Now rolls the deep where grew the tree.

-- Alfred Lord Tennyson

AN ANALYSIS OF CARDIUM FORMATION EVENT STRATIGRAPHY

AN ANALYSIS OF
SEQUENCE BOUNDARIES OF THE
EVENT STRATIGRAPHY OF THE
CARDIUM FORMATION, ALBERTA

By

JEREMY JOHN BARTLETT, A.B. (HONS.)

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AUTHOR: Jeremy John Bartlett, A.B. (Hons.) (University of California, Berkeley)

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ABSTRACT

Analysis of the sedimentary facies, early diagenesis and micropaleontology of event stratigraphy within the transgressive phase of the Cardium Formation indicates that changes of sea level occur during extremely short timespans possibly as short as 10,000 years. These rapid sea level changes produce either erosive or gradational boundaries between stratigraphic sequences. These boundaries are termed Horizons.

Quantitative consideration of the foraminiferal population below, at and above these Horizons indicates that there was probably very little pause during the change in sea level; no unusual accumulations of biogenic debris occur. The foraminifera indicate that the waterbody was turbid and very likely diluted by fresh water. The resulting environmental stress persisted throughout Cardium time over a topographic 'bench' shorewards of the maximum extent of the regressive shoreline.

Fresh water dilution and possible increased organic supply encouraged the formation of synsedimentary siderite. Its ubiquitous occurence at the Horizons examined may indicate a short pause in sedimentation prior to renewed

transgression, but the possibility of rapid sideritization makes this hypothesis unprovable.

Although subtle, some of the burrowing and cementation patterns characteristic of carbonate hardgrounds appear in the ubiquitously erosional fifth Horizon. The other Horizons are too gradational to show such behaviour.

All Horizons show rapid sedimentological changes. Erosion in one location may appear as a correlative conformity in another. Their behaviour indicates rapid changes in water depth.

As a whole the Cardium Formation probably represents a shoreline response to Late Turonian eustatic sea level change which was further influenced by shorter term tectonically induced sea level changes. With the exception of the fifth Horizon, the Horizons probably all formed subaqueously without a pause in sedimentation. Apart from changes from erosive to gradational contacts, Horizon behaviour is the same across the area studied.

ACKNOWLEDGEMENTS

Although acknowledgements are perhaps (hopefully) the most boring portions of a thesis and are usually skimmed over as just another list of personages by most readers, they are in many ways the most important part. For no work, particularly in the world of science, is done in isolation, and without the support and interaction of those listed below this thesis would have been impossible. So I would like the reader, despite the necessarily compressed form of any thanks I can give here, to bear in mind the magnitude of the help that all below have given me.

I must first of all thank Dr. Roger Walker for supervising this work; his comments and careful supervision have proven invaluable. I should also make note of the help I have recieved from Dr. A. G. (Guy) Plint who, in addition to providing encouragement at the begining of this work, put up with endless pestering about the ins and outs of his Cardium stratigraphy; my work relies heavily on his preceding work and would not have been possible without it.

Thanks is also due to many people in technical positions. The staff at the E.R.C.B. in Calgary were most helpful, particularly Laurie Wilcox. In addition all of the fine photographic work contained herein is courtesy of the expert services of Jack Whorwood. Len Zwicker is to be thanked for producing all thin sections. Rick Hamilton of the McMaster Geography Dept. also helped me reduce well-logs to a common scale.

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TABLE

OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1. THE PROBLEM

Since the publication by the A.A.P.G. in 1977 of Vail et al.'s work on eustatic sea level changes, much has been said about the overall control that sea level has on sedimentary environments and their distribution. Modelling of such control is usually discussed on the detailed scale, similar to that of a single sedimentary environment, such as a barrier or shoreface (Vail et al., 1977). However, since the advent of plate tectonic theory and the attending change in postulated mechanisms for sea level control, little has been published on the existence, recognition or behaviour of small scale, relative sea level 'cycles' in siliciclastic sediments and the transitions between such cycles. Small scale changes are those occurring over less than a million years. Such a data gap leaves the question, how do siliciclastic sediments respond to rapid relative sea level changes (i.e. how do Vail et al.'s (1977) fourth and fifth order cycles appear in the rock record)?

2. EVENT STRATIGRAPHY

Studies in the Western Interior basin and elsewhere are begining to show that these short term changes appear in the rock record in terms of "event stratigraphy" (e.g.

Plint et al., 1986, Leckie 1983, Hein et al., 1986, Schlee, 1984). Events are defined as the results of widespread, correlatable, short-term or geologically almost instantaneous processes. Typical examples are erosion surfaces (Schlee, 1984) and bentonite deposition, but very rapid, extensive change in sedimentary environment (e.g. progradation) could produce a thin sequence correlatable as an event. In the case of erosion that produces a recognizable surface, the surface may be termed an 'event surface'. Events may become obscure if correlated over a large enough area because of the nature of variation in basinal sedimentation, but they should be recognizable on the scale of the typical oil and gas basin.

3. THE SETTING

Recent work by Plint et al. (1986) on the Cardium Formation in Alberta has established a detailed event stratigraphy with seven rapid relative sea level changes inside an approximately 1 million year period. The events are based on erosion followed by transgression. This stratigraphy provides an excellent framework within which the response of clastic systems to short-term sea level change may be examined. This thesis examines the transgressive phase of this event stratigraphy in the Albertan subsurface.

4. QUESTIONS POSED

There are several questions as to the nature of the Cardium events and the behaviour of the sediment across them. The presence of erosion raises the question of subaerial exposure. However, such handy mechanisms must be viewed with caution; to paraphrase Bromley (1975), geologists tend to view pause or omission as equivalent to emergence because of a view that submarine processes are ubiquitiously depositional, but this is not necessarily so, as recent suboceanographic exploration has revealed.

Study of these events may be carried out using many techniques. Variations in sedimentary facies and microfaunal content and ubiquitous patterns of early diagenesis, particularly the occurrence of siderite, have all been considered in constructing a summary of how rapid relative sea level changes affect siliciclastic sediments across event 'surfaces' as demonstrated in the Cardium.

The particular questions posed in this study are:

1. Are the events a) pauses or b) actively erosional episodes and do they differ from one another?
2. How rapid are the events?
3. Do event surfaces change laterally and if so, how?
4. Does sea level change affect early diagenesis or are any early diagenetic products indicative of surface behaviour?

5. How do sediments respond right at the surfaces over the time frame involved?

6. Can any direct mechanism for the events be discerned? Is eustatic or tectonic control more reasonable. (Or in the convenient catch-all of Kauffmann, are they "tectono-eustatic")

7. Do siliciclastic analogues exist for carbonate hardgrounds and firmgrounds as summarized by Bromley (1975) and Kennedy (1975)? Such analogs might be expected at the tops of sedimentary sequences where significant pauses in sedimentation have occurred.

8. Are there any signs of subaerial exposure?

5. DATABASE

Because the Cardium Formation is an important oil and gas resevoir many diamond drill cores are available for study in conjunction with outcroping beds. Examination of forty two cores, approximately in the Kakwa field region, (Townships 58 to 71, Ranges 16 West 5 to 10 West 6) (see map in Appendix 1) allowed for the detailed study of 36, 24, 19, and 8 examples through E-T4, E-T5, E-T6 and E-T7 of Plint et al. (1986). Appendix 1 lists the location of every core examined (both areally and relative to well logs and the designated event Horizons), the location of each sample within the core and shows lithological sections, more fully described below, across each Horizon examined.

Samples, described in more detail below, were taken where indicated for siderite analysis and micropaleontological sampling.

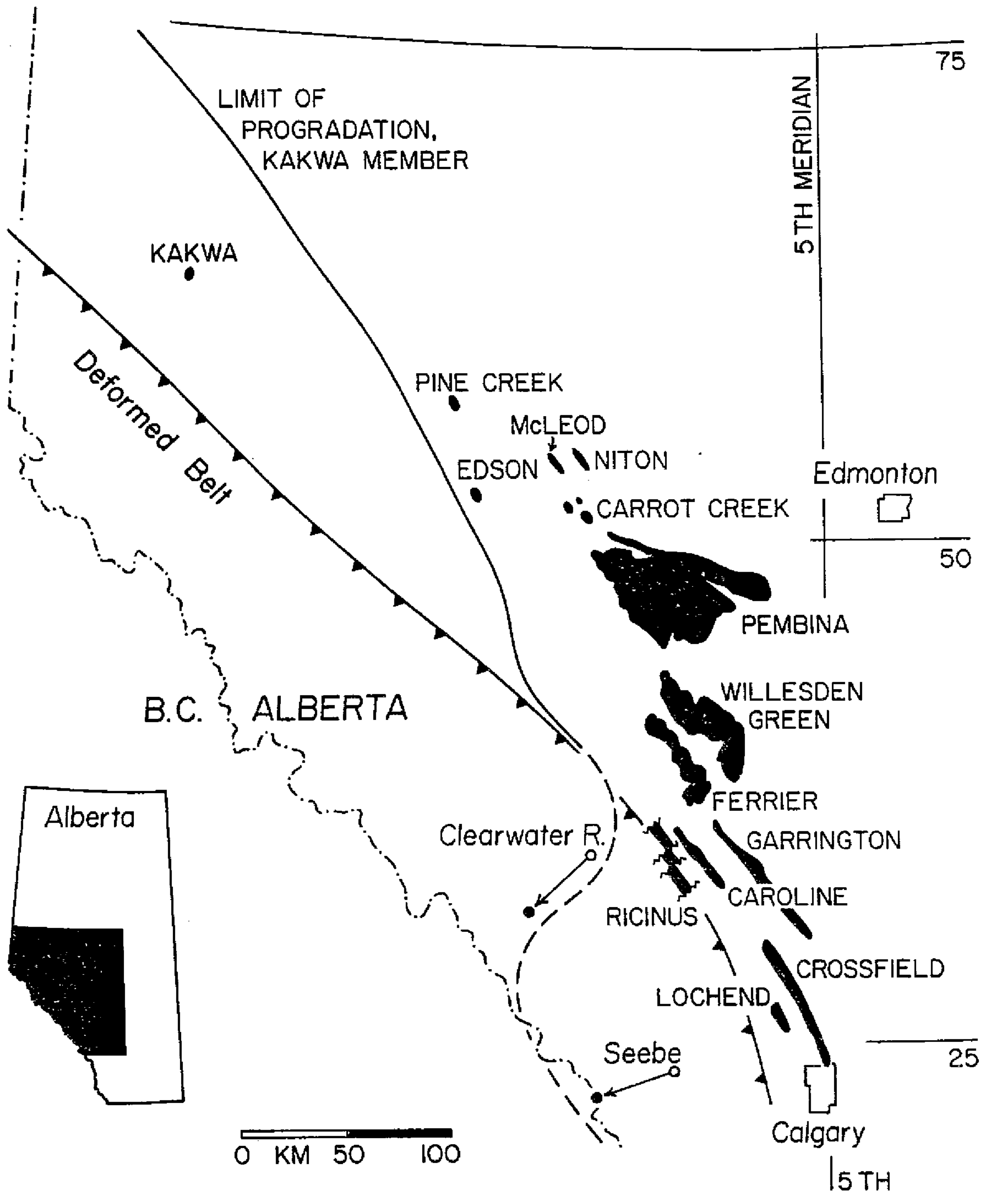
CHAPTER 2

BACKGROUND

1. LOCATION AND STRATIGRAPHY

The Cardium Formation occurs in parts of British Columbia in outcrop and widely throughout southern Alberta, both in outcrop and subsurface where it contains important accumulations of oil and gas. An idea of the extent of the Cardium in subsurface may be had by examining a map of oil fields producing from Cardium strata (figure 2-1); although the fields imply a patchy distribution, the Cardium is, in fact, generally extensive with particular regions of 'sand' bodies controlling economic field location (e.g. Walker, 1983b).

Stratigraphically, the Cardium Formation is part of the Alberta (or Colorado) Group and is sandwiched by the Blackstone Formation below and the Wapiabi Formation above, both of which are almost entirely shale formations. The Wapiabi is approximately 500m thick and the Blackstone approximately 250m thick (Bergman and Walker, 1986). Figure 2-2 shows the large scale stratigraphy. The time scale of this figure is the D.N.A.G. scale (Palmer, 1983) which, within the framework considered, matches that of Obradovich and Cobban (1975). The Cardium itself is of Late Turonian age, about 88.5 million years old, and may


LIMIT OF
PROGRADATION,
KAKWA MEMBER
75
5TH MERIDIAN
KAKWA
Deformed Belt
PINE CREEK
McLEOD
NITON
EDSON
Edmonton
CARROT CREEK
50
PEMBINA
WILLESDEN
GREEN
B.C.
ALBERTA
FERRIER
Alberta
Clearwater R.
GARRINGTON
CAROLINE
RICINUS
CROSSFIELD
LOCHEND
Seebe
25
Calgary
0 KM 50 100
5 TH

have been deposited within approximately one million years. The dating is by inference from the surrounding faunal zones; the underlying Blackstone contains fossils of the Late Turonian *Prionocyclus woollgari* zone and the overlying basal Wapiabi shales contain fauna of Late Turonian to Earliest Coniacian age, *Scaphites preventricosus* and *Inoceramus deformis* (Wall and Sweet, 1982).

