PENNSYLVANIAN SHALLOW MARINE AND AEOLIAN SEDIMENTS, TYRWHITT, STORELK AND TOBERMORY FORMATIONS OF SOUTHEASTERN BRITISH COLUMBIA

By

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ABSTRACT

The Tyrwhitt, Storelk and Tobermory Formations constitute the major part of a Pennsylvanian siliciclastic succession in the Southern Canadian Rocky Mountains. The eight defined facies composing the Tyrwhitt and Tobermory Formations are mutually exclusive from five of the six facies composing the Storelk Formation. The Storelk Formation, and part of the Tyrwhitt Formation, are further divisible into laterally persistent facies and facies assemblages (Intervals).

Major facies in the Tyrwhitt and Tobermory Formations, interpreted in the context of a storm dominated shallow marine shelf, are: (1) a fossiliferous thoroughly bioturbated structureless sandstone facies which dominates the sequences, and represents background conditions of sedimentation; (2) a medium scale trough crossbedded facies, with paleoflow directed offshore; (3) a small scale crosslaminated facies, and (4) a horizontal laminated facies, both of which are intimately vertically and laterally associated. Three carbonate facies and a siltstone facies, deposited during periods

of restricted sand supply, constitute a minor proportion of Formational thicknesses. Virtually all facies interbed with the structureless facies, and all were apparently deposited at or below storm wave base, where storm surge currents with weaker superimposed oscillatory flow are interpreted to be the primary depositional mechanisms. The strength of the storm surge currents, together with the grain size and rate of sediment supply, controlled the lithology of the facies and the type and preservability of the sedimentary structures.

Facies constituting the Storelk Formation, interpreted in an aeolian context, are: (1) a megaplanar facies, composed of planar sets 2 - 10 m thick; (2) a megatrough facies, composed of trough sets 2-6 m thick; (3) a large scale trough crossbedded facies, and (4) a large scale planar crossbedded facies, containing sets less than 2 m thick which interbed with (1) and (2); (5) the Storelk structureless facies, composed of structureless sandstone devoid of body or trace fossils, and which has a problematical origin; and (6) a thin fossiliferous carbonate facies, interpreted as the deposit of a brief marine transgression during Storelk time. The aeolian interpretation is based on the abundance of giant crossbedding, the moderate (10-25 degrees) foreset dip angles, the total absence of body or trace fossils (except for one facies), and the presence of widespread truncation surfaces. Each of these features is comparable to that of ancient or modern aeolian examples, and a shallow marine origin is improbable. Facies assemblages in the crossbedded Storelk Intervals appear to be correlative with specific types of wind regimes. The Storelk succession was deposited in a low latitude coastal desert under the influence of prevailing north-easterly tradewinds. Aeolian deposition commenced in this area possibly as a result of a glacioeustatic lowering of sea level, and was terminated by a major marine transgression during Tobermory time.

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CHAPTER 1

INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

This thesis presents the results of a sedimentological study of a Pennsylvanian siliciclastic succession in the Rocky Mountain Front Ranges of southeastern British Columbia. Specifically, the study involves the Tyrwhitt, Storelk and Tobermory Formations in the lower part of the Rocky Mountain Supergroup as defined by Scott (1964). Interest was generated in this area by reports of extremely large scale crossbedding in vertical association with fossiliferous shallow marine sediments. The crossbedding occurs in the Storelk Formation, and the possibility of an aeolian interpretation was first suggested by Scott (1964, p.122). A major reason for initiating this study was to attempt to establish the depositional context of the Storelk crossbeds relative to interpreted shallow marine sediments in the vertically adjacent Tyrwhitt and Tobermory Formations. This is of particular interest because of the recent controversy regarding supposed "classical" ancient aeolian sediments, which in some cases have been re-interpreted to be deposits of tide dominated shallow marine settings (e.g. Freeman and Visher, 1975; Pryor, 1971).

1.2 PURPOSE AND SCOPE OF THIS STUDY

The purpose of this study is two-fold. First, it is intended to provide a detailed description of the physical characteristics of sediments composing the Tyrwhitt, Storelk and Tobermory Formations. The second purpose of this study is to attempt to interpret the sedimentological processes that were operative during deposition of these three Formations.

Previous studies of this Pennsylvanian sequence have focussed on the problems of nomenclature, age and correlation, with only generalized references to interpretation of depositional environments. This study contributes to the environmental interpretation of these rocks, and has implications in paleogeographic reconstructions for this time period. In particular, the interpretation of aeolian sediments has implications regarding the position of the shoreline, which is here placed further west than previously thought, and regarding paleowind directions during the Middle Pennsylvanian. The latter permits comparison with Permo-Pennsylvanian sequences in the southwestern U.S.A., where aeolian sediments have been recognized for some time. Also, the documentation of interpreted aeolian sediments contributes to the controversial literature on this subject, and constitutes the first Canadian example of its kind. Finally, this study contributes to knowledge of sedimentary processes that are active in shallow marine settings, which is useful in the construction of models for this depositional regime.

The study area of this thesis is small, and it is not intended to be a regional study. However, the detailed description and interpretation of this core area can serve as a fundamental base for later studies more regional in scope.

1.3 LOCATION AND ACCESS

The study area of this thesis corresponds to the location of the type section for the Tyrwhitt, Storelk and Tobermory Formations as designated by Scott (1964). Scott (p.18) describes the position of the type section as being at the north end of the Elk Valley in southeastern B.C., and

> ... on the southwest side of Mount Storelk, 1 mile east 32 degrees north from the mouth of Tobermory Creek, and 4 miles east 20 degrees south from Lower Elk Lake. A conspicuous large, low alluvial fan composed of cobbles and boulders, and covered with low vegetation marks the mouth of Storelk Canyon.

All measured sections in this thesis are exposed on the east side of the Elk Valley, in deeply incised steep walled canyons over an 8 km stretch between Mount Storelk and Mount Loomis (Figure 1.1). The sections are all on the backside of the Lewis Thrust Sheet which forms the Continental Divide in this area. Exposure within the canyons is excellent, approaching 100% in some cases. Sedimentary structures are generally viewed in two dimensions on high east-west trending cliff walls in the main canyons, with occasional three dimensional views afforded by north-south trending tributary canyons.

Access to the area is via the Elk Valley road north of Elkford, B.C. The road is composed of dirt and gravel, and is passable by two wheel drive truck.

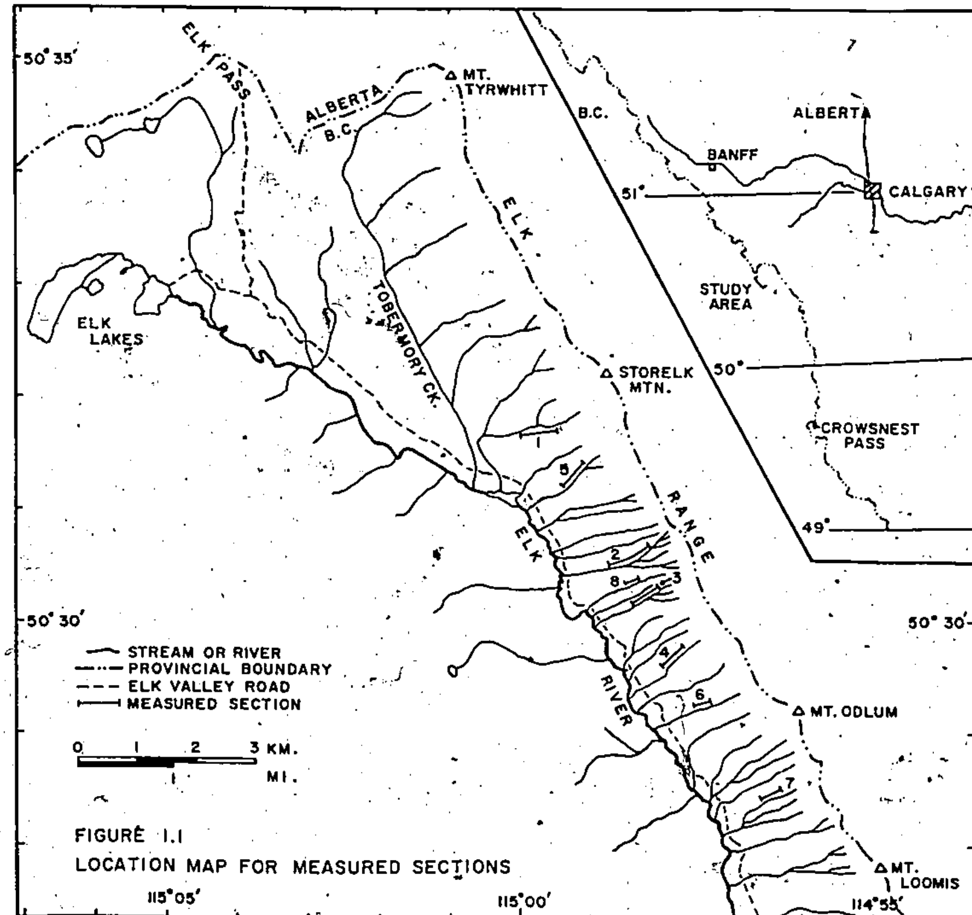


FIGURE 1.1
LOCATION MAP FOR MEASURED SECTIONS

1.4 SPECIAL METHODS UTILIZED IN THIS THESIS

<u>Collection of Paleocurrent Data</u>: paleocurrent data were primarily derived from crossbedding, with a minor contribution from the strikes of symmetrical ripple axes. Two types of crossbedding were involved: trough and planar crossbedding. Orientation measurements from the foresets of the latter yield true paleocurrent directions once field measurements are restored to their original horizontal positions by stereonet rotation. For trough crossbeds, however, a true paleocurrent direction can only be obtained from measurements of the trough axes. This was prohibited by a paucity of plan views. Hence, orientation measurements were made on the crosslaminae of the troughs in the same way that they were made on foresets of the planar crossbeds. All trough measurements were listed separately from planar set measurements.

In some cases, the geometry or scale of a crossbed could not be discerned from the outcrop. Orientation measurements from these were classified accordingly. In the Storelk Formation, what appeared to be foreset surfaces were sometimes exposed on dip slopes. Orientation measurements were recorded from these and listed as "surfaces" (Appendix 1).

Treatment of Paleocurrent Data: all field measurements were restored to their original horizontal positions using a stereonet. Data from the planar sets needed no further treatment, since the resultant azimuths reflected true paleocurrent directions. For the trough sets, a vector mean azimuth was calculated for specific data groupings using the methodology outlined by Curray (1956) and adapted by Martini (1965). This azimuth should represent the preferred crossbed orientation, provided that the sample is sufficiently large and that the troughs are fairly consistently orientated. A Chi-square test was used to determine the level of significance of the resultant vector mean.

The treatment of data described above has the disadvantage that if more than one preferred paleocurrent direction is involved, the resultant vector mean would give an erroneous impression of the paleocurrent pattern. Identification of more than one mode had to be made by observation of point clustering on stereographic projections of the data. This method is subjective, but should be accurate where sufficient measurements were made, and where point clusters were well separated. In some cases, however, a spread of data was involved and the apparent point clusters were not well separated. Thus, the identification of potential preferred paleoflow modes would have become tenuous and subjective. In such cases, a vector mean for all data was calculated. All paleocurrent data are listed in Appendix 1. Stereographic projections of the data are included in the text in places where paleocurrent data are discussed.

Petrography: detailed petrography was not attempted in this thesis due to time limitations. Cursory examination was given to a number of thin sections stained for potassium feldspar. This, together with field observations, provided the lithological descriptions in this thesis. Some petrographic work was also done by Scott (1964).

1.5 FORMAT OF THIS THESIS

Chapter 2 discusses general geology and structure of the study area, together with previous work and the stratigraphic scheme of the Pennsylvanian sequence. Individual facies are described in detail in Chapter 3. In Chapter 4, laterally persistent facies and facies associations (Intervals) are discussed, followed by a quantitative approach to the analysis of facies transitions. The defined facies are interpreted in Chapter 5, drawing on extensive comparison with modern and other ancient examples. Chapter 6 lists the major conclusions reached in this thesis. Appendix 1 lists all collected paleocurrent data. Detailed stratigraphic sections that were measured for this thesis are in the back pocket.

CHAPTER 2

GEOLOGIC SETTING AND STRATIGRAPHY

2.1 GEOLOGIC SETTING

The Pennsylvanian succession considered here is a small part of a tectono-stratigraphic assemblage composed of carbonates, shales and mature sandstones ranging in age from Helikian to Late Jurassic. Terrigenous detritus, mainly derived from the North American craton, accumulated on a prograding terrace wedge likened by Price (1971) to that on the present eastern coast of the U.S.A. The supra-crustal rocks progressively overlapped and buried the cratonic interior, resulting in a southwestward thickening wedge more than 15 km in thickness.

During the Proterozoic and Lower Paleozoic, sedimentation took place along a generally static continental margin. Island arcs above subduction zones of unknown polarity are postulated to have existed to the west (Monger et al., 1972). At the commencement of the Late Paleozoic, there was a major change in the tectono-depositional regime of the Cordillera. Uplift in the west contributed the first sediments from a western source in the northern Cordillera. Deformation of the outer continental terrace wedge occurred with contemporaneous décollement thrusting in the southeastern Cordillera (Wheeler et al., 1972). These phenomena are attributed by Monger et al. (1972) to reorganization of the lithospheric plates, converting the western margin of North America from an interplate boundary to a plate margin which interacted with a plate to the west.

From the Mississippian through Middle Triassic Periods, the lithological assemblage in the Rocky Mountain Belt is interpreted to have been deposited in a relatively stable shelf-slope environment (Monger et al., 1972). To the west, there were two relatively mobile volcanic arc systems separated by a belt of oceanic crust. The volcanic arc in the Omineca Crystalline Belt, immediately west of the Rocky Mountain Belt, was active at least during the Mississippian and Permian. It was, however, apparently well removed from the Rocky Mountain Belt, because of the lack of evidence for volcanic byproducts in the shelf sediments (Monger et al., 1972).

In reconstructions of the continental margin for the Carboniferous, it is generally shown to have a NNW-SSE trend (e.g. Monger et al., 1972, p.587). This trend parallels the structural grain of the present Rocky Mountain Belt. In the absence of definitive evidence to the contrary, the shoreline regional trend must also be taken to be NNW-SSE. There is no control on localized variations in this trend.

Periodic interruptions in sedimentation were at times accompanied by widespread erosion, accentuating the northeast taper of the sedimentary wedge through bevelling towards the craton (Wheeler et al., 1972). The major pre-Jurassic unconformity truncates Mississippian strata at the eastern edge of the Foothills, and splits westward into lesser unconformities (Dahlstrom, 1970). These include pre-Middle Pennsylvanian, pre-Permian and pre-Triassic unconformities, in addition to the pre-Jurassic unconformity. The pre-Permian unconformity is the major one in the study area of this thesis (Macauley et al., 1964). Extensive erosion during post-Pennsylvanian Periods had the effect of isolating Pennsylvanian strata in the southeastern Canadian Cordillera from those in the Peace River area to the north, and from those in Montana to the south (Scott, 1964, p.96, 97). Hence, correlations among these widely separated areas are uncertain (Table 2.1), and are of limited value in reconstructing a detailed paleogeographic picture of the Pennsylvanian Period.

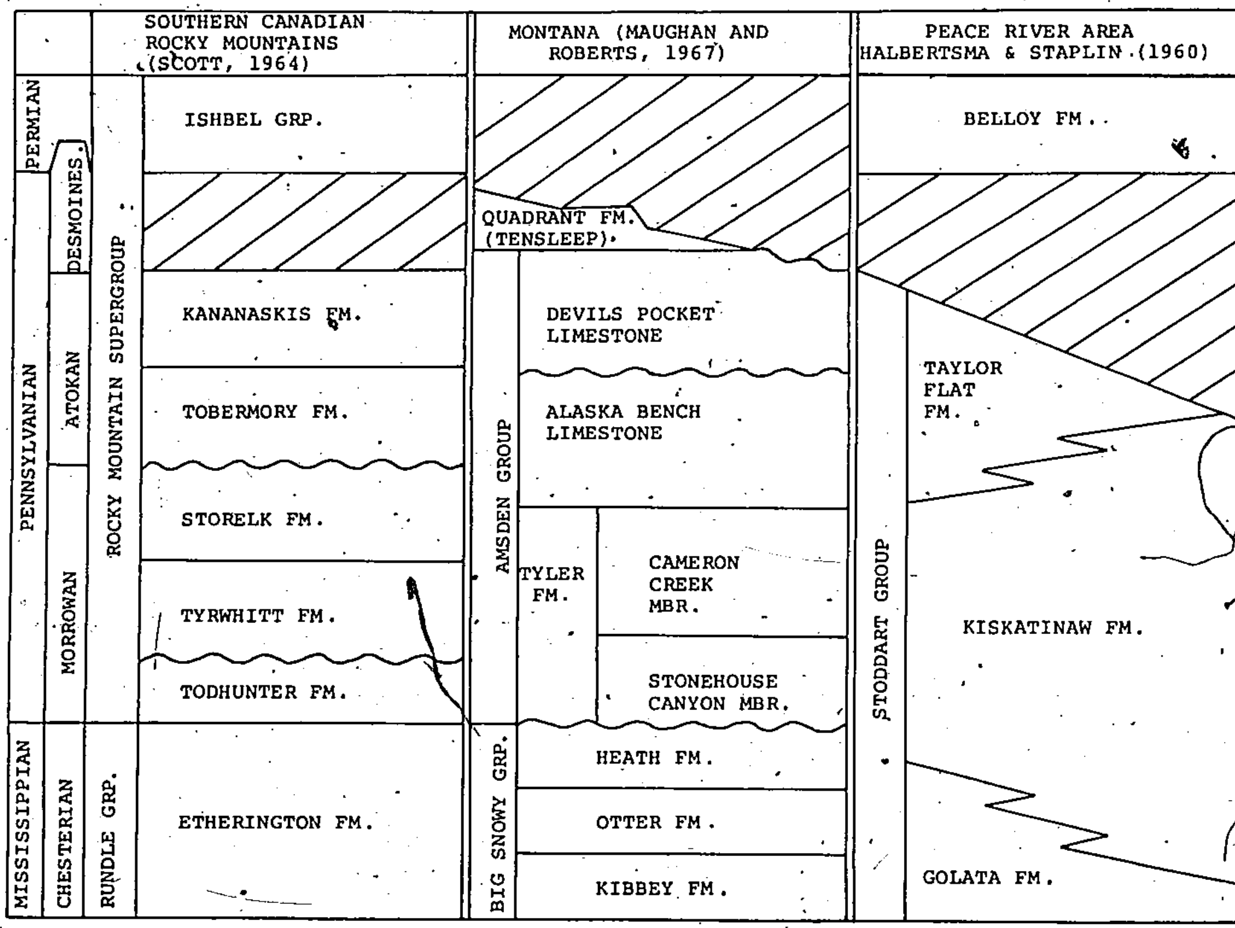


Table 2.1 Correlation of Late Paleozoic sequences in southern Canadian Rocky Mountains and other areas

2.2 STRUCTURAL SETTING

The study area of this thesis is located in the Front Ranges (Price and Mountjoy, 1970), also called the Foreland Thrust and Fold Belt (Wheeler et al., 1972). This is the easternmost structural subprovince of the Cordillera, and it is bounded on the west by the Main Ranges of the Rocky Mountains. The southern part of the Front Ranges is dominated by a series of southwestward dipping subparallel fault slices stacked in imbricate fashion. In the study area of this thesis, all measured sections are located on the backside of the Lewis Thrust Sheet, which has a local strike of about 330 degrees and local dips ranging from 56-70 degrees in this area. Other exposures of the Pennsylvanian succession studied by Scott (1964) are on this and other thrust sheets which form a series of mountain ranges in southeastern British Columbia and southwestern Alberta (Figure 2.1).

2.3 STRATIGRAPHY OF THE PENNSYLVANIAN SUCCESSION AND BOUNDING FORMATIONS

The Late Paleozoic sandstone sequence was first recognized by McConnell (1887) in the Bow Valley, and later

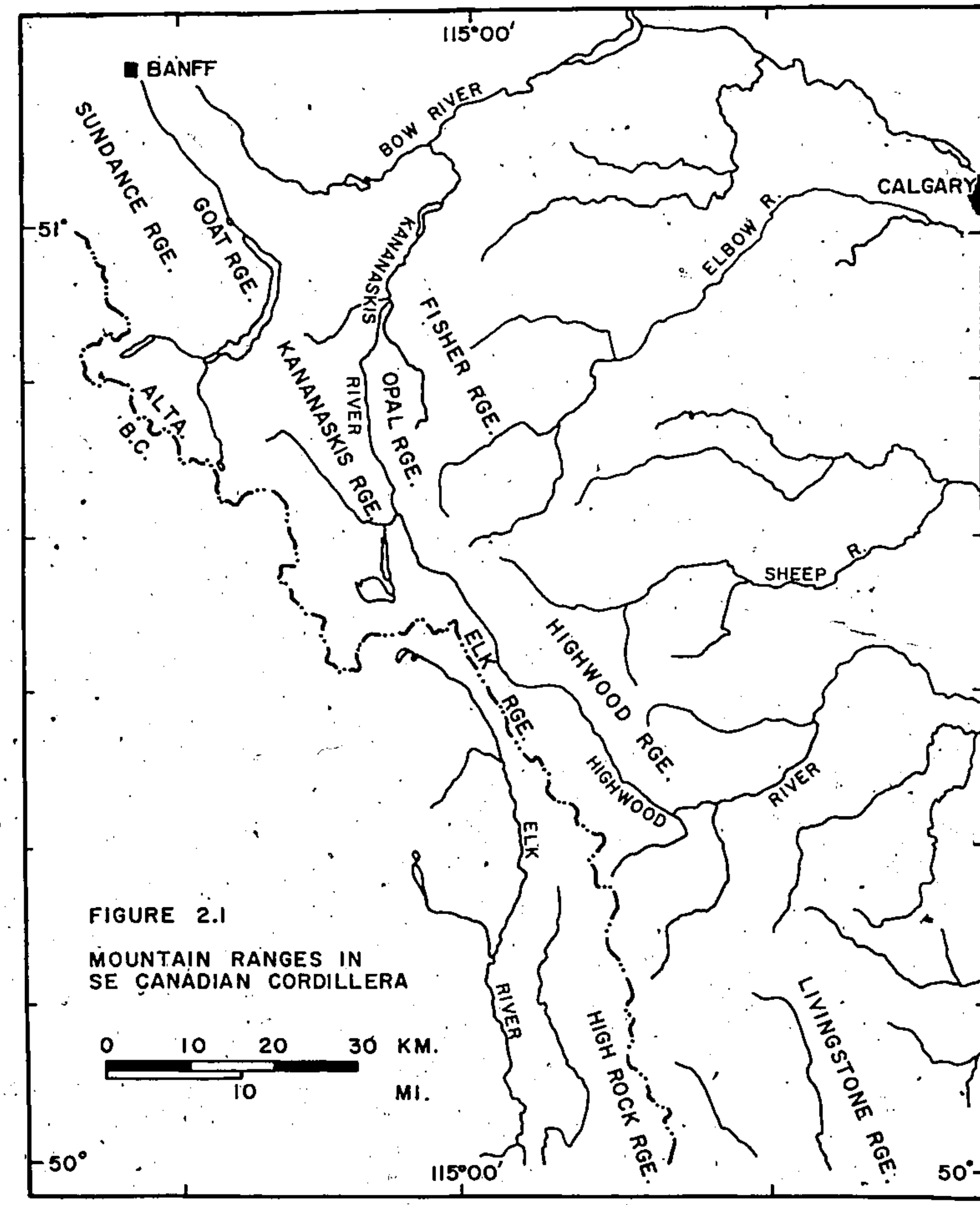


FIGURE 2.1

MOUNTAIN RANGES IN SE CANADIAN CORDILLERA renamed the "Rocky Mountain Quartzite" in the Canmore area by Dowling (1907). Since that time the nomenclature and correlations of the succession have undergone considerable evolution as better fossil and lithological control was attained. Historical summaries are given by various authors, the most recent being by Norris (1965).

The principal studies of the Pennsylvanian and vertically adjacent successions are by Raasch (1956, 1958), McGugan and Rapson (1960, 1962, 1963), Scott (1964) and Norris (1965). Each of these authors has proposed unique Formational names, and in many cases, unique ages and correlations for parts of the succession. A comparison of the four major schemes that are in use is given in Table 2.2.

The Formational nomenclature proposed by Scott (1964) is utilized in this thesis (Table 2.2). His scheme divides the Pennsylvanian siliciclastic sequence into five Formations, in contrast to the single Formational name used by other authors. Scott's (1964) scheme is accepted in this thesis because (1) the Formations are readily recognized in the study area of this thesis, and (2) it is the only scheme that recognizes possible unconformities or diastems in the sequence. The latter are especially important in a sedimentological interpretation.

Table 2.2 Comparison of Formational nomenclature for Late Paleozoic sediments, southern Canadian Rocky Mountains

SCOTT (1964) AND THIS THESIS

PERMIAN		ROCKY MOUNTAIN SUPERGROUP	ISHBEL GROUP
PENNSYLVANIAN	ATOKAN	ROCKY MOUNTAIN SUPERGROUP	KANANASKIS FORMATION
PENNSYLVANIAN	ATOKAN	ROCKY MOUNTAIN SUPERGROUP	TOBERMORY FORMATION
PENNSYLVANIAN	MORROWAN	ROCKY MOUNTAIN SUPERGROUP	STORELK FORMATION
PENNSYLVANIAN	MORROWAN	ROCKY MOUNTAIN SUPERGROUP	TYRWHITT FORMATION
PENNSYLVANIAN	MORROWAN	ROCKY MOUNTAIN SUPERGROUP	TODHUNTER FORMATION
MISSISSIPPIAN	CHESTERIAN	RUNDLE GROUP	ETHERINGTON FORMATION (EWIN CREEK MEMBER)

McGUGAN AND RAPSON (1961)

PERMIAN		ROCKY MOUNTAIN GROUP	ISHBEL FORMATION
PENN.	L. ATOKAN	ROCKY MOUNTAIN GROUP	KANANASKIS FORMATION
CHESTERIAN TO LOWER PENNSYLVANIAN		ROCKY MOUNTAIN GROUP	TUNNEL MOUNTAIN FORMATION (RESTRICTED)
MISS.	CHESTERIAN	RUNDLE GROUP	ETHERINGTON FORMATION

McGUGAN AND RAPSON (1963)

PERMIAN			ISHBEL GROUP
PENNSYLVANIAN	L. ATOKAN	SPRAY LAKES GROUP	KANANASKIS FORMATION
PENNSYLVANIAN	MORROWAN	SPRAY LAKES GROUP	TUNNEL MOUNTAIN FORMATION (RESTRICTED)
MISSISSIPPIAN	CHESTERIAN	RUNDLE GROUP	ETHERINGTON FORMATION

NORRIS (1965)

PERMIAN		ROCKY MOUNTAIN GROUP	FANTASQUE FORMATION
PERMIAN		ROCKY MOUNTAIN GROUP	ISHBEL FORMATION
PENNSYLVANIAN	ATOKAN	ROCKY MOUNTAIN GROUP	KANANASKIS FORMATION
PENNSYLVANIAN	MORROWAN	ROCKY MOUNTAIN GROUP	MISTY FORMATION
MISSISSIPPIAN	CHESTERIAN	RUNDLE GROUP	ETHERINGTON FORMATION — TODHUNTER MEMBER
MISSISSIPPIAN	CHESTERIAN	RUNDLE GROUP	ETHERINGTON FORMATION

2.3.1 Stratigraphic Scheme of Scott (1964)

Scott (1964) proposes that the term "Rocky Mountain Supergroup" be used to incorporate all Permo-Pennsylvanian clastics and carbonates. The Supergroup is divided into five Pennsylvanian Formations and the Permian Ishbel Group (Table 2.2). Of the Pennsylvanian Formations, the Tyrwhitt, Storelk and Tobermory are described and interpreted in this thesis, whereas the Todhunter and Kananaskis Formations were superficially examined to help establish the context of the Formations between them.

Todhunter Formation: this Formation rests conformably and often gradationally on the bioclastics of the Etherington Formation, which constitutes the upper part of the Rundle Group. Scott (1964) interprets the Todhunter to be Morrowan in age, whereas Norris (1965) interprets a Chesterian age for the Formation and assigns it to the upper part of the Etherington Formation (Table 2.2). Scott's (1964) age assignment is based on two fossils not reported by Norris (1965), and the question of age has not been resolved. The contact between the Pennsylvanian siliciclastics and the Etherington carbonates is considered diachronous by some authors (Nelson, 1962; Drummond, 1959), which could explain the difficulty.

In gross aspect, the Todhunter Formation is lithologically transitional between the Etherington and Tyrwhitt Formations, in that it contains major units similar in lithology to its bounding Formations. Scott (1964) recognizes two major carbonate units in the Todhunter, named the Lower and Upper Spirifer Tongues. The top of the Lower Tongue forms the base of all measured sections in this study; the Upper Tongue is apparently absent due to erosion in this area.

Scott (1964) interprets the contact between the Todhunter and Tyrwhitt Formations to be regionally unconformable. This is based on two main lines of evidence:

1. Where the full Todhunter sequence is developed, it is informally divided into lower, middle and upper divisions. The basal Tyrwhitt bed, a widespread Productid-bearing siliceous sandstone, rests on different levels in the Todhunter in different areas.
2. The uppermost part of the complete Todhunter sequence consists of an Orbiculoidea-bearing siltstone. At localities where the upper Todhunter is missing, a conglomeratic deposit of rounded detrital phosphorite pebbles and

fragmented Orbiculoidea shells is present. If this is a lag deposit, it appears to preclude the possibility of facies changes being responsible for the situation in (1) above.

The nature of the Todhunter-Tyrwhitt contact is attributed by Scott (1964) to a combination of differential subsidence and sedimentation rather than to subaerial erosion. The time break involved is not substantial, since both Formations are interpreted to be Morrowan in age. In the study area of this thesis, the contact is paraconformable, and there is no evidence of a break. Hence, no new information can be advanced.

Tyrwhitt Formation: the Tyrwhitt Formation is composed dominantly of sandstone with subordinate dolomite and siltstone. Thin shale units are present in areas removed from the study area of this thesis. A distinctive Orbiculoidea-bearing dolomite unit occurs about mid-Tyrwhitt, and appears to persist laterally through the High Rock and Kananaskis Ranges. The Formation is interpreted by Scott (1964) to have a Morrowan age, based on fossil data.

The upper contact of the Tyrwhitt with the Storelk Formation appears to be regionally conformable. Thickness of the Tyrwhitt ranges regionally from about 30 m to about

106 m, and the Formation generally thins to the NW and SW.

Storelk Formation: the Storelk Formation is entirely composed of unfossiliferous sandstone, and varies regionally in thickness from 12 m to 86 m. The Formation thins to the NW and SW. Abundant cross stratification is reported by Scott (1964) in the Elk Mountains and High Rock Range, although in other areas it may appear to be a single massive bed. The Storelk Formation is interpreted to be Morrowan in age, based on its intermediate position between the Morrowan Tyrwhitt Formation and the Atokan Tobermory Formation.

The contact between the Storelk and Tobermory Formations is interpreted by Scott (1964) to be a regional angular unconformity. This is based on the following lines of evidence:

1. the local presence of a chert-phosphorite or sandstone-pebble conglomerate at the contact;
2. evidence of erosion (relief up to 20 cm) at the contact at one locality;
3. regional stratigraphic relationships between the Tobermory and older Pennsylvanian Formations (see below).

Tobermory Formation: the Tobermory Formation is composed mainly of sandstone, but dolomite beds become thicker and more numerous in its upper part. The Formation may be as little as less than 1 m thick in the Bow Valley, and as much as 100 m thick in the Crowsnest Pass. It generally thins to the NW and SW. The Tobermory Formation is assigned an Atokan age by Scott (1964) on the basis of fossil data.

The Tobermory Formation thins eastward from the Elk Mountains to the Misty Range, and an interpreted Tobermory correlate thickens eastward into the Highwood and Livingstone Ranges. In the latter two Ranges, the Tobermory correlate overlies progressively older Carboniferous Formations, so that the Todhunter, Tyrwhitt and Storelk Formations are missing altogether in the Livingstone Range. This is a major line of evidence for an unconformity between the Storelk and Tobermory Formations.

The contact between the Tobermory and Kananaskis Formations is interpreted by Scott (1964) to be conformable on the basis of lack of evidence for erosion and the lithologically transitional nature of the contact at some localities. McGugan and Rapson (1961) consider this contact to be unconformable because apparent distinctions between the erosional and depositional factors affecting the Kananaskis Formation, and those affecting the underlying siliciclastic succession. The status of the contact has not been fully resolved.

Kananaskis Formation: the Kananaskis Formation is composed of sandy microcrystalline dolomite with abundant chert nodules and layers, and intraformational chert breccias (described in detail by McGugan and Rapson, 1961; Rapson, 1962). The Kananaskis is thickest in the High Rock, Elk and Kananaskis Ranges, and thins in all directions away from these areas. Thinning is apparently due to pre-Permian erosion (Scott, 1964). The Formation is dated as Atokan by McGugan and Rapson (1961, 1962).

2.4 PRESENT GROSS INTERPRETATION OF THE PENNSYLVANIAN SILICICLASTICS AND BOUNDING FORMATIONS

The Etherington Formation together with the Todhunter, Tyrwhitt and Storelk Formations have been interpreted by Scott (1964) as representing a major regressive cycle. This is essentially a continuation of transgressive-regressive cycles of various magnitudes that pervaded Mississippian sedimentation (e.g. Douglas, 1958; Middleton, 1963; Macqueen et al., 1972). Scott (1964) asserts that in the study area, the Etherington Formation was deposited mainly in an open shelf environment west of an area of restricted lagoons. The Todhunter, Tyrwhitt and Storelk Formations are interpreted to have been deposited in progressively shallower water or more nearshore conditions, and the Storelk Formation is postulated to be partly aeolian in origin. At the termination of this major regressive cycle, Scott (1964) believes that the Storelk, Tyrwhitt, Todhunter and Etherington Formations were uplifted and erosionally truncated. During early Middle Pennsylvanian time, a transgressive sequence of Tobermory sandstones and overlying Kananaskis dolomites was deposited west of a postulated topographic high formed by the Storelk sandstones, located in the present Misty Range. The Kananaskis Formation may in part represent another regressive cycle, as Rapson (1962) reports evidence of subaerial and restricted-evaporitic conditions north of the study area of this thesis. With continued transgression, a Tobermory correlate was deposited east of the topographic high on eroded strata of older Carboniferous Formations. Uplift and erosion during the Middle and Late Pennsylvanian terminated the cyclic sedimentation, and the Pennsylvanian Formations were overlain unconformably by the Permian Ishbel Group.

CHAPTER 3

FACIES DESCRIPTIONS

3.1 THE FACIES APPROACH

The sedimentological study of this stratigraphic sequence was undertaken using a facies approach. The term "facies" is a descriptive term unconfined by stratigraphy, wherein a rock body is differentiated from vertically and laterally adjacent rock bodies on the basis of physical, biological or chemical characteristics (Harms et al., 1975, p.63). Specifically, the assemblage of characteristics includes lithology, sedimentary structures, paleocurrent data, and trace and body fossil content. The combination of these characteristics defines the total aspect of the rock unit, and aids in the interpretation of depositional environments. While recognition of facies is ideally objective, it depends to some degree on the experience of the operator, his familiarity with the observed sedimentary features, and the relative significance of those features.

3.2 ORGANIZATION OF THE DESCRIPTION

The descriptive portion of this thesis is discussed on two levels. This Chapter deals with the descriptive characteristics of individual facies. In Chapter 4, Intervals are described, followed by a discussion of the interrelationships of the facies. Two terms used in this thesis require definition:

1. Facies unit: a facies unit is defined as a discrete occurrence of a particular facies at some point in the stratigraphic sequence. Taken together, all facies units of the same type compose the facies, which itself is a term unconfined by stratigraphy (Section 3.1).

2. Interval: an Interval is composed of a specific facies or facies assemblage that persists laterally N-S through most measured sections (a distance of 5-8 km). Intervals are stratigraphically confined. In a strict nomenclatural sense, the term "Interval" is equivalent to the term "Member".

The Storelk Formation, and part of the Tyrwhitt Formation, are divided into a series of Intervals (Figure 3.0). The

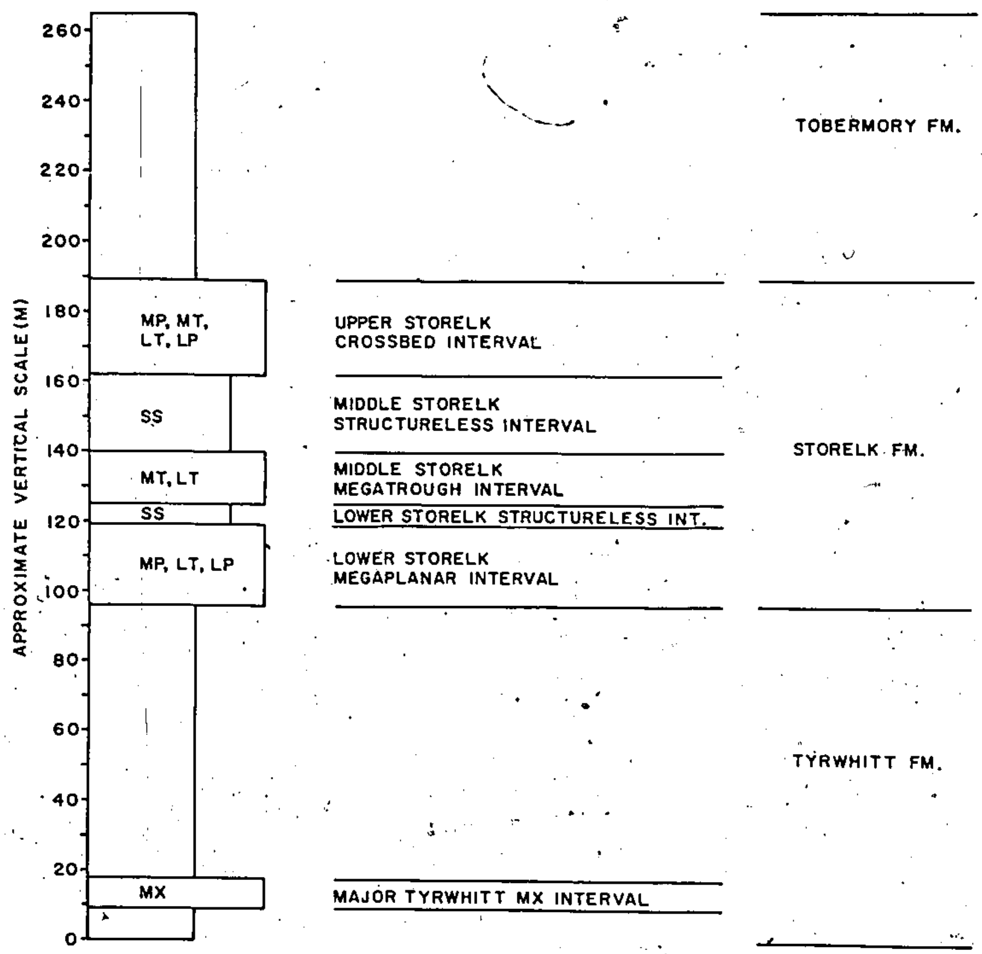


FIGURE 3.0

RELATIVE POSITIONS OF INTERVALS AND THEIR CONSTITUENT FACIES

Intervals are distinctive enough that certain descriptive parameters, particularly paleocurrent data, are discussed at the Interval level as well as at the facies level. The use of two levels of description serves to clarify some of the inherent vertical variability in some facies.

All facies are designated by shorthand symbols. These are summarized along with full facies names, basic descriptions, and basic interpretations in Table 3.1.

In the following discussion, the stratigraphic position, physical characteristics, biogenic characteristics and bounding relationships of individual facies are described. The latter is based on the results of a statistical treatment of facies transitions, which is discussed more generally in Chapter 4. Since the Major Tyrwhitt MX Interval is an exceptionally thick, laterally persistent MX facies unit, the paleocurrent data for the entire MX facies is discussed in this Chapter. The MP, MT, LT and LP facies each occur in more than one Interval, and each Interval is characterized by a unique paleoflow configuration. Hence, the paleocurrent data for each of these facies is discussed at the Interval level in Chapter 4.

Table 3.1 Facies names, symbols, descriptions and basic interpretations

FACIES NAMES	SYMBOL	DESCRIPTION		INTERPRETATION
STRUCTURELESS FACIES	ST	Structureless sandstone; mottled texture evident in X-radiographs; thin remnant crosslaminated layers	SHALLOW MARINE, DEPOSITED SEAWARD OF FAIR WEATHER WAVE BASE	Thoroughly bioturbated sand with evidence of former current activity
MEDIUM SCALE CROSSBEDDED FACIES	MX	Dominantly trough crossbeds 10-50 cm thick, subordinate planar sets and thicker sets; paleoflow towards SSW		Deposited by offshore directed storm surge currents
SMALL SCALE CROSSLAMINATED FACIES	XL	Dominantly small scale trough crosslaminae 0.5-5 cm thick; subordinate wave forms		Probably deposited by storm surge currents; superimposed oscillatory flow
HORIZONTAL LAMINATED FACIES	HL	Horizontal even parallel laminae, sometimes slightly wavy or irregular		As above
SILTSTONE FACIES	SI	Massive bedded probably thoroughly bioturbated siltstone		Deposited during period of inactive currents and restricted sand supply
NON-FOSSILIFEROUS CARBONATE FACIES	NC	Massive bedded microcrystalline sandy dolomite		As above
FOSSILIFEROUS CARBONATE FACIES	FC	Sandy limestone or dolomite containing thin layers of <u>Orbiculoidea</u> or <u>Spiriferid</u> brachiopods		Deposited during period of active currents and restricted sand supply
CROSSBEDDED CARBONATE FACIES	TC	Trough crossbedded sandy dolomite		Probably deposited by storm surge currents during period of restricted sand supply
MEGAPLANAR FACIES	MP	Planar tabular sets up to 10 m thick; wedge shaped planar sets up to 5 m thick; foresets usually dip 10-25 degrees	AEOLIAN SEDIMENTS	Aeolian dunes, probably straight crested
MEGATROUGH FACIES	MT	Trough sets up to 6 m thick; broad lateral curvature to sets; foresets usually dip 10-[illegible] degrees		Aeolian dunes, probably sinuous crested
LARGE SCALE TROUGH CROSSBED FACIES	LT	Wide subtly curved trough sets less than 2 m thick		Relatively small aeolian dunes
LARGE SCALE PLANAR CROSSBED FACIES	LP	Planar tabular and wedge shaped planar sets less than 2 m thick		Relatively small aeolian dunes
STORELX STRUCTURELESS FACIES	SS	Structureless sandstone; absence of mottled texture in X-radiographs; minor parallel laminae, siltstone zones		Origin problematical; intense large scale post-depositional deformation?

3.3 STRUCTURELESS FACIES (ST)

3.3.1 Introduction and Basic Interpretation

The ST facies is composed dominantly of thick, laterally extensive units of structureless sandstone. A mottled texture is evident in X-radiographs. The facies is interpreted to be shallow marine in origin, and to have been deposited seaward of fair weather wave base where extensive bioturbation effectively destroyed most sedimentary structures.

3.3.2 Stratigraphic Position

The ST facies forms thick laterally extensive units in the Tyrwhitt and Tobermory Formations (Figure 3.1). In the Tyrwhitt, facies units range in thickness from less than 1 m to more than 25 m (e.g. MS 5: 20-46 m), and the thickest units can persist laterally N-S at least 5 km. The facies may constitute up to 65% of the total Formation thickness. Facies units in the Tobermory Formation are usually less than about 3 m thick, except in the lower part of the Formation where they may be up to 15 m thick (e.g. MS 3: 193-208 m), and can persist laterally up to 5 km. The facies may account for up to about 30% of

Formation thickness.

3.3.3 Facies Description

ST facies units are characterized by an almost total lack of sedimentary structures observable in the field. A mottled texture, however, is evident in X-radiographs of samples taken from the facies (Figure 3.2). The mottling may be somewhat subtle or very pronounced, although a few samples appear to have a uniform texture. In some cases, vague wispy laminae are visible. The observed mottled texture is interpreted to be the result of bioturbation, which is responsible for the apparent structureless condition of the facies.

Most thick ST facies units contain thin zones of crosslaminae a few centimeters or less thick. Such zones often contain vertical burrows. In some cases, crosslaminae are vaguely defined, and most zones persist laterally only a few decimeters. Symmetrical, low amplitude ripple marks (ripple index 8-20) are occasionally visible on bedding plane exposures (Figure 3.3).

The facies is composed of well sorted very fine grained sandstone for the most part. The maximum observed grain size was fine sand. Sands are cemented by dolomite or silica, or a combination of both.

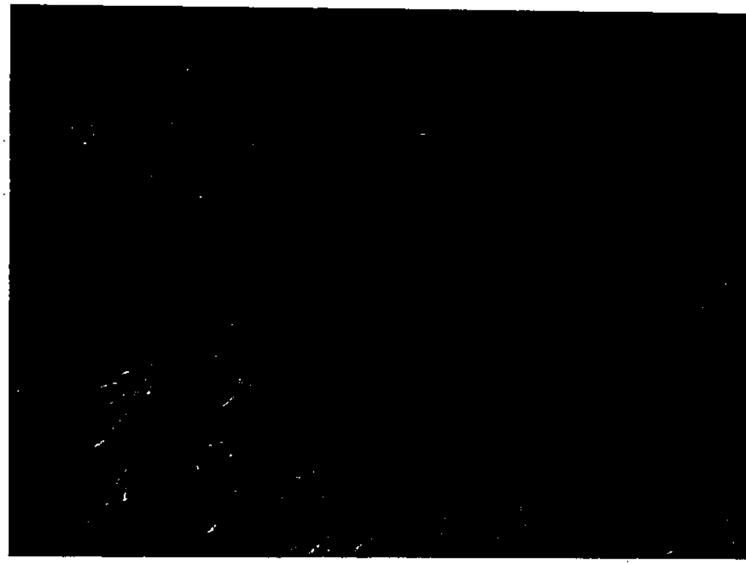


Figure 3.1 Gross appearance of ST facies. Note massive bedding. Man is 1.8 m tall (Lower Tyrwhitt of measured section 1).

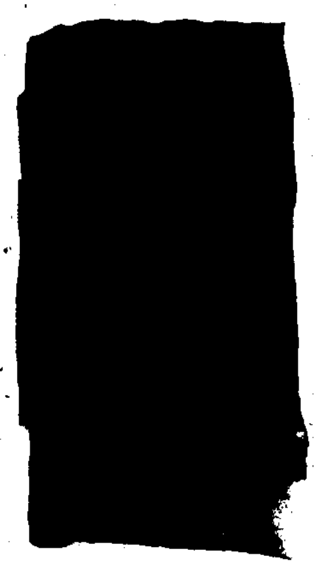


Figure 3.2 X-radiograph of sample from ST facies showing characteristic mottled texture; natural size (MS 1: 35 m).

3.3.4 Bounding Relationships

Both contacts of facies units may be sharp or gradational against vertically adjacent units. The ST facies is interbedded with almost all other facies characteristic of the Tyrwhitt and Tobermory Formations.

