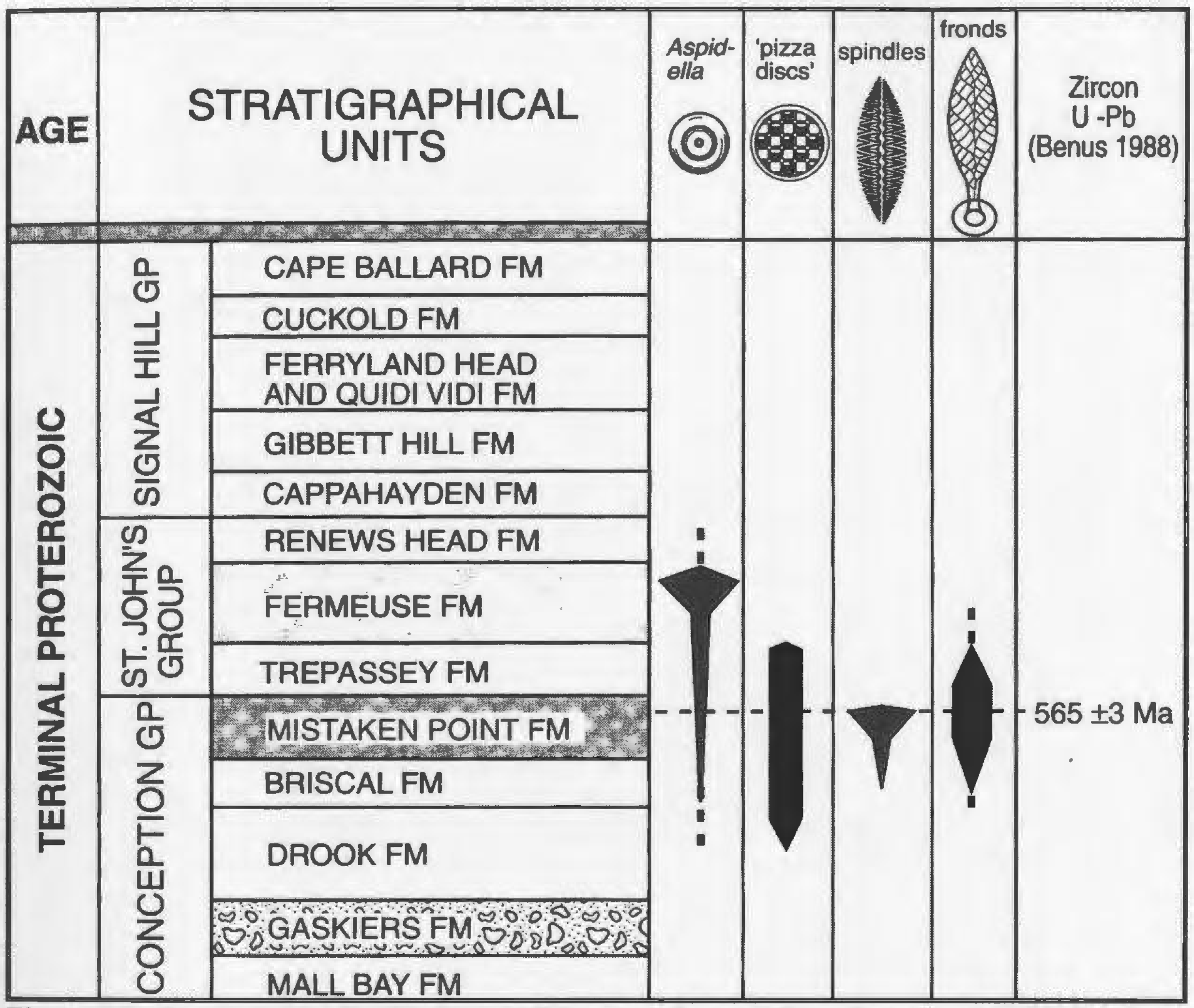
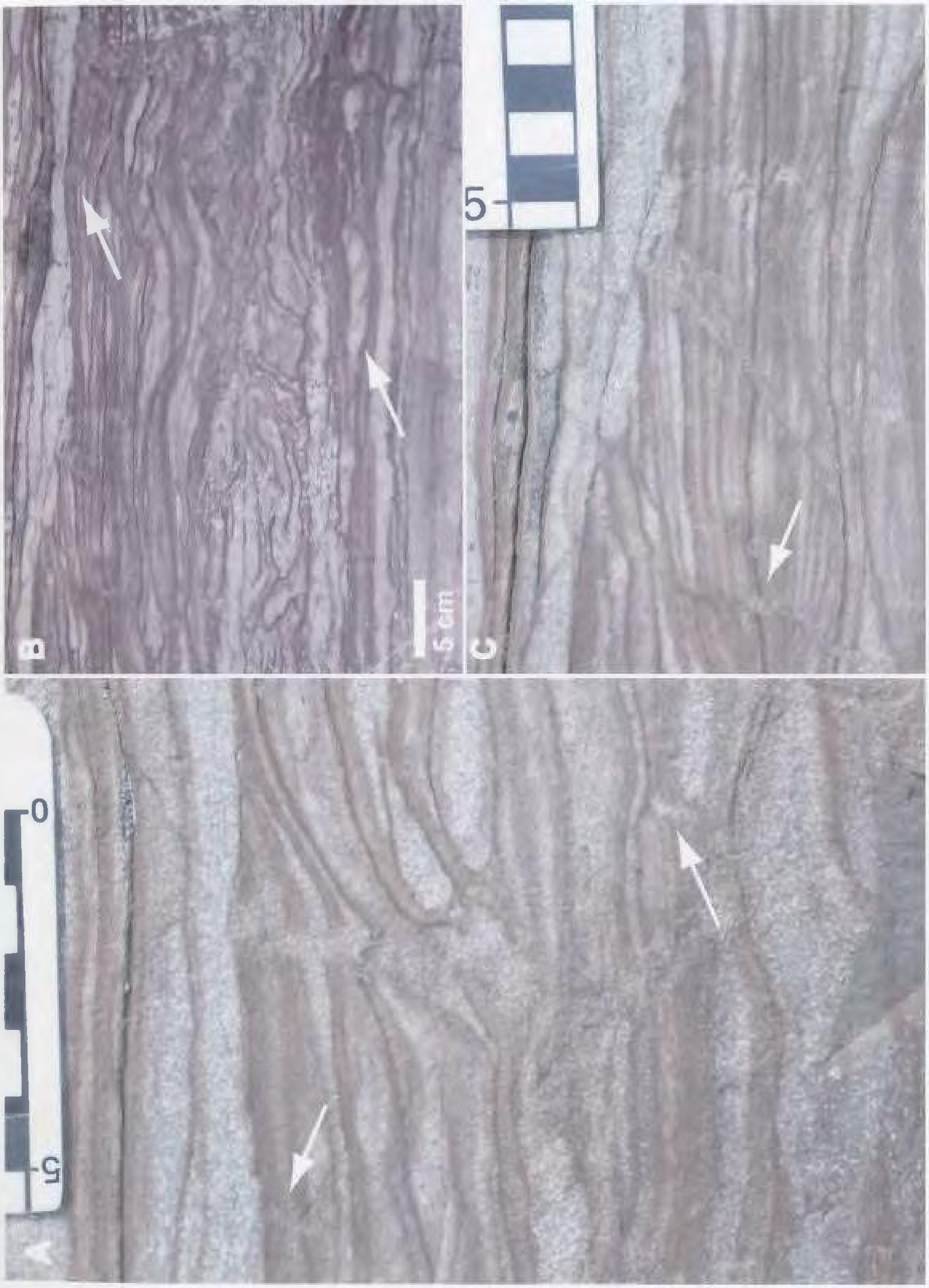


Figure 2.2. Stratigraphic distribution of Ediacaran fauna of Newfoundland and Labrador (Text figure 2, Gehling et al., 2000). Note the lack of fossils in the Signal Hill Group.

Figure 2.3. Abiogenic synsedimentary deformation structures of the Ferryland Head Formation resembling biogenic structures. **A:** Tension cracks in interlaminated sandstone and siltstone. The arrows point to burrow-like tension cracks (scale bar shows 1cm segments). **B:** shows interlaminated sandstone and siltstone with convoluted bedding in the centre. The top arrow indicates a circular burrow-like sand-filled structure. The arrow toward the bottom of the photograph shows a burrow-like structure with apparent backfill texture. **C:** shows a close up of photograph B with burrow-like tension cracks.


B
5 cm
C
5
A
0
5

Chapter 3

STRATIGRAPHIC SECTIONS

3.1. INTRODUCTION

The purpose of this Chapter is to describe the principal outcrop localities examined and place the sedimentary facies analyses that follow in stratigraphic context. All the Ferryland Head Formation exposures are located along the eastern coast of the Avalon Peninsula (Figure 1.1). The type locality at Ferryland, approximately 72 km south of St. John's, was the focus of this study. Excellent exposures are readily accessed via an unpaved road from the town of Ferryland leading to the Ferryland lighthouse on Ferryland Head. Ferryland Head has a rocky coastline that comprises locally steep cliffs (Figure 3.1.) Beds average a strike of 000° and a dip of 75°–80° to the East throughout the study area. Regional and local palaeocurrents are dominantly southerly-directed and therefore the outcrops provide stratigraphic dip sectional view.

Approximately 540 m of the basal High Rocks Member of the Ferryland Head Formation are exposed in the study area above the first appearance of red-coloured beds which occur near a small sinkhole halfway between Burns Head and Burns Head Point (Williams and King, 1979; Figure 3.2). Three detailed stratigraphic sections were drawn on a bed by bed basis totalling 677 m and covering all of the exposed succession; the Flat Point Section, Ferryland Head section and Lighthouse Section.

3.2. FLAT PIONT SECTION

A basal stratigraphic section was described that commences near Burns Head Point and ends at Flat Point covering a total of 201.13 m (Figure 3.2). Although the first appearance of red sandstones marks the lower boundary of the Ferryland Head Formation (Williams and King, 1979), this lower boundary is not a sharp contact. Intercalation of Ferryland Head Formation facies and facies characteristic of the underlying Gibbet Hill Formation occurs within the lower 40 m of the formation. The first few metres of red siltstones are overlain by greenish grey sandstones indistinguishable from the underlying Gibbet Hill formation. The Flat Point section comprises predominantly tabular, upward fining sandstone bodies interbedded with siltstone. There are a few examples of sandstone beds with lenticular geometries most notably at 86 m and 100 m. There are two upward coarsening predominantly sandy strata at about 50 m and 105 m, 2 and 5 m thick respectively. A composite of the Flat Point section is shown in Figure 3.4. A detailed version of this section can be viewed in Appendix 1.

3.3. FERRYLAND HEAD SECTION

The base of the Ferryland Head section is located at the northern side of the unnamed cove and extends continuously to the tip of Ferryland Head (Figure 3.1). This section covers approximately 157 m of unbroken succession. There are approximately 20 m of overlap between the upper Flat Point section and the base of the Ferryland Head section. The section is predominantly sandy toward the top, although no upward coarsening trend is obvious. Bedding is mostly tabular with a few examples of lenticular bed geometries most notably at 20, 40, 73, 84, 115 and 127 m. Thick sandy units less than 10 m each punctuate the section but are most common in the upper parts of the section more than116 m above the base. The section ends by the cliff adjacent to Bread and Cheese Cove (Figure 3.2).

3.4. LIGHTHOUSE SECTION

The base of the Lighthouse Section begins approximately 100 m south of the Ferryland Head section on the southern side of the unnamed cove and continues unbroken towards the Hare's Ears in the east, for a total of just over 319 m (Figure 3.2). There are about 20 m of stratigraphic overlap between the lower portions of the Lighthouse Section and the upper parts of the Flat Point Section .The section could not be continuously described in detail and approximately 45 m are missing due to the inaccessibility of cliff face outcrops. The missing succession however, has equivalents in the upper parts of the Ferryland Head section. The sand body geometry of the Lighthouse section is similar to that of the Ferryland Head with good examples of large scale sandstone lenses with up to two metres of basal erosive relief at 15 m, 33 m, 179 m, 190 m and 205 m.

Finer grained beds in the High Rocks Member of the Ferryland Head Formation are thickest in the upper part of the Lighthouse Section with an approximately 30 m thick example between 211 and 240 m. Thick and relatively coarse-grained units punctuate the section similarly to the Ferryland Head Section.

Figure 3.1. View looking north ,of the northeastern tip of Ferryland Head showing the unnamed cove in the foreground. The point in the background is Cape Broyle Head (Photograph courtesy of Andrew J. Pulham)

Figure 3.2. Aerial photograph of Ferryland Head showing the locations of the drafted stratigraphic sections. The Ferryland Head section is marked by a red line, the Lighthouse section is shown by a yellow line and the Flat Point section location is shown by a blue line. The basal contact of the Ferryland Head Formation is indicated by the red arrow.

Figure 3.3. Flat Point stratigraphic section. See Appendix 1 for the legend. Vertical scale shown in metres. The photograph indicated in the section can be seen in Appendix 2.

Flat Point Section, lower Ferryland Head Fm

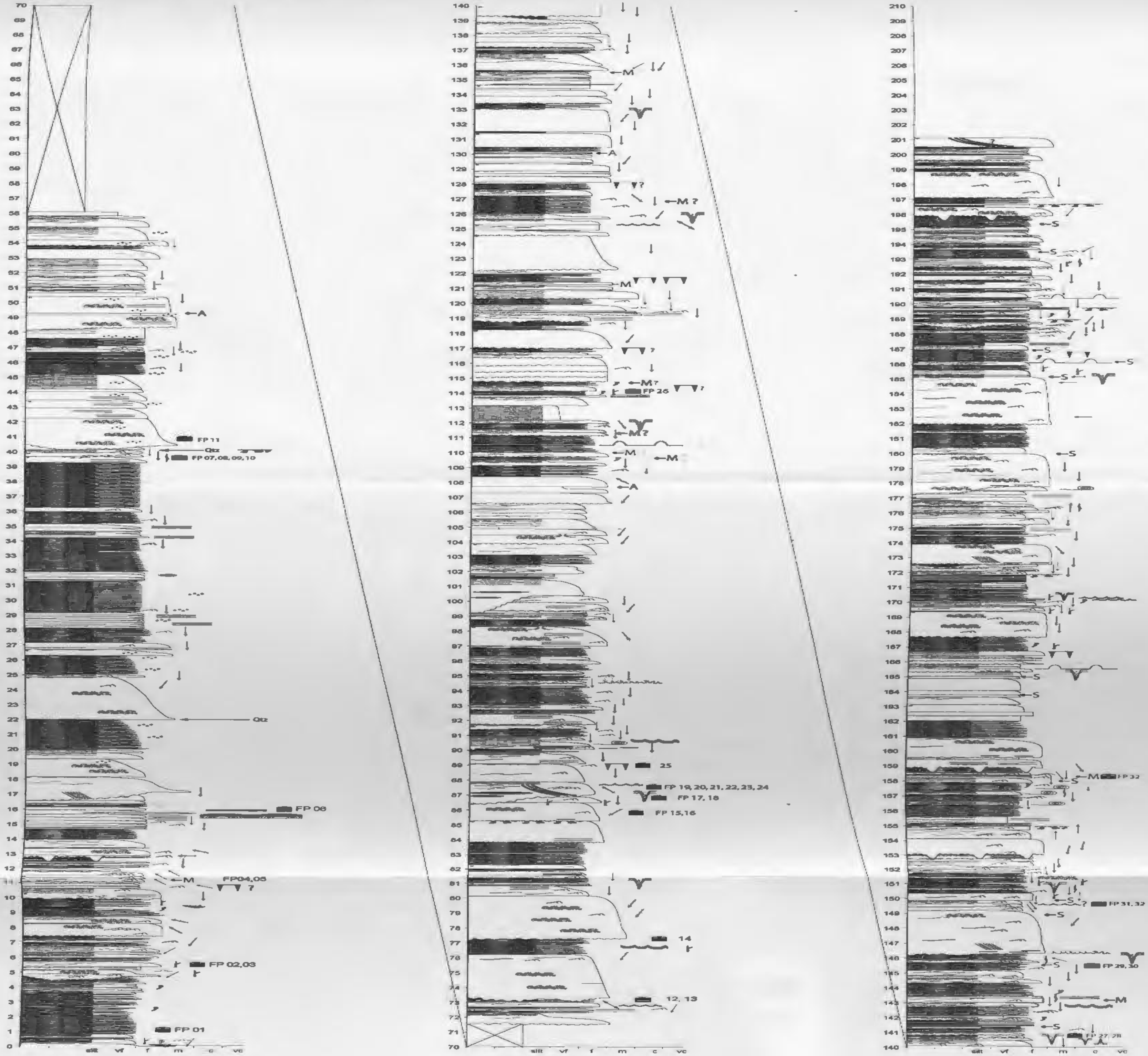


Figure 3.4. Ferryland Head section. Vertical scale shown in metres. The photograph indicated in the section can be seen in Appendix 2.

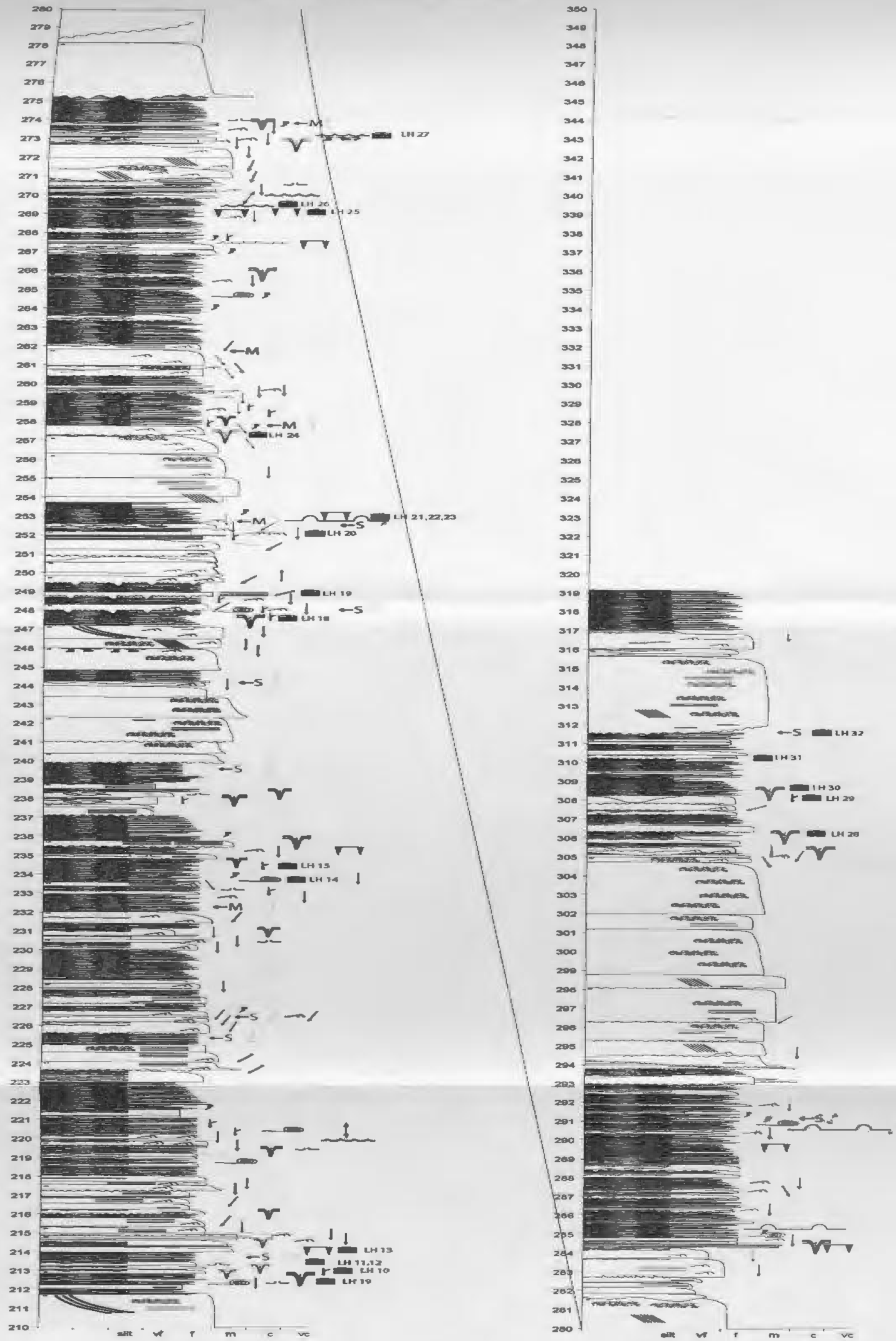
Ferryland Head section, Ferryland Head Fm

Figure 3.5. Lighthouse stratigraphic section. Vertical scale shown in metres. The photograph indicated in the section can be seen in Appendix 2.

Lower Lighthouse Section, Ferryland Head Fm

Figure 3.6. Ferryland Head section. Vertical scale shown in metres. The photograph indicated in the section can be seen in Appendix 2.

Upper Lighthouse Section, Ferryland Head Fm



Chapter 4

SEDIMENTARY FACIES ANALYSIS AND DEPOSITIONAL SUBENVIRONMENTS

4.1. INTRODUCTION

The aims of this chapter are to describe and interpret the sedimentary facies and the key depositional subenvironments of the Ferryland Head Formation at its type locality. Before describing the sedimentary facies, a brief summary of the sandstone petrography is provided.

4.2. PETROGRAPHY

A petrographic study of the Signal Hill Group was carried out by Singh (1969). The study focused on the Signal Hill and Blackhead Formations which were later renamed by Williams and King (1979) (see section 1.2.2. in Chapter 1). The Ferryland Head Formation corresponds to the distal facies of most of Singh's Middle Member of the Signal Hill Formation. The sandstone in the High Rocks Member of the Ferryland Head Formation can generally be classified as lithofeldspathic arenite with minor occurrences of lithic arenite, feldspatholithic arenite and lithic arenite. The petrographic data are summarized in Figure 4.1.

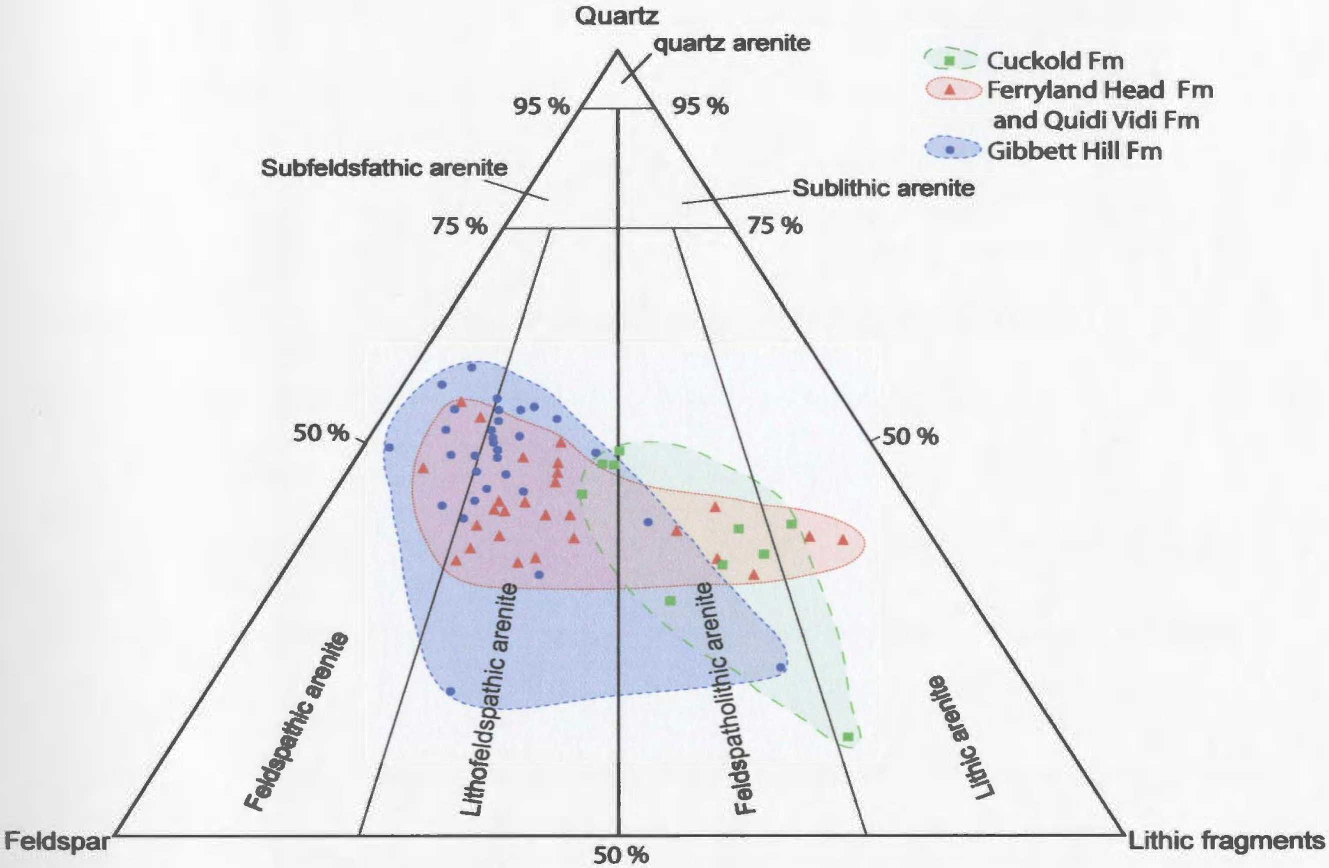


Figure 4.1. Ternary diagramme showing the different sandstone types in the Cuckold, Ferryland Head and Gibbet Hill formations. Shaded outlined areas show the field in which the data fall (modified from Singh, 1969).

Quartz forms 30.4% of the total rock, potassium feldspar grains account for 8.2 %, plagioclase for 20.6%, rock fragments 18.1% and interstitial material 22.7% (Singh, 1969). The most abundant rock fragments are sedimentary and include sandstone, siltstone, argillite and siliceous rock fragments. Volcanic, igneous intrusive and metamorphic rock fragments are all present in lesser amounts. Pure ash or tuff beds are not known from the Ferryland Head Formation but are common in the older stratigraphy of the Avalon Peninsula (Williams and King, 1979; Narbonne et al., 2000).

Mean grain size in the Ferryland Head area was found to be approximately 3ϕ (Singh, 1969) or fine to very fine sand. There is a progressive increase in average sphericity towards the south from 0.59 in Flat Rock to 0.65 in Petty Harbour. Roundness also increases towards the south with average roundness of 0.59 in Flat Rock to 0.62 in Petty Harbour. The arenites were found to be well sorted in the Ferryland Head area (Singh, 1969).

4.3. SEDIMENTARY FACIES ANALYSIS

4.3.1. Facies Classification

The lower Ferryland Head Formation consists of interbedded tabular reddish to purplish brown siltstones, and buff to greenish grey sandstones. There is a strong correlation between colour and grain size in the High Rocks Member. The fine grained rocks tend to have a higher iron content and a red to purplish-red colour. Sandstones are tan to greenish grey and contain little or no haematite. Five lithofacies comprising collectively 22 sedimentary subfacies have been defined for the Ferryland Head

Formation at Ferryland (Table 4.1). Facies 1 comprises siltstone and the finer grained sandstones. Facies 2 encompasses silty sandstone. Facies type 3 is matrix-poor sandstone. Facies 4 and 5 comprise intraformational conglomerates and ash-rich beds, respectively. Lithofacies are designated according to overall lithology, whereas subfacies are defined by the presence or absence of particular sedimentary structures. Lithofacies and subfacies are described and interpreted in terms of primary depositional processes in the following sections.

4.3.2. Facies 1: Heterolithic Facies

4.3.2.1 Description

Eleven subfacies are recognized in the fine-grained heterolithic rocks of the Ferryland Head Formation. These are all characterized by a high silt content and an overall reddish colouration. Ridges and furrows (Plate 1) are common on siltstone-draped, sandstone bedding surfaces of all the heterolithic subfacies except 1A. These structures may cover extensive surfaces, sometimes greater than 5 m^2. The structures are long, straight to gently curved, subparallel and bifurcate upcurrent (converge in the direction of palaeoflow). The ridges and furrows have a separation of less than 2 mm. They occur in association with "bumpy" surfaces (Plate 1) characterized by mounds less than 5 cm in height and 10 cm in diameter, surrounded by hollows of similar dimensions. The ridges and furrows radiate outward within the hollows and curve around raised features. The ridges and furrows have a relief of up to 2 mm on sandstone surfaces.

Table 4.1. A summary of the facies identified in the High Rocks Member of the Ferryland Head Formation.

Facies	Sub-facies code	Description	Interpretation
Facies 1	1A	Massive reddish to purplish brown siltstone with minor sandstone	Low energy pool/abandoned channel
	1B	Wavy, interlaminated, buff-coloured sandstone and reddish-brown siltstone laminae	Episodic fluctuating low energy flow/ interdistributary deposition
	1C	Horizontally interlaminated buff-coloured sandstone and reddish to purplish brown siltstone laminae	Episodic fluctuating low energy flow/ interdistributary deposition/possible tidal influence
	1D	Buff-coloured lenticular sandstone in reddish to purplish brown siltstone	Fluctuating low energy flow/possible tidal influence
	1E	Interbedded to laminated sandstone and siltstone with abundant collapse structures, dewatering pipes synaeresis and sandstone dykes	Episodic fluctuating flow/ interdistributary deposition Instability due to proximity to channel or in delta front setting or earthquake -induced
	1F	Siltstone laminae/beds with complete polygonal shrinkage cracks defined by buff-coloured sandstone	Subaerial exposure/shallow delta plain
	1G	Interbedded sandstone beds and siltstone laminae	Episodic fluctuating flow/ interdistributary deposition
	1H	Ripple-laminated load casts	High sedimentation rates
	1I	Sandstone load casts in siltstone	High sedimentation rate

	1J	Wave-rippled silty sandstone draped in siltstone	Shallow delta plain/front
	1K	Convoluted sandstone and siltstone laminae (convolute bedding)	High sedimentation rates
Facies 2	2A	Buff to reddish–buff-coloured, very fine upper to fine upper, silty sand	Fluctuating waning flow/crevasse splay/distal flood stage sheet flow
	2B	Current-rippled to planar-laminated silty sandstone	Unidirectional flow/crevasse splay/ distal flood stage sheet flow
	2C	Silty sandstone with climbing-ripples	
	2D	Structureless silty sandstone	
Facies 3	3A	Crossbedded matrix-poor sandstone	Migrating dune /channel
	3B	Rippled sandstone	Unidirectional current/ channel
	3C	Planar-laminated sandstone	Upper flow regime unidirectional current/channel
	3D	Climbing rippled sandstone	Unidirectional current/channel/ flood stage deposition
	3E	Massive sandstone	various
	3F	Convoluted sandstone	Rapidly deposited sand/ flood stage deposition/ possibly earthquake-induced deformation
	3G	Wave-rippled sandstone	Wave reworking in shallow marine environment
Facies 4		Intraformational conglomerate	High energy flow /channel lag
Facies 5		Ashy sandstone	Fallout ash/reworked ash

Subfacies 1A consists of generally structureless, reddish to purplish-brown siltstone with minor sand (Plate 2A). Sand content never exceeds 5%. This subfacies occurs generally at the top of upward-fining beds or as discrete beds less than 20 cm thick and mostly just a few centimetres thick. Discrete lenses of this facies are common. The lenses have concave-upward bases and are flat-topped, They can be up to 3 m in length but never exceed 20 cm in thickness.

Subfacies 1B consists of wavy, interlaminated, buff-coloured sandstone and reddish-brown siltstone laminae (Plate 2, B and C). The silt content in this subfacies is approximately 75–85%. Individual wavy sandstone laminae vary in thickness along strike by a few millimetres. Where the sandstone laminae swell, current-ripple cross-lamination can often be seen. The sandstone laminae vary in overall thickness from 1mm to 1 cm and are draped by 1–3 mm-thick siltstone laminae. The siltstone laminae maintain a constant thickness laterally. The sand grain size ranges from very fine lower (4.0–3.5ϕ) to fine upper (2.5–2.0ϕ). The thickness of the sandstone laminae tends to decrease upward in most examples of this subfacies. Palaeoflow does not vary greatly within single occurrences of this facies.

Subfacies 1C consists of horizontally interlaminated buff-coloured sandstone and reddish- to purplish-brown siltstone laminae (Plate 3, A and B). Subfacies 1B and 1C differ only in that 1B contains laminae that are of constant thickness and are straight and parallel. There is a repetitive occurrence of thick sandstone laminae, draped by thin siltstone laminae overlain by thin sandstone laminae, in turn, draped in thin siltstone laminae (Plate 3A).