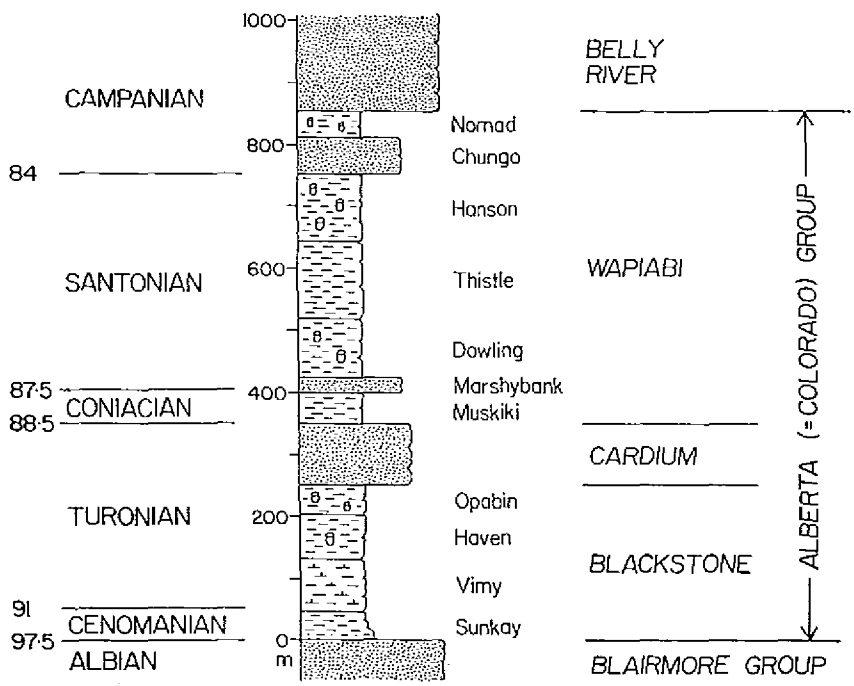


Figure 2-2. Stratigraphy of the Colorado Group (from Bergman and Walker, 1986).

In this stratigraphy (figure 2-2), the Vimy member of the Blackstone Formation is equivalent to the subsurface

Second White Specks and the Thistle member of the Wapiabi Formation is crudely correlative with the First White Specks (Wall and Rosene, 1977). The Frontier, Ferron and Gallup Formations in the United States, are approximately equivalent to the Cardium Formation of Alberta (Bergman and Walker, 1986).

In the terminology of Dickinson (1974), the Cardium was deposited at the western edge of a retroarc, foreland basin although the terminology now stands as a little ambiguous due to the recent recognition of accretionary terranes to the West. During the Late Cretaceous, the basin was generally covered by a shallow epeiric sea, the estimated maximum extent of which is shown in figure 2-3.

2. PREVIOUS WORK

The Cardium Formation has been economically important since the discovery of the Pembina field in 1953 (Nielsen and Porter, 1984), and, in part because of this economic importance, has been widely studied by numerous workers both in industry and academia. Of all the published works, the most important for this study are those dealing with the debate over the environmental nature of the sediments. These have been well summarized by Walker (1983a) up to the most important recent developments and hence will be only briefly reviewed here.

The intense economic development of the Cardium Formation occurred around the time that the theory of turbidites was being established so, somewhat naturally, some of the enigmatic sands and conglomerates in the formation were postulated to be due to this newly discovered phenomenonon (Beach, 1955).

It was also during this period that the first significant subsurface correlations began. Interestingly, the event stratigraphy of the Cardium was almost established very early on by workers such as Michaelis (1957). In a rather dramatic example of "plus ca change plus ca rest la meme", he states, "Cycles are separated by minor disconformities that are marked by erosion, or by the presence of a pebble conglomerate, a shell bed, or a ferruginous siltstone with casts of numerous burrows. It is believed that these breaks are widespread. It is reasonable to use a widespread but minor break of this type as a geological time datum" (Michaelis, 1957). Michaelis concerned himself more with correlation and less with interpretation of the sediments, an interesting lesson for those attempting to study detailed behaviour of sediments within basins whose regional setting remains questionable.

Following the initial discussion of Beach (1955), to paraphrase Walker (1983a), the ideas on the Cardium sands then underwent a long series of alternating interpretations ranging from turbidites deposited far from the shoreline to tidal barrier deposits to shoreline deposits. Various authors suggested different amounts of storm and tidal influence. Around the late 1960's ideas settled into a fairly commonly accepted shallow marine model which was re-examined by Walker in the early 1980's in terms of the turbidite model proposed by Beach (1955).

It was during this 'calm' period that intensive stratigraphic study of the Cardium in outcop was undertaken by Stott (1963) (see below). He did the first thorough field work on the formation and established the initial member division shown in figure 2-4. (see Walker, 1983b for a discussion of some problems with Stott's stratigraphy.)

One of the most important factors in the debate over depositional processes which followed Walker's reconsideration of turbidites in the Cardium was the relative position of the shoreline. The turbidite theory of Walker (e.g. 1983b) implied a roughly northeast trending shoreline in the northern Cardium crudely perpendicular to the field trends, whereas the existing theory postulated a shoreline roughly parallel with the Canadian cordillera. The work of Plint et al. (1986) and Duke (1985) confirmed that the Cardium shoreline did, indeed, run parallel to the cordillera near the current limits of the deformed zone, generally as a prograding barrier system. This resurrected the problem of the nature of the more basinal sediments as represented by most of the oil bearing sand and conglomerate bodies.

The problem of the basic nature of these basinal sands and conglomerates was solved by the same work that resurrected it. The outcrop work of Duke (1985) combined with the subsurface work of Plint et al. (1986), with particularly important details of the conglomerate behaviour provided by Bergman and Walker (1986), indicates that the 'basinward' sediments are lowstand shorefaces. These lowstand shorefaces rest on hiati or diastems within the Cardium Formation. The Cardium may be grossly divided into a progradational sandy phase, the Kakwa member, and a transgressive muddy phase, the overlying Raven River to Amundson members (see figure 2-5). The pebbly members defined in the event stratigraphy erected to reflect these repeated lowstand deposits are extensively worked across their associated Horizons (see discussion and figures below). The event stratigraphy erected by Plint et al. (1986) may be correlated with the outcrop stratigraphy of Duke (1985) and Stott (1963) as shown in figure 2-4. The responses of the various sand bodies of the Cardium to the sea level changes implied therein are currently under investigation at McMaster. The work of Leckie (1986) and

Downing (p. comm., 1986) along with the general "event" stratigraphy work of Kauffman strongly hints that such events may actutually be quite characteristic of foreland basins, making their detailed study important.

This event stratigraphy, discussed in detail below, raises interest in work on relative sea level changes that could lead to such events. The contributions and problems of this body of work are better discussed in chapter 8 at the end of this thesis following a better understanding of the Cardium events.

Before considering the details of the Cardium, some mention should be made of the previous work on similar unconformites. Unconformities have always held the attention of geologists and several summaries exist discussing their extent and cyclicity at different scales (e.g. Schlee, 1984 and Duff et al., 1967). Unfortunately, there are many examples (e.g. Merewether et al. (1979) who talk briefly of several unconformities in the Late Cretaceous Frontier Formation in Wyoming) in which very little mention is made of their possible cause or areal behaviour. Unlike the Carboniferous cyclothems (see Duff et al., 1967 for a good summary) extensive and repetitive marine unconformities have received rather little study recently from the behavioral point of view.

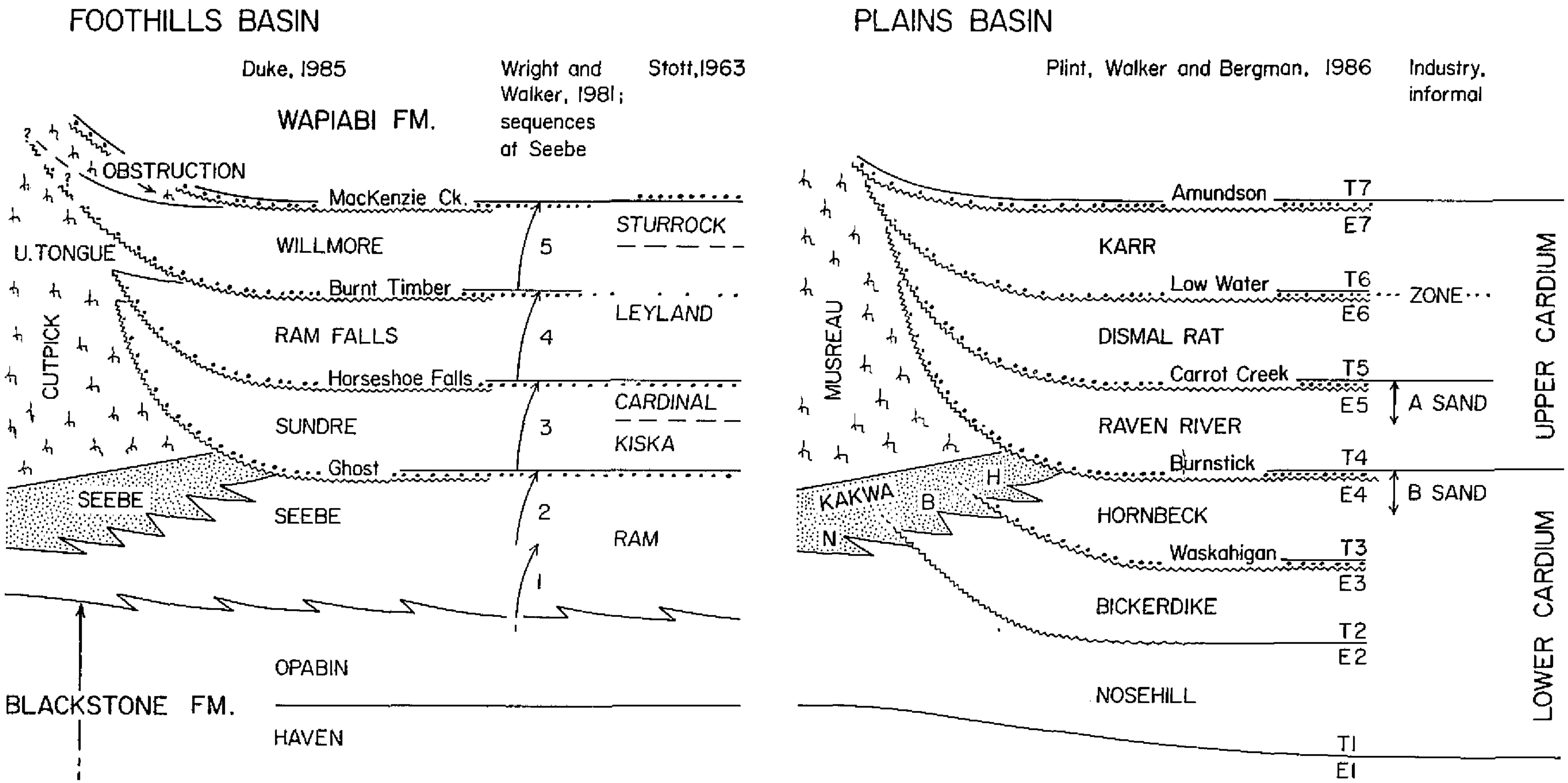
Little is known about mechanisms of submarine erosion that may have been responsible for scouring some of the Cardium surfaces. Only the work of Donovan and Stride (1961) exists as a possible example of scouring of the modern shelf similar to that observed at the base of some of the Cardium conglomerate bodies (e.g. the Carrot Creek Member in Bergman and Walker, 1986).

However, a literature does exist on accumulation surfaces and diagenetic changes during sea level change (see Pemberton and Frey, 1984 and Duff et al. 1967 for an entry into some of this literature). This allows for the behaviour of the Cardium events to be compared to what is already known in terms of a rather new approach to stratigraphy. Work on carbonate hardgrounds and firmgrounds is well developed and important for comparative studies with siliciclastic events; it will be discussed after details of the Cardium Horizons have been presented so that the reader may have a better grasp of the comparisons.

3. CARDIUM EVENT STRATIGRAPHY

Because this thesis focuses on the event stratigraphy mentioned above, further discussion of its details is in order.

Pending the finalization of the correlations shown in figure 2-4, I have relied only on the subsurface


FOOTHILLS BASIN
Duke, 1985
Wright and Walker, 1981; sequences at Seebe
Stott, 1963
WAPIABI FM.
OBSTRUCTION
MacKenzie Ck.
STURROCK
U.TONGUE
WILLMORE
5
Burnt Timber
LEYLAND
CUTPICK
RAM FALLS
4
Horseshoe Falls
CARDINAL
SUNDRE
3
KISKA
Ghost
SEEBE
SEEBE
2
RAM
1
OPABIN
BLACKSTONE FM.
HAVEN
PLAINS BASIN
Plint, Walker and Bergman, 1986
Industry, informal
Amundson
T7
E7
KARR
Low Water
T6
ZONE
E6
MUSREAU
DISMAL RAT
Carrot Creek
T5
E5
A SAND
RAVEN RIVER
Burnstick
T4
E4
B SAND
KAKWA
H
B
N
HORNBECK
Waskahigan
T3
E3
BICKERDIKE
T2
E2
NOSEHILL
T1
E1
UPPER CARDIUM
LOWER CARDIUM

stratigraphy of Plint et al. (1986) shown in greater detail in figure 2-5.

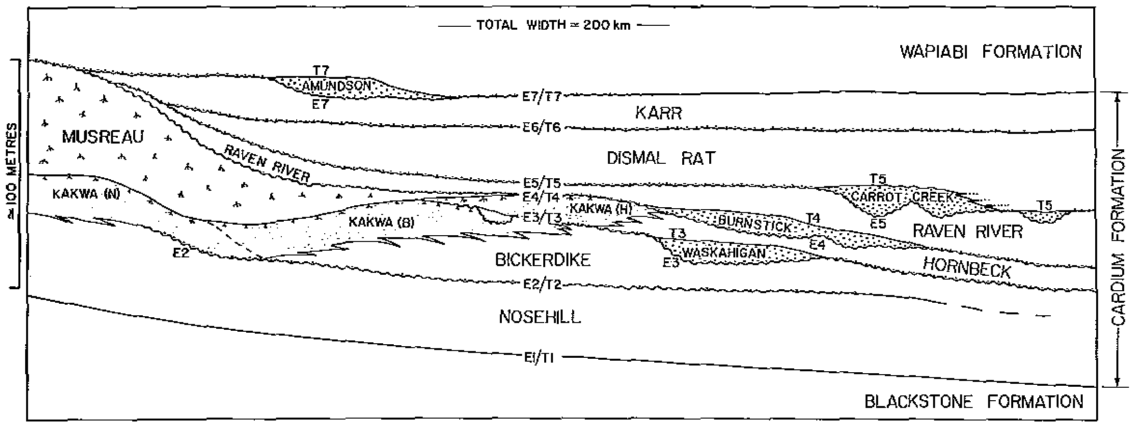


Figure 2-5. The Event Stratigraphy of the Cardium Formation (from Plint et al., 1986).