3.3.5 Body Fossil Content

The ST facies commonly contains Spiriferid brachiopods and lesser numbers of Orbiculoidea and Productid brachiopods. The fossils are usually concentrated into thin layers a few centimeters thick, although some are always randomly distributed between the layers. The brachiopods are always disarticulated and are not in living position (Figure 3.4). One distinctive unit containing 2-4 Spiriferid brachiopod layers occurs at similar stratigraphic positions in the Lower Tyrwhitt of each measured section (e.g. MS 5: 26-34 m; MS 3: 22-27.5 m). Small tubule-like bodies (bryozoa?) are commonly associated with the brachiopods (e.g. MS 5: 40-45 m; Figure 3.5). Pelecypod molds (?) also occur in the Tobermory Formation (Figure 3.6).

3.3.6 Trace Fossil Assemblage

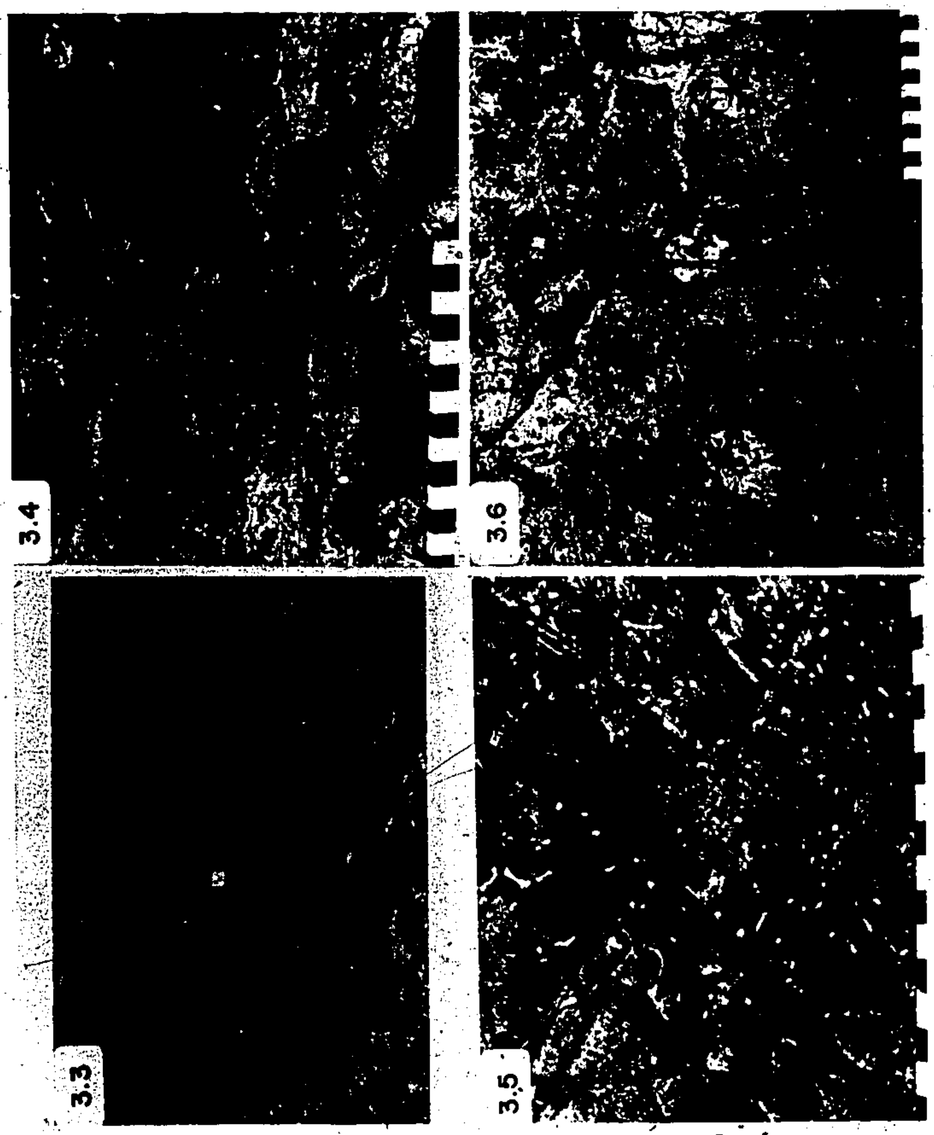
Preserved trace fossils are uncommon in the ST

Figure 3.3 Bedding plane exposure of symmetrical low amplitude ripples. Book is 19 cm long (MS 1: 70 m).

Figure 3.4 Spiriferid brachiopods in ST facies. Scale in cm.

Figure 3.5 Bryozoa (?) in ST facies. Scale in cm. (MS 3: 32 m).

Figure 3.6 Pelecypod molds (?) on bedding plane. Scale in cm. (MS 3: 228.5 m).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facies except in the Tobermory Formation where they are exposed on large bedding planes (e.g. MS 3: 228-235 m). Only a few vertical forms were observed in the Tyrwhitt Formation, also on bedding planes (e.g. MS 1: 31.5 m; MS 2: 49 m). A common feature of trace fossils in the Tobermory Formation is that horizontal and vertical forms occur on the same bedding plane.

The identifications of trace fossils is tenuous because all were identified from photographs. Also, the vertical forms were only seen in plan view on bedding planes, and without cross-sectional views their identifications are subject to question. Hence classifications are only at the generic level, including a number of form genera. A further limitation is that the trace fossil assemblage could not be defined quantitatively to determine the relative abundances of the ichnogenera. Moreover, the assemblage may be incomplete. Therefore, only generalities are possible in relating the forms to a depositional environment.

The following trace fauna are tentatively identified from the ST facies by G. Pemberton (McMaster University):

1. Paleophycus sp.? (Figure 3.7): Paleophycus is a form ichnogenus describing horizontal feeding trails formed by deposit feeding worms. The burrows may branch or cross over one another, and the sediment in the burrow is the same as the enclosing sediment. The ichnogenus occurs at a wide variety of depths, and is usually indicative of a relatively low energy environment.

2. Planolites reticulatus?; Planolites annulutus? (Figures 3.8, 3.13): Planolites is a form ichnogenus describing horizontal feeding trails with no branches. Its formation is attributed to deposit feeding worms. The ichnogenus occurs at a wide range of depths, and is usually indicative of a relatively low energy environment.

3. Rhizocorallium? (Figure 3.9): this ichnogenus is composed of horizontal or inclined burrows with internal laminae that are concave in the direction of movement of the organism. Formation of the burrows is attributed to deposit feeding organisms if they are horizontal, and to suspension feeding organisms if they are inclined. The interpretation of the type of organism is problematical. The form may occur at a wide range of depths, and is generally indicative of a relatively low energy environment.

4. _Lingulichnus_? (Figure 3.10): _Lingulichnus_ burrows are oval shaped in plan view, resembling the forms observed in the ST facies. In the absence of cross-sectional views, however, identification is very tentative. The burrows are formed by suspension feeding _Lingulid_ brachiopods. Depth zonation is problematical since _Lingulid_ brachiopods have been recently discovered _in situ_ at great depth (G. Pemberton, in press) whereas they once were considered classic shallow marine forms.

5. _Radially Groping Feeding Burrows_ (cf. _Asterichnus_?, Figure 3.11): these forms have a central core with a series of horizontal radiating arms. Their origin is problematical, but they are thought to be formed by large organisms. The forms occur at a wide range of depths.

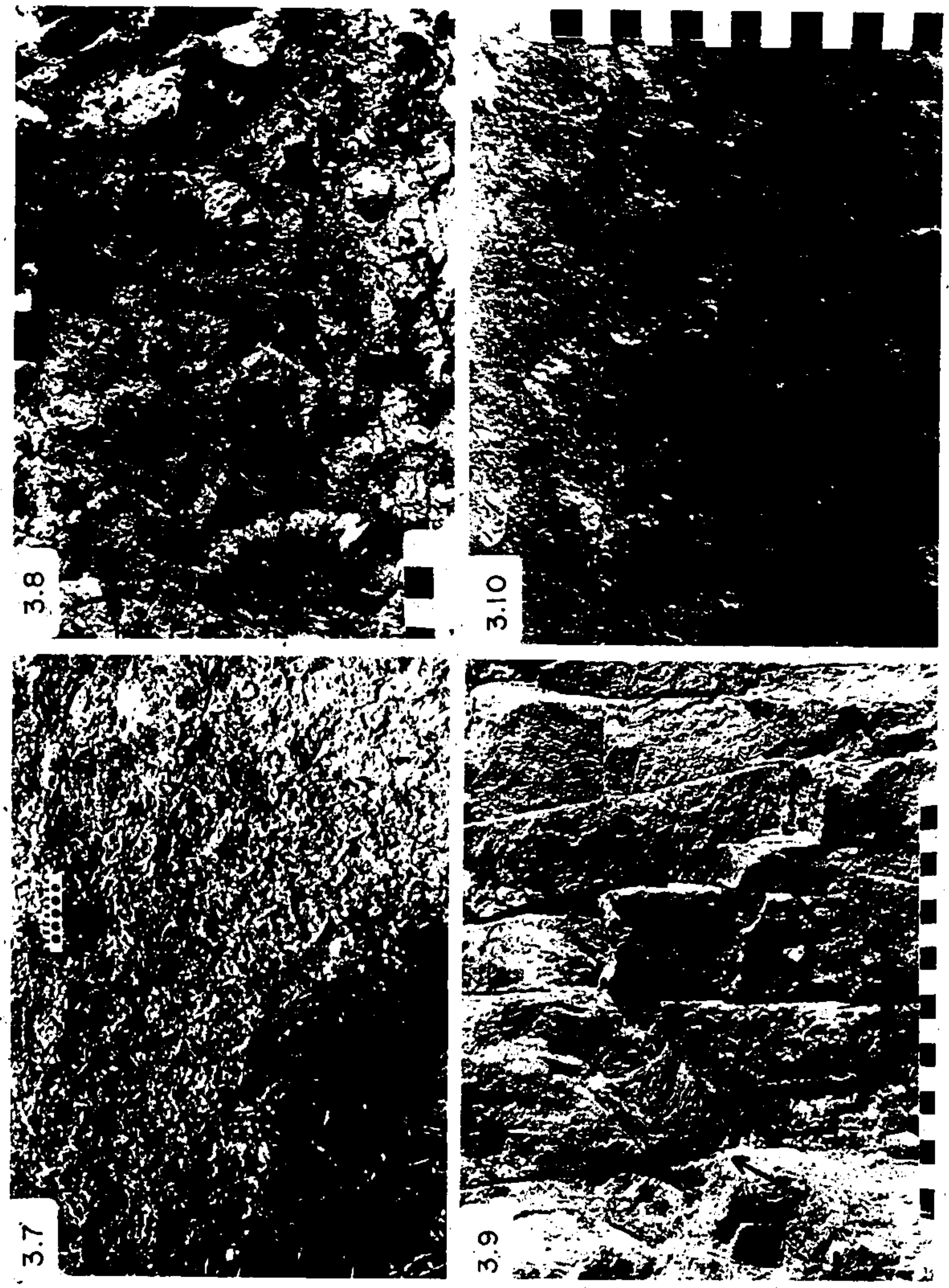
6. _Bergaueria_? (Figure 3.12): this ichnogenus is a vertical stubby burrow formed by burrowing actinian sea anemonies. In the single example observed in the ST facies, only a plan view is visible, making identification highly tentative. The form is generally characteristic of relatively high energy environments with active currents.

Figure 3.7 Intensely burrowed bedding plane exposure. Burrows are _Paleophycus_ sp? Scale in cm. (Upper Tobermory Formation).

Figure 3.8 _Planolites annulutus_? on bedding plane exposure. Scale in cm. (MS 3: 228 m).

Figure 3.9 _Rhizocorallium_? burrow (arrowed) in cross-sectional view. Scale in cm. (MS 5: 229 m).

Figure 3.10 _Lingulichnus_? burrows, bedding plane exposure. Scale in cm. (MS 3: 67 m).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7. *Skolithos*? and *Plichnia*? (Figure 3.13): both of these are form ichnogenera describing straight vertical burrows thought to be formed by suspension feeding worm-like organisms. The difference between the two forms is in scale. *Skolithos* is generally less than about 1.5 cm in diameter, whereas *Plichnia* generally has a larger diameter. The forms may occur at a wide range of depths, and commonly indicate a relatively high energy environment with active currents.

3.3.7 Problems of Recognition of the ST Facies

The ST facies is defined primarily by the lack of sedimentary structures observable in the field, and by a characteristic mottled texture visible in X-radiographs. The latter is useful in confirming a tentative field designation, but it is not practical to X-ray samples from every suspected ST facies unit. Of 39 samples from all parts of the Tyrwhitt and Tobermory Formations, 26 had a mottled texture, 9 had a relatively uniform texture or slight mottling and 4 contained laminae not visible in the outcrop. Lack of recognition of laminae stems largely from insufficient weathering of the outcrop, especially in silica cemented sandstone characteristic of much of the

Figure 3.11 Radially groping feeding burrow (arrowed) on bedding plane exposure. Scale in cm. (MS 1: 233 m).

Figure 3.12 *Bergaueria*? burrows on bedding plane exposure. Scale in cm. (MS 1: 32 m).

Figure 3.13 Bedding plane exposure showing vertical *Skolithos*? and *Plichnia*? burrows in plan view. Long straight horizontal burrow in lower left is *Planolites*. Scale in cm. (MS 3; 228 m).


3.11


3.12


3.13

Tobermory Formation. Also, the relatively uniform grain size of sands constituting the facies would make laminations difficult to see if they were developed. However, the presence of at least slight mottling in the great majority of samples suggests that field identifications of the ST facies are correct in most cases.

3.3.8 Facies Recognition

The ST facies is recognized by the:

1. almost total lack of sedimentary structures observable in the field;
2. presence of a mottled texture visible in X-radiographs;
3. occasional preservation of horizontal and vertical trace fossils; and the
4. presence of body fossils.

3.4 MEDIUM SCALE CROSSBEDDED FACIES (MX)

3.4.1 Introduction and Basic Interpretation

The MX facies is dominantly composed of trough crossbeds 6-50 cm thick, which are occasionally interbedded with planar crossbeds (10-180 cm thick) and large scale trough crossbeds (up to 1.6 m thick). The facies is interpreted to have a shallow marine origin, and to have been deposited by storm surge currents seaward of fair weather wave base.

3.4.2 Stratigraphic Position

The MX facies occurs in both the Tyrwhitt and Tobermory Formations. In the Tyrwhitt, the facies may constitute up to about 20% of Formation thickness, and there are usually 4-6 facies units present. The Major Tyrwhitt MX Interval (Figure 3.0) is actually an exceptional example of the MX facies, since the former may attain thicknesses as great as 9 m (e.g. MS 1: 10.5-19.5 m) and persist laterally at least 5 km. The MX facies may account for up to about 10% of the total thickness of the Tobermory Formation. Individual facies units for both Formations are almost universally thicker than 1 m, and more than half are thicker than 2 m (e.g. MS 3: 45-47 m; 56-58.5 m;

60-62.0 m). These units are laterally traceable at least 100 m before they are lost under cover.

3.4.3 Facies Description

The MX facies is composed of poorly to moderately sorted fine and medium sand, with occasionally abundant coarse grains. The sandstones may be cemented by dolomite or silica, or some combination of the two. This lithology contrasts markedly with vertically adjacent facies which are dominantly composed of well sorted very fine grained sand.

Medium scale trough crossbedding 6-50 cm thick is the most common set type in the MX facies (Figure 3.14). The average set thickness is about 30 cm. The width of the sets has not been clearly established due to a paucity of plan views. Planar tabular crossbeds with similar thicknesses are occasionally interbedded with the troughs (Figure 3.15).

Large scale trough sets up to 1.6 m thick and planar sets up to 1.8 m thick are occasionally interbedded with their smaller scale counterparts (e.g. MS 1: 45-47 m; MS 2: 60-64 m). The Major Tyrwhitt MX Interval always contains a few troughs of the maximum scale about mid-unit (e.g. MS 5: 10-18 m; MS 3: 8-16 m; Figure 3.16). In the

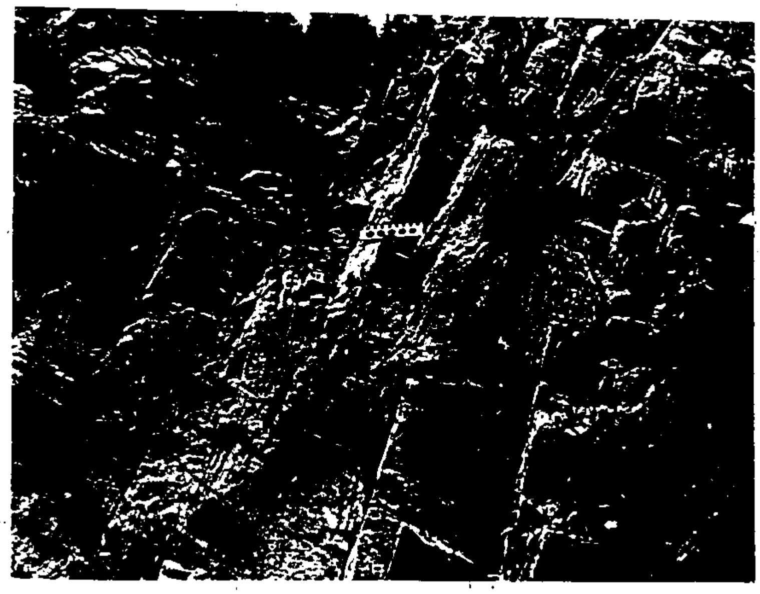


Figure 3.14 Medium scale trough crossbedding in MX facies. Scale in cm. (MS 3: 44.8-47.5 m).

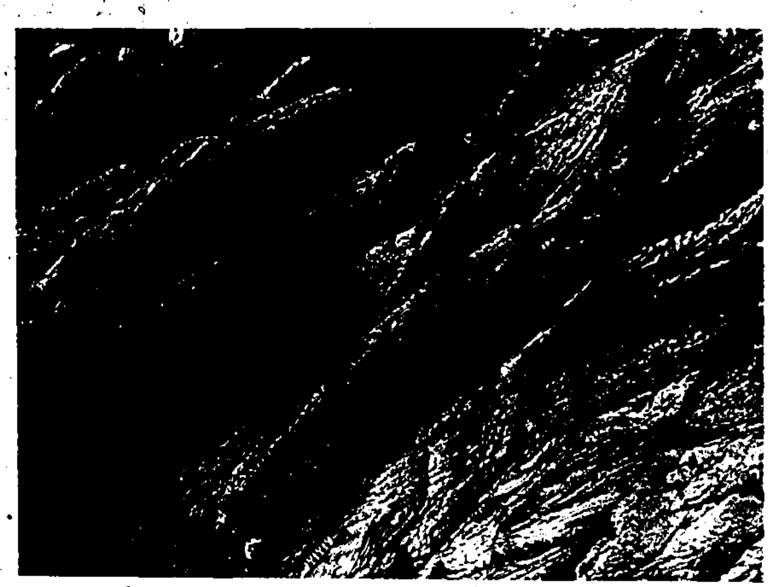
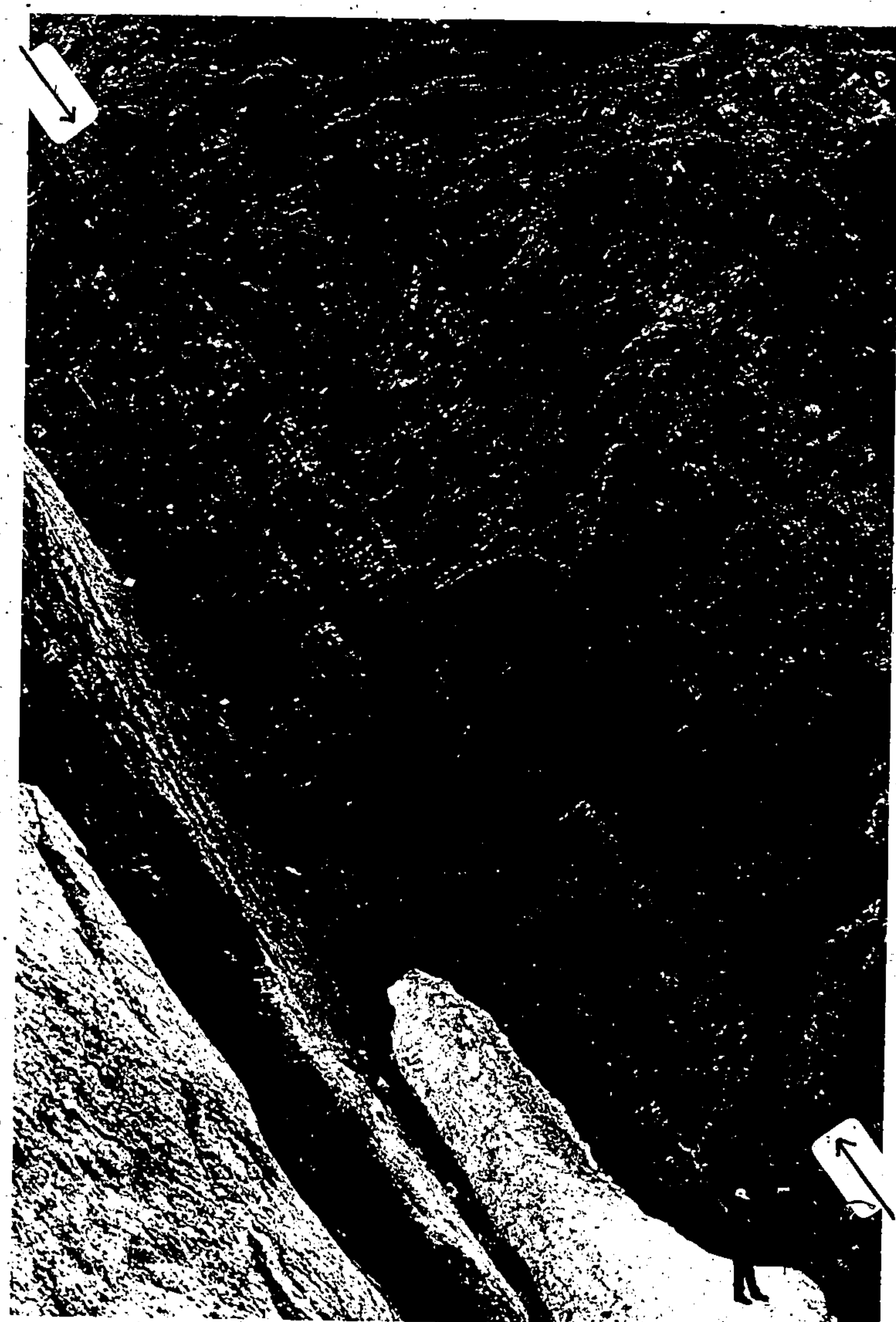


Figure 3.15 Trough and planar crossbedding in MX facies. Scale in cm. (MS 3: 55.8-58.7 m).

Figure 3.16 Large scale trough crossbedding in Major Tyrwhitt MX Interval (MS 1: 10.5-19.5 m). Crossbedded unit has sharp flat base (arrowed on photo), which is parallel to regional horizontal. Man is 1.8 m tall.



Tobermory of measured section 2 (208-211 m), an MX facies unit is composed only of the larger scale sets; a 1.8 m thick planar set is succeeded respectively upward by trough sets, 1.3 and 0.9 m thick (Figure 3.17). Similar large scale trough sets occur at about the same stratigraphic level in measured section 5 (220-226 m). Both of these examples are exceptional relative to other MX facies occurrences.

Where large and medium scale sets are interbedded, the upward transition from the large to the medium scale sets may be marked by either a gradual or abrupt decrease in set scale (e.g. MS 2: 9-16 m). Upward decreases in set scale are also accompanied by an upward fining of grain size. Two to three such sequences may be superimposed in some MX facies units.

In two cases, deformation was evident within single trough sets. In measured section 1 (5 m), a set contains folded laminae (Figure 3.18). A 30 cm thick set is folded into a recumbent fold in measured section 2 (65 m). Both examples are exceptional, and reflect soft sediment deformation.

3.4.4 Bounding Relationships

The lower boundary of MX facies units tends to be

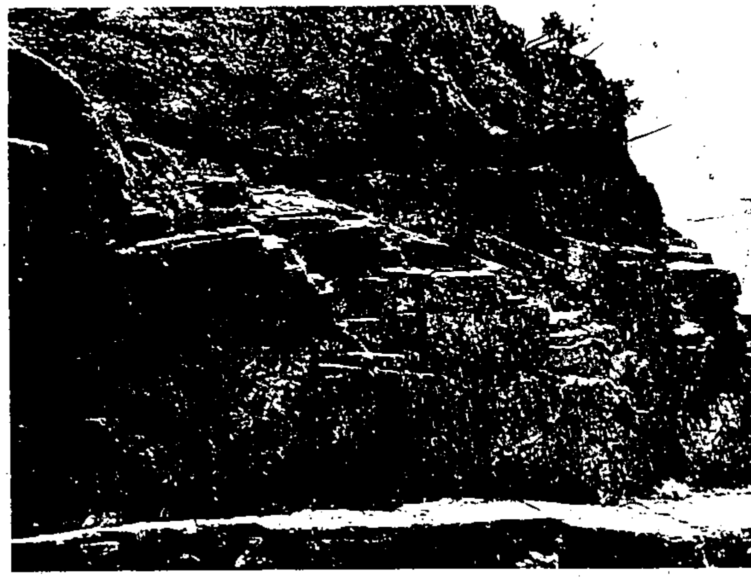


Figure 3.17 Large scale planar and trough crossbedding, MX facies (MS 2: 208-211 m). Planar set has horizontal flat base (arrowed on photo). Photo rotated to correct for regional dip. For scale, planar set is 1.8 m thick at thickest point.

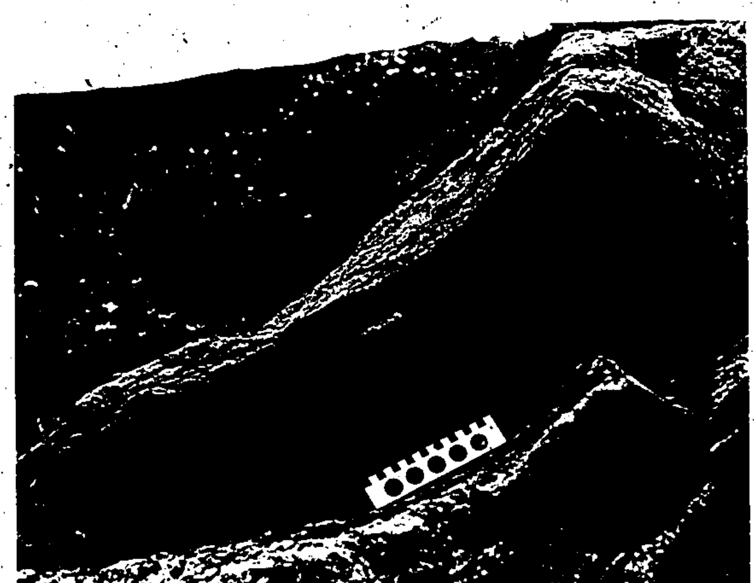


Figure 3.18 Trough crossbedding exhibiting folded laminae, MX facies. Scale in cm. (MS 1: 5 m).

slightly irregular but not noticeably scoured. In some cases it is very flat (Figure 3.16) and in all cases it is horizontal. The upper boundary of the facies units is usually sharp and also horizontal.

The MX facies is most commonly interbedded with the ST facies, and to a lesser extent with the XL facies. Less commonly, the MX facies may pass upward into the SI and TC facies.

3.4:5 Trace and Body Fossil Content

Trace fossils are exceedingly rare in the MX facies except in a few cases where organisms burrowed down into the tops of facies units (e.g. S 1: 44 m). In the cited example, the burrows are vertical, about 3 cm in diameter, and are characterized by a concentric ring structure. G. Pemberton (pers. comm.) states that they were formed by organisms which packed sediment against the sides of the burrow, a process that can only take place under little or no current activity. No genus name has yet been assigned to this form.

Body fossils or fragments are totally lacking from the MX facies.

3.4.6 Paleocurrent Data

Paleocurrent data for the MX facies was subdivided according to set type, set thickness and stratigraphic position of MX facies units in an attempt to discern variations in paleoflow direction among the various groupings (Table 1, Appendix 1; Figure 3.19). An assessment of variations in paleoflow direction is complicated by the inherent high variation in the data that results from measuring lamina dips as opposed to trough axes (Section 1.4). The latter were not possible to measure due to a paucity of plan views of the troughs. The calculated vector mean azimuths for each of the various data groups, as well as a grand vector mean for all data is given in Table 3.2.

It is evident from Table 3.2 that there are no significant differences in paleoflow directions among the various groupings of data for the MX facies. The vector mean azimuth for each data group has a relatively high standard deviation which overlaps with that of other data groups. Hence there is no significant difference in paleoflow direction in sets of different type, scale or stratigraphic position. The grand vector mean azimuth for the entire MX facies (202 degrees; Table 3.2) is taken to be representative of the paleoflow direction.

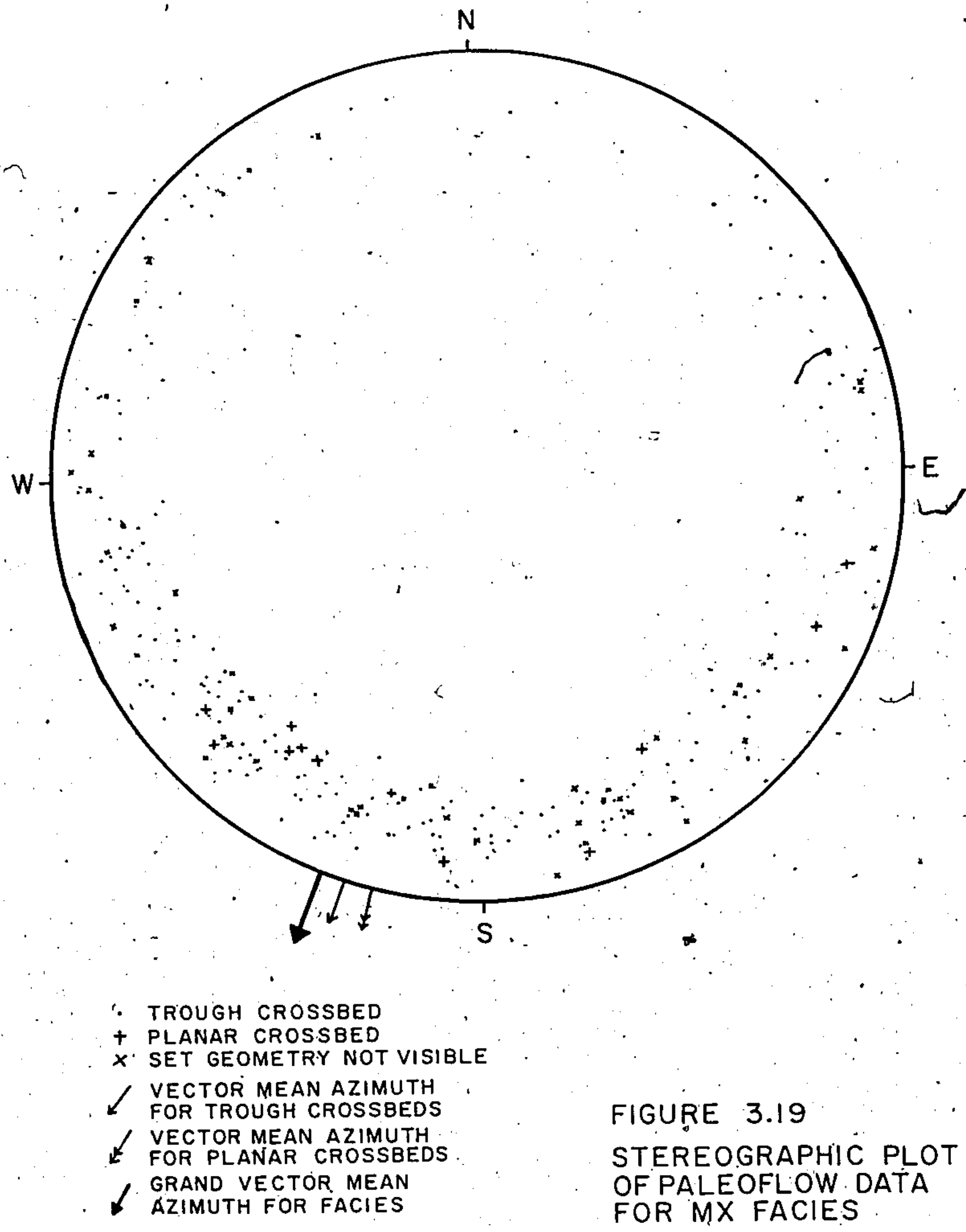


FIGURE 3.19

STEREOGRAPHIC PLOT OF PALEOFLOW DATA FOR MX FACIES

Table 3.2 Results of vector mean calculations for MX facies in Tyrwhitt and Tobermory Formations. Data plotted on stereonet in Figure 3.19

Description of data grouping	No. of readings	Vector mean Azimuth[1]	Vector length (%)	Standard deviation (degrees)
MAJOR TYRWHITT MX INTERVAL				
Trough sets thicker than 1 m	22	213	74	46
Trough sets less than 1 m thick	72	221	35	78
Sets, scale or geometry not visible	12	211*	61	57
MX FACIES UNITS IN OTHER PARTS OF TYRWHITT FM				
Trough sets, all measured sections	85	195	48	68
Planar sets, all measured sections	10	199	81	38
Sets, scale or geometry not visible	27	176	52	63
GRAND VECTOR MEAN PALEOFLOW AZIMUTH, MX FACIES IN TYRWHITT FM	228	202	48	67
MX FACIES UNITS IN TOBERMORY FORMATION				
Trough and planar sets	14	187	66	53
Sets, scale or geometry not visible	8	228**	51	64
GRAND VECTOR MEAN PALEOFLOW AZIMUTH, MX FACIES IN TOBERMORY FM	22	199	57	61
GRAND VECTOR MEAN AZIMUTH FOR MX FACIES, TYRWHITT AND TOBERMORY FMS	250	202	49	66

[1] All vector means significant at greater than 99.5% (2 degrees of freedom) except:
* G.T. 99%; ** L.T. 75%

3.4.7 Facies Recognition

The MX facies is characterized by:

1. abundant medium scale trough crossbeds 6-50 cm thick with a few interbedded planar tabular sets of the same scale;
2. large scale trough crossbeds up to 160 cm thick and planar crossbeds up to 180 cm thick which are occasionally interbedded with their medium scale counterparts; and
3. its common interbedding with the ST facies, and to a lesser extent with the XL facies.

3.5 SMALL SCALE CROSSLAMINATED FACIES (XL) HORIZONTAL PARALLEL LAMINATED FACIES (HL)

3.5.1 Introduction and Basic Interpretation

The XL and HL facies have a common intimate lateral and vertical relationship, and are described together as a facies association. The XL facies is composed of small scale crosslamination and subordinate symmetrical wave form crosslamination, whereas lamination in the HL facies is generally horizontal and straight or somewhat irregular.

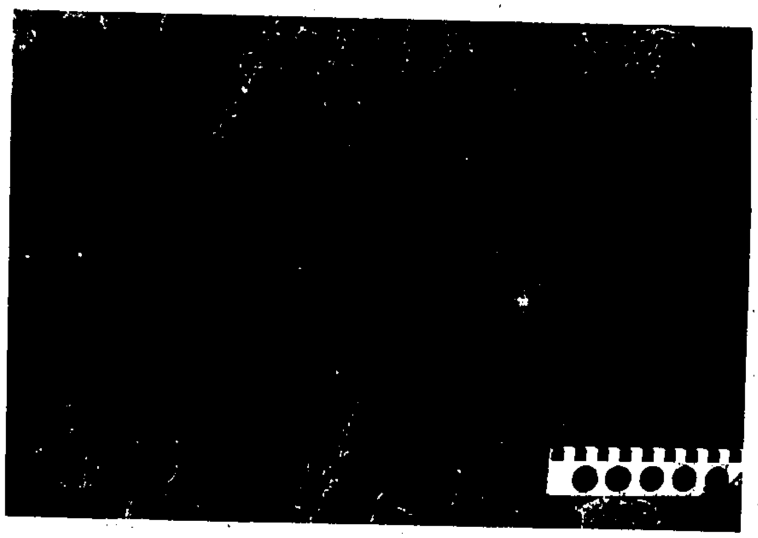
Both facies are interpreted to have a shallow marine origin, and to have been deposited seaward of fair weather wave base by storm surge currents with superimposed weaker oscillatory flow.

3.5.2 Stratigraphic Position

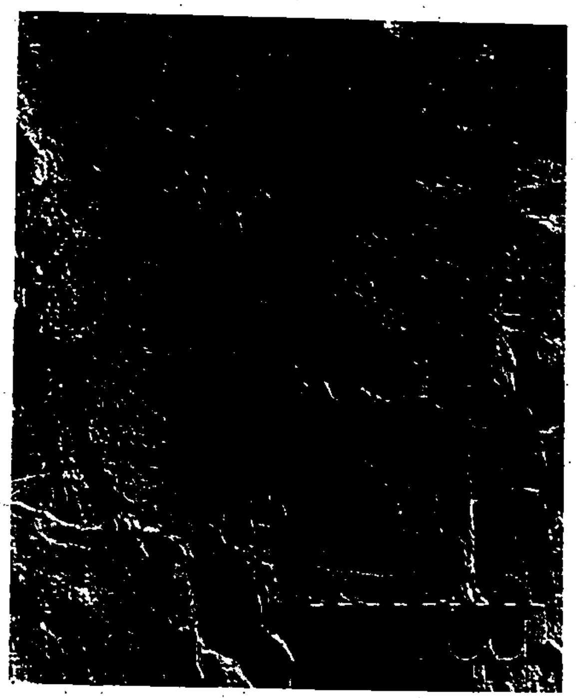
The XL and HL facies occur in both the Tyrwhitt and Tobermory Formations, although facies units are thicker and more abundant in the latter. In the Tyrwhitt Formation, XL facies units are generally several decimeters thick (maximum about 1 m thick), and thin interpreted remnants of XL facies units are usually present in parts of the ST facies (e.g. MS 2: 70-96 m). HL facies units are rare in this Formation (e.g. MS 1: 61-62 m; 71-72 m). In the Tobermory Formation, XL facies units may attain thicknesses of several meters (e.g. MS 2: 212-219 m; 240.5-244 m). HL facies units are generally less than 25 cm thick, although a range of 9-100 cm is possible.

3.5.3 Facies Description

The XL facies is dominantly composed of small scale trough crosslaminae in sets 0.5 to 2 cm thick and 2-10 cm wide (Figure 3.20). Set laminae are concave upward, and



(a)



(b)

Figure 3.20 Common vertical relationships between horizontal laminae and small scale crosslaminae. Note irregularity of laminae in upper part of (b). Scale in cm. (a: MS 1: 208 m; b: MS 5: 236 m).

intersect the lower set boundary tangentially. The degree of set preservation is variable, and in many cases only small remnants of crosslaminae are preserved. Wave form crosslaminae are much less commonly preserved (Figure 3.21). Laminae within the wave form may be form concordant, where they arch upward, or form-discordant, where they truncate against the wave form (terminology of de Raaf et al., 1977).

Laminae in the HL facies are generally horizontal and straight, and less than 1 mm thick (Figure 3.20 a,b). These may be traced laterally without change in form over a few decimeters, and commonly terminate in tiny concave upward scours. Some laminae have an undulatory aspect (Figure 3.22). In some cases, laminae appear to have been deformed somewhat, causing them to be irregular (Figure 3.20 b; Figure 3.22). The irregularities are often due to disruption by burrowers or to soft sediment deformation.

Figure 3.20 demonstrates the initmate vertical relationship between horizontal laminae and small scale crosslaminae. Predominantly horizontal laminated units can also pass laterally over about a meter into units containing thin interbedded crosslaminated and horizontal laminated subunits (Figure 3.23).

The XL facies can be developed in grain sizes

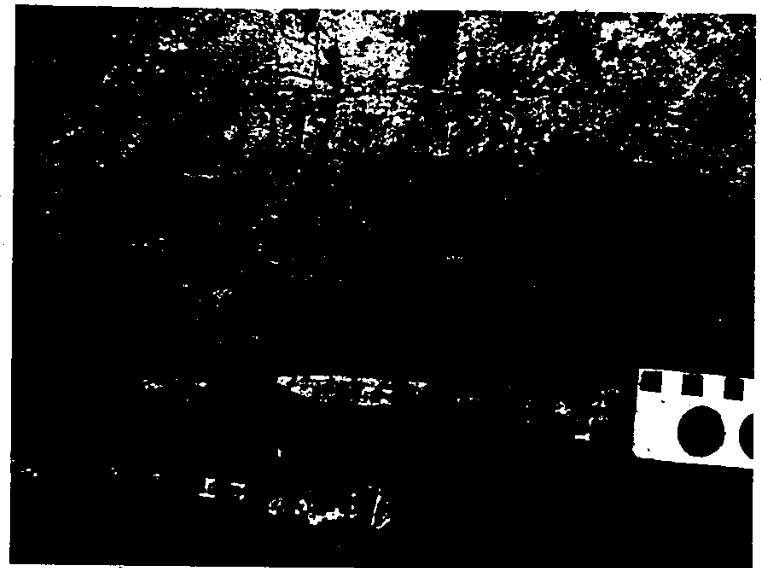


Figure 3.21 Form-concordant and form-discordant wave form crosslaminae. Scale in cm. (MS 5: 230 m).

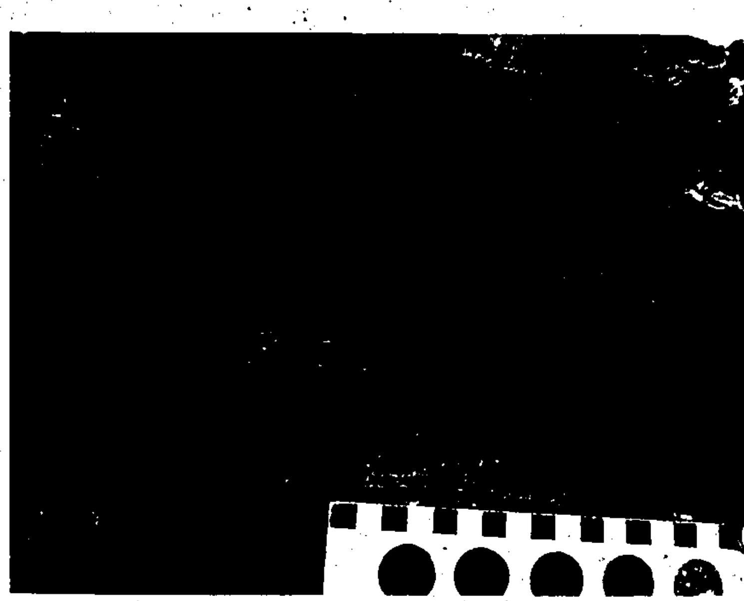


Figure 3.22 Burrowed and undulatory horizontal laminae. Scale in cm. (MS 5: 229 m).

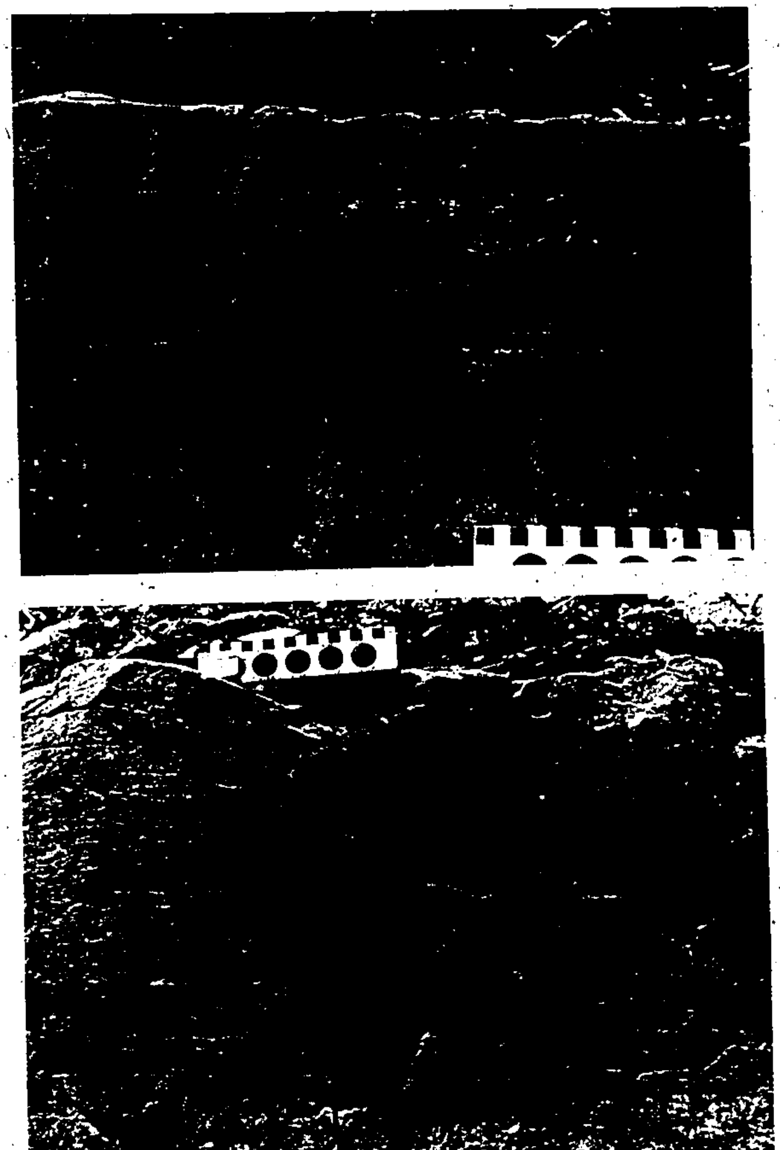


Figure 3.23 (a) dominantly parallel and slightly wavy laminae. Note single wave form which truncates laminae.

(b) approximately 1 m laterally from (a), small scale crosslaminae and horizontal laminae are intimately related. Note sharp base. Scale in cm. (MS 1: 245 m).

ranging from coarse silt to fine sand. The most commonly occurring grain size is very fine sand. Sands in the HL facies range from very fine to medium grade, but most commonly are very fine grained. Where HL:XL transition couplets are found, the grain size is always very fine sand.

3.5.4 Bounding Relationships

The XL facies is commonly interbedded with the ST, HL and MX facies. It also may vertically succeed the TC facies. In most cases facies boundaries are sharp. A type of gradational transition is sometimes observed between the HL and XL facies, where horizontal laminae become undulatory before passing upward into the XL facies.

The HL facies may vertically succeed the XL, ST and carbonate facies. The facies most commonly passes upward into the XL facies, and less commonly upward into the ST facies.

3.5.5 Trace Fossil Assemblage

Trace fossils are moderately abundant in the XL facies, and are less common in the HL facies. Most of the observed trace fossils in these facies were described earlier from the ST facies (Section 3.3.6), including <u>Plichnia</u>?, <u>Skolithos</u> (Figure 3.24) and <u>Bergaueria</u> (Figure 3.25). A fourth form identified here by G. Pemberton (McMaster University) is <u>Arenicolites</u> sp? (Figure 3.26). <u>Arenicolites</u> is a U-shaped burrow lacking spreiten. Its origin has not been well established, and it has been attributed to both crustaceans and suspension feeding worms. The form usually develops in a relatively high energy environment with active currents.