Subfacies 1D consists of buff-coloured lenses of sandstone in reddish to purplish brown siltstone (Plate 3, C and D). Siltstone comprises up to 75% of this facies, the rest being sandstone. The sand grain size varies from very fine upper (3.5ϕ) to fine upper (2.0ϕ). Lenses are 1–3 cm thick and 5–10 cm long. This subfacies occurs both as discrete horizons and in successions of up 70 cm thick. Current-ripple cross-lamination is commonly observed within the sandstone lenses.

Subfacies 1E comprises interbedded to interlaminated sandstone and siltstone with abundant collapse structures (Plate 4A, B, C and D), dewatering pipes (Plate 4E), sandstone dykes and sills (Plate 4F), and synaeresis cracks. The siltstone content in this subfacies is approximately 75–85%. The collapse structures range in diameter from 5 cm to 50 cm and vary from 5 cm to 60 cm in depth. They are funnel-shaped with curved sides. The interbedded sandstone and siltstone laminae curve downward into the upper part of the structure in the upper portions. In the lower two-thirds of each structure, siltstone laminae terminate against structureless sandstone. Broken-up and disorganised siltstone laminae are present at the base of the structure. Dewatering pipes are less than 3 cm wide and less than 20 cm high. They are vertical to subvertical to bedding, have sharp edges and are filled with structureless sandstone. Sandstone dykes vary greatly in length but never exceed 3 cm in width. They are also perpendicular to subperpendicular to bedding. Branching is common. Dykes can be distinguished from dewatering pipes by their connection to thinned sandstone laminae and beds. Tensional cracks do not connect to sandstone beds or laminae.

Subfacies 1F is composed of siltstone laminae and thin beds with complete polygonal shrinkage cracks filled with buff-coloured sandstone (Plate 5). The polygons, in plan view, generally have a longer axis oriented north-south and are shortened in the east–west direction. The long axis varies in length from 10–20 cm and the short axis from 5 to 8 cm. The maximum width of the cracks does not vary greatly and is of 0.5–1.5 cm. All cracks taper downward stratigraphically and are most commonly perpendicular to bedding. When subperpendicular to bedding, the cracks share a common orientation with angles ranging from 90° to 60° to bedding. The depth of the cracks in cross-section varies from 1–3 cm.

Subfacies 1G consists of alternating sandstone beds and siltstone laminae (Plate 6A). This subfacies differs from subfacies 1A and 1C only in the proportions of sandstone and siltstone. The latter two contain more than 70% siltstone whereas facies 1G is predominantly sandy, with less than 70% siltstone.

Subfacies 1H consists of rippled sandstone forming load casts into siltstone (Plate 6 B, C and D) similar to structures described by Dżulyński and Kotlarczyk (1962). The sandstone ranges in grain size from fine lower (3.0–2.5ϕ) to medium lower (2.0–1.5ϕ). Sandstone content in this facies is approximately 75%. Current-ripple cross-lamination is preserved within the load casts. The load casts average 4.5 cm in width. Load casts which exceed 10 cm in depth tend to be highly sinuous.

Subfacies 1I consists of sandstone loaded into siltstone (Plate 7). Load casts vary in cross-section from 10–20 cm long, 4–5.5 cm wide sinuous loads to pillows that are 10–

40 cm wide and 10–30 cm deep. Sandstone content is highly variable in this facies, ranging from 30% to50%. Pseudonodules are uncommon.

Subfacies 1J comprises wave-rippled silty sandstone (Plate 8 and Plate 9A, 9B and 9C). Grain size in this facies varies from very fine upper to fine upper sand. Ripple wavelengths are from 4–6 cm; amplitudes are from 0.5–1 cm. The wave-rippled sandstone horizons are continuous and 2–10 cm thick and are often draped in thin (1–2 mm) siltstone laminae. The crests of the wave ripples are oriented predominantly northwest–southeast and north–south.

Subfacies 1K consists of convoluted sandstone and siltstone laminae (convolute bedding). The deformation is confined to individual beds. Bed thickness varies from 10–40 cm. The beds consist of interlaminated very fine to fine sandstone and siltstone. The convolutions are characterised by broad synclines up to 20 cm wide and closed anticlines. The axial planes of the folds are normal to subnormal to bedding. Recumbent folds are not present. The deformation is mainly plastic with rare evidence of brittle deformation (Plate 9D). Sandstone content in this facies averages 20%, the remainder being siltstone.

4.3.2.2. Interpretation of Facies 1

The relationship between fine-grained facies and red colouration (haematite content) in the High Rocks Member of the Ferryland Head Formation is similar to that found by McBride (1974) in the Difunta Group of northeastern Mexico. This relationship is believed to be a result of the attachment of poorly crystalline or amorphous iron oxides to clays; the oxides are later altered to haematite (McPherson, 1980). Tomlinson (1916), however, found that the Fe^{3+}/Fe^{2+} (ferric/ferrous) ratio controls the development of colour, not the total iron percentage. The fact that diagenesis can affect the sediment at an early stage means that the environment of deposition cannot be correctly inferred from colour alone (Miall, 1999). The decrease of greenish to greyish beds in the increase of red-coloured sediment upwards through the Ferryland Head Formation suggests an increase in oxygen in the formation waters through time and not necessarily a change in surface-water oxygenation or exposure to the atmosphere.

The fine-grained nature of the sediment in subfacies 1A requires deposition in a low energy environment. The occurrence of this facies at the top of fining-upward beds is interpreted to indicate the deposition of sediment from waning flows at the terminal stages of floods. Lenticular occurrences of this facies formed as pools were filled in with silts and clays. These pools could be troughs of large bed-forms or scours on bedding surfaces.

The interbedded sandstone and siltstone of subfacies 1B suggests energy fluctuations in the environment of deposition. The wavy-bedding style as well as current-ripple cross-lamination indicate deposition in the lower flow regime, fluctuating with quieter periods. Ridges and furrows have been described by several authors as longitudinal scours (longitudinal ridges and furrows) resulting from unidirectional currents eroding a somewhat cohesive substrate (Collinson and Thompson, 1982; Allen, 1982b). Dżulyński and Walton (1965) describe similar structures from Oligocene flysch deposits in Poland as dendritic ridge moulds. Identical structures were described by Glaessner and Walter (1975) from Australia and interpreted to be of organic origin. They recognized a new fossil, *Arumberia banksi* which they "interpreted as the remains of cup-shaped animals, probably of coelenterate grade." Bland and Anderson (1982) described examples of *Arumberia* from Ferryland (Anderson, M. M., pers. comm., 2003). The biological origin of *Arumberia* was reconsidered by McIlroy and Walter (1997). They proposed that the structures were formed by currents impinging in microbially-bound sediment.

Subfacies 1C is interpreted to have been deposited in lower flow regime conditions. Lower plane beds, rather than ripples, suggested by the flat and parallel laminae, are present in this facies. A tidal influence can be iferred from packages of alternating thick and coarse, thin and fine, thin and coarse, followed by thin and fine (Nio and Yang, 1991). The siltstone laminae are deposited during slack water and thin sandstone laminae are deposited during rising or falling tide. The differential thickness in the sandstone laminae is explained by thicker laminae deposited during the dominant tide and thin sandstone laminae during the subordinate tide.

The contrasting lithologies in Subfacies 1D suggest significant fluctuations in the flow. Current-induced bedload transport and sandstone deposition alternates with slack-water deposition of mud from suspension-forming flaser, wavy and lenticular bedding (Reineck and Singh, 1980). These bedding styles, although most common in tidal settings, are also known from fluvial, lacustrine and marine delta-front environments.

Subfacies 1E is lithologically identical to subfacies 1B and 1C and therefore is interpreted to have been deposited subaqueously by relatively slow, fluctuating currents. The abundance of soft-sediment deformation structures in this subfacies indicates a very unstable substrate due to extremely rapid deposition, wave pounding, current shearing, or sudden shock from channel bank collapse or seismic tremors.

The polygonal shrinkage cracks of subfacies 1F are interpreted as desiccation cracks. Periods of subaerial exposure might be due to tidal influence or intermittent fluvial flooding.

Subfacies 1G is interpreted to have been deposited under similar conditions to subfacies 1B and 1C, but the sandier lithology suggests a higher flow velocity. The higher sandstone : siltstone ratio suggests a more proximal location to the sand source (channel axis) than subfacies 1B and 1C. The presence of current-ripples suggests velocities of approximately 40 m/s (Allen, 1982a).

The loaded ripples in subfacies 1H suggest very high sedimentation rates. The sand-bed began to sink into the underlying sediment where it was thickest (i.e., at ripple crests). The sinking of the ripple created further accommodation space which was subsequently filled by more sand, and so on. The ripple laminae are often preserved in spite of the pervasive deformation.

Subfacies 1I load structures suggest rapid deposition and partial liquefaction of sand at the time of deposition. Wave ripples suggest that wave pounding might have triggered the loading.

The wave ripples in subfacies 1J indicate oscillatory motion. Micro-wave-ripples suggest wind-generated waves in shallow pools on a delta plain. The northwest–southeast and north–south orientation of the crests is interpreted as being perpendicular to the coast due to offshore or onshore winds. The palaeoshoreline was therefore oriented southwest–northeast to east–west.

The convoluted lamination of subfacies 1K indicates unstable sediment due to rapid deposition. Convolution might have been induced by shearing by currents, or shock due to seismic activity, or wave pounding, or collapse of nearby distributary channel banks.

4.3.3. Facies 2: Silty Sandstone

4.3.3.1. Description

Subfacies 2A consists of buff to reddish-buff, very fine upper to fine upper, silty sandstone (Plate 10 A and B). Discontinuous siltstone laminae less than 2 mm thick and 20 cm long are common toward the top of most occurrences of this facies. The siltstone laminae are wavy, suggesting ripples; however, ripple cross-lamination is not visible.

Subfacies 2B consists of current-rippled to planar-laminated silty sandstone. Ripple trains are laterally extensive and can be followed for metres (Plate 10 D and E). The height of the ripples varies from 1–3 cm. The ripple cross-lamination is commonly defined by thin drapes of reddish-coloured silt.

Subfacies 2C consists of silty sandstone with climbing-ripples (Plate 10F and G). The angle of climb ranges from 10–20° but is constant within individual occurrences of the subfacies. The angle of climb is commonly steeper than the stoss-side slope and stoss-side laminae are therefore preserved (type B ripple-drift cross-lamination of Jopling and Walker, 1968).

Subfacies 2D consists of structureless, buff argillaceous sandstone with a reddish-brown tinge (Plate 10C). This facies can occur as a part of a bed or as individual beds less than 50 cm thick.

4.3.3.2. Interpretation of Facies 2

Current-ripples in very fine upper to fine upper sandstone suggest water velocities of 40–60 cm/s (Allen, 1982a). The upward fining of occurrences of subfacies 2A implies a waning unidirectional unchannelized flow. This subfacies therefore probably represents crevasse splay deposits, levee deposits or sheet flow-deposits.

Subfacies 2B contains better defined ripples and planar lamination than subfacies 2A. A slightly higher velocity of 50–100 cm/s (Allen, 1982a) is suggested for this subfacies. This subfacies most likely represents proximal crevasse splay deposits or flood-stage sheet-flows.

The climbing-ripples of subfacies 2C indicate rapid sedimentation rates probably associated with floods. The abundance of sediment and rapid deposition imply a rapid decrease in water velocity placing this subfacies near a channel margin.

Subfacies 2D is structureless or contains poorly defined structures. This results from a uniformity of grain size or loss of structures due to dewatering. This subfacies is interpreted to be the result of rapid deposition from waning flows.

4.3.4. Facies 3: Matrix-poor Sandstone

4.3.4.1. Description

Pyrite crystals up to 0.5 cm^3 are common in all the greenish-grey sandstones that comprise facies 3. The crystals are euhedral and range in size from 0.1–0.5 cm^3.

Subfacies 3A is composed of buff to greenish grey, cross-bedded sandstone (Plate 11). Grain size ranges from fine upper to coarse sand. Foreset dip angles range from 10°–25°. Greater angles only occur in association with dewatering and convolution. Cosets are less than 1 m thick and most commonly approximately 50 cm thick. Foresets are sometimes defined by tabular siltstone granules. Tabular cross-bedding is the most common type. Trough cross-bedding is rare.

Subfacies 3B consists of buff to greenish grey, current-rippled sandstone (Plate 12A). The grain size varies from fine upper sand to medium upper (1.5–1.0ϕ) sand. Ripples occur in trains that are laterally continuous for tens of centimetres to a few metres. Cross-lamination is not always well defined due to the well-sorted nature and uniform colour of the sandstone. Ripples are generally of uniform size with a height of 2–3 cm. At any given locality, ripple forset dips are unimodal.

Subfacies 3C consist of planar-laminated, buff to greenish-grey sandstone (Plate 12 B). Laminations are either clearly defined or are locally obscured by the uniformity of grain size. Parting lineations are common on exposed surfaces. The grain size varies from fine upper to medium upper sand.

Subfacies 3D is composed of climbing ripple-laminated buff to greenish grey sand. Grain size varies from upper fine to upper medium sand. The angle of climb ranges from 5–15°. The angle of climb is sometimes less than the angle of the stoss side slope in which case sets are separated by an erosional surface.

Subfacies 3E consists of buff to greenish grey, structureless sandstone. Grain size varies from fine upper to medium upper sand. This facies occurs most often at dm-scale within beds but can sometimes consists of beds up to 4 m thick.

Subfacies 3F consists of convoluted buff to greenish grey sandstone (Plate 12C). Grain size ranges from lower fine sand to upper medium sand. This subfacies occurs in units thicker than 30 cm. Convolution is shown by oversteepened and folded laminae.

Subfacies 3G comprises wave-rippled sandstone (Plate 12D). The wave-ripple amplitudes do not exceed 2 cm. Wavelengths average 4 cm. This subfacies is most common towards the tops of sandstone beds. Grain size ranges from very fine upper to fine upper.

4.3.4.2. Interpretation of Facies 3

The abundance of pyrite crystals in the greenish grey sandstones of the lower portion of the Flat Point section can be interpreted as an indication of anoxic conditions in the post depositional environment. The pyrite is not detrital and is interpreted as diagenetic.

The cross-bedding in subfacies 3A formed as the result of the migrating of two (tabular cross-bedding) or three dimensional (trough cross-bedding) dune bedforms. Deposition is interpreted to have taken place in a unidirectional current during lower flow regime probably during flood stage. Minimum water flow velocities are estimated to be 40–100 cm/s (Allen, 1982a).

Subfacies 3B is interpreted as having been deposited from a waning unidirectional flow as indicated by the current-ripple lamination.

The parallel-laminated sandstone of subfacies 3C is interpreted to represent deposition in the upper flow regime from episodic flows.

Subfacies 3D suggest high rates of deposition from suspension to explain the formation of climbing-ripples.

Subfacies 3E is interpreted to represent rapid depositional rates inhibiting tractional processes (Arnott and Hand, 1989). Dewatering might have contributed to the structureless nature of these deposits (Bhattacharya and Walker, 1991).

Rapidly deposited sand accounts for the soft sediment deformation and dewatering in subfacies 3F. The sand was not well compacted and unstable. The most likely trigger for the liquefaction and subsequent convolution is shearing beneath the flow which deposited the sediment.

Subfacies 3G is interpreted to represent sediment reworking by waves in a very shallow marine setting.

4.3.5. Facies 4: Intraformational Conglomerate

4.3.5.1. Description

Facies 4 comprises intraformational conglomerate (Plate 13). It is commonly found at the base of coarse beds overlying pronounced erosional surfaces. Clasts range in size from granules to pebbles, are angular to subangular, and tabular to oblate. Granule-sized clasts are subrounded and larger clasts tend to be more angular. All clasts are reddish-brown siltstone indistinguishable from the fine grained components of facies 1.

4.3.5.2. Interpretation of Facies 4

Facies 4 represents the highest flow velocities in the studied succession. The clasts are interpreted as lag material resulting from erosion during initiation of floods.

4.3.6. Ash-rich sandstone

4.3.6.1. Description

Facies 5 is composed of greenish to light grey ash-rich sandstone. Grain size varies from very fine upper to fine lower sand. A well-defined subvertical tectonic cleavage similar to that of ash and tuff beds in the Conception Group, characterises this facies. No primary sedimentary structures were observed.

4.3.6.2. Interpretation of Facies 5

Facies 5 is rare in the stratigraphy and most likely represents reworked ash beds related to ongoing, albeit diminishing, distal volcanism. A low preservation potential might also be responsible for the scarcity of ash. The older Conception Group represents deep-marine environments with higher preservation potential. By the time of deposition of the Ferryland Head Formation, the basin had become shallow and reworking would have been common.

4.4. FACIES ASSOCIATIONS

4.4.1. Facies Association Classification

Facies associations are defined as sets of co-occurring facies and subfacies which may show particular stratigraphic order. Three facies associations are recognised in the Ferryland Head stratigraphy (Table 4.2). Facies associations II and III are further subdivided into IIa, IIb, IIIa and IIIb.

4.4.2. Facies Association I

4.4.2.1. Description

Facies association I consists of an upward coarsening and/or thickening succession of 0.5–2 m thick beds of predominantly sandy facies (Figure 4.2). The thickness of occurrences of this facies association ranges from 1.37–10.43 m, averaging approximately 5 m. The median thickness is 5.13 m. This association is bounded at its base by a relatively horizontal, sharp erosional surface with relief varying from a few centimetres to 40 cm. Erosional surfaces also occur within examples of this association. Facies 4 commonly lies directly above the basal erosional surface, overlain by a combination of subfacies 3A, 3B, 3C, 3D and 3E. Facies 4 occurs also occurs at the bases of individual beds within the facies association. Convoluted horizons (subfacies 3F) are especially common in the upper portions of this association. Subfacies 2A or 2D are sometimes present at the very top of this association. Facies association I makes up approximately 16 % of the Ferryland Head Formation at Ferryland and occurs with more

Table 4.2. Summary of the facies association identified in the High Rocks Member of the Ferryland Head Formation.

Facies Association	Description	Thickness (m)	Facies present	Interpretation
I	Coarsening-and/or-thickening-upward	~1–10	4,3A,3B,3C,3D,3E,3F	Prograding mouth-bar
IIa	Thinning-and/or -fining-upward sandstone over erosional surface	~0.5–2	4, 3A, 3B, 3C, 3D,3E, 3F, 2A,2B	Coarse-grained distributary channel
IIb	Thinning-and/or-fining-upward silty sandstone and siltstone over erosional surface	1.6–2.5	4,3A,3B,3C,3D,3E,3F, 2A,2B,±1A,1B,1C,1E,1G	Fine-grained distributary channel
IIIa	thin tabular sandstone beds	0.2–3	2A,2B,2C,2D,±1B,1C,1E,1G	Crevasse splay/sheet flow
IIIb	Fine grained Heterolithic sediments	0.1–5	1A,1B,1C,1D,1E,1F,1G,1H,1I,1J, 2A, 2B, 2C, 2D	Interdistributary deposits

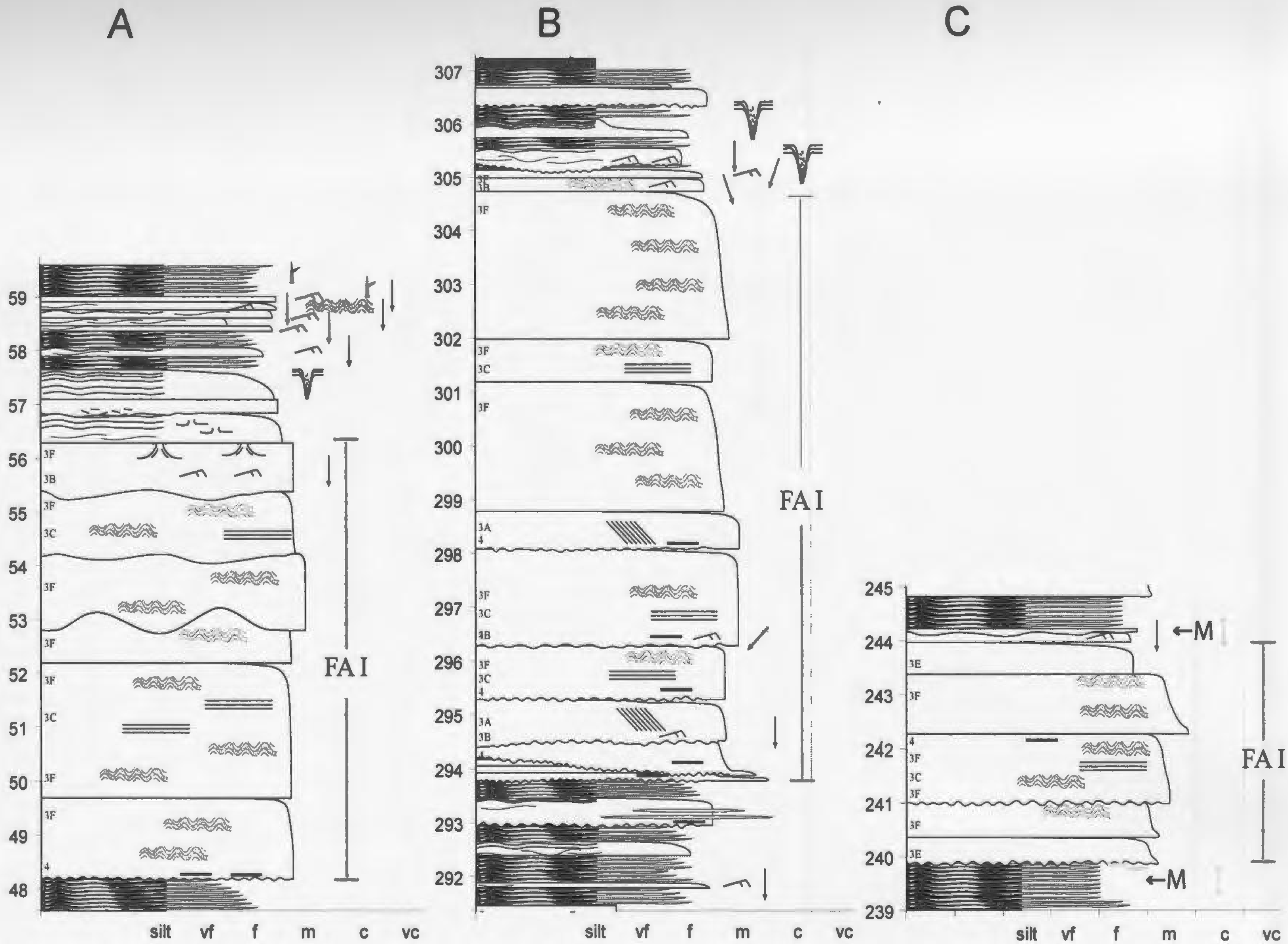


Figure 4.2. Examples of facies association I from the Ferryland Head section (A) and the upper Lighthouse section (B and C).

frequency towards the top of the succession (Figure 4.3). Palaeoflow within this facies association is unimodal and predominantly towards the south-southwest (Figure 4.4A), with minor north, southwest and southeast-directed palaeoflow.

4.4.2.2. Interpretation of Facies Association I

The upward-coarsening character of facies association I is interpreted to result from progradation of a distributary mouth-bar complex (Bhattacharya and Walker, 1992; Boggs 1995; Elliot, 1974). The abundance of relatively thin examples of this association suggests short-lived, broad, shallow distributary channels characteristic of braided river systems. Another possibility is that the body of water that the delta was prograding into was shallow (Røe, 1995). Thicker examples of this facies association most likely were fed by the main channel system which remained active for several consecutive seasons.

4.4.3. Facies association II

4.4.3.1. Description

Facies association II is characterized by an upward fining and thinning succession of normally-graded beds bounded at the base by a concave erosional surface. This facies association consists of a continuum from which the two end members are described. Facies association II constitutes approximately 23 % of the High Rocks Member of the Ferryland Head Formation. The two end members are facies associations IIa and IIb and are described below.

Facies association IIa encompasses a thinning and/or fining upward succession of beds belonging to facies 2 and 3 (Plate 14A, 14B and Figure 4.5). This association is

Figure 4.3. Complete stratigraphic sections of the Ferryland Head Formation showing the facies associations. Section A, B, and C are the Ferryland Head, Lighthouse and Flat Point sections respectively. Note the scarcity of facies association I in the lower part of the Ferryland Head Formation (Flat Point section) and its abundance in the upper two-thirds of the formation and the abundance of facies III in the lower part of the formation. Dashed red lines are shown to correlate between the sections.

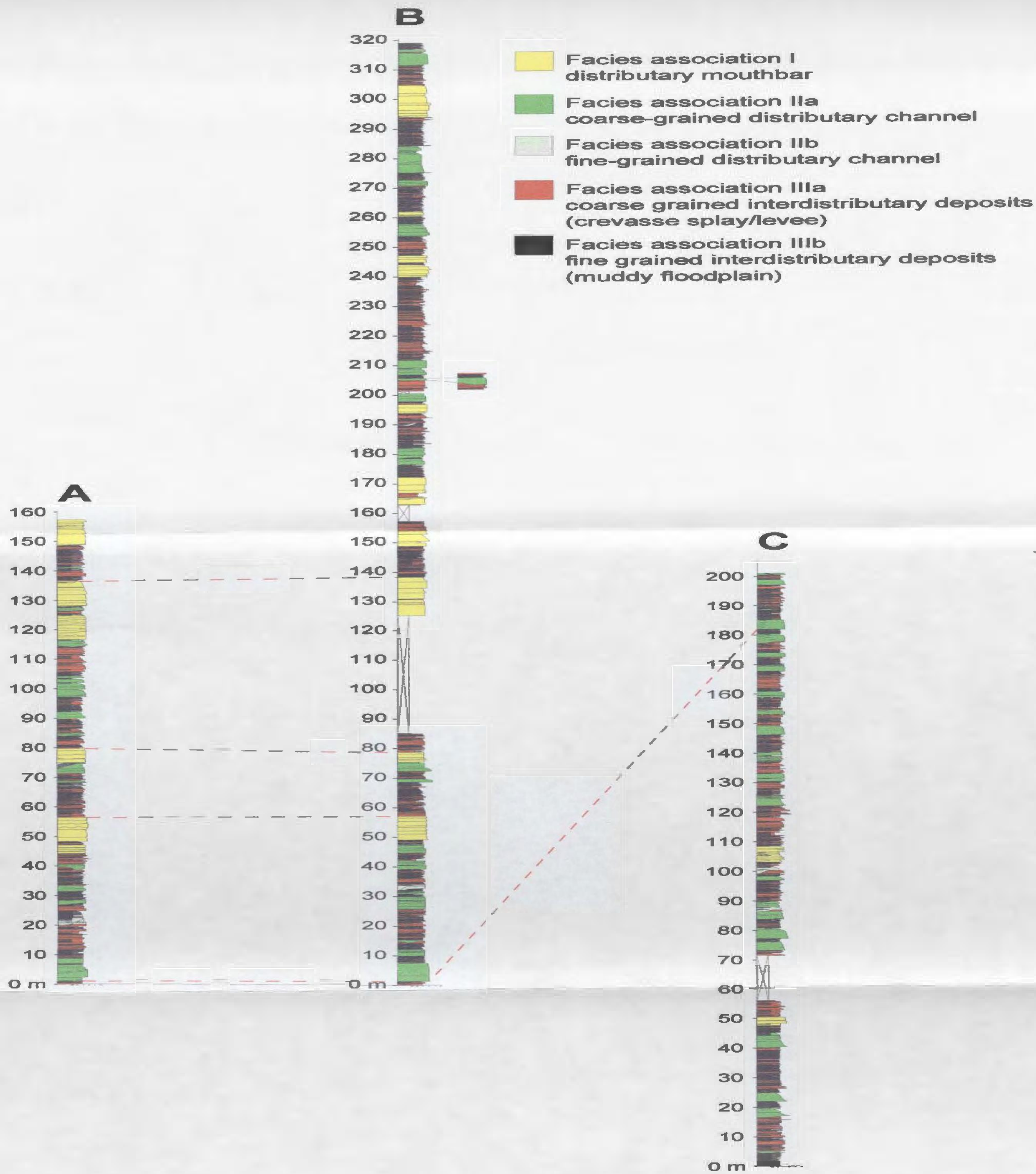
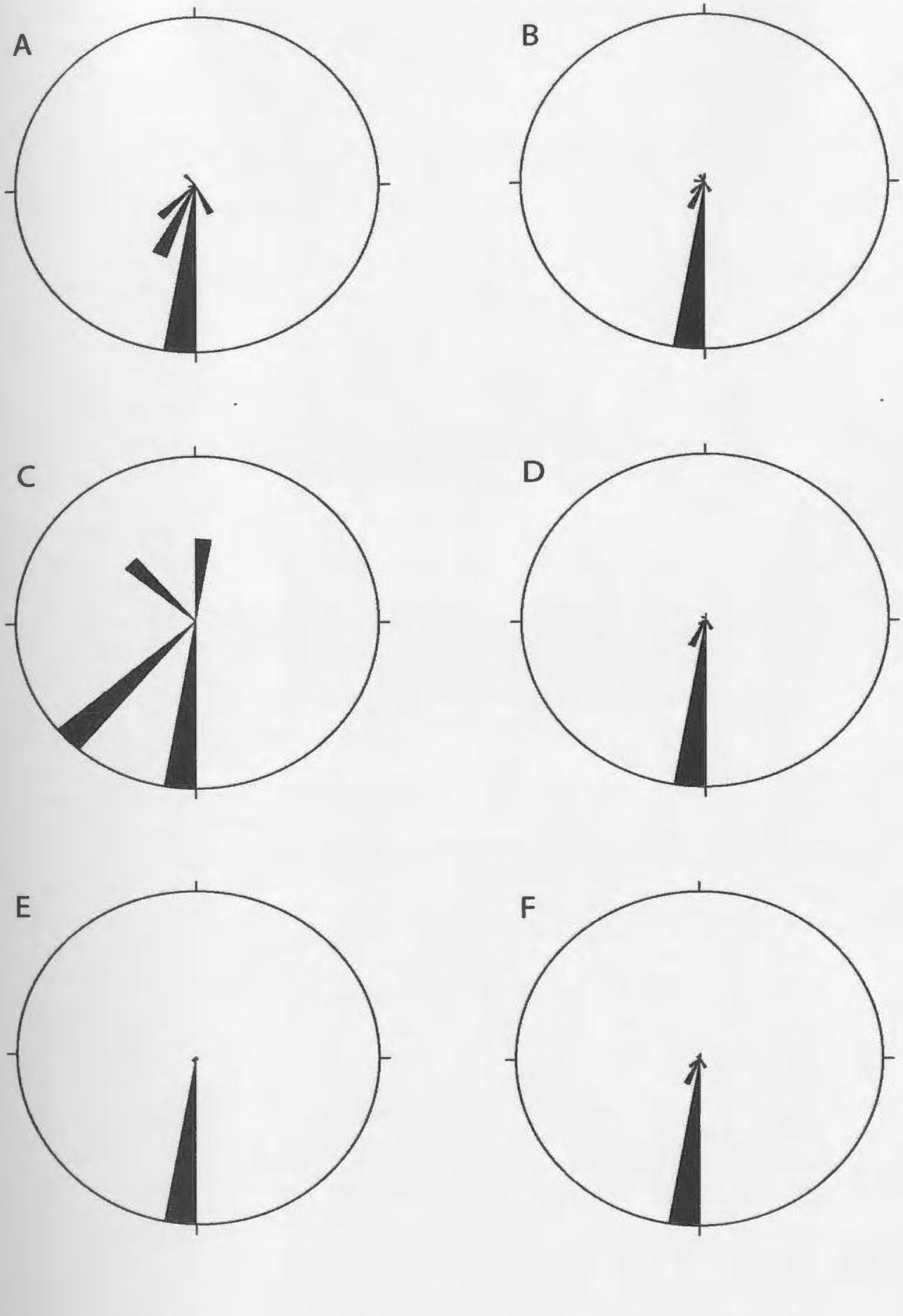

A
B
C
0 m
Facies association I
distributary mouthbar
Facies association IIa
coarse-grained distributary channel
Facies association IIb
fine-grained distributary channel
Facies association IIIa
coarse grained interdistributary deposits
(crevasse splay/levee)
Facies association IIIb
fine grained interdistributary deposits
(muddy floodplain)

Figure 4.4. Palaeoflow data plotted as rose diagrammes. Rose diagramme showing palaeoflow data collected in facies association I from the Ferryland Head formation at Ferryland. Sample number is 53 with 10° classes (A). Rose diagramme showing palaeoflow collected from facies association IIa. Sample number is 115 with 10° classes (B). Rose diagramme indicating palaeoflow directions for facies association IIb. Palaeoflow direction is polymodal with flow predominantly south and southwest. Sample number is 6 with a 10° classes (C).Rose diagramme illustrating palaeoflow from facies association IIIa. Sample number is 280 with a 10° class (D). Rose diagramme showing palaeoflow from 74 measurements in facies association IIIb. 10° classes (E).Total palaeoflow data collected in the Ferryland Head Formation at Ferryland. Sample number is 528 with 10° classes. Note the strong unimodality of southerly palaeoflow (F).