In this stratigraphy, each pebble bed, whether meters or a single grain thick, is assigned member status, e.g. the Bickerdike Member. The intervening shallowing upwards sequences also become members of the Cardium, e.g. the Dismal Rat Member. This idealized diagram shows a general sigmoid shape for the conglomerate members. Other work (e.g. Bergman and Walker, 1986) suggests their lowstand shoreface nature. The members between the conglomerate members have typical coarsening-upward (sandier upward) facies sequences as discussed by Plint et al. (1986).

Plint et al. (1986) use the terminology of Erosional and Transgressive surfaces for the events at the top of each cycle because the conglomerate sometimes lies on a demonstrably erosive surface and is in turn transgressed by mud and silt which shallows upwards into the sandier top of the next cycle. I will modify this terminology somewhat because, as I will demonstrate, some surfaces are not neatly erosive and transgressive. Under my modified scheme, each event is labelled as a Horizon which may be composed of different styles of events, either Erosive followed by Transgressive events or rapid but gradational events. When distinguishable, the Erosion thus lies at the base of the Horizon and the Transgression at the top. Both Erosion-Transgression and gradational response may occur at the same Horizon, the gradational area corresponding to a "correlative conformity" (Vail et al., 1977). Figure 2-6 shows the application of this terminology, and how different styles grade into one another laterally.

Hereafter, Horizons will be abreviated as H, e.g. H6, and particular cases of Erosion-Transgression as E,T, e.g. E5.

This thesis will focus on the transgressive Horizons H4 through H7. This allows all the Horizons to be considered within a similar framework (i.e. transgression). Additionally, the core database for the transgressive

Horizons is large because they overly the usual oil company drilling targets or form them themselves.

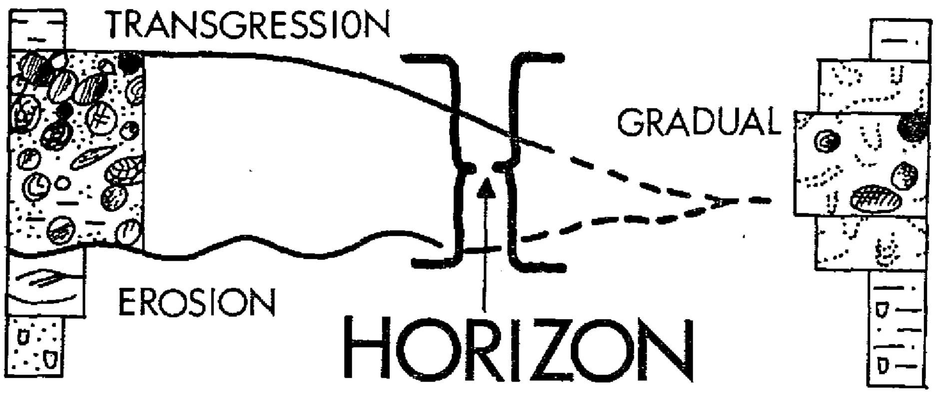


Figure 2-6. The relationship between a Horizon and gradational or erosive-transgressive events.

4. THE NATURE OF THE STRATIGRAPHIC EVENTS

The Cardium event stratigraphy probably extends over regions significantly larger than that described in the defining work of Plint et al. (1986). Similar, probably correlative, event stratigraphy may be seen both in the vicinity of Dawson Creek, Alberta and in the Waterton Lakes area in southern Alberta (A. G. Plint, p.comm., 1986). In fact, Stelck (1955), in earlier paleontological work on the Cardium, states that diastems of the Cardium can be traced into a major disconformity reaching down to the Dunvegan Formation in northwestern British Columbia. It may even be likely that some of the unconformities may eventually be traced into equivalent formations in the United States such as the Frontier Formation which contains several unconformities as reported by Merewether et al. (1979).

The events of the above stratigraphy may be naturally seperated into two major divisions, a regressive phase represented by the Nosehill through Hornbeck members and a transgressive phase from the Burnstick to the Amundson members (fig. 2-5). The transition occurs at the maximum progradation of the Kakwa shoreface of Plint et al. (1986) immediately after the deposition of the Burnstick member. The transgressive phase thus contains four Horizons, H4, H5, H6 and H7.

The estimated time span of these events is very small, geologically speaking. The entire Cardium may have been deposited in about one million years (figure 2-2) as an order of magnitude estimate. Dividing this by the number of surfaces, seven, gives an approximate order-of-magnitude maximum time between events of 140,000 years. This assumes no hiati. The duration of these packages is so small that few even display approximate time markers independent of the surfaces themselves. This makes the use of "Wheeler" diagrams as used by Sloss (1984) in his discussion of

Cretaceous unconformities impractical. It also makes the "lacuna" of Wheeler (1958) indiscernible at this scale. So on the scale of a formation, event expression is subtle in many ways.

Consideration of this subtlty first requires a consideration of the facies of the rocks.

CHAPTER 3

FACIES DESCRIPTIONS AND INTERPRETATIONS

1. THE APPROACH

The sediments examined have been broken down into descriptive facies on the basis of sedimentary structure, grain size and trace fossils. Interpretations usually rely on consideration of the sedimentary structures and trace fauna present but in this case will be slightly modified by reference to the micropaleontological data presented in the following chapter. Interpretations follow the descriptions.

Most of the facies discussed below have already been described by researchers at McMaster University working on the Cardium formation (i.e. Walker, 1983c, Walker, 1985, Plint and Walker, 1986 and Bergman, 1986); consequently the facies numbers assigned by these workers have been retained and subdivided where necessary. Because the facies have, for the most part, been written up in detail in the above references only brief descriptions will be presented here for the conveniece of the reader. Information not of direct interest for this work, such as typical thicknesses, has been omitted except for new facies. Since facies sequences have already been discussed by Plint et al.

(1986), the presentations here are primarily intended to provide a clear reference for the later discussions of faunal and diagenetic data and to allow for a better understanding of sediment response to the event Horizons. For new facies, mostly subdivisions of exisiting ones, a complete description will be presented.

Standard sedimentary facies criteria have been used in erecting the facies; petrographic variations, in particular consistent products of paradiagenesis (or early diagenesis) such as siderite, and micropaleontological data have not been included. Paradiagenetic products are more usefully considered as overprinting of more 'purely' sedimentary facies due to variations in chemical conditions of the water column and sediment-water interface. This overprinting is reflected in drafted sections (see Appendix 1). Exactly the same reasons apply for the exclusion of the micropaleontological data which varies with changes in the water column insufficient to effect either the nature of the sediments deposited or the style of bioturbation. Both early diagenesis and micropaleontology vary importantly over the Cardium transgressive Horizons, however, and will be discussed in detail in later chapters where their refinement of the environments indicated by the sedimentary facies can be considered fully.

In addition to the photographs presented in this chapter, a facies legend for drafted sections can be found in appendix 1.

Facies are discussed in numerical rather than any environmental order, and, where appropriate, references to the original and more complete description follow the facies name.

The reader should note that many of these facies occur in essentially muddy units, and consequently, particularly for the gradational, low sand content, marine facies, there would be extreme difficulty in distinguishing any equivalents in outcrop sediments where only the grosser variations in muds and silts are apparent.

2. INDIVIDUAL FACIES

Facies 1: MASSIVE DARK MUDSTONES (Walker, 1983c)

Just as the name implies, this facies consists of monotonous, structureless mudstone. The only traces present are an occasional indistinct mottling, perhaps attributable to *Gordia* which occasionally appears as less than millimeter thick pyrite lines in "bedding" planes. Animals have probably completely bioturbated the sediment. (see Plate 3-1A)

Interpretation:

Walker (1983c) cites micropaleontological data indicating this facies is "inner shallow marine" (no definition given). It is most accurately considered to represent basinal silt and mud generally deposited in depths below storm wave base due to the lack of sand. However, as with facies 3, below, care must be taken that the lack of sand does not also represent a simple lack of supply in a transgressive, mud-dominated system. Analysis of the faunal content may help to distinguish between ambiguous cases. For example, results in the next chapter indicate that the facies may occur in probably relatively shallow 'brackish' water.

Facies 2: LAMINATED DARK MUDSTONES (Walker, 1983c)

These are mudstones which contain up to about 15% silt/sand laminae. In the original definition of Walker (1983c),the sand reaches a maximum size of very fine. I have modified this definition slightly to include larger sizes to reflect an identical behaviour of the sediment which appears independent of grain size. Nevertheless, most occurences are typically silty muds. The laminae almost never reach bed size (greater than one centimeter) and are frequently discontinuous being disrupted by an indistinct bioturbation like that of the dark massive mudstones. Some small subvertical mud-filled burrows occasionally penetrate thicker laminae. The laminae are massive to sub-parallel laminated.

(see Plate 3-1B)

Interpretation:

In the original work of Walker (1983c), facies 2 was described broadly using faunal data as "coastal subaqueous" (no definition given). There are numerous possibilities as to why the sediment is preserved in relatively delicate laminae or beds. The water column may have been too turbid due to common storm activity to support sufficient infauna. Storm currents likely led to the deposition of the graded to roughly parallel laminated laminae and beds in a broad, muddy 'bench' setting close enough to the transgressing shoreline to supply terriginous material and fresh water for dilution of the 'normal' marine water (see next chapter). This dilution may have helped suppress extensive marine bioturbation.

It is possible that the lack of bioturbation reflects a high energy in the area of deposition rather than water column conditions, or both may be occuring. For example, Howard (1978) reports cases of sediment in a high energy estuarine setting being apparently completely unbioturbated compared to sediment in calmer areas but which, in fact, are microbioturbated.

Facies 3: DARK BIOTURBATED MUDDY SILTSTONES (Walker, 1983c)

These siltstones resemble those of facies one but contain visible bioturbated patches of silt to very fine sand.

(see Plate 3-1C)

Interpretation:

The similarity of facies 3 to facies 1 leads to a similar interpretation, but due to its sandier nature and position in sandier upwards sequences (Walker, 1983c, and Plint, et al., 1986), it likely generally represents slightly shallower settings.

As noted above for facies 1, care must be taken in assigning depth interpretations to the facies. The micropaleontological data discussed in the next chapter indicates that the conditions in the water column changed significantly while continuous deposition of facies 3 occurred (see the discussion of samples 7/11-7-63-5W6/f-i in Chapter 4). The gradual increase in the foraminiferal population described is stratigraphically consistent with increasing depth or distance from brackish shoreline effects. Facies 3, then, may concievably represent any environment from nearshore to basinal silts. Its identical appearance probably depends on the size input of the sediment and the ability of hardier worms, possibly polycheates, to survive in stressed environments (Kauffman, 1977) and produce bioturbated texture.

Facies 4: PERVASIVELY BIOTURBATED MUDDY SILTSTONES (Walker, 1983c)

This facies is gradational with facies 3 and contains some preserved bedding showing the parallel to low angle lamination of wave ripples. Distinct trace fauna includes Terebellina, Teichichnus and Rhizocorallium in varying proportions.

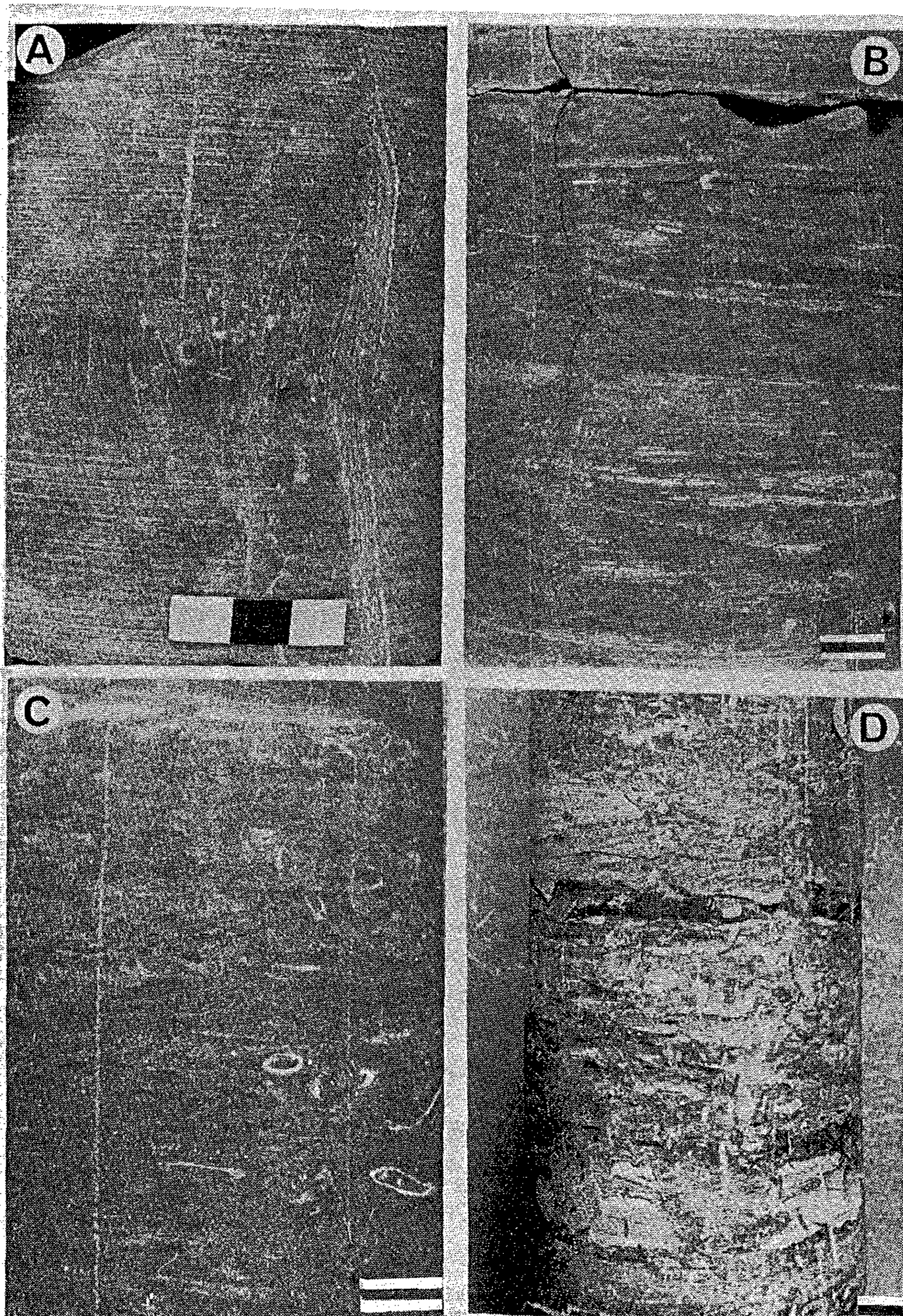
(see Plate 3-1D)

Interpretation:

Facies 4 does not commonly occur near the Horizons examined so its interpretation is of less importance. The muddiness of the unit, the structures and, most importantly, the trace fossil assemblage place it as a shallow marine storm influenced sand in Seilacher's Cruziana ichnofacies (Pemberton and Frey, 1984 and Walker, 1983c).