3.5.6 Facies Recognition

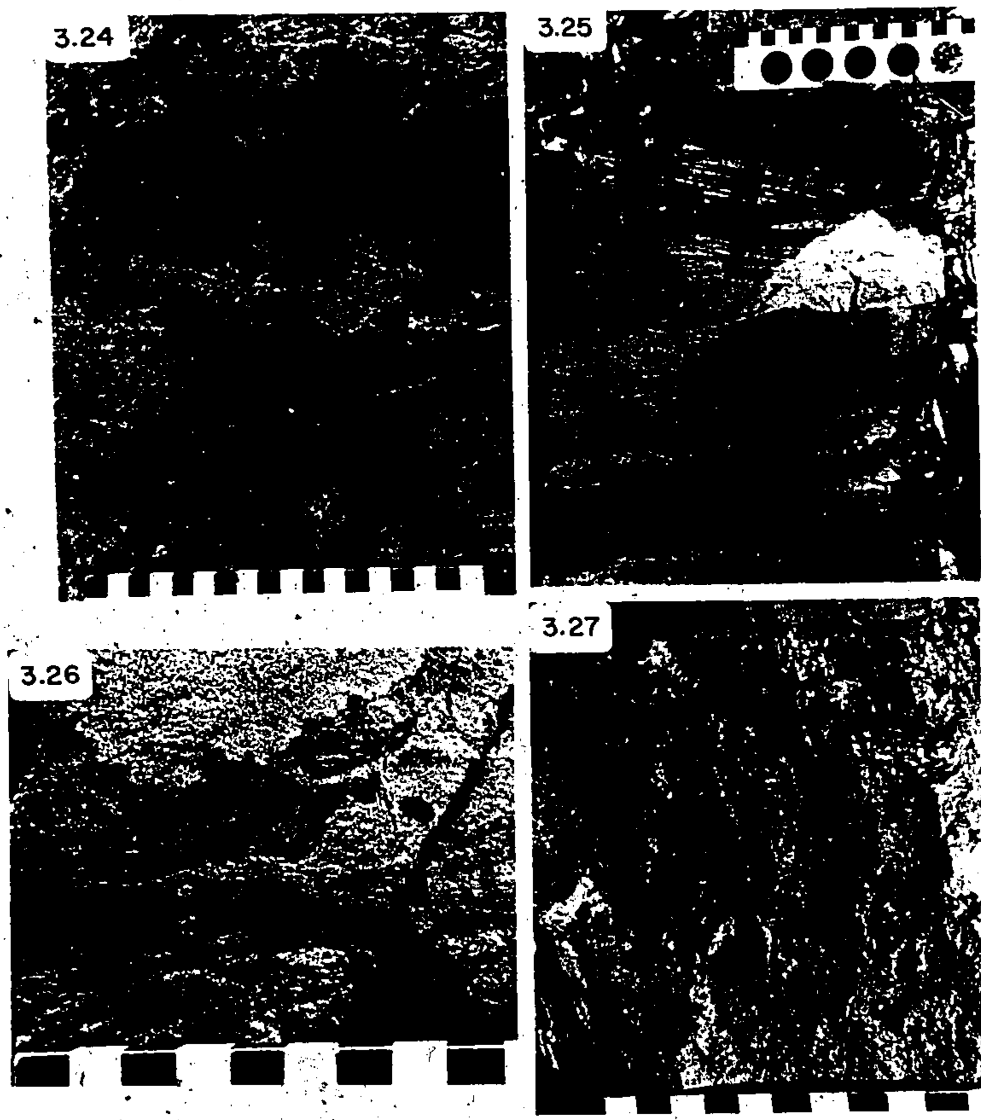
The XL facies is recognizable on the basis of an abundance of small scale crosslaminae and subordinate wave-form sets, and its interbedding with the ST, HL and MX facies. The HL facies is recognizable on the basis of its characteristic horizontal parallel laminae and its intimate vertical and lateral association with the XL facies.

Figure 3.24 *Skolithos* burrows (arrowed) in cross-sectional view. Scale in cm. (MS 1: 212 m).

Figure 3.25 *Bergaueria* burrow (arrowed) in cross-sectional view. Scale in cm. (MS 3: 228 m).

Figure 3.26 *Arenicolites* sp? in cross-sectional view. Scale in cm. (MS 5: 216 m).

Figure 3.27 *Orbiculoidea* layers in middle FC facies unit. Scale in cm. (MS 1: 54 m).


3.24
3.25
3.26
3.27

3.6 SILTSTONE FACIES (SI)

3.6.1 Introduction and Basic Interpretation

The SI facies is composed of massive bedded siltstone, and is the finest grained clastic sediment observed in the Pennsylvanian sequence. It is interpreted to have a shallow marine origin, and to have been deposited seaward of fair weather wave base during a period of restricted sediment supply and current activity.

3.6.2 Stratigraphic Position

Two siltstone units 0.5-1 m thick are present at similar stratigraphic levels in the Tyrwhitt Formation of most measured sections (e.g. MS 1: 19-20 m; 50-51 m). Hence, both appear to persist laterally a minimum of 5 km in a N-S direction.

3.6.3 Facies Description

The SI facies is composed of siltstone which may be somewhat dolomitic or argillaceous in some cases. Sandy layers are occasionally present, and the facies units commonly exhibit heavy iron stains.

The siltstone units are usually massive bedded except for occasional thin partings where muscovite flakes are concentrated. No sedimentary structures were observed, and the units appear to be thoroughly bioturbated.

3.6.4 Bounding Relationships

The SI facies is commonly interbedded with the ST facies. The lower SI facies unit may directly succeed the Major Tyrwhitt MX Interval (e.g. S 1: 19.5 m). Unit contacts are always sharp.

3.6.5 Facies Recognition

The facies is readily recognizable on the basis of its lithology and interbedding with the ST facies.

3.7 NON-FOSSILIFEROUS CARBONATE FACIES (NC)
FOSSILIFEROUS CARBONATE FACIES (FC)
CROSSBEDDED CARBONATE FACIES (TC)

3.7.1 Introduction and Basic Interpretation

The NC, FC and TC facies constitute only a minor proportion of the predominantly siliciclastic Pennsylvanian succession. All are interpreted to have a shallow marine origin and to have been deposited under conditions of limited siliciclastic supply.

3.7.2 Stratigraphic Position

The NC facies is usually restricted to the upper part of the Tobermory Formation (e.g. MS 2: 239-240 m; 244-245 m; 248-252 m), although in one case the facies occurs at the base of the Formation (MS 1: 189-190 m). The facies is apparently not laterally persistent between measured sections, spaced 0.5-2 km apart. The usual thickness of the facies is 0.37-1.61 m, and exceptionally 3.9 m.

The FC facies incorporates three distinctively different fossiliferous carbonate units, each of which occurs once in each measured section. The lower FC facies unit (e.g. MS 1: 0-1 m) forms the base of all measured sections, and is part of the Lower Spirifer Tongue in the Todhunter Formation as defined by Scott (1964). The middle FC facies unit (e.g. MS 2: 55-56.5 m) averages about 1.5 m thick, and occurs at about the middle of the Tyrwhitt Formation in all measured sections. The upper FC facies unit (e.g. MS 2: 121.5-122.5 m) averages about 0.5-1 m thick, and occurs in the Storelk Formation of most measured sections. All three FC facies units are laterally persistent at least 5 km.

The TC facies is present in the Tyrwhitt Formation of two measured sections (MS 1: 77-78 m; MS 3: 76.5-77 m). Facies units pinch out laterally over a distance of a few tens of meters.

3.7.3 Facies Descriptions

The NC facies is composed of sandy microcrystalline dolomite, although where sand becomes highly abundant the lithology of parts of some units reverts to a highly dolomitic sandstone. Chert layers up to about 1 cm thick and chert nodules are common in individual facies units. The units are massive bedded and structureless, and the undersides of units display intense bioturbation. No specific ichnogenera could be identified.

The lower FC facies unit is composed of highly sandy limestone, and contains numerous irregular light brown weathering impure chert nodules (identified by Scott, 1964). Fine to coarse grained echinoderm fragments and abundant Spiriferid brachiopods are scattered throughout. Units are massive bedded with no indication of internal stratification.

The middle FC facies unit is composed of highly sandy fine to coarse crystalline dolomite, or, with abundant sand, a highly dolomitic sandstone in parts. The unit contains abundant Orbiculoidea brachiopods usually concentrated into layers a few centimeters thick (Figure 3.27). Poorly preserved articulate brachiopods are rare. The facies unit is always horizontally stratified, and commonly beds are irregular and are about 2-3 cm thick.

The upper FC facies unit is composed of highly sandy dolomite or highly dolomitic sandstone. The unit contains Terebratulid and Spiriferid brachiopods at some localities, and is massive bedded with no indication of sedimentary structures.

The TC facies is usually composed of dolomite containing abundant sand and phosphorite grains. Texturally, it is highly porous and vuggy (Figure 3.28), and contains abundant casts and fragments of shells thereby resembling a coquina. The facies is crudely cross stratified in trough sets 20-30 cm thick. An insufficient number of paleocurrent measurements could be obtained to establish a paleoflow direction.

3.7.4 Bounding Relationships

The NC facies is usually interbedded with the ST facies, and contacts between the facies tend to be gradational. The HL facies sometimes vertically succeeds the NC facies via a sharp contact. In one case, an MX facies unit vertically succeeds the NC facies, and prominent load casts are visible at the base of the MX unit (Figure 3.29).

The lower FC facies unit usually passes upward into the ST facies where the contact is exposed. The middle FC facies unit is usually succeeded vertically by the ST facies, although in one case (MS 1: 55 m) it is overlain by the MX facies. The lower contact of the facies is poorly exposed except in measured section 1 where it gradationally overlies the ST facies. The upper FC facies unit gradationally overlies the SS facies, and rests in sharp contact with the vertically succeeding LT facies in the Middle Storelk Megatrough Interval.

The TC facies may pass upward into the XL or HL facies via a sharp contact. It is usually underlain by the MX or HL facies.

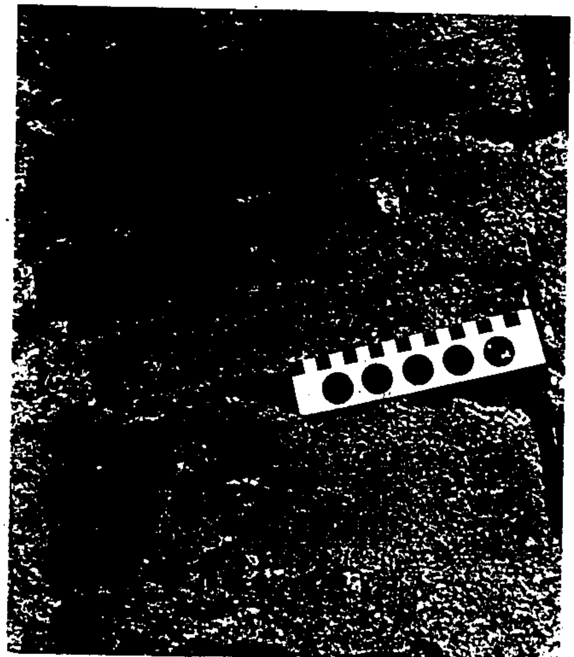


Figure 3.28 Porous texture of TC facies. Scale in cm. (MS 3: 62 m).

Figure 3.29 Load casts on base of MX facies unit vertically succeeding an NC facies unit. Scale in cm. (MS 2: 240 m).

3.7.5 Facies Recognition

All facies may be distinguished by their predominantly carbonate lithology. The following criteria distinguish the carbonate facies from one another: fossil content in the FC facies; extensive bioturbation and lack of body fossils in the NC facies; and cross stratification in the TC facies.

3.8 MEGAPLANAR FACIES (MP)

3.8.1 Introduction and Basic Interpretation

The MP facies consists of megaplanar crossbeds with a maximum thickness of 10.15 m. The sets may be solitary, or may be interbedded with the LT, LP or MT facies. The MP facies is interpreted to have been deposited by aeolian dunes.

3.8.2 Stratigraphic Position

The MP facies is confined to the Storelk Formation, where it occurs in the Lower Storelk Megaplanar Interval and in the Upper Storelk Crossbed Interval (Figure 3.0;

e.g. MS 1: 98.5-116 m; MS 5: 168-195 m). Solitary megaplanar sets also occur in other parts of the sequence (e.g. MS 2: 156.6-162.2 m; Figure 3.30).

3.8.3 Facies Description

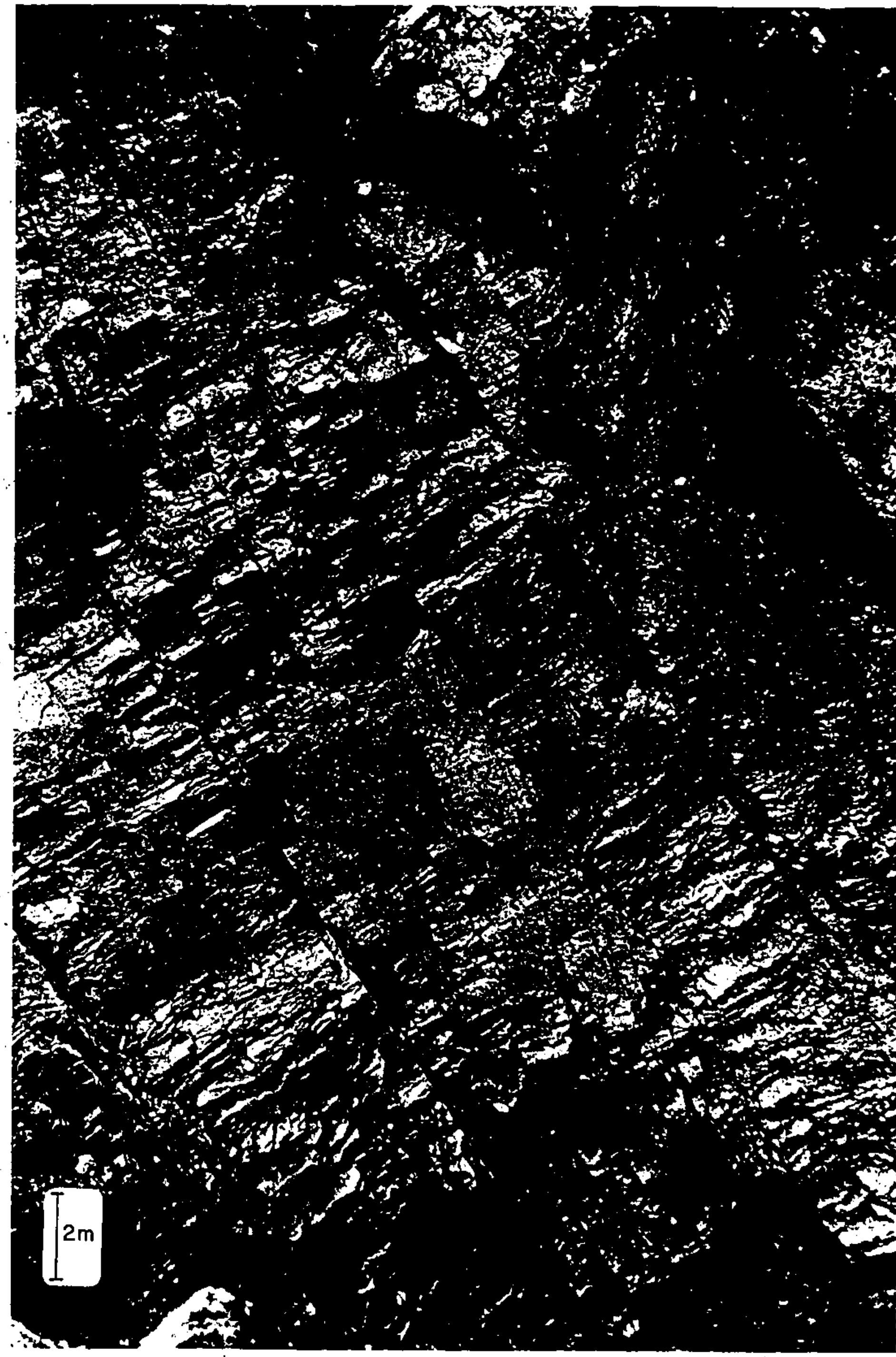
The MP facies is composed of well sorted very fine grained silica cemented sandstone. The paucity of other grain sizes appears to be the reason why laminae are very difficult to discern in parts of most sets. Rare grains up to medium sand size are scattered throughout many sets, but do not concentrate along the laminae.

The MP facies is characterized by two set types: planar tabular sets, and sets with divergent set boundaries (wedge shaped planar sets). These are discussed separately below:

Megaplanar Tabular Sets: megaplanar tabular sets are the thickest types observed in the Storelk sequence. Where sets occur by themselves in Intervals, they can reach a maximum thickness of 10 m. In Intervals where there is more than one set, set thickness is generally less than 3 m.

The lower set boundary is generally horizontal and flat, although it may undulate slightly. The boundary

Figure 3.30 Solitary megaplanar tabular set. Bounding surfaces are sharp, flat, and parallel to regional horizontal. Note how parting planes approach lower set boundary asymptotically. Set is 5.7 m thick, and is underlain by SS facies. (MS 2: 156.5 - 162.2 m).


2m

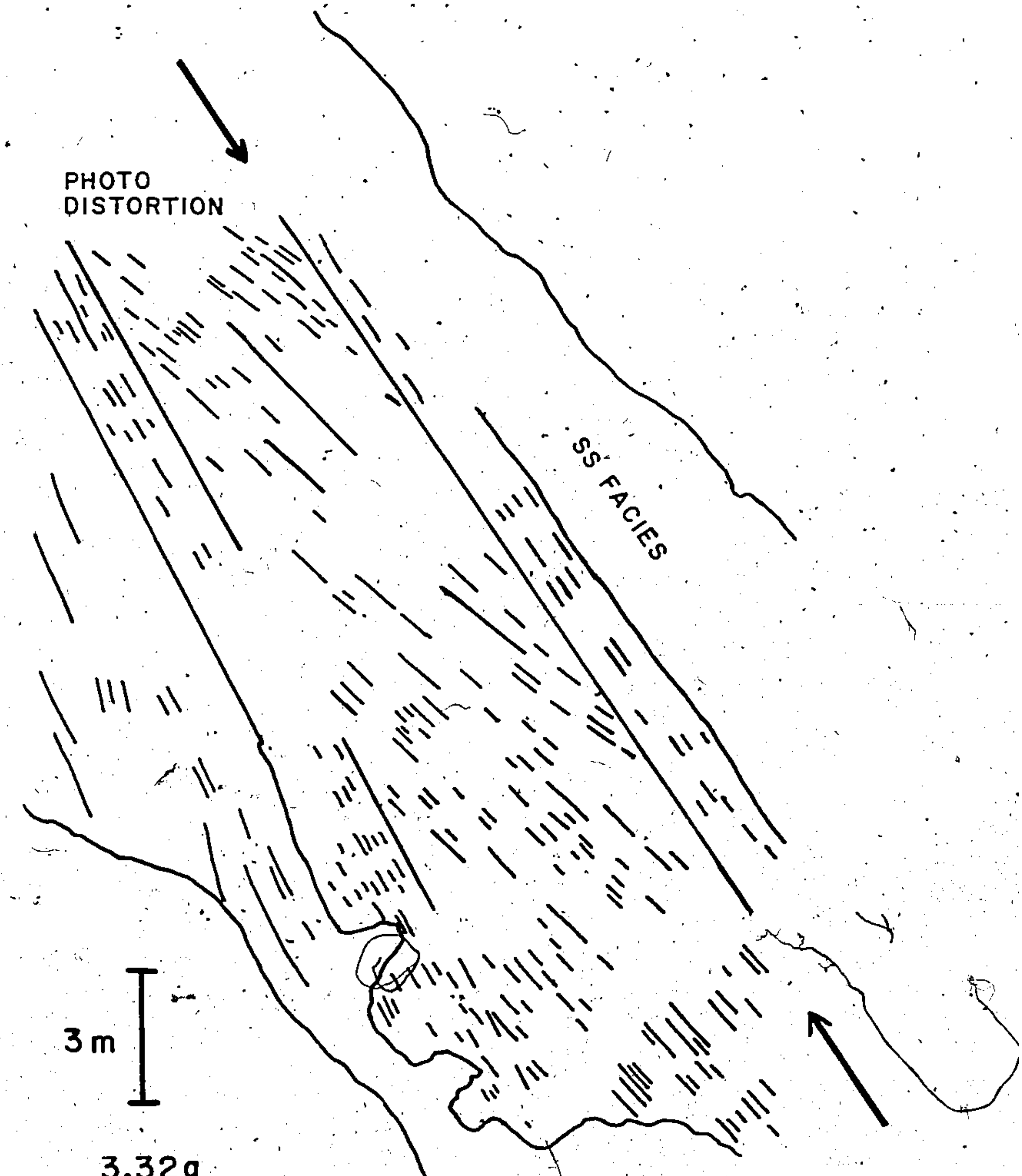
truncates underlying sets if present. In almost all tabular sets, cross strata in the lowermost part approach the lower set boundary asymptotically (Figures 3.30, 3.31), and in only a few cases was an angular relationship observed. Upwards in both types of tabular sets, the foresets form regular planar surfaces which maintain a consistent orientation throughout the rest of the set (Figures 3.30, 3.31, 3.32). Where orientation measurements could be made from the same set on opposite sides of a canyon, there was no detectable variation in the orientation of the cross strata. This suggests that the foresets are true geometric planes, and do not have a broad lateral curvature. The upper set boundary of all megaplanar tabular sets is generally horizontal and flat or slightly undulatory. It truncates the underlying cross stratification (Figures 3.30, 3.32).

In some cases, sets bounded by horizontal parallel set boundaries were observed to contain curved cross stratification. The foresets approach the lower set boundary asymptotically, and closely resemble the lowermost portion of megaplanar sets described earlier (e.g. Figure 3.31). Sets of this type are interpreted to be erosional remnants of originally thicker megaplanar sets, so that only the asymptotic base was preserved. In such

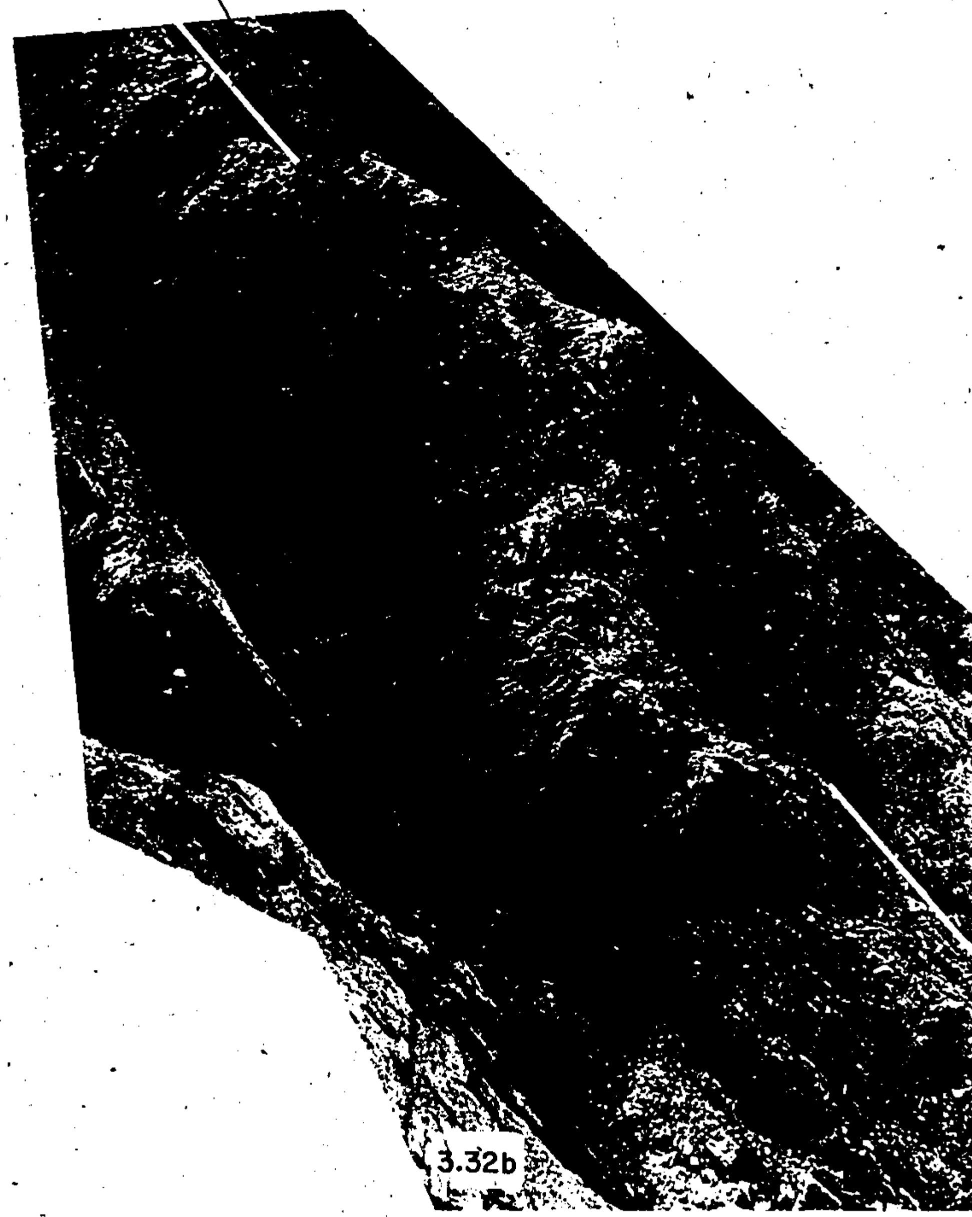
Figure 3.31 Asymptotic base of 10 m thick megaplanar tabular set. Bedding below set parallel to regional horizontal (arrows). Note regularity and constant dip of parting planes in rest of set. Man is 1.8 m tall. (Lower Storelk Megaplanar Interval, MS 5: 112.8-123 m).

Figure 3.32 Megaplanar tabular set 6 m thick (Lower Storelk Megaplanar Interval, MS 2).

Man (1.8 m tall) is about 15 m in foreground relative to outcrop (3:32B), and true scale is shown in 3.32A. "Photo distortion" due to convergence effect with increasing distance of outcrop from camera. Regional horizontal indicated by arrows in 3.32A and by white lines in 3.32B.



3.32a


3.32b

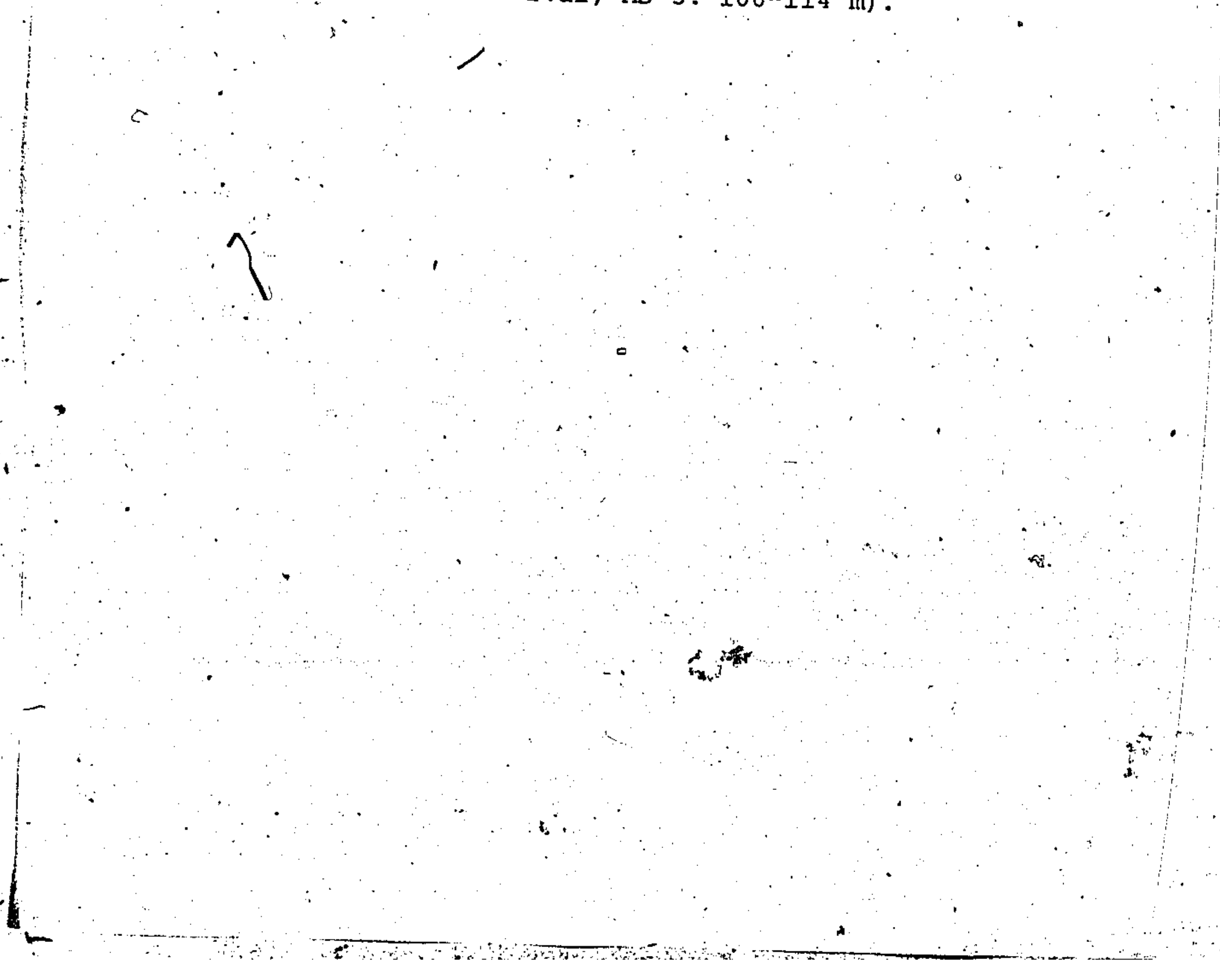
cases, if the lower set boundary was poorly exposed, the set could be mistakenly identified as a megatrough set.

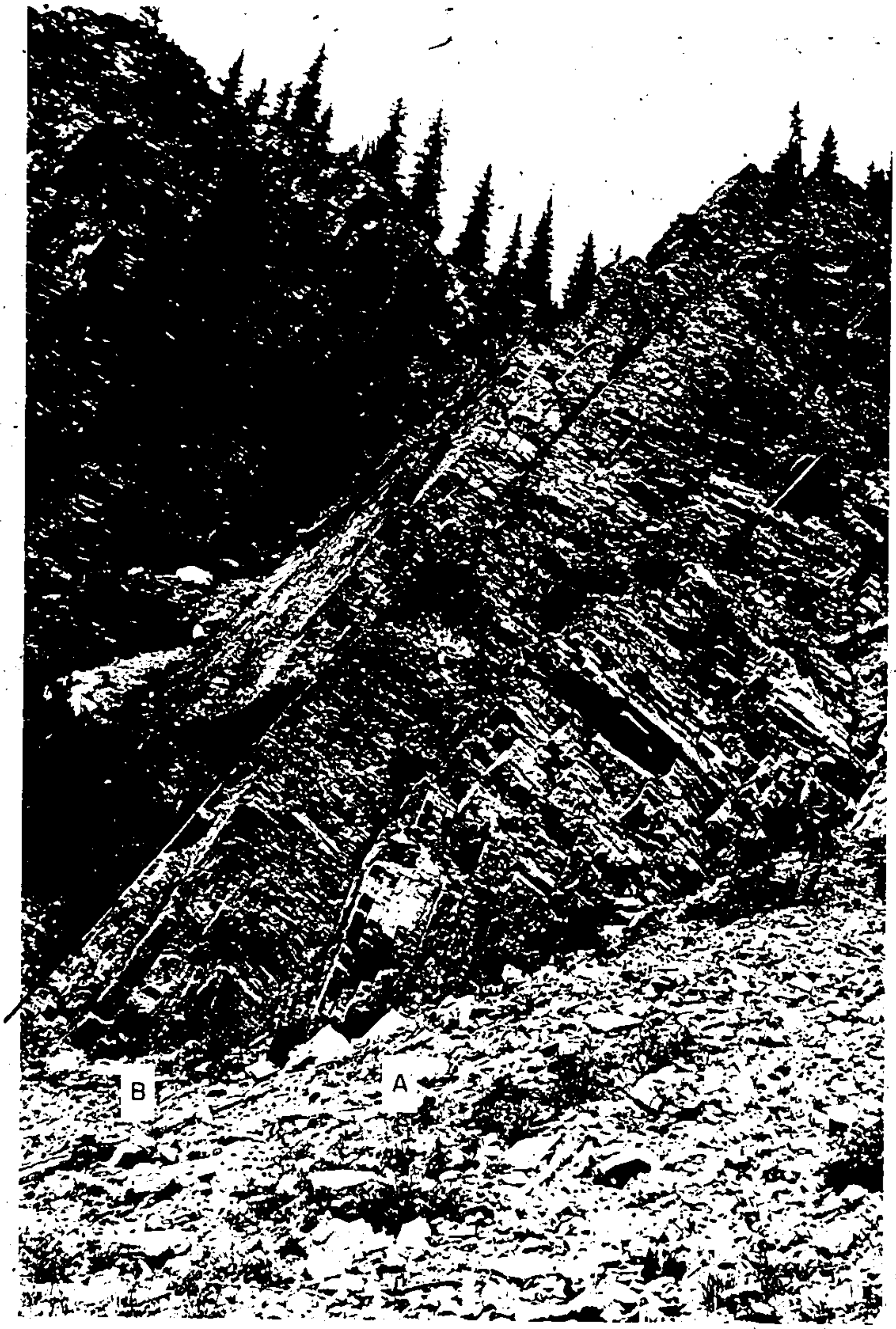
In a unique case, a megaplanar set was observed to contain convex upward cross stratification (Figure 3.33). Stratification within the set becomes progressively steeper upwards (Figure 3.33A), and the set appears to be overridden by another set in which foresets are slightly convex up and dip less steeply (Figure 3.33B).

Megaplanar tabular sets could rarely be traced laterally far enough to observe changes in form. An exceptionally well exposed set in the Upper Storelk of measured section 2 (Figure 3.30), however, could be traced laterally at least 40 m without discernible changes in thickness or set boundary configuration.

In the Upper Storelk of measured section 8, an exceptional cliff wall exposure of a megaplanar set demonstrates how some megaplanar tabular sets may appear if they could be traced laterally over long distances (Figure 3.34). The set has a maximum thickness of about 8.5m and can be traced laterally a minimum of about 37 m (all measurements from photographs due to inaccessibility). The internal cross stratification of the set is straight in cross sectional view, except where it approaches the lower set boundary asymptotically, similarly to previously

Figure 3.33 Convex upward cross stratification in megaplanar set. Morphology described in text. Regional horizontal indicated by arrows. Man (right hand corner) is 1.8 m tall. (Lower Storelk Megaplanar Interval, MS 3: 106-114 m).




B
A

described megaplanar sets. High on the cliff wall (Figure 3.34A), the lower set boundary is horizontal and flat. As this boundary is traced laterally to the bottom of the canyon (Figure 3.34B), it curves and climbs stratigraphically. The upper set boundary is gently inclined high on the cliff wall (Figure 3.34C), becoming more steeply inclined towards the canyon bottom (Figure 3.34D). In the canyon bottom, the two set boundaries nearly converge, and the set at this point is only about 1 m thick. From the above description, the set geometry does not strictly adhere to that for a megaplanar tabular set, since the set boundaries converge laterally. Significantly, however, had only the part of the set high on the cliff been exposed, it would have been termed a megaplanar tabular set. Moreover, had only the portion of the set in the canyon bottom been exposed, it would have been termed a large scale wedge shaped planar set. Hence the degree of exposure is crucial in accurate identification.

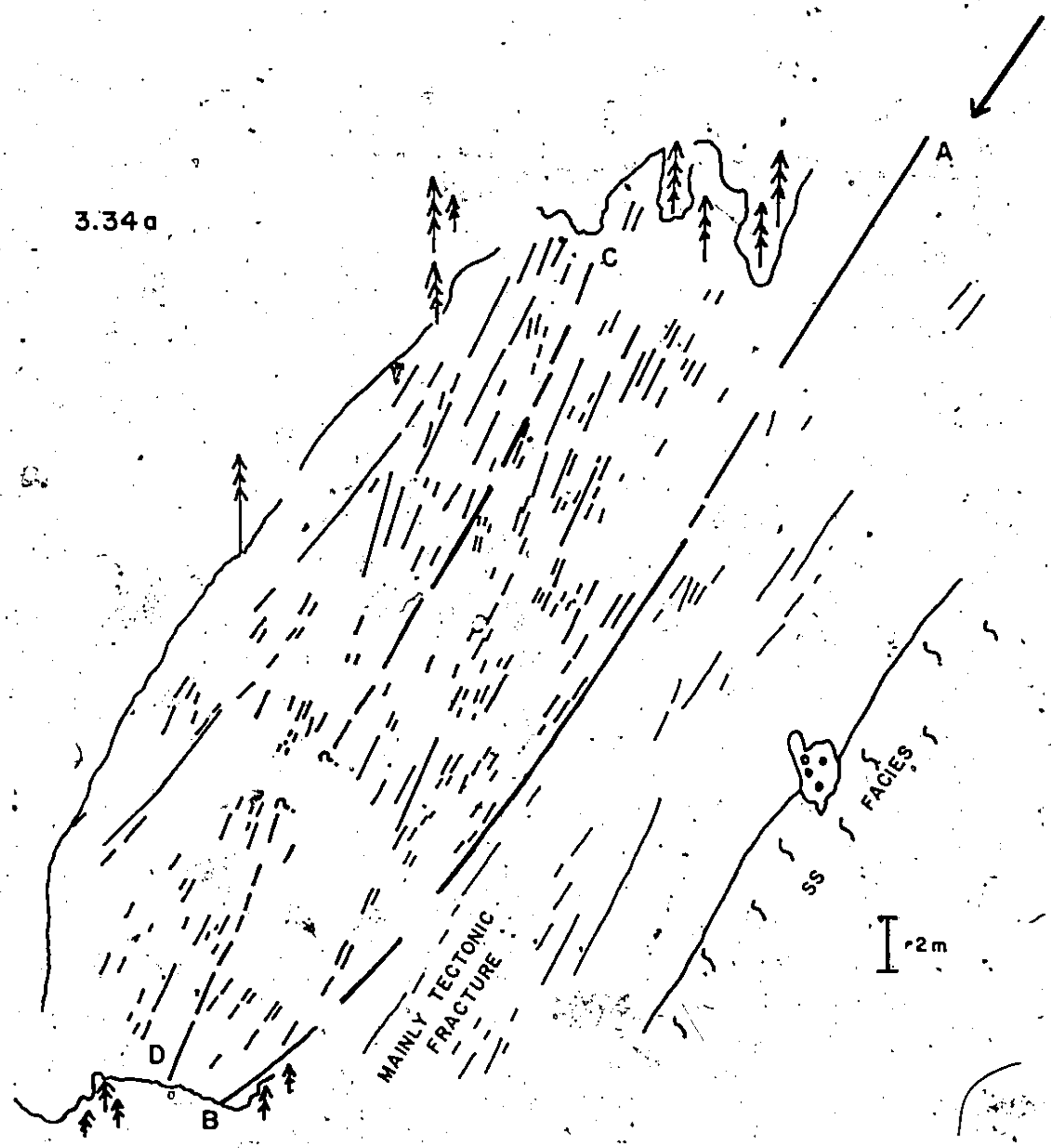
The dips of foresets in megaplanar tabular sets range from 6 degrees to a maximum of 26 degrees. The lowermost dips, however, were measured from sets where only the lowermost asymptotic portion of the set was exposed or accessible. Hence, these are unrepresentative of the foreset dip values from higher in the set.

Figure 3.34 Cliff wall exposure of megaplanar set showing set wedging out towards base of canyon.

Morphology of set discussed in text. Set bounded by other megaplanar sets. Regional horizontal indicated by arrows in 3.34a and by white lines in 3.34b. Man (1.8 m tall) circled in 3.34b (Upper Storelk Crossbed Interval, MS 8).

L

3.34a




3.34b
A
C
D
B

The foregoing description makes it possible to portray a three dimensional view of megaplanar tabular set geometry (Figure 3.35). The drawing emphasizes the fact that in some exposures (Figure 3.35, face 1) all that can be seen is a series of apparently horizontally stratified beds. In such cases the presence of a megaplanar set can be confirmed by measuring the dip angle of the strata together with the observation that individual strata can be traced laterally without apparent curvature.

Megaplanar Sets with Divergent Set Boundaries: almost all sets with this configuration adopt a classic wedge shape with planar set boundaries, although the set described earlier from measured section 8 shows that the overall configuration of some sets may be slightly more complicated. The usual range of thickness for wedge shaped megaplanar sets is 2-5 m. Their foresets range in dip between 13 and 26 degrees, with most falling in the 13-20 degree range. The angle of dip may gradually lessen upwards in the set.

The lower set boundary may be gently to steeply inclined, truncating underlying sets if present. Cross stratification either parallels the lower set boundary,

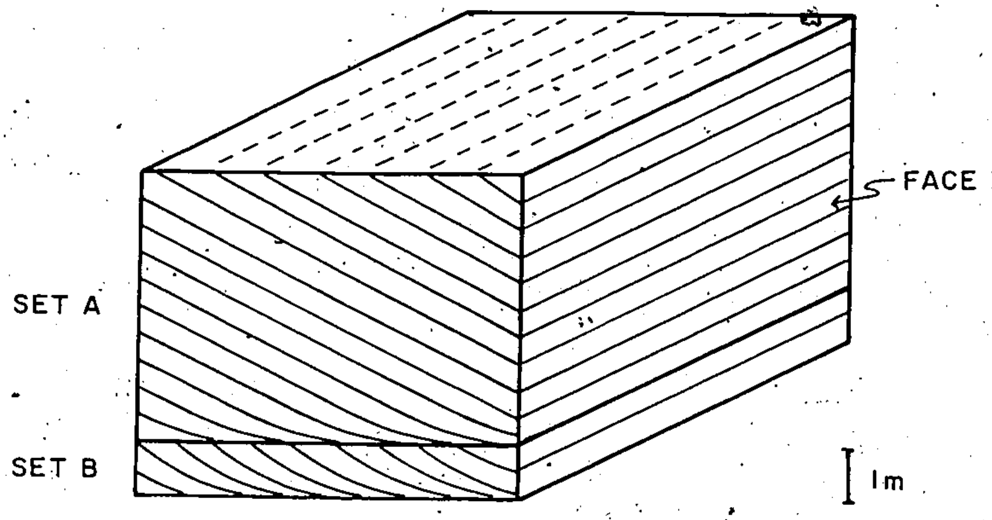


FIGURE 3.35
THREE DIMENSIONAL GEOMETRY OF MEGAPLANAR TABULAR CROSSBEDS

or has an angular relationship to it. The foresets are true geometric planes, based on rare bedding plane exposures and on the consistent orientations of foresets exposed on opposite sides of canyons. The upper set boundary truncates the cross stratification, is generally flat, and is horizontal or steeply inclined. Set boundaries converge over short distances, giving the set a wedge shape (Figure 3.36).

Where wedge shaped sets occur in the Storelk sequence, they tend to be paired. Foreset dip azimuths of vertically adjacent sets are divergent, tending to be about 25-60 degrees apart (e.g.MS 2: 109-117 m).

3.8.4 Bounding Relationships

The MP facies characteristically is interbedded with, or succeeds the LT and LP facies in the Lower Storelk Megaplanar Interval (e.g. MS 1: 99-116 m, MS 2: 96.5-117 m). It may also vertically succeed the SS facies (e.g. MS 2: 156.5 m) or pass upward into it (MS 5: 173 m). The MP facies can also interbed with the MT facies (MS 5: 175-190 m).

Figure 3.36 Paired wedge shaped megaplanar sets.

Lower set dips into photograph (to SSW) and hence appears to be horizontal bedded. Set is truncated by inclined lower set boundary of upper set, which dips towards SE (laminae parallel lower set boundary).

Upper set truncated by horizontal surface to right of photo. Regional horizontal indicated by arrows in 3.36a and by white lines in 3.36b. Man is 1.8 m tall (Lower Storelk Megaplanar Interval, MS 2: 109-117 m).

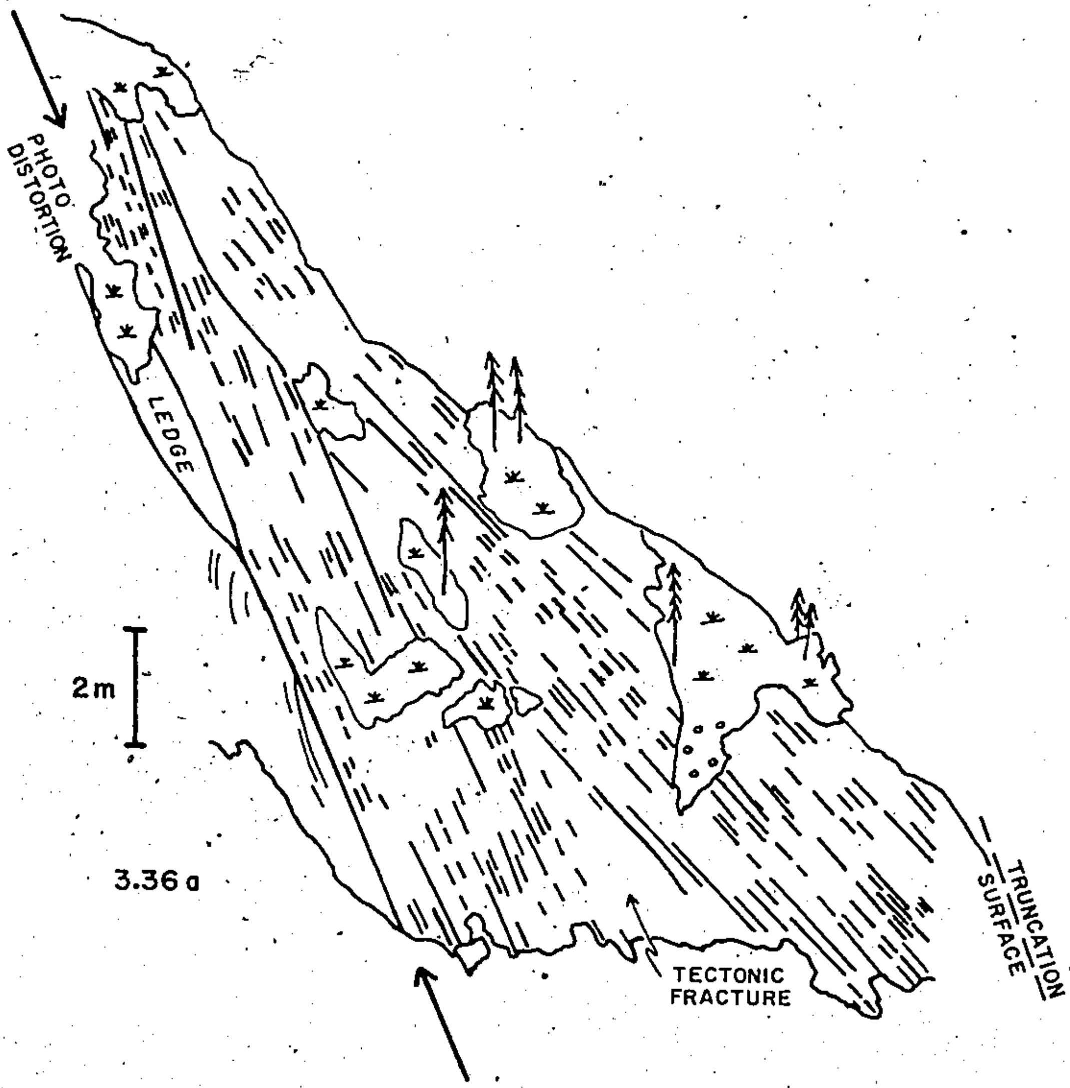


PHOTO DISTORTION
LEDGE
2 m
TECTONIC FRACTURE
TRUNCATION SURFACE

3.36 a


3.36b

3.8.5 Facies Recognition

With good exposure, the chief identifying characteristics of the MP facies are:

1. generally flat bounding surfaces, which are parallel and horizontal in tabular sets, and which converge in wedge shaped sets;
2. internal cross strata which are true geometric planes except at the base of the set where they usually curve to meet the lower set boundary asymptotically. Rarely, cross strata may be convex upward; and
3. their immense scale. Sets vary in thickness from 2 m to 10 m.