A
B
C
D
E
F

bound at its base by a sharp, gently concave erosional surface. Overall relief on the basal erosional surface ranges from 0.5–2 m whereas small-scale relief within the concave surface generally varies form 5–30 cm. Intraformational conglomerate (facies 4) commonly overlies the erosional surface, and is in turn overlain by crossbedded sandstone (subfacies 3A), followed by current-rippled sandstone (subfacies 3B) and/or planar-laminated sandstone (subfacies 3C). Climbing-ripples (subfacies 3D) are sometimes present. Massive sandstone (subfacies 3E) is locally present. Convoluted sandstone (subfacies 3F) is commonly present, especially towards the top of the succession.

The upper third to upper half of each occurrence of facies association IIa comprises fine-grained, silty sedimentary rocks of facies 2. Very fine upper to fine upper, silty sandstone (subfacies 2A), and current-rippled to planar-laminated silty sandstone (subfacies 2B), are common in the upper part of this succession. Massive reddish to purplish-brown siltstone with minor sandstone (subfacies 1A), wavy (subfacies 1B) and horizontally interlaminated (subfacies 1C), buff-coloured sandstone and reddish-brown siltstone laminae are locally present. Other subfacies which are common in this facies association are interbedded to interlaminated sandstone and siltstone with abundant collapse structures, dewatering pipes, synaeresis cracks and sandstone dykes (subfacies 1E), and interbedded sandstone beds and siltstone laminae (subfacies 1G). The thickness of this association varies from a 0.34–9 m. The average thickness for this association is 2.76 m; the mode thickness is 1.88 metre and the median thickness is 2.22 m. Facies association IIa comprises a total cumulative thickness of 143.64 m or 21% of the entire

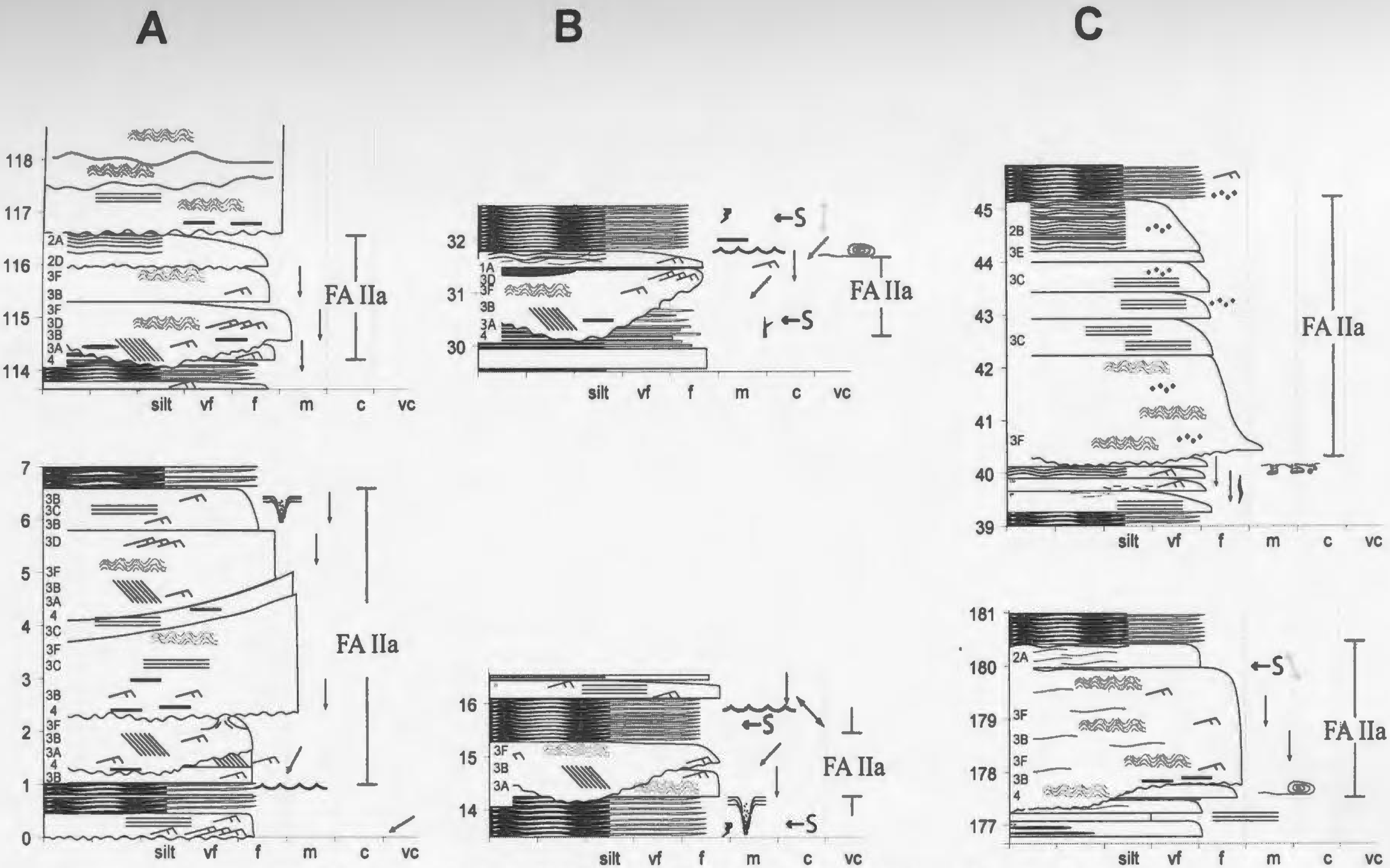


Figure 4.5. Examples of facies association IIa from the Ferryland Head section (column A) lower Lighthouse section (column B) and Flat Point section (column C).

exposed Ferryland Head Formation in the study area. The occurrence of this facies association is sporadic throughout the stratigraphy, first appearing approximately 5 m from the basal contact of the Ferryland Head Formation (Figure 4.3). The dominant palaeoflow within this association is south to south-south-west (Figure 4.4B). At least six examples of gently dipping, poorly defined surfaces, dipping 10°–20° from bedding plane. All of the examples occur within facies association IIa in current-rippled (subfacies 3B) to parallel-laminated sandstone (subfacies 3C), convoluted sandstone (3F), and silty current-rippled sandstone (subfacies 2B).

Facies association IIb comprises a thinning and/or fining upward succession of normally-graded beds of facies 1 and 2 (Plate 12C and Figure 4.6). This association makes up only approximately 2% of the stratigraphy with a total cumulative thickness of approximately 12 m (Figure 4.3). The thickness of the occurrences of this facies association ranges from 1.6 m to 2.5 m with an average thickness of approximately 2 m. The distribution of this facies association is limited to the lower two thirds of the succession in the study area. This facies association is bounded by a concave erosional base with pronounced relief of, in some cases, more than 2 m. Cross-bedding, although present in some cases, is otherwise rare. Current-rippled silty sandstone (subfacies 2B) commonly overlies the erosional surface. Climbing-ripples (subfacies 2C) are very common. Sandy siltstone (subfacies 1A) is ubiquitous in this association. Wavy (subfacies 1B) and horizontally (subfacies 1C) interlaminated and interbedded, buff-coloured sandstone and reddish-brown siltstone are always present towards the top of this facies association. Lenticular sandstone (subfacies 1D) is rarely present in this

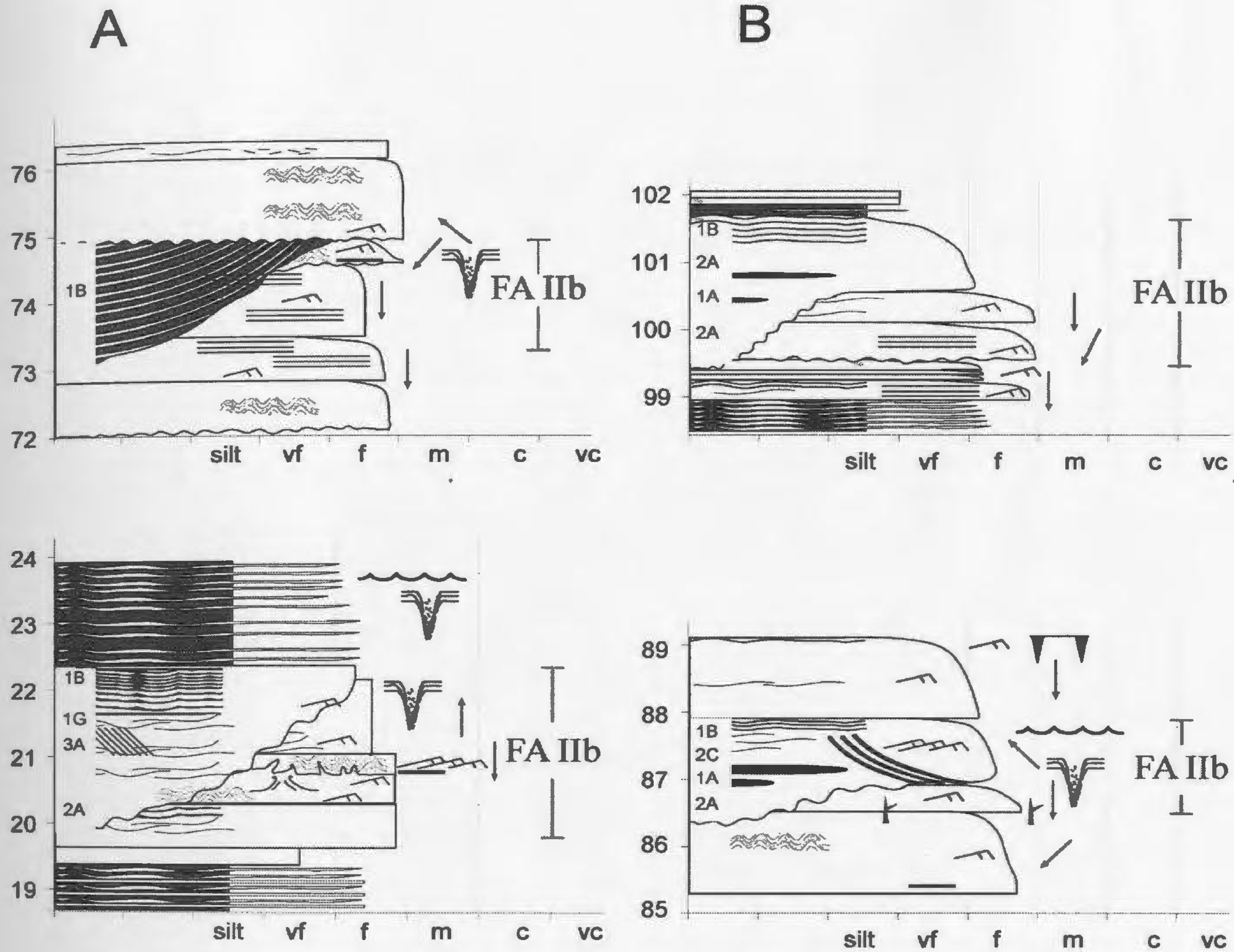


Figure 4.6. Examples of facies association IIb from the Ferryland Head section (column A) and Flat Point section (column B).

association. Wave ripples (facies 1J) can be seen toward the top of the succession in more than one occurrence. Limited palaeoflow measurements indicate predominant flow to the southwest with a minor northeasterly component (Figure 4.4C).

4.4.3.2. Interpretation of Facies Association II

Facies association II is composed of upward-fining sedimentary rocks bound at their base by generally concave erosional surfaces. These deposits are interpreted as channel or channel complex fill (Bhattacharya and Walker 1995). The two end members represent differences in the flow velocities within each channel type. Facies association IIa is interpreted as the fill of a high energy distributary channel or channel complex. The abundance of erosional surfaces within facies association IIa indicates frequent flood conditions. Cross-bedding is suggestive of dune migration during such floods. The rare examples of gently-dipping surfaces are interpreted as lateral accretion surfaces due to point-bar migration. The scarcity of lateral accretion surfaces in this facies association suggests that the channels had low sinuosities and high width-to-depth ratios characteristic of braided river systems (Miall, 1992; Collinson, 1986; Reineck and Singh, 1980; Boggs, 1995). It should be noted that the concavity of the master surfaces of the channels/ channel complexes are not commonly observed due to the dip-sectional nature of the outcrop. This might also be the cause of an apparent lack of lateral accretion surfaces.

Facies association IIb is interpreted to have been deposited under slower flows than facies association IIa. The fine-grained fill suggests that deposition occurred either during the latest stages of floods, that these channels where somehow disconnected from the main channel. This facies association is not interpreted as deposition in an abandoned channel (channel plug). The structures above the erosional base, although indicative of lower flow velocities than association IIa, are still indicative of lower to upper flow regimes (subfacies 2B and 2C as well as most of facies 1).

4.4.4. Facies association III

4.4.4.1. Description

The remaining 61 % of the Ferryland Head stratigraphy (Figure 4.3) consists of a combination of tabular beds (Plate 14D), generally silty and less than a metre thick, belonging to facies 1 and 2. Facies association III represents a continuum for which two end members (facies associations IIIa and IIIb) are described below. In reality, there is a wide spectrum of deposits as mixtures of both end members, and the end members themselves are uncommon.

Facies association IIIa comprises stacked, tabular, normally-graded beds less than a metre thick (Figure 4.7), consisting mainly of facies 2 intercalated with rare beds of facies 1. This association varies in thickness from 0.2 m to approximately 5 m. Facies association IIIa is bounded by a basal sharp and horizontal erosional surface. Parallel erosional grooves, 10–20 cm deep and 10–30 cm wide, evenly spaced at approximately 60 cm, are common on the erosional surface. The beds within this facies association, are mostly 10–70 cm thick and are composed mainly of silty sandstone (subfacies 2A), ripple to planar-laminated sandstone with minor siltstone (subfacies 2B), climbing-ripples (subfacies C), convoluted sandstone (subfacies 3F) and structureless sandstone (subfacies 2D). The most common sediment however is parallel laminated sandstone (subfacies 2B). Wavy (subfacies 1B) to horizontally (subfacies 1C) interlaminated to interbedded (subfacies 1G) sandstone and siltstone, synsedimentary deformed heterolithic rocks (subfacies 1E) generally make up the finer heterolithic portions of this facies association. Palaeoflow directions (Figure 4.4D) within this association are unimodal towards the south.

Facies association IIIb is characterized by tabular, laterally continuous, fine-grained heterolithic beds of sedimentary rocks belonging to facies 1, punctuated by a few thin sandstone intervals belonging to facies 2 (Figure 4.8). The thickness of this association ranges from 0.1 m to approximately 4 m. Individual beds in this facies association typically fine upwards because of a decrease in sand to silt ratio. Sandy siltstone (subfacies 1A), wavy interlaminated sandstone and siltstone (subfacies1B), horizontally-laminated sandstone and siltstone (subfacies 1C), lenticular sandstone (subfacies 1D), heterolithic facies with synsedimentary deformation structures (subfacies 1E), desiccation cracks (subfacies 1F), sandy heterolithic facies (subfacies 1G), loaded ripples (subfacies 1H), loaded sandstone (subfacies 1I) and wave-rippled sandstone and silt (facies 1J) are all present within this association. Facies 1F is commonly found in association with facies 1J towards the tops of beds within this association.

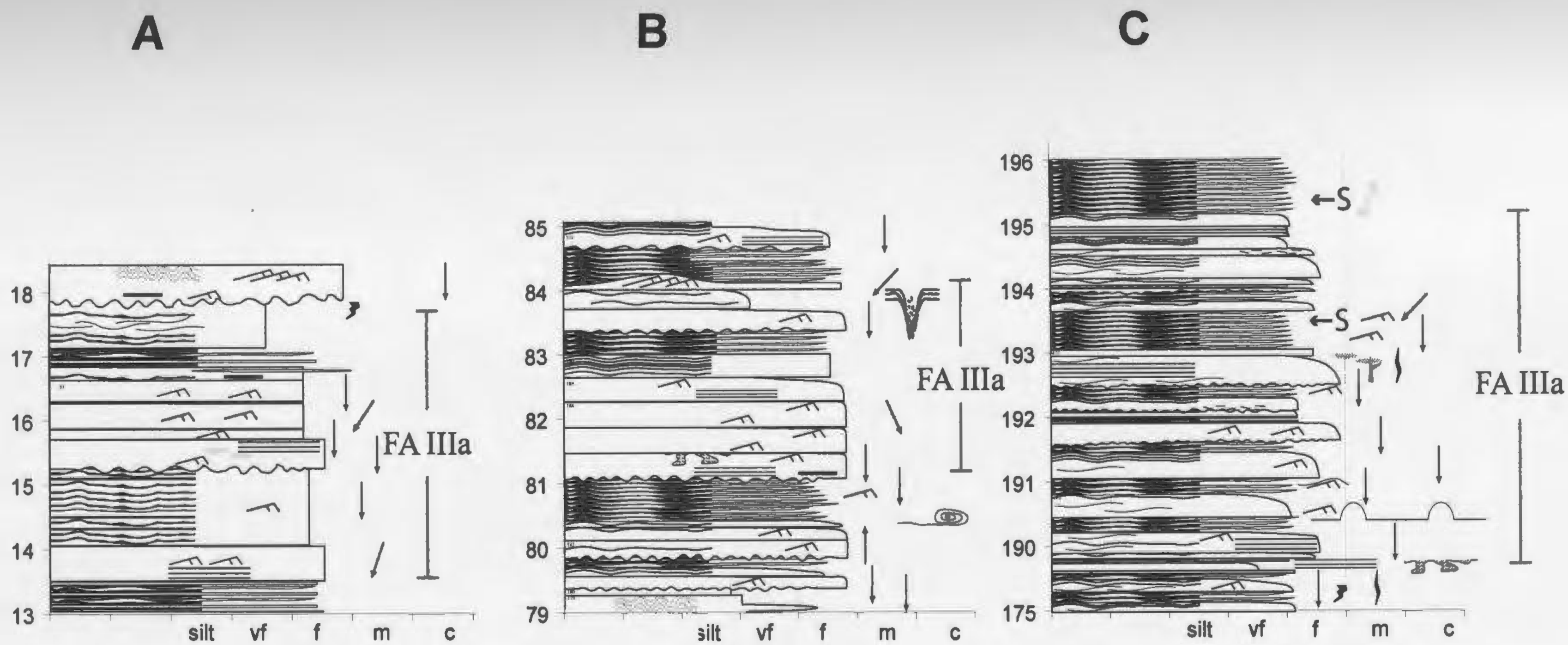


Figure 4.7. Examples of facies association IIIa (proximal end of the spectrum) from the Ferryland Head section (A), Lighthouse section (B), and the top part of the Flat Point section (C).

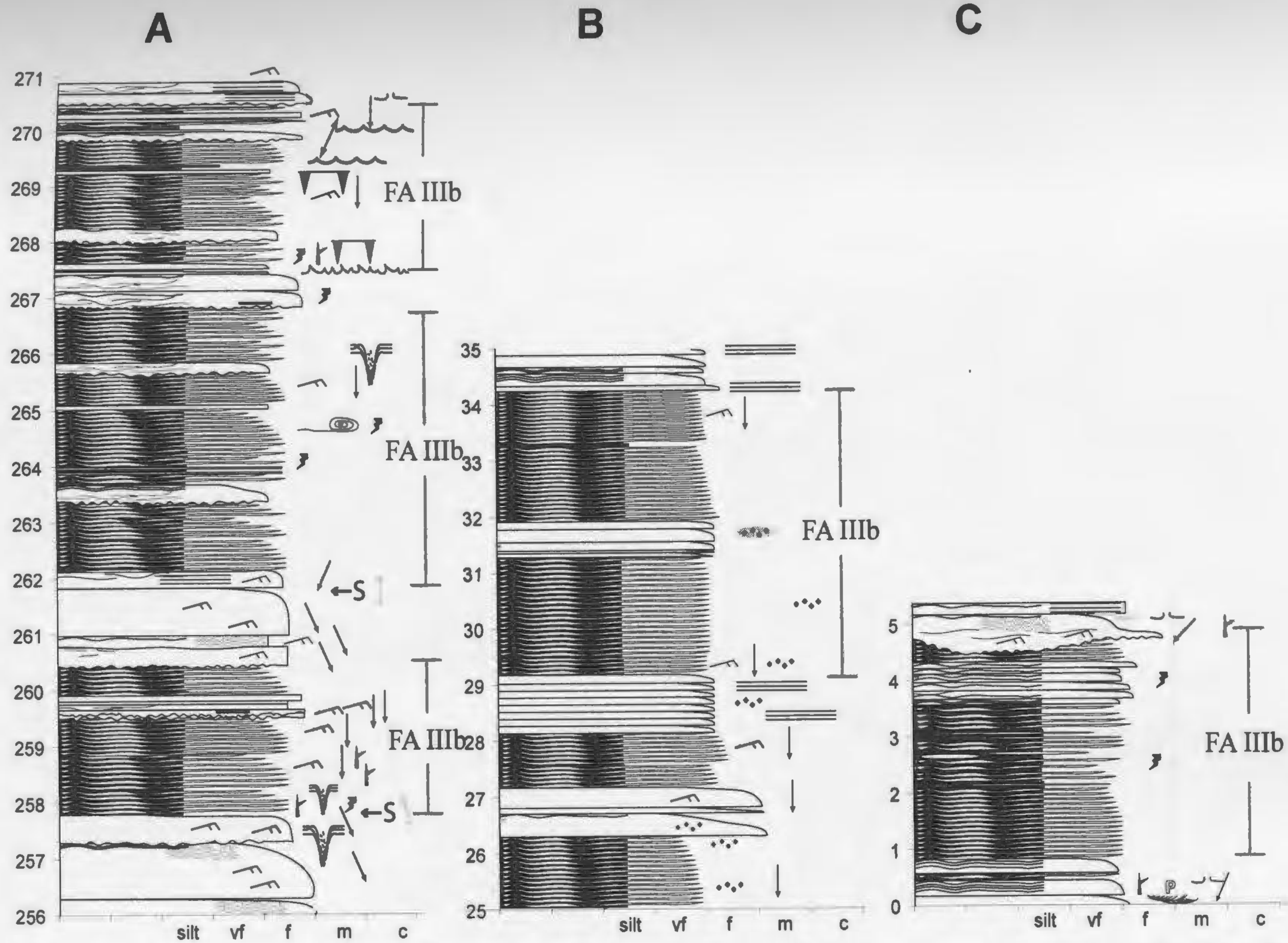


Figure 4.8. Examples of facies association IIIb (the more distal end of the spectrum) from the upper Lighthouse section

4.4.4.2. Interpretation of facies Association III

Facies association III is interpreted as interdistributary deposits of a marine delta. The tabular and laterally extensive character of deposition implies that these deposits were not emplaced within channels. The more coarse-grained facies association IIIa represents more proximal, higher energy deposition during flood stage and facies association IIIb represents lower energy environments more distal to channels with possible tidal influence of minor significance with respect to sediment transport and reworking.

The stacked, thin tabular sandstone beds of association IIa are interpreted to have been deposited as overbank sheet flows or crevasse splays (Elliot, 1974, 1986) and the fine grained heterolithic sediments (facies 1) are characteristic of interdistributary bay deposits (Elliot, 1974). The presence of subaerial exposure indicators (subfacies 1F) and microwave ripples (subfacies 1J) are indicative of interdistributary delta plain deposits. The formation of small shallow pools (subfacies 1A) is also characteristic of humid delta plain sedimentation (Elliot, 1986).

PLATE 1: RIDGES AND FURROWS

A: Example of "bumpy" surface from the upper Lighthouse section. Note how the striae on top of bed curve around the raised areas. Palaeoflow is from top to bottom.

B: Close up of ridges and furrows, showing the relief in the sandstone. Note the criss-crossing of striae. Flow is from upper right to lower left.

C: Close up of ridges and furrow from the lower Flat Point section.

D: Ridges and furrows from the upper Lighthouse section. Flow is from left to right.

E: Siltstone draped current-ripples with striae on ripple crests from the Ferryland Head Formation, Cape Broyle. Palaeoflow is from right to left. Note the occasional millimetre long prod marks.

F: Prod marks in siltstone-draped sandstone. Prod marks were probably made by mud chips from highly cohesive siltstone laminae.

G: "Dimple surface" of possible biogenic origin associated with ridges and furrows from the lower Flat Point section.

H: Ridges and furrows from the lower Flat Point section with dimple-like texture.

N.B. all the examples on the following page are plan view photographs of bedding surfaces.

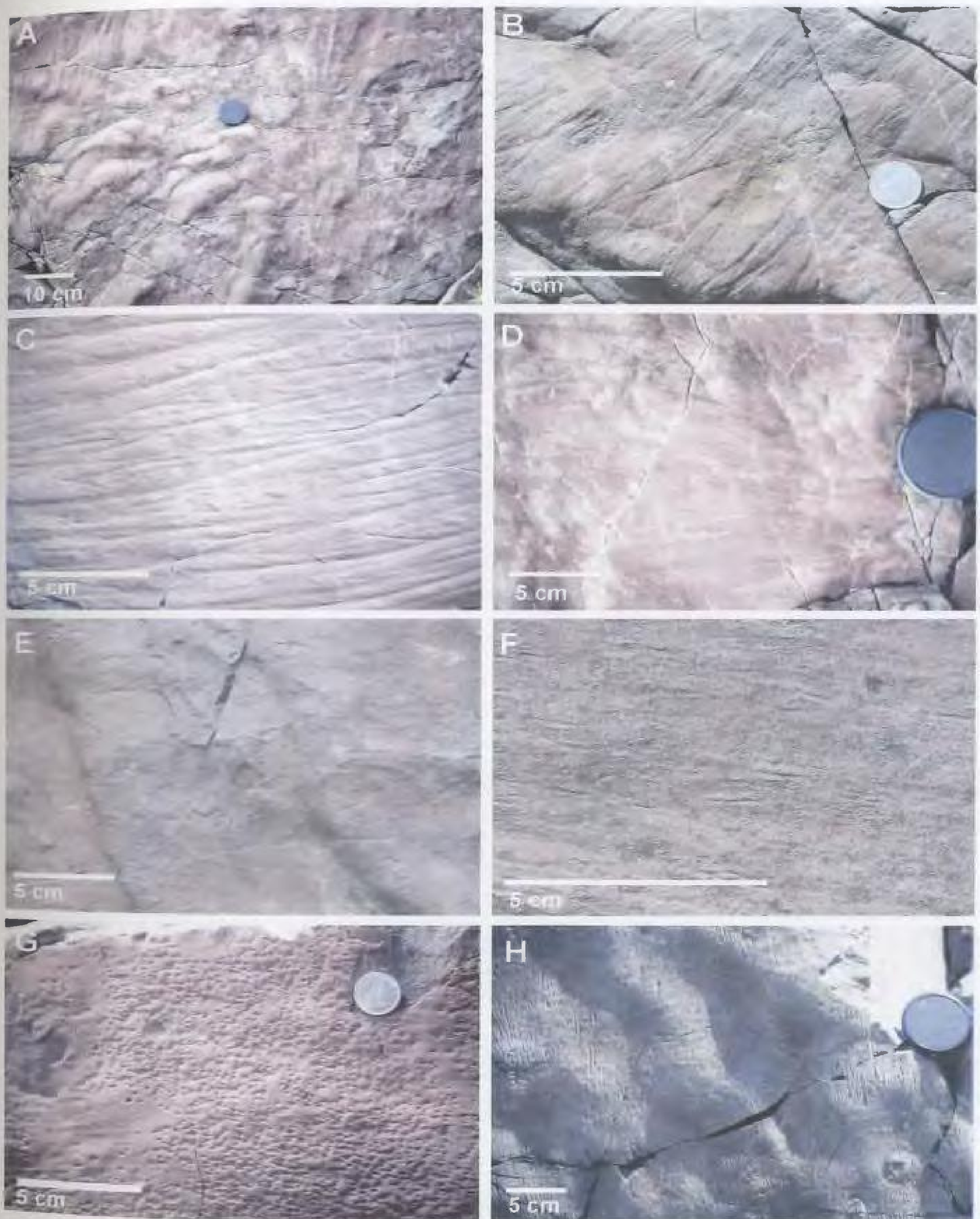

A
10 cm
B
5 cm
C
5 cm
D
5 cm
E
5 cm
F
5 cm
G
5 cm
H
5 cm

PLATE 2: SUBFACIES 1A / 1B

A: Example of facies 1A. Note the non-erosive contact at base and clear erosional contact at top right. This example is from the lower Lighthouse section on the southern side of the unnamed cove.

B: An example of facies 1B from the lower Ferryland Head section on the north side of the unnamed cove. Note the upward increase in abundance of siltstone laminae. Ruler for scale is 15.5 cm long.

C: Wavy interlaminated sandstone and siltstone laminae (subfacies 1B). The arrow in the lower right of the photograph shows a contact between underlying facies and facies 1B. Lens for scale is 5.5 cm in diameter.

N.B. all examples on the following page show cross-sectional views. Stratigraphic up is shown by the black arrow on the upper right of the plate.

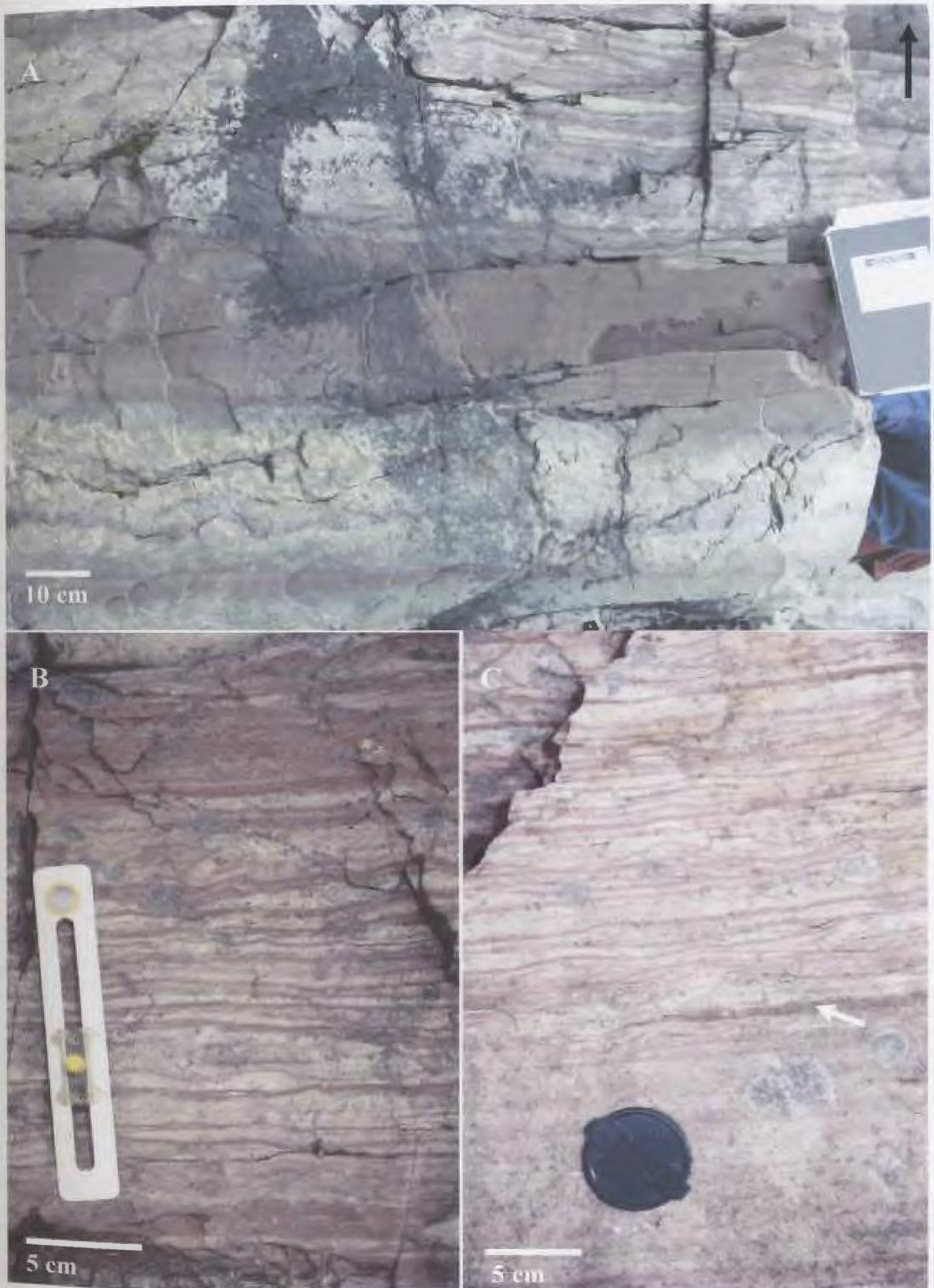

A
10 cm
B
5 cm
C
5 cm

PLATE 3: SUBFACIES 1C/1D

A: Sketch of horizontal, parallel interlaminated sandstone and siltstone (subfacies 1C) showing the repetitive pattern of thick and coarse, thin and fine, thin and coarse, thin and fine.