Facies 5: BIOTURBATED SANDSTONE (Walker, 1983c)

Facies 5 is gradational with facies four and contains more sand, over 50%. Preserved sand beds are thicker but maintain similar sharp-based graded to wave rippled structures. The trace fauna is slightly more diverse and includes Zoophycus, Chondrites and small Skolithos in


A
B
C
D

addition to traces found in facies 4. Note the facies is not a clean sandstone.

(see Plate 3-2A)

Interpretation:

Facies 5 represents a shallower (i.e. sandier) equivalent to facies 4 again being in the Cruziana ichnofacies (Walker, 1983c).

Facies 6 (general): SPECKLED GRITTY MUDSTONE (Walker, 1983c)

This facies has been subdivided and expanded to include siltstones that have a strongly bimodal size distribution with medium to coarse sand in varying proportions in addition to the granular to pebbly mudstones of Walker's original definition (1983c).

Facies 6A: DISPERSED SANDY MUDSTONE

Usually occuring immediately above a transgressed sand bed, this facies contains no distinct trace fauna and consists of very finely disseminated sand set in dark mud and silt. The sand is typically fine to medium in size but is usually merely a function of underlying sediment size. Sand accounts for less than 5% of the rock, and its dispersed nature precludes any sedimentary structures. The facies is typically 3 to 10 cm thick. Facies 6A occurs most commonly at the fourth Horizon and occasionally within the sixth.

(see Plate 3-2B)

Interpretation:

Facies 6A is interpreted entirely on the basis of context since it contains neither sedimentary structures or trace fauna. It is sand dispersed into overlying mud by current activity and bioturbation.

Facies 6B: SPECKLED SANDY MUDSTONE

Facies 6B consists of distinctly bimodal sediment, usually medium to coarse sand, intensely bioturbated into mud or silt. Sand content may vary from roughly 10 percent to 80 percent, all bioturbated with only very rare remnants of bedding or lamination. When present these rare laminae are sharp based and generally massive; they sometimes show a crude sub-parallel lamination and are either sharply or sometimes rapidly gradationally topped. Occasionally, fragments of beds and laminae which have been almost completely bioturbated occur. Maximum bed size is on the order of two centimeters. Rare very coarse sand, granules or pebbles may occur within the bioturbated sand or remnant bedding and in rare cases the facies grades into the Speckled Gritty Mudstone of Walker (1983c). The facies is typically around 60cm thick but can vary drastically.

Within the generally indistinguishable bioturbation, there consistently occur several traces. These include 2 to 3 mm by 2 to 3 cm *Skolithos*, *Planolites* of similar dimensions, occasional Terebellina of 1 to 3 mm diameter, Helminthopsis, 2 to 20cm Arenicolites, and rare but dramatic Bergauria (see Plates 3-3B and 3-3A for respective examples of the latter two).

The faunal content is ubiquitously low (see chapter 4).

Facies 6B is gradational with facies 6C and facies 10 and 14 and rarely so with facies 6A.

Facies 6B predominates throughout H6 and occurs commonly in H7.

(see Plate 3-2C)

Interpretation:

Although this facies contains very variable amounts of sand of somewhat differing size, the environment of deposition is consistent. The interpretation relies primarily on the visible trace fauna with consideration of the relative amount and type of sand within the facies and below and above it.

The marked 'bimodality' of grain size combined with the complete bioturbation implies that small beds or lamina of sand were dispersed basinwards (probably by storms given the nature of the basin as a whole and the commonly overlying facies 6C, 15 and 10) into an infaunally rich region where animals completely churned the mud and sand before the next storm could add more sand.

The discernible trace fauna indicate that within this setting there were many active polycheates, probably responsible for the general bioturbation in addition to the specific traces such as Terebellina and Arenicolites. Polycheates, which typically line their burrows with sand (Dr. M. Risk, p. comm., 1985), probably produced the Terebellina traces. Anemones were also present as indicated by the Bergauria traces.

As discussed in the next chapter, there is also a general paucity of foraminifera within this facies which is probably due to its location on a relatively shallow 'bench' at the edge of a brackish sea. The facies is thus likely confined in depth to just below storm wave base on this 'bench', a depth of about 20m (?).

The predominance of polycheate traces and the paucity of foraminifera suggests a reduced oxygen, probably somewhat turbid relatively high energy setting; Kauffman (1977) has noted that polycheate traces are the last to disappear as increasing stress, mostly in the form of oxygen levels, is placed on a biological community. However, as with the variations demonstrable in facies 1-3, this environment may not be characteristic of occurences of facies 6 in other regions.

Facies 6C: MUD SPECKLED SANDSTONE

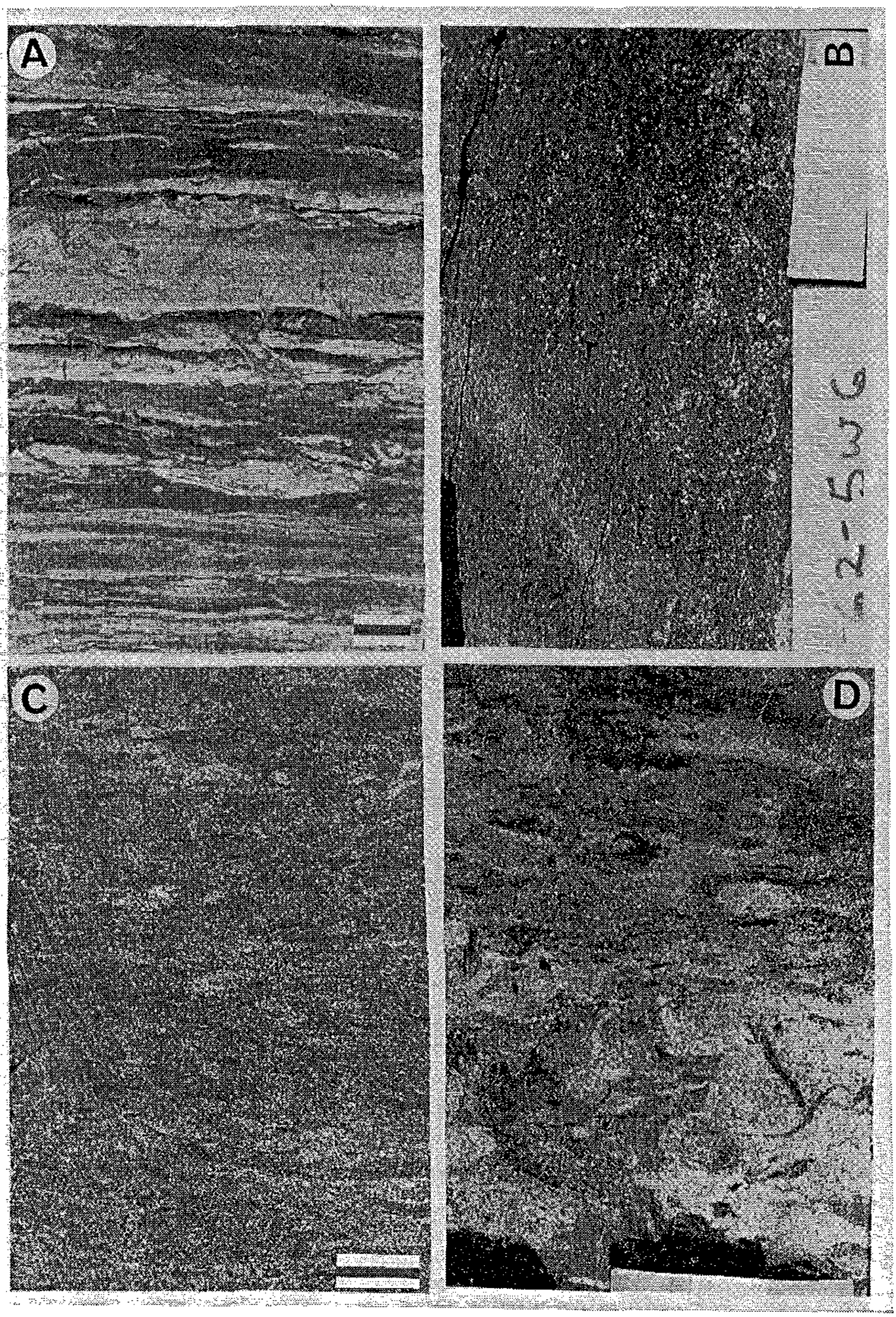
Consisting of about 80% to 95% sand, facies 6C forms the 'cleaner' equivalent of facies 6B but occasionally occurs as a recognizable bed with a definite base. It too usually comprises medium to coarse sand with rare coarser grains up to small pebbles in size. When beds are not gradational with other facies of the 6 series or facies 10 or 14, they are sharp based, sometimes containing small millimeter to three millimeter size angular clasts of the underlying silt. Although rarely showing a crude lamination, the generally massive appearance probably corresponds to intense bioturbation or original depostional texture in 'cleaner' cases.

The only visible bioturbation is 1mm size mud-filled Helminthopsis burrows.

Facies 6C occurs primarily in H6 and H7 and is usually thin, on the order of 20 cm or less. When definite beds occur, they lie in the thinner end of the spectrum. (see Plate 3-2D)

Interpretation:

The facies represents a shallower equivalent of 6B in which much higher sand supply has inhibited the distinct traces of that facies. When beds are present, their sharp based nature with occasional mud rip ups at the base suggests storm epmlacement analagous to the storm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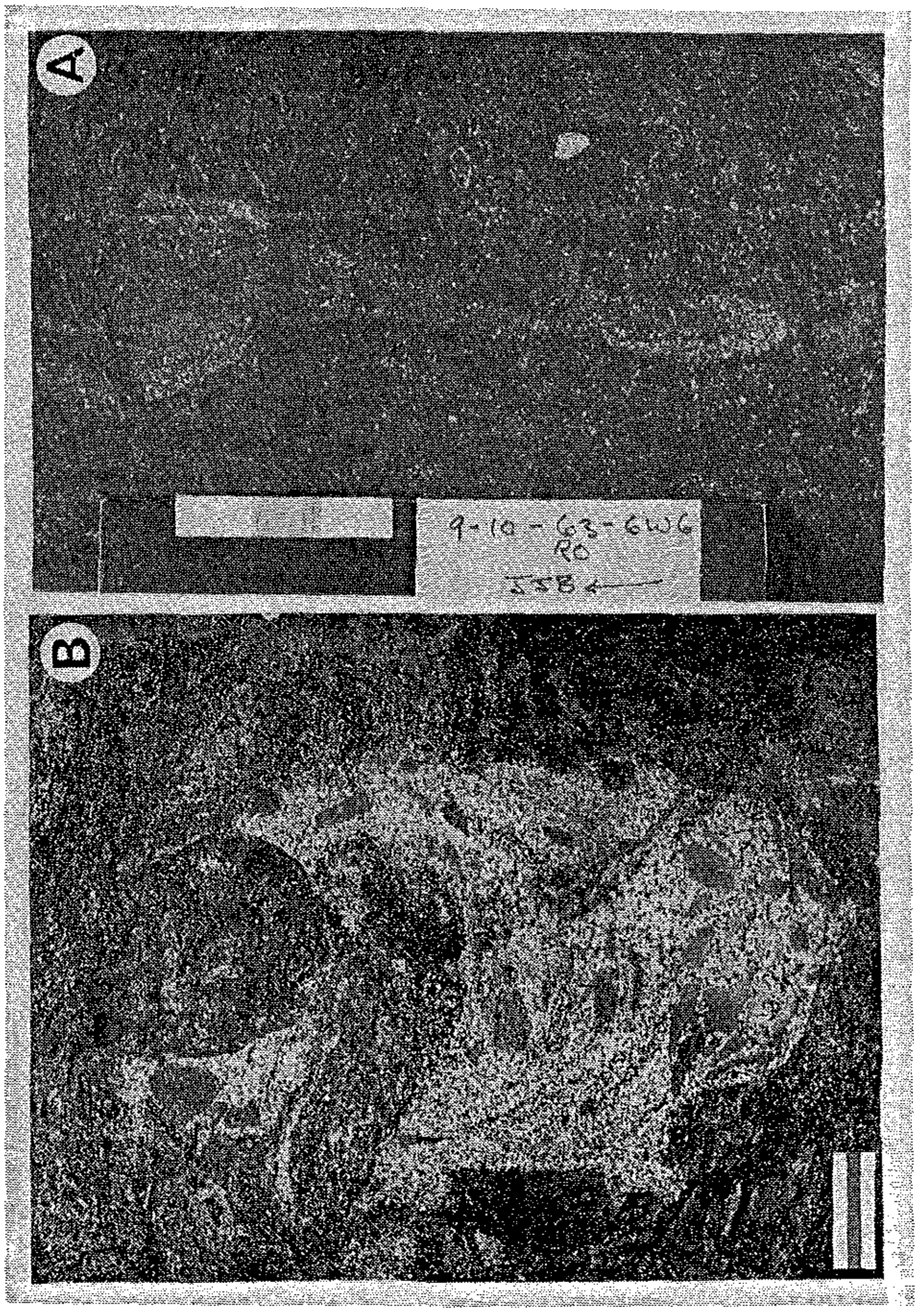

A
B
9-10-63-6W6
RO

structures observed by Reineck and Singh (1972) in the North Sea. This is particularly likely given their basinal setting on a flat 'bench' (see next chapter) and their association with facies 15, and general storm dominated nature of the basin.