3.9 MEGATROUGH FACIES (MT)

3.9.1 Introduction and Basic Interpretation

The MT facies is composed of megatrough sets which attain a maximum thickness of 6 m. The sets are most commonly interbedded with sets from the LT and MP facies. The MT facies is interpreted to have been deposited by aeolian dunes.

3.9.2 Stratigraphic Position

The MT facies is confined to the Storelk Formation, where it occurs in the Middle Storelk Megatrough Interval and the Upper Storelk Crossbed Interval (Figure 3.0; e.g. MS 3: 126-144 m; 163-186 m). Megatrough sets occur in groups, and no solitary examples were noted elsewhere in the Storelk sequence.

3.9.3 Facies Description

The MT facies is composed of silica cemented quartz sandstone. In the Middle Storelk Megatrough Interval, the sand is fine grained with scattered medium and coarse grains. In each measured section there is always a single megatrough set containing numerous alternating fine to medium and coarse grained laminae, and in many cases abundant coarse pink chert grains. Laminae are generally well defined in this Interval as a consequence of a wider grain size range, and hence grain size segregation. Sands in the Upper Storelk Crossbed Interval are generally uniformly very fine grained, and consequently laminae are poorly developed in parts of most sets.

The megatrough sets have maximum thicknesses of 6 m. Their foresets generally dip between 10 and 20 degrees, although dips as high as 26 degrees were recorded.

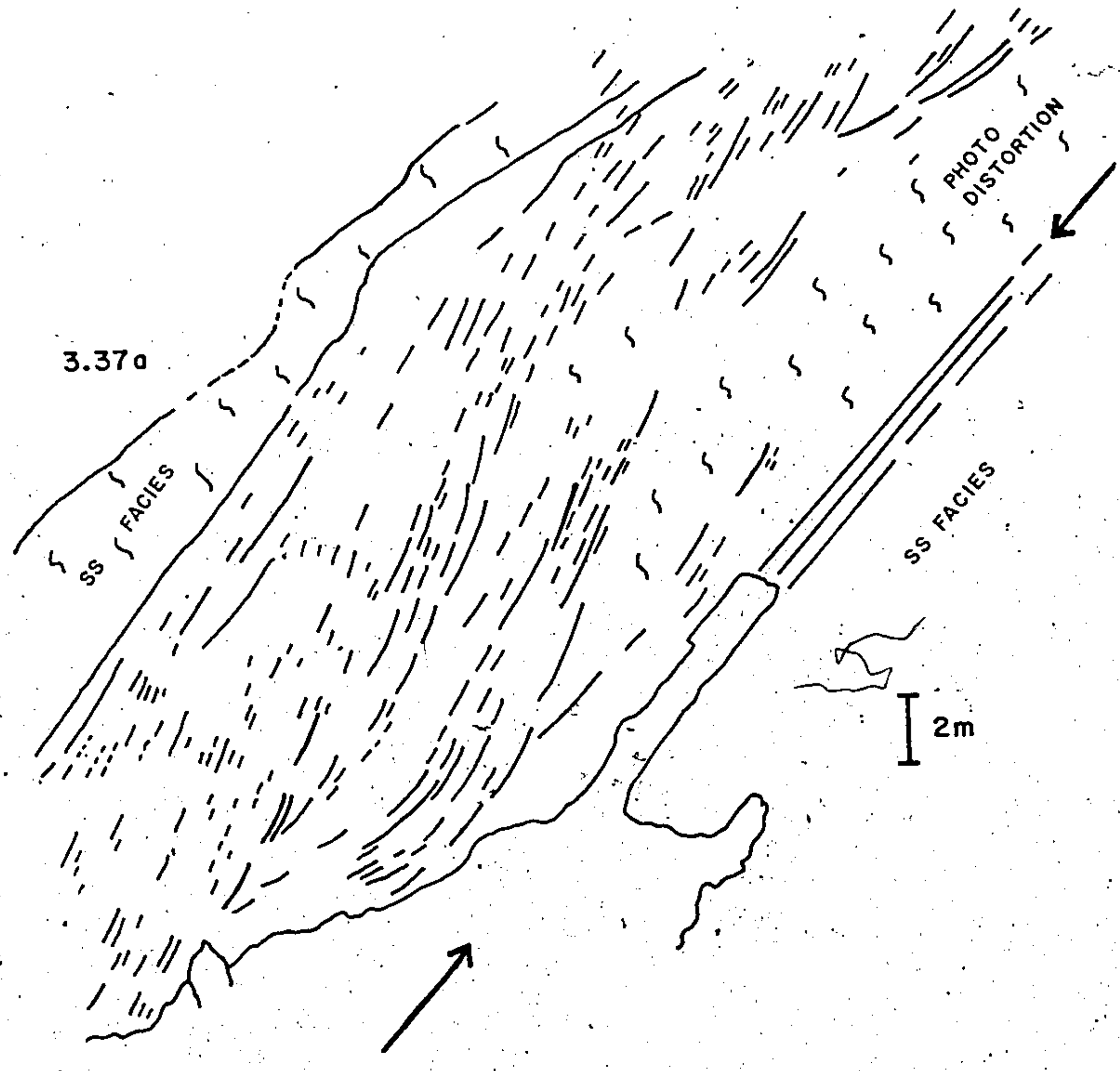
The lower set boundary of a megatrough set is broadly curved, and erodes into underlying sets (Figures 3.37, 3.38). In some cases where the megatroughs are scoured down to a consistent level, the lower boundary may appear to be relatively straight in two dimensions. Since no plan views of megatrough foresets were observed, they are inferred to have a very broad subtle lateral curvature in three dimensions on the basis of occasional three dimensional views and paleocurrent data:

1. Three dimensional views: the main canyons in which the stratigraphic sections were measured were usually oriented sub-parallel to the direction of trough infill (side view, Figure 3.39). End views (Figure 3.39) were occasionally exposed in tributary canyons oriented at 90 degrees to this trend. In end view, cross stratification planes are very broadly curved, and the overall scoop shape is subtle. Where large blocks spall off, broadly curved surfaces can be seen to dip into the cliff. Often this is the only indication that a megatrough is being observed, showing that in the absence of side views recognition of such sets may be difficult.

Figure 3.37 Megatrough sets in Middle Storelk Megatrough Interval, MS 1 (124-136 m).

Regional horizontal indicated by arrows in 3.37a and by white lines in 3.37b. Man (circled) is 1.8 m tall.

3.37a



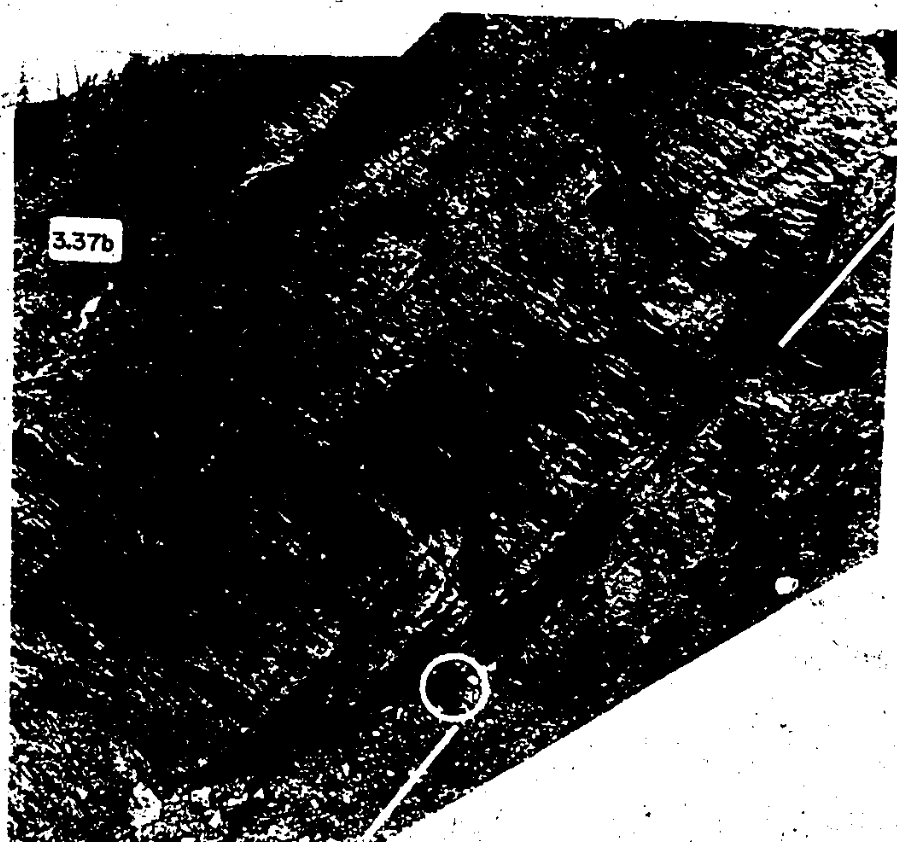
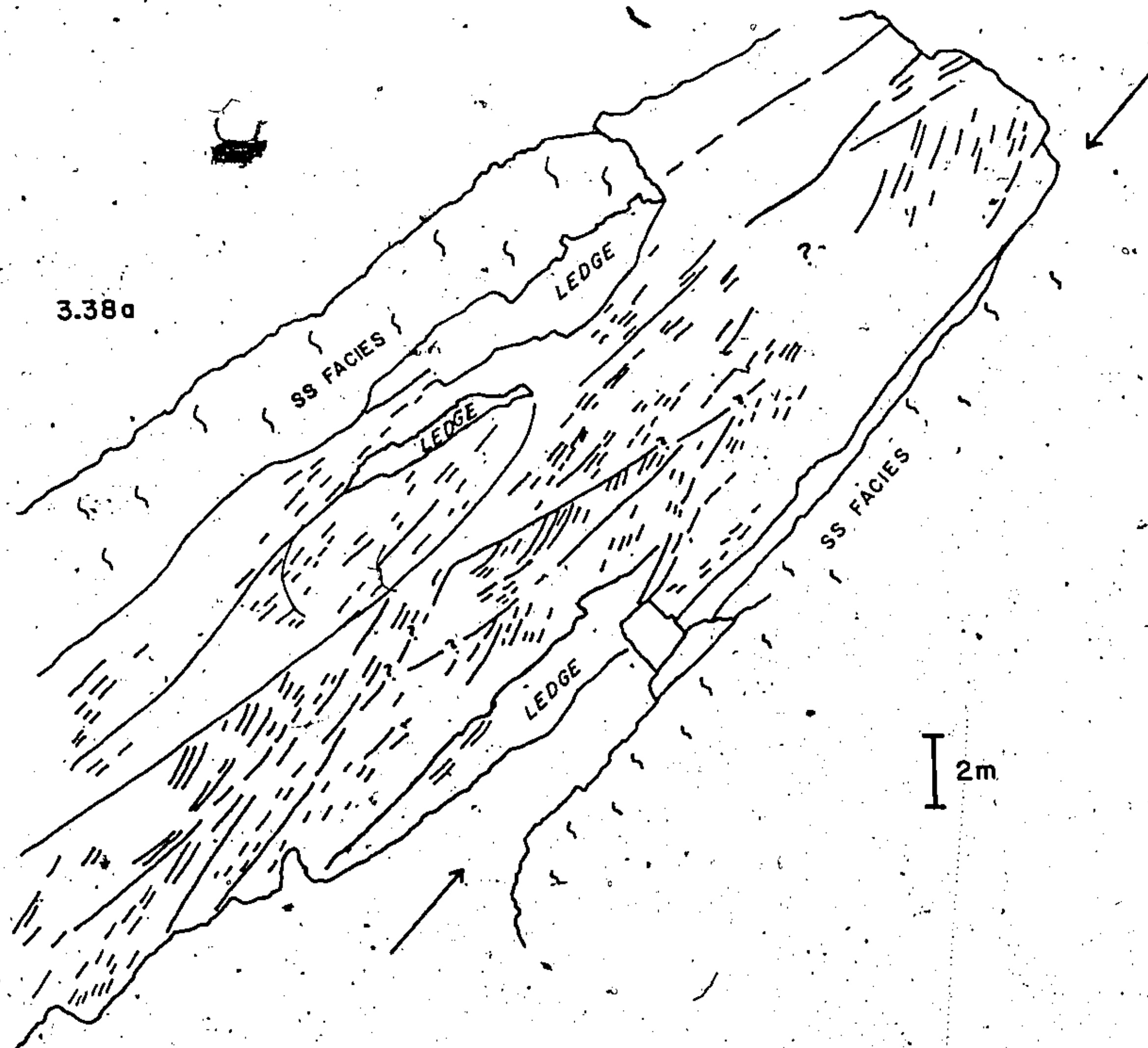
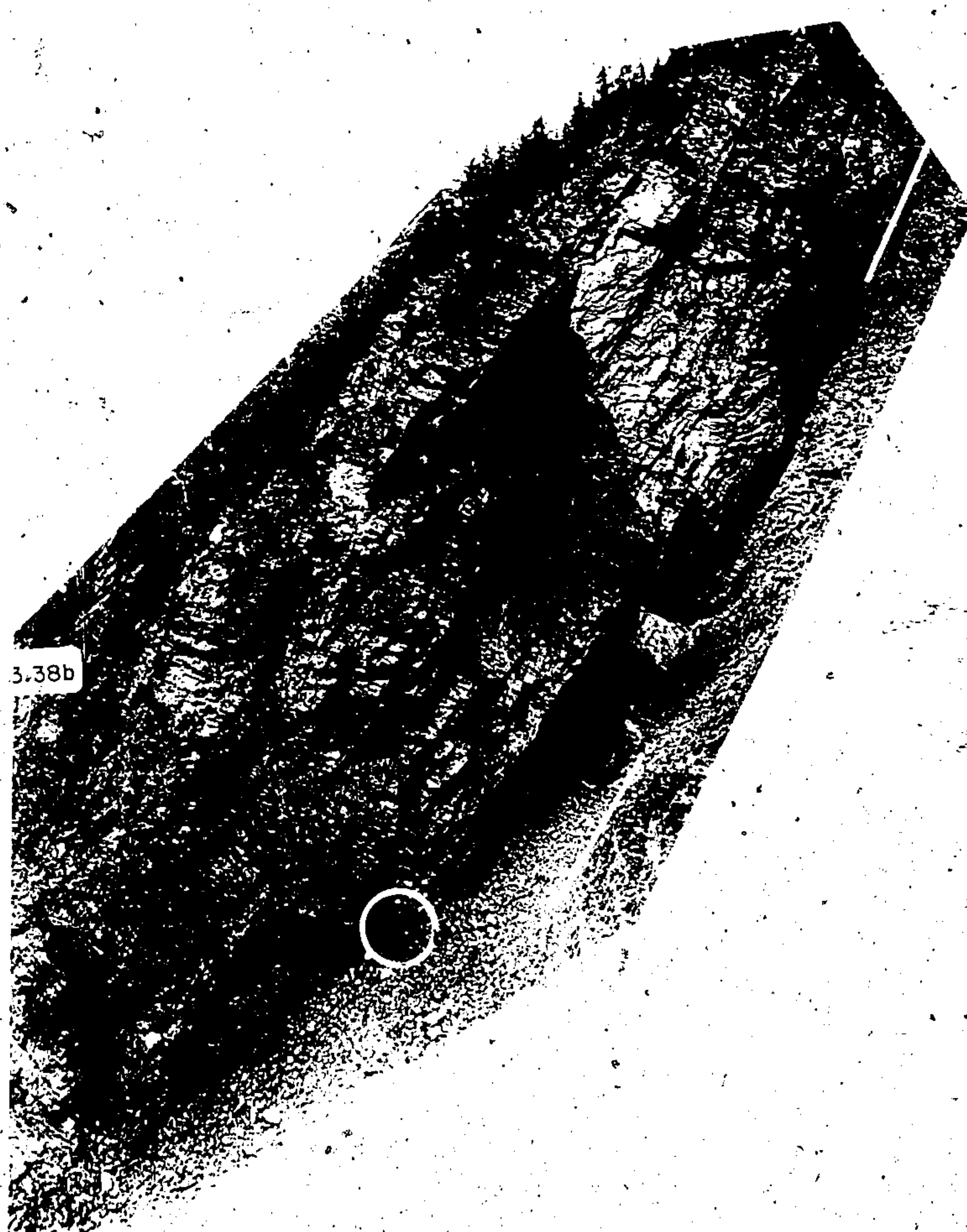

3.37b

Figure 3.38 Megatrough crossbeds in Middle Storelk Megatrough Interval, MS 2 (123-134 m).

Recessive zone below crossbedded outcrop contains FC facies unit with Terebratulid brachiopods. Regional horizontal indicated by arrows in 3.38a and by white lines in 3.38b. Man (circled) is 1.8 m tall.


3.38a
SS FACIES
LEDGE
LEDGE
LEDGE
SS FACIES
?
2m


3.38b

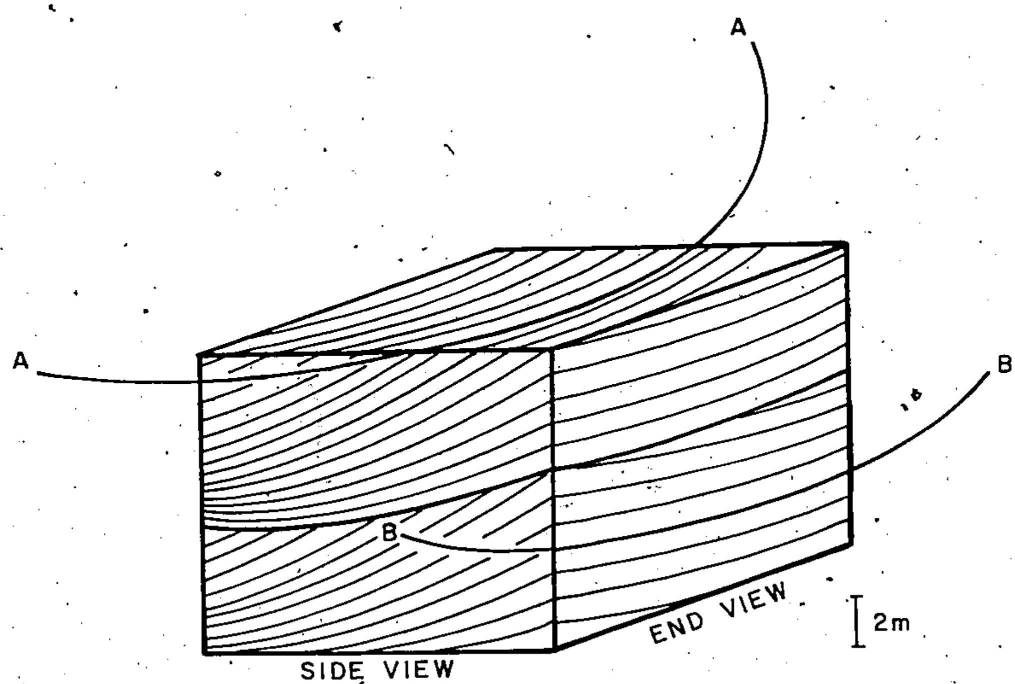


FIGURE 3.39

INFERRED THREE DIMENSIONAL GEOMETRY OF MEGATROUGH SETS

2. <u>Inferences from paleocurrent data</u>: where orientation measurements were taken from the same set on opposite sides of a canyon (lateral displacement about 15 m), the strikes of the cross stratification surfaces varied by a few degrees. The difference may in part be due to errors in measurement, but a subtle variation in strike, suggesting subtle lateral curvature, seems well established based on a number of measurements. Also, foresets of 28 of the 30 measured megatrough sets in the Middle Storelk Megatrough Interval have dip azimuths clustered within a 56 degree spread (Figure 4.3). Since the values are single measurements taken from each set, they can be considered to be a more or less random sample of measurements from different parts of the foresets. If the troughs had a pronounced spoon shape, the spread of dip azimuths would have been expected to be much larger even if it were assumed that all foresets were oriented in precisely the same direction. Hence, the data suggests that the degree of lateral curvature is subtle (and that the trough sets are fairly consistently orientated). The above data permit a hypothetical reconstruction of the scour pit in which the cross strata were deposited (Figure 3.40). The broadness of the scour pit suggests that the degree of sinuosity of the dunes

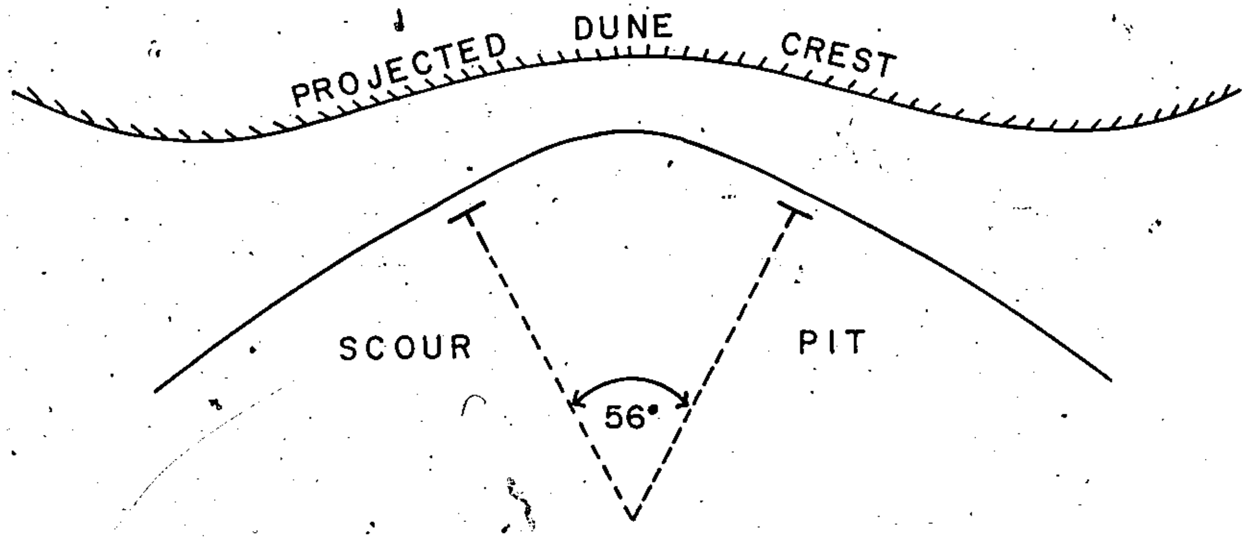


FIGURE 3.40
HYPOTHETICAL RECONSTRUCTION OF SCOUR PIT IN WHICH MEGATROUGH SETS WERE DEPOSITED

that deposited the megatroughs was not very high.

3.9.4 Bounding Relationships

The MT facies is most commonly interbedded with the LT facies (e.g. MS 3: 126-144 m) in the Middle Storelk Megatrough Interval. In the Upper Storelk Crossbed Interval, the MT facies may be vertically associated with both the LT and MP facies (e.g. MS 3: 167-186 m).

3.9.5 Facies Recognition

In view of the three dimensional geometry of the megatrough sets, they may resemble the lower part of a megaplanar tabular set with an asymptotic base. The two may be distinguished by the following criteria:

1. the lower set boundary of megaplanar tabular sets is planar in three dimensions, whereas for megatrough sets it is broadly curved, and cuts into underlying sets. In cases where the megatrough is scoured down to a consistent level, differentiation is more subtle without a fortuitous end view which would show the overall scoop shape of the lower set boundary. However, in such cases the megatrough set

boundary tends to undulate somewhat if it can be traced far enough laterally.

2. the curved stratification in the lower part of a megaplanar tabular set is usually 1-2 m thick. The observed megatrough sets are much too thick to be mistaken for this.

3.10 LARGE SCALE TROUGH CROSSBED FACIES (LT)

3.10.1 Introduction and Basic Interpretation

The LT facies is composed of broad, sometimes subtly curved trough crossbeds 0.20-2 m thick. The upper thickness limit is arbitrarily defined from field observations and does not imply a genetic or morphologic difference between these and megatrough sets. Large scale trough sets of the LT facies are almost always interbedded with sets from the MP and MT facies, although on occasion they may interbed with the SS facies. The LT facies is interpreted to have been deposited by relatively small aeolian dunes.

3.10.2 Stratigraphic Position

The LT facies is ubiquitous in the Storelk sequence. It forms a large proportion of the Lower Storelk Megaplanar Interval (e.g. MS 1: 99-116 m) and the Middle Storelk Megatrough Interval (e.g. MS 5: 130-144 m). The facies is less common in the Upper Storelk Crossbed Interval (e.g. MS 3: 163-186 m), and may occur within the Middle Storelk Structureless Interval (e.g. MS 2: 147-152 m).

3.10.3 Facies Description

The LT facies is generally composed of well sorted very fine grained silica cemented quartz sand. Fine grained sand may be scattered throughout the sets.

Individual trough sets are generally very wide relative to their thickness. Sets can vary in width from less than 1 m to several meters, and range in thickness from 0.20 m to nearly 2 m. Most sets are in the 0.5-1 m thickness range. Laminae vary in dip between 10 and 30 degrees for the most part, although in many cases dips less than 10 degrees were observed. Examples of large scale trough sets are given in Figures 3.41 and 3.42.

The large scale trough sets are variable in configuration, and many appear transitional to planar forms.

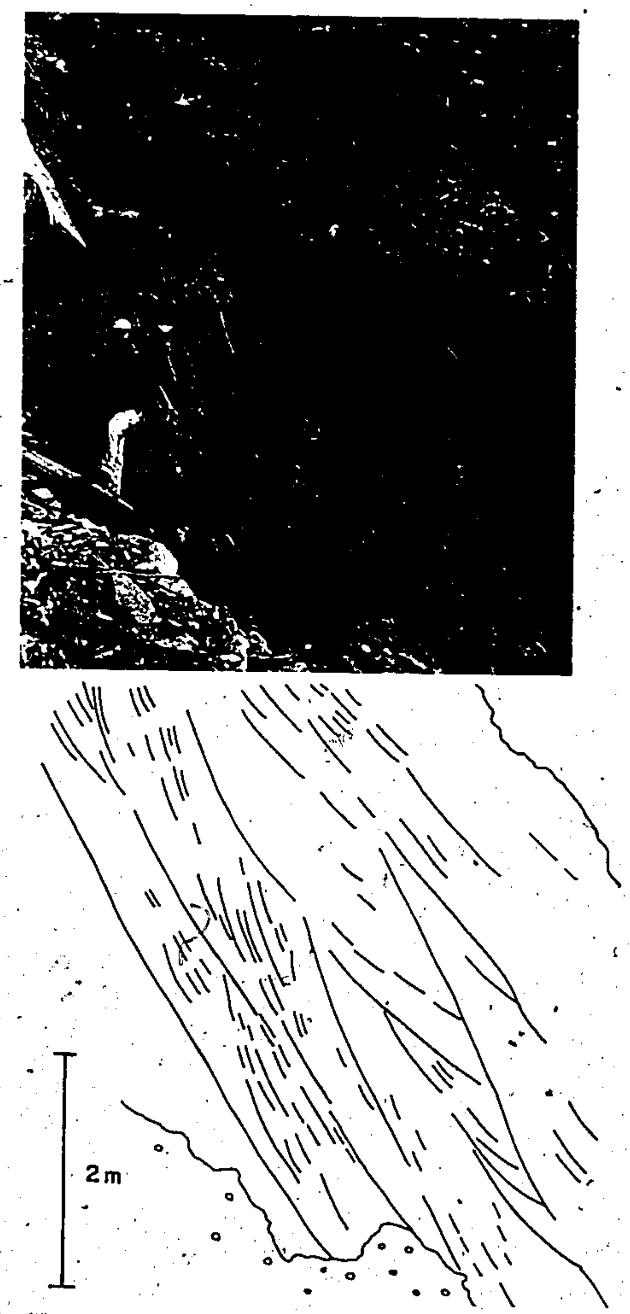
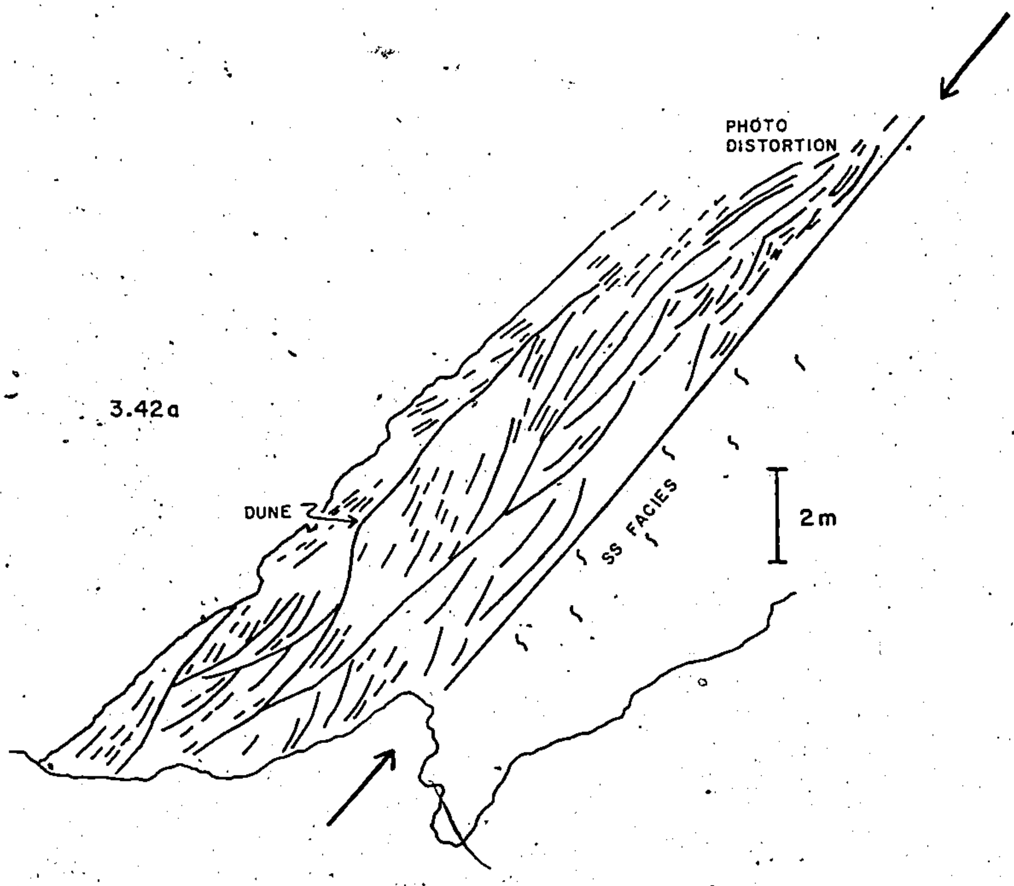


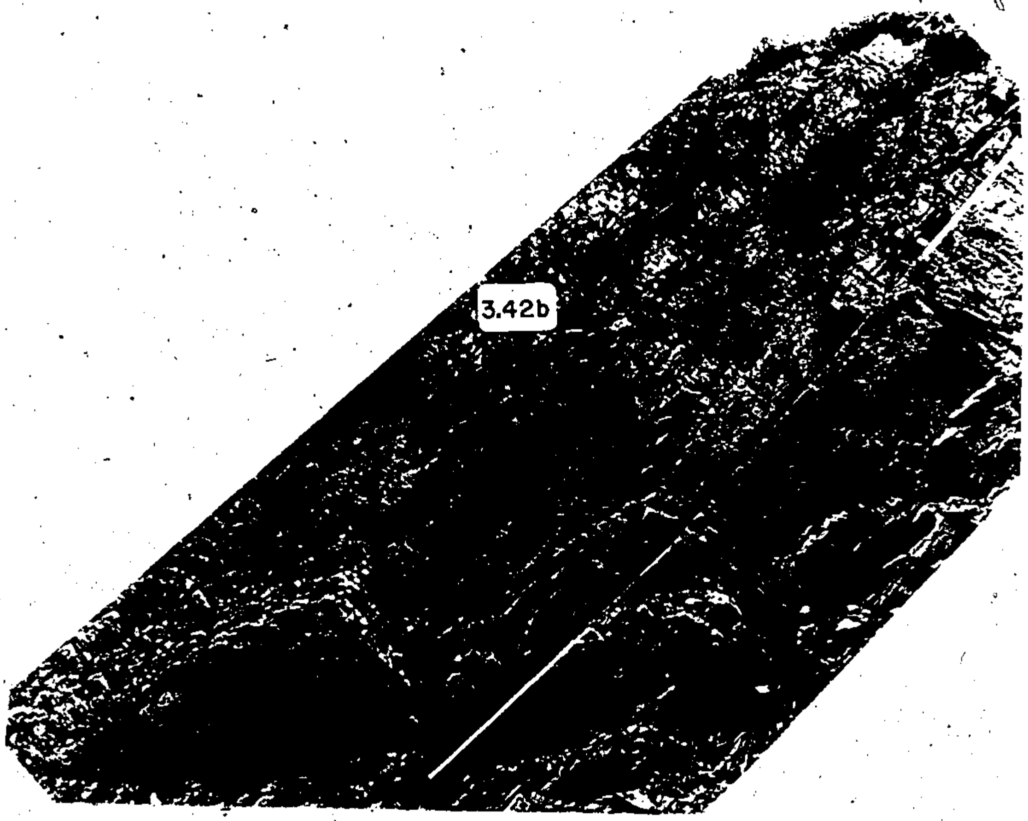
Figure 3.41. Large scale trough crossbeds (LT facies) in Lower Storelk Megaplanar Interval of MS 1 (99-102 m). Man is 1.8 m tall.

Figure 3.42 Large scale trough crossbedding (LT facies) in Upper Storelk Crossbed Interval of MS 1 (159-165 m).

Note small preserved dune (described in text). Regional horizontal indicated by arrows in 3.42a and by white lines in 3.42b. Man is 1.8 m tall.

L




3.42b

In some cases, the trough form is immediately obvious; laminae have a pronounced curvature, and the troughs cut down into one another. In other cases, recognition of the overall trough geometry is more subtle and requires good exposure. Laminae are subtly curved, and the sets do not erode deeply into underlying sets. If several relatively thin sets of this type are stacked on top of one another, all that is seen in small outcrops is divergent sets of laminae. In the Upper Storelk of measured section 2 (166-181 m), subtly curved troughs are interbedded with wedge shaped planar sets of similar thicknesses. Over the length of the outcrop (about 5 m), laminae in the trough sets can be seen to curve, whereas laminae in the planar sets are straight over this distance. In poorly exposed or small outcrops, then, the distinction between the two is not always possible.

3.10.4 Bounding Relationships

Because of its common occurrence throughout the Storelk sequence, the LT facies is interbedded with all other facies that occur in the Formation. Hence no preferred transitions could be distinguished.

3.10.5 Facies Recognition

The LT facies is readily distinguished from other Storelk facies by its scale and by its trough geometry. When sets are subtly curved, however, it is difficult to distinguish between the LT and LP facies without good exposure.

The LT facies resembles the MX facies in many aspects, except that sets in the latter are on the average thinner and have a pronounced trough geometry. Sets in the LT facies resemble the largest sets found in the MX facies. However, the LT facies crossbeds are always interbedded with megaplanar and megatrough sets, whereas the larger sets in the MX facies are usually interbedded with medium scale trough crossbeds. Where solitary large scale trough sets occur in the Tobermory Formation, they are assigned to the MX facies on the basis of their vertical transitions to the bioturbated XL and ST facies, which places them in a different context than that for the sets in the LT facies.

3.11 LARGE SCALE PLANAR CROSSBED FACIES (LP)

3.11.1 Introduction and Basic Interpretation

The LP facies contains planar tabular and wedge shaped planar crossbeds 0.75-2 m thick. The upper thickness limit was defined similarly to that for the LT facies. The LP facies is commonly interbedded with the LT and MP facies, and is interpreted to have been deposited by relatively small aeolian dunes.

3.11.2 Stratigraphic Position

The facies is fairly common in the Upper Storelk Crossbed Interval, especially in measured section 2 (170-181 m) where it dominates the sequence (Figure 3.43). The LP facies is relatively uncommon in the Lower Storelk Megaplanar Interval (e.g. MS 2: 96-117 m).

3.11.3 Facies Description

The LP facies is composed of well sorted very fine or fine grained quartz sand. The sole cementing agent is silica.

Two set types are present in the facies: wedge shaped planar sets, which are the most common, and planar

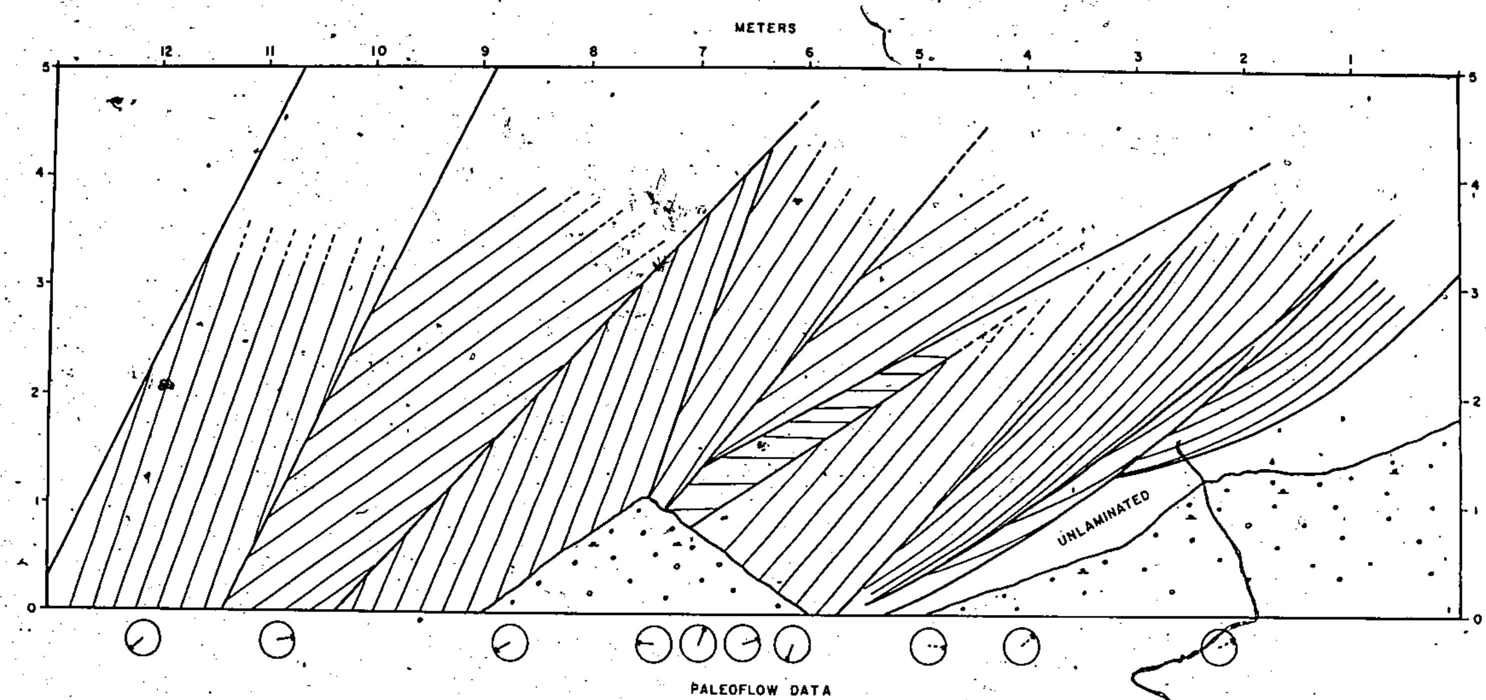


FIGURE 3.43
LARGE SCALE PLANAR AND TROUGH CROSSBEDS, UPPER STORELK CROSSBED INTERVAL OF MEASURED SECTION 2.

tabular sets. These are discussed separately below:

<u>Wedge Shaped Planar Sets</u> (Figures 3.43, 3.44): these sets vary between 0.75 m and 2 m thick, and their foreset laminae dip between 11 and 17 degrees. The lower set boundary is flat, gently to steeply inclined, and truncates underlying sets. Foresets are true geometric planes, as suggested by their consistent orientations laterally within a set, and either parallel the lower set boundary or have an angular relation to it. The upper set boundary may be horizontal or steeply inclined, and truncates the cross stratification. Set boundaries converge laterally, giving the set a wedge shape.

<u>Planar Tabular Sets</u> (Figures 3.43, 3.44): tabular sets vary in thickness between 1 m and 1.75 m, and their foresets dip between 11 and 33 degrees, averaging about 20 degrees. Sets are bounded by horizontal flat surfaces, and internal foresets are true geometric planes based on orientation data. Laminae generally have an angular relationship with the lower set boundary.

Figure 3.44 Large scale wedge shaped planar sets (LT facies) in Upper Storelk Crossbed Interval of MS 2 (166-181 m).

Uppermost set (visible only in upper left corner) is planar tabular. Compare to upper part of sequence (left side) of Figure 3.43. Canyon too narrow to permit full photographic coverage. Book is 19 cm in length.


3.44

3.11.4 Bounding Relationships

The LP facies is most commonly interbedded with the LT facies (e.g. MS 1: 107-112 m). It is also vertically associated with the MP facies (e.g. MS 2: 98-105 m).

3.11.5 Facies Recognition

The LP facies is recognized on the basis of set thickness and the planar geometry of set foresets. Problems of differentiation between the LP and LT facies were outlined earlier. Differentiation between the LP facies sets and planar sets in the MX facies of the Tyrwhitt and Tobermory Formations is made on the basis of context, as was described earlier for the LT facies.

3.12 STORELK STRUCTURELESS FACIES (SS)

3.12.1 Introduction and Basic Interpretation

The SS facies is characterized by an almost total lack of sedimentary structures observable in the field, and by a uniform texture evident from X-radiographs. On the basis of its context within a sequence composed of facies with interpreted aeolian origins, the SS facies is interpreted to have originated in this environment also. However, the type of processes involved are problematical to interpret. Possibly, intense post-depositional soft sediment deformation may be the cause of the structureless condition.

3.12.2 Stratigraphic Position

The SS facies composes two Storelk Intervals. The Middle Storelk Structureless Interval (e.g. MS 1: 136-158.5 m) is the major one, and ranges in thickness from 19.2-23.4 m in the usual case. The Lower Storelk Structureless Interval (e.g. MS 1: 116-122 m) is usually about 6 m thick where it is fully exposed. Thin SS facies units sometimes occur in the Upper Storelk Crossbed Interval (e.g. MS 5: 173-174 m).

3.12.3 Facies Description

The SS facies is generally composed of well sorted very fine grained silica cemented quartz sandstone. The uppermost few meters of the Middle Storelk Structureless Interval are often composed of well sorted fine grained sand. Thin green argillaceous sandstone zones (e.g. MS 1: 140.5m, 150 m) are usually present along major horizontal bedding planes. In one case (MS 5: 148.5 m), at 10 cm thick fissile siltstone zone was observed.

The chief identifying characteristic of the SS facies is the almost total absence of sedimentary structures observable in the field. The facies is characteristically massive bedded, broken only by 2-3 major horizontal bedding planes (Figure 3.45). Samples from the SS facies have a uniform texture, evident in X-radiographs (Figure 3.46).

The only sedimentary structures observed in the SS facies were sets of horizontal-parallel laminae in the Middle Storelk Structureless Interval (MS 1: 142.5-143 m; MS 3: a 10 cm thick zone about 3 m below top of Interval). A set of crude inclined laminae was also present about 5.6 m above the base of the Interval in measured section 4. In measured section 2, the Middle Storelk Structureless Interval is broken into two parts (134-146.5 m; 152-156.6 m), with an intervening LT facies unit. This situation is unique relative to all other measured sections.

3.12.4 Bounding Relationships

Lower Storelk Structureless Interval: the lower contact of this Interval is always a major horizontal

Figure 3.45 Gross appearance of SS facies. Note massive bedding and characteristic vertical fracture. Man (near base of photo just right of centre) is 1.8 m tall. (MS 3: 144-163 m).

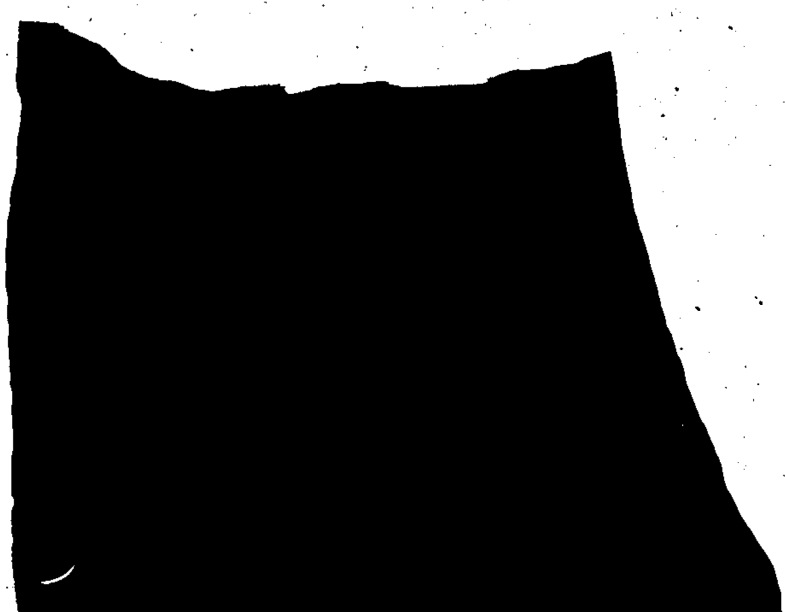


Figure 3.46 X-radiograph of sample from SS facies. Note uniform texture. Natural size. (MS 1: 148 m).

bedding plane which truncates underlying megaplanar sets (e.g. MS 1: 116 m) belonging to the Lower Storelk Megaplanar Interval. Where exposed, the uppermost part of this Structureless Interval becomes progressively more dolomitic in content, and grades into an FC facies unit (e.g. MS 2: 121-122 m).

Middle Storelk Structureless Interval: the upper and lower contacts of this Interval are always major horizontal bedding planes that may be flat or slightly undulatory in configuration. The lower contact truncates large scale trough sets in the upper part of the Middle Storelk Megatrough Interval (e.g. MS 5: 144.5 m), and the uppermost part of this latter Interval is often iron stained. The uppermost few meters of the Structureless Interval are commonly iron stained, and the overlying unit usually belongs to the LT facies (e.g. MS 5: 168 m) or occasionally the MP facies (e.g. MS 2: 156.6 m).