B: Example of facies 1C from the lower Flat Point section. Note the thinning upward of the sandstone laminae in the section shown by the vertical white bar.

C: Alternating wavy sandstone and siltstone laminae and beds, and lenticular sandstone (facies 1D). Sand lenses show both depositional and erosional examples. Note the convolute lamina in the centre.

D: Sandstone lenses encased in siltstone (subfacies 1D). The lenses are shown by white arrows. Faint ripple lamination can be seen in the lens to the right (palaeocurrent to the right).

N.B. All examples shown are cross-sectional views. Stratigraphic up is shown by the black arrow on the upper right corner of the plate.

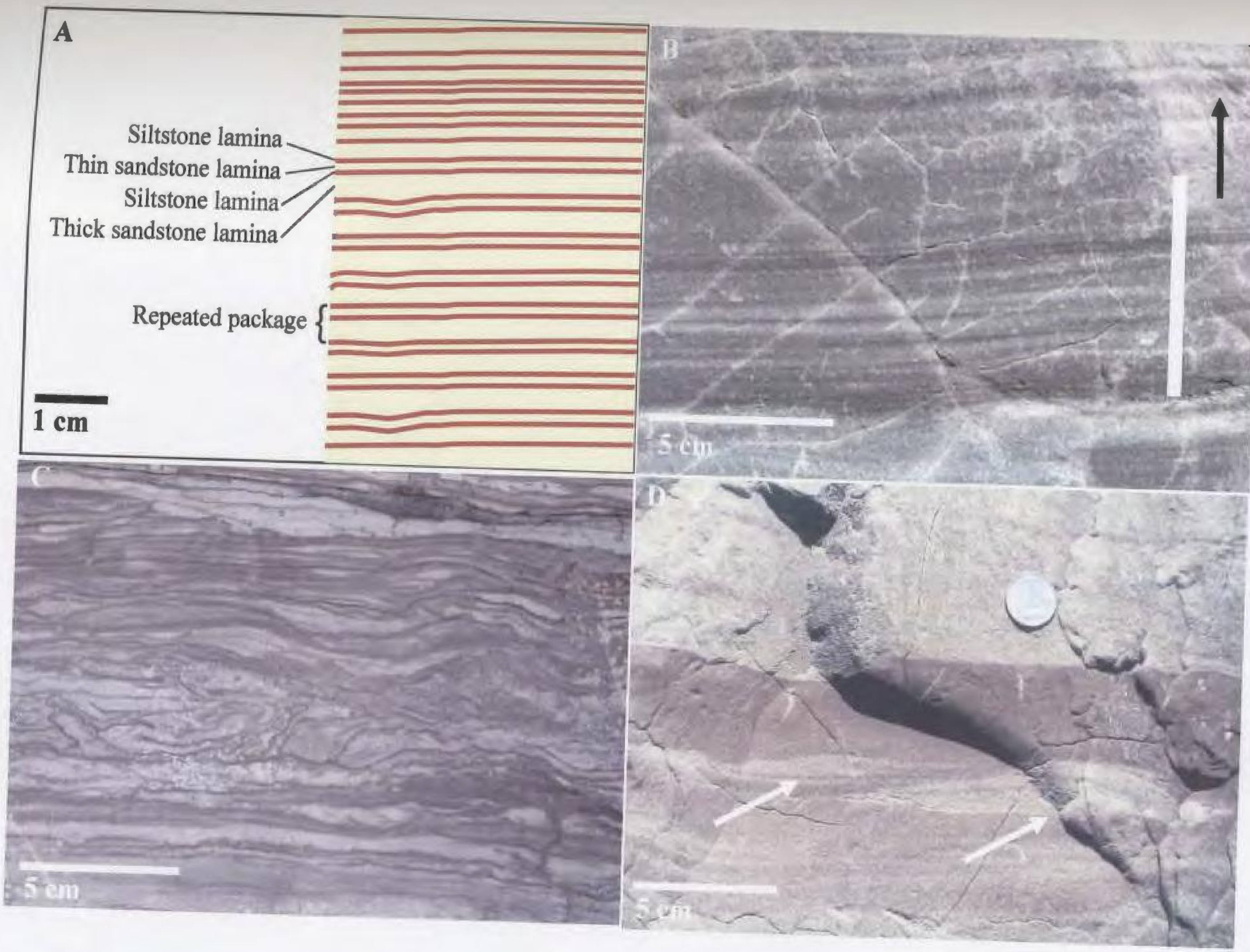

A
Siltstone lamina
Thin sandstone lamina
Siltstone lamina
Thick sandstone lamina
Repeated package
1 cm
B
5 cm
C
5 cm
D
5 cm

PLATE 4: SUBFACIES 1E

A: Interbedded and interlaminated sandstone and siltstone beds and laminae respectively, with collapse structure(subfacies 1E). Note the column of discontinuous, chaotically oriented siltstone laminae. (each division on the scale bar is 1 centimetre).

B: Subvertical collapse structure involving two interlaminate/interbedded sandstone and siltstone beds/laminae(subfacies 1E) separated by a sandstone bed. Note the upward turned laminae in the lower part and downward directed laminae in the top bed.

C: Tear-shaped, sandstone filled dewatering structure in interlaminated/interbedded sandstone and siltstone(subfacies 1E), with fragmented siltstone laminae. Note the well-defined boundary truncating siltstone laminae (reddish-brown). The structure might be associated with dewatering pipes.

D: Collapse structure with downward dipping siltstone laminae associated with the dewatering of underlying sandstone bed. Note the fragments of siltstone laminae corresponding to the interlaminated strata above the hand lens.

E: Sandstone dewatering pipe in interlaminated sandstone and siltstone. Note the well-defined edge of the feature.

F: Sandstone dyke and sills in interlaminated sandstone and siltstone. Note that the dyke cross cuts depositional laminae.

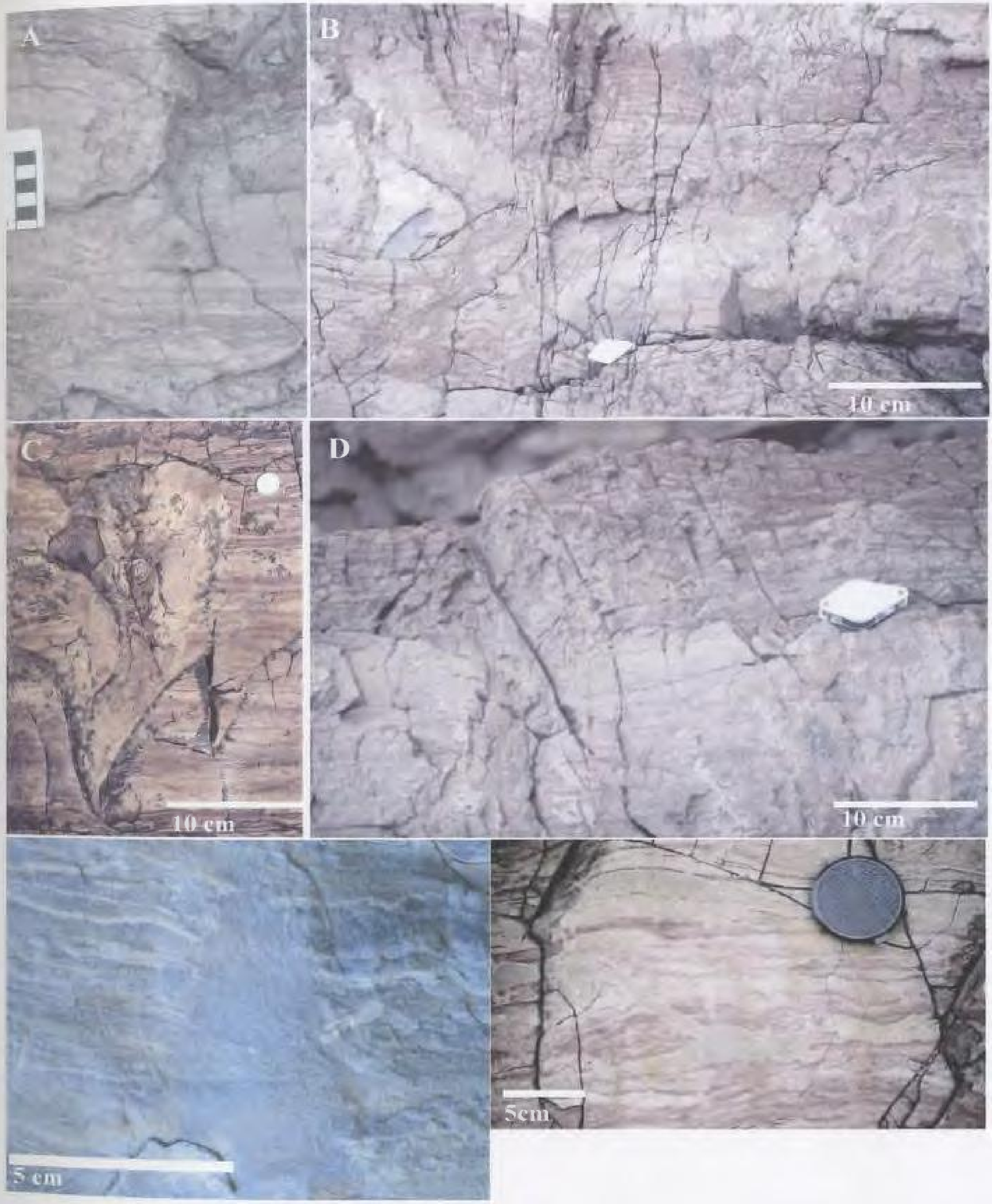

A
B
10 cm
C
10 cm
D
10 cm
5 cm
5cm

PLATE 5: SUBFACIES 1F

A: Close-up of polygonal mudcracks from the lower Lighthouse section (southern part of unnamed cove).
B: Top of mudcracked bed surface from the southern part of the unnamed cove.
C: Mudcracks form the upper Lighthouse section. Note the upward turned edges.
D: Mudcracked surface from the middle part of the Lighthouse section on cliff face. Scale bar is approximately 5m.


A
B
C
D
5 cm

PLATE 6: SUBFACIES 1G/1H

A: Predominantly sandy interbedded sandstone beds and siltstone laminae. Note the wavy nature of bedding. Sandstone beds are locally thickened due both to erosion and deposition.

B, C and D: Loaded ripples subfacies 1H) from the north side of the unnamed cove, lower part of the Ferryland Head section. Note the relatively undeformed ripple-lamination in upper part and the ripple-lamination within the sinuous load casts below.

N.B. All examples show cross-sectional views. Stratigraphic up is indicated by the white arrow on the upper right of the plate.


A
B
5 cm
C
cm
0
5
D

PLATE 7: SUBFACIES 1I

A: Example of sandstone loaded into siltstone, from the middle of the Lighthouse section just north of the lighthouse. Note the symmetrical wave ripples towards the top of the sandstone.

B: Sandstone pillow in silty sandstone from the middle lighthouse section. Note siltstone laminae outlining the pillow structure.

N.B. All examples show cross-sectional views. Stratigraphic up is indicated by the black arrow on the upper right of the plate.

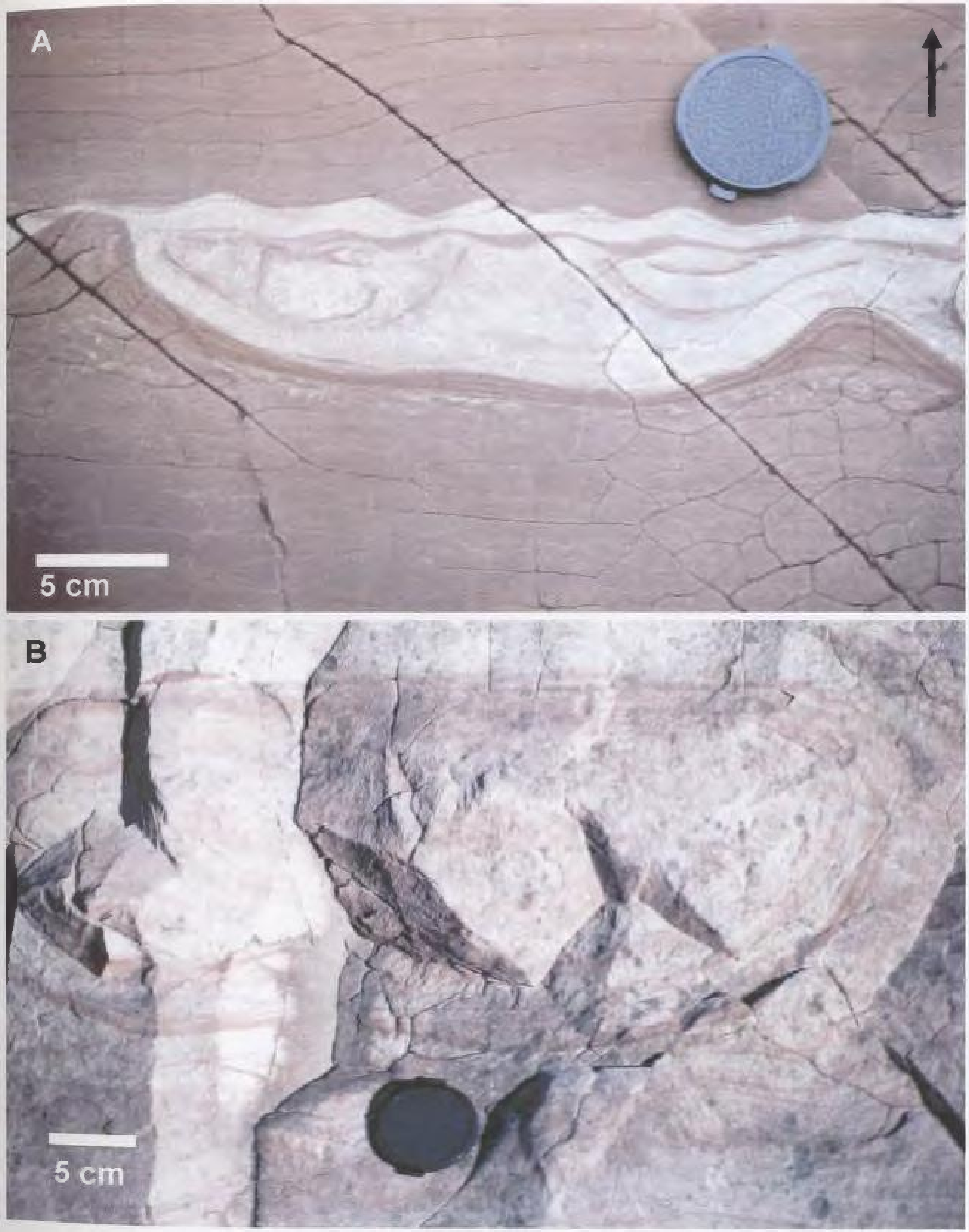

A
5 cm
B
5 cm

PLATE 8: SUBFACIES 1J

A: Wave ripples from the upper Flat Point section. Note the characteristic straight and parallel crests. Lens cap for scale is 5.5 cm in diameter.

B: Examples of wave ripples (black arrows) and climbing wave ripples (white arrow) from the lower Ferryland Head section, northern side of unnamed cove. Note the climbing wave ripples in the upper part of the figure

C: Example of small-scale wave ripples from the lower Ferryland Head section (lens cap for scale is 5.5 cm diameter).

D: Very small wave ripples from the upper Lighthouse section.

E: Small-scale wave ripples showing wave diffraction probably in a shallow pool.

F: Very small wave ripples from the upper Flat Point section (lens cap for scale is 5.5 cm in diameter.

G: Very small wave ripples from the lower Flat Point section (scale bar is 5 cm long).

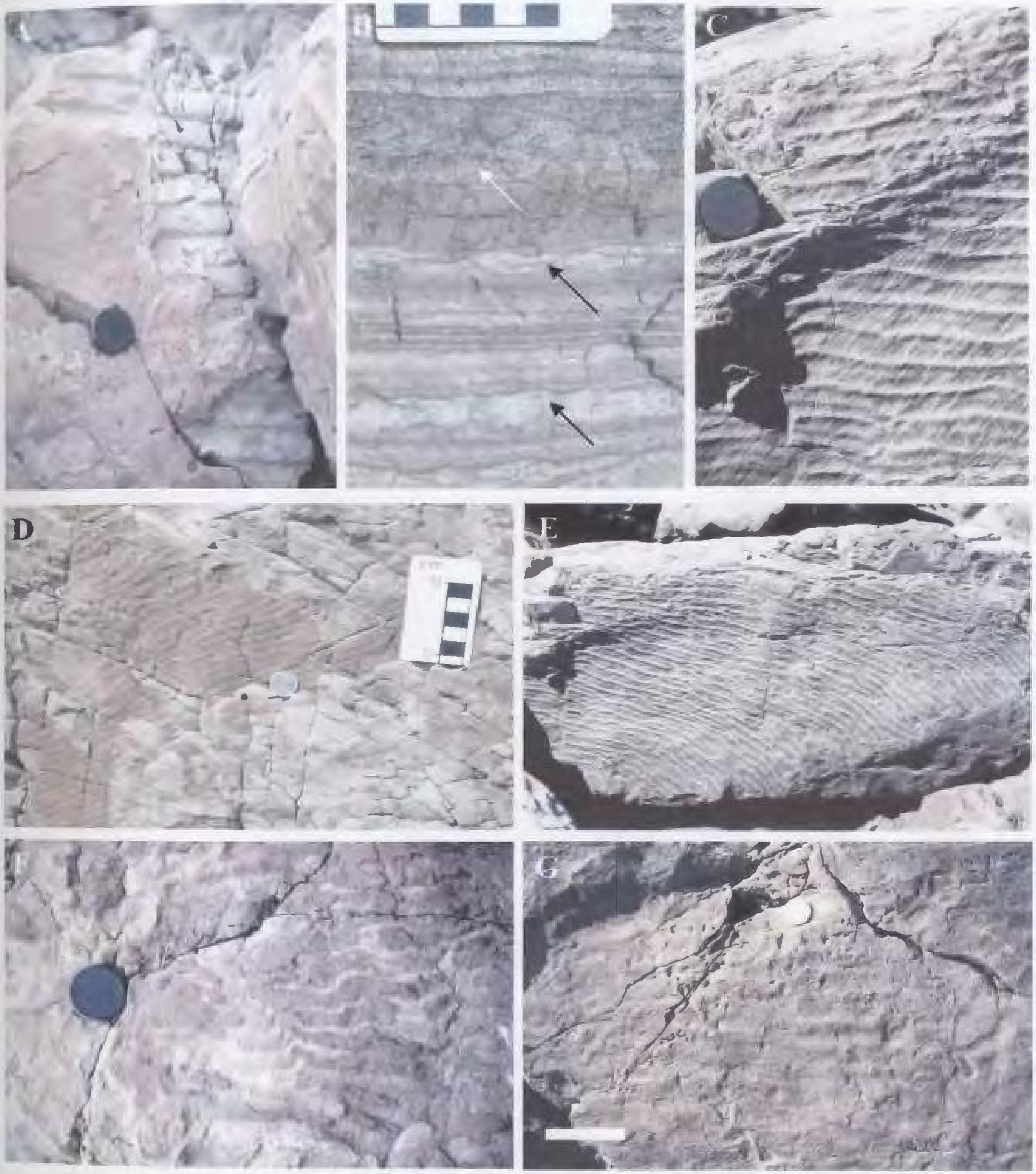

A
B
C
D
E
F
G

PLATE 9: SUBFACIES 1J/1K

A: Example of micro-wave-rippled bedding-surface draped by siltstone (subfacies 1J) from the upper Lighthouse section. The wavelength of the ripples is less than a centimetre and the amplitude less than half a centimetre implying extremely shallow water of at least a few centimetres and no more than a few tens of centimetres.

B: A cross-sectional view of siltstone-draped wave-rippled sandstone laminae (subfacies 1J) from the lower Ferryland Head section.

C: Close up of a micro-wave-rippled bedding-surface (subfacies 1J) from the upper Lighthouse section.

D: Cross-sectional view of convoluted bedding (subfacies 1K) from the upper Lighthouse section. Note the brittle deformation (shown by white arrow) of the siltstone associated with the otherwise plastic deformation. Deformation in this case is probably due to shearing by wave orbital motion indicated by the overlying wave-rippled horizon (subfacies 1J) (black arrow).

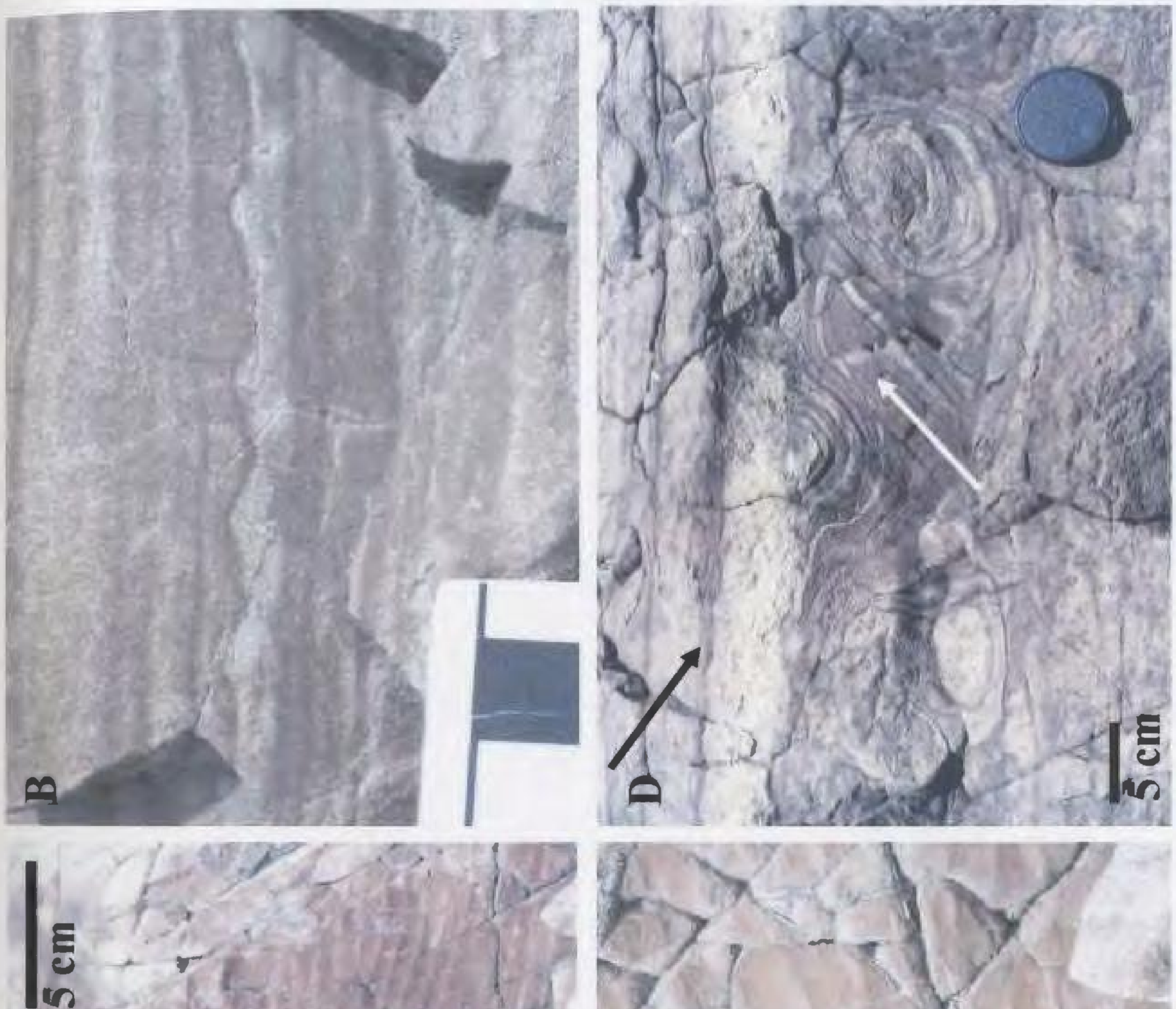

A
5 cm
B
C
5 cm
D
5 cm

PLATE 10: SUBFACIES 2A/2B/2C

A: An example of silty sandstone (subfacies 2A) from the Flat Point section underlying interlaminated wavy sandstone and siltstone (subfacies 1A).

B: Flat Point section example of silty sandstone (subfacies 2A).

C: Structureless sandstone (subfacies 2D) is shown in the lower half of the sandstone bed. Silty current-rippled sandstone (subfacies 2B) can be seen in the upper half of the bed. This example is from the lower part of the Flat point section

D: Horizontally laminated silty sandstone (subfacies) 2B from the lower Ferryland Head section.

E: Current-rippled sandstone with minor siltstone (subfacies 2B) from the upper Lighthouse section.

F and G: Climbing-ripples in silty sandstone (subfacies 2B) from the Flat Point section.

N.B. All examples show cross-sectional views. Stratigraphic up is indicated by the black arrow on the upper right of the plate.

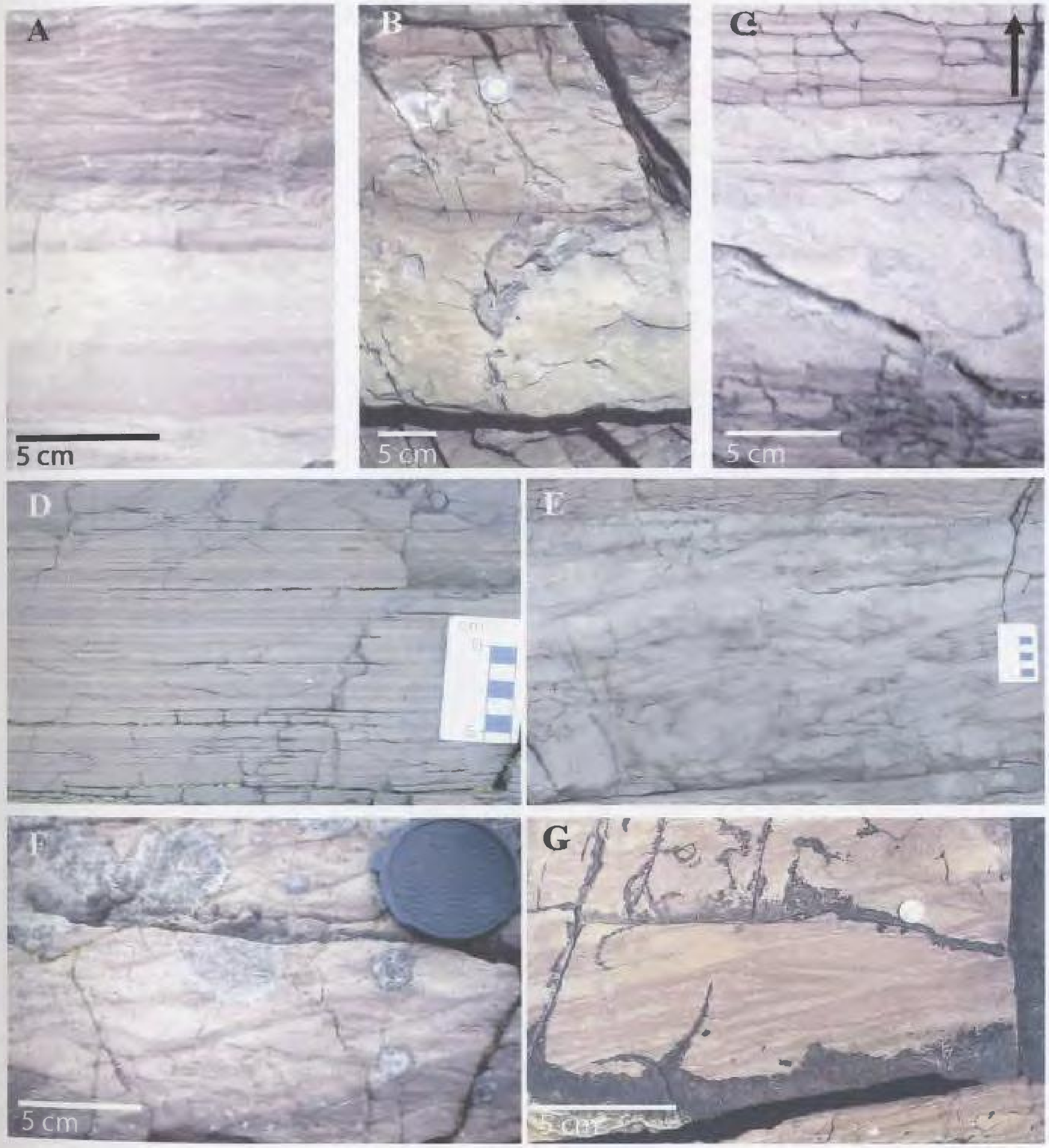

A
B
C
D
E
F
G
5 cm
5 cm
5 cm
5 cm
5 cm

PLATE 11: SUBFACIES 3A

A: Example of tabular cross-bedded sandstone (subfacies 3A) over an erosional surface from the lower Ferryland Head section.

B and C: Two examples of trough cross-bedded sandstone (subfacies 3A) over erosional surfaces from the Ferryland Head section. Note the intraformational conglomerate in places (facies 4).

D: Cross-bedded sandstone (subfacies 3A) from the upper Ferryland Head section.

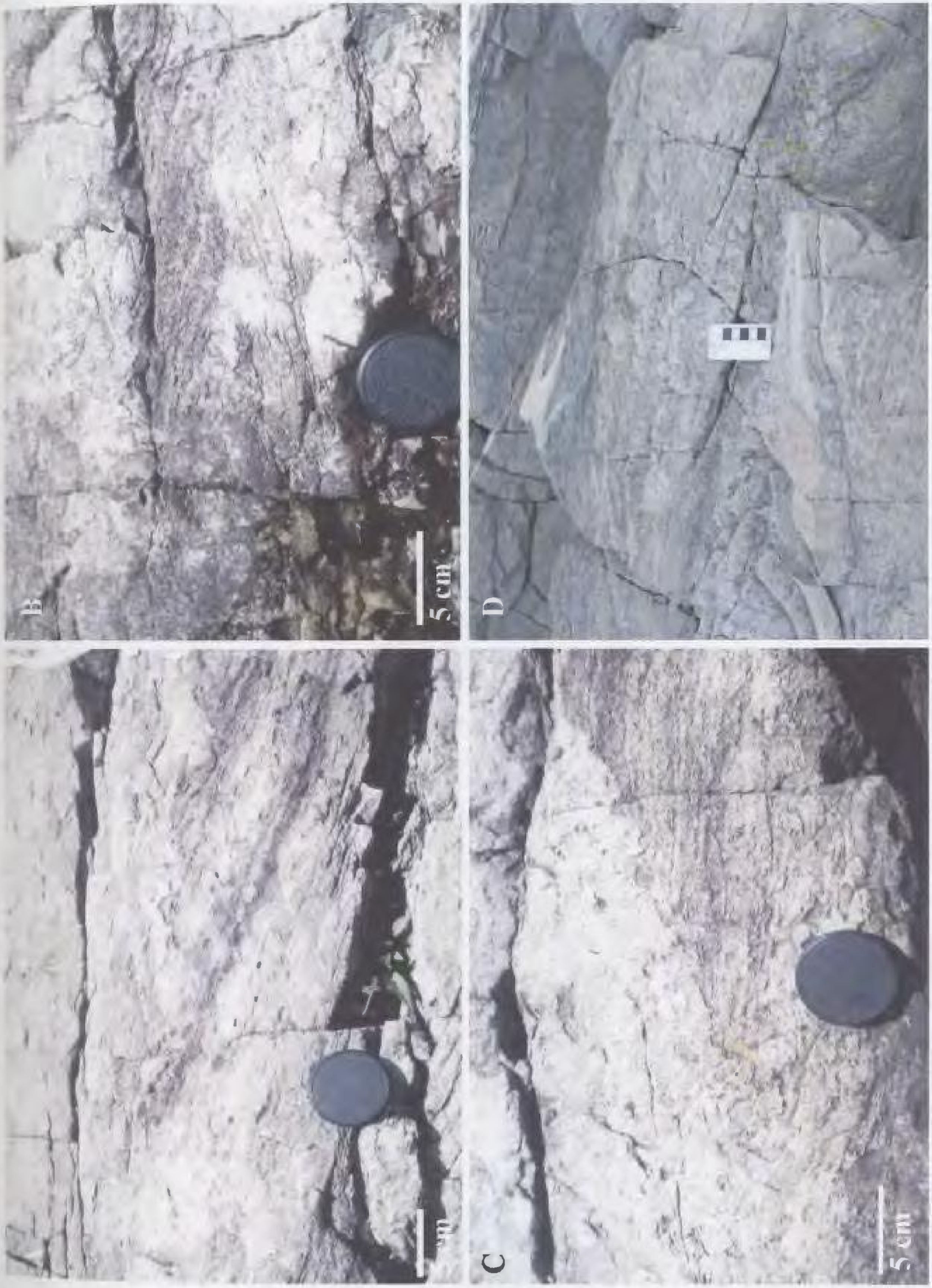

B
5 cm
D
C
5 cm

PLATE 12: SUBFACIES 3B/3C/3F/3G

A: Current-rippled sandstone (subfacies 3B) from the lower Ferryland Head Formation, Cape Broyle.