Facies 6D: STRUCTURED SPECKLED MUDSTONE

This facies contains anywhere from traces to about 20% fine to coarse sand in mud; unlike the previous series 6 facies the sand is not bioturbated but is interlaminated with mud in sedimentary structures. The interlamination is on a single grain scale with the mud laminae between sand grain laminae being about the same thickness or slightly more than the sand laminae. The sand may occur as just a single sand lamina over a bedform. It has been included in the facies 6 divisions because of the distinct bimodality of the grains and its association with other forms of facies 6. The facies is very rare, and when it occurs shows wave to possible combined flow ripple forms over no more than 5 cm thick.

Facies 6D occurs in H6.

(see Plate 3-4A)

Interpretation:

This facies is analagous to facies 6A but contains hints of sedimentary structures within mud in distinct interlamination implying concurrent movement. Mud was probably of approximately the same size as the sand grains due to pelletization. The rare occurrences of facies 6D are as wave reworked caps to relatively rapidly transgressed muddy sand sequences of H6. Some 'structures' are ambiguous but may represent combined flow bedforms.

Facies 7: NON-BIOTURBATED SANDSTONE (Walker, 1983c)

Generally, facies 7 is a very fine grained sand interbedded with mud on the centimeter to ten centimeter scale. The sands are sharp based and show low angle intersecting lamination (HCS) and/or wave ripples. Mud rip ups may be present. Bioturbation is almost absent.

In keeping with the name of the facies I have also included "non-bioturbated" sandstones showing different structures that occur just below the transgressed Horizons examined. These most commonly include low angle laminated sands and trough cross bedded sands (as illustrated in Appendix 1) although in a study considering facies sequences up to the Horizons these would more properly be included in facies 16 and 17 of Plint and Walker (1986). (see Plate 3-4B)

Interpretation:

As described by Walker (1983c), facies 7 represents sediment deposited between storm and fairweather wave base by (or reworked by) storm wave currents. In my expanded use it also includes structured sand with fairweather depths up to and including beach lamination. The more detailed sequence study of Plint and Walker (1986) places these sands into inner shelf and shore facies (facies 16 and 17) which is sedimentologically preferable.

Facies 8 (general): CONGLOMERATE (Walker, 1983c)

This originally general facies has been subdivided in the detailed work of Bergman (1986) and these facies have been numbered to fit her work.

Facies 8A1: SANDY INTERBEDDED PEBBLES, SAND AND MUD (Bergman, 1986)

This facies comprises clast to sand supported conglomerate with at least 10% granules to pebbles in the core surface. Chert and/or quartz granules and pebbles are present (as opposed to pure mud pebbles). The facies shows a rough sense of bedding and the sand and granules/pebbles commonly occur in centimeter to ten centimeter scale alternating pulses.

(see Plate 3-4C)

Interpretation:

The interpretation of all Cardium conglomerates has only recently been revised and is best referred to in Bergman and Walker (1986). The interpretation hinges heavily on regional studies (see for example Plint et al., 1986) which suggests that they represent relative lowstand deposits laid down by longshore drift under the influence of storms.

Facies 8A1 represents shallower, higher energy (sandier) deposits of the conlomerates, The pulsed nature likely reflects individual storm events.

Facies 8A3: MUDDY INTERBEDDED PEBBLES, SAND AND MUD (Bergman, 1986)

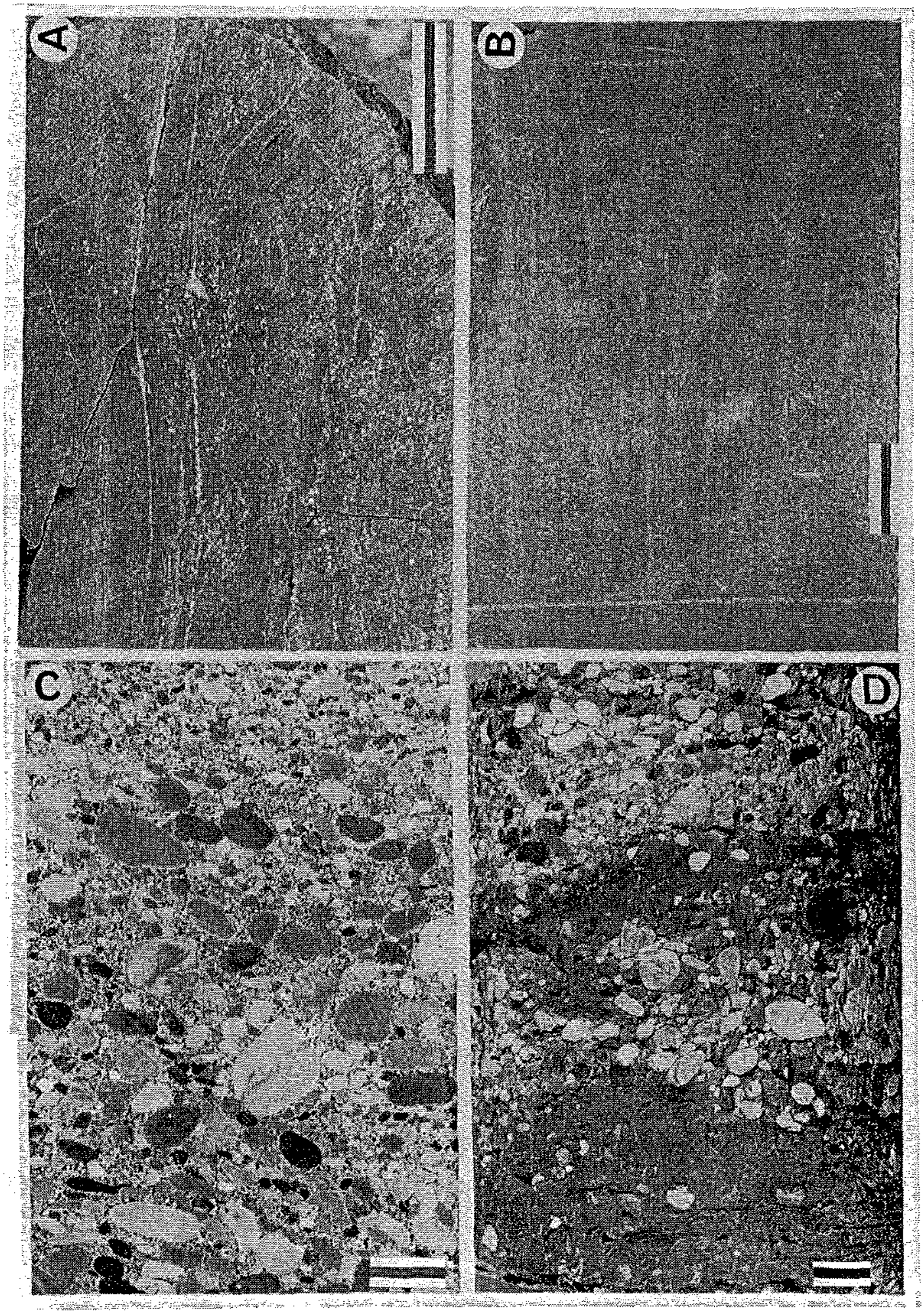
Facies 8A3 is similar to 8A1, but mud dominates the facies rather than sand. The facies may have a dramatically pulsed appearance and portions may be intensely bioturbated. The pebbles are accompanied by minor sand, usually medium to coarse. No structures appear although rare Thalassinoides burrows occur in the mud filled with sand and granules (see Plate 6-1B).
(see Plate 3-4D)

Interpretation:

Facies 8A3 represents the muddier, generally slightly deeper, or perhaps earlier, equivalent to 8A1.

Facies 8B: PEBBLY MUDSTONE (Bergman, 1986)

Facies 8B consists of pebbles or granules set in mud with much less sense of bedding than facies 8A3; the rock is frequently completely bioturbated. The facies may be dominated by mud to such an extent that only a single pebble or granule "lamina" occurs between centimeters of mud.


A
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D

(see Plate 3-5A)

Interpretation:

This facies is interpreted as occuring in regions of lesser or slower conglomerate supply where mud build up and bioturbation can predominate. This may occr either 'offshore' of the main conglomerate bodies or shorewards once the system has been transgressed and small amounts of granules and pebbles are reworked back over a wave damped platform.

Facies 10: MASSIVE SANDSTONE (Walker, 1985)

In this facies, the sands occur in centimeter to ten centimeter scale beds that are sharp-based and show no signs of grading. Sand size is usually medium to coarse, and sand beds are usually intercalated with 1 to 10 or more cm of mud and are themselves of 10 to 40 cm thickness. They are thus smaller than the beds described in the original definition Walker (1985). (Sample 6/10-3-62-4W6/g from this facies contains a rich mica component.)

Beds may contain one to five centimeter size well-rounded mud clasts which may be sideritized and are not described in the original definition. These mud clasts may rarely show signs of sand armouring.

(see Plate 3-5B)

Interpretation:

Walker (1985) interpreted the sands of this facies as having suddenly settled out of suspension in turbidity currents. Unlike Walker, I interpret the initial suspension of the sands in these thinner beds to be due to the immediate effect of storms leading to massive beds (see Reineck and Singh, 1972). This is in keeping with the occurrence of this facies at or near the top of shallowing upward sequences in a shallow, flat (discussed in the next chapter) storm dominated basin. The occasional mud clasts of the underlying substrate imply that the storms had sufficient energy to tear up already sideritized material.

The large micaceous component of some beds seems to imply a direct sourcing from shoreline sediments.

Facies 15: INTERBEDDED SANDSTONES AND BLACK MUDSTONES (Plint and Walker, 1986)

This facies comprises alternating fine to coarse sand beds and mud beds. The sand beds are sharp-based and frequently sharp-topped; little structure is visible but rare parallel lamination occurs in the up to 5 centimeter beds along with very rare linsen in the muds suggesting the presenece on some form of rippling. The beds are somewhat thinner than those in the original definition and seem to have a less pronounced trace fauna. The mud interbeds may be sideritized. Trace fauna includes

1/2 cm Planolites and similar scale Skolithos but is somewhat sparser than in the finer grained but similar facies described by Plint and Walker (1986). This facies occurs in H6 and H7.

(see Plate 3-5C)

Interpretation:

The facies forms part of the transition to a storm-dominated shoreface. Each of the sand beds representing deposition of a massive bed close to the shore in the style of beds recognized by Reineck and Singh (1972) in the North Sea. The comparitive thinness and lack of trace fauna compared to the original definition by Plint and Walker (1986) is probably due to the setting. The original facies was defined in a fully marine location while this case represents deposition in a brackish, generally muddier, flat `bench' (see the next chapter).

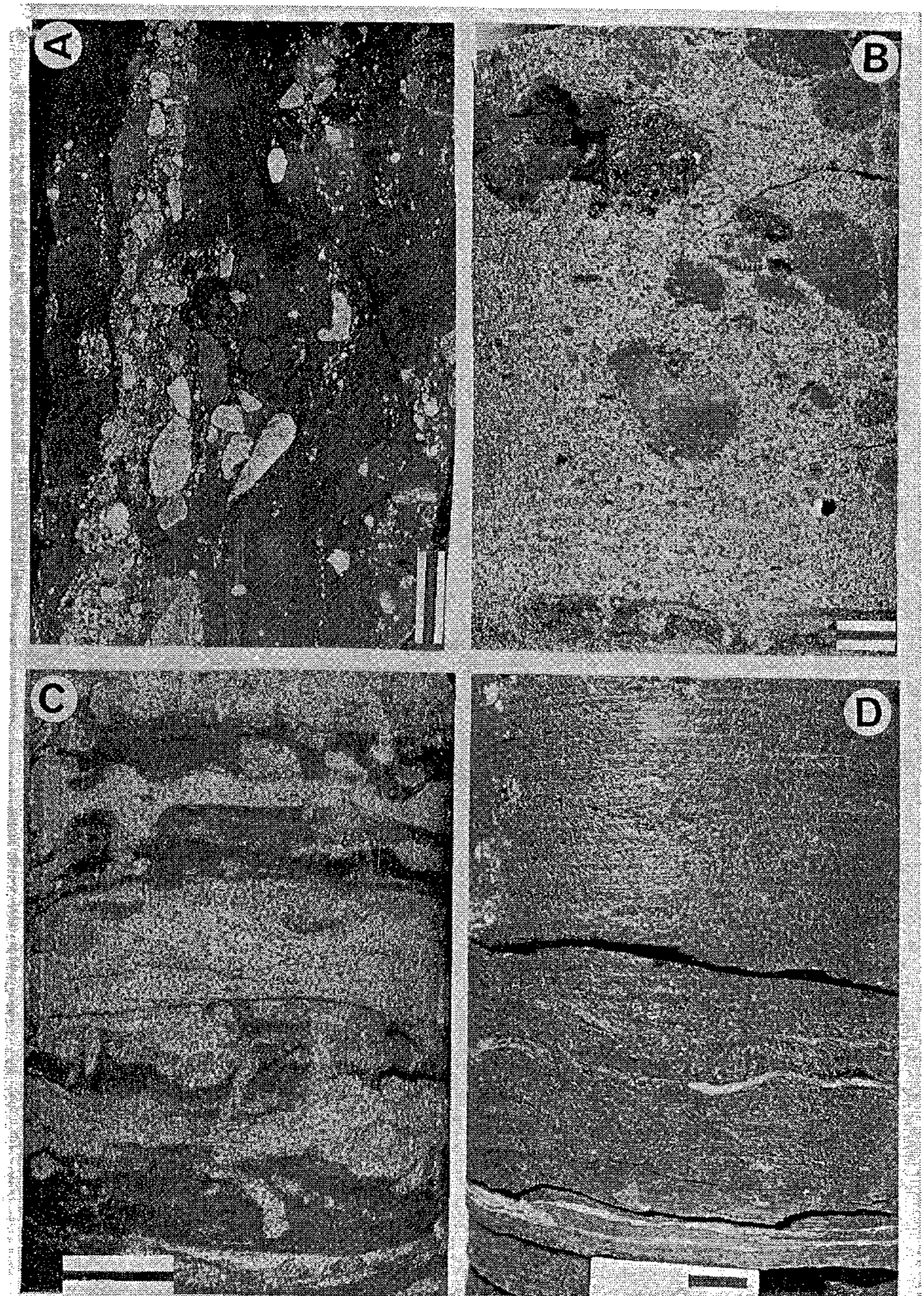
Facies 18: COAL (Plint and Walker, 1986)

This facies consists of centimeter to tens of centimeters of coal which may or may not contain silty laminae and almost always overlies a rooted horizon. This facies occurs at H4.