3.12.5 Facies Recognition

The SS facies is characterized by its:

1. almost total lack of observable sedimentary structures;

2. uniform texture, as is evident in X-radiographs; and its
3. context, where it is vertically associated with the LT and MP facies.

The latter two characteristics are essential in differentiating between the SS facies, and the ST facies of the Tyrwhitt and Tobermory Formations. The ST facies has a mottled texture, and does not interbed with either of the LT or MP facies, setting it within a different context than that for the SS facies. Moreover, the ST facies is fossiliferous, containing both body and trace fossils, whereas the SS facies contains neither of these forms.

3.13 DESCRIPTION OF FEATURES NOT INCLUDED IN FACIES SCHEME

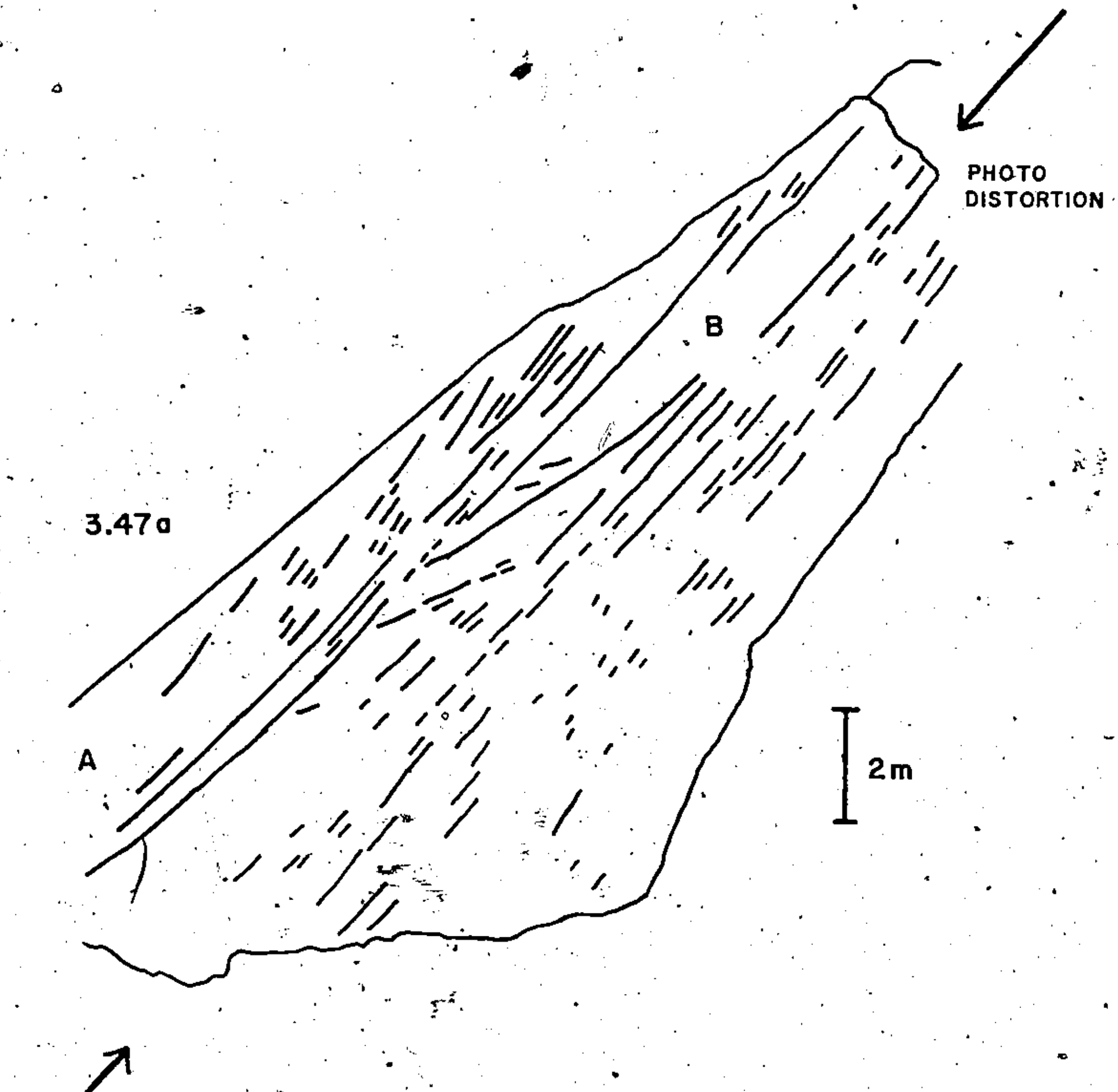
3.13.1 Low Angle Inclined Strata, Tobermory Formation

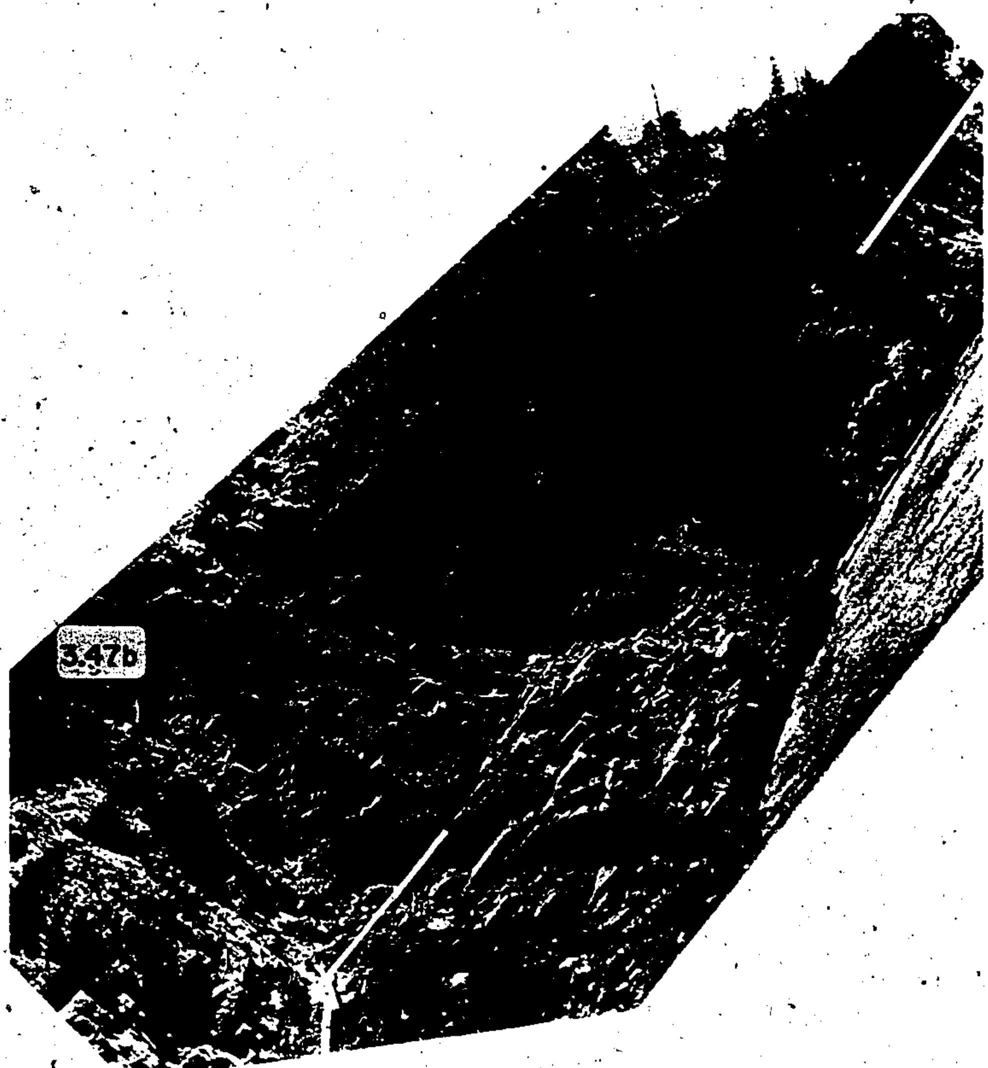
Two sets of low angle inclined strata, each 2.5 m thick, occur in the Tobermory Formation of measured section 1 (215.5-218.5 m). Both contain broadly concave upward strata, inclined at 10-11 degrees (Figure 3.47). The lower set is inclined southward (188 degrees), and its lowermost strata approach the lower contact tangentially,

Figure 3.47 Low angle inclined strata, Tobermory Formation of MS 1 (215-218 m).

Two sets are visible (A and B); upper set truncated by major horizontal bedding plane. Regional horizontal indicated by arrows in 3.47a and by white lines in 3.47b. Man is 1.8 m tall.

L




3.47b

with no noticeable erosion. The upper set is inclined westward (262 degrees), and its lowermost portion erodes into the underlying set. The inclined strata have a very broad lateral curvature, as seen in an end view (perpendicular to azimuth of inclination) on the opposite side of the canyon. Individual parting planes within the upper set can be traced laterally at least 18 m. The sets are directly underlain by an MX facies unit, which itself is underlain by the XL facies. The sets are truncated by a prominent horizontal bedding plane, which is overlain by a laterally impersistent sandy dolomite unit (NC facies) and the ST facies.

In gross morphology, the Tobermory sets resemble megatrough sets from the MT facies. Foresets in the latter usually dip more steeply than 10 degrees, but dip angles of this value are common in the lower parts of megatrough sets. However, the context of the Tobermory sets is different from that for the MT facies. The MT facies is vertically associated only with the LT and MP facies. In contrast, the Tobermory sets are bounded vertically by the MX, ST and NC facies. It will be interpreted later that the latter three facies are marine in origin, and that their vertical association with the Tobermory sets suggests that the sets are also marine in origin.

3.13.2 Deformed Laminae

Deformed laminae are common in the Upper Tobermory Formation of all measured sections. The deformation is interpreted to have occurred in unlithified sediments within a relatively short time after deposition. Since the deformed intervals probably represent former horizontally laminated or crosslaminated units, they are not considered as a separate facies. Two types are recognized:

Convoluted laminae: convoluted laminae are most commonly warped upward into sometimes broken sharp peaks (Figure 3.48), and in some cases resemble dish structures. The convoluted laminae may pass vertically and laterally into irregular laminae or undeformed laminae, and the latter two may have a broad undulatory aspect. All examples occur in very dolomitic sandstone or highly sandy dolomites characteristic of the Upper Tobermory Formation.

Deformed laminae associated with chert: irregular and undulatory laminae are characteristic of units containing a large number of chert layers and chert nodules (Figure 3.49). The chert layers are horizontal, usually about 1-30 cm thick, and often contain deformed or undeformed laminae that can be traced laterally into unreplaced sandstone. They often have a pronounced pinch and swell configuration, and are laterally discontinuous.

Figure 3.48 Deformed laminae exhibiting peaks. Scale in cm. (MS 1: 256 m).

Figure 3.49 Deformed laminae in unit with abundant chert layers and nodules. Scale in cm. (MS 3: 216 m).

CHAPTER 4

INTERVAL DESCRIPTIONS AND FACIES SEQUENCE

4.1 INTRODUCTION

As discussed earlier in Chapter 3, the Storelk Formation and part of the Tyrwhitt Formation were divided into a series of Intervals, consisting of a facies or a facies association that persists laterally through all measured sections (Figure 3.0). In the following, the composition of the Intervals and their lateral variation is discussed.

The latter part of this Chapter discusses the interrelationships among the facies in a vertical sense. Due to the complexity of the sequence, the facies transitions are treated statistically to determine preferred transitions.

4.2 INTERVAL DESCRIPTIONS

4.2.1 Major Tyrwhitt MX Interval

The Major Tyrwhitt MX Interval is only briefly discussed here, since its major characteristics were described previously in the general description of the MX facies (Section 3.4). This Interval was separated from other MX facies units because of two major characteristics:

1. Its relatively great thickness (up to 9 m), which is at least three times greater than that of other MX facies units.
2. Its lateral persistence (minimum of 5 km) and uniformity over a wide area in a N-S direction. In contrast, other MX facies units cannot be correlated between measured sections about 0.5-2 km apart.

In other aspects, the Interval is not significantly different from other MX facies units. The types of sets and set thicknesses, and paleoflow data (Section 3.4.6) are comparable between the two.

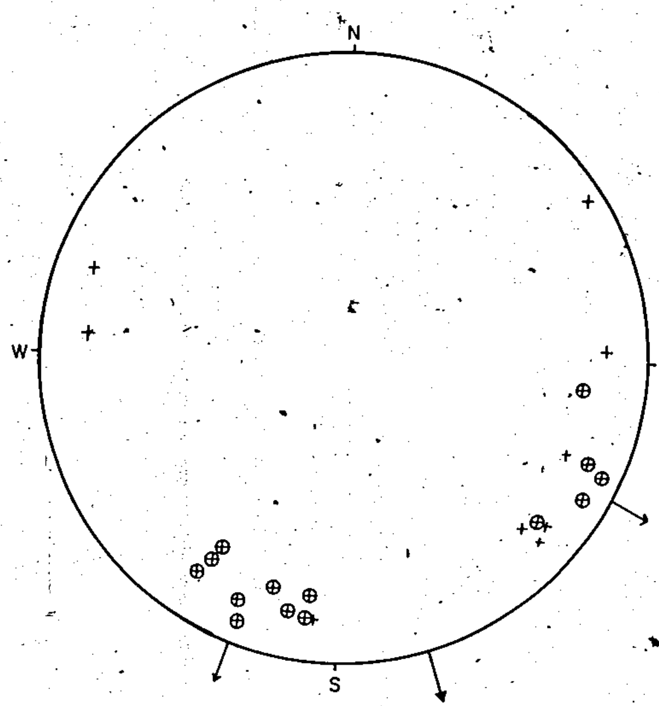
4.2.2 Lower Storelk Megaplanar Interval

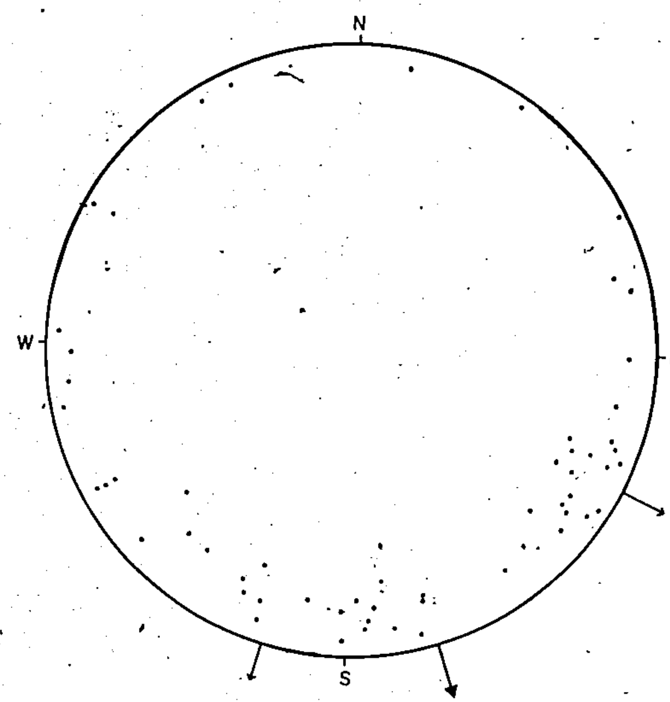
The Lower Storelk Megaplanar Interval is dominantly characterized by a facies association involving the MP and LT facies. The LP facies is a minor constituent in the association. The Interval occurs at the base of the Storelk Formation of all measured sections, and varies in thickness between 17.15 m and 23.32 m.

Interval Contacts: the lower contact of the Interval is always marked by the abrupt appearance of cross stratification above a thick ST facies unit in the uppermost Tyrwhitt Formation. In measured sections 2 (96.5 m), 3 (95.5 m) and 4 (89 m), the lowermost facies in the Interval is the LT facies. The base of the Interval in measured section 1 (93 m) is marked by a 1.3 m thick set of inclined strata bounded by horizontal surfaces, which is interpreted as the lowermost portion of an eroded megaplanar tabular set. It is vertically succeeded by a 4.16 m thick unit of horizontally thin bedded but otherwise structureless sandstone, which is unique in all the measured sections. In measured section 5, the lowermost unit in the Interval is a thin horizontally laminated unit (100-100.5 m), which is vertically succeeded by a thick LT facies unit. The upper Interval contact in all measured sections is a major horizontal bedding plane (e.g. MS 1: 116 m; MS 5: 122 m), succeeded vertically by the Lower Storelk Structureless Interval. The consistent stratigraphic position of the bedding plane in all measured sections suggests that it may be a widespread truncation surface.

Lateral Variability within Interval: the Interval displays a fairly high degree of lateral variability, caused by variable proportions of its constituent facies and by changes in the nature of their vertical association. In measured sections 1 (99-116 m) and 2 (96-117 m), the MP facies is interbedded with the LT, and to a lesser extent the LP, facies. In measured sections 5 (101-121 m), 3 (95-120 m) and 4 (89-108 m), the lower part of the Interval is dominated by the LT (and/or LP) facies, whereas the upper part of the Interval is composed of the MP facies (sometimes a single megaplanar set).

Paleocurrent Data: for purposes of analysis, paleocurrent data for the MP-LP facies (Table 2, Appendix 1; Figure 4.1), and that for the LT facies (Table 2, Appendix 1; Figure 4.2) were treated separately. Table 4.1 lists the vector mean values for the various groupings of data.





⊕ MEGAPLANAR CROSSBED (MP)
\+ LARGE SCALE PLANAR CROSSBEDS (LP)
· LARGE SCALE TROUGH CROSSBEDS (LT)
↙ VECTOR MEAN AZIMUTH FOR DATA CLUSTER
↙ GRAND VECTOR MEAN AZIMUTH FOR FACIES

FIGURE 4.1
STEREOGRAPHIC PLOT OF PALEOFLOW DATA FOR PLANAR SETS IN LOWER STORELK MEGAPLANAR INTERVAL

FIGURE 4.2
STEREOGRAPHIC PLOT OF PALEOFLOW DATA FOR LARGE SCALE TROUGH CROSSBEDS IN LOWER STORELK MEGAPLANAR INTERVAL

Table 4.1 Results of vector mean calculations for facies in Lower Storelk Megaplanar Interval. Data plotted on stereonets in Figures 4.1 and 4.2

Description of data grouping	No. of readings	Vector mean azimuth[1]	Vector length (%)	Standard deviation (degrees)
MP AND LP FACIES SE cluster	10	117	97	15
MP AND LP FACIES SSW cluster	10	200	98	7
GRAND VECTOR MEAN, MP AND LP FACIES	23	162	58	60
LT FACIES SE cluster	18	116	99	3
LT FACIES SSW cluster	24	195	91	24
GRAND VECTOR MEAN, LT FACIES	56	162	50	67
GRAND VECTOR MEAN, ALL FACIES IN INTERVAL	79	162	50	67

[1] All vector means significant at greater than 99.5% (2 degrees of freedom)

The configuration of the clustering of data for the MP-LP facies (Figure 4.1) strongly suggests a bimodal distribution. The three points that do not plot within the two main clusters represent sets that do not appear different in morphology from other sets, and their significance is not known.

The configuration of the clustering of data for the LT facies (Figure 4.2) is suggestive of a bimodal distribution, although it is not as well defined as for the MP-LP facies. Hence, vector means for the SE and SSW clusters were calculated (Table 4.1), although admittedly the selection of data points to be included in each cluster was arbitrary. It remains possible that with more data collection, more azimuth values intermediate between those for the two clusters may be found. However, the number of sets measured (56) should have been adequate to establish the paleocurrent pattern. The grand vector mean azimuth for all data from the LT facies (162 degrees; Table 4.1) is in good agreement with that for the MP-LP facies (also 162 degrees; Table 4.1).

4.2.3 Middle Storelk Megatrough Interval

The Middle Storelk Megatrough Interval is characterized by a facies association between the MT and LT facies.

The thickness of the Interval varies between 11.20 m and 17.79 m, averaging 13.80 m.

Interval Contacts: the lower contact of the Interval, where exposed, is marked by the abrupt appearance of large scale trough sets (LT facies) above a thin FC facies unit (e.g. MS 2: 123 m). The bottoms of the lowermost sets are often lined with chert, and there is little evidence of scour at the contact. The upper Interval contact is always a major horizontal bedding plane, overlain by the Middle Storelk Structureless Interval. In its uppermost meter, the Interval usually exhibits an iron stain. The consistent stratigraphic position of the upper Interval contact in all measured sections suggests that it is a widespread truncation surface.

Lateral Variability within Interval: in all measured sections where the entire Interval is exposed, the base of the Interval is occupied by the LT facies, followed upward by 2-4 megatrough sets from the MT facies, which are capped by the LT facies (e.g. MS 1: 122-136 m; MS 2: 123-134 m). In some measured sections, the upper LT facies unit is thicker than in others (e.g. MS 1 vs. MS 5: 137-144 m). Otherwise, the Interval maintains a laterally consistent facies configuration.

Paleocurrent Data: paleocurrent data for the MT facies (Table 3, Appendix 1; Figure 4.3), and that for the LT facies (Table 3, Appendix 1; Figure 4.3) were treated separately. Table 4.2 summarizes the vector mean azimuth values for the various groupings of data.

The clustering of the data from both facies suggests a unimodal paleocurrent distribution (Figure 4.3), and the direction of trough infill for most sets was towards the southwest (219 degrees). The data for the MT facies is confined in a much narrower spread than that for the LT facies. This was previously related to both a consistent set orientation laterally, and to the overall geometry of the megatrough sets (Section 3.9.3).

4.2.4 Lower Storelk Structureless Interval
Middle Storelk Structureless Interval

Both Structureless Intervals are composed solely of the SS facies, and are treated only briefly here since they were described earlier in the discussion of this facies (Section 3.12). The Lower Interval maintains a constant thickness of about 6 m in each measured section where it is fully exposed. The Middle Interval usually

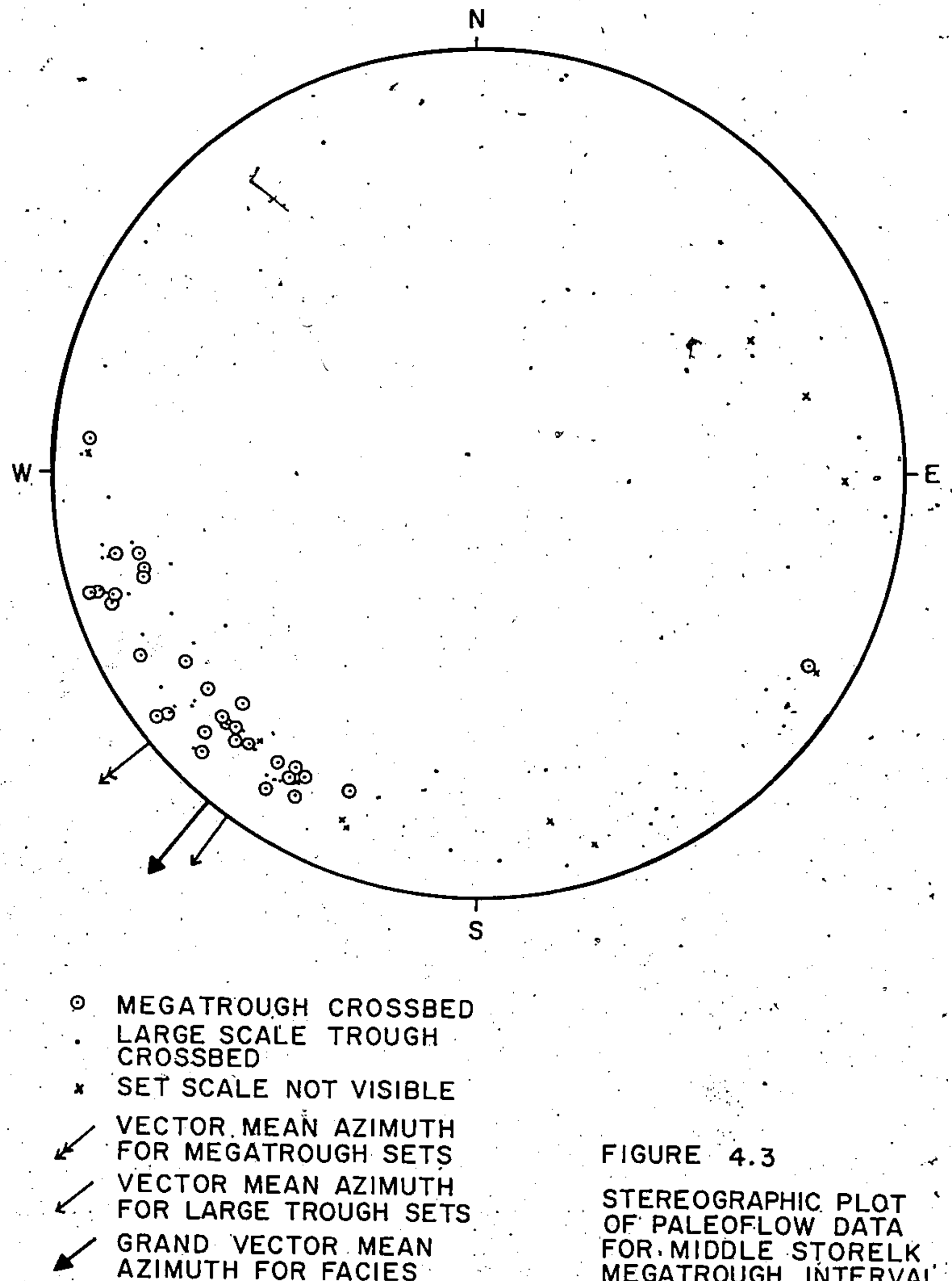


FIGURE 4.3

STEREOGRAPHIC PLOT OF PALEOFLOW DATA FOR MIDDLE STORELK MEGATROUGH INTERVAL

Table 4.2 Results of vector mean calculations for facies in Middle Storelk Megatrough Interval. Data plotted on stereonet in Figure 4.3

Description of data grouping	No. of readings	Vector mean azimuth[1]	Vector length (%)	Standard deviation (degrees)
MT FACIES	30	230	91	24
LT FACIES	45	216	46	70
SETS, GEOMETRY OR SCALE NOT VISIBLE	11	165*	49	66
GRAND VECTOR MEAN, ALL DATA FOR INTERVAL	86	219	59	58

[1]All vector means significant at greater than 99.5% (2 degrees of freedom) except:

* G.T. 90.0%

varies between 19.2 m and 23.4 m thick. In the southernmost section where it was measured (6), this Interval is only 13.2 m thick. In measured section 2, the Middle Interval is divided into two parts 12.80 and 4.87 m thick, separated vertically by a 4.94 m thick LT facies unit. The combined thickness of all three units (22.61 m) is comparable to the thicknesses of the Middle Intervals on either side (MS 5; 23.4 m; MS 3; 19.2 m). Hence, the three combined units in measured section 2 are considered equivalent to the Middle Storelk Structureless Intervals of other measured sections. The configuration in measured section 2 also represents the only major deviation from the otherwise uniform lateral character of the Middle Interval, aside from its apparent thinning to the south. No noticeable lateral changes were evident in the Lower Storelk Structureless Interval.

4.2.5 Upper Storelk Crossbed Interval

The Upper Storelk Crossbed Interval is characterized by a facies association involving the MP, MT, LP and LT facies. The Interval is the most complex relative to other Intervals in terms of lateral variation. Unfortunately, identification of facies types was hindered in many cases by heavy vertical fracture and black lichen cover (especially measured sections 1 and 4, and parts of most other sections). The Upper Storelk Crossbed Interval ranges in thickness between 25.35 m and 30.10 m, averaging 27.10 m.

Interval Contacts: in most measured sections where the lowermost sedimentary structures were visible, the base of the Interval was marked by the abrupt appearance of the LT facies (e.g. MS 1: 158.5-164.5; MS 5: 168-170 m) above the Middle Storelk Structureless Interval. In measured sections 2 (156.5-162 m) and 3 (163-167 m), a megaplanar set (MP facies) forms the base of the Interval. The lower contact in all cases is a major horizontal bedding plane that occurs at a fairly consistent stratigraphic level in all measured sections. The upper Interval contact is also a major horizontal bedding plane, and is equivalent to the contact between the Storelk and Tobermory Formations. The contact is marked by a thin granule conglomerate composed of quartz sandstone fragments set in a sandy dolomite matrix. The uppermost Storelk beds are poorly defined because of heavy vertical fracture and cover in most measured sections.

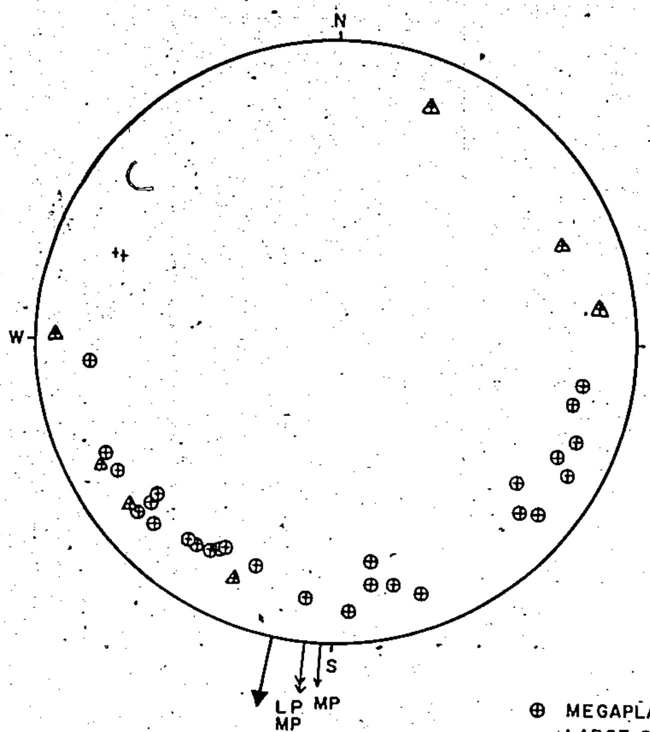
Lateral Variability in Interval: the Upper Storelk Crossbed Interval exhibits the most complex lateral variability of all Intervals. The variability is mainly due to lateral changes in the relative proportions of the constituent facies. There appears to be no predictable pattern to these changes, and each measured section contains a unique facies assemblage. The stratigraphic sections are self-explanatory in this regard, and only the more unusual features require further description.

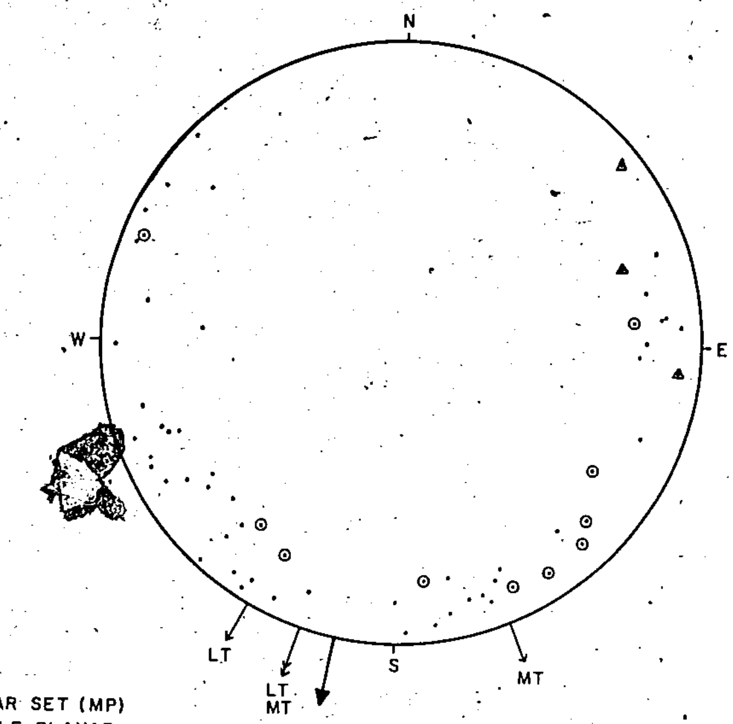
In measured section 1 (158.5-164.5 m), the base of the Interval contains an LT facies unit, with some interbedded large scale planar sets. A small preserved lens-shaped dune with a maximum thickness of 2.4 m and a maximum length of 11 m is preserved in this unit (Figure 3.42). The lower boundary of the set is undulatory, and truncates underlying sets. Internal cross stratification is gently concave upward in the forward part of the dune, becoming convex upward on the stoss side. The front of the dune wedges out, passing laterally into large scale trough sets.

The Interval in measured section 2 (170-181 m) is dominated by the LP facies, with minor interbedded large scale trough sets (Figure 3.43). This is one of a minority of cases where sets of this scale dominate the Upper Storelk Crossbed Interval. The sets are also uniquely oriented relative to sets from other measured sections (Figures 4.4, 4.5). The section 2 sets face either southwesterly or northeasterly, and thus have an apparent bipolar distribution. In many cases, vertically adjacent sets have nearly opposite orientations.

Paleocurrent Data: the paleocurrent data for the MP-LP facies (Figure 4.4) and for the MT-LT facies (Figure 4.5) were treated separately. In addition, data were taken from sets in which the scale or geometry was not visible (Figure 4.6), and from what appeared to be foreset surfaces of sets exposed on dip slopes (Figure 4.7). All data are listed in Appendix 1 (Table 4). The vector mean azimuth data for the various data groupings are given in Table 4.3.

There is a much wider spread in the paleocurrent data for the Upper Storelk Crossbed Interval than for other Intervals. The clustering of data in some cases, particularly that in Figures 4.4 and 4.6, suggests a possible bimodal distribution, but the apparent gaps between point clusters may be due to insufficient data collection, so it cannot be confirmed. The clustering of data in Figure 4.5 appears to be trimodal, but a similar problem may be involved. Hence in each case, grand vector mean azimuths were calculated for the data, and an overall SSW (191 degrees; Table 4.3) paleoflow is indicated.





⊕ MEGAPLANAR SET (MP)
+ LARGE SCALE PLANAR SET (LP)
⊙ MEGATROUGH SET (MT)
· LARGE SCALE TROUGH SET (LT)
▵ SETS FROM MS 2
↙ VECTOR MEAN AZIMUTH FOR FACIES
↙ GRAND VECTOR MEAN AZIMUTH, COMBINED FACIES
↙ GRAND VECTOR MEAN AZIMUTH FOR INTERVAL

FIGURE 4.4
STEREOGRAPHIC PLOT OF PALEOFLOW DATA FOR PLANAR SETS IN UPPER STORELK CROSSBED INTERVAL

FIGURE 4.5
STEREOGRAPHIC PLOT OF PALEOFLOW DATA FOR TROUGH SETS IN UPPER STORELK CROSSBED INTERVAL

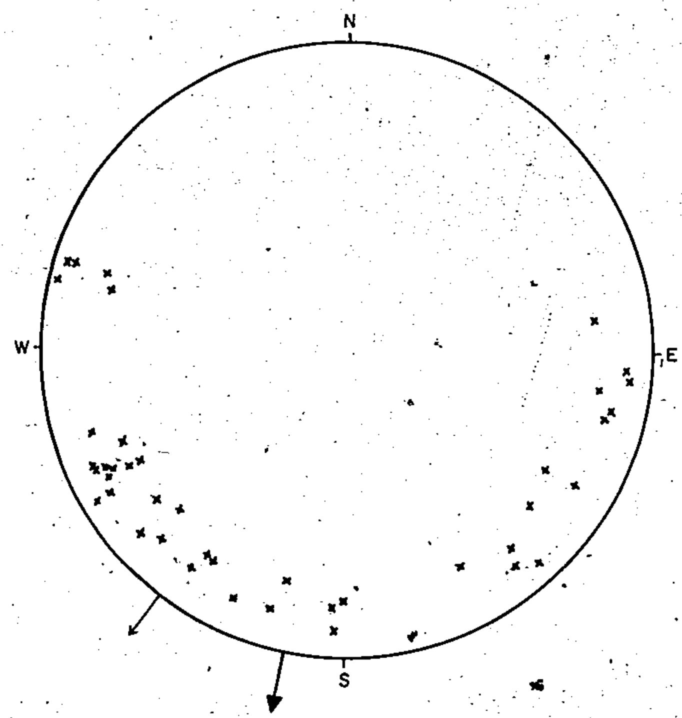


FIGURE 4.6

STEREOGRAPHIC PLOT OF PALEOFLOW DATA FROM SETS (SCALE OR GEOMETRY NOT VISIBLE), UPPER STORELK CROSSBED INTERVAL

× SET SCALE OR GEOMETRY NOT VISIBLE

• SURFACE

↙ VECTOR MEAN AZIMUTH FOR DATA

↙ GRAND VECTOR MEAN AZIMUTH FOR INTERVAL

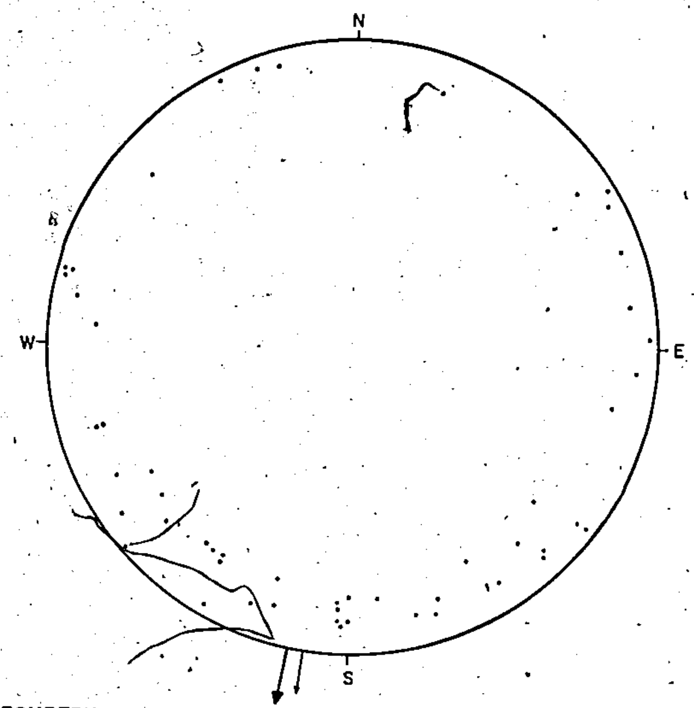


FIGURE 4.7

STEREOGRAPHIC PLOT OF PALEOFLOW DATA FROM SURFACES IN UPPER STORELK CROSSBED INTERVAL

Table 4.3 Results of vector mean calculations for facies in Upper Storelk Crossbed Interval. Data plotted on stereonets in Figures 4.4-4.7

Description of data grouping	No. of readings	Vector mean azimuth[1]	Vector length (%)	Standard deviation (degrees)
MT FACIES	10	157*	63	55
LT FACIES	50	209	42	73
GRAND VECTOR MEAN, MT AND LT FACIES	60	198	42	73
MP FACIES	27	182	68	50
LP FACIES	9	307**	10	96
GRAND VECTOR MEAN, MP AND LP FACIES	36	185	50	65
SETS, GEOMETRY OR SCALE NOT VISIBLE	43	217	50	65
SURFACES	52	188	38	77
GRAND VECTOR MEAN, ALL PALEOFLOW DATA FOR INTERVAL	191	198	44	71

[1]All vector means significant at greater than 99.5% (2 degrees of freedom) except:
* G.T. 97.5%; ** L.T. 75%

4.3 FACIES TRANSITIONS

4.3.1 Introduction and Method

Specific interrelationships among the defined facies are not immediately obvious because of the inherent vertical and lateral complexity of the Pennsylvanian sequence. Hence, a quantitative approach was undertaken to analyze vertical facies transitions. This approach is useful in that it establishes preferred transitions between facies, and also shows which facies are mutually exclusive.

The method used was first proposed by Selley (1970) and modified by Miall (1973). Facies transitions for the complete sequences in measured sections 1, 5, 2 and 3 were first recorded in an observed transition matrix. A transition probability matrix was then calculated from this data (Table 4.4a). A third matrix was subsequently calculated assuming an identical abundance of facies, except in random sequence (Table 4.4b). Then, a difference matrix was calculated by subtracting the random transition probabilities from the observed transition probabilities (Table 4.5). The latter matrix emphasizes transitions which have a higher or lower probability of occurrence than they would have had the sequence been random.

FIGURE 4.4a TRANSITION PROBABILITY MATRIX

	MP	MT	LP	LT	SS	ST	MX	XL	HL	SI	FC	TC	NC
MP	0.00	.08	.08	.46	.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MT	.33	0.00	0.00	.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LP	.33	0.00	0.00	.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LT	.40	.20	.15	0.00	.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SS	.33	0.00	0.00	.44	0.00	0.00	0.00	0.00	0.00	0.00	.22	0.00	0.00
ST	0.00	0.00	0.00	.02	0.00	0.00	.35	.25	.17	.08	.05	.02	.07
MX	0.00	0.00	0.00	0.00	0.00	.67	0.00	.21	.03	.06	0.00	.03	0.00
XL	0.00	0.00	0.00	0.00	0.00	.45	.29	0.00	.21	0.00	0.00	0.00	.05
HL	0.00	0.00	0.00	.05	0.00	.32	.09	.45	0.00	0.00	0.00	.05	.05
SI	0.00	0.00	0.00	0.00	0.00	.86	0.00	.14	0.00	0.00	0.00	0.00	0.00
FC	0.00	0.00	0.00	.20	0.00	.60	.10	0.00	.10	0.00	0.00	0.00	0.00
TC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.50	.50	0.00	0.00	0.00	0.00
NC	0.00	0.00	0.00	0.00	0.00	.75	.13	0.00	.13	0.00	0.00	0.00	0.00

FIGURE 4.4b RANDOMIZED PROBABILITY MATRIX

	MP	MT	LP	LT	SS	ST	MX	XL	HL	SI	FC	TC	NC
MP	0.00	.03	.02	.09	.04	.30	.15	.16	.09	.03	.04	.01	.04
MT	.06	0.00	.02	.09	.04	.29	.14	.15	.09	.03	.04	.01	.04
LP	.05	.03	0.00	.08	.04	.29	.14	.15	.09	.03	.04	.01	.04
LT	.06	.03	.02	0.00	.04	.31	.15	.16	.10	.03	.05	.01	.04
SS	.06	.03	.02	.09	0.00	.29	.15	.15	.09	.03	.05	.01	.05
ST	.08	.04	.03	.12	.05	0.00	.19	.21	.12	.04	.06	.02	.06
MX	.07	.03	.02	.10	.04	.33	0.00	.17	.10	.03	.05	.01	.05
XL	.07	.03	.02	.10	.04	.33	.16	0.00	.10	.03	.05	.01	.05
HL	.05	.03	.02	.09	.04	.31	.15	.16	0.00	.03	.05	.01	.05
SI	.06	.03	.02	.09	.04	.29	.14	.15	.09	0.00	.04	.01	.04
FC	.05	.03	.02	.09	.04	.29	.15	.15	.09	.03	0.00	.01	.04
TC	.06	.03	.02	.08	.04	.28	.14	.15	.09	.03	.04	0.00	.04
NC	.06	.03	.02	.09	.04	.29	.15	.15	.09	.03	.04	.01	0.00

FIGURE 4.5 DIFFERENCE MATRIX

	MP	MT	LP	LT	SS	ST	MX	XL	HL	SI	FC	TC	NC
MP	0.00	.05	.06	.37	.34	-.30	-.15	-.16	-.09	-.03	-.04	-.01	-.04
MT	.27	0.00	-.02	.58	-.04	-.29	-.14	-.15	-.09	-.03	-.04	-.01	-.04
LP	.28	-.03	0.00	.58	-.04	-.29	-.14	-.15	-.09	-.03	-.04	-.01	-.04
LT	.34	.17	.13	0.00	.21	-.31	-.15	-.16	-.10	-.03	-.05	-.01	-.04
SS	.27	-.03	-.02	.36	0.00	-.29	-.15	-.15	-.09	-.03	.18	-.01	-.05
ST	-.08	-.04	-.03	-.10	-.05	0.00	.16	.04	.05	.05	-.01	.00	.01
MX	-.07	-.03	-.02	-.10	-.04	.34	0.00	.04	-.07	.03	-.05	.02	-.05
XL	-.07	-.03	-.02	-.10	-.04	.12	.13	0.00	.11	-.03	-.05	-.01	.00
HL	-.05	-.03	-.02	-.05	-.04	.01	-.06	.29	0.00	-.03	-.05	.03	-.00
SI	-.06	-.03	-.02	-.09	-.04	.57	-.14	-.01	-.09	0.00	-.04	-.01	-.04
FC	-.05	-.03	-.02	.11	-.04	.31	-.05	-.15	.01	-.03	0.00	-.01	-.04
TC	-.05	-.03	-.02	-.08	-.04	-.28	-.14	.35	.41	-.03	-.04	0.00	-.04
NC	-.05	-.03	-.02	-.09	-.04	.45	-.02	-.15	.03	-.03	-.04	-.01	0.00

From this matrix, a facies relationship diagram can be drawn to illustrate facies transitions which occur more frequently than random (Figure 4.8).

4.3.2 Discussion

The most obvious aspect inherent in the difference matrix (Table 4.5) and the facies relationship diagram (Figure 4.8) is that there are two major facies associations which are linked by transitions out of the FC facies. The upper facies association is composed solely of facies in the Storelk Formation, whereas the lower facies association is composed of facies occurring in the Tyrwhitt and Tobermory Formations. The linkage of the two via the FC facies indicates only that it is the only facies that occurs in both the Storelk and Tyrwhitt Formations. The actual Tyrwhitt-Storelk transition in most cases is from the ST facies to the LT facies, but this is masked by the large number of transitions from the ST facies into other facies. The facies relationship diagram therefore indicates that all of the facies that occur in the Storelk Formation (except for the FC facies) are mutually exclusive from those which occur in the Tyrwhitt and Tobermory Formations. Each of these facies associations are discussed separately below.