B: Horizontally-laminated sandstone (subfacies 3C) from the lower Ferryland Head section.

C: Convoluted sandstone (subfacies 3F) from the upper Ferryland Head section.

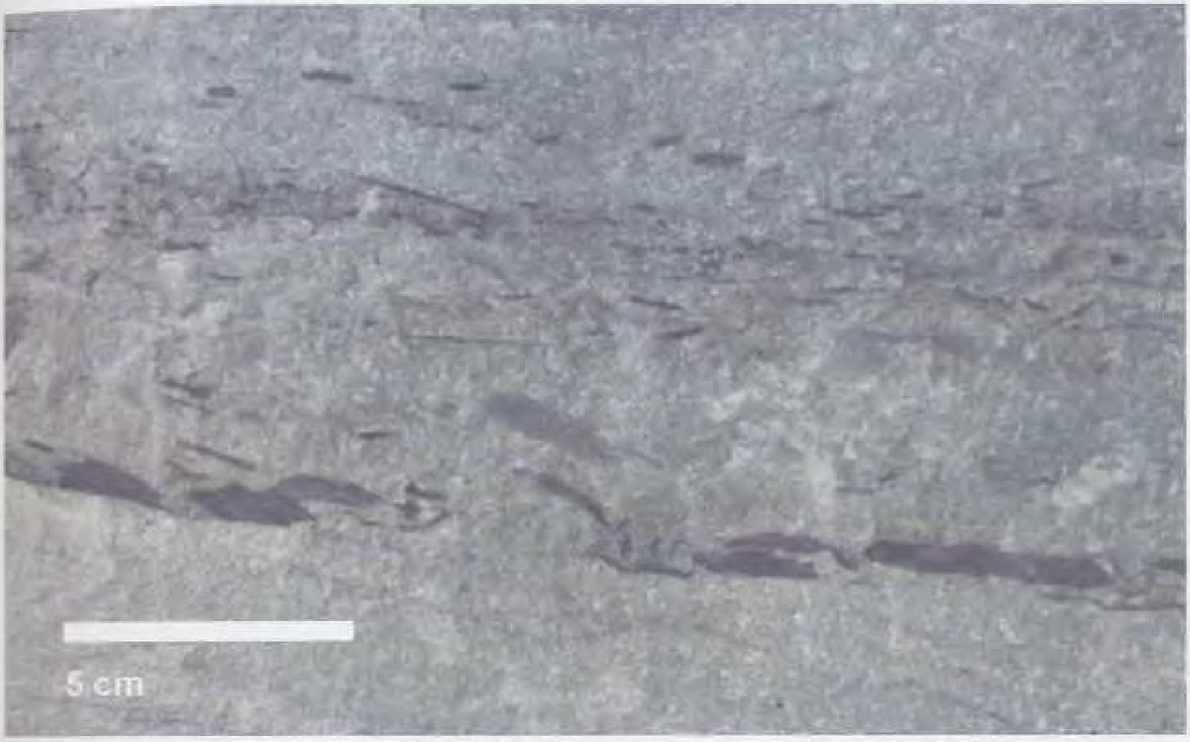
D: Climbing wave-rippled sandstone (facies 3G) from the lower Ferryland Head section. Note the symmetrical crests.


A
B
C
D
cm 0 5
5 cm
1 m

PLATE 13: FACIES 4

A: Intraformational conglomerate from the lower Ferryland Head section. Note the angularity of the clasts. The clasts consist of interlaminated sandstone and siltstone(subfacies 1B and 1C) and horizontally-laminated siltstone(subfacies 1A).

B: Intraformational conglomerate (facies 4) in association with cross-bedded sandstone (facies 3A) above erosional surface. Note the angularity and oblate shape of clasts. Example from the lower Ferryland Head section.


5 cm


5 cm

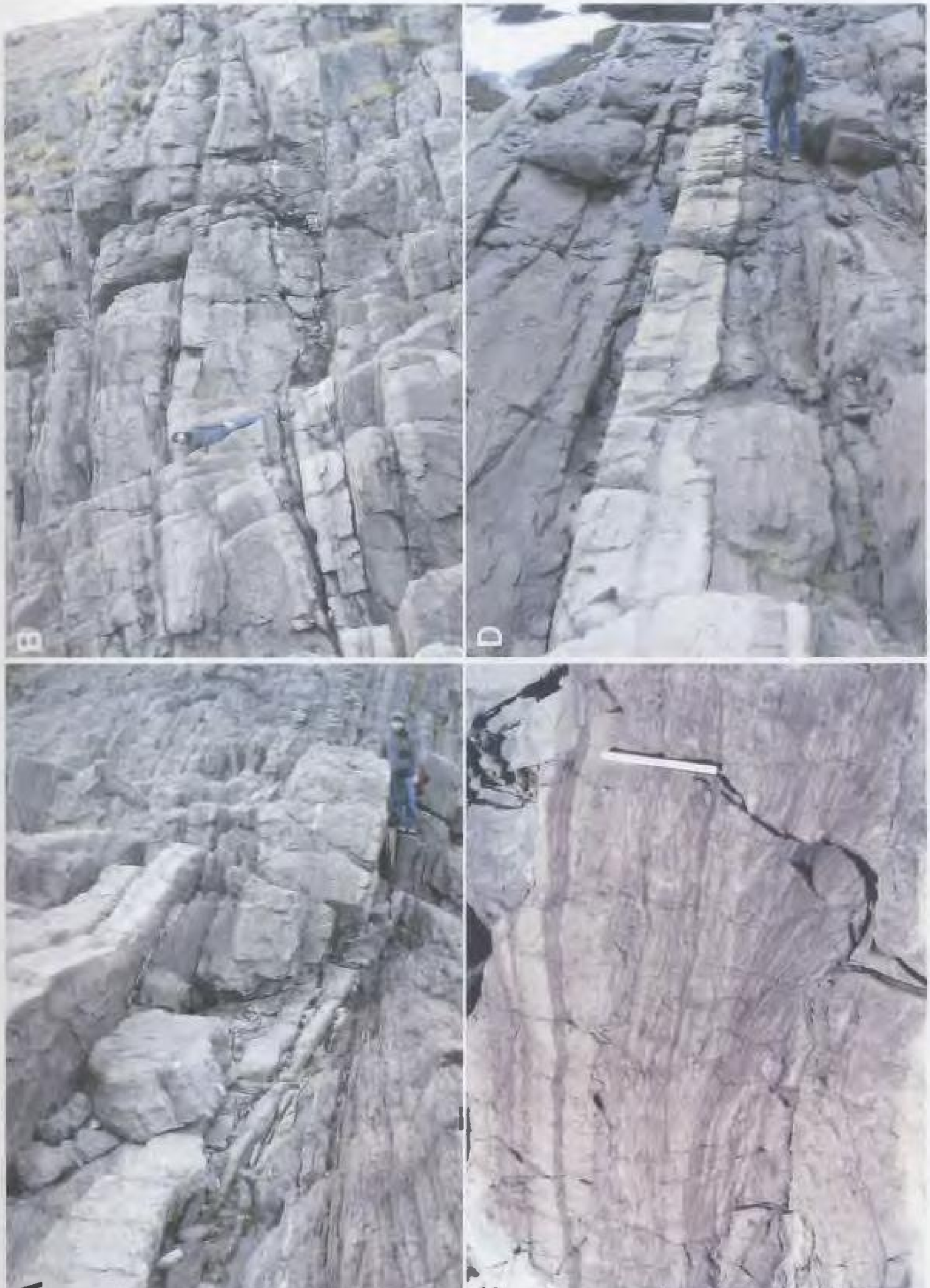
PLATE 14: FACIES ASSOCIATION EXAMPLES

A: Example of facies association IIa (coarse-grained channel) from the lower Lighthouse section, southern side of unnamed cove (1.7m person for scale). Note that scale varies with perspective.

B: Example of facies association IIa (coarse-grained channel) from the lowermost Lighthouse section on the south side of the unnamed cove Note that scale varies with perspective (person 1.7m high for scale).

C: Example of channel filled with silty sandstone and siltstone (facies association IIb) from the lower Flat Point section (Ruler 30 cm long, for scale).

D: Example of thin, tabular sandstone bed overlain and underlain by interbedded sandstone and siltstone laminae (facies association III) from the lower Ferryland Head section, north side of unnamed cove. Note that scale changes with perspective (person 1.7m for scale).


A
B
C
D

Chapter 5

SOFT SEDIMENT DEFORMATION

5.1. INTRODUCTION

Soft-sediment deformation occurs syndepositionally or shortly after burial, predominantly in coarse silt to fine sand (Allen, 1982b; Mills, 1983). Liquefaction and fluidization, density inversion, slope failure, and shear stress are the primary causes of soft-sediment deformation (Mills, 1983). During liquefaction (Casagrande, 1936) a sand body is temporarily supported by pore fluid pressures and not by grain-to-grain contacts. The volume of sediment or pore fluid need not change for this process to take place (Allen, 1982b). The fluid source is therefore considered to be within the sand body during liquefaction. The result is a net downward movement of grains and an upward movement of water (Mills, 1983).

Liquefaction can occur when shock is applied to sediment that is saturated with water and loosely packed. The shocks can be provided by earthquakes, sudden deposition, slumping, collapse of channel banks, shearing by currents, or wave pounding (Collinson and Thompson, 1982; Middleton and Hampton, 1973). Liquefaction can be either partial or total. In total liquefaction all grain contact is broken, resulting in a free flow of the sediment. In partial liquefaction, not all grain contact is broken; therefore, there is some remaining strength in the sediment and lamination might be preserved but is distorted. The dewatering of liquefied sands results in different types of structures created by the movement of water and fluidized sand through the bed.

Fluidization occurs when rapid dewatering produces fluid drag greater or equal to the gravitational force (Mills, 1983), sometimes resulting in upward movement of sand particles. In systems with reverse density stratification there is gravitational instability and depending on additional factors such as cohesion and viscosity of the sediment, load structures may form (Mills, 1983; Anketell et al., 1970).

An array of synsedimentary deformation structures is present in the Ferryland Head Formation. The great majority of these occur in the fine grained heterolithic subfacies 1E. Deformation in the sandstone (subfacies 3F) is pervasive but limited to large metre-scale convolutions and sand volcanoes. There are very few examples throughout the succession where facies 1 and facies associations I and IIa do not exhibit soft sediment deformation. The stratigraphic distribution of deformation structures is therefore related to the facies distribution.

5.2 DEFORMATION STRUCTURES

Sandstone dykes and sills are relatively common structures in subfacies 1E. These range in width from 1–5 cm and a few centimetres to tens of centimetres. Dykes and sills are tabular structures and are sometimes exposed in three dimensions. Most sandstone injection structures are normal to subnormal to bedding (dykes) with a few bedding-parallel examples (sills) (Plate 15). Many injections can be traced to their source beds. The source beds for sandstone injection structures are typically medium to thick (< 1m) tabular beds (facies 1 and 2). There are no obvious examples of very thick sandstone beds to which dykes can be traced. Oblique sandstone pipes are known, and these might be connected to thick sandstone beds. Dykes tend to be small in the Ferryland Head

Formation. The rare large examples of sandstone dykes in the Ferryland Head Formation occur within specific horizons and do not exceed 1 m in length. Sills, when laterally continuous, have the appearance of tabular structureless sandstone beds and are difficult to distinguish from depositional beds.

Sandstone dykes are believed to result from the liquefaction and fluidisation of overpressured sand (Mills, 1983; Allen, 1982). The interlaminated sandstone and siltstone facies has a very low vertical permeability due to the siltstone laminae. Pore fluid pressure could have easily increased within buried sandstone beds due to the vertical permeability barriers presented by the siltstone laminae. Dykes most likely were able to break through weakened sediment where pre-existing synaeresis or desiccation cracks existed. The rare horizons in which sandstone dykes wider than 2 cm and longer than 20 cm are present in abundance are interpreted to have been shocked either seismically or due to riverbank collapse.

The conical to cylindrical structures defined by downward and sometimes upward dipping siltstone laminae that terminate against a central sandstone core, with chaotically arranged siltstone fragments (Plate 4 and Plate 16), are termed dewatering collapse structures. These structures are very common in the heterolithic subfacies 1F and sometimes involve underlying sandstone beds. Dewatering collapse structures vary in diameter form 2 m to a few centimetres; they are also 2 m to a few centimetres deep. Examples larger than 1m are rare and only one 2 m example is known from the northern side of the peninsula. These structures occur in abundance along specific horizons which typically lie above convoluted sandstone beds (subfacies 3F). Some sandstone beds thicken over dewatering collapse structures (Plate 16C). Several circular depressions can be seen on a bedding surface corresponding to underlying dewatering collapse structures (Plate 17).

Collapse structures are interpreted to have formed at the surface due to the dewatering of underlying sandstone beds. The thickened sandstone beds over dewatering collapse structures (Plate 16C) suggest that the circular depressions existed prior to, or contemporaneously, with deposition of the sandstone.

Interpenetrative cusps (Owen, 1995), cusps (Owen, 1996) and sand volcanoes can be seen in cross section throughout the Ferryland Head Formation. Both structures are rare in the lower section (Flat Point section) but common in the Ferryland Head section and lower Lighthouse section. They occur in the tops of beds within facies 3 deposits and almost exclusively occur above convoluted sandstone horizons (subfacies 3F). In a few examples (Plate 18), the laminations in the volcanic edifice can be seen. All cusps and sand volcanoes are less than 1.5 m across and less than 0.6 m thick. These structures are interpreted to have formed by a combination of liquefaction and fluidization. When fluidized sediment ruptures the surface sediment, it is deposited as a volcano-like structure at the surface. This can happen both subaqueously and subaerially (Allen, 1982b). The sand volcanoes, cusps and penetrative cusps, form as a result of dewatering of rapidly deposited sand. Clearly the thick sandstone beds comprising facies associations I and IIa accumulated rapidly, perhaps during the flood stage in a river.

There is an abundance of bed-normal to near bed-normal, lenses to circular shaped and sand-filled structures in the interlaminated sandstone and siltstone subfacies

1E (Plate 19). These structures vary from millimetre to decimetre scale. The structures typically have well defined, sharp boundaries that cut across depositional laminations. The fill within these features is structureless. These cross cutting features are interpreted as dewatering pipes. Dewatering pipes are believed to form due fluidized sand escape from overpressured, water-saturated sand beds. Once a weak zone fails and ruptures, the void is filled with locally derived fluidized sediment. The trigger for fluidization in this case is believed to be the creation of volume due to the tensional forces. These structures might therefore be genetically different from sandstone dykes because forceful injection might not have occurred.

Complete, polygonal, sand-filled shrinkage crack are abundant throughout the Ferryland Head Formation. The polygons are typically hexagonal and 10–15 cm across. The sand-filled cracks are v-shaped in cross section, less than 1 cm wide and less than 2 cm deep (Plate 6). These are interpreted as desiccation cracks (Plummer and Gostin, 1981). They increase in abundance toward the top of the Ferryland Head Formation but also occur in the lower parts of the section. Incomplete shrinkage cracks are similar to the desiccation cracks but have a spindle shape and have been interpreted as synaeresis cracks (Plate 20). Synaeresis cracks are common in the Ferryland Head Formation and there is no obvious trend associated with their stratigraphic distribution. Synaeresis cracks are believed to form subaqueously in an environment of salinity fluctuations (Kuenen, 1965; Burst, 1965; Plummer and Gostin, 1981).

Convolute bedding involves partial liquefaction of rapidly deposited sediment. It is characterized by folded or contorted bedding overlying undeformed strata, typically with erosional truncations of the top. The contorted laminations commonly have rounded synforms and cuspate antiforms. There are two types of convoluted bedding that occur in the Ferryland Head Formation. The first type is large-scale convolute bedding in the sand-rich facies 3. These convoluted horizons are always underlain by undeformed master surfaces or beds. The second type of convolute bedding is much smaller in scale. Convolute beds within the heterolithic facies are commonly less than 15 cm thick and extend laterally for several metres (Figure 2.3 B). The cause for convolution can be inferred in some cases where there is a direct association between convolution and an overlying wave-rippled horizon (Plate 8A and 10D). Shearing from oscillatory motion or differential pressure due to passing waves, might trigger loading.

Loaded ripple structures (Plate 7), loaded siltstone laminae, pillows (Plate 8B), flame structures and pseudonodules are common small-scale structures in the Ferryland Head Formation. Loaded interlaminated siltstone and sandstone is relatively common (Plate 21). These are interpreted to be incipient load structures (Anketell et al., 1970).

Rolled up siltstone laminae or roll-up structures are common in the heterolithic facies (Plate 22A). The structures are composed of flattened spirals of coiled siltstone laminae. When extended, the length of rolled up siltstone can be as much as 20 cm. These structures are interpreted to have formed by disruption of interlaminated non-cohesive sand and cohesive silt. The silt laminae when broken by shrinkage cracks, dewatering pipes, cracks due to loading, or dykes, were easily plucked up by currents and rolled up as they moved downstream. These structures can therefore be used as paleoflow indicators in the Ferryland Head Formation.

There is only one known example of synsedimentary faulting in the Ferryland Head Formation (Lighthouse section, 175 m, figure 3.5, Appendix 1). Several authors (Elliot, 1986; Galloway, 1998) believe that synsedimentary faulting can be indicative of slope deposition. Its absence in the Ferryland Head might suggest that the depositional gradient was relatively flat, although the presence of ruptured and separated siltstone laminae (Plate 22), suggest that some gradient was present at least locally.

The abundance of soft sediment deformation in the Ferryland Head Formation suggests that the sediment was unstable shortly after deposition. This in turn suggests rapid depositional rates, periodic shocking, and/or slope instability. The absence of faulting suggests a relatively flat environment. Deposition must have therefore been fast and episodic such as in seasonal flash floods. The presence of ash-rich sandstone (facies 5), although uncommon and most likely reworked, is suggestive of a distant volcanic source. Although there was a decrease though time in Avalon Zone volcanism, volcanic activity associated with the Avalonian Orogeny is interpreted to have been ongoing at the time of deposition.

Soft sediment deformation in the Ferryland Head Formation is so common that a sedimentological predisposition to liquefaction is inferred, probably a result of rapid deposition. The seismicity in the area, associated with the late Precambrian Avalonian Orogeny, is probably responsible for the abundance of synsedimentary deformation when it occurs concentrated along certain horizons. Examples of surfaces similar to the pock-marked cliff-face surface shown in Plate 17 have been recorded in the Recent on mud flats after earthquakes (Singh et al., 2001).

5.3. SUMMARY

Liquefaction and fluidization, density inversion, slope failure, and shear stress are all causes of synsedimentary deformation in thee Ferryland Head Formation. Sandstone dykes and sills, dewatering collapse structures, interpenetrative cusps, cusps, sand volcanoes and dewatering pipes are all the result of liquefaction and fluidization. Shrinkage cracks are a result of shear stresses caused by the removal of pore fluid pressure in cohesive sediment and rolled up siltstone laminae are the result of current shearing. Convolute bedding, loaded ripple structures, load casts, pillows, flame structures and Pseudonodules are all the result of density inversion and partial or total liquefaction. Synsedimentary faulting results from slope instability.

None of the structures present in the Ferryland Head Formation is attributable to an organic origin. The burrow-like appearance of some of the structures (especially the dewatering pipes) results from the cohesive nature of the interlaminated sand and silt. The only organic factor in these structures is the possible organic binding of the sediment making it more cohesive allowing sharp-edged dewatering pipes to have formed.

PLATE 15: SANDSTONE DYKES

A: Examples of sandstone dykes and sills from the lower Flat Point section. Note how the dykes connect sills of different stratigraphic elevation. The sandstone dykes and sills have been highlighted and their edges outlined by a dashed line.
B: Example of sandstone dykes and sills which have caused the sediment to almost become brecciated (lower Flat Point section).
C: Examples of discrete dykes connecting sandstone laminae (Flat Point section). The sandstone dykes and sills have been outlined by a dashed line and highlighted for clarity.
D: Sandstone dykes and sills from the lower Flat Point section. The structures are highlighted and outlined for clarity.

N.B. All examples show a cross-sectional view. Stratigraphic up is shown by the black arrow on the upper right corner of the plate.


A
5 cm
B
C
D
5 cm

PLATE 16: COLLAPSE STRUCTURES

A: A very small dewatering collapse structure from the lower Lighthouse section. The dewatering structure shown here only involves one bed. The lower edge of the structure is outlined by the dashed line.

B: A large dewatering collapse structure from the lower Ferryland Head section. In this example the sand which fills the structure is silty. A few siltstone laminae are chaotically arranged at its base. The structure is outlined by a dashed line.

C: Dewatering collapse structure from the upper Lighthouse section showing that the collapse occurred contemporaneously with sedimentation of the overlying bed or soon after. The dashed white line outlines the structure.

D: An example of a large dewatering collapse structure involving several sandstone beds. This structure is similar to Owen's (1995) penetrative cusps but the laminae instead of curving upward curve downward. Dashed black lines show the curvature of deformed laminae.

E: A large example of a dewatering collapse structure from the upper Lighthouse section. The structure is outlined by a white dashed line.

N.B. All examples show a cross-sectional view. Stratigraphic up is shown by the white arrow on the upper right corner of the plate.

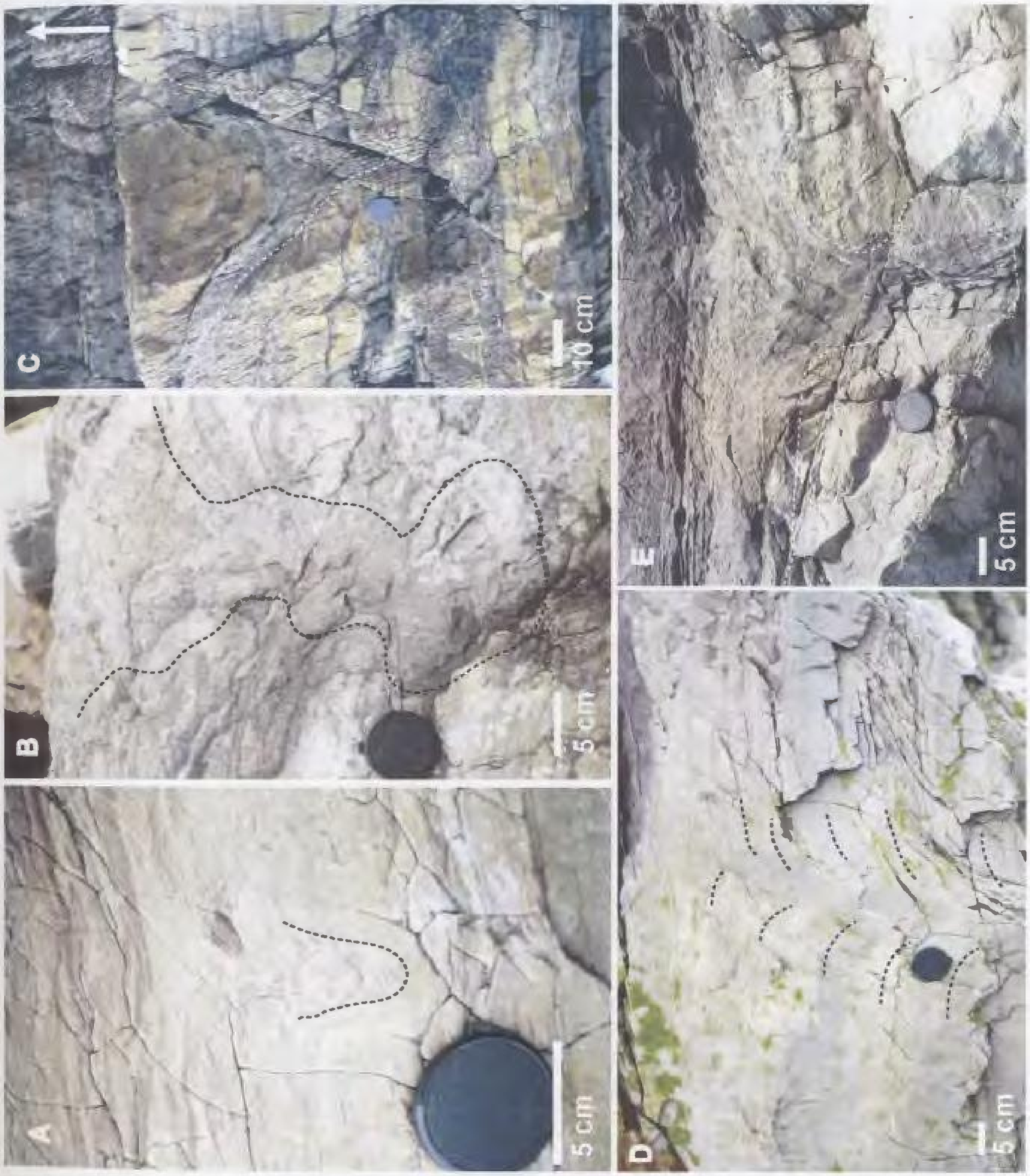

A
5 cm
B
5 cm
C
10 cm
D
5 cm
E
5 cm

PLATE 17: DEWATERING COLLAPSE STRUCTURES ON BEDDING-SURFACE

A cliff face north of the lighthouse (lower Lighthouse section) shows the surface expression of dewatering collapse structures (white arrows). The width of the cliff is approximately 9 metres. Desiccation mudcracks can be seen on the left centre of the photograph (black arrows).

PLATE 18: SAND VOLCANOES

A: Example of large sand volcano from the upper Lighthouse section. Note the laminated volcano structure pinching out laterally from the central cone. Laminae are indicated by the arrow.

B: Cuspate laminated sandstone from the lower Ferryland Head Formation. Dashed lines show the curvature of the laminae.

C: An example of a diapiric structure in sandstone from the lower Ferryland Head section. The structure is outlined by a dashed line.

N.B. All examples show a cross-sectional view. Stratigraphic up is shown by the black arrow on the upper right corner of the plate.

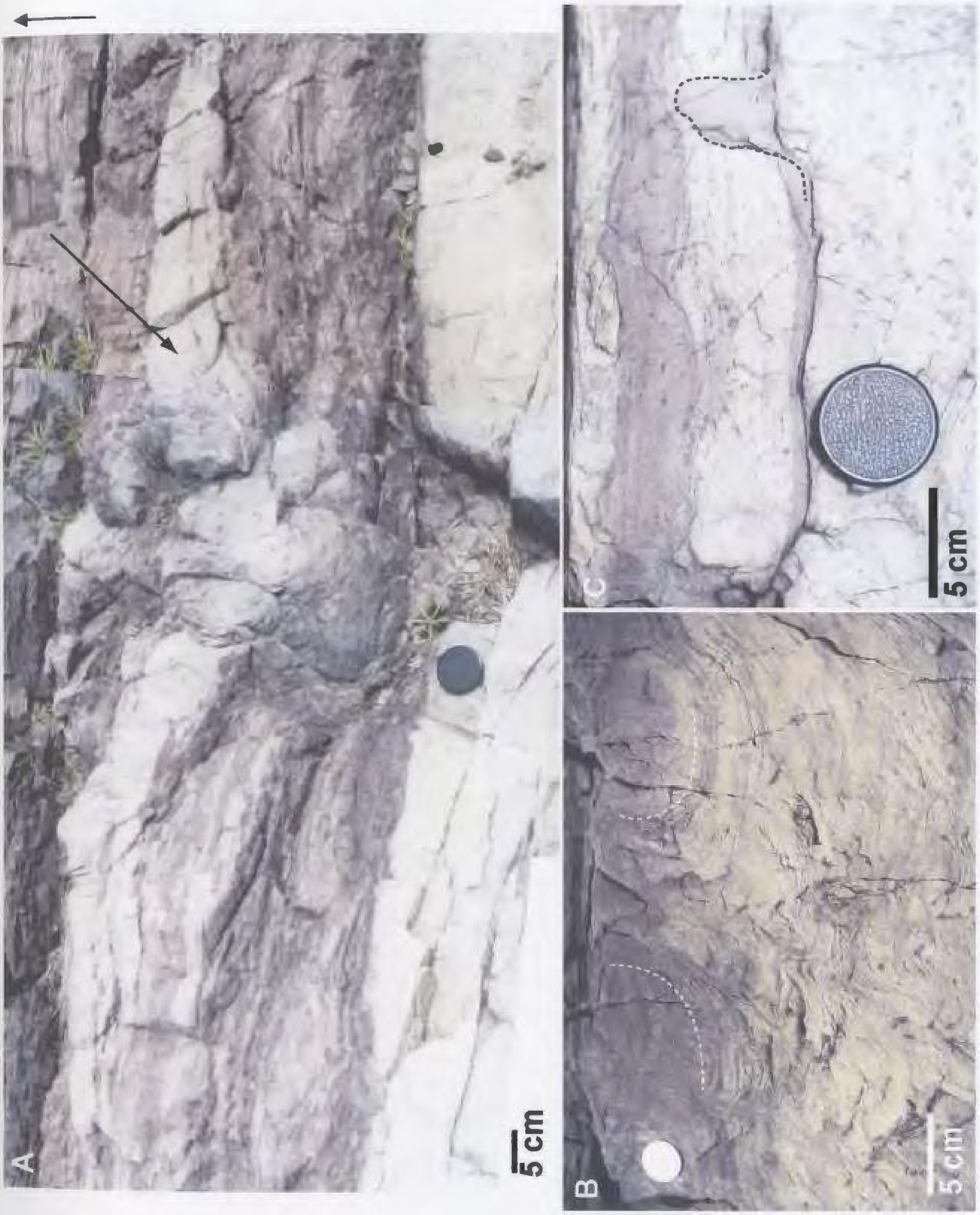

A
5 cm
B
5 cm
C
5 cm

PLATE 19: DEWATERING PIPES

A: Example of dewatering pipes in sandstone and siltstone from the lower Flat Point section. Note the sharp edges of the structure and structureless sand within it.
B: An example of an oval-shaped dewatering pipe. The edges of this structure are rounded possibly due to fluidisation of, and erosion by sand.
C: An example of a dewatering pipe from the lower flat Point section.
D: An example of a rounded dewatering pipe from the lower Flat Point section. As in shown in B, the edges have been possibly eroded by fluidized sand.

N.B. All structures have been outlined by dashed lines and highlighted. All examples show a cross-sectional view. Stratigraphic up is shown by the black arrow on the upper right corner of the plate.