(see Plate 3-5D)

Interpretation:

Coal represents fairly heavily vegetated areas such as marshes near shore in a non-marine setting.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Facies 19: BLACK NON-MARINE MUDSTONES (Plint and Walker, 1986)

Facies 19 is composed of dark grey to black mudstones which frequently contain thin laminae of different colour which may be either sharp or gradational. Several species of non-marine fossils are present (summarized by Plint and Walker, 1986). Finely disseminated carbonaceous debris is common. Rare Cypridacea ostracods occur.

(see Plate 3-6A)

Interpretation:

Facies 19 represents lagoonal to estuarine mudstones as indicated by the delicate lamination and fauna. The relatively large amount of carbonaceous debris also suggest a non-marine setting.

Facies 20: CARBONACEOUS BLACK MUDSTONES AND SANDSTONES (Plint and Walker, 1986)

Essentially a sandier equivalent of facies 19, this facies also contains larger carbonaceous fragments in general. Post-depositional structures such as slumping are very common. Sand size may be up to fine.

(see Plate 3-6B)

Interpretation:

Plint and Walker (1986) interpret these sediments as forming in a "lagoonal or coastal lake with a marine connection". The common occurrence of deformed bedding supports a non-marine interpretation, the deformation having a small scale slumped appearance as expected from the generation of 'swamp' gas. Fauna also support this conclusion (Plint and Walker, 1986).

Facies 22: ROOTED MUDSTONES (Plint and Walker, 1986)

Facies 22 comprises relatively well cemented grey mudstones with a black or waxy grey appearance containing roots of millimeter to 8 centimeter size.

(see Plate 3-6C)

Interpretation:

The waxy grey variety are probably floodplain paleosols and the darker, blacker variety are probably products of marshier more poorly drained settings (Plint and Walker, 1986).

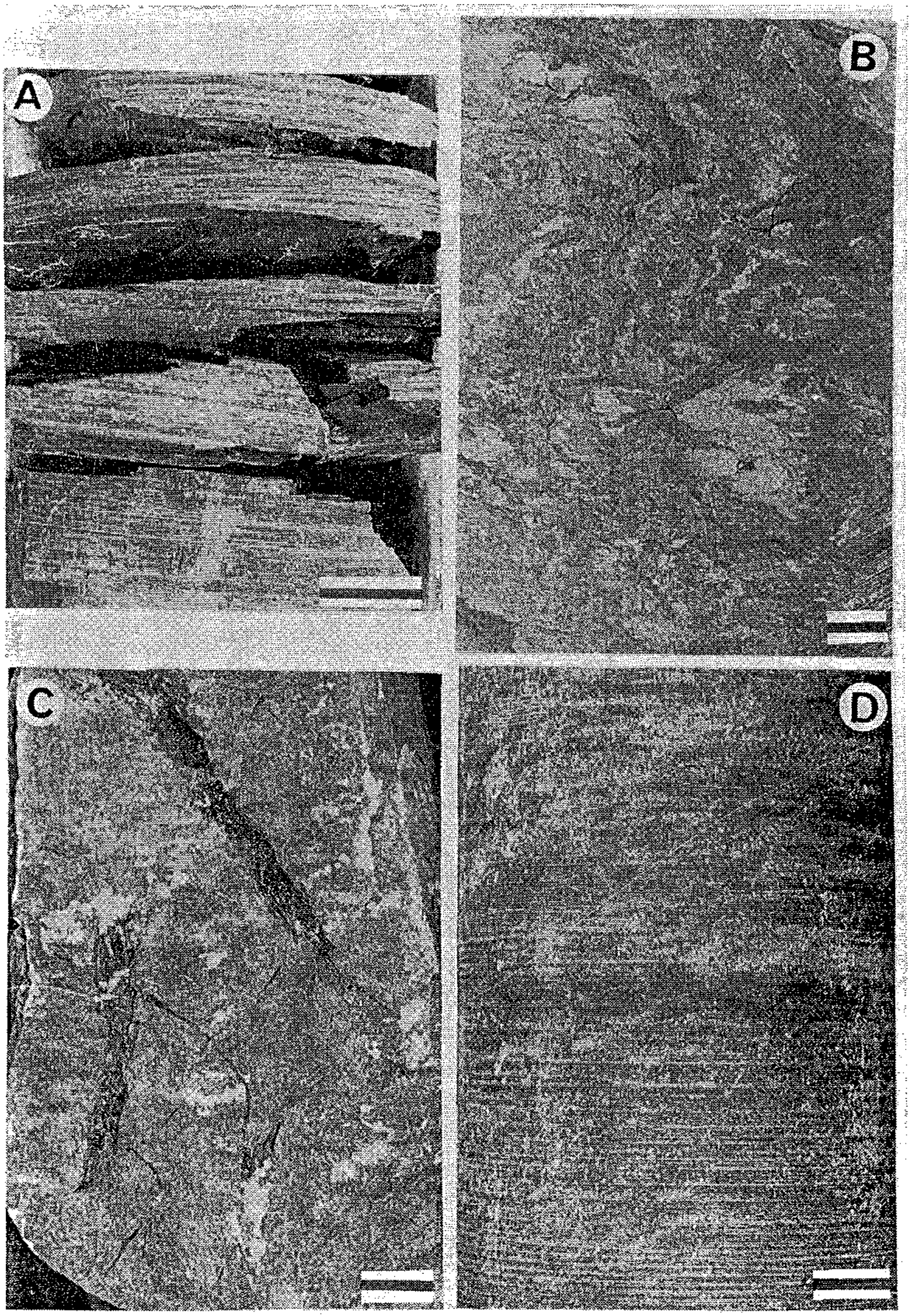
Facies 23: GREY NON-MARINE MUDSTONES

Although similar to facies 20, this facies contains no immediately visible carbonaceous debris. Apart from its consequently lighter colour it is identical.

(see Plate 3-6D)

Interpretation:

The lack of relatively significant carbonaceous material led to a redefinition in order to map the occurence of carbon rich sediments. Facies 23 may represent more lacustrine, as oppossed to marsh settings. (Although no pattern emerged on the scale of this study, I


A
B
C
D

have maintained the facies under the assumption that as a standard facies it may be useful in more extensive examination of the non-marine facies of the Cardium formation.

Gradational Facies

Although rocks may be divided into descriptive facies many facies are in fact gradational into each other. In the region studied the following facies form gradational series which at times can be difficult to divide or place in one facies or the other.

Facies 1, 3, 6B and 8B; facies 14 and 10; facies 19, 20 and 23.

Before the facies can be most usefully assembled into sequences and hence related to the behaviour of the basin as a whole, the fauna associated with particular facies should be considered.

CHAPTER 4

MICROPALEONTOLOGY

1. PURPOSE

The microfaunal study concentrates on foraminiferal work; dinoflagellates common to the Cardium (Wall and Sweet, 1982) were not examined. However, a few occurences of non foraminiferal remains, specifically ostracod fragments, were considered and identified. Foraminiferal work was not intended to establish zones but rather to determine behaviour of the fauna within the Pseudoclavulina sp.1 zone (Caldwell et al., 1978) (see discussion below). Foraminifera quantities were examined across the boundaries of Cardium members in order to shed light on any environmental variations or changes in sedimentation rate. **The reader should bear in mind that most samples are within one to two meters of the Horizons examined.**

2. BACKGROUND

Before discussing the results of the analyses, I should refer to works that have set the micro-paleontological framework of the Cardium.

According to Caldwell et al. (1978), the Cardium Formation lies between the Pseudoclavulina and Trochammina sp. 1 zones, which are assemblage zones, but Wall and Sweet

(1982) seperate these zones by a gap, an un-named fauna and the Nyassollinites Suite, all corresponding to the time of deposition of the Cardium members as defined by Stott (1967) (see the above discussion of Stott's cycles). These differing zonal divisions may be seen in figure 4-1.

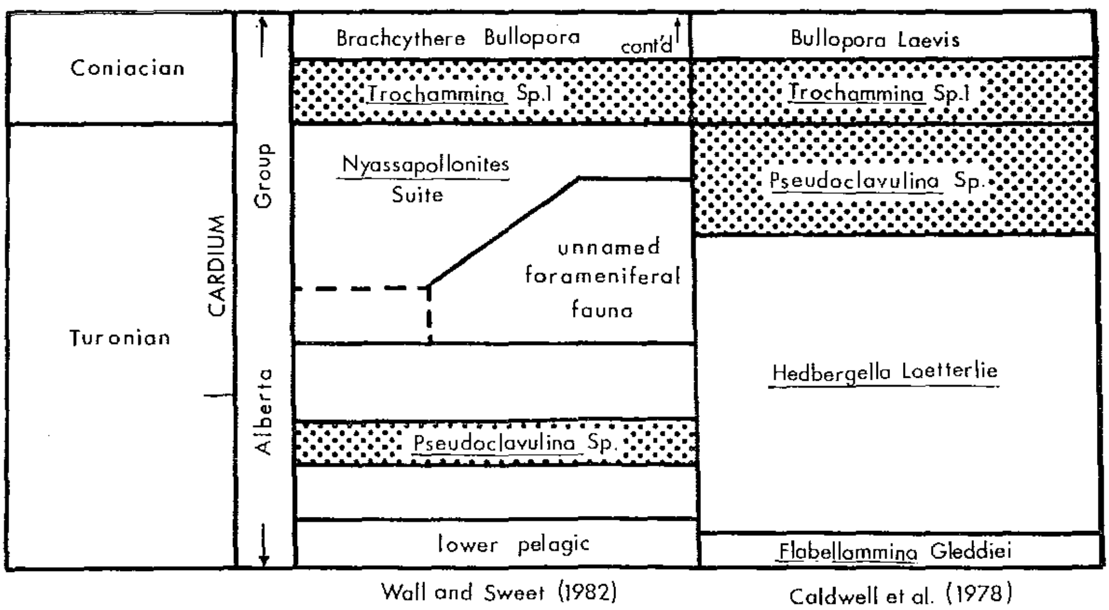
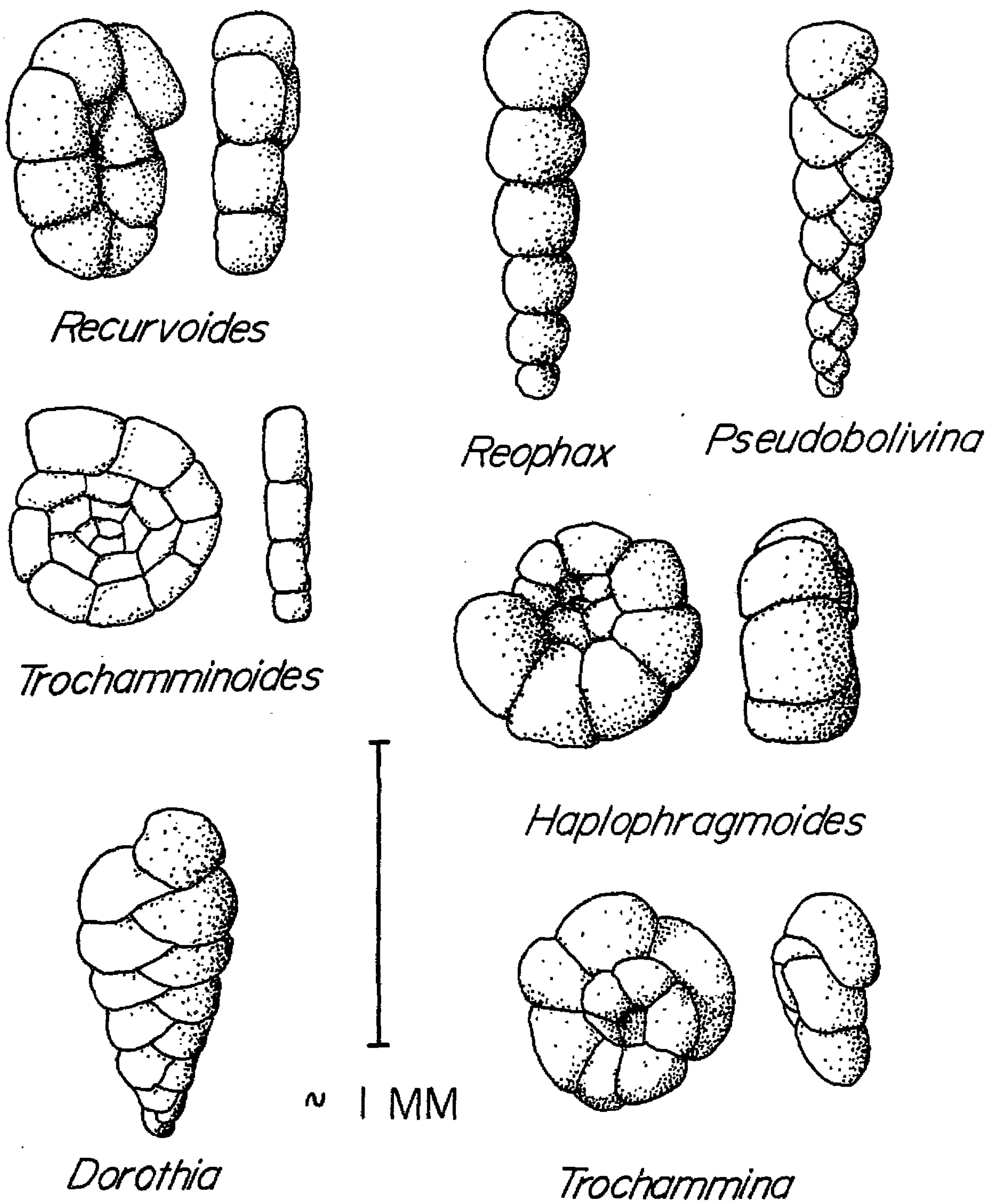


Figure 4-1. The zones of Wall and Sweet (1982) and Caldwell et al. (1978) and their timespans.

Generally, the fauna shows more in common with that of the Opabin Member of the Blackstone than with that of the Muskiki of the Wapiabi (see figure 2-2) although some species range through the whole sequence (Wall and Sweet, 1982).