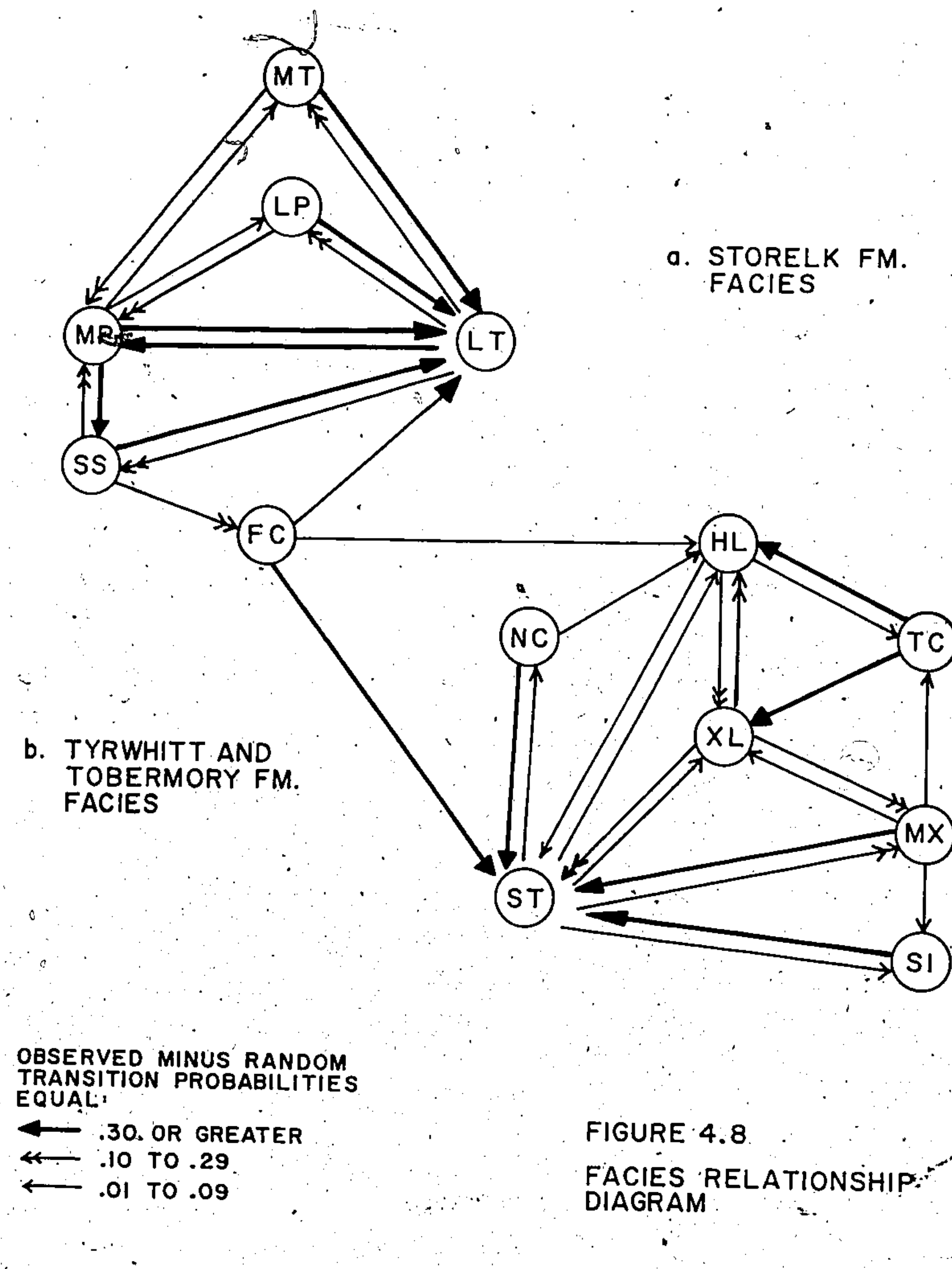


FIGURE 4.8

FACIES RELATIONSHIP DIAGRAM

Tyrwhitt-Tobermory Facies Transitions (Figure 4.8b): the total aspect of the facies relationship diagram shows that all facies except for the TC facies have preferred transitions both into and out of the ST facies. This relationship highlights the dominance of the ST facies in the Tyrwhitt, and to a lesser extent, the Tobermory Formations, and the fact that the ST facies is intimately interbedded with virtually all other facies at some point in the sequence. In the next Chapter, this relationship becomes highly important in establishing the depositional context of all these facies. The large number of vertical transitions into and out of the XL facies is also a reflection of its ubiquity in the Tyrwhitt, and especially the Tobermory, Formations. The fact that most of the preferred transitions are two-way emphasizes the intimate interbedding of certain of these facies. Although the diagram demonstrates the complexity of interrelationships among facies, it clarifies somewhat certain specific vertical associations. Certain of these will be discussed in the next Chapter.

Storelk Facies Transitions (Figure 4.8a): the total aspect of the facies relationship diagram indicates that all facies (except for the FC facies) show preferred vertical transitions into and out of the LT facies. This is mainly a reflection of the ubiquity of the LT facies throughout the Storelk sequence. The two-way nature of almost all facies transitions emphasizes the intimate interbedding of certain of the facies. Moreover, the diagram clarifies which facies are mutually exclusive from one another (e.g. MT from LP and SS).

In summary, the quantitative analysis of facies transitions indicates that there are two mutually exclusive facies associations: that of the Storelk Formation, and that of the Tyrwhitt and Tobermory Formations. The commonness of two-way transitions between facies in both associations suggests that both are characterized by an intimate interbedding of facies, and that there is no one preferred facies sequence.

CHAPTER 5

FACIES INTERPRETATIONS

5.1 INTRODUCTION

Each facies described in this Chapter is interpreted on the basis of lithology, sedimentary structures, body and trace fossil content, paleocurrent data and context. The vertical association of facies and their contexts then can be used to interpret depositional frameworks of which the facies are a part.

In the following discussion, two depositional frameworks are interpreted: shallow marine, represented by the Tyrwhitt and Tobermory Formations, and aeolian, represented by the Storelk Formation. The Tyrwhitt facies are interpreted in the context of a storm-dominated shelf setting. All facies were deposited seaward of fair weather wave base, and the transition to Storelk continental deposits does not resemble a normal prograding shoreline sequence involving a vertical succession of facies deposited in progressively shallower water. Instead, shoreline progradation was rapid, possibly due to glacio-eustatic control or a sharp increase in sand supply. The Storelk aeolian sediments are interpreted in the context of a low-latitude coastal desert affected primarily by prevailing tradewinds. Changes in wind pattern and rates of sediment supply were important variables. Rapid marine transgression terminated aeolian sedimentation. The overlying Tobermory sequence was deposited under storm dominated conditions similar to those of the Tyrwhitt.

The facies from the Tyrwhitt-Tobermory Formations, and those from the Storelk Formation, are distinctively different owing to their deposition in dissimilar depositional frameworks. This feature is suggested by the facies relationship diagram (Figure 4.8). Hence, the facies interpretations are divided into two natural groups corresponding to the two frameworks. Section 5.2 deals with the interpreted shallow marine facies, and Section 5.3 discusses the interpreted aeolian facies.

5.2 FACIES IN THE TYRWHITT AND TOBERMORY FORMATIONS

5.2.1 Structureless Facies (ST)

Summary

The ST facies is marine and thoroughly bioturbated. This process destroyed most evidence for current activity which originally introduced the sediment. The facies is interpreted to have been deposited seaward of fair weather wave base where current activity was intermittent and usually unable to disrupt biogenic activity. Other facies with which the ST facies is intimately interbedded represent temporary deviations from this prevailing depositional regime.

Salient Characteristics

The most distinguishing trait of the ST facies is the almost total absence of sedimentary structures observable in the field, and the presence of a mottled texture discernible in X-radiographs (Section 3.3.3). Preserved trace fossils are uncommon, and, where found, disarticulated brachiopods are concentrated into thin layers. The facies may constitute up to 65% of total

Tyrwhitt thickness, in which facies units range up to 25 m thick and persist laterally at least 5 km. Tobermory units are thinner and less persistent laterally, and account for a maximum of about 30% of total Formation thickness.

Context and Process Interpretation

The ST facies is interpreted to be of marine origin by virtue of preserved body fossils and trace fossils. The facies occurs throughout the Tyrwhitt and Tobermory Formations, suggesting that both are wholly marine.

The mottled texture of the facies is the result of thorough bioturbation, implying that the rate of faunal reworking exceeded the rate of sedimentation (Howard, 1978). Sequences thicker than the depth of penetration of the organisms are built up as successive generations of trace fauna shift upward with accumulating sediment (Seilacher, 1978). Hence, the great thicknesses (up to 25 m) observed in the Tyrwhitt and Tobermory indicate that long time periods were involved when bioturbation was the dominant process. These conditions prevailed over a wide area at least in a N-S direction, in view of the lateral persistence of some facies units.

Evidence for Current Activity in the ST Facies

Certain relatively rare features suggest the type of current activity that was involved in deposition of the ST facies. The thin crosslaminated layers observed in parts of the facies probably represent remnants of originally thicker XL facies units, which the trace fauna had insufficient time to totally destroy. Thin shell layers composed of disarticulated brachiopods may be analogous to macrofauna concentrations in North Atlantic Holocene sediments at depths of 15-45 m, attributed to the passage of high amplitude swell waves (Powers and Kinsman, 1953). Similar "swell lags", interpreted to have been deposited by storm generated high amplitude swell waves, have been observed in ancient sediments (Brenner and Davies, 1973). The presence of vertical suspension feeding trace fauna (e.g. ?Skolithos, ?Plichnia) in parts of the facies suggest that conditions were occasionally turbulent and organic matter was held in suspension (Frey, 1978). Since the vertical forms are often associated on the same bedding plane with horizontal deposit feeding forms (e.g. Planolites, Paleophycus), it is probable that current activity was intermittent. With an initial influx of sediment, trace fauna responded by constructing vertical burrows. During later conditions of slow or nil sedimentation, horizontal forms took over, but had insufficient time to homogenize the sediment prior to the next sediment influx. Hence, both forms were preserved together.

The above lines of evidence suggest that current activity was intermittent, and that only exceptional events (e.g. storm generated currents) were preferentially preserved. If continuous tidal or semipermanent oceanic currents were operative, they were incapable of depositing sediment at a high enough rate to outpace faunal reworking. It will be suggested later (end of Section 5.2.2) that these currents were unimportant in the system, and that storm surge currents were a more likely means of sediment transport.

Association with other Facies

The ST facies is vertically associated with a number of facies, the most important of which were entirely deposited by current activity (XL, HL, MX; Section 4.3.2). All of these facies pass preferentially both into and out of the ST facies. A second important fact is that the ST facies dominates the Tyrwhitt and Tobermory sequences in terms of stratigraphic thickness. These relationships suggest that the ST facies is representative of the background conditions of sedimentation. Other facies represent temporary deviations from the conditions of sedimentation prevailing during ST facies accumulation. The temporary deviations reflect the products of intermittently occurring processes resulting from some combination of changes in sediment supply, current strength or depth of flow. This interpretation is fundamental to the interpretations of other Tyrwhitt and Tobermory facies with which the ST facies is intimately interbedded (Section 4.3.2).

Depth of ST Facies Accumulation

The depositional site of the ST facies must have been removed from zones of appreciable continuous current activity and sediment supply. This suggests that the facies was deposited seaward of fair weather wave base, where it was beyond the zone affected by normal oscillatory wave action and nearshore currents (e.g. rip currents, longshore currents). The depth of fair weather wave base is dependent on several factors. These include wave period and height, which depend on wind fetch, and the slope and type of continental margin (wide or narrow shelf). Dietz (1963) suggested that effective wave base for the Atlantic Shelf lies at an approximate depth of 10 m. H.E. Clifton (pers. comm.) asserts that thoroughly bioturbated sediments are present below the same depth on the higher energy Pacific Coast (San Diego area) which is characterized by long period swells. He suggests that fine and very fine grained sediments are more susceptible to bioturbation than medium sands, which could account for similar effective wave bases for two coastal areas experiencing different wave regimes. In the Mediterranean Sea, a semi-enclosed microtidal basin, sediments are thoroughly bioturbated at depths as little as 4 m (H.E. Clifton, pers. comm.).

Establishment of a maximum depth of accumulation and the relative position of storm wave base is considered in the next Section.

5.2.2 Medium Scale Crossbedded Facies (MX)

Summary

The MX facies is marine in origin, and was deposited in a laterally extensive dune field. The depositing currents were unchannelized, essentially unidirectionally oriented offshore, and primarily depositional. Variations in set scale in some facies units suggest deposition by multiple events rather than a single continuous event. "Bundled" MX facies units appear to have been deposited by multiple events occurring in relatively rapid succession.

Semipermanent oceanic currents and tidal currents are concluded to be unsuitable analogues of the Pennsylvanian paleocurrents that deposited the MX facies. Rip currents are also unsuitable mechanisms, although under storm conditions they may contribute significantly to offshore sediment transport. Barometric storm surge currents are the most likely process to have deposited the MX facies, and their characteristics most closely match those of the Pennsylvanian paleocurrents.

Salient Characteristics

The MX facies is composed of trough crossbeds 10-50 cm thick (exceptionally up to 160 cm thick), with subordinate planar crossbeds usually less than 50 cm thick. Set scale in facies units may be uniform or variable, and in the latter case vertical changes in set scale may be gradational or abrupt. Paleoflow was directed towards the SSW, although there is a fair degree of variability.

The facies is composed of poorly to moderately sorted fine to medium sand. Trace fossils are rare, and body fossils are lacking. Facies units are commonly thicker than 2 m, and persist laterally at least 100 m. The Major Tyrwhitt MX Interval is exceptional in that it may be 9 m thick and persist laterally at least 5 km in a N-S direction. The MX facies occurs in both the Tobermory and Tyrwhitt Formations, but is more common in the latter.

Context and Process Interpretation

The MX facies is interpreted to be marine in origin on the basis of observed intimate interbedding between it and the fossiliferous ST facies. There is no evidence that the MX facies was emergent nor is there definitive evidence that it formed in shallower water as part of a progradational shoreline sequence. The thickness of MX facies units is minor compared with that of ST facies units, and moreover the MX facies passes preferentially both into and out of the ST facies (Section 4.3.2). In the previous Section it was interpreted that the ST facies is representative of the background conditions of sedimentation, and that it was deposited seaward of fair weather wave base. Hence, the two relationships between the ST and MX facies named above suggest that the MX facies represents a temporary deviation from conditions of background sedimentation, and that it was deposited in this zone also.

The trough crossbedding of the MX facies was deposited by dune migration. Subordinate interbedded planar crossbeds indicate that straight crested sand waves were also active at times. The lateral extent of the facies, especially in the case of the Major Tyrwhitt MX Interval, demonstrates that the dune field was widespread in at least a N-S direction.

The MX facies units are thick (greater than 1 m), and have relatively flat bases which show little evidence of scour. This indicates that the currents were capable of transporting a large volume of sediment, and that they were primarily depositional rather than erosional. In addition, facies units are traceable laterally long distances without evidence of an overall lenticular shape. Hence, the currents are interpreted to have been unchannelized.

Orientation of Paleoflow Relative to the Shoreline

The dominant paleoflow direction indicated by the crossbeds is SSW (Figure 3.19) relative to a NNW-SSE regional trend of the shoreline (Section 2.1). Hence, paleoflow was essentially unidirectional, although there is a fair degree of variability, and was directed obliquely offshore relative to the regional trend of the shoreline. There is no control on local variation in shoreline trend, so the exact angle between this and the dominant paleoflow direction cannot be specified for this area. Barring any major deviations in the regional trend of the shoreline, paleoflow is interpreted to have been directed offshore.

Implications of Variation in Set Thickness

A variety of set thicknesses is commonly preserved within single facies units. Typically, where the range in set thickness is more extreme, the crossbeds are ordered into sequences characterized by upward decreasing set thicknesses. For example, in measured section 2, there are two superimposed sequences (9-10 m; 10-13 m) of this type. In the lower sequence, set thickness decreases upward abruptly from 80 cm to 10 cm. In the upper sequence, set thickness decreases gradually upward from 90 cm to 10 cm. Both sequences fine upwards. In each sequence, the lower large scale crossbeds were probably deposited under conditions of relatively high flow strength. The abrupt upward decrease in set thickness in the lower sequence suggests that current strength waned sharply, assuming sufficient sediment supply. In the upper sequence, however, current strength apparently waned more gradually to deposit progressively thinner sets (again assuming sufficient sediment supply). Each sequence is interpreted to be the result of a single depositional event. The superimposition of sequences suggests that this and other similar facies units were deposited by successive events rather than one continuous event.

Modes of Occurrence of MX Facies Units

MX facies units may be solitary or "bundled". Solitary units (e.g. MS 2: 240-241 m; MS 3: 45-47 m) are usually relatively thin (0.5-2 m) and contain sets of similar thicknesses. These probably represent the products of single depositional events. Commonly several such units, separated vertically from one another by thin ST facies units, occur together within a limited stratigraphic thickness (e.g. MS 1: 42-50 m; MS 2: 57-66 m). These "bundled" units taken together are bounded above and below by thick intervals dominated by the ST facies. The Major Tyrwhitt MX interval is a variation on this, since it contains superimposed sequences deposited by single depositional events but without intervening ST facies units. Apparently the events were closely spaced in time, prohibiting re-establishment of trace fauna, or trace fauna together with reworked sediments were swept away during the succeeding event. The modes of occurrence of MX facies units suggest that the depositional events occurred more frequently during some periods than during others.

Implications of Interbedding of MX and ST Facies

The MX and ST facies apparently accumulated at the same depositional site, even though they were the products of markedly different depositional conditions. Strong unidirectional currents and rapid aggradation characterizing MX facies deposition temporarily eliminated trace fauna. Upon re-establishment, trace fauna were unable to rework the deposit except for the uppermost part. These departures from background conditions of sedimentation were temporary and exceptional, and more importantly, occurred intermittently through time.

Summary of Current Characteristics

The following summarizes the essential characteristics of the currents which deposited the MX facies. The currents -

1. were essentially unidirectional;
2. were directed offshore;
3. were capable of transporting large volumes of sand;
4. were strong enough to generate dunes in fine to medium sand;
5. were unchannelized, and mainly depositional rather than erosional;
6. waned gradually or abruptly during a single depositional event;
7. affected a wide area in a N-S direction, and extended well offshore; and
8. occurred intermittently through time.

Comparison with Currents Operating on Modern Shelves

Delineation of the nature of the currents which deposited the MX facies makes it possible to compare them with currents operating on modern shelves. Three main types of currents have been defined by Swift et al. (1971): semipermanent oceanic currents, tidal currents, and meteorological currents. The latter two types may be subdivided into a heirarchical array of components. Any of these currents and their components may be superimposed in a natural system.

Semipermanent Currents: formation and migration of bedforms under the influence of semipermanent currents is poorly understood. Recent studies have indicated, however, that semipermanent currents are capable of generating large bedforms. Harms et al. (1974) have described sand waves up to 4.5 m high in carbonate sand, migrating under the influence of the Yucatan Current where it is constricted in a strait between the Yucatan Peninsula and an island. The water depth is 5-6 m, and the current is unidirectional with an average velocity of 50 cm/sec. Flemming (1978) describes large bedforms 0.5-8 m high migrating under the influence of the Agulhas Current on the outer shelf along the southeastern African continental margin. The bedforms are at depths between 50 and 100 m, and the Current is unidirectional, attaining near-bottom speeds of 130 cm/sec.

Semipermanent currents are an unsuitable mechanism to explain the origin of the MX facies. Most importantly, this mechanism does not explain the apparent intermittent nature of the paleocurrents.

Tidal Currents: tidal currents are known from modern studies to be capable of forming migrating dunes on tide-dominated continental shelves. In the North Sea, active dunes have been observed on the gentle and steep slopes of tidal current ridges (Houbolt, 1968; Caston, 1972). The dunes form in response to tidal current flow parallel to the ridge crest. McCave (1971a) reports dunes mantling "sand waves" (actually low sand mounds) off the coast of Holland. All of the observed dunes from these studies are active at depths of 31-40 m, which could be an exceptional situation since the North Sea is characterized by a high tidal range and tidal currents which attain high speeds.

The concept of strong, continuously operating tidal currents during Tyrwhitt and Tobermory sedimentation is contradicted by the interpreted intermittent nature of the currents that deposited the MX facies. There is also no evidence of bipolar-directed crossbedding, nor is there evidence of other sedimentary features in the sequence suggesting a macrotidal environment (e.g.

extensive tidal flat deposits). Moreover, since tidal currents were apparently too weak to significantly affect relatively quiescent sedimentation during ST facies deposition, they are interpreted to have been relatively unimportant in the depositional system.

An alternative possibility is that relatively weak tidal currents may be significantly enhanced by storm processes. Data from the North Sea indicates that storm waves may induce strong oscillatory near-bottom movement, which enhance the rate of sediment transport by tidal currents (Johnson and Stride, 1969). Kenyon and Stride (1970) cite two studies which report near-bed current velocities in excess of 1 knot (51 cm/sec) at depths of 160-200 m on a significant number of days per year. They also state that for given waves, the strength of these currents would increase with decreasing depth. It is doubtful, however, that this mechanism could be solely responsible for deposition of the MX facies. Simple oscillatory current input on weak tidal currents cannot account for the large amounts of sediment introduced, and current velocities comparable to those observed in the North Sea would be barely capable of generating dunes. It will be shown later that bottom surges from storm waves apparently had little or no effect on the MX facies, and that the facies was probably deposited near or below storm wave base.

Meteorological Currents: the types of meteorological currents are direct wind currents, wave surge currents, longshore currents, rip currents and barometric storm surge currents (Swift et al., 1971). Fair weather direct wind and wave surge currents are not likely to have had a significant input into the Tyrwhitt and Tobermory depositional systems since the MX (and ST) facies are interpreted to be deposited seaward of fair weather wave base. Their input under storm conditions has been partly discussed in the preceding section, and will be returned to later. Longshore, rip, and barometric storm surge currents require further discussion.

Longshore and rip currents are active in the nearshore zone as parts of a system of cell circulation (Komar, 1976, p.168). Longshore currents are usually confined landward of the breaker zone, although they may extend further seaward in a late pre-storm stage (Murray, 1970). Rip currents flow offshore through the breaker zone. Davidson-Arnott and Greenwood (1976) describe crossbeds up to 20 cm thick being deposited by dunes migrating under the influence of rip currents with velocities exceeding 75 cm/sec on a microtidal barred coastline. The maximum depth to which the dunes migrate is approximately equal to 5/4 of the wave height (H.E. Clifton, pers. comm.). The greatest reported depth to which active bedforms have been observed in rip channels is 4-6 m (Ingle, 1966). These data suggest that fair weather longshore and rip currents do not operate to a great enough depth to act as possible mechanisms for the deposition of the MX facies. However, Clifton et al. (1971) state that the chief effect of winter storms on the Oregon Coast is the great intensification of rip currents. The effects of more intense storms such as hurricanes would be expected to have more drastic effects, and it is conceivable that intensified rip currents under these conditions would contribute significantly to offshore sediment transport. The transport of sediment further out onto the shelf, though, must be accounted for by some other mechanism.

Barometric storm surges are rises in sea level that result from lowered atmospheric pressure and increased wind stress (Lisitzin, 1974, p.69). Water piles up along the coast, then returns seaward generating strong near-unidirectional offshore directed bottom currents. Hayes (1967) describes storm surge currents that were active during Hurricane Carla in 1961 on the Texas Coast. Strong currents ripped through hurricane channels in barrier islands and apparently evolved into density currents which deposited sediment at least 24 km offshore at depths of 40 m and more. Gadow and Reineck (1969, cited in Kenyon and Stride, 1970) report that storm surge currents transported sand about 50 km from the German Coast into water up to 40 m deep. The velocities attained by these currents in offshore areas are unknown. Direct measurements by Murray (1970) in shallow water (6.3 m deep), however, show that bottom current speeds up to 160 cm/sec were generated during Hurricane Camille in 1969. The above data suggest that storm surge currents are capable of transporting sand well out onto the shelf. One location where they are most pronounced is in relatively shallow shelf areas that experience hurricanes (Listizin, 1974, p.70).

Storm Surge Currents as a Mechanism for MX Facies Deposition

Storm surge currents are the most likely process to have deposited the MX facies. These currents best explain the nature and context of the Tyrwhitt and Tobermory paleocurrents, which are considered below.

The Pennsylvanian paleocurrents are characterized as being unchannelized, essentially unidirectional, and generally directed offshore. These are all characteristic of modern storm surge currents. The relatively high degree of variability in the paleocurrent data is partly due to the method of data collection (Section 1.4), although it is also likely related to primary sedimentary processes. The initial storm surge current probably flowed approximately perpendicular to the shoreline. Further out on the shelf, the direction of flow would be largely controlled by the direction of the paleoslope, which is not necessarily perpendicular to the shoreline. Moreover, minor bottom irregularities may affect the current path, causing local deviations. Similar effects were documented by Hayes (1967). Other factors that could affect the initial orientation of the storm surge current are local variations in shoreline trend, and the orientation of the storm track relative to the shoreline.

The Pennsylvanian paleocurrents were capable of transporting large volumes of sand which formed units at least a meter thick during single depositional events. Deposits of this thickness have not been observed in modern sediments. The maximum thickness of sand layers deposited during Hurricane Carla is 9 cm (Hayes, 1967). Storm sand layers observed in the North Sea are on the order of a few centimeters thick (Reineck and Singh, 1972). However, units comparable in thickness to those in the Tyrwhitt and Tobermory Formations have been described in other interpreted storm surge deposits. Hamblin (1978) describes sand units averaging 75 cm thick interpreted to be deposited by single depositional events in Jurassic-Cretaceous sediments in Western Canada. It is possible that in the case of the Tyrwhitt and Tobermory, much more intense storms than those described from the modern were involved. Hence, stronger and relatively long-lived currents may have been generated. The type of coastline may also have been important. It will be suggested later that the Tyrwhitt and Tobermory shelves bordered on a desert area. Thus, a large volume of unstabilized sand could have been made available during extensive coastal erosion by intense storms. As a result, currents would have been heavily sand-laden, which would explain why they were primarily depositional rather than erosional.

The Pennsylvanian paleocurrents were capable of generating dunes (and sand waves) in fine to medium sand grades, depositing trough and planar crossbedding. These deposits are unlike modern storm surge current and other storm generated deposits, which are generally described as graded beds characterized by parallel lamination

(Hayes, 1967; Reineck and Singh, 1972; Kumar and Sanders, 1976). Storm related deposits similar to these modern examples have been described from the ancient (Howard, 1972; Kumar and Sanders, 1976). The Pennsylvanian deposits are also unlike ancient storm deposits described as being characterized by hummocky cross-stratification (Harms *et al.*, 1975; Hamblin, 1978).

The formation of trough crossbedding rather than parallel lamination may be partly a function of grain size. In flume experiments involving unidirectional currents and shallow depths, dunes and upper plane bed can be produced under equivalent flow strengths and flow depths, except that dunes form in grain sizes coarser than very fine sand (Figure 2-5 in Harms *et al.*, 1975). If the Pennsylvanian current conditions are assumed to be roughly analogous, current speeds of several tens of centimeters per second might similarly have produced dunes rather than upper plane bed because of this difference in grain size.

Hummocky cross stratification is interpreted to be a storm generated deposit. Bottom currents apparently transport sand in suspension, and mold it into a low undulating crest and trough topography. These "bedforms" are continually moved and modified by variously oriented currents. Harms *et al.* (1975, p.88) attribute this current action to strong storm wave surges which are characterized by larger velocity and displacement than that required to form wave ripples. The nature and depth to which these reach were described earlier. None of the facies in the Tyrwhitt or Tobermory Formations contain evidence of remolding of the substrate into a hummocky topography by this process. This suggests that the MX and other facies were deposited just above or seaward of maximum storm wave base. In this zone, strong oscillatory wave motion would be relatively weak or absent, so that it would be incapable of eroding and redistributing sand. In some cases, however, the largest waves were apparently capable of concentrating shell material in this zone, as was suggested earlier.

The variations in set scale observed in the Tyrwhitt and Tobermory is also compatible with a storm surge hypothesis. The initial storm surge current would be relatively strong and capable of depositing the largest crossbeds. With waning flow and decreasing amounts of sand held in suspension, successively deposited sets would be progressively smaller. The time period involved would be on the order of a few hours to a few days (Lisitzin, 1974, p.70), or even longer in more intense storms. The abrupt decrease in set scale noted in some MX facies units could be the result of a rapid decrease in suspended sediment load, which would restrict the size of the set being deposited despite continued current action.

The lateral continuity of Tyrwhitt and Tobermory MX facies units would also be expected if storm surge currents were involved. With a broad storm front, large sections of the coastline would be affected, and return storm surge flow would occur laterally over long distances.

The two observed configurations of the MX facies, solitary and "bundled" units, have implications on the frequency of occurrence of the storm surge currents. In a short term sense, major modern storms are infrequent. Hayes (1967) estimated that tropical cyclones pass over the Texas coast at the rate of 0.67 per year. "Rare" events such as these, taken in the context of geological time, have high absolute frequencies (Gretener, 1967). Hence, in a longterm sense, storm processes may dominate a depositional system, and storm-generated deposits could dominate the stratigraphic record. This could explain the "bundling" of MX facies units, but does not explain the much thicker intervals dominated by the ST facies and minor solitary MX facies units. It is possible that MX facies units were only deposited and preserved during periods when large volumes of sand were available to the system. There is evidence that the rate of sand supply varied markedly during Tyrwhitt and Tobermory times, since units suggesting abundant sediment supply (e.g. MX facies) are in close vertical proximity with units suggesting a very restricted sand supply (siltstone and carbonate facies). Hence, it is suggested here that the transport agents involved in MX and ST facies deposition were essentially the same. With comparatively sand-deficient currents, only thin sand beds would be deposited, and these would be thoroughly bioturbated if the bed thickness did not exceed the depth of penetration of the organisms (i.e. a few centimeters). Deposition of slightly thicker layers at times would explain why evidence of current activity is sometimes preserved in the ST facies. In this regime, deposition of MX facies units would be the product of exceptionally intense storm-generated currents together with a high rate of sediment supply. The above processes explain the observed relationships between the ST and MX facies.

In conclusion, storm surge currents are interpreted to be the only current type capable of depositing the MX facies in the zone around storm wave base. Moreover, such currents likely introduced the sediment constituting the ST facies. The interpretation of storm surge currents appears to explain why the Pennsylvanian paleocurrents were essentially unidirectional, oriented offshore, unchannelized, primarily depositional and intermittently occurring. The latter is most important in discounting the effects of tidal or semipermanent oceanic currents.

5.2.3 Small Scale Crosslaminated Facies (XL) Horizontal Parallel Laminated Facies (HL)

Summary

The XL and HL facies are interpreted to be marine in origin, and to have accumulated seaward of fair weather wave base. Both could have been deposited under unidirectional or oscillatory flow, and experimental data suggests that they need not have accumulated under radically different flow conditions.

Evidence for both unidirectional flow and oscillatory flow is preserved in the XL facies. This, combined with a lack of development of hummocky cross stratification, suggests that the XL and HL facies accumulated near storm wave base. Storm surge currents of variable intensity, with weaker superimposed oscillatory wave components, are interpreted to have deposited the facies. Preservation of more abundant sedimentary structures in the upper

Tobermory is likely a function of sediment supply.

Salient Characteristics

The XL facies is characterized mainly by trough crosslamination in sets 0.5-5 cm thick and 2-30 cm wide. Rare wave forms with form concordant and discordant internal laminae are preserved. Facies units range in thickness from a few decimeters to several meters, and commonly contain vertical burrows of suspension feeding organisms.

The HL facies is characterized by horizontal straight to somewhat undulatory or irregular laminae. Facies units are usually less than 25 cm thick (exceptionally 100 cm thick), and rarely contain vertical burrows of suspension feeding organisms.

Both facies are usually composed of very fine sand. The XL facies is ubiquitous throughout the Tyrwhitt and Tobermory Formations, and is commonly interbedded with the ST, HL and MX facies. The HL facies is less common in both Formations, and passes preferentially upward into the XL facies. XL to HL transitions also occur laterally over several decimeters.

Context and Process Interpretation

The XL facies is interpreted to be marine in origin on the basis of intimate interbedding between it and the fossiliferous ST facies. By close association with the XL facies, the HL facies is also interpreted to be marine. Interbedding with the ST facies suggests that the XL (and HL) facies accumulated seaward of fair weather wave base.

Ripples and upper plane bed are formed under symmetric and asymmetric oscillatory flow (Clifton, 1976) and under unidirectional flow. It is unlikely that the horizontal laminae in the HL facies were deposited from migrating low amplitude bedforms under lower flow regime conditions, which has been shown experimentally by McBride et al. (1975). It is doubtful that units up to 1 m thick can be deposited by this mechanism. Moreover, the presence of suspension feeding forms (e.g. Skolithos) suggest a higher flow strength than would be expected in conditions compatible with the lower part of the lower flow regime.

The intimate vertical and lateral association of the XL and HL facies requires special consideration. Direct transitions between ripples and upper plane bed have been observed under unidirectional flow in flumes (various authors, in Harms et al., 1975), and in oscillatory flow tunnels (various authors, in Davidson-Arnott and

Greenwood, 1976). Under unidirectional flow at shallow depths, these transitions occur without an intermediate dune phase in silt and very fine sand (less than 0.125 mm). This is compatible with the HL to XL transitions in the Tyrwhitt and Tobermory, where sand is very fine grained. The effect of flow depth constitutes a third variable, but its effects on the positions of phase boundaries is minor compared to velocity and grain size when flow depth is large relative to bedform height (Harms et al., 1975, p.11). Clifton (1976) states that under symmetric oscillatory flow, the most important factor governing ripple to plane bed transitions is the maximum orbital velocity at the bed. The threshold velocity for this transition is directly dependent on grain size, and possibly partly dependent on wave period.

From experimental data, approximate estimates of the threshold velocity of the ripple to flat bed transition can be made. Experimental data cited by Clifton (1976) gives a threshold velocity of about 55 cm/sec for 0.08 mm sand when the wave period is 7-10 sec. The threshold velocity under unidirectional flow is about 65 cm/sec for 0.08 mm sand at a flow depth of about 20 cm (Harms et al., 1975, Fig. 2-5). These two threshold velocities, while subject to modification by a large variety of variables, give a qualitative feel for the strength of currents necessary to induce a ripple to flat bed transition under given conditions. The values suggest that high current strengths are not required, and demonstrate that a minor increase or decrease in current strength may be all that is needed to induce a phase transition.

Types of Crosslamination and Their Implications

The XL facies contains trough crosslaminae and symmetrical wave forms, suggesting deposition by unidirectional currents and oscillatory flow. Crosslaminae deposited by these processes may be very similar depending on the degree of asymmetry of oscillatory flow, as has been demonstrated by de Raaf et al. (1977). Hence, no attempt was made to differentiate between crosslaminae formed by unidirectional and oscillatory flow, and as defined the XL facies contains both types.

Very little paleocurrent evidence was recorded from the XL or HL facies, so it has not been quantitatively determined whether the currents that deposited these facies flowed in the same direction as those depositing the MX facies. Therefore, the origin of the currents must be identified by inference and context.

Position of Depositional Site Relative to Storm Wave Base

The presence of symmetrical wave forms in the XL facies suggests that it was deposited within a zone influenced by wave activity. Storm waves are likely responsible for these and possibly some of the trough crosslamination in the XL facies, since the facies was apparently deposited seaward of fair weather wave base. The storm wave surges, however, were incapable of remolding the substrate into a hummocky topography and depositing hummocky cross stratification. The slight undulatory appearance of some HL facies units indicates minor influence only. Hence, it is probable that the XL and HL facies accumulated just above or at storm wave base, where although storm wave surges were felt, they were only capable of rippling the substrate.

Type of Currents

For the Tyrwhitt and Tobermory sequences, it was previously interpreted (end of Section 5.2.2) that storm surge currents were the most effective agents of sediment transport and deposition in the zone near storm wave base. The same currents could be responsible for depositing the majority of sedimentary structures composing the XL and

HL facies. The common intimate vertical and lateral association between the facies is probably largely a function of grain size (very fine sand) and could explain why dunes did not develop as in the MX facies. The vertical associations of the HL and XL facies resemble storm sand layers described from modern and ancient sediments, although there is a lack of grading in the former. In cases where ripple crosslaminae are observed in coarser grain sizes, the storm surge currents apparently had lower flow velocities than those depositing the MX facies. Vertical transitions from the MX facies into the XL facies could reflect waning flow of the current. The rare cases where horizontal laminae are developed in fine and medium sand suggest even higher flow velocities than those required to form dunes. Hence, the various types and sequences of sedimentary structures in the Tyrwhitt and Tobermory Formations can be explained in terms of storm surge currents of variable intensities, with superimposed (but weaker) symmetric and asymmetric wave surge components.

Differences Between Tyrwhitt and Tobermory Formations

The thickness and abundance of XL and HL facies units differ between the Tyrwhitt and Tobermory Formations.

In the latter, facies units tend to be thicker and more common than in the Tyrwhitt Formation. Also, sedimentary structures become more abundant in the upper part of the Tobermory Formation, whereas in the Tyrwhitt Formation the facies do not appear to be more abundant in one part of the sequence over another.

The dissimilarities described above can result from two factors. The upper Tobermory sequence could have been deposited in slightly shallower water than the Tyrwhitt and lower Tobermory sequences, and thus be subject to more wave action. As mentioned previously, the depositional site for the upper Tobermory would still be seaward of the zone of strong wave surges. Alternatively, the more frequent preservation of sedimentary structures would be a function of sediment supply. A higher rate of sediment supply being distributed by (geologically) frequent storm surge currents would prohibit extensive bioturbation, as was postulated in discussing the preservation of MX facies units (end of Section 5.2.2).

5.2.4 Siltstone Facies (SI)

Salient Characteristics

The SI facies constitutes only a minor proportion of the stratigraphic thickness of the Tyrwhitt Formation. The facies represents the finest grained clastic sediments of the entire Pennsylvanian succession. Two laterally persistent units occur in most measured sections, and both appear to be thoroughly bioturbated.

Context and Process Interpretation

Interbedding with the fossiliferous ST facies suggests that the SI facies is marine, and that it accumulated seaward of fair weather wave base. The lithology of the SI facies shows that it accumulated during a period of severely restricted sand supply. This, together with its thoroughly bioturbated nature, suggests that there was no appreciable current activity during facies deposition. The lateral persistence of the facies shows that these conditions prevailed over a wide area in a N-S direction.

In most measured sections, an SI facies unit vertically succeeds the Major Tyrwhitt MX Interval. Barring the possibility of a sudden relative deepening of the depositional site, this suggests that the facies accumulated in a zone that might potentially be subjected to storm surge currents. Apparently, the SI facies represents a period of time when there was a paucity of storms intense enough to generate surge currents capable of reaching the depositional site.

5.2.5 Non-Fossiliferous Carbonate Facies (NC) Fossiliferous Carbonate Facies (FC) Crossbedded Carbonate Facies (TC)

Salient Characteristics

The NC facies is composed of thoroughly bioturbated microcrystalline dolomite, and occurs only in the Tobermory Formation. The facies usually succeeds the ST facies, passes upward into the HL or ST facies, and contains no body fossils.

Two distinctively different FC facies units occur in the Tyrwhitt Formation. The lower unit, composed of sandy limestone, contains *Spiriferid* brachiopods and echinoderm fragments. It passes up into the ST facies. The middle unit is composed of highly sandy dolomite, contains abundant *Orbiculoidea* brachiopod layers, and succeeds the ST facies. It may pass upward into the MX, HL or ST facies. A single (upper) FC facies unit is present in the Storelk Formation of most measured sections, and will be considered later (Section 5.3.4).

The TC facies consists of trough crossbedded (sets 20–30 cm thick) sandy dolomite or dolomitic sand containing abundant casts and fragments of shells. Facies units are laterally discontinuous over a few tens of meters, and are vertically associated with the MX, HL and XL facies.

Context and Process Interpretation

The FC and TC facies are marine in origin on the basis of body fossil content, and the NC facies is interpreted to be marine in view of its close association with the fossiliferous ST facies. Interbedding with other facies interpreted previously to be deposited seaward of fair weather wave base suggests that the carbonate facies were deposited in this zone also.

The lithology of the facies shows that they were deposited during periods of restricted sand supply, although in all cases minor to abundant amounts of sand were introduced. In the case of the FC facies where sand-rich and sand-deficient layers commonly alternate, sand influx appears to have been periodic.

Crossbedding in the TC facies, and shell layers in the middle unit of the FC facies, indicate current activity. The admixture of disarticulated brachiopods and echinoderm fragments in the lower FC facies unit suggests that it is transported debris. The NC facies accumulated during conditions of inactive currents.

Origin of Currents

The carbonate facies likely accumulated under essentially the same depositional conditions as the siliciclastic parts of the sequence, except that sand supply was restricted in the former. Hence, each carbonate facies has a siliciclastic counterpart. The TC facies is comparable to the MX facies, the NC facies to the SI facies, and the FC facies to the ST facies. The processes previously interpreted for the siliciclastic facies apply to their carbonate counterparts.

5.2.6 Interpretation of Features not Included in Facies Scheme

Low Angle Inclined Strata, Tobermory Formation

Low angle inclined strata occurring in the Tobermory Formation of measured section 1 were described in Section 3.13.1. Although the sets resemble megatrough sets from the MT facies, their context suggests that they are marine (i.e. a vertical association with the MX, NC and ST facies). If the inclined strata are marine in origin, then modern and ancient analogues are lacking. It is possible that the sets are lateral accretion features, in view of the low angles of stratal dips (10-11 degrees). This forces the hypothesis that erosive currents were capable of forming a broad depression in the substrate, which was later infilled from one side. Within the interpreted context, storm surge currents are apparently the only type with sufficient strength. It would have to be assumed that they were not carrying a sufficient sediment load, so as to be effective erosive agents. The interpretation of the inclined strata cannot be taken beyond this suggestion. The alternative that the sets are aeolian would entail a drop in sea level, followed by a rapid rise. There is no evidence from laterally equivalent stratigraphic intervals suggesting that such a drop occurred.

Deformed Laminae

The deformed laminae characterizing the upper Tobermory Formation (Section 3.13.2) are interpreted to be the product of soft sediment deformation. The observed structures likely resulted from the combined effects of sediment loading and dewatering of underlying sediments. Rapid aggradation of sediment introduced by storm surge currents is probably the cause of sufficient loading to induce deformation.

5.2.7 Conclusion

1. All facies in the Tyrwhitt and Tobermory Formations are interpreted to have been deposited on a storm dominated shelf. There is no definitive evidence for tidal or oceanic currents.

2. The physical characteristics of the ST facies, together with the abundance and thickness of facies units, suggest that the facies was deposited seaward of fair weather wave base, and that it represents background

conditions of sedimentation.

3. The intimate interbedding of the ST and virtually all other facies suggests that all facies were deposited seaward of fair weather wave base.

4. The relative unimportance of wave-generated sedimentary structures, and the lack of development of hummocky cross stratification in the sequence, suggest a depositional site near storm wave base. This supports the interpreted offshore origin of the ST and other facies.

5. Storm surge currents are interpreted to be the only effective sediment transporting agents at the depositional site, and most closely match the characteristics of the Pennsylvanian paleocurrents as defined from the MX facies. The strength of the surge current, together with the grain size and rate of sediment supply, determined the type and preservability of sedimentary structures, and the lithology of facies units.

5.3 FACIES IN STORELK FORMATION

Megaplanar Facies (MP), Megatrough Facies (MT), Storelk Structureless Facies (SS), Fossiliferous Carbonate Facies (FC), Large Scale Planar Crossbed Facies (LP), Large Scale Trough Crossbed Facies (LT)

The above facies are grouped into a facies association for the purposes of interpretation. In subsequent discussion, it will be shown that the first four facies are the most diagnostic in interpretation of the depositional framework that prevailed during Storelk time.

5.3.1 Salient Characteristics

Facies in the Storelk Formation occur in specific combinations at certain stratigraphic levels, and are accordingly assigned to a series of Intervals (Section 4.2). A generalized sequence showing distribution of facies, ranges of set thickness and paleoflow data is presented in Figure 5.1. Pertinent facies characteristics are summarized below.

The MP facies consists of planar tabular sets and subordinate wedge shaped planar sets. Foresets are true geometric planes, and range in dip between less than 10

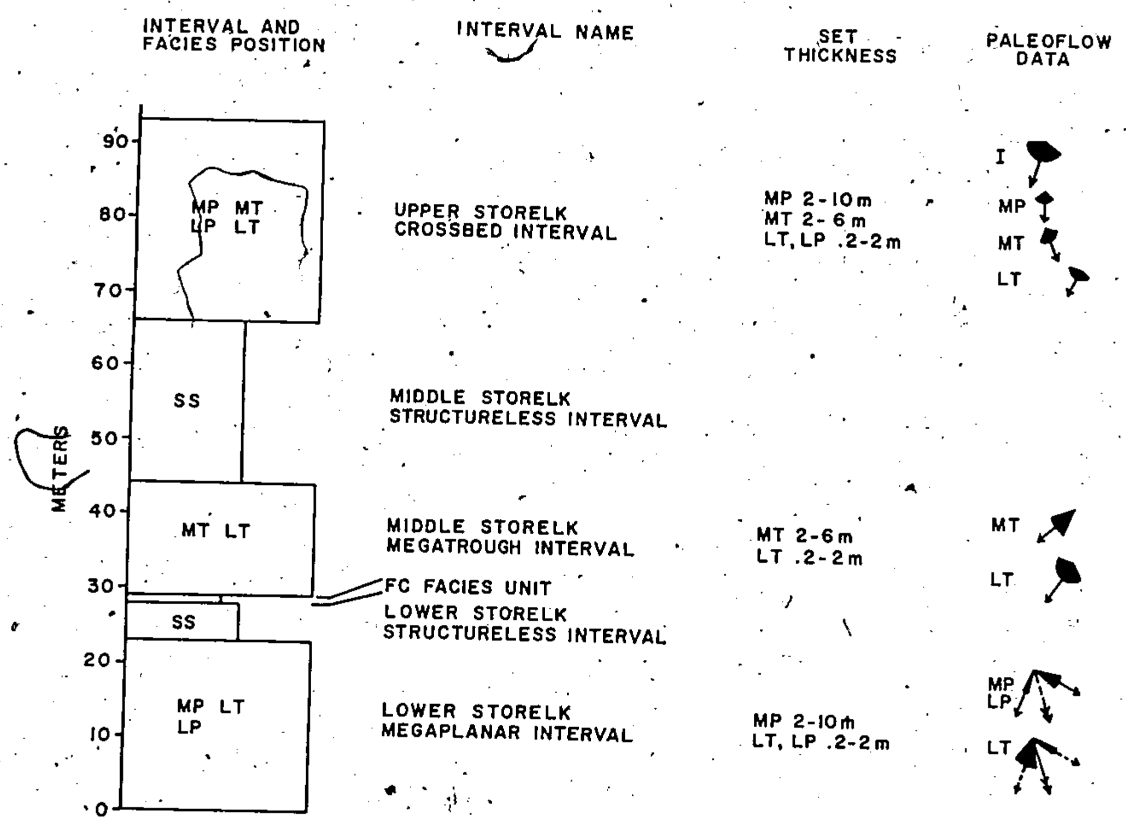


FIGURE 5.1

RELATIVE POSITIONS AND OTHER FEATURES OF FACIES AND INTERVALS IN STORELK FORMATION degrees to a maximum of 26 degrees. In tabular sets, laminae are generally asymptotic to the lower set boundary, whereas in wedge shaped sets the laminae may parallel this boundary. Angular relationships between laminae and the lower set boundary are also possible for both set types. Sets in the LP facies resemble those in the MP facies, differing only in scale.

The MT facies consists of trough sets which have broadly concave upward foresets. The foresets have a broad lateral curvature, and generally dip between 10 degrees and 25 degrees. Sets in the LT facies resemble their MT facies counterparts, differing only in scale.

The single most important characteristic of the SS facies is the almost total absence of sedimentary structures. X-radiographs reveal a uniform texture with no evidence of mottling. Rare thin horizontally laminated zones may be present (e.g. S 1: 143-143.5 m), and thin argillaceous or siltstone zones are always present.

A single thin FC facies unit is usually present at the base of the Middle Storelk Megatrough Interval (Figure 5.1). The unit is composed of highly dolomitic sandstone or sandy dolomite, and in places contains <u>Spiriferid</u> or <u>Terebratulid</u> brachiopods.