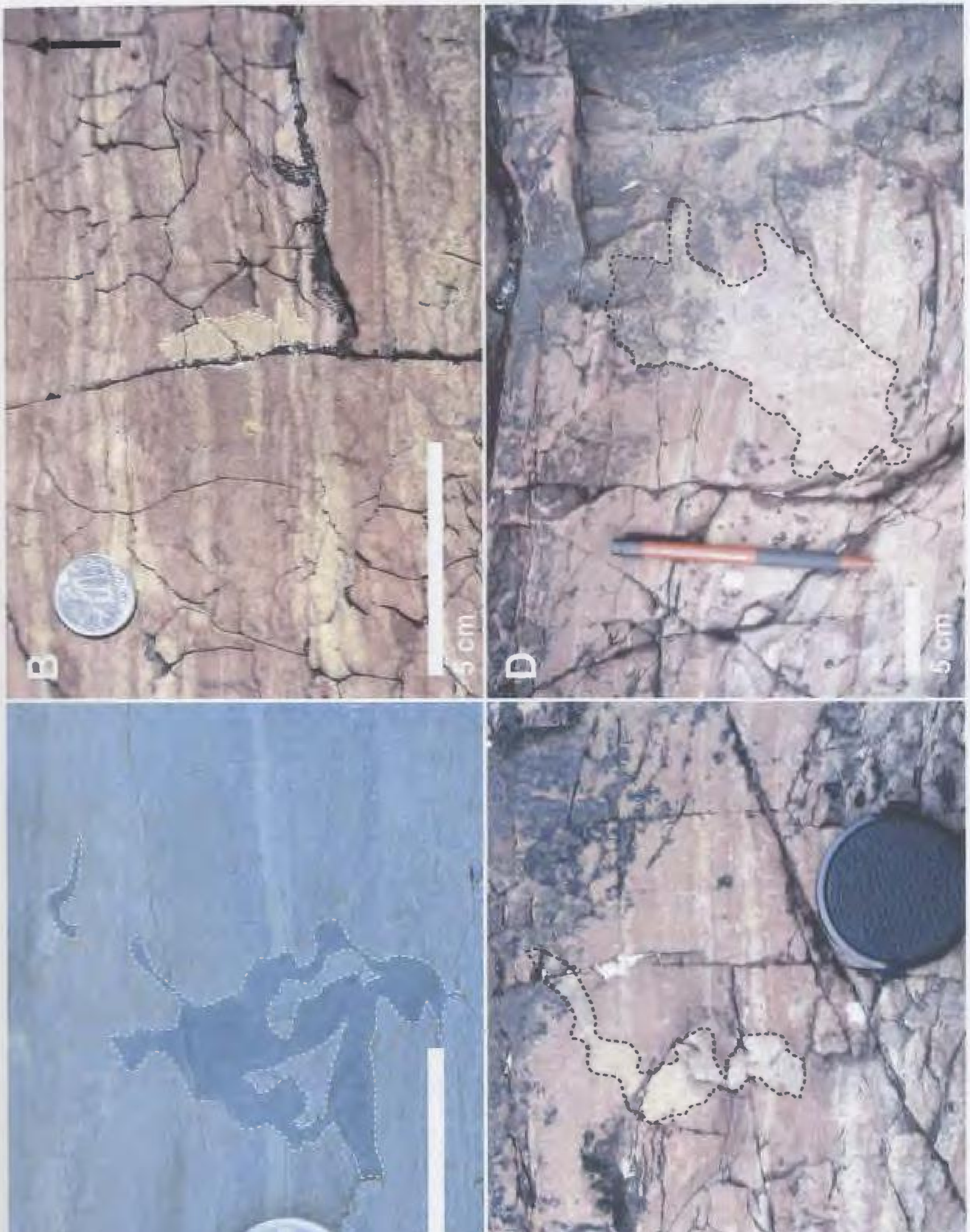

A
5 cm
B
5 cm
C
5 cm
D
5 cm

PLATE 20: SYNAERESIS SHRINKAGE CRACKS

A: Wave-crest-parallel synaeresis cracks seen on a bedding-surface from the Lower Flat Point section. Note that cracks taper laterally and connectivity between them is poor.

B: Possible synaeresis or desiccation cracks from the middle Flat point section. The cracks were filled with sand and later covered in a layer of silt. Cracks are indicated by black arrows (cross-sectional view; stratigraphic way up is towards top of page).

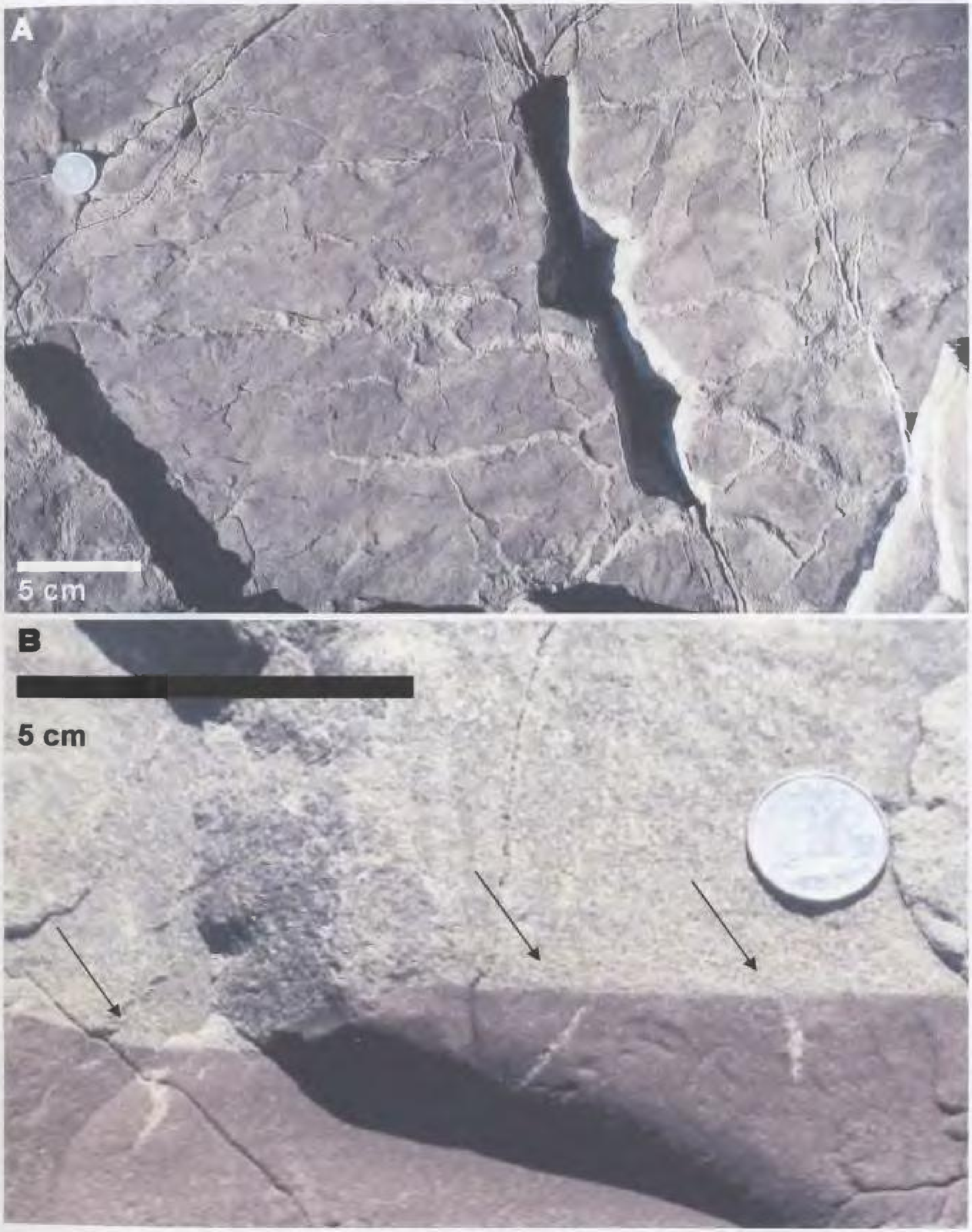

A
5 cm
B
5 cm

PLATE 21: LOADED SILTSTONE LAMINAE

A: Cuspate interlaminated siltstone and sandstone laminae from the lower Lighthouse section formed as a response to loading.
B: An example of loaded interlaminated siltstone and sandstone from the lower Lighthouse section. These are incipient load structures.

N.B. All examples show a cross-sectional view. Stratigraphic up is shown by the black arrow on the upper right corner of the plate.

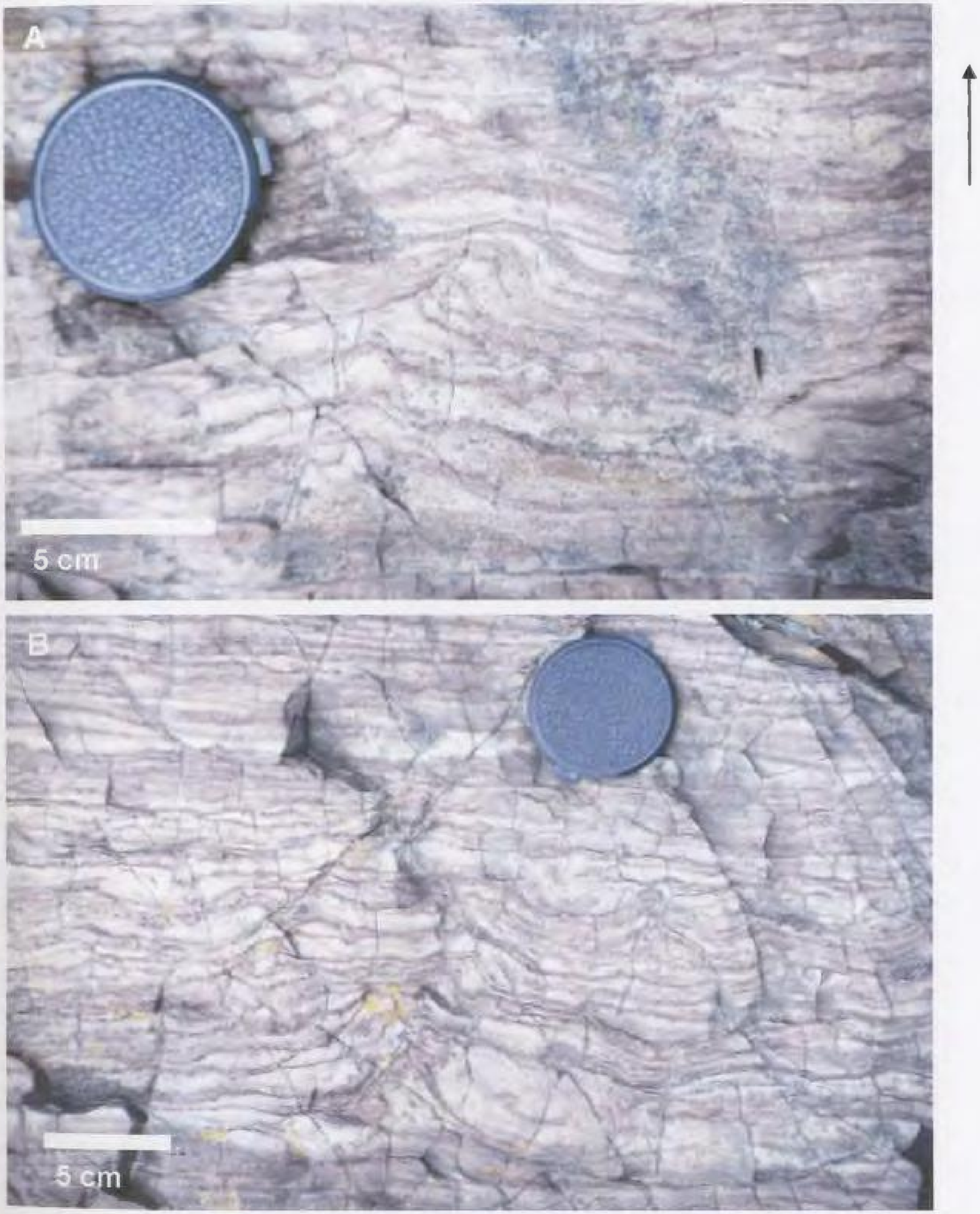
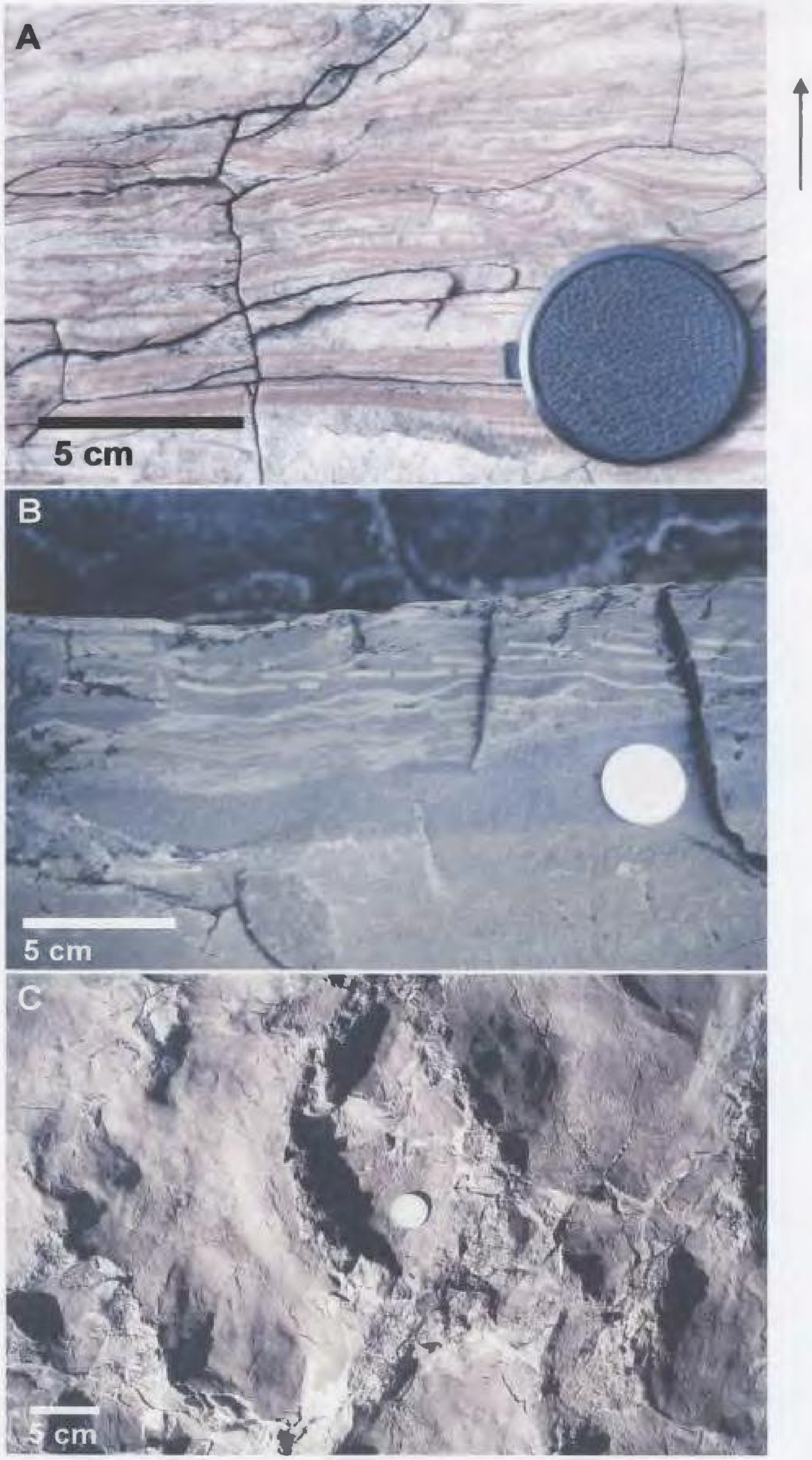

A
5 cm
B
5 cm

PLATE 22: ROLL UP STRUCTURES AND LOADED SILTSTONE CRACKS

A: Roll-up structure from the lower Lighthouse section. Direction of palaeoflow is from right to left.
B: Broken siltstone laminae from the lower Flat Point section that have been pulled apart either as a response to shearing from currents or movement down a palaeoslope.
C: Polygonal cracks in silt, filled with sand from the underlying bed. These structures form as a response to loading and might be mistaken for desiccation or synaeresis cracks.

N.B. All examples show a cross-sectional view. Stratigraphic up is shown by the black arrow on the upper right corner of the plate.


A
5 cm
B
5 cm
C
5 cm

Chapter 6

DEPOSITIONAL MODEL FOR THE FERRYLAND HEAD FORMATION: DISCUSSION

6.1. PREVIOUS INTERPRETATION

The Ferryland Head Formation has been previously interpreted as the distal equivalent of the Quidi Vidi and Cuckold formations. The Quidi Vidi and Cuckold formations are in turn believed to be the deposits of a braided alluvial-plain to alluvial-fan complex (Williams and King, 1979; O'Brien and King, 1982; King et al., 1988a, 1988b;). During the early stages of the development of the alluvial-fan–alluvial-plain complex, the sediment source is thought to have been uplifted equivalents of the Conception Group. Due to continuing uplift to the north of the present-day Avalon Peninsula, related to the Avalonian Orogeny, even older igneous intrusions and volcanic rocks become an additional sediment source during the later stages of sedimentation. This represents progressive unroofing of the source.

The more proximal alluvial-fan facies in the northern part of the basin comprise debris-flow and sheet-flow deposits characteristic of alluvial-fans (O'Brien and King, 1982; King et al., 1988a, 1988b). However, the details of the morphology and evolution of the basin are not well known. An arc-related or strike-slip setting was suggested by Myrow (1995), Murphy et al. (1999) and Narbonne et al. (2001) based on characteristics of the basal volcanic succession (Harbour Main Group), with the chemistry of rift volcanics in pull-apart basins. Oblique subduction is believed to be responsible for strike-slip motion in contemporaneous rocks of the Avalon superterrane in New

Brunswick, Nova Scotia and Great Britain (Narbonne et al., 2001; Myrow, 1995; Murphy et al., 1999, 2001). Narbonne et al. (2001, p.2) suggested that deposition took place "in a tectonically active, transtensional and/or transpressive basin".

6.2. FACIES ARCHITECTURE AS EVIDENCE FOR DEPOSITIONAL ENVIRONMENT

The grain size in the Ferryland Head Formation ranges from silt to coarse sand. The Ferryland Head Formation lacks conglomerates other than intraformational conglomerates. The most common sand grain size is fine sand. There is an abundance of channellised sandstone bodies (facies association II; Plate 16). The sandstone bodies are tabular, composed of fine to coarse sandstone encased within fine-grained sediment. Tabular and trough cross-bedding (subfacies 3A) are common in the Ferryland Head Formation, particularly in the distributary channels (facies association IIa), and less so in the mouthbar deposits (facies association I). The average thickness of the channels (i.e. channel depth) is two metres. Widths of the channels are unknown due to the combination of a stratigraphic dip-sectional view and low sinuosity of channels. The channels are interpreted as relatively straight distributary channels of low mobility. This interpretation is inferred from the unimodal palaeoflow directions (Plate 15) and the abundance of fine grained, cohesive interdistributary deposits. The paucity of lateral accretion conforms to the fluvial style interpreted. The abundance of interdistributary silt allowed the formation of deeper more stable channels (possibly anastomosed) than those typical of braided systems (Eriksson et al., 1998). The more proximal braided feeder channels became more fixed within in the silty fringe of the delta. This coastal silt-fringe in deltas associated with alluvial-fan–braidplain systems is common in Precambrian successions (Smith, 1983).

The scarcity of wave-generated structures and abundance of unidirectional structures (cross-bedding and current-ripples) in the Ferryland Head succession suggests that deposition was dominated by fluvial processes (Figure 6.1). The fine-sand grain-size range and abundance of silt places the Ferryland Head Formation somewhere between the mixed mud/silt and sand-dominated fields in Orton's (1988) delta classification (Figure 6.1).

There is abundant evidence for shallow water and emergence (micro-wave ripples and desiccation cracks in the interdistributary deposits of facies association IIIb. The profusion of synsedimentary deformation structures suggests that deposition was rapid and that sediments remained waterlogged after burial. Paleosols are common in non-marine Precambrian sedimentary deposits (Eriksson et al., 1998). Their absence in the Ferryland Head Formation, in spite of the evidence for emergence and extremely shallow water, indicates that water tables must have been relatively high. High water tables were common for humid-climate, perennial–ephemeral fluvial systems of the Precambrian (Eriksson et al., 1998). The inferred high water-table accounts for the profusion of synsedimentary deformation structures and the absence of palaeosols (Eriksson et al., 1998; Tisgaar and Øxnevad, 1998).

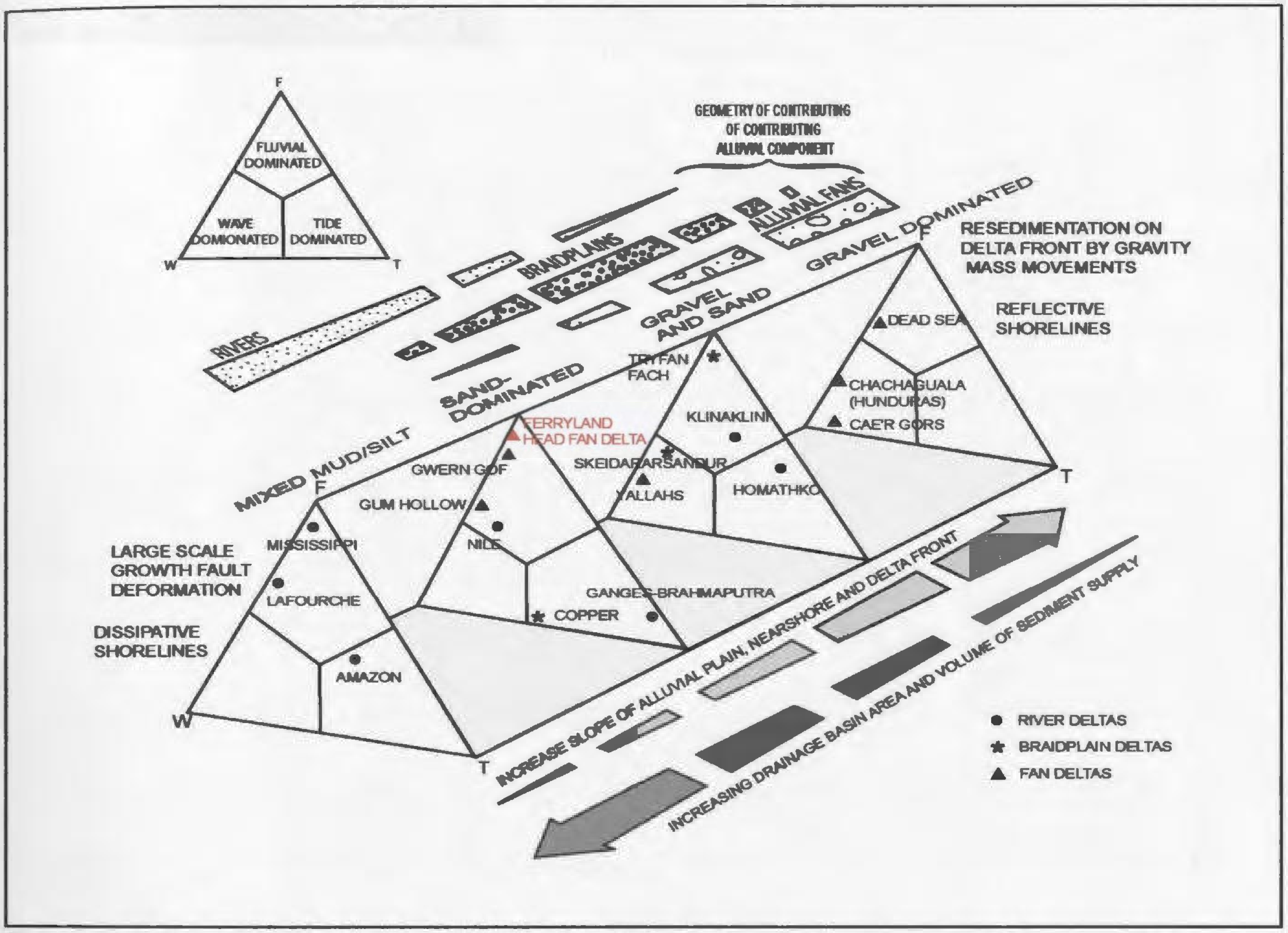


Figure 6.1. Expanded ternary diagramme showing modern and ancient deltas. The Ferryland Head Formation fan delta is shown in relation to other known deltas (modified from Orton, 1988).

6.3. A DEPOSITIONAL MODEL

The main criterion for the recognition of deltaic depositional systems is the transition from non-marine depositional environments such as alluvial deposits, to open-marine depositional environments such as shelfal or deep basinal deposits (Eriksson et al., 1998). In the Avalon stratigraphy, the Ferryland Head Formation is underlain by the Gibbet Hill Formation, interpreted to be shallow marine deltaic sediments (King et al., 1988a), and the Cappahayden Formation, interpreted to be delta front to prodeltaic deposits (Narbonne et al., 2001). The Ferryland Head Formation is overlain by the Cape Ballard and Cuckold formations, both of which have been interpreted as terrestrial alluvial-plain and distal alluvial-fan deposits (King et al., 1988b).The Ferryland Head Formation is therefore transitional between overlying terrestrial (Cuckold Formation) and underlying marine (Cappahayden Formation) deposits. The depositional environment for the Ferryland Head Formation is consequently inferred to be deltaic.

6.3.1. DISTINCTION BETWEEN BRAID DELTAS, BRAIDPLAIN DELTAS, FAN DELTAS AND ALLUVIAL-FANS

As a consequence of rapid physical and chemical weathering, severe erosion, and the absence of vegetation to bind loose material, braidplain systems characterised by high sediment discharge rates were common in the Precambrian (Eriksson et al., 1998). There are abundant Precambrian examples of coarse grained deltaic systems. A few examples include the Witwatersrand Supergroup (Minter, 1978), the Archaean Moodies Group (Eriksson, 1979; Eriksson et al., 1998), Hedmark Group, southern Norway (Dryer, 1988),

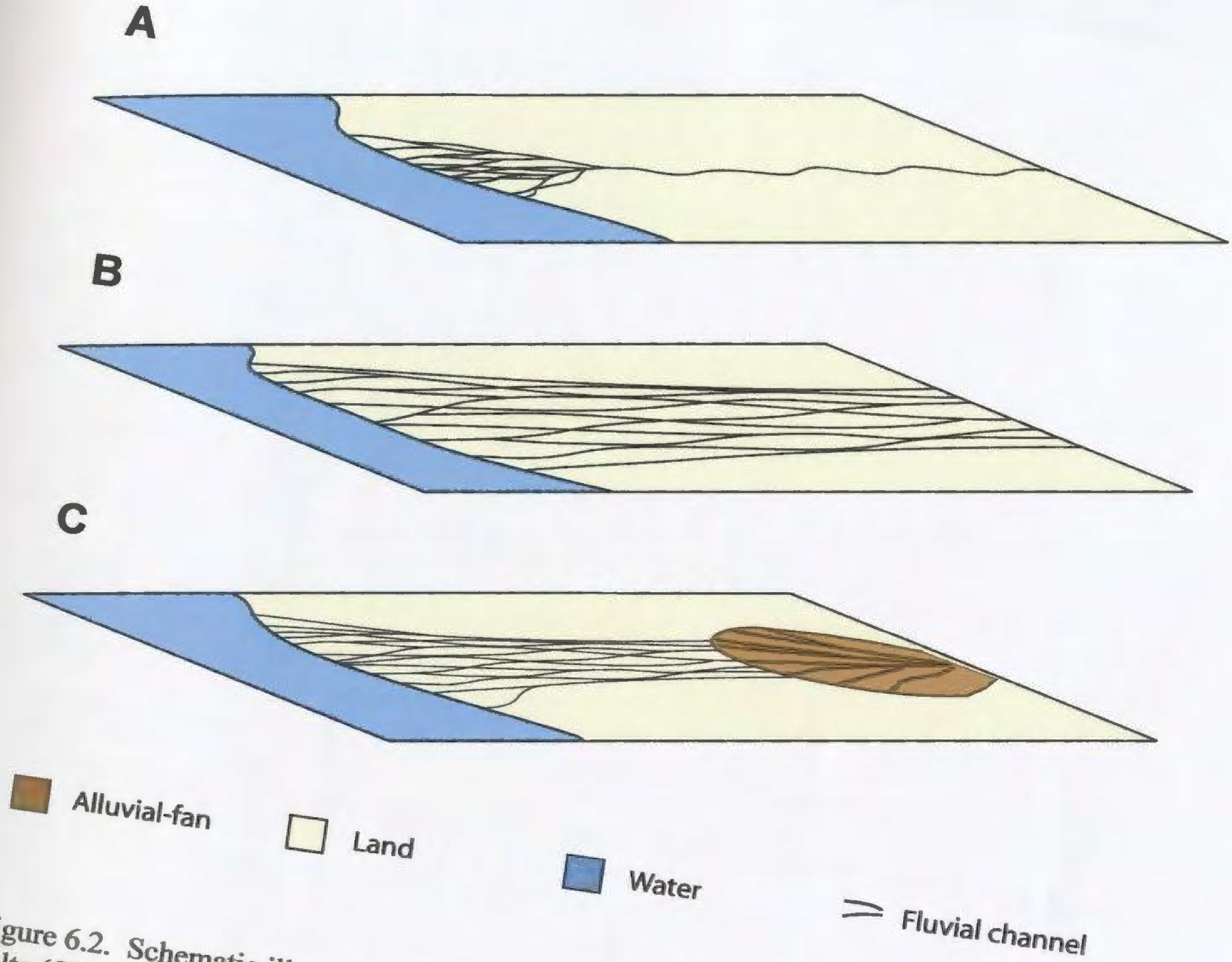


Figure 6.2. Schematic illustration of a braid delta (A), braidplain delta (B), and a fan delta (C) (modified from Nemec and Steel, 1988).

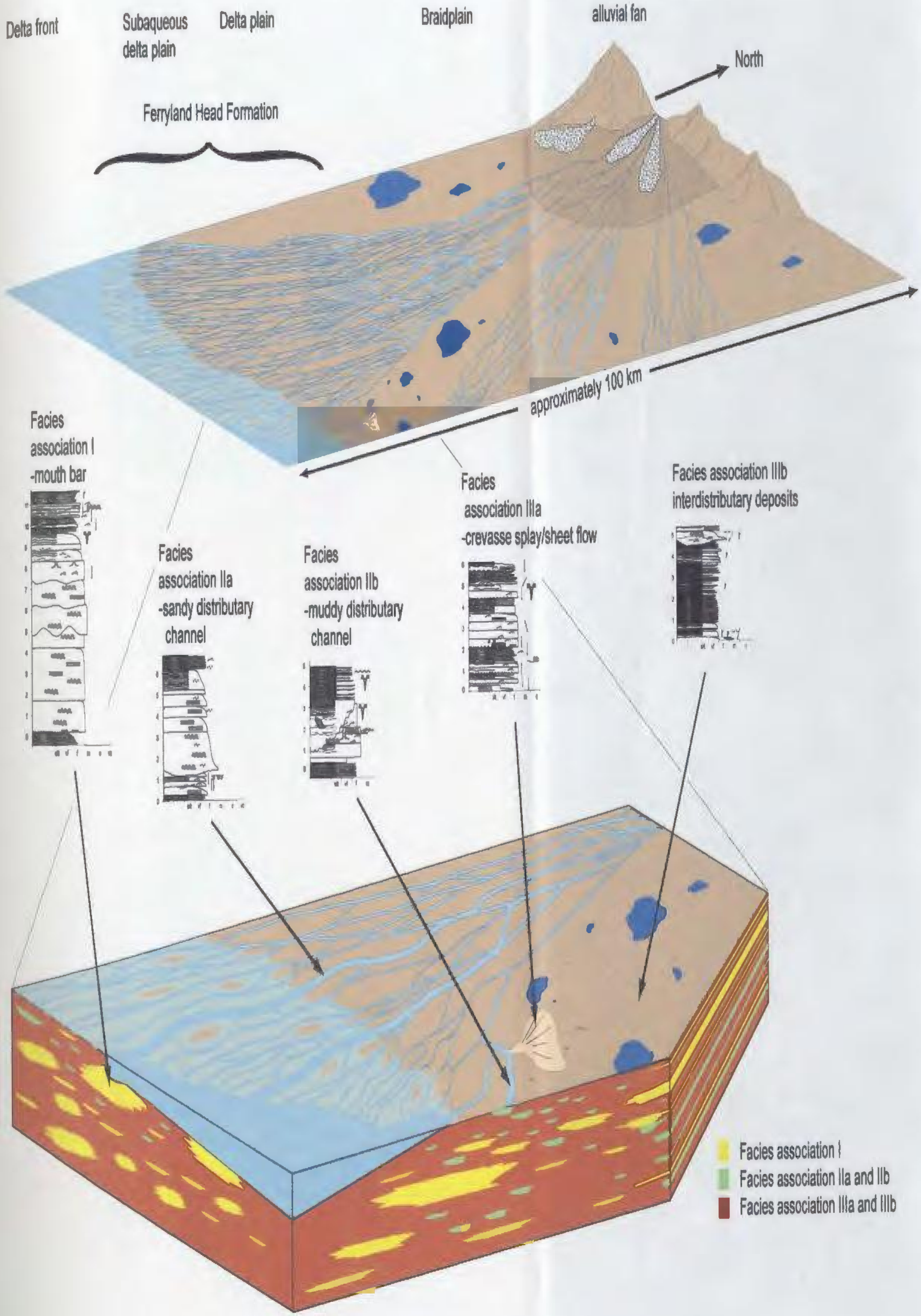
Godkeila Member, northern Norway (Røe, 1995) and the Ingta, Backbone Ranges, and Vampire formations in the Mackenzie Mountains (MacNaughton et al., 1997). McPherson et al. (1988) also note an abundance of braid delta deposits in Pleistocene sediments and pre-Devonian rocks.