The Cardium has not been dated on the basis of foraminiferal zones because these endure longer than the more accurate ammonite zones and are still in the process of being defined accurately (Caldwell et al., 1978).

According to the most recent reference, (Wall and Sweet, 1982), "the Cardium assemblages are characterized by the dominance of _Haplophragmoides_ spp. with _Dorothia_ sp.1 of Wall (1967) and _Trochammina_ spp. also being fairly prominent ... species of _Reophax_, _Miliammina_, _Trochamminoides_ and _Arenobulimina_ are much less represented." I have also observed the common presence of _Pseudobolivina_ genera, in particular sp. 1 and _pepperensis_ species. All species of foraminifera fall into the _Textularina_ sub-order. The most common genera observed are shown in figure 4-2; only the most distinctive species are shown. The genera of foraminifera recovered include _Haplohpragmoides_, _Dorothia_, _Pseudobolivina_, _Trochamminoides_, _Trochammina_ and _Reophax_. The species shown in figure 4-2 are _Haplophragmoides_ sp.1, _Reophax_ sp.1, an uncertain species of _Trochamminoides_, _Trochammina_ sp.1, _Pseudobolivina pepperensis_ and _Dorothia_ sp.1 (as identified from type examples labelled by Dr. Wall of the I.S.P.G. in Calgary and reference to the _Treatise on_


Recurvoides
Reophax
Pseudobolivina
Trochamminoides
Haplophragmoides
~ 1 MM
Dorothia
Trochammina

Invertebrate Paleontology (Loeblick and Tappan, 1964)).
These fit into the zonal shemes of Wall and Sweet (1982)
and Caldwell et al. (1978) described above.

3. RESULTS

A. Techniques

The technique used for disaggregating core samples to obtain the fossils is described in Appendix 2. Haynes (1981) also provides a good reference list of disaggregation techniques. The results of this disaggregation procedure are described in the following order:

1. The raw data is presented.
2. Bulk variation in vertical and lateral faunal content is considered.
3. The direct environmental implications are discussed.

Many of the results are discussed with reference to the basin topography described in chapter 8, specifically the 'bench' of figure 8-3. The reader may want to refer ahead to this chapter from time to time.

B. The Raw Data and Results

Tables 4-1 and 4-2 show the raw data where the lower horizontal scale indicates the Horizon sampled and the upper horizontal scale shows the samples at that Horizon for the well number shown in the vertical axis. The samples

123 / 45.6	
123	← gms of sample
45.6	← gms of disaggregated sample

:GUIDE

SAMPLE

Sequence 4

WELL	A	B	C	D	E	F	G
10-26-58-25W5		93.9 / 2	106.5 / 6.3	87 / 3.6			
4-31-59-16W5	51.0 / .3		136.1 / 30	89.8 / 2.8			
6-13-59-18W5	27.6 / 9.3	47.3 / 4.3	126.2 / 37	145.2 / 48.7	235 / 1.8	18.7 / .36	61.2 / 3.79
10-20-59-19W5	178.4 / 1.7	122.1 / .2	55.6 / .2	80 / 16.4	53.1 / .5	71.5 / .4	145 / 2.1
7-29-59-4W6	69.2 / 7.3	49 / 7.9		28.7 / 4.7	46.5 / .5	68.9 / 11.2	102.1 / .4
2-19-62-20W5							
10-3-62-4W6							
6-8-62-5W6	56.2 / 5.2	112.8 / 2.7	212.5 / tr	160 / .3		74.8 / tr	212.5 / 2
4-25-62-5W6							
7-29-62-5W6							
7-10-62-6W6	70.6 / 5.2		— / 4.7	196.6 / tr.	181.6 / —		
7-10-62-7W6							
10-15-62-8W6	223 / 2.5	165 / 2.9	90.4 / 5.8	177 / .1	242 / —		
11-7-63-5W6							
6-29-63-5W6	— / tr.		49.3 / 12.1	54.3 / 2.1			
9-7-64-5W6							

Sequence 5

WELL	A	B	C	D	E
10-26-58-25W5					
4-31-59-16W5					
6-13-59-18W5					
10-20-59-19W5					
7-29-59-4W6	69 / 2.1	40 / 6.0			
2-19-62-20W5	115 / 49.4	69.3 / 2.4			
10-3-62-4W6					
6-8-62-5W6		179.7 / 8.1	119.2 / 3.2		
4-25-62-5W6	— / 2.9	— / 8.5	154.3 / 54.6	77.9 / 2.6	
7-29-62-5W6	9.5 / .85	— / .15		— / 21.2	— / 18.3
7-10-62-6W6	208 / —	63.2 / 3.9	174.8 / 5.3	308 / 13.1	164 / 3.1
7-10-62-7W6	98 / 8.2		72 / 11.7		199 / .46
10-15-62-8W6					
11-7-63-5W6					
6-29-63-5W6					
9-7-64-5W6					

Sequence 6

WELL	A	B	C	D	E	F	G	H	I
10-26-58-25W5									
4-31-59-16W5									
6-13-59-18W5									
10-20-59-19W5									
7-29-59-4W6	67.6 / 29.6	36.8 / 9.1		53.8 / 8.1					
2-19-62-20W5									
10-3-62-4W6	98 / 3.8	— / 6.5	54.6 / 12.2	103.4 / 18.9		82.7 / .8	39.3 / 1.7	129.3 / 41.3	106 / .4
6-8-62-5W6	155.2 / 86.5	96.3 / 21	31.7 / 17.7		39.2 / 10.1	162.5 / 27.2			
4-25-62-5W6									
7-29-62-5W6									
7-10-62-6W6									
7-10-62-7W6									
10-15-62-8W6									
11-7-63-5W6									
6-29-63-5W6									
9-7-64-5W6									

Sequence 7

WELL	A	B	C	D	E	F	G	H
10-26-58-25W5								
4-31-59-16W5								
6-13-59-18W5								
10-20-59-19W5								
7-29-59-4W6								
2-19-62-20W5								
10-3-62-4W6								
6-8-62-5W6								
4-25-62-5W6								
7-29-62-5W6								
7-10-62-6W6								
7-10-62-7W6								
10-15-62-8W6								
11-7-63-5W6								
6-29-63-5W6	111.3 / 19	52 / 19.5	31.6 / 6.9	48 / 2.9	125.8 / 5.9	131.9 / 1.5	189 / 2.1	115.8 / 2.5
9-7-64-5W6	83 / .8							

WELL 4 5 ← SEQUENCE → 6 7

SAMPLE

34 1

34 — % "sand"
1 — foraminifera / gm.

:GUIDE

Sequence 4

WELL	A	B	C	D	E	F	G
10-26-58-25W5		2 .27	6 .14	4 .14			
4-31-59-16W5	1 6.41		22 .02	3 0			
6-13-59-18W5	34 0	9 0	29 .11	34 .04	1 3.98	2 6.52	6 2.94
10-20-59-19W5	1 0	0 .02	0 0	21 .13	1 .87	1 .66	1 .75
7-29-59-4W6	11 —	16 —	16 —		1 —	16 —	0 .01
2-19-62-20W5							
10-3-62-4W6							
6-8-62-5W6	9 —	2 —	0 —	0 —		0 —	1 .26
4-25-62-5W6							
7-29-62-5W6							
7-10-62-6W6	7 .03		— 0	0 .62	— —		
7-10-62-7W6							
10-15-62-8W6	1 —	2 —	6 —	0 —			
11-7-63-5W6							
6-29-63-5W6			25	4 .37			
9-7-64-5W6							

Sequence 5

WELL	A	B	C	D	E
10-26-58-25W5					
4-31-59-16W5					
6-13-59-18W5					
10-20-59-19W5					
7-29-59-4W6	3 .06	15 .25			
2-19-62-20W5	43 1	3 24			
10-3-62-4W6					
6-8-62-5W6		5 1.11	3 .81		
4-25-62-5W6			35 .02	3 4	
7-29-62-5W6	9 .11				
7-10-62-6W6		6 .005	3 1.23	4 .22	2 2.65
7-10-62-7W6	8 .28		16 .97		0 .24
10-15-62-8W6					
11-7-63-5W6					
6-29-63-5W6					
9-7-64-5W6					

Sequence 6

WELL	A	B	C	D	E	F	G	H	I
10-26-58-25W5									
4-31-59-16W5									
6-13-59-18W5									
10-20-59-19W5									
7-29-59-4W6	44 .06	25 .24		16 .46					
2-19-62-20W5									
10-3-62-4W6	— .36		22 .37	18 .02		1 .53	4 0	32 .43	0 .99
6-8-62-5W6	56 .08	22 .09	56 .16		26 .28	17 .2			
4-25-62-5W6									
7-29-62-5W6									
7-10-62-6W6									
7-10-62-7W6									
10-15-62-8W6									
11-7-63-5W6									
6-29-63-5W6									
9-7-64-5W6									

Sequence 7

WELL	A	B	C	D	E	F	G	H
10-26-58-25W5								
4-31-59-16W5								
6-13-59-18W5								
10-20-59-19W5								
7-29-59-4W6								
2-19-62-20W5								
10-3-62-4W6								
6-8-62-5W6								
4-25-62-5W6								
7-29-62-5W6								
7-10-62-6W6								
7-10-62-7W6								
10-15-62-8W6								
11-7-63-5W6								
6-29-63-5W6	17 .34	37 .17	22 .09	6 .35	5 1.26	1 1.31	1 2.8	2 2.68
9-7-64-5W6	1 1.61							

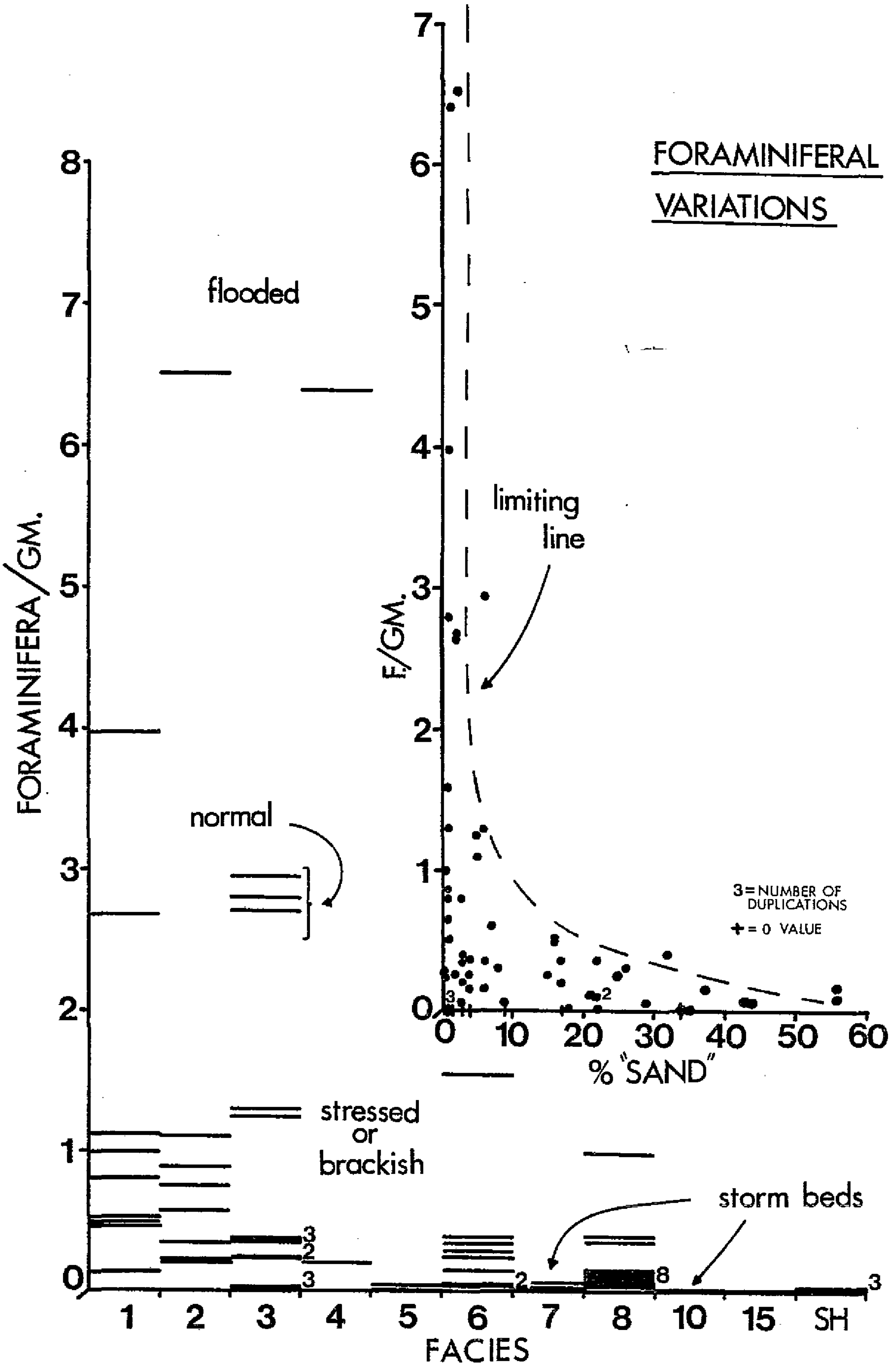
WELL — 4 — 5 — SEQUENCE — 6 — 7

can be located against a lithological column in appendix 1. Each sample is described numerically as follows: Horizon (sequence) number/well number/sample letter.

Table 4-1 shows the weight of sample disaggregated (as recovered from a 4 phi seive) and the weight of the initial crushed sample.

Table 4-2 shows the data collected from the sample as "sand" percent and number of foraminiferal tests per gram of crushed sample. The number of individuals of a single species in each sample has not been considered. This is because the relatively small sample weight in each case, due to restrictions in core sampling, produces a relatively small number of each species. Such small numbers would not allow for any statistically significant comparisons to be made between species. The percent "sand" represents the ratio of the material coarser than 4 phi to the original weight of crushed material.