The top of each Interval is marked by horizontal surfaces which truncate underlying sets. The surfaces occur at similar stratigraphic levels in all sections, and hence could be continuous laterally. The SS facies commonly overlies the truncation surfaces. Within Intervals, facies units are commonly separated by horizontal truncation surfaces (e.g. between LT and MP facies units, MS 1: 99-116 m).

5.3.2 Organization of the Interpretation

Three depositional environments are known or are interpreted to be characterized by large migrating bedforms which can deposit cross stratification of the scale observed in the Storelk. These are aeolian environments, tide dominated shallow marine environments, and fluvial environments. It will be shown that a fluvial interpretation is improbable. Then, the major lines of evidence regarding aeolian and shallow marine interpretations will be assessed. Subsequently, an aeolian interpretation will be favoured. From that point, a comparison of the Storelk with modern and ancient aeolian sediments will be made, and specific features in the Storelk will be interpreted. Also, a comparison will be made to an interpreted ancient shallow marine example (by Nio, 1976) which is characterized by giant crossbedding. Finally, the vertical relationships between the Storelk and adjacent Formations will be discussed, and the source of the sand constituting the Pennsylvanian siliciclastic succession will be considered.

5.3.3 Improbability of a Fluvial Interpretation

Extremely large bedforms have been reported in modern river systems. In the Brahmaputra River, Coleman (1969) reports "dunes" 1.5-7.5 m in height, and "sand waves" 7.5-15 m in height. Based on numerous natural exposures and excavations, Coleman (1969) found that these features were composed of complexly interbedded cross sets less than 2 m thick. Thus they were not composed of giant crossbeds as their external form might imply.

Giant crossbeds up to 40 m thick with an interpreted fluvial origin have been described from Upper Carboniferous deltaic sediments in northern England (McCabe, 1977). The sets are interpreted to have been deposited by foreset accretion of side-attached alternate bars. Coleman (pers. comm. to McCabe) also reports similar morphological features 25-30 m high in the Mississippi River, although these do not have avalanche faces. If McCabe's (1977) interpretation is correct, individual giant cross sets can be deposited in a fluvial environment.

A similar origin for giant crossbeds observed in the Storelk is unlikely based on several lines of evidence. There is no evidence of channelization on any scale in the Storelk. There is also a lack of upward fining sequences characterized by a progressive upward decrease in set scale, as are reported from point bar and braided stream deposits (e.g. McGowen and Garner, 1970; Williams and Rust, 1969). Moreover, fluvial systems are characterized by an abundance of small bedforms (e.g. small dunes, ripples, climbing ripples), which are absent in the Storelk. Vertical accretion deposits characteristic of flood basins are also lacking in the Storelk. Thick (up to 23 m) laterally extensive structureless units like those in the Storelk are unknown from modern fluvial environments. A fluvial model also does not account for the presence of a laterally persistent marine horizon (the FC facies unit). Hence, the Storelk facies do not resemble modern and ancient fluvial deposits, and a fluvial origin is improbable.

5.3.4 Aeolian versus Shallow Marine Interpretation

The determination of whether the Storelk facies accumulated in an aeolian or a tidal dominated shallow marine environment is complicated by conflicting evidence.

Thus, the major lines of evidence must be weighed against one another to reach a plausible interpretation. Two opposing lines of argument could be advanced:

1. Certain characteristics of the Storelk facies favour an aeolian interpretation: the abundance and giant scale of the crossbedding, the angle of inclination of the foresets, the lack of body or trace fossils, and the presence of multiple parallel truncation surfaces. In this case, the presence of the thin fossiliferous marine FC facies unit requires special interpretation.

2. Alternatively, the presence of the FC facies unit could be taken to indicate that the entire sequence is marine, in which case the characteristics named in (1), especially the giant crossbedding, would require interpretation in a marine context. However, basing an interpretation of the entire Storelk sequence on the presence of a single marine horizon would have to be assessed.

Aeolian Interpretation: Consideration of the Evidence

The most important evidence supporting an aeolian origin for the Storelk sequence is the abundance of giant scale crossbedding. Abundant sets at least as thick as those observed in the Storelk are characteristic of interpreted ancient aeolian examples (e.g. Walker and Harms, 1972; Sanderson, 1974). Cross stratification of the scale observed in the Storelk is not known from known modern tide-dominated shallow marine environments (evidence discussed below).

The lack of development and preservation of angle of repose foresets is common in aeolian environments. In the Storelk Formation, the maximum observed foreset dip was 29 degrees, while most foresets had dips in the 10-25 degree range. By comparison, the angle of repose for dry sand in air is about 34 degrees (Bagnold, 1941, p.201). The relatively low angle dips in the Storelk may be due in part to post-depositional compaction. For example, Walker and Harms (1972) calculate that if an initial porosity of 40% is reduced to 20%, a 34 degree dip angle would be reduced to 27 degrees. This mechanism, however, does not account for dip angles less than this. Observations from both modern and ancient examples suggest that lower dips are the result of primary depositional mechanisms, and that mass avalanching is not the only means of foreset accretion. The lower slopes of many modern dunes accrete as a result of sand being driven laterally along the face by variable winds (Walker and Harms, 1972). Since the lowermost part of the dune is preferentially preserved, foresets with low dip angles would be characteristic of ancient deposits. Foresets accreting by this means should be characterized by wind ripples with crests aligned approximately parallel to the direction of maximum foreset dip. These were not observed in the Storelk, perhaps because large foreset faces were not seen, and because low amplitude wind ripples are difficult to discern except under low angle light conditions.

The development of intermediate dips (10-25 degrees) does not appear to be characteristic of shallow marine environments, where a similar primary mechanism does not operate. In these environments, only very gentle dips (less than 6 degrees) or angle of repose dips are common on bedforms (see below).

The absence of marine fauna in all Storelk facies except the FC facies unit suggests that the sequence is dominantly non-marine. A lack of fossils in the cross-bedded facies is not surprising since fauna would have been swept away by current activity. However, there is no evidence for such physical constraints in the SS facies, which, if marine, would be expected to contain some preserved fossils as does the ST facies of the Tyrwhitt and Tobermory Formations.

The unmottled texture of the SS facies suggests that faunal reworking cannot be invoked to explain the structureless condition as it was in the case of the marine ST facies. The absence of faunal bioturbation is often cited as evidence for an aeolian interpretation, although bioturbation is reported from modern dunes (Ahlbrandt et al., 1978) and from some ancient aeolian deposits (e.g. Picard, 1977). Trace fossils apparently require special conditions of preservation in aeolian sands (e.g. cohesive sand, reinforcement of burrow walls; Ahlbrandt et al., 1978). However, when they are preserved, trace fossils are minor features in ancient aeolian sediments. The absence of faunal bioturbation in shallow marine sediments is clearly anomalous, especially since trace fauna were so prolific during Tyrwhitt and Tobermory sedimentation. There is no evidence of physical constraints on faunal activity in the SS facies, unless it is hypothesized that water conditions were abnormal (e.g. arguments by Freeman and Visher, 1975). Therefore, the lack of evidence for trace fauna is a feature more indicative of an aeolian environment.

The Storelk sequence is characterized by multiple horizontal truncation surfaces. Since the truncation surfaces at the tops of Intervals are apparently widespread, it is suggested that each was formed by a single mechanism operating over a wide area. Truncation surfaces are characteristic of ancient aeolian deposits (e.g. Sanderson, 1974), and are interpreted to be forming in modern aeolian settings (Brookfield, 1977), although they cannot be documented directly. Stokes (1968) interprets them to be deflation surfaces, the level of which is controlled by the water table. Other authors attribute the surfaces to migration of large bedforms (McKee and Moiola, 1975; Brookfield, 1977). The relative importance of these is discussed later.

The formation of similar extensive surfaces in shallow marine environments is difficult to explain. Freeman and Visher (1975) suggest that truncation surfaces may form with a lowering of wave base over the tops of tidal ridges during heavy weather. Steidtmann (1977) notes, however, that short term processes such as this would cause local discontinuous truncation surfaces, and not widespread continuous truncation (like that in the

Storelk).

If the preceding lines of evidence are accepted as favouring an aeolian interpretation for the bulk of the Storelk sequence, then the marine FC facies unit must be interpreted in this context. The lateral persistence of of the unit indicates that the marine incursion was fairly widespread, at least in a N-S direction. The lithology of the unit (sandy dolomite and dolomitic sand) suggests that sand supply was restricted, in contrast to the abundant sand supply evident in the Lower Storelk Megaplanar Interval stratigraphically below. If sand supply were restricted, it is probable that wave and storm processes degraded the shoreline at a greater rate than it could be rebuilt, resulting in a temporary transgression. The transgression was not substantial, since the marine horizon is thin. Moreover, it is abruptly succeeded by the aeolian Middle Storelk Megatrough Interval without intervening foreshore sediments, suggesting rapid shoreline progradation into shallow water. The presence of brachiopods does not necessarily imply relatively deep water. Stevens (1971) states that some Pennsylvanian brachiopods (including Spiriferids) were capable of living nearshore and almost onshore in the Minturn Formation of Colorado (the Storelk Spiriferids are too poorly preserved to be identified to species level for direct comparison).

Shallow Marine Interpretation: Consideration of the Evidence

It was previously postulated that the FC facies might indicate a shallow marine origin for the entire Storelk sequence. On the other hand, it was shown that the presence of a thin marine horizon is not necessarily detrimental to an aeolian interpretation. Nevertheless, there are two morphological features observed on modern tide dominated shelves that some authors consider to be models for bedforms that deposit giant crossbeds: tidal current ridges and "sand waves". The merits of this require special consideration.

Tidal current ridges have been described from the North Sea by various authors (Stride, 1963; Houbolt, 1968; Caston, 1972). They are described as large sand banks 30-40 m high, 1-2 km wide and 20-60 km long (data from Houbolt, 1968) and oriented parallel to tidal flow. Sparker sections across the features show that they are asymmetrical, and apparently contain steep internal stratification surfaces resembling large foresets. However, the profiles published by Houbolt (1968) are vertically exaggerated, and calculations demonstrate that the "steep" faces of the ridges dip an average of only 5 degrees (Walker and Middleton, 1977; 4-7 degrees calculated by Caston, 1972). The reflections from the apparent stratification planes may be from erosion surfaces or clay layers, and are not foresets in the sense of those in dunes.

"Sand waves" are reported from the North Sea (McCave, 1971a; Terwindt, 1971) and the Atlantic Shelf (Jordan, 1962; Swift, 1975). North Sea "sand waves" have heights up to 7 m and wavelengths of 200-500 m. Some are asymmetrical, and the "steep" slopes shown on profiles of the bedforms are only about 5 degrees. On Georges Bank, "sand waves" have heights up to 13 m, but the "steep" faces of the bedforms dip only 2-3 degrees. Dips of 18-20 degrees are recorded from "sand waves" up to 10 m high on Cultivator Shoal, representing the steepest recorded examples (Walker and Middleton, 1977).

The low dip angles of the "steep" faces of tidal sand ridges and most "sand waves" suggest that these are unsuitable models of bedforms that deposit giant crossbeds with foreset dip angles between 10 and 25 degrees. A possible exception is the "sand waves" on Cultivator Shoal, although it has not been demonstrated that these are composed of large foresets. Most studies indicate that megaripples cover tidal current ridges and "sand waves" (e.g. Houbolt, 1968; McCave, 1971a). Hence, it is probable that these features are composed of abundant medium scale crossbedding (Walker and Middleton, 1977; Johnson, 1977). This interpretation, if true; suggests that recent reinterpretations of "classic" aeolian deposits (e.g. Pryor, 1971; Freeman and Visher, 1975) are unfounded. It would appear that for the most part, bedforms produced in tide dominated shallow marine environments either have gentle "lee" slopes (less than about 6 degrees) or angle of repose slopes (on megaripples), and do not deposit abundant crossbeds containing foresets with intermediate (10-25 degree) dips.

If the Storelk sequence were deposited by reversing tidal currents, there should be some evidence of reactivation surfaces and bipolar paleoflow. No reactivation surfaces were observed. Apparent bipolar paleoflow was observed in an isolated case (MS 2: Upper Storelk Crossbed Interval; Section 4.2.5), but this cannot be taken to imply a tidal origin for the entire Storelk sequence. A tidal hypothesis also does not account for the apparent bimodal distribution of foreset dip azimuths observed in the Lower Storelk Megaplanar Interval (Section 4.2.2). Preservation of a unidirectional paleoflow configuration, like that in the Middle Storelk Megatrough Interval (Section 4.2.3), may be possible under some circumstances in a tide dominated environment. This would involve cases where one tidal current direction dominates over another, or where unidirectional storm generated currents are superimposed on tidal currents (Johnson, 1977). However, some evidence of bipolar flow would be expected laterally, which is not the case in the Storelk. The Middle Storelk Megatrough Interval can be traced laterally at least 8 km without noticeable variation in paleoflow direction.

A final argument against a tidal current origin for the Storelk facies can be advanced with reference to the context of the Storelk relative to the Tyrwhitt and Tobermory Formations. In the latter Formations there is no definitive evidence for tidal currents. It would be difficult to explain why tidal currents would become so effective during Storelk time, when tidal current effects could not be discerned in sediments deposited before and after Storelk deposition.

Conclusion

The lines of evidence presented above strongly favour an aeolian interpretation for the Storelk facies.

In short, a tide dominated shallow marine interpretation cannot satisfactorily explain the abundance of giant crossbedding, the common intermediate foreset dips on the crossbeds, the absence of body or trace fossils, the presence of laterally extensive truncation surfaces, or the observed paleoflow configurations. Each of these features can be interpreted in the context of aeolian sedimentation.

5.4 INTERPRETATION OF FACIES IN THE STORELK FORMATION: COMPARISON WITH MODERN AND ANCIENT EXAMPLES

5.4.1 Problems Involved in the Interpretation

Direct comparison between modern and ancient aeolian deposits is complicated by the current limited knowledge of the internal structure of modern dunes. This reduces the confidence with which dune type can be determined through matching sedimentary structures in ancient examples with those in modern examples. In the most recent review of aeolian sediments, Walker and Middleton (1977) were able to identify an assemblage of characteristic features of aeolian deposits. However, they failed to ascertain any preferred sequence of sedimentary structures or consistent lateral changes that could be used to identify ancient dune types. Similar problems are addressed in this thesis, and even though similarities can be found between the Storelk example and modern examples, no comprehensive attempt will be made to identify ancient dune types.

Wilson (1972) has identified two mutually exclusive classifications of large aeolian bedforms which can be divided into transverse and longitudinal elements: draas and dunes. The internal structures of draas are virtually unknown from direct investigation. Their complex external form is a poor indicator of the configuration and orientation of internal structures, which may be simpler than would be expected (Walker and Middleton, 1977). Studies of the internal structures of dunes are inhibited by the problems of adequate trenching, and have been restricted to relatively small desert dunes (e.g. McKee, 1966; McKee and Tibbitts, 1964) and various forms of coastal dunes (e.g. Bigarella et al., 1969; Goldsmith, 1973). Structures observed in studied desert dunes may not be typical of those preserved in ancient examples. For example, McKee (1966) was able to trench various dune types in New Mexico, but these were composed of gypsum sand which is relatively easily stabilized by rainfall. Hence the observed dune stratification may not be typical of quartz sand dunes, although documentation of the structures is an invaluable aid, and has been used successfully in matching certain modern and ancient dune types (Thompson, 1969). The internal structure of some other dunes is only known from surface trenching (e.g. McKee and Tibbitts, 1964). These, however, may not be representative of the deposits of the lower parts of dunes, which are most likely to be preserved. The deposits of interdune areas contain eroded remnants of dunes, and hence are more likely to contain structures analogous to those found in ancient deposits. Interdune deposits have not been studied in detail except for a brief note by McKee (1966).

In the absence of a comprehensive knowledge of dune stratification, much of this information must be inferred from the ancient record. Hence, the modern and ancient cannot be divorced from one another during comparison with the Storelk facies. The salient characteristics of interpreted ancient aeolian deposits from the U.S.A., Great Britain and South America are compared with those of the Storelk in Table 5.1. Several aspects of this Table will be elaborated below, including the abundance, scale and geometry of cross stratification, dip angles of the foresets, presence of a laterally extensive structureless Interval, presence of multiple truncation surfaces and

Table 5.1 Comparison of characteristics from Storelk and other interpreted ancient aeolian deposits (modified and expanded from Walker and Middleton, 1977)

FORMATION	AGE	APPROX. MAX THICKNESS (m)	CROSSBED THICKNESS (m)	DIP OF CROSSBEDS (DEGREES)	TYPE OF CROSSBEDS	REFERENCE
STORELK	PENNSYLVANIAN	100	Planars up to 10; troughs up to 6	10-25 (max. 29)	Tabular and wedge shaped planar; trough	
1. CASPER (U.S.)	PENN.-PERM.	240	15 (min.) (305 m wide, several times as long)	15-25	Mostly trough	Steidtmann (1974); Knight (1929, in Walker and Middleton, 1977)
2. COCONINO (U.S.)	PERMIAN	330	"huge"	25-30	Wedge shaped sets	Baars (1962)
3. CEDAR MESA (U.S.)	PERMIAN	450	up to 30	up to 25 sweeping toesets	Mostly planar tabular	Baars (1962)
4. DE CHELLY (U.S.)	PERMIAN	330	up to 35	15-35	Simple planar tabular sets	Baars (1962)
5. ENTRADA (SLICK ROCK MEMBER) (U.S.)	U. JURASSIC	280	up to 8		"Wedging sets" "Sweeping aeolian crossbeds"	Craig and Shaw (1975)
6. LYONS (U.S.)	PERMIAN	40	up to 13	commonly 25 max. 28	Mostly planar tabular	Thompson (1948) Walker & Harms (1972)
7. NAVAJO (U.S.)	L. JURASSIC	700	Planars up to 15; troughs up to 6	20-30 long toesets	Lower part: mostly planar tabular Upper part: mostly troughs	Sanderson (1974)
8. WHITE RIM (U.S.)	PERMIAN	200	up to 20	19-27 long toesets	Mostly planar tabular	Baars and Seager (1970)

Table 5.1/continued

FORMATION	AGE	APPROX. MAX THICKNESS (m)	CROSSBED THICKNESS (m)	DIP OF CROSSBEDS (DEGREES)	TYPE OF CROSSBEDS	REFERENCE
9. WINGATE (U.S.)	U. TRIASSIC	130	up to 15	up to 30		Dane, 1935
10. BOTUCATU SANDSTONE (BRAZIL-URUGUAY)	TRIASSIC	320	Commonly less than 2 m; some 12-15 m	up to 33 (20 common)	Trough; some planar tabular	Bigarella and Salamuni, 1961; Bigarella, 1972
11. YELLOW SANDS (N.E. ENGLAND)	PERMIAN	35	0.25-3	18 (av.)	Trough; minor planar with convex up foresets	Pryor, 1971
12. CHUSKA SANDSTONE (U.S.)	TERTIARY	520 (usually 150-360)	1.5-4.5	15-25 (some more than 34)	"Concave up" sets	Wright, 1956
13. NEW RED SANDSTONE (SCOTLAND)	U. CARB. - TRIASSIC	300 (min.)	up to 15	Approx. 30	Trough	Piper, 1970
14. NEW RED SANDSTONE (EXE GP.) (ENGLAND)	PERMIAN	230	up to 9 (60 m wide)	Max. 33	Wedge planar; some trough and tabular	Laming, 1966
15. SLIEVE MISH GP. (IRELAND)	DEVONIAN	200	1-12	up to 43 long toesets	Planar tabular	Horne, 1971
16. "KEUPER" SANDSTONE FRODSHAM MBR. (ENGLAND)	TRIASSIC	55	up to 13 (commonly less than 1.5 m)	10-20	Wedge and tabular planar; minor troughs convex upward foresets	Thompson, 1969
17. NO FM. NAME (LOCH-ARBRIGGS, SCOTLAND)	PERMIAN		Approx. 1-7 (measured from drawings)	Max. 26	Planar tabular; wedge planar; minor trough	Brookfield (1977)

paleoflow data.

5.4.2 <u>Set Scale</u>

The maximum thicknesses of crossbeds in the Storelk are comparable with those in other interpreted ancient aeolian deposits (Table 5.1). In the latter, however, cross stratification may attain much greater maximum thicknesses (e.g. 3, 4, 8; Table 5.1). Since only the lower part of a dune is favoured for preservation, the original bedforms could have been substantially higher than the maximum preserved thickness in each case.

Most authors emphasize the thickest sets, although most ancient examples contain crossbeds with a wide range of set thicknesses like that observed in the Storelk. In some (e.g. 10; Table 5.1), the relatively smaller sets may dominate.

Crossbed thicknesses measured in modern desert dunes are somewhat less than their ancient counterparts. The maximum set thickness observed at White Sands National Monument, U.S.A., is 6 m (McKee, 1966). These dunes, however, are relatively small (maximum 12 m high) relative to other modern dunes which have heights up to 100 m, and draas which have heights up to 450 m (Wilson, 1972). The thicknesses of crossbedding in the largest bedforms are unknown, but in view of their scale they must be capable of depositing cross stratification at least as thick as that observed in ancient examples.

5.4.3 Set Geometry

Trough, planar tabular, and wedge shaped planar crossbeds similar to those in the Storelk are very common in ancient examples (Table 5.1). Planar crossbeds appear to be the most common, and either dominate or are the sole set type in many examples (3, 4, 6, 8, 15; Table 5.1). Trough crossbeds are relatively less common, although they may dominate a sequence (1, 10; Table 5.1), or dominate a particular part of the sequence (7; Table 5.1) as in the Storelk Formation.

Planar sets in most ancient examples are composed of cross strata that can be traced vertically up to tens of meters without discontinuities or changes in dip (e.g. Lyons Sandstone; Walker and Harms, 1972). The Storelk megaplanar sets can be similarly traced up to 10.15 m. A prominent feature in both the Storelk and other examples (e.g. 3, 7, 8; Table 5.1) is long toesets that intersect the lower bounding surface asymptotically (Figure 3.31). Often this is the only portion of the set preserved. Walker and Middleton (1977) suggest that these toesets aggrade into thicker and longer sets than those formed subaqueously.

Planar tabular sets are the most abundant set type at White Sands, being common in all studied dune types (McKee, 1966). Two classifications of tabular sets were established: those with subhorizontal bounding surfaces formed in the upper parts of dunes, and those with moderately to steeply dipping bounding surfaces formed in the lower and downwind portions of dunes. The latter bounding surfaces are attributed by McKee (1966) to increases in wind velocity. They were not observed in the Storelk, and have only been seen in a few ancient examples (16, 17; Table 5.1). Hence, wind velocity during deposition of a single Storelk set was either fairly constant, or the bounding surfaces went unrecognized because crosslaminae above and below them dipped at equal angles.

Wedge shaped sets are apparently most common in areas of variable wind direction (McKee, 1966), but their formation also depends on dune shape. Such sets are common in the upper parts of seif dunes, where wind is dominantly bidirectional (McKee and Tibbitts, 1964). Wedge shaped sets are also common in parabolic dunes, which is probably a function of the sinuous shape of the crest. Modern transverse dunes may also have somewhat sinuous crests, so wedge shaped sets might be expected to form in these types as well.

In some of the megaplanar sets of the Lower Storelk, foresets are convex upward (Figure 3.33). Similar configurations have been observed in parabolic dunes at White Sands (McKee, 1966), and in precipitation ridge dunes on the coast of Brazil (Bigarella et al., 1969). Convex-upward foresets form in the latter because of sand stabilization by high humidity and vegetation effects. The cross sets in this case are too small in scale, however, (1-2 m) to be comparable to the Storelk example. McKee (1966) attributes the convex-upward configuration in parabolic dunes to dune shape, since the slip face is exposed to cross winds by the protruding front margin of the dune. Cross winds undermine the base of the slip face and oversteepen the lower part. Parabolic dunes are common in coastal areas, which is the geographic location suggested by the position of the Lower Storelk Megaplanar Interval (which contains the set) immediately above the shallow marine Tyrwhitt sequence. Hence it is conceivable that parabolic dunes were active during Lower Storelk deposition, and these may have deposited the observed convex-upward sets.

The Storelk megatroughs are inferred to be broadly concave upward, and to have a broad lateral curvature. Thus, differentiation between these and planar sets can be subtle unless the lower curved set boundary is exposed. This configuration is common in other ancient examples. Knight (1929, cited in Walker and Middleton, 1977) reported trough sets that were very wide (up to 305 m) relative to their depth (up to 15 m). Sanderson (1974) noted a similar configuration for trough sets in the Navajo Sandstone, which he attributed to deposition by transverse dunes with crescentic reentrants. The subtlty of distinction between megatrough and megaplanar sets may explain the relative scarcity of the former in the literature.

Trough crossbeds are relatively uncommon in the dunes at White Sands, where they form largely along dune crests as blowout features. These would have low preservation potential, and are highly unlikely to be analogous to those seen in the Storelk and other ancient examples. Brookfield (1977) asserts that trough cross stratification may form in front of a sinuous crested aklé dune or draa ridge in a manner analogous to deposition of trough cross-bedding in front of sinuous crested subaqueous ripples and dunes. This is the only reasonable interpretation of the mechanism of formation of the megatrough and large scale trough facies. It can also be concluded that during certain periods of Storelk deposition, sinuous crested bedforms were the only type present (e.g. during deposition of the Middle Storelk Megatrough Interval). Mixed megatrough and megaplanar crossbeds (e.g. Upper Storelk Crossbed Interval) imply that sinuous and straight crested bedforms coexisted during the same time period.

5.4.4 Dip of Foresets

The dips of foresets of cross stratification in the Storelk Formation generally range between 10 and 25 degrees. This range compares well with foreset dips recorded from almost all other interpreted ancient aeolian examples (Table 5.1). No examples of oversteepened foreset dips greater than the angle of repose (34 degrees) were observed in the Storelk, as in the case of some ancient examples (15; Table 5.1). Oversteepened foresets are generally attributed to wetted sand which is cohesive under action of surface tension, permitting development of higher slope angles (Bigarella, 1972). This situation is common in coastal dunes (McBride and Hayes, 1962; Land, 1964).

The mechanism contributing to the abundance and preservation of moderately dipping foreset strata was reviewed previously (Section 5.3.4).

5.4.5 Paleoflow Data and Source of Winds

A general comparison between the paleoflow configurations of the Storelk Formation and other interpreted ancient aeolian examples of similar age permits identification of the types of winds involved. Then, two other important aspects of the Storelk paleocurrent data can be evaluated: the stratigraphic separation of different paleoflow configurations, and a corresponding vertical variation in set type.

Source of Winds: in an overall sense involving paleoflow data from the entire Storelk Formation, a dominant paleowind component from the NNE to the SSW is indicated by the grand vector mean azimuth (196 degrees; S.D. = 68 degrees; n = 356 measurements). This paleoflow configuration is similar to observed paleoflow patterns from Permo-Pennsylvanian Formations with interpreted aeolian origins from the southwestern U.S.A. (Opdyke and Runcorn, 1960; Poole, 1962).

These authors, and others (Bigarella and Salamuni, 1961), have noted widespread consistencies in wind directions recorded from ancient examples, and have attributed the observed paleoflow configurations to paleotradewind belts. Modern tradewinds blow between about 20 degrees N latitude and 20 degrees S latitude, except in the monsoon belt of India. In the northern hemisphere, tradewinds blow dominantly from NE to SW. On the continents, topographic and seasonal effects may modify the wind pattern (Opdyke and Runcorn, 1960). The major assumption made is that similar tradewind belts existed in the past, although there may have been some degree of latitudinal variation due to different temperature gradients between equatorial and polar regions, and a difference in the angular velocity of the earth in the past.

The Permo-Pennsylvanian paleoequator passed obliquely through the southwestern U.S.A. (Opdyke and Runcorn, 1960; Seyfert and Sirkin, 1973), placing the U.S. examples in the northern hemisphere (Figure 5.2). When the approximate 30 degree clockwise rotation of North America relative to its present orientation is taken into account, the general SSE-SW paleoflow directions for the U.S. examples fall between south and west. Opdyke and Runcorn (1960) conclude that these paleoflow directions correspond to inferred NE paleotradewinds of the northern hemisphere. The merits of this cannot be

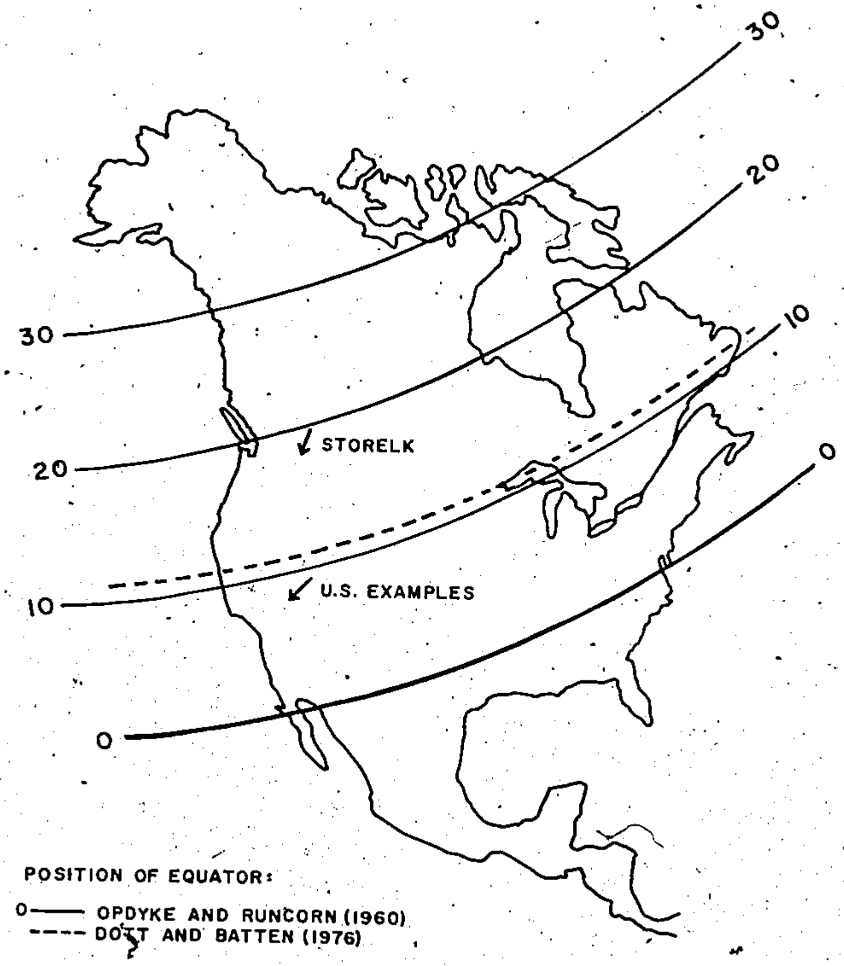


FIGURE 5.2

POSITIONS OF AEOLIAN EXAMPLES RELATIVE TO PENNSYLVANIAN PALEOEQUATOR fully assessed until the precise position of the paleo-equator is determined. Dott and Batten (1976) tentatively place the paleoequator about 10 degrees further north, which would put the U.S. examples in the southern hemisphere. Whatever the actual position of the paleoequator, the geographic location of the Storelk Formation is about 10-20 degrees north (Figure 5.2), and hence it would be within a postulated tradewind belt. Assuming that the U.S. examples were in the northern hemisphere during the Permo-Pennsylvanian, it is suggested here that the similarity of paleoflow directions between the Storelk and U.S. examples is the result of their locations within the same paleotradewind belt. Thus, the paleoflow configurations represent prevailing tradewind patterns. To test the validity of this assertion, it would be necessary to establish a more regional paleoflow picture for the Storelk, since measurements were made only in a small area.

Some authors stress the importance of storm winds, which may dominate over prevailing winds for short periods (e.g. Sharp, 1966) or impart a second wind mode unrelated to prevailing winds. Bigarella (1972) asserts that this may be true for local areas, but the consistency of wind direction recorded from ancient examples over wide areas indicates the long term dominance of prevailing winds. For example, paleowind directions are consistent over more than 1600 km for Permo-Pennsylvanian sandstones in the southwestern U.S.A., and over more than 2500 km for the Botucatu Sandstone of Brazil. The dominance of prevailing winds is supported by Goldsmith (1973) who found that dip azimuth distributions for coastal dunes correlated with prevailing winds rather than with the dominant (storm) winds.

Stratigraphic Separation of Different Paleoflow Configurations: the Storelk sequence is characterized by different configurations of paleoflow at different stratigraphic levels (Figure 5.1). In the Lower Storelk Megaplanar Interval, winds apparently blew dominantly from WNW to ESE, and from NNE to SSW (Figure 5.1; Section 4.2.2). The Middle Storelk Megatrough Interval is characterized by a unimodal distribution, where winds blew dominantly from NE to SW (Figure 5.1; Section 4.2.3). During deposition of the Upper Storelk Crossbed Interval, wind direction was apparently more variable, and winds blew over a broad arc. The grand vector-mean for all data from this Interval (191 degrees; S.D. = 71 degrees; Section 4.2.5), however, suggests an average wind component from the NNE to the SSW. Hence it is evident that the southeasterly directed (NW) wind component that prevailed during deposition of the Lower Storelk Megaplanar Interval became active again after its apparent disappearance, during deposition of the Middle Storelk Megatrough Interval.

As previously suggested, the overall SSW directed Storelk paleoflow component could be the result of deposition under the influence of prevailing paleotradewinds. The presence of southeasterly directed paleoflow components in two of the Storelk Intervals, however, suggests that there was considerable variability in the wind regime. Bigarella (1972) states that seasonal variations in wind direction are characteristic of low latitude deserts due to alterations of temperature distribution by the oceans and continents. It is possible that a regular seasonal shift of the wind from the NE to the NW quadrant is responsible for the two well separated paleoflow directions recorded in the Lower Storelk Megaplanar Interval. Less regular seasonal shifts, perhaps combined with topographic effects, could be the cause of the wide spread in paleoflow directions in the Upper Storelk Crossbed Interval. This possibility, however, is speculative.

The common case in the Lower Storelk Megaplanar

Interval where vertically adjacent sets are oriented towards each of the two dominant paleoflow directions is unlikely to strictly represent a succession of dunes deposited in different seasons. For large bedforms, there is a long lag time between a change in wind direction and subsequent modification of the bedform. It is possible that once a dune nucleates under one prevailing wind, it retains the slip face orientation imparted on it despite later shifts in wind direction. This situation would be because the second wind is neither long enough in duration, nor does it have a sufficiently large angular displacement relative to the original wind direction to substantially modify the bedform. Hence, a dune could grow until it is deflated or buried by other bedforms, preserving the original paleoflow direction. If the above growth sequence were followed by the Storelk bedforms, there should be reactivation surfaces in the sets. These were not observed, possibly because of problems of recognition discussed earlier.

The paleoflow configuration in the Middle Storelk Megatrough Interval is consistent with the inferred paleo-tradewind direction, but evidence for a southeasterly paleoflow component is almost lacking. Sharp (1966) notes that thick deposits of ancient aeolian sandstones involve a long time of accumulation, and hence have a high probability of experiencing a meteorological change. Possibly, a temporary climatic change eliminated the regular seasonal wind shift, so that only the dominant SW directed paleotradewind component prevailed.

Up to this point, it has been assumed that the variation in crossbed orientation is a direct result of variation in wind direction. Under some circumstances, certain types of dunes may be characterized by differently oriented cross stratification even though the dunes developed under a dominantly unidirectional wind regime.

Coastal dunes often exhibit bimodal dip azimuth distributions, where the dominantly unimodal wind vector bisects the modes (Goldsmith, 1973). The crossbedding with this orientation pattern is attributed to "pyramidal wind shadow dunes", first described by McBride and Hayes (1962). The observed coastal dunes are composed of cross stratification less than 1 m thick, which resembles sets from the LT and LP facies. It is unlikely that similar dunes were responsible for depositing the crossbeds in the Lower Storelk Megaplanar Interval, since sets with thicknesses comparable to those in the MP facies have not been observed in modern coastal dunes.

Bimodally orientated crossbeds may also be deposited in longitudinal dunes, which can develop parallel to a unidirectional wind (Hanna, 1969). The dunes grow as sand is blown across the crest alternately from one side to the other. The resultant cross stratification could be similar to that observed near the dune crest by McKee and Tibbitts (1964). The dune studied by them grew by a similar process, except that bidirectional winds were involved. The observed crossbeds were wedge shaped and oriented in nearly opposite directions approximately normal to the dune crest. The paleocurrent pattern seen in the Lower Storelk Megaplanar Interval is unlikely to be the result of this process, since the dominant paleoflow azimuths have an angular separation of 83 degrees, not close to 180 degrees. Similarly, bipolar dip azimuth distributions were not observed in the Upper Storelk Crossbed Interval, except in one case described below.

An apparent bipolar dip azimuth distribution was observed in measured section 2 (170-181 m; described in Section 4.2.5). If the opposed crossbed dip azimuths were interpreted to be the result of opposed wind directions, then it would have to be hypothesized that substantial airflow modification about local topography occurred at this locality. Hence the crossbedding in this part of the measured section is interpreted to be the result of deposition in a different dune type than those observed laterally. The type of crossbedding and paleoflow pattern resemble that observed in modern longitudinal dunes by McKee and Tibbitts (1964), and conform to the model for such dunes suggested by Glennie (1970, p.85). The preservation of a vertical sequence of oppositely oriented sets would require that the longitudinal dune shifted laterally as it grew at the downwind end. Modern longitudinal dunes apparently do not do this, and it is not known whether the structures observed in surface trenches conform to those deeper in the dune. In spite of these uncertainties, the interpretation of a longitudinal dune in this case is more likely than interpreting the NE dipping sets to be upwind dipping strata, which have low preservation potential.

<u>Comparison to Other Ancient Examples</u>: a direct comparison of the consistency of configurations of paleoflow between the Storelk and other ancient aeolian deposits is not possible except in a generalized way. For the Storelk Formation, paleocurrent data were subdivided according to set type and scale, as well as stratigraphic level within the Formation. Other authors tend to group together all types of crossbedding, omit cross strata with

dips less than 10 degrees in some cases, and calculate a vector mean for the entire Formation. The analysis of cross stratification in other ancient examples (principally by Reichie, 1938, and Opdyke and Runcorn, 1960) generally indicates a unimodal pattern, with a standard deviation of 38-76 degrees. Treatment of the Storelk data in the same manner yields a similar pattern with a comparable standard deviation of 68 degrees.

At the Interval level, however, the Storelk data show that variations from this basic pattern are possible. The narrow spread of megatrough dip azimuths in the Middle Storelk Megatrough Interval demonstrates that deposition of crossbeds with highly consistent orientations is possible in the aeolian environment. Also, the bimodal paleoflow distribution inherent in the Lower Storelk Megaplanar Interval has not been observed in any other ancient example, presumably because of the method of data treatment normally employed. This stratigraphic separation of different paleoflow configurations is rarely documented in other ancient aeolian examples. However, Sanderson (1974) reports changes in paleoflow configuration upward within the Navajo Sandstone, and uses this as a criterion for correlation between sections.

Vertical Variation in Set Type: the Storelk sequence is characterized by different facies associations at different stratigraphic levels, which is the basis for dividing the succession into Intervals (Figure 5.1). In the Lower Storelk Megaplanar Interval, the MP-LT(LP) facies association developed in response to a bidirectional wind regime. The MT-LT facies association of the Middle Storelk Megatrough Interval formed in response to a unidirectional wind regime. In the Upper Storelk Crossbed Interval, an MP-MT-LT-LP facies association (i.e. essentially a combination of associations from the lower two Intervals) developed in response to a more variable wind regime. This vertical variation suggests a connection between the type of wind regime and the types of bedforms that are produced (and hence the type of cross stratification that is produced). It appears that under certain wind regimes, specific large bedform types (depositing megaplanar or megatrough sets) grow to equilibrium. Moreover, the bedform type that is produced persists over a large area, as is demonstrated by the lateral consistency of the facies association in each Interval. The relatively small bedforms that deposited the LT and LP facies, however, appear to develop in all types of wind regimes. Their formation could be related to wind strength rather than wind configuration.

Vertical variations in set type and paleoflow configuration have also been observed in the Navajo Sandstone (Sanderson, 1974). Trough crossbeds dominate the upper part of the sequence, whereas planar crossbeds dominate the lower part. However, from Sanderson's (1974) data, there is no obvious correlation between set type and paleoflow configuration.

5.4.6 Summary

The preceding discussion compares Storelk cross stratification to that of modern and ancient examples. A comprehensive interpretation of the bedform types or sedimentary processes active during Storelk time is not possible due to the problems outlined in Section 5.4.1. The following summarizes the pertinent points:

1. The Storelk crossbeds are similar in scale and geometry to those known from other ancient examples, and to those known or inferred from modern examples.

2. Certain features of the Storelk crossbeds are comparable to features in modern dunes (e.g. convex upward foresets and bipolar oriented wedge shaped planar sets). These are tentatively used to suggest bedform type.

3. The moderate (10-25 degree) foreset dips in the Storelk are comparable to those in modern and other ancient examples, and probably result from foreset accretion by sand blowing across the foreset face.

4. The Storelk paleoflow configuration suggests control by prevailing tradewinds. Seasonal variation is a possible explanation for deviations from the general SSW directed paleoflow.

5. The gross Storelk paleoflow configuration is comparable to that of other ancient aeolian examples. Specific Storelk features (highly consistent unidirectional paleoflow, bidirectional paleoflow at certain stratigraphic levels), are generally unrecognized in other ancient examples.

6. The vertical changes in facies association in the Storelk suggest that specific types of large bedforms can be correlated with certain types of wind regimes.

5.4.7 Thick Laterally Extensive Structureless Intervals

Thick structureless intervals similar to the SS facies in the Storelk have only been reported in one other ancient aeolian deposit: the Navajo Sandstone (Sanderson, 1974). Sanderson describes the units as being apparently structureless from field observation, although highly deformed and dislocated relict stratification is evident in X-radiographs. The units are usually vertically transitional upward from thick units of contorted stratification, and are overlain by a major bedding plane above which is undisturbed cross stratification. In some cases structureless intervals directly succeed undisturbed cross strata, in which case the lower contact is a major bedding plane. Sanderson (1974) interprets the structureless condition to be the result of intense penecontemporaneous deformation which destroyed the laminae, on the basis of the X-radiograph data and close association with the large scale contorted stratification. He asserts that deformation occurred in water saturated or wetted sand, and is a large scale counterpart of deformation produced experimentally by McKee *et al.* (1971).

The possibility of a similar origin for the SS facies requires invoking temporary abnormal conditions which apparently did not prevail during the deposition and preservation of most of the Storelk sequence. This mechanism is, however, the only documented one which can produce thick, apparently structureless intervals, even though it has not been observed in the modern environment.

X-radiographs of Storelk samples do not reveal the deformed laminae noted by Sanderson (1974). The grain size in the Navajo Sandstone ranges from very fine to medium, and laminae are well defined because of grain size segregation (Sanderson, 1974, p.222). In contrast, the SS facies is dominantly composed of well sorted very fine sand, with subordinate zones of well sorted fine sand. It is possible that laminae are not visible in the SS facies because of lack of grain size segregation. In crossbedded parts of the Storelk which are similarly composed of well sorted very fine sand, laminae are frequently indistinct or are not visible.

The Storelk sequence lacks the thick zones of large scale contorted strata like those in the Navajo Sandstone, and there is no evidence of even small scale deformation like that reported in modern dunes (McKee, 1966; McKee and Bigarella, 1972). If, as Sanderson (1974) suggests, the flowage took place in water saturated or wetted sand, then special high groundwater levels would have to be assumed to have existed during certain periods of Storelk deposition and not others. Alternatively, high groundwater levels could have been present at all times during Storelk deposition, except that sand was fully water saturated about the time the SS facies sediments were being deposited, inducing mass flowage at this time and not others. It is unlikely that mass flowage would occur in dry sand, if experiments by McKee et al. (1971) can be extrapolated to large scale deformation. There is evidence that groundwater levels could have risen during deposition of the Lower Storelk SS Interval. In this case, sand supply was restricted, resulting in a marine transgression. The groundwater level would have risen correspondingly, providing water to induce mass flowage. There is no such evidence for the Middle Storelk Structureless Interval, however.

The lateral persistence of the SS facies (min. 8 km in a N-S direction) shows that if a rise in the water table was involved, it occurred over a wide area. Sanderson (1974) found that contorted and undisturbed cross stratification graded laterally into the structureless unit, and there is no evidence of lateral persistence of the latter like that in the Storelk.

The presence of argillaceous and siltstone zones within the SS facies is probably not related to the processes that formed the facies. Silt and clay dropped from suspension are common in interdune areas. The zones in the Storelk may have been originally present at the base of foresets prior to deformation of the cross strata. Had any of these zones been seen in three dimensions, they would presumably have been contorted laterally.

In summary, the concept of mass deformation being the cause of the structureless condition of the SS facies is based only on inference and speculation through comparison with another ancient example. There is no solid evidence confirming this process, and some of the features of the facies, particularly its lateral persistence, are difficult to explain. There are no known modern analogues for such large scale deformation. It will be shown below that known processes producing structureless sands in modern examples are not suitable for explaining the origin of the SS facies.

Bigarella (1972) states that internal structures of stabilized vegetated dunes on the Brazillian coast were probably lost because of heavy concentrated rainfall during a change in climate. It is unlikely, however, that this process could build up thick laterally extensive units like those in the Storelk.

McKee and Tibbitts (1964) observed structureless sand in interdune areas in Libya, but did not ascribe any particular origin to it. Brookfield (1977) states that interdune areas intercepted by the water table should show features of inland sabkhas. Structureless sand forms immediately below the sabkha surface when salt deposits deflate or dissolve, and the sand sinks into the sediment below. However, it is improbable that thick structureless sand deposits could be formed by this process, and no features typical of inland sabkhas (e.g. adhesion ripples, dessication cracks, sand dikes) were observed.

A third possibility is that structureless sand may be the result of floral and faunal bioturbation. This would necessitate a restricted sand supply to allow extensive reworking, and cohesionless sand so that the traces would not be preserved. In addition, for non-preservation of plant roots, it would have to be assumed that the groundwater was not mineral-rich (Glennie, 1970, p.117). Even if these special conditions were attained, they would have to had prevailed for a long time period to form thick deposits. Plants were not likely abundant because of the presumably dry desert conditions, and trace fauna were likely sparse because of a lack of organic matter which would be exploited for food. Hence, it is probably unreasonable to expect that this mechanism would account for the SS facies.

In conclusion, there is no completely satisfactory interpretation of the processes that formed the SS facies, based on what is known from modern environments and interpreted from ancient ones. Sanderson's (1974) proposed process is perhaps the best explanation, but its application to the Storelk has no firm base in the available evidence.

5.4.8 Multiple Truncation Surfaces

Multiple truncation surfaces are almost universal in interpreted ancient aeolian deposits. They are usually described as near-horizontal surfaces truncating sedimentary structures, and spaced about 0.5-15 m apart (Walker and Middleton, 1977). Their extent may be greater than 2.6 sq km (Stokes, 1968). By comparison, surfaces in the Storelk may be 2-10 m apart. Most cannot be traced between measured sections, but major surfaces at the tops of Intervals are present at similar stratigraphic levels over a distance of at least 8 km.

The truncation surfaces in the Storelk are mainly first order surfaces following Brookfield's (1977) classification. The dipping bounding surfaces of the wedge shaped sets would be considered second order surfaces. No third order (reactivation) surfaces were observed.