There has been much debate about the recognition and classification of coarse-grained deltaic successions (McPherson et al., 1988; Nemec and Steel, 1988; Orton, 1988; Nemec, 1990). Braid deltas (Figure 6.2A) are defined as coarse-grained deltas with braided distributaries that are fed by a solitary river flowing into a standing body of water (Orton, 1988). Without a standing water body the distributary network would revert to a solitary braided river (Nemec and Steel, 1988). Braidplain deltas (Figure 6.2B) are defined as the delta of a braidplain with no upstream transition into proximal alluvial-fan deposits (i.e. those characterized by debris flows) (Orton, 1988). Fan deltas (Figure 6.2C) were originally defined by Holmes (1965) to be the deposits of an alluvial-fan which has prograded into a standing body of water. In this study, a fan delta is defined as the deltaic sediments formed as a result of an alluvial-fan being in contact with a body of standing water (Nemec and Steel, 1988). In other words these are the deposits of deltas, for which the sediment supply is an alluvial-fan. Alluvial-fans are characterised by interbedded gravity-flow and water-lain deposits (debris-flow and sheet-flow deposits, respectively) (McPherson et al., 1988). Braided river deposits can be distinguished from alluvial-fan deposits by their deeper channels suggestive of a more sustained flow of the fluvial system as well as by the abundance of cross stratification and lack of debris-flow deposits (McPherson et al., 1988).

6.2.2. THE FERRYLAND HEAD FORMATION: A HUMID FAN DELTA

Gravity-flow deposits are considered important and integral elements of alluvial-fans (McPherson et al., 1988). Debris-flow deposits are absent in the Ferryland Head Formation. Sediments interpreted as an alluvial-fan are known, however, from more proximal areas toward the north (King et al., 1988a). In the absence of alluvial-fan deposits, and only braidplain deposits to the north, the Ferryland Head Formation, could be interpreted as a braidplain delta (Orton, 1988). Given the presence of an alluvial-fan to the north of the study area and the interpretation of the Ferryland Head formation as the distal equivalents of the Quidi Vidi and Cuckold formations (Williams and King, 1979; King et al., 1982; King et al., 1988 a, 1988b; King 1990), the Ferryland Head Formation is interpreted as a fan delta *sensu strico* (Nemec and Steel, 1988). Because of the abundance of soft-sediment deformation, the presence of small-scale wave-generated structures, and the lack of paleosols, it is concluded that much of the Ferryland Head Formation was deposited subaqueously in very shallow water (Figure 6.3). The paucity of wave generated structures, the absence of large-scale wave-generated structures (i.e. swaly or hummocky cross stratification), and the average thickness of the mouth-bar deposits (5 metres for facies association I) indicate that the delta was prograding into a low energy, shallow body of water. The gradient of the braidplain and delta plain is believed to have been low, resulting in a "mouth bar type delta" (Wood and Ethridge, 1988). The low gradient of the depositional system, making it a dissipative shoreline, also accounts for the paucity of wave generated structures (Orton, 1988). The low gradient for the alluvial-fan–braidplain–fan delta complex suggests that deposition might have taken place in a humid, temperate climate (Orton, 1988; Ramli, 1988)

Figure 6.3. Palaeogeographic reconstruction for the depositional environment of the Ferryland Head Formation. The whole alluvial-fan–braidplain–fan delta complex is shown in the upper part of the figure. The width of the diagramme is approximately the distance from the town of Ferryland to the area just north of St. John's (approximately 80 kilometres). The lower diagramme is a close up of that part of the reconstruction indicating the environment of deposition of the Ferryland Head Formation. Note that a large portion of the delta plain is submerged. The five facies associations described in chapter four are shown and the arrows point to where they would have occurred on the fan-delta plain. A cross-sectional view of the subsurface architecture of the facies association is shown in relation to the stratigraphic down-dip view seen in outcrop. Note that the crevasse splays shown on the surface can have palaeoflow indicators opposite to the overall palaeoflow direction.


Delta front
Subaqueous delta plain
Delta plain
Braidplain
alluvial fan
North
Ferryland Head Formation
approximately 100 km
Facies association I -mouth bar
Facies association IIa -sandy distributary channel
Facies association IIb -muddy distributary channel
Facies association IIIa -crevasse splay/sheet flow
Facies association IIIb interdistributary deposits
Facies association I
Facies association IIa and IIb
Facies association IIIa and IIIb

Chapter 7

CONCLUSIONS

7.1. KEY CONCLUSIONS

The Ferryland Head Formation belongs to the upper Neoproterozoic Signal Hill Group and crops out along the southeastern shore of the Avalon Peninsula, Newfoundland and Labrador. The top of the Formation is not exposed in the study area. It is conformably underlain by the marine Gibbett Hill Formation. The Ferryland Head Formation is considered a distal equivalent of the terrestrial Cuckold and Quidi Vidi formations.

The High Rocks Member of the Ferryland Head Formation consists of interbedded tabular reddish-to-purplish-brown siltstones, and buff to greenish grey sandstones. Five lithofacies incorporating 22 subfacies are defined at Ferryland Head (Table 4.1). Lithofacies are designated according to overall lithology, whereas subfacies are defined by the presence or absence of particular sedimentary structures. Facies 1 comprises 11 subfacies composed of siltstone and the finer grained sandstones representing deposition in generally low but fluctuating energy environments. Facies 2 includes 4 subfacies composed of silty sandstone. Facies 3 comprises 7 subfacies and is composed of clean sandstone. Facies 4 and 5 comprise intraformational conglomerates and ash-rich beds respectively.

Three facies associations are recognised in the Ferryland Head Formation (Table 4.2). Facies associations are defined by the co-occurrence of a number of facies and subfacies, and the stratigraphic order in which they occur. Facies association I comprises upward coarsening or thickening packages of sandstone (facies 3) and is interpreted as mouth-bar deposits. Facies association II is subdivided into two end members representing a continuum of channel environments. Facies association IIa is interpreted as high energy, (possibly anastomosed) distributary channel deposits. Facies association IIb is interpreted as low energy, possibly meandering distributary channel deposits. Facies association III is also subdivided into two end members of a spectrum. It comprises tabular unchannelised deposits. Facies association IIIa comprises stacked, tabular, normally-graded beds less than a metre thick (Figure 4.5) consisting mainly of facies 2, sparsely intercalated with beds of facies 1.

Facies association IIIa is interpreted as crevasse-splay and sheet-flow deposits. Facies association IIIb, characterized by tabular, laterally continuous, fine grained heterolithic beds of facies 1, punctuated by a few thin sandstones of facies 2, is interpreted as overbank deposits more distal from the channel axis than those of facies association IIIa.

Due to its stratigraphic position below terrestrial deposits (Cuckold and Quidi Vidi formations) and above marine deposits (Gibbet Hill and Cappahayden formations), the overall depositional setting of the Ferryland Head Formation is inferred to be deltaic. The presence of a braidplain fed by an alluvial fan to the north of the study area leads to the interpretation of the Ferryland Head Formation as a fan delta with a silty coastal fringe (Figure 6.1). The low gradient for the alluvial fan–braidplain–fan delta complex and the estimated high paleolatitude, suggests that deposition took place in a humid, temperate climate. Deposition is believed to have taken place in a tectonically active pull-apart basin where seismic activity would have promoted synsedimentary deformation of the already weak, waterlogged sediments.

7.2. RECOMMENDATIONS

The age of the Ferryland Head Formation is not well constrained. The age is constrained by U-Pb dating of ash (565±3 Ma) at Mistaken Point (G. Dunning, pers. Comm.. to A. Benus, in Benus, 1988). There are no true ash beds or tuffs in the Ferryland Head Formation which can be dated. There is a tuff bed, however, in the lower part of the Gibbett Hill Formation at Ferryland which might yield zircons for more accurate dating of the Formation.

This study focused on the type locality at Ferryland. The Ferryland Head Formation is also exposed at Cape Ballard to the south and Cape Broyle to the north. Further study is needed to correlate these three outcrop localities of the Ferryland Head Formation in detail and to document the facies variations up-dip and down-dip from the type locality. Special consideration should be given to the upper part of the Ferryland Head Formation which is not exposed at Ferryland.

The channel morphology, as interpreted from the exposures at Ferryland is not well understood. Further study incorporating the other two localities might determine if the channels are anastomosed, braided or meandering. A follow-up study should be done to include the uppermost rocks of the Ferryland Head Formation at cape Ballard to determine if there are facies differences between the High Rocks Member and the rest of the Ferryland Head Formation.

REFERENCES

Allen, J. R. L., 1982a. Sedimentary structures, their character and physical basis, volume 1, Elsevier, 593 p.

Allen, J. R. L., 1982b. Sedimentary structures, their character and physical basis, volume 2, Elsevier, 663 p.

Anderson, M.M. and Morris, S.C, 1982. A review, with descriptions of four unusual forms, of the soft–bodied fauna of the Conception and St. John's Groups (Late Precambrian), Avalon Peninsula, Newfoundland. Proceedings of the Third North American Paleontological Convention, volume 1, p.1–8.

Anketell, J. M. Cegła, J. and Dżułyński, S., 1970. On the deformational structures in a system with reversed density. Annals of the Geological Society of Poland, volume 40, p.3–30.

Arnott, R. W. C., and Hand, B. M., 1989. Bedforms, primary structures and grain fabric in the presence of suspended sediment rain. Journal of Sedimentary Petrology, volume 59, number 6, p.1062-1069.

Bhattacharya, J.P. and Walker, R.G. 1992. Deltas. In: Facies models – response to sea level change. R.G. Walker and N.P. James (editors). Geological Association of Canada, p.157–177.

Bergström, J., 1990. Precambrian trace fossils and the rise of bilaterian animals. Ichnos, volume 1, number 1, p.3–13.

Bland, B. H. and Anderson, M. M., 1982 Reinterpretation of the fossil *Arumberia* from new finds in Newfoundland (abstract). 95th annual meeting, The Geological Society of America Abstracts with Programs - Geological Society of America, volume 14, number 7.

Boggs, S., 1995. Principles of Sedimentology and Stratigraphy (2nd edition).Prentice–Hall, Englewood Cliffs, New Jersey, 774p.

Bowring, S., Myrow, P., Landing, E., Ramezani, J., and Grotzinger, J., 2003. Geochronological constraints on terminal Neoproterozoic events and the rise of metazoans. Geophysical Research Abstracts, volume 5, p.13219.

Buddington A. F., 1919. Precambrian rocks of southeast Newfoundland. Journal of Geology, volume 27, number 6, p.470.

Burst, J. F., 1965. Subaqueously formed shrinkage cracks in clay. Journal of Sedimentary Petrology, volume 35, number 2, p.348-353.

Casagrande, A., 1936. Characteristics of cohesionless soils affecting the stability of slopes and earth fills. Journal of the Boston Society of Civil Engineers, volume 23, number 1, p.19.

Chumakov, N. M., 2003. Global climates of the Vendian. Russian Journal of Earth Sciences, volume 5, number 6. Abstract www.agu.org/wps/rjes/abstract/v05/abjes136.htm

Collinson, J. D., 1986. Alluvial sediments. In: Sedimentary environments and facies Reading (editor), 2nd edition, Blackwell Scientific publications, 194p.

Collinson, J. D. and Thompson, D.B., 1982. Sedimentary structures. George Allen & Unwin.

Crimes, P. T., 1994. The period of early evolutionary failure and the dawn of evolutionary success; the record of biotic changes across the Precambrian–Cambrian boundary. In: The Palaeobiology of Trace Fossils, edited by S.K. Donovan. J. Wiley & Sons, p. 105–133.

Dalziel, I.W.D., 1997. Neoproterozoic–Paleozoic geography and tectonics: Review, hypothesis, environmental speculation. Geological Society of America Bulletin, volume 108, p.16–42.

Droser, M. L., Jensen, S. and Gehling J. G., 2002. Trace fossils and substrates of the terminal Proterozoic–Cambrian transition: Implications for the record of early bilaterians and sediment mixing, Proceding of the National Academy of Science U.S.A., volume 99, number 20, p.12572–12576.

Dryer, T., 1988. Later Proterozoic (Vendian) to early Cambrian sedimentation in the Hedmark Group, southwestern part of the Sparagmite Region, southern Norway. Norges Geologiske Undersøkelse Bulletin 412, page 1–27.

Dżulyński, S., and Kotlarczyk, J., 1962. On load–casted ripples. Annals of the Geological Society of Poland, volume 32, p.148–159.

Dżulyński, S. and Walton, E.K., 1965. Sedimentary features of flysch and greywackes. Developments in Sedimentology, 7. Elsevier, Amsterdam, 274p.

Elliot, T. 1974. Interdistributary bay sequences and their genesis. Sedimentology, volume 21, p.611–622.

Elliot, T. 1986. Deltas. In: Sedimentary environments and facies, Reading (Ed.), 2nd edition, Blackwell Scientific publications, p.113–154.

Eriksson, K. A., 1979. Marginal marine depositional processes from the Archean Moodies Group, Barberton Mountain Land, South Africa: evidence and significance. Precambrian Research, volume 8, p.153–182.

Eriksson, P.G., Condie, K.C., Tirsgaard, H., Mueller, W.U., Altermann, W., Miall, A.D. , Aspler, L.B. , Catuneanu, O. and Chiarenzelli, J.R., 1998. Precambrian clastic sedimentation systems. Sedimentary Geology, volume 120, p.5–53.

Fedonkin, M. A., 1994. Vendian body fossils and trace fossils. In: Bengston, S. (editor), Early life on Earth. Nobel Symposium number 84. Columbia University Press, New York, p.370–388.

Fedonkin, M. A. & Runnegar, B. ,1992. Proterozoic metazoan trace fossils. In: The Proterozoic biosphere, Schopf, J. W. & Klein, C. (editors). Cambridge University Press, Cambridge, p.389–395.

Galloway, W. E., 1998. Siliciclastic slope and base-of-slope depositional systems; component facies, stratigraphic architecture, and classification. American Association of Petroleum Geologists Bulletin, volume 82, number 4, p.569–595.

Gehling, J. G. and Narbonne, G. M., 2000. The first named Ediacaran body fossil, *Aspidella Terranovica*. Palaeontology, volume 43, part 3, p.427–456.

Glaessner, M. F. and Walter M. R., 1975. New Precambrian fossils from the Arumbera sandstone, Northern Territory, Australia. Alcheringa, volume 1, number1, p.59–69.

Hofmann, H. J. and King, A. F., 1979. Late Precambrian microfossils, southeastern Newfoundland. Current Research, Part B, Geological Survey of Canada, Paper 79–1B, p.83–98.

Hofmann, H.J., 1971. Precambrian fossils, pseudofossils and problematica in Canada. Geological Survey of Canada Bulletin, volume 189, p.1–146

Hofmann, H.J., Narbonne, G.M. and Aitken, J.D., 1990. Ediacaran remains from intertillite beds in Northwestern Canada. Geology, volume 18, p.1199–1202.

Hofmann, H. J., Mountjoy, E. W. and Teitz, M.W., 1991. Ediacaran fossils and dubiofossils, Miette Group of Mount Fitzwilliam area. British Columbia. Canadian Journal of Earth Sciences, volume 28, p.1541–1552.

Holmes, A., 1965. Principles of Physical Geology, 2nd edition. New York, Ronald Press, 1288 p.

Jukes, J. B., 1839–1840. General report of the geological survey, Newfoundland, during the years 1839 and 1840. London, England, 1843.

Jensen, S. 2003. The Proterozoic and Earliest Cambrian Trace Fossil Record; Patterns, Problems and Perspectives. Integrative and Comparative Biology, volume 43, number 1, p.219–228.

Jopling, A. V. and Walker, R. G., 1968. Morphology and origin of ripple-drift cross-lamination, with examples from the Pleistocene of Massachusetts. Journal of Sedimentary Petrology, volume 38, number 4, p.971-984.

Kaufman, A. J., Knoll, A. H. and Narbonne, G. M., 1997. Isotopes, ice ages, and terminal Proterozoic Earth history. Proceedings of the National Academy of Science, U. S. A., volume 95, p.6600–6605.

Keppie, J.D. and Dostal, J., 1998. Birth of the Avalonian arc in Nova Scotia, Canada: geochemical evidence for ~700–630 Ma back–arc rift volcanism off Gondwana. Geological Magazine, volume 135, p.171–181.

King, A.F., 1990. Geology of the St. John's Area, Report 90–2, Geological Survey Branch, Department of Mines and Energy, Government of Newfoundland and Labrador, 88 p.

King, A. F., Anderson, M. M. and Benus, A. P., 1988a. Late Precambrian sedimentation and related orogenesis of the Avalon Peninsula, eastern Avalon Zone. Geological Association of Canada/Mineralogical Association of Canada/Canadian Society of Petroleum Geologists Annual Meeting, Trip A4, Guidebook, St. John's, Newfoundland, 84p.

King, A. F., Boyce, W. D., Pickerill, R. K. and Williams, S. H., 1988b. The St. John's Region: Field Excursion Guide Book. Edited by Williams, S. H. Vth International Symposium on the Ordovician System St. John's, Newfoundland (Subcommission on Ordovician Stratigraphy/ International Commission on Stratigraphy, 39 p.

Krogh, T.E., Strong, D.F., O'Brien, S.J. and Papezik, V.S., 1988. Precise U–Pb zircon dates from the Avalon Terrane in Newfoundland. Canadian Journal of Earth Sciences, volume 25, p.442–453.

Kuenen, Ph. H., 1965. Value of experiments in geology. Geolgie en Mijnbouw, volume 44, p.22–36

Landing, E., Myrow, P., Benus, A. P. and Narbonne, G. M., 1989. The Placentian Series: appearance of the oldest skeletalized faunas in southeastern Newfoundland. Journal of Paleontology, volume 63, p.739–769.

MacNaughton, R. B., Dalrymple, R. W. and Narbonne, G. M., 1997.Early Cambrian braid-delta deposits, MacKenzie Mountains, north–western Canada. Sedimentology, volume 44, number 4 p.587–609.

MacNaughton, R.B. and Narbonne, G.M., 1999. Evolution and ecology of Neoproterozoic – Lower Cambrian trace fossils, NW Canada. Palaios, volume 14, p.97–115.

McBride, E. F, 174. Significance of color in red, green, purple, olive, brown, and gray beds of Difunta Group, northeastern Mexico. Journal of Sedimentary Petrology, volume 44, p.760–773.

McIlroy, D. and Walter, M. R., 1997. A reconsideration of the biogenicity of *Arumberia banksi* Glaessner & Walter. Alcheringa 21, 79-80.

McNamara, A.K., 2001. West African proximity of the Avalon terrane in the latest Precambrian. Geological Society of America Bulletin, volume113, number 9, p.1161–1170.

McPherson, J. G., Shanmugam, G., and Moiola, R. J., 1988. Fan deltas and braid deltas: Conceptual Problems. In: Nemec, W., and Steel, R. J., editors, Fan deltas and related systems: Sedimentology and tectonic settings: U. K., Blackie Publishing Group, p.14–22

McPherson, J. G., 1980. Genesis of variegated redbeds in the fluvial Aztec siltstone (late Devonian), southern Victoria Land, Antarctica. Sedimentary Geology, volume 27, p.119–142.

Middleton, G. V. and Hampton, M. A., 1973. Sediment gravity flows: Mechanics of flow and deposition. In: Turbidites and Deep–water sedimentation, Pacific section Society for Sedimentary Geology, p.10–11.

Mills, P. C., 1983. Genesisi and diagnostic value of soft sediment deformation structures – a review. Sedimentary Geology, 35, p.83–104.

Miall, A. D., 1992. Alluvial deposits. In: Facies models – response to sea level change. R.G. Walker and N.P. James (editors), Geological Association of Canada, p.119–142.

Miall, A. D., 1999. Principles of Sedimentary basin Analysis. 3rd Edition. Springer–Verlag, 616 p.

Minter, W., 1978. A sedimentological synthesis of placer gold, uranium and pyrite concentrations in Proterozoic Witwatersrand sediments. In: Miall, A.D. (editor) Fluvial sedimentology. Canadian Society of Petroleum Geologists Memoir 5, p.801–829.

Misra, S. B., 1969. Late Precambrian (?) fossils from southeastern Newfoundland, Geological Society of America Bulletin, volume 80, p.2133–2140.

Misra, S. B., 1971. Stratigraphy and depositional history of late Precambrian coelenterate–bearing rocks, southeastern Newfoundland. Geological Society of America Bulletin, volume 82, p.979–988.

Misra, S. B., 1981. Depositional Environment of the Late Precambrian Fossil-Bearing rocks of Southeastern Newfoundland, Canada. Journal of the Geological Society of India, volume 22,number 8, p372–382.

Morris, S. C., 1989. Southeastern Newfoundland and ajacent aeas. In: Cowie, J. W. and Brasier, M. D. (editors). The Precambrian–Cambrian Boundary. Claredon Press, Oxford.

Murphy, J.B., Keppie, J.D., Dostal, J. and Nance, R.D., 1999. Neoproterozoic–early Paleozoic evolution of Avalonia. In: V.A. Ramos and J.D. Keppie (Editors), Laurentia–Gondwana connections before Pangea. Geological Society of America Special Paper 336, p.253–266.

Murphy, J. B., Pisarevsky, S. A., Nance, R. D. and Keppie, J. D. 2001. Animated history of Avalonia in Neoproterozoic – Early Proterozoic. In: Jessell, M. J. 2001. General Contributions: 2001. Journal of the Virtual Explorer, 3, p.45–58.

Myrow, P. M., 1995. Neoproterozoic rock of the Newfoundland Avalon Zone. Precambrian Research, 73, p.123–136.

Myrow, M. M. and Kaufman, A. J., 1999. A newly discovered cap carbonate above

Varanger–age glacial deposits in Newfoundland Canada. Journal of Sedimentary Research, volume 69, number 3, p.784–793.

Myrow, P. M. and Landing, E., 1992. Mixed siliciclastic–carbonate deposition in a lower Cambrian oxygen–stratified basin, Chapel Island Formation southeastern Newfoundland, Journal of Sedimentary Petrology, volume 62, p.455–473.

Nance, R.D. and Murphy, J.B., 1996. Basement isotopic signatures and Neoproterozoic paleogeography of Avalonian–Cadomian and related terranes in the circum–North Atlantic. In: R.D. Nance and M.D. Thompson (Editors), Avalonian and Related Peri–Gondwanan Terranes of the Circum–North Atlantic Geological Society of America Special Paper number 304, p.333–346.

Nance, R.D., Murphy, J.B. and Keppie, J.D., 2002. A cordilleran model for the evolution of Avalonia. Technophysics, volume 352, p.11–31.

Narbonne, G. M.,. Dalrymple, R. W., Gehling, J. G., Wood, D. A., Clapham, M. E. and Sala, R. A., 2001. Neoproterozoic fossils and environments of the Avalon Peninsula, Newfoundland.Guidebook, Trip B5, Geological Association of Canada/Mineralogical Association of Canada Annual Meeting, St. John's, Newfoundland, 100p.

Narbonne, G. M., Dalrymple, R. W., Gehling, J. G., Wood, D. A., Clapham, M. E. and Sala, R. A., 2002. Life after Snowball Earth: The Mistaken Point Biota and the early evolution of animals. Geological Association of Canada, Newfoundland Section, St. John's, Newfoundland, Canada. Field Trip Guidebook, 49p.

Narbonne, G. M., and Hofmann, H. J., 1987. Ediacaran biota of the Wernecke Mountains, Yukon, Canada. Palaeontology, volume 30, number 4, p.647–676.

Narbonne, G. M., Aitken, J. D., 1990.Ediacaran fossils from the Sekwi Brook area, Mackenzie Mountains, northwestern Canada. Palaeontology, volume 33, p.945–980.

Nemec, W. and Steel, R. J., 1988. What is a fan delta and who do we recognize it?. In: fan deltas:sedimentology and tectonic settings. Nemec, W. and Steel, R.J. (Editors). Blackie and Son, p.3–13.

Nemec, W., 1990. Deltas–remarks on terminology and classification. In: Collelea, A. and Prior, D. B., (editors), coarse grained deltas. Special publication number 10 of the International Association of sedimentologists, p.3–12.

Nio S-D, Yang C-S. 1991. Diagnostic attributes of clastic tidal deposits: a review. In: Clastic Tidal Sedimentology. Smith, D. G., Reinson, G. E, Zaitlin, B.A., Rahmani, R.A. (editors). Canadian Society of Petroleum Geologists, Memoir 16, p.3–28.

O'Brien, S. J. and King, A. F., 1982. The Avalon Zone in Newfoundland. In: Field Guide for the Avalon and Meguma Zones, The Caledonide Orogen IGCP Project 27, Atlantic Canada, NATO Advanced Study Institute, p.1–27.

O'Brien, S. J., Wardle, R. J. and King, A. F., 1983. The Avalon zone: a Pan–African terrane in the Appalachian orogen of Canada. Geological Journal, volume 18, p.195–222.

O'Brien, S.J., O'Brien, B.H., Dunning, G.R. and Tucker, R.D., 1996. Late Neoproterozoic Avalonian and related peri–Gondwanan rocks of the Newfoundland Appalachians. In: Nance, R.D. and Thompson, M.D. (editors), Avalonian and Related Peri–Gondwanan Terranes of the Circum–North Atlantic. Geological Society of America Special Paper 304, p.9–28.

Orton, G. J., 1988. A spectrum of Middle Ordovician fan deltas and braidplain deltas, North Wales: a consequence of varying fluvial clastic input. In: Fan deltas: sedimentology and tectonic settings. Nemec, W. and Steel, R. J. (editors). Blackie and Son, p.23–49.

Owen, G., 1995. Soft–sediment deformation in upper Proterozoic Torridonian sandstones (Applecross Formation) at Torridon, Northwest Scotland. Journal of Sedimentary Research, volume A65, number 3, p.495–504.

Owen, G., 1996. Anatomy of a water–escape cusp in upper proterozoic Torridon Group sandstones, Scotland. Sedimentary Geology, volume 103, p.117–128.

Plummer, P.S. and Gostin, V. A., 1981. Shrinkage cracks: desiccation or synaeresis?. Journal of Sedimentary Petrology, volume 51, number 4, p.1147–1156.

Ramli, N, 1988. Development of a humid, tropical fan-delta system: the middle Tertiary "K" sandstone in the southeastern Malay Basin, offshore West Malaysia. In: Fan deltas: sedimentology and tectonic settings. Nemec, W. and Steel, R. J. (Editors). Blackie and Son.p341–353.

Reineck H. –E. and Singh, I. B., 1980. Depositional Sedimentary Environments with reference to terrigenous clastics, 2nd edition. Springer–Verlag, 549 p. .

Reineck, H. –E., and Wunderlich, F., 1968. Classification and origin of flaser and lenticular bedding. Sedimentology, volume11, p.99–104.

Røe, S. –L., 1995. Stacked fluviodeltaic cycles in the upper Proterozoic Godkeila Member, Varanger Peninsula, northern Norway. Norsk Geologisk Tidsskrift, volume 75, p.229–242.

Rose, E. R., 1952. Torbay map-area, Newfoundland. Geological Survey of Canada Memoir 265, 64p.

Seilacher, A., Bose, P. K. and Pflüger F., 1998. Triploblastic animals more than 1 billion years ago: trace fossil evidence from India. Science, volume 282, p.80–83.

Singh, C. K., 1969. Petrology of the Signal Hill and Blackhead formations, Avalon Peninsula, Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, 96p.

Singh, R. P., Sahoo, A. K., Bhoi, S., Girish Kumar, M. and Bhuiyan, C. S., 2001. Ground deformation of the Gujarat Earthquake of 26 January Journal of Geological Society of India, volume 58, p.209–214.

Smith, S.A., 1983. The sedimentology of the late Precambrian Rencontre Formation, Fortune Bay, Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, 191p.

Tirsgaard, H. & Øxnevad, I.E.I. 1998. Preservation of pre–vegetational mixed fluvio–aeolian deposits in a humid climatic setting: an example from the Middle Proterozoic Eriksfjord Formation, Southwest Greenland. Sedimentary Geology, volume120, p.295–317.

Tomlinson, C. W., 1916. The origin of the red beds; a study of the conditions of origin of the Permo-Carboniferous and Triassic red beds of the western United States. Journal of Geology, volume 24, p.153–179.

Tucker, M. E. 1992. The Precambrian–Cambrian boundary: Seawater chemistry,ocean circulation, and nutrient supply in metazoan evolution, extinction, and bio–mineralization. Journal of the Geological Society, London, volume 149, p.655 – 668.

Veevers, J.J., 1990. Tectonic–climatic supercycle in the billion–year plate–tectonic eon: Permian Pangean icehouse alternates with Cretaceous dispersed–continents greenhouse. Sedimentary Geology, volume 68, p.1–16.

Williams, H. and King, A.F., 1979. Trepassey map area, Newfoundland, Geological Survey of Canada Memoir 389, 24p.

Wood , M. L. and Ethridge F. G., 1988. Sedimentology and architecture of Gilbert- and mouth bar type fan deltas, Paradox Basin, Colorado. In: Fan deltas: sedimentology and tectonic settings. Nemec, W. and Steel, R. J. (Editors). Blackie and Son, p.251–263.

Young, G.M., 1995. Are Neoproterozoic glacial deposits preserved on the margins of Laurentia related to fragmentation of two supercontinents? Geology volume. 23, p.153–156.

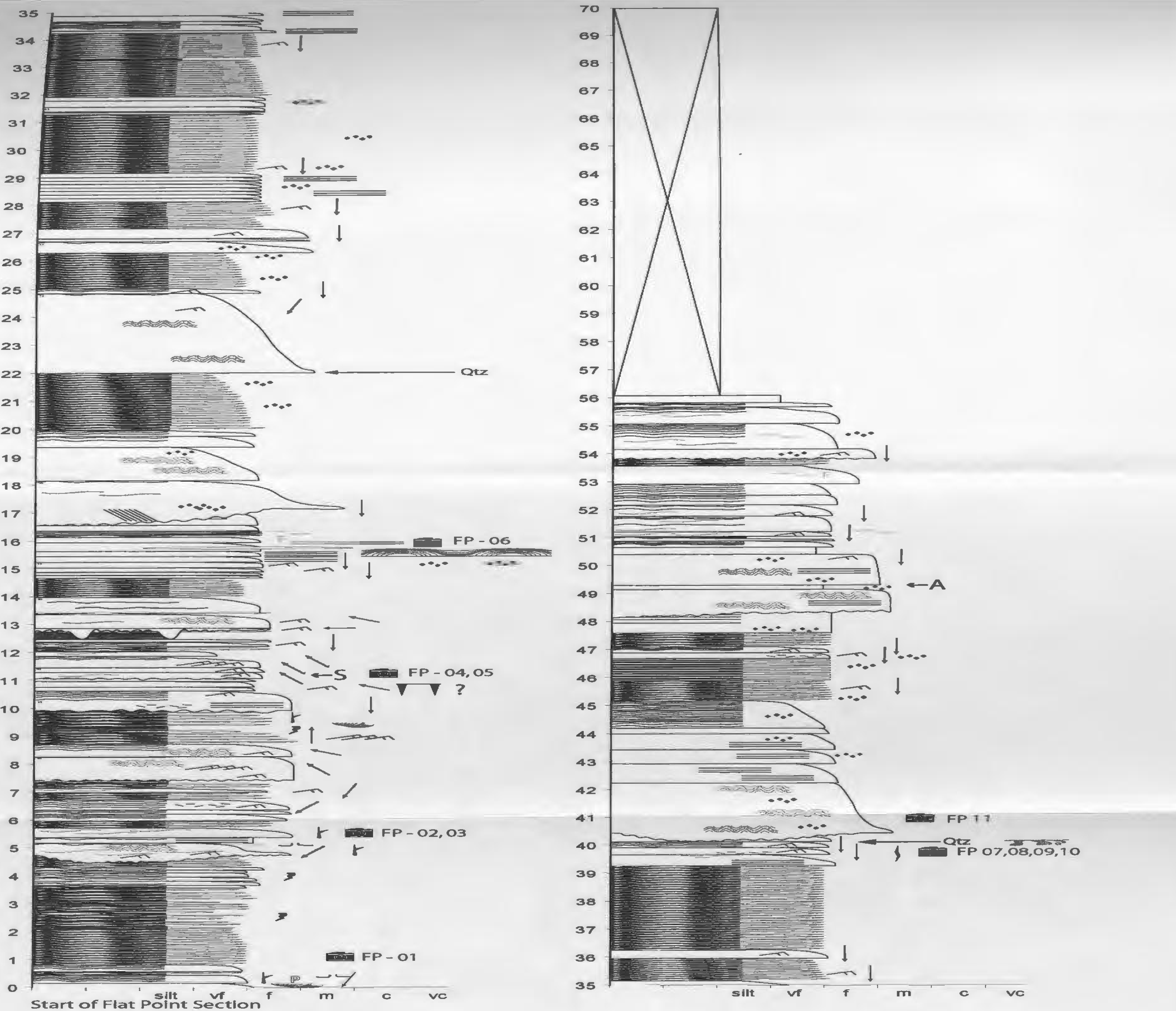
Appendix 1

Legend

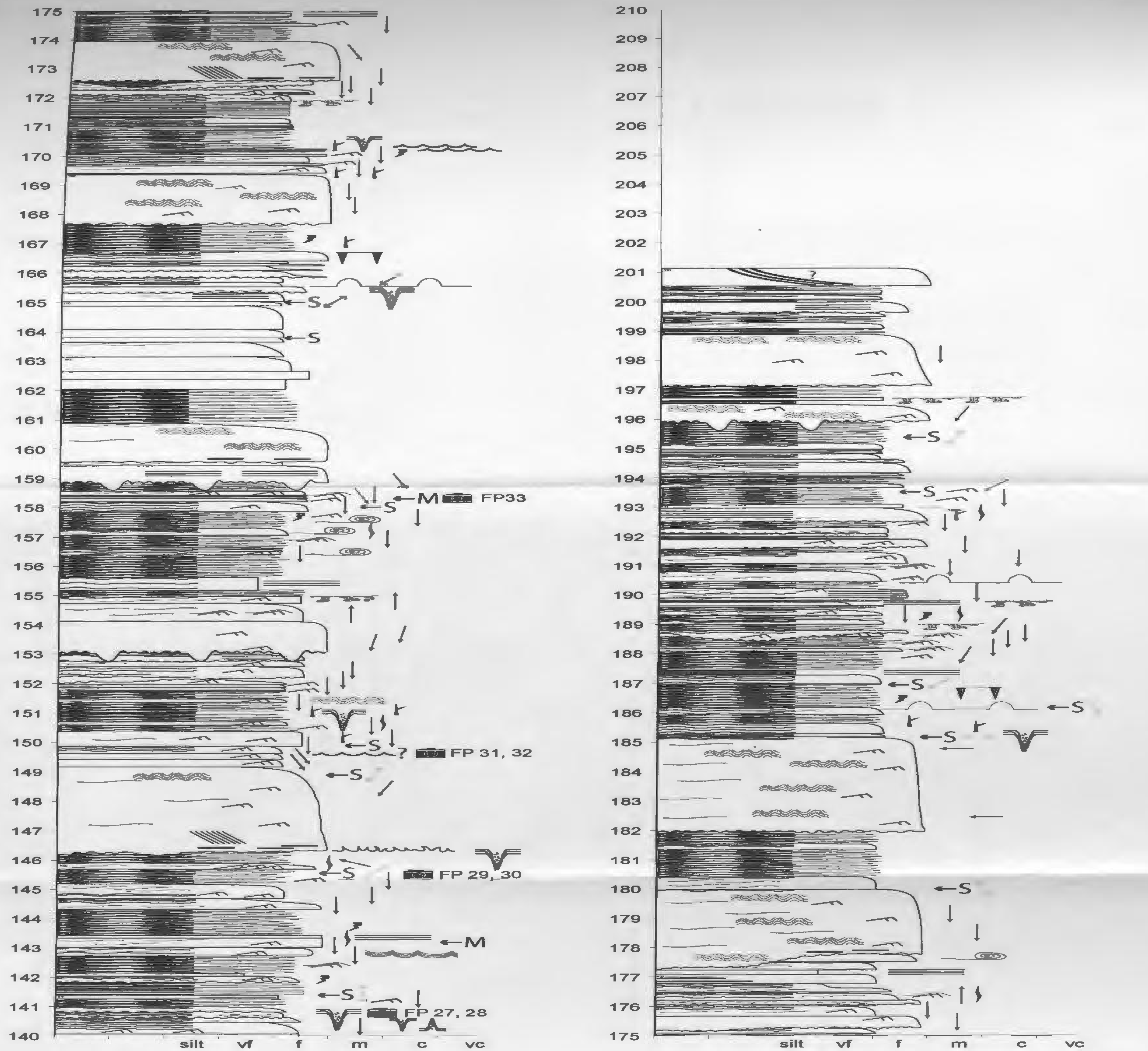
- loaded laminae
- silt flasers
- mud chips
- silt lamina
- wavy silt lamina
- flasers
- rip up clasts
- planar silt lamina
- parallel laminations
- upturned silt laminae
- planar sand lamina
- wavy sand lamina
- flame structure
- siltstone-draped ripples
- current ripples
- trough cross ripple lamination

- climbing-ripples
- cross-bedding
- micro-wave-ripple-lamination
- lateral accretion
- sandstone clast
- bumpy striated surface
- ←S striated surface
- ←M Microbial texture?
- wind
- orientation of ridges and furrows
- pyrite crystals
- ←A ashy
- palaeocurrent
- syneresis
- tension crack
- rollup structure

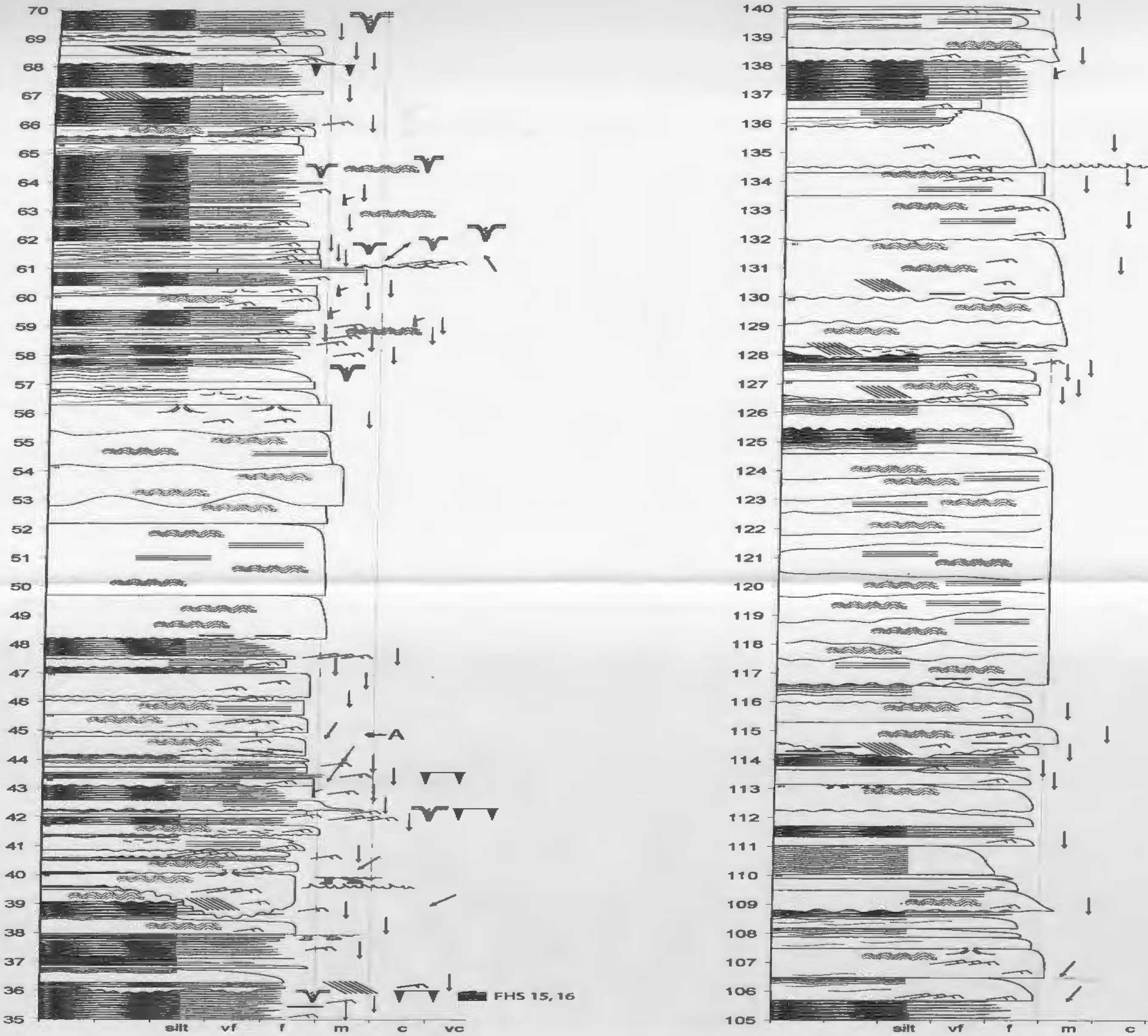
- photograph
- pseudonodules
- dessication cracks
- sandstone dyke
- erosional grooves
- domal erosive surfaces
- reworked phosphate
- phosphate nodule
- nodules / concretions
- concretion around pyrite
- soft sediment faulting
- dewatering collapse structure
- sand volcano
- convolute bedding
- loaded ripples
- load casts and pseudonodules

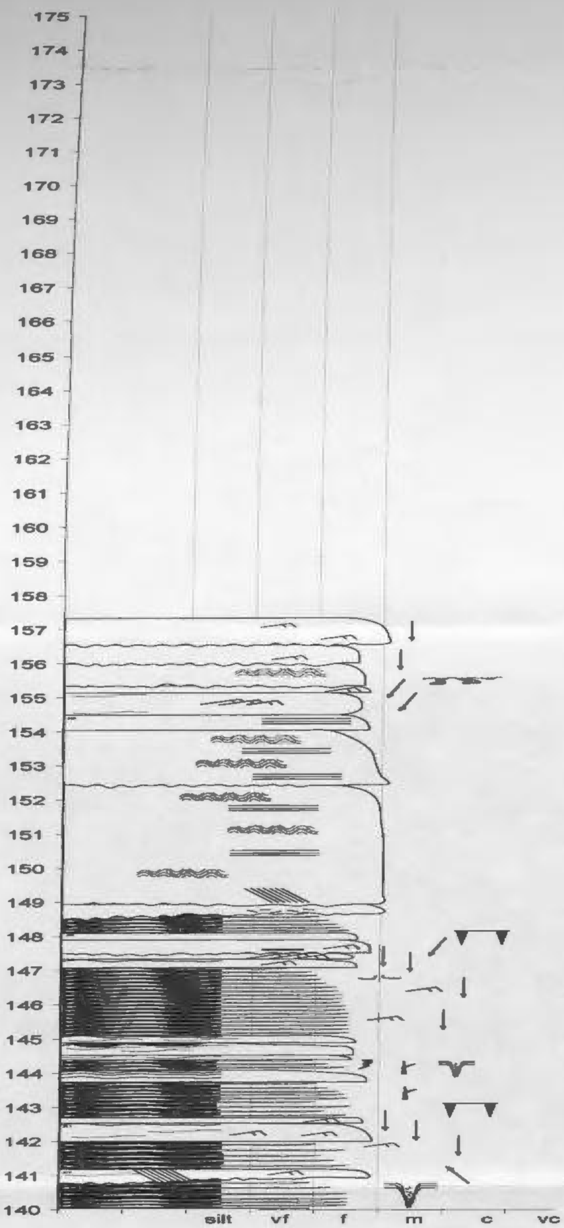

Qtz
FP - 06
S
FP - 04,05
?
FP - 02,03
FP - 01
silt vf f m c vc
Start of Flat Point Section
A
FP 11
Qtz
FP 07,08,09,10
silt vf f m c vc

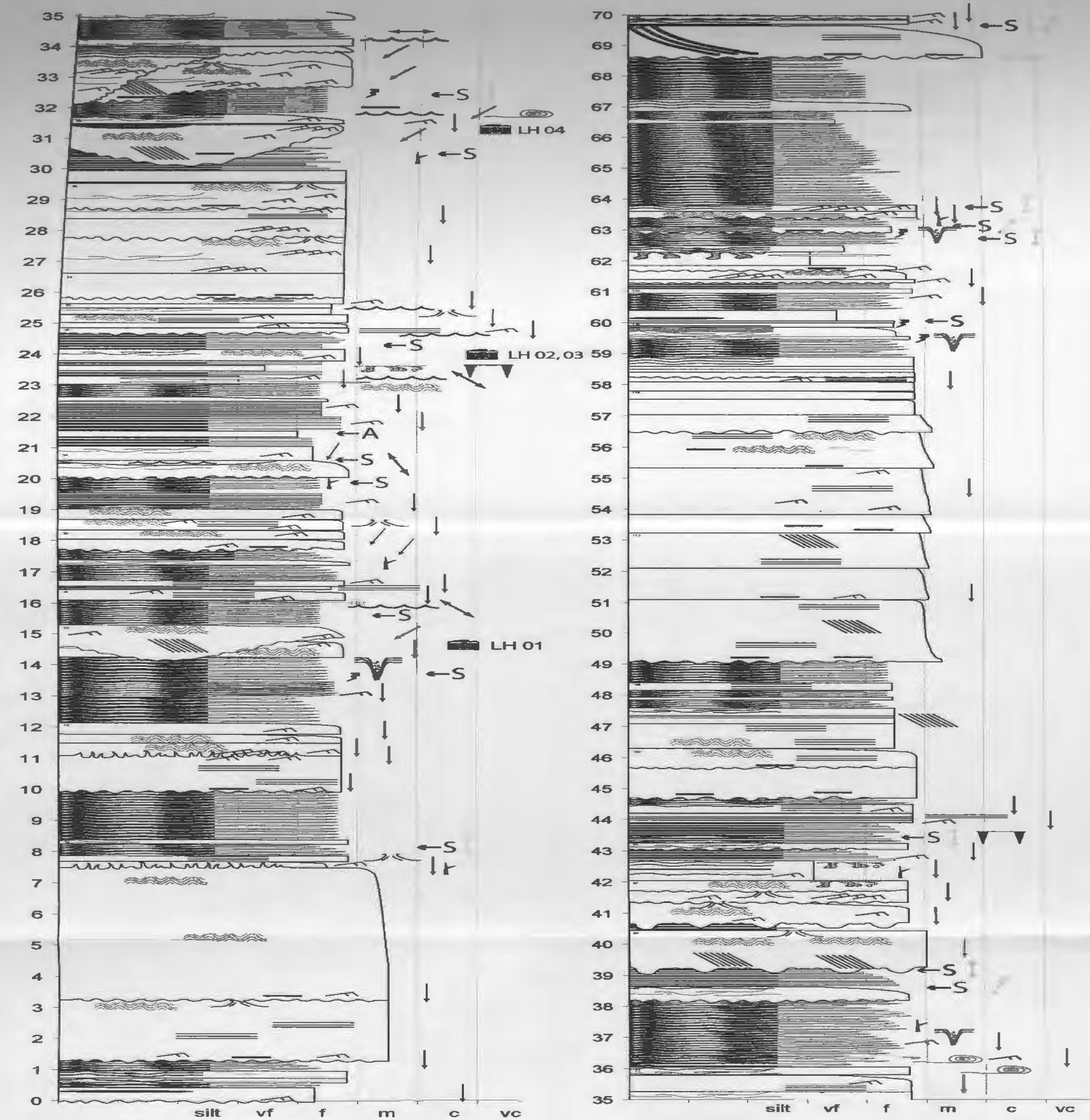
105
104
103
102
101
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
73
72
71
70
25
19,20,21,22,23,24
17, 18
FP 15, 16
14
12, 13
silt
vf
f
m
c
vc
140
139
138
137
136
135
134
133
132
131
130
129
128
127
126
125
124
123
122
121
120
119
118
117
116
115
114
113
112
111
110
109
108
107
106
105
S
A
?
M ?
S
?
M ?
FP 26
?
M ?
S
S
A
silt
vf
f
m
c
vc


175
174
173
172
171
170
169
168
167
166
165
164
163
162
161
160
159
158
157
156
155
154
153
152
151
150
149
148
147
146
145
144
143
142
141
140
silt vf f m c vc
S
M
FP33
FP 31, 32
FP 29, 30
FP 27, 28
210
209
208
207
206
205
204
203
202
201
200
199
198
197
196
195
194
193
192
191
190
189
188
187
186
185
184
183
182
181
180
179
178
177
176
175
silt vf f m c vc

Start of Ferryland Head Section

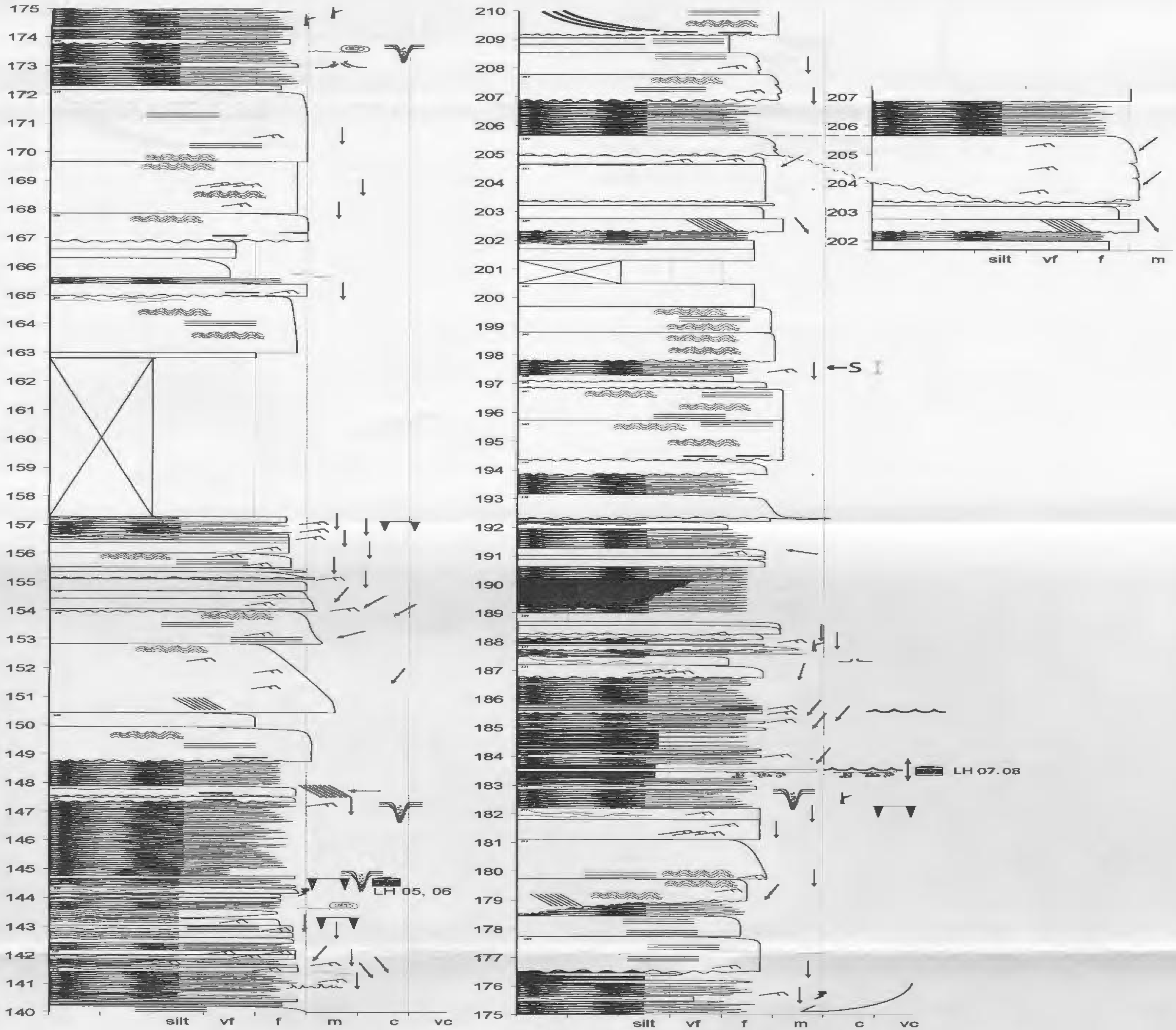

A
FHS 15, 16
silt vf f m c vc
silt vf f m c vc

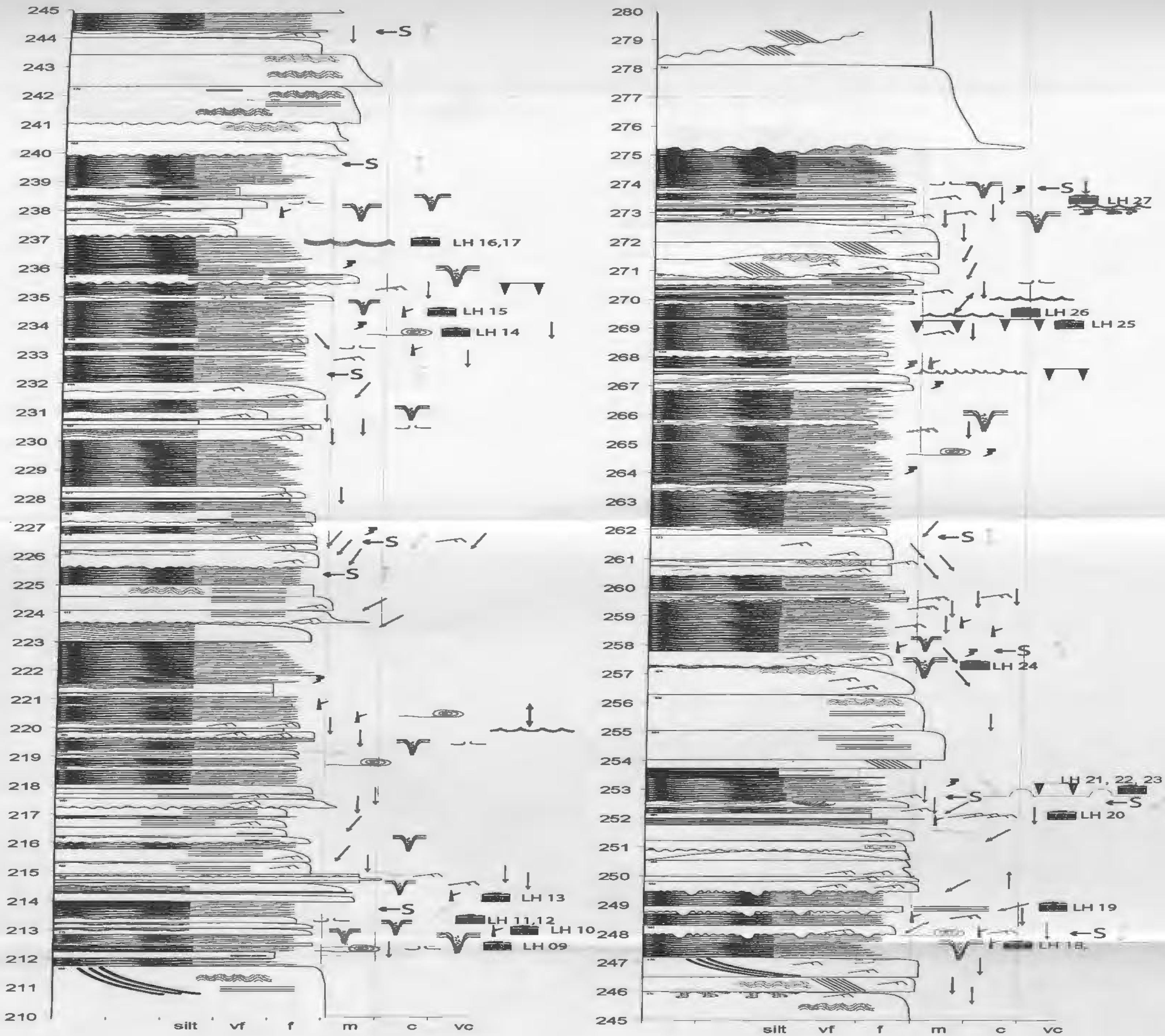

175
174
173
172
171
170
169
168
167
166
165
164
163
162
161
160
159
158
157
156
155
154
153
152
151
150
149
148
147
146
145
144
143
142
141
140
silt
vf
f
m
c
vc

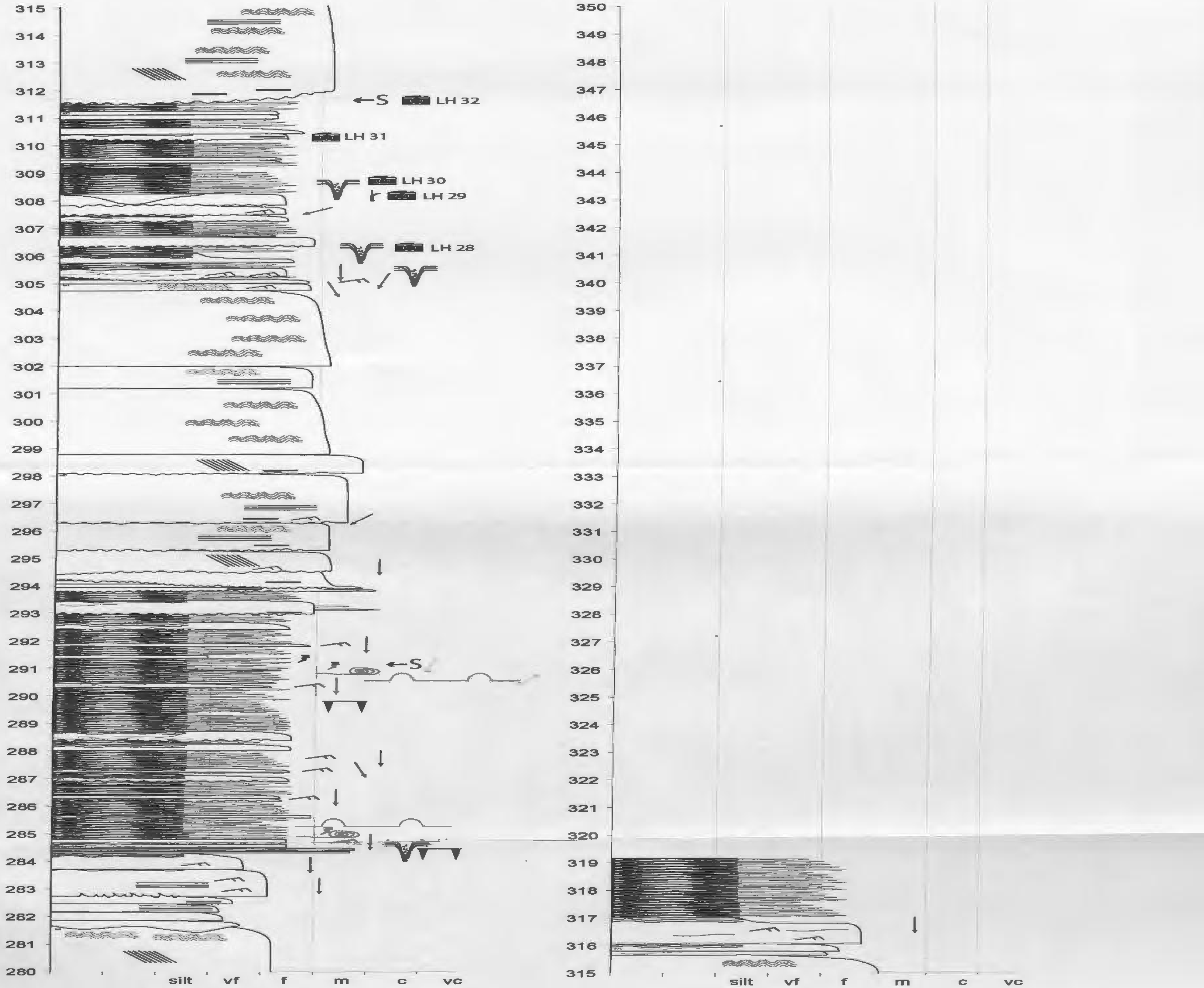


Start of Lighthouse Section


105
104
103
102
101
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
73
72
71
70
silt vf f m c vc
140
139
138
137
136
135
134
133
132
131
130
129
128
127
126
125
124
123
122
121
120
119
118
117
116
115
114
113
112
111
110
109
108
107
106
105
silt vf f m c vc


175
174
173
172
171
170
169
168
167
166
165
164
163
162
161
160
159
158
157
156
155
154
153
152
151
150
149
148
147
146
145
144
143
142
141
140
LH 05, 06
silt
vf
f
m
c
vc
210
209
208
207
206
205
204
203
202
201
200
199
198
197
196
195
194
193
192
191
190
189
188
187
186
185
184
183
182
181
180
179
178
177
176
175
S
LH 07.08
silt
vf
f
m
c
vc
207
206
205
204
203
202
silt
vf
f
m


245
244
243
242
241
240
239
238
237
236
235
234
233
232
231
230
229
228
227
226
225
224
223
222
221
220
219
218
217
216
215
214
213
212
211
210
silt vf f m c vc
S
LH 16,17
LH 15
LH 14
LH 13
LH 11,12
LH 10
LH 09
280
279
278
277
276
275
274
273
272
271
270
269
268
267
266
265
264
263
262
261
260
259
258
257
256
255
254
253
252
251
250
249
248
247
246
245
silt vf f m c vc
LH 27
LH 26
LH 25
LH 24
LH 21, 22, 23
LH 20
LH 19
LH 18



LH 32
LH 31
LH 30
LH 29
LH 28
S
S
315
314
313
312
311
310
309
308
307
306
305
304
303
302
301
300
299
298
297
296
295
294
293
292
291
290
289
288
287
286
285
284
283
282
281
280
silt
vf
f
m
c
vc
350
349
348
347
346
345
344
343
342
341
340
339
338
337
336
335
334
333
332
331
330
329
328
327
326
325
324
323
322
321
320
319
318
317
316
315
silt
vf
f
m
c
vc

Appendix 2

FP 01

FP 02

FP 03

FP 04

FP 05

FP 06

FP 07

FP 08


FP 09

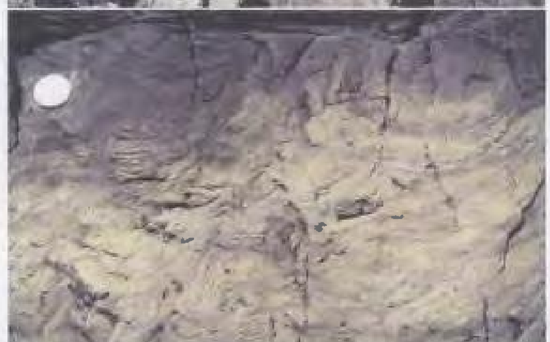

FP 10


FP 11


FP 12


FP 13


FP 14


FP 15


FP 16


FP 17


FP 18


FP 19


FP 20


FP 21


FP22


FP23


FP24


FP25

FP 31

FHS 01

FHS 02

FHS 03

FHS 04

FHS 05

FHS 06

FHS 07


FHS 08


FHS 12


FHS 09


FHS 13


FHS 14


FHS 10


FHS 11

LH 01-see plate 16A

LH 02-see Plate 6A

LH 03-see Plate 6B

LH 04-see Plate16B

LH 05-see Plate 19

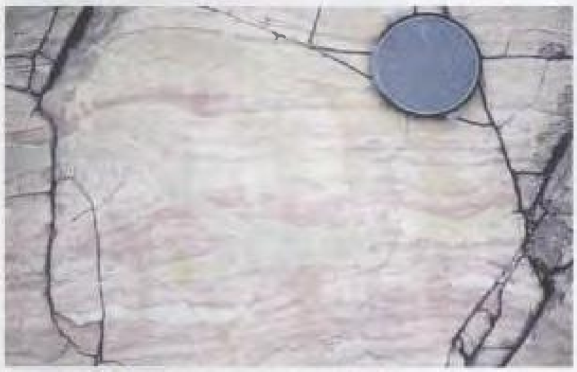
LH 04-see Plate 6D

LH 07-see Plate 8A

LH 08-see Plate 8B

LH 09-see Plate 18A

LH 10



LH 11

LH 12-see Plate 18D

LH13

LH 14-see Plate 24A

LH 15

LH 16-see Plate 23A

LH 17-see Plate 23B

LH 18-see Plate 20A

LH 19

LH 20-see Plate 11F

LH 21-seePlate 2A

LH 22

LH 23- see Plate 2D

LH 24-see Plate 18E

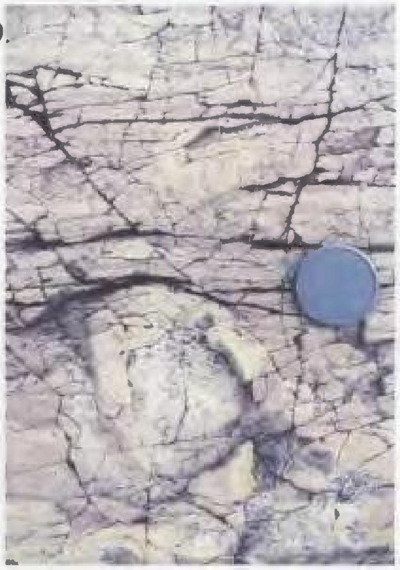
LH 25-see Plate 6C

LH 26-see Plate 10A

LH 27-see Plate 10D

LH 28-see Plate 18C

LH 29.



LH 30

LH31