Brookfield (1977) asserts that first order bounding surfaces, especially those spaced more than a few meters apart, can only be attributed to the passage of draas. Draas are unlikely to have developed in the inferred coastal area of the Storelk paleodesert, since the bedforms tend to grow only in the upwind portions of ergs where sand supply is abundant. It is possible that the surfaces could be attributed to the passage of large dunes, but this cannot explain the apparent very widespread nature of the Storelk truncation surfaces.

The Storelk truncation surfaces could represent deflation surfaces developed in a similar manner to that inferred by Stokes (1968). Deflation would have occurred during periods when sand supply was relatively restricted, and the level of deflation would be controlled by the level of the water table. Since restriction in sand supply would affect a wide area, the deflation surface could be extensive. The significance of the fact that the truncation surfaces are overlain by the SS facies is unknown.

5.4.9 Commonly Cited Evidence for an Aeolian Interpretation not Observed in the Storelk

The presence of certain minor sedimentary structures considerably strengthen an aeolian interpretation when they occur in association with abundant giant crossbeds. The most important of these, documented in the Lyons Sandstone (Walker and Harms, 1972) include wind ripples, raindrop impressions, animal tracks, avalanche structures and grain lag layers. All of these except the latter would be preserved on the foresets of the crossbeds, which were rarely exposed in the Storelk. Grain lag layers would be seen on truncation surfaces, which were not exposed in the Storelk.

Evidence of soft sediment deformation, particularly that characteristic of dry or wetted sand, is also conspicuously absent in the Storelk. Deformation is characteristic of the Navajo Sandstone (Sanderson, 1974) and the Casper Sandstone (Steidtmann, 1974). Slump and sandflow deposits are conceivably absent because the preserved portions of the Storelk sets apparently do not contain true slipfaces. Also, many deformation structures observed in modern dunes occur high in the dune, and are not likely to be preserved.

5.5 ANCIENT SHALLOW MARINE COMPARISONS

It has been argued that in known tide-dominated shallow marine environments, giant crossbedding is unlikely to be deposited. There are, however, interpretations of ancient shallow marine deposits containing giant crossbedding. Chief among these is the Lower Tertiary Roda sand wave complex of northern Spain (Nio, 1976).

Nio (1976) interprets a transgressive sequence, beginning with tidal flat-estuarine deposits at the base. These are followed upward respectively by a "pre-sandwave facies" and a "sandwave facies", the latter of which contains crossbeds up to 20 m thick. Sets in both facies are characterized by reactivation surfaces, showing evidence of a change in current direction, and discontinuity surfaces, showing no evidence of erosion. Both are marked by clay layers or current ripples. Significantly, the "sandwave facies" is separated from the overlying "slope facies" by a major erosion surface. The latter facies is composed of low angle surfaces (less than 15 degrees) on which there are crossbeds up to 1.5 m thick. Nio (1976) interprets the "pre-sand wave" and "sandwave" facies to have been deposited by strong tidal currents in a transgressive situation. Under initial relatively shallow conditions and with abundant sediment supply, giant bedforms were built up. With continued deepening, active upbuilding diminished, and the action of waves and reversing tidal currents planed off the giant bedforms, depositing the "slope facies". Nio (1976) compares these facies to "sand waves" in the Southern North Sea, where sand wave upbuilding is interpreted to have taken place in the former Rhine-Meuse estuary complex during the Holocene transgression. These bedforms are presumed to have ceased building up because they are now at too great a depth.

On the basis of data presented, Nio's (1976) interpretation is somewhat ambiguous, and in view of the scale of the crossbedding a possible aeolian origin should have been considered. An alternative possibility is that a regression could have taken place following deposition of the lowermost facies. The "major erosion surface" separating the "sand wave facies" and the "slope facies" is a potential transgressive surface, and hence the latter facies is probably marine. The "slope facies" strongly resembles interpreted storm influenced tidal sand ridge deposits interpreted in North Norway (Johnson, 1977). The reactivation surfaces in the giant crossbeds might be interpreted as being due to fluctuations in wind strength or velocity, or local airflow modification caused by configuration changes in dune patterns as suggested for aeolian bedforms by Brookfield (1977). The clay layers could be suspension deposits that settled during lulls in wind velocity, although admittedly they should have low preservation potential. The current ripples reported to be on these surfaces would, however, be difficult to interpret in this context.

The validity of a possible alternate aeolian interpretation for the giant crossbeds in the Roda complex cannot be properly assessed until Nio's forthcoming detailed paper is published. It is apparent from previous discussion (Section 5.3.4) that North Sea "sand waves" are unsuitable models of bedforms that deposit giant crossbedding, and hence a direct comparison between these and the Roda complex sand waves may not be valid. In addition, there are no known modern examples of macrotidal estuaries in which giant crossbeds are being deposited. If Nio succeeds in establishing definite evidence of tidal action in the Roda complex, then it would have to be assumed that under certain circumstances giant crossbedding could be deposited by tidal currents. This does not threaten the present aeolian interpretation of the Stoqelk Formation, which is the most reasonable one based on the evidence outlined earlier.

5.6 VERTICAL RELATIONSHIPS AMONG THE PENNSYLVANIAN FORMATIONS

Up to this point, the Tyrwhitt, Tobermory and Storelk Formations have been treated as isolated entities because Formational boundaries coincide with major changes in depositional regime. No new information can be derived from this thesis regarding the Todhunter-Tyrwhitt, or the Tobermory-Kananaskis transitions. These were described in Section 2.3.1. However, the interpretation of aeolian deposition has implications regarding the Tyrwhitt-Storelk and Storelk-Tobermory transitions. These are discussed below.

5.6.1 Tyrwhitt-Storelk Transition

The contact between the Tyrwhitt and Storelk Formations has been interpreted by Scott (1964, p.59) as being conformable on a regional basis, and there is no evidence in the study area of this thesis to suggest otherwise. The uppermost Tyrwhitt strata are composed of the ST facies, interpreted earlier to have been deposited seaward of fair weather wave base. The lowermost Storelk strata are characterized by the LT and MP facies, which are interpreted to be aeolian in origin. Hence, it appears that aeolian deposits rest in direct contact with offshore shallow marine sediments, and the transition bears no resemblance to prograding shoreline sequences known from other ancient examples (e.g. Land, 1972; Dickinson et al., 1972; Harms et al., 1975, p.84-91). There are two possible reasons for this unusual stratigraphic relationship: eustatic changes in sealevel and the effects of variable rates of sediment supply to the system.

Eustatic Changes in Sea Level: widespread glaciation in the Southern Hemisphere is interpreted to have culminated during the Pennsylvanian Period. Figure 5.3 presents the time ranges of glaciation on five continents composing the Gondwanaland Supercontinent, which drifted across the south rotational pole during the late Paleozoic (data from several authors, in Crowell and Frakes, 1975). The style of glaciation is interpreted to be characterized by the development of large ice caps which occupied different places at different times from the late Mississippian until the Permian. It is apparent that during this time interval, there is a strong probability that eustatic changes in sea level could have affected coastal and shallow marine systems.

It is suggested here that the Storelk aeolian

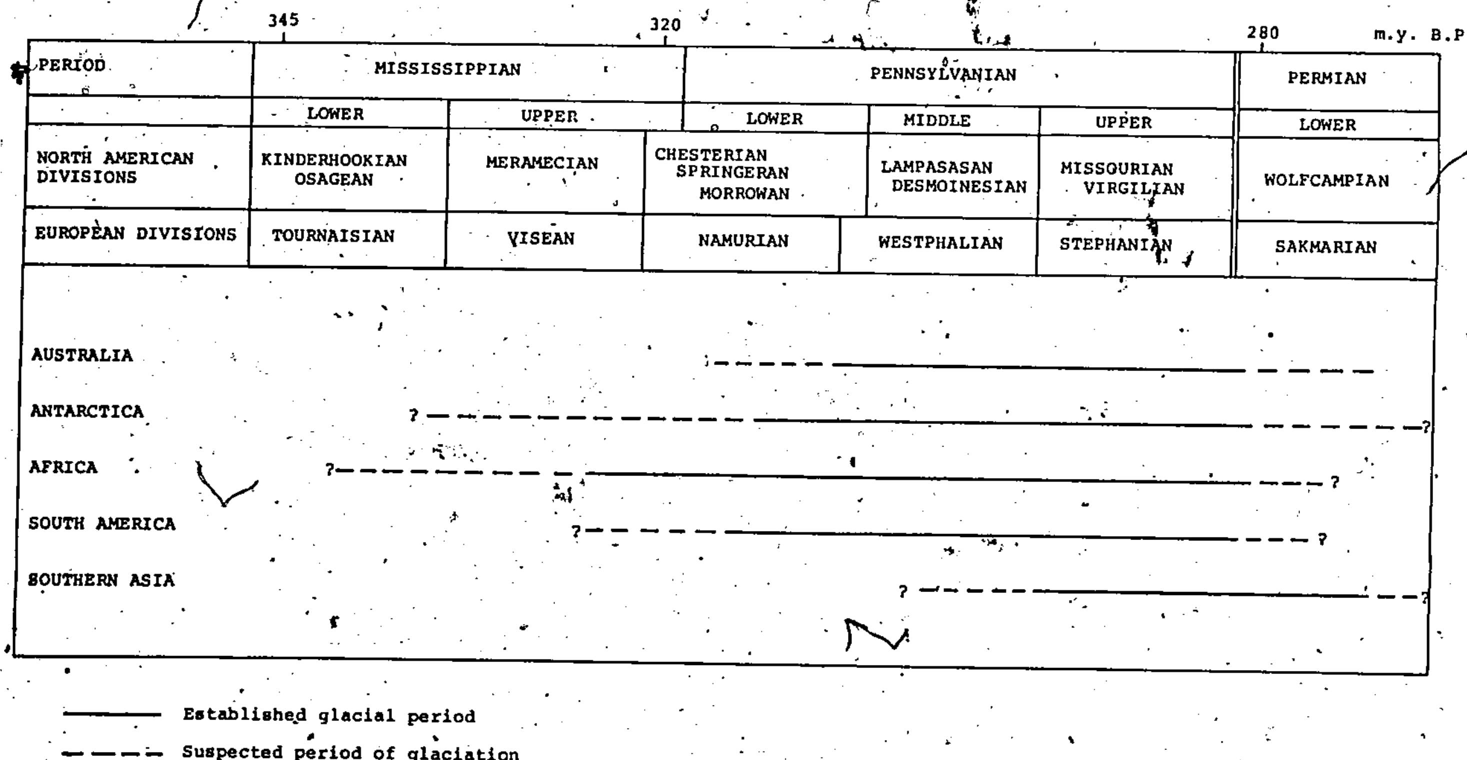


Figure 5.3 Timing of Gondwanaland glaciation (data from Crowell and Frakes, 1975)

sediments could have blown out over portions of the adjacent continental shelf exposed by a glacioeustatic drop in sea level. With abundant sediment supply, progradation of the shoreline would be rapid (instantaneous in geologic terms), especially when driven by southwesterly directed offshore winds. Further factors that would aid rapid progradation would be a low shelf gradient and relatively low wave action (a consequence of low gradient) impinging on the shoreline. With rapid progradation aided by these factors, foreshore and shoreface deposits might be poorly developed and subsequently not preserved. Moreover, it is possible that remnants of these deposits were reworked by wind action, therby removing them from the stratigraphic record.

Effects of Variable Sediment Supply: it was previously suggested that the rate of sand supply varied markedly during Storelk deposition, ranging from very low rates (initiating a marine transgression in the Lower Storelk), to very high rates (allowing deposition of very large bedforms). It is possible that an abrupt increase in the rate of ~~sediment~~ supply, combined with the action of offshore winds, upset the equilibrium between wave erosional processes and aeolian depositional processes, and resulted in rapid shoreline progradation.

Desert coastlines could hypothetically be prone to rapid shoreline progradation, because of potentially large volumes of unstabilized sand that could be made available to the system. In a system which is normally sand starved relative to the transport capacity of the prevailing winds, the coastline would be stable or even eroding. An abrupt increase in the rate of sand supply, exceeding the transport competence of the winds, would lead to progradation of the shoreline as bedforms are driven seaward by offshore winds. As previously stated, the rate of shoreline progradation could be high if there is a combination of low offshore gradient and low or moderate wave activity. Hence, climatic changes causing intensification of the wind need not be invoked.

Whether or not the above mechanisms could induce a rapid enough shoreline progradation to prohibit deposition and preservation of shoreface and foreshore deposits can only be speculated upon. There are no modern examples establishing rates of progradation of desert coastlines known to the author. Progradation is occurring along desert coasts on parts of the Persian Gulf and the Mediterranean Sea, but these involve development of protective offshore bars, followed by a buildup of lagoons and sabkhas which later become covered by dunes (Glennie, 1970, p.126). There is no evidence for this type of sequence in the Tyrwhitt or Storelk, and it appears that this type of progradation would be too slow to explain the nature of the contact between these two Formations.

5.6.2 Storelk-Tobermory Transition

The Storelk-Tobermory contact represents a major marine transgression that terminated aeolian deposition. Scott (1964, p.77) interprets the contact to be regionally unconformable. The evidence for this was outlined in Section 2.3.1. The contact appears paraconformable in the study area of this thesis.

Within the limited thesis area, the Storelk-Tobermory transition can be interpreted in terms of a major marine transgression. The lowermost Tobermory beds are composed of sandy dolomite or dolomitic sandstone, suggesting that initially the rate of sand supply was restricted. Hence the transgression itself could be the result of termination of significant sand supply, perhaps in combination with an increased subsidence rate, causing a reversal of shoreline progradation. The cutoff of sand supply could be the result of erosional removal of the source rocks that fed Storelk deposition, exposing non-siliciclastic rocks (source discussed later). Whatever the cause, the transgression was rapid and left only a basal lag. As a result, foreshore and shoreface deposits were not preserved, and the first Tobermory facies above the contact were deposited in relatively deep water (ST and NC facies).

The uppermost Storelk beds below the contact are usually massive and structureless. The loss of structures at this stratigraphic level may be the result of two factors: (1) the effects of rainfall and vegatation growth on inactive dunes cut off from their sediment supply, or (2) loss of structure due to intense soft sediment deformation associated with the rising water table. In some cases, there are thin medium scale crossbedded and/or small scale crosslaminated units below the contact (e.g. S 2: 182-185 m), suggesting a primary marine incursion prior to the main transgression.

East and southeast of the study area, the Tobermory Formation rests unconformably on older Carboniferous Formations. Hence, extensive erosion was occurring to the east and southeast while sedimentation was taking place in the study area. Areas to the east were eventually inundated with continued transgression, but not before part or all of the Tyrwhitt and Storelk sediments were eroded.

Hence, much of the sediment supply for Tobermory deposition probably was derived from recycled sands derived from older Pennsylvanian sediments.

5.7 SOURCE OF SEDIMENT

The thickness and areal extent of the Pennsylvanian siliciclastic Formations testify to the existence of a source capable of providing a large volume of sand. The source area is interpreted by Scott (1964, p.107) to be the craton to the east and northeast, based on evidence of subaerial erosion in this area and on petrographic data. The paleocurrent evidence presented in this thesis confirms that sediments were derived from the direction of the craton. There is no evidence of input from island arcs postulated to have existed in the Omineca Crystalline Belt to the west. These are considered to have been well removed from the Rocky Mountain Belt in view of the absence of tuffaceous material or other evidence of volcanism in this area (Monger _et al._, 1972).

Detailed petrographic examination has not been attempted in this thesis, so little new information on the lithology of the source rocks can be presented. Cursory examination of thin sections stained for K-feldspar indicates that the Pennsylvanian sediments are texturally mature and are composed almost entirely of quartz and chert. There is very little feldspar and few heavy mineral grains. These features suggest a sedimentary or metasedimentary source for the sediments. Since the craton was almost entirely covered by sedimentary rocks, a dominantly sedimentary origin is plausible.

Sandstone units are rare in post-Cambrian sedimentary rocks of the Interior Plains, and only minor amounts of disseminated sand are present in the predominantly limestone-dolomite-anhydrite-shale sequences. Scott (1964, p.109) suggests that the sands comprising the Pennsylvanian sequence were derived from this disseminated sand and possibly from the Coleville Sandstone Member of the widespread Bakken Formation. The latter attains thicknesses of up to 18 m at its erosional edge in Saskatchewan. Other sandy units may have existed locally elsewhere, but now are eroded. As was suggested previously, a large proportion of the Tobermory sediments were probably derived from erosion of older Carboniferous Formations.

The Pennsylvanian sandstones are remarkably free of shale, even though extensive shale units in the Interior Plains might form potential sources. There are two possibilities that could contribute to this. Since much of the sand probably accumulated in a sand sea prior to being transported offshore, clay could have been winnowed out, blown away and deposited elsewhere. Scott (1964, p.51) noted minor quantities of shale at some localities away from the study area. It is also possible that under conditions of relatively low suspended sediment concentration, wave and current activity prohibited the deposition of mud. Evidence for strong current activity and lesser wave activity in the Tyrwhitt and Tobermory were presented earlier. McCave (1971b) used these parameters to explain mud distribution in the North and Celtic Seas.

CHAPTER 6

CONCLUSIONS

The following general conclusions are made regarding the interpretations of the depositional frameworks that prevailed during sedimentation of the Pennsylvanian siliciclastic succession:

1. The Pennsylvanian siliciclastic succession can be divided into a series of 13 facies which aid in environmental reconstruction. However, both the low angle inclined strata in the Tobermory Formation of measured section 1, and units of deformed laminae, do not fit into the facies scheme.

2. Facies in the Storelk Formation are mutually exclusive from facies in the Tyrwhitt and Tobermory Formations, except for the FC facies.

3. The Storelk Formation, and part of the Tyrwhitt Formation, can be divided into a series of laterally persistent facies or facies associations, called Intervals.

4. The Tyrwhitt and Tobermory Formations are interpreted to have been deposited entirely in a shallow marine environment. This is based on the body and trace fossil assemblages in some facies, and on the intimate vertical interrelationships between these and all other facies occurring in the Formations.

5. The Storelk Formation is interpreted to have an aeolian origin, except for a single thin marine transgressive unit. The aeolian interpretation is based on the abundance of giant crossbedding (maximum 10 m thick), the moderate dip angles (10-25 degrees) characteristic of the crossbed foresets, the total absence of body or trace fossils (with the exception of a single thin unit), and the presence of widespread truncation surfaces. Each of these features is comparable to that known from ancient aeolian examples, and that known or inferred from modern

aeolian examples. None of these characteristics is known from modern tide-dominated shallow marine settings.

6. The Tyrwhitt and Tobermory sequences were probably deposited on a stable shelf, which bordered the North American craton from which sediments were derived. The "Pacific Ocean" to the west was open, except for possible volcanic arc systems which had no discernible effect on shelf sedimentation.

7. The Storelk sequence was deposited in a low latitude (10-20 degrees north) coastal desert, apparently under the influence of prevailing northeasterly tradewinds. The winds probably varied in strength and direction on a seasonal basis, contributing to variations in paleoflow direction as reflected by the Storelk crossbeds.

The following conclusions are reached regarding specific interpretations of facies, vertical facies relationships, and the sequence of deposition from Tyrwhitt through Tobermory times:

1. The Tyrwhitt Formation was deposited under storm dominated conditions. There is no definitive evidence for the effects of continuously operating tidal or oceanic currents in the sequence.

2. On the basis of the physical characteristics of the ST facies, it is interpreted to have been deposited seaward of fair weather wave base, where the rate of infaunal reworking generally exceeded the rate of sediment supply. The thickness and abundance of the ST facies throughout the Tyrwhitt Formation suggest that the facies is representative of background conditions of Tyrwhitt sedimentation.

3. The intimate interbedding of the ST facies with virtually all other facies occurring in the Tyrwhitt suggests that the latter facies were also deposited seaward of fair weather wave base. The other facies represent deviations from the background conditions of sedimentation.

4. The lack of evidence for the effects of strong storm wave surges (e.g. in the form of hummocky

cross stratification or abundant wave-formed structures) suggests that the depositional site for all facies was at or below storm wave base. This supports the interpreted offshore origin of the ST facies.

5. Storm surge currents are interpreted to have been operative in the depositional system, based on paleocurrent characteristics inferred from the MX facies. Such currents were probably the only effective sediment transporting agents at the depositional site, and hence are interpreted to have deposited both the sediment and most of the sedimentary structures inherent in all facies.

6. The strength of the storm surge currents, together with the grain size and rate of sediment supply, were the controlling factors that determined the type and preservability (relative to destructive biogenic activity) of the sedimentary structures, and the lithology of facies in the Tyrwhitt Formation.

7. Shallow marine sedimentation was terminated by rapid progradation of the Storelk shoreline as

aeolian dunes were blown seaward by offshore-directed winds. Aeolian sediments are superimposed on interpreted offshore shallow marine sediments, possibly as a result of glacioeustatic lowering of sea level and/or a sharp increase in the rate of sand supply.

8. Crossbedding in the Storelk Formation is comparable in scale and geometry to that known from other ancient aeolian examples, and to that known or inferred from modern aeolian examples. However, confident identification of the types of dunes active during Storelk deposition is not possible in the absence of a comprehensive knowledge of the crossbed types in modern aeolian bedforms.

9. The Storelk sequence is characterized by a vertical succession of distinctive, laterally persistent facies and facies assemblages (Intervals). In the crossbedded Intervals, the types of facies assemblages appear to be correlative with specific kinds of wind regimes that are inferred from paleoflow data.

10. The gross paleoflow configuration in the Storelk Formation is comparable with that of other ancient aeolian examples. Specific aspects of paleoflow in the Storelk Formation (highly consistent unidirectional paleoflow; bidirectional paleoflow) are generally unrecognized in other ancient aeolian examples.

11. The SS facies is interpreted to have an aeolian origin based on its context and on the total absence of trace or body fossils. A specific origin cannot be ascribed to this facies in the absence of modern analogues. There is no definitive evidence to suggest that similar structureless units in the Navajo Sandstone (Sanderson, 1974) are ancient analogues of the SS facies.

12. Aeolian deposition in the Storelk Formation was interrupted by a brief marine transgression which probably resulted from a temporary severe restriction in sand supply, followed by rapid degradation of the shoreline. Renewed sand supply caused subsequent rapid progradation of the shoreline.

13. Storelk sedimentation was terminated in the study area by a major marine transgression at the commencement of Tobermory time. Erosional removal of Pennsylvanian Formations eastward could have supplied much of the sediment in the Tobermory Formation.

14. Tobermory sedimentation is interpreted to have taken place under storm dominated conditions similar to those characterizing Tyrwhitt sedimentation. The greater abundance of sedimentary structures in the Tobermory Formation relative to that in the Tyrwhitt Formation could be a function of slightly shallower conditions, or a greater rate of sediment supply in the former.

15. An increase in the number and thickness of carbonate facies in the Upper Tobermory Formation reflects decreasing amounts of siliciclastic sediment supply, which culminated in the establishment of predominantly carbonate deposition in Kananaskis time.

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APPENDIX 1

PALEOCURRENT DATA

All paleocurrent data collected for this thesis is listed in tabular form. Each value in Tables 1 through 4 represents the azimuth of maximum dip of crosslaminae from an individual set (regional dip has been removed by stereonet rotation). Symmetrical ripple crests and parting lineations are linear features, so the corresponding values in Table 5 represent the strikes of these features (also corrected for regional dip).

Stereonet plots of the paleocurrent data, together with tables showing the results of vector mean calculations on that data, are given in the text. The tables in this Appendix are cross-referenced with data in the text to permit easy comparison.

Details of paleocurrent data collection and treatment are given in Section 1.4.

Table 1. Paleocurrent data (dip azimuths of crosslaminae) for MX facies in Tyrwhitt and Tobermory Formations (see Figure 3.19; Table 3.2)

1. MAJOR TYRWHITT MX INTERVAL

(a) Trough sets thicker than 1 m	128	174	187	188	199	202	204	75
	181	199	220	222	223	251	260	194
	200	235	240	258	269	291		
(b) Trough sets less than 1 m thick	80	106	124	202	300	25	42	53
	76	90	187	205	205	212	218	227
	238	244	254	256	259	264	283	342
	6	47	64	108	125	142	156	158
	180	190	207	210	215	230	233	233
	237	259	277	282	294	315	315	318
	59	77	94	119	144	156	160	175
	185	188	203	203	217	222	230	235
	256	260	264	268	283	283	293	307
(c) Sets, scale or geometry not visible	95	164	225	226	250	157	170	186
	205	249	275	304				

Table 1/continued (2)

2. <u>MX FACIES UNITS IN OTHER PARTS OF TYRWHITT FM</u>								
(a) Trough sets	47	61	62	131	135	144	166	177
	179	181	208	219	219	221	242	242
	249	258	262	283	311	323	14	83
	101	124	148	154	162	164	171	150
	160	168	182	189	194	199	205	239
	253	299	314	336	170	176	179	186
	187	191	221	227	47	186	191	211
	230	233	234	267	288	305	348	244
	56	78	87	101	133	148	158	158
	161	165	172	179	195	201	239	259
	269	211	218	297	179			
(b) Planar sets	104	150	187	197	226	230	214	216
	218	211						
(c) Sets, scale or geometry not visible	159	232	260	78	78	118	123	130
	131	136	147	150	158	160	166	166
	169	182	190	195	201	227	269	270
	272	298	336					

Table 1/continued (3)

3. MX FACIES UNITS IN TOBERMORY FM								
(a) Trough sets	110	120	133	161	168	233	258	231
	231	220	220	227				
(b) Planar sets	164	115						
(c) Sets, scale or geometry not visible	101	150	218	224	227	242	282	324

Table 2. Paleocurrent data (dip azimuths of crosslaminae) for facies in Lower Storelk Megaplanar Interval (see Figures 4.1 and 4.2; Table 4.1)

1. MEGAPLANAR AND PLANAR SETS (MP AND LP FACIES)								
(a) SE data cluster	97	113	114	120	129	132	133	129
	88	113						
(b) SSW data cluster	187	187	191	196	213	211	212	202
	186	213						
(c) Readings in neither cluster	56	274	288					
2. LARGE SCALE TROUGH SETS (LT FACIES)								
(a) SE data cluster	91	101	108	109	111	112	112	113
	113	118	118	122	122	124	125	126
	130	131						
(b) SSW data cluster	162	162	165	170	171	173	175	176
	177	180	183	188	196	198	200	202
	203	214	219	226	227	238	238	239
(c) Readings in neither cluster	11	34	62	74	77	143	257	262
	268	272	298	298	327	334		

Table 3. Paleocurrent data (dip azimuths of crosslaminae) for facies in Middle Storelk Megatrough Interval (see Figure 4.3; Table 4.2)

1. MEGATROUGH SETS (MT FACIES)	120	201	209	209	211	211	214	220
	222	225	225	225	226	226	231	232
	233	237	241	250	251	252	253	253
	257	258	275	254	214	223		
2. LARGE SCALE TROUGH SETS (LT FACIES)	12	13	56	61	84	95	106	123
	128	129	146	151	153	168	167	176
	184	187	212	213	215	219	223	225
	230	232	236	238	244	245	251	252
	254	257	257	259	259	266	273	286
	305	335	197	230	239			
3. CROSSBEDS, SCALE NOT VISIBLE	91	163	168	211	219	273	64	77
	120	200	201					

Table 4. Paleocurrent data (dip azimuths of crosslaminae) for facies in Upper Storelk Crossbed Interval (see Figures 4.4-4.7; Table 4.3)

1.	MEGATROUGH SETS (MT FACIES)	84	145	172	122	132	136	153	216
		292	207						
2.	LARGE SCALE TROUGH SETS (LT FACIES)	78	89	163	50	95	92	159	110
		139	160	167	177	70	84	84	86
		154	157	167	171	180	297	212	213
		234	232	250	256	274	220	221	279
		236	308	249	274	211	229	239	245
		248	199	205	222	243	250	270	291
		304	316						
3.	MEGAPLANAR SETS (MP FACIES)	165	116	171	130	170	176	200	231
		213	216	228	229	244	265	211	207
		209	239	99	103	111	120	127	132
		160	224	186					
4.	LARGE SCALE PLANAR SETS (LP FACIES)	21	66	81	70	231	242	291	291
		202							

Table 4/continued (2)

5. <u>SETS, SCALE OR GEOMETRY NOT VISIBLE</u>	110	82	103	119	93	98	102	141
	179	167	175	122	127	194	198	212
	224	239	234	267	215	287	204	184
	190	211	258	204	228	241	243	243
	245	245	284	288	288	241	283	284
	287	287	287					
6. <u>SURFACES</u>	95	130	139	151	284	55	58	61
	70	81	88	103	127	127	166	173
	182	182	197	201	209	211	228	234
	252	274	280	285	285	333	341	345
	19	310	136	238	147	162	160	180
	216	226	137	182	182	196	214	231
	252	241	211	180				

Table 5. Miscellaneous paleocurrent data

1.	LOW ANGLE INCLINED STRATA, TOBERMORY FM., MS 1 (215.5-218.5 m): DIP AZIMUTHS	188	262	
2.	STRIKES OF SYMMETRICAL RIPPLE CRESTS, TYRWHITT AND TOBERMORY FMS.	330	344	205
3.	STRIKE OF PARTING LINEATION, TYRWHITT FM., MS 1	113		

APPENDIX 2

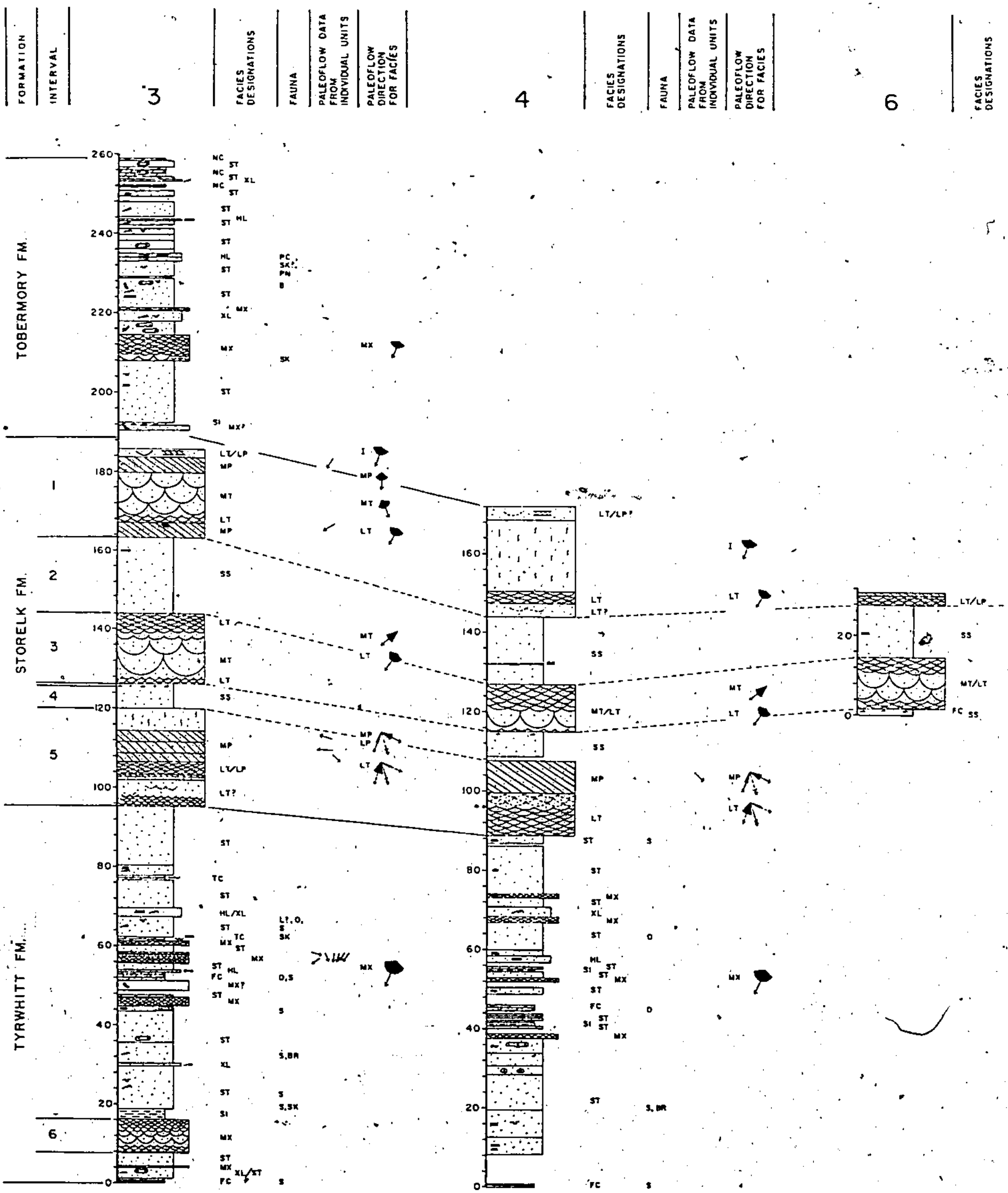
MEASURED SECTIONS

Detailed scale drawings of all eight outcrop sections measured for this thesis are found in the pocket (inside of back cover). All symbols and letters used are explained in the legend. The measured sections are correlated on two levels: (1) correlations of Formational boundaries (solid lines) and (2) correlations of Interval boundaries (dashed lines). The vertical scale for all measured sections is in meters. Measured section 1 is the northernmost section, and measured section 7 is the southernmost section (see location map, Figure 1.1).

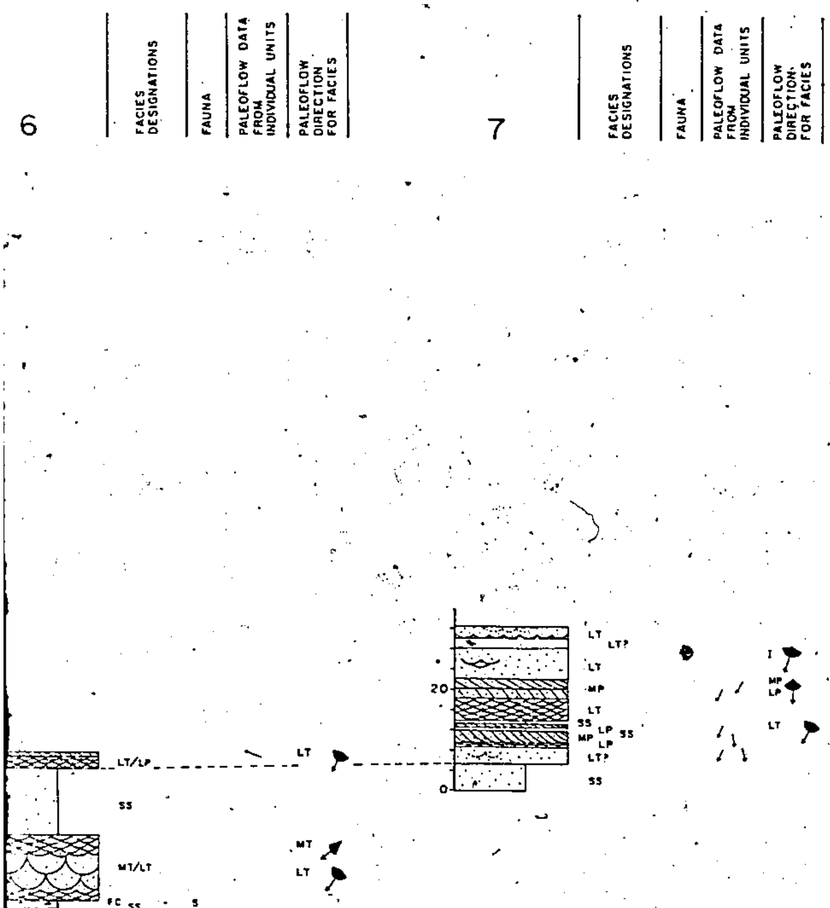
Facies symbols and fossil locations are plotted on the measured sections for ease of location. Where facies symbols are separated by a diagonal line (e.g. XL/HL), it indicates that the facies are too closely interbedded to be illustrated directly. Since in many cases the carbonate and siltstone facies are relatively thin, they have been vertically exaggerated slightly to make them visible.

All crossbedding in the measured sections is plotted to scale, except for sets less than about 50 cm thick. The latter are vertically exaggerated. Since facies symbols are given, the ranges of set scales for each facies can be found in the text.

Two types of paleocurrent data are plotted. "Paleoflow data from individual units" shows true paleocurrent azimuths from individual planar sets, as well as the strikes of symmetrical ripple crests and parting lineations. "Paleoflow direction for facies" indicates the vector mean azimuth(s) for a specific facies, and for a specific Interval (I) in the case of the Upper Storelk Crossbed Interval. North is to the top of each section.


FORMATION
INTERVAL
3
FACIES DESIGNATIONS
FAUNA
PALEOFLOW DATA FROM INDIVIDUAL UNITS
PALEOFLOW DIRECTION FOR FACIES
4
FACIES DESIGNATIONS
FAUNA
PALEOFLOW DATA FROM INDIVIDUAL UNITS
PALEOFLOW DIRECTION FOR FACIES
6
FACIES DESIGNATIONS
TOBERMORY FM.
STORELK FM.
TYRWHITT FM.
1
2
3
4
5
6
260
240
220
200
180
160
140
120
100
80
60
40
20
0
LT/LP
MP
MT
LT
SS
LT/LP?
LT?
MT/LT
FC

1 oF



LEGEND

INTERVAL NAMES

1	UPPER STORELK CROSSBED INTERVAL
2	MIDDLE STORELK STRUCTURELESS INTERVAL
3	MIDDLE STORELK MEGATROUGH INTERVAL
4	LOWER STORELK STRUCTURELESS INTERVAL
5	LOWER STORELK MEGAPLANAR INTERVAL
6	MAJOR TYRWHITT MX INTERVAL

FACIES DESIGNATIONS

MP	MEGAPLANAR FACIES
MT	MEGATROUGH FACIES
LP	LARGE SCALE PLANAR CROSSBED FACIES
LT	LARGE SCALE TROUGH CROSSBED FACIES
SS	STORELK STRUCTURELESS FACIES
MX	MEDIUM SCALE CROSSBEDDED FACIES
ST	STRUCTURELESS FACIES
HL	HORIZONTAL LAMINATED FACIES
XL	SMALL SCALE CROSSLAMINATED FACIES
SI	SILTSTONE FACIES
FC	FOSSILIFEROUS CARBONATE FACIES
NC	NON-FOSSILIFEROUS CARBONATE FACIES
TC	CROSSBEDDED CARBONATE FACIES
Z	NOT IN FACIES SCHEME - SEE TEXT

LEGEND CONTINUED

LITHOLOGY

- SANDSTONE
- SANDY DOLOMITE
- SANDY LIMESTONE
- SILTSTONE
- CHERT LAYERS AND NODULES
- C — BASAL TOBERMORY CONGLOMERATE

SEDIMENTARY STRUCTURES

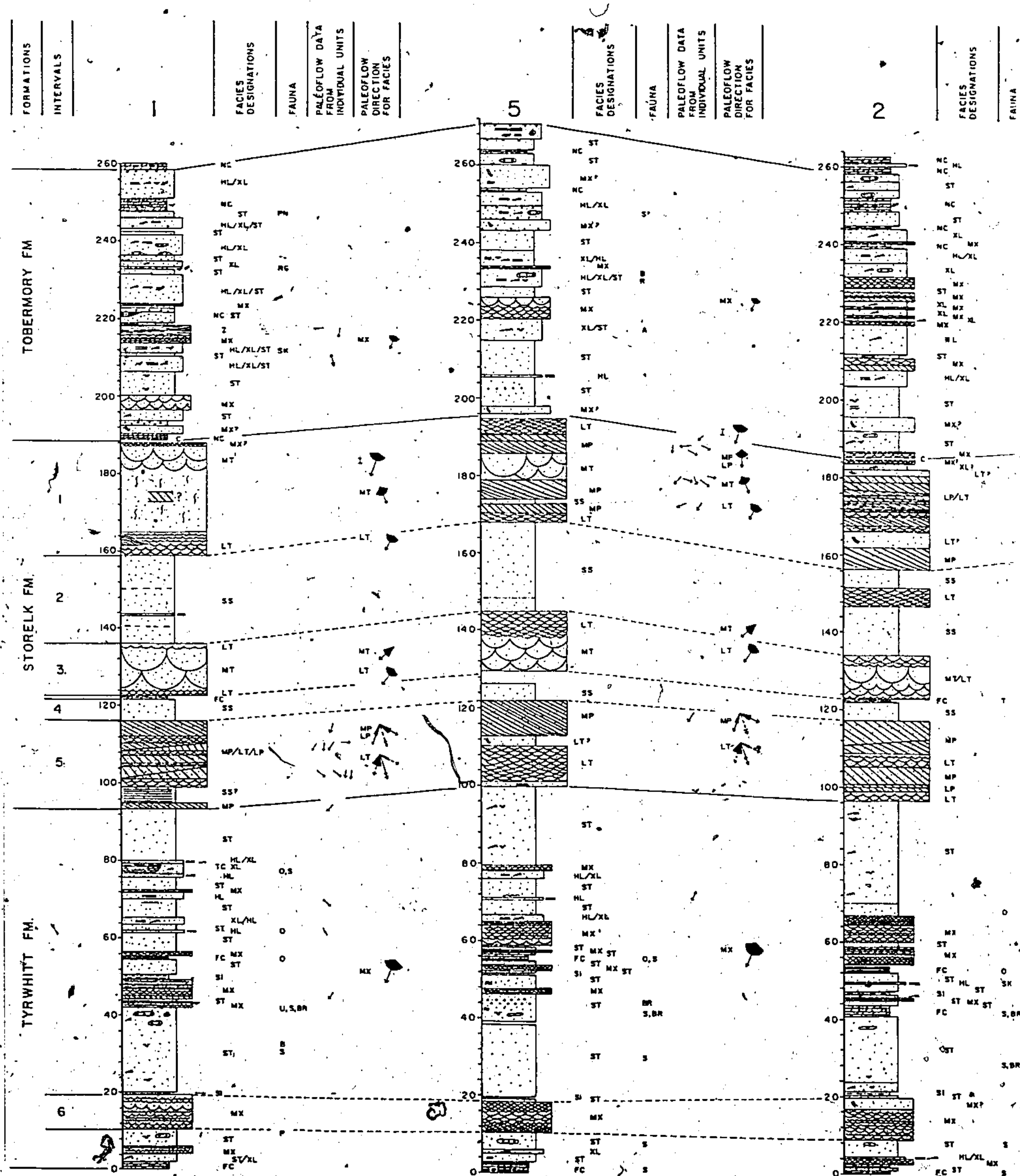
- PLANAR TABULAR SETS
- PLANAR SETS WITH DIVERGENT SET BOUNDARIES
- TROUGH CROSSBEDS
- HORIZONTAL LAMINAE
- SMALL SCALE CROSSLAMINAE
- CONVOLUTE LAMINAE
- WAVY OR IRREGULAR LAMINAE
- CURVED LAMINAE, SET TYPE NOT VISIBLE
- SYMMETRICAL RIPPLES
- LOW ANGLE INCLINED STRATA, TOBERMORY FM.
- HEAVY VERTICAL FRACTURE, POORLY LAMINATED — SEDIMENTARY STRUCTURES OBSCURED
- SEDIMENTARY STRUCTURE IN PARTS OF UNIT

PALEOCURRENT DATA

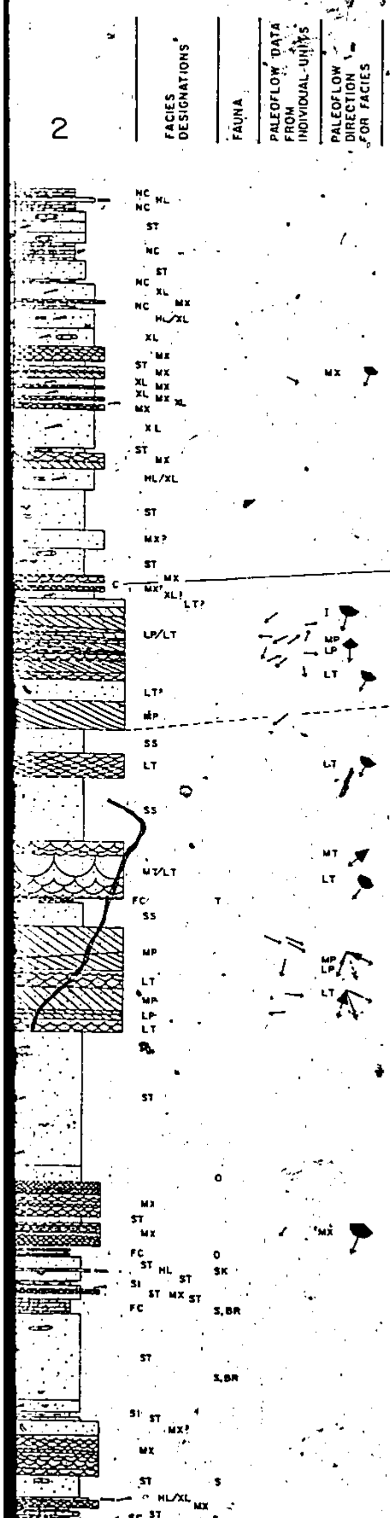
- PALEOFLOW AZIMUTH FOR INDIVIDUAL CROSSBED
- DENOTES ONE STANDARD DEVIATION ON EACH SIDE OF VECTOR MEAN
- VECTOR MEAN AZIMUTH FOR FACIES OR INTERVAL (I)
- GRAND VECTOR MEAN FOR FACIES IGNORING BIMODALITY
- STRIKE OF SYMMETRICAL RIPPLE CREST
- STRIKE OF PARTING LINEATION

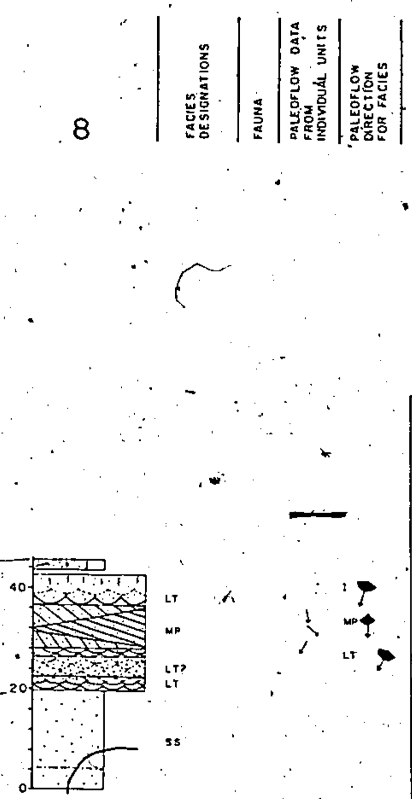
FAUNA

S	SPIRIFERID BRACHIOPOD
O	ORBICULOIDEA BRACHIOPOD
P	PRODUCTID BRACHIOPOD
T	TEREBRATULID BRACHIOPOD
BR	BRYOZAN?
A	ARENICOLITES
B	BERGAUERIA
L	LINGULICHNUS?
PC	PLICHNIA ?
PN	PLANOLITES
R	RHIZOCORALLIUM?
RG	RADIALLY GROPING FEEDING BURROW
SK	SKOLITHOS
U	UNAMED ICHNOGENUS


FORMATIONS
INTERVALS
FACIES DESIGNATIONS
FAUNA
PALEOFLOW DATA FROM INDIVIDUAL UNITS
PALEOFLOW DIRECTION FOR FACIES
1
5
2
TOBERMORY FM.
STORELK FM.
TYRWHITT FM.

1 oF





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