Of greatest concern to this study is the distribution of the fauna above and below the "erosive" surfaces of Plint et al. (1986). Figure 4-3 displays a clarified version of Tables 4-1 and 4-2 in which the number of foraminifera per gram of sample are shown plotted against both "sand" percent and facies. Included in the facies is SH, indicating samples immediately above distinctly erosive Horizons, particularly E5 of Plint et al. (1986). **These**


FORAMINIFERAL VARIATIONS
FORAMINIFERA/GM.
flooded
normal
stressed or brackish
storm beds
FACIES
1 2 3 4 5 6 7 8 10 15 SH
F./GM.
limiting line
% "SAND"
3 = NUMBER OF DUPLICATIONS
+ = 0 VALUE

graphs include all Horizons examined because no pattern was found for any Horizon in particular. The interpretation of the divisions shown on these graphs is discussed in the next section. The graphs themselves may be described as follows.

The plot in the upper right is made on the basis of sand content. Each dot represents one sample. This plot shows an overall decline in population with increasing sand content. The limiting line and the samples below it are described under the interpretation of bulk variation.

The lower plot of facies against foraminiferal content is analagous to that above except lines replace dots. The label 'storm beds' applies to the interpretation of facies 7 and 10 described in chapter 3. Other labels are more directly interpretive and are discussed below. However, I should draw attention here to the four basic divisions of this graph. They are the flooded, the normal, the stressed and the storm (or sandy) regions.

C. Additional Data

Not indicated on the graph are qualitative notes on the amount of pyrite and carbonaceous debris present in each sample. Samples in the area marked 'stressed or brackish' (discussed below) contain more carbonaceous debris and less pyrite than those in the 'normal' and 'flooded' areas.

Of particular note within this area are the occurrences of ostracod fragments not tabulated in the figures or tables due to the impossibility of estimating the number of individuals and their marginal to non-marine nature. All these fragments occur in samples from the distal, lagoonal toe of the Musreau Member. They probably represent Cypridea of the super-family Cypridacea and were identified by reference to Brasier (1980) and the Treatise on Invertebrate Paleontology Part Q, Arthropoda, (R.H. Benson et al., 1961). The samples bearing these remains are 4/7-29-59-4W6/a, 4/10-15-62-8W6/d and 4/7-10-62-6W6/c. The latter sample is particularly interesting because it also contain 5 foraminiferal tests.

There are three samples that occur in none of the above tables or graphs because they were processed after the information revealed by the above samples was aquired. These samples come from well 9-10-63-6W6 and are located at 1801.3, 1791.9 and 1778 meters. They are samples from the middle of the Raven River, Dismal Rat and Karr Members respectively. They are important for providing a measure of the consistency of conditions in the stratigraphic column in the region marked stressed, and will be discussed below. The first sample, from the Raven River, weighed 185.8 gm before processing, 0.96 after and contained no foraminifera. The second sample, from the Dismal Rat, weighed 134.0 gm before processing, 27.1 after and contained 44 foraminifera. The third sample, from the Karr, weighed 157.9 gm before processing, only traces after and contained 44 foraminifera. In order, the samples come from facies 1, facies 3 and facies 3. The reader may confirm that all these results plot in the stressed area marked on figure 4-3.

4. BULK VARIATION AND INTERPRETATION

In this section the general form of the graphs will be discussed first then particular points about figure 4-3 will be emphasized.

In the upper graph of figure 4-3, I have drawn a limiting curve above the data to show the population trend to be expected as sand content increases. This limiting line shows a general decrease in foraminiferal content with increasing sand input. This result is in keeping with the common observation (Haynes, 1981) that the coarser the sand and more energetic and turbid the environment the smaller the number of individuals present. The trend may also be partially explained by the decrease in effective sample size imposed by the increasing percentage of sand over mud (J.H. Wall, p.comm., 1986). Sand grains take up more space than mud and effectively dilute the sample. However, there are a large number of samples that fall below this line rather than on it. This implies that sand content and, by extension, energy of the site of deposition and the volumetric effects of sand are not the only controls on population. This is not surprising considering that facies, and hence environment, have not been considered.

The lower graph in figure 4-3 takes facies variations into account. Generally, the graph mimics that of the percent sand plot because the proportion and size of sand, roughly speaking, increases with facies number. There are a number of subtle differences, however, which have a strong bearing on the interpretation of conditions in the area of deposition. Note that some facies, such as 1, 2 and 3 contain a large range of numbers of microfossils indicating that the facies itself does not reveal all the variations in the environment of deposition.

These differences will be discussed point by point and summarized in the concluding paragraph of the chapter.

A. The Normal Level of Accumulation

Differences are may be most coherently discussed by taking foraminiferal levels in 'normal' marine silts as a reference point. The area marked 'normal' is based on the study of samples 7/11-36-63-7W6/f,g,h,i which show an increase in test numbers with height as the samples enter the Wapiabi Formation which overlies the Cardium. This muddy marine silt is taken as the marine standard because there are no discernible close to shore sediments in the base of the Wapiabi. The number of tests in the upper three samples stabilizes at the value marked 'normal'. Measurements of flooded or stressed are made relative to this value. Importantly, only one sample showing 'normal' accumulation of tests, sample 5/7-10-62-6/e, occurs west of the begining of the 'bench' of chapter 8. This lack of 'normal' accumulations west of this topographic line is important in interpreting the cause of the depletion (see below).

B. Flooded Samples

Relative to this standard, samples 4/6-13-59-18W5/f and 4/4-31-59-16W5/a are both 'flooded', or significantly above the standard in number of tests found. Both samples occur offshore of the 'bench'; however, they lie both below and above the Burnstick Member, as may be confirmed in Appendix 1, indicating that the flooding is not directly related to the presence or transgression of this member. **There is thus no stratigraphic pattern to the occurence of 'flooded' samples.** There is insufficient data to determine if such samples consistently occur only East of the 'bench'.

C. Facies Related Depletion of Foraminifera

One cause of depletion relative to the 'normal' standard is a function of the sedimentary environment of some facies. For facies 7 and 10, which are interpreted as deposits of storms, this depletion likely reflects the high energy of the environment. It may also indicate a depletion at the source of the sediment as indicated in sample 6/10-3-62-4W6/g which contains a large amount of micaceous and carbonaceous debris probably derived immediately from the shore. Facies 5 also shows a depletion. This might be due to predation, but given the occurence of foraminifera in facies 5 in the Carrot Creek region (K.M. Bergman, p.comm., 1986) is more likely due either to the small number of samples or a genuine environmental stress. The facies at the right of the graph, particularly facies 6 and 8, may be lower in test content than those marked 'normal' because of a higher energy of deposition reflected in the sand size of coarse sand to conglomerate. They lie in a region where it is difficult to separate the effects of the sand content discussed above and other environmental stress discussed below. However, the presence of foraminifera, even from within some very conglomeratic occurences of facies 8 confirms their marine nature.

D. The Lack of a Pause Plane

Of particular note is the fact that SH samples 4/6-29-63-5W6/c, 5/7-29-62-5W6/d and 5/7-10-62-6W6/b all have zero or close to zero tests per gram. **Thus, these surfaces probably do not represent pause planes, or**

surfaces of accumulation. If pauses in sedimentation occured, one would expect to find consistently higher than normal accumulations of organic detritus. This debris (shells etc.) would ordinarily be diluted by sediment input. With the decrease or cessation of sedimentation it would accumulate over the substrate as it continued to fall out of the water column, unchallenged for space in the rock record by siliclastic sediment. One other possibility is that the agent of erosion at these Horizons prohibited accumulation in association with any pause. However, the presence of accumulated mud would seem to imply the possibility of accumulating small organic debris. Given the lack of any continuously large accumulation of 'debris' at any of the other Horizons it seems resonable to dismiss this possibility.

E. Stressed Samples

The region labelled stressed (or brackish) has been so labelled based on a sub-normal number of foraminifera per sample. This implies that some (or several) mechanism(s) suppressed the population. These terms rely heavily on environmental conditions inferred from other evidence and discussed in greater detail in the next section. **I must emphasize that samples with higher numbers of tests tend to occur East of the edge of the 'bench' of figure 8-3.** This trend is discussed in greater detail below with reference to figure 4-4. Since the same facies may or may not contain microfossils despite the similarity of bioturbation the water column must be the controlling variable. The benthic fauna indicates that sufficient organic matter was present in the sediment to support feeding. However, foraminifera would probably ordinarily thrive on organic rich silt and mud (Brasier, 1980) so their absence requires an inhospitable water column. However, the water must not have been inhospitable enough to destroy or inhibit all benthic fauna.

Distinguishing foraminiferal content in the stressed region from that in the sandier facies is difficult. This is because stress due to water conditions and dilution due to sand input apparently produce similar results. Nevertheless, the stressed region distinctly differs from the areas of higher foraminiferal content. Taking into account the relative absence of sand in these facies, there must therefore be other factors responsible for the reduction in test numbers.

Several factors may be postulated as causing such reduction. These include reduced salinity, excessive turbidity and reduced oxygen levels. The possibility of any particular cause is best considered in light of other environmental data and with consideration of a slighter larger view of the problem.

5. ENVIRONMENTAL IMPLICATIONS

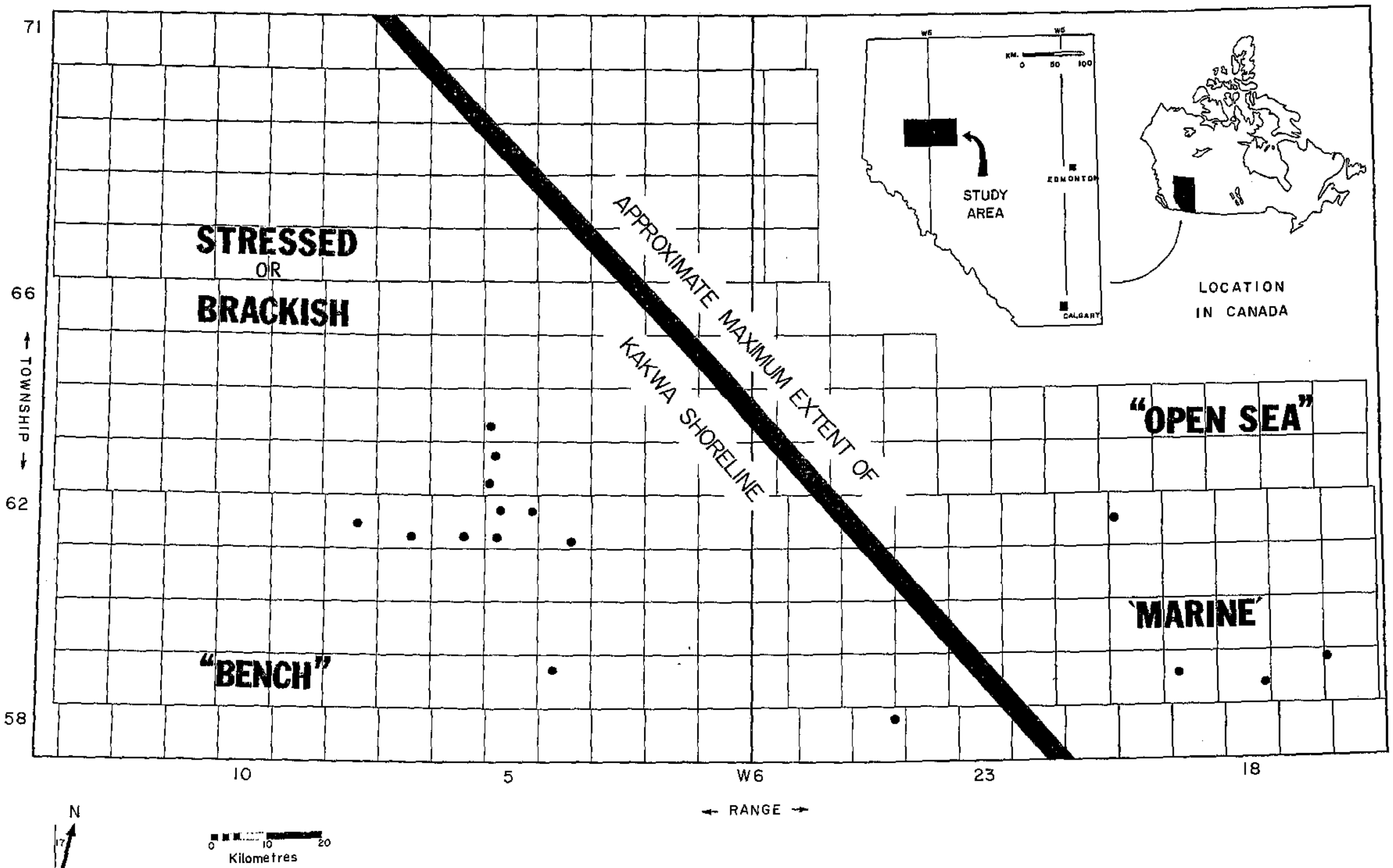
A. The Framework

Figure 4-4 is designed to highlight the pattern in the above reduction of faunal content 'shorewards' of the 'bench' and the corresponding occasional flooding of fauna immediately offshore of this line. Note that the maximum extent of the Kakwa shoreline coincides through time with the edge of the 'bench'; it is thus useful as a geographic marker. Figure 4-4 show the framework within which the fluctuating faunal densities may be discussed.

B. Environmental Background

Before considering these fluctuations a few words should be added on the gross environmental implications of the faunal assemblages.

On a very large scale, like that of the sedimentary Group, arenaceous-walled assemblages of foraminifera characterize the deposits of active phases of transgression and regression and calcareous-walled assemblages mark the deposits of the times of widespread inundation (Caldwell et al., 1978). The predominance of arenaceous tests in the Cardium therefore implies a 'shallow' setting for the silts and muds (as opposed to the Second White Specks which contains calcareous pelagic foraminifera Caldwell et al. 1978).



FORAMINIFERAL SAMPLE LOCATIONS

Furthermore, both the Pseudoclavulina and the Trochammina sp. 1 zones are described as characteristic of nearshore environments (Wall and Rosene, 1977) and are generally indicative of cool to mid-temperate conditions (Caldwell et al., 1978).

Given this large scale information what other information combined with the above data can be used to eliminate or confirm possible mechanisms of stress?

C. Anoxicity Unlikely

Anoxicity could conceivably kill off the foraminifera, but the high degree of bioturbation shown in almost all silt and mud facies (facies 1, 2, 3, 4, 5 and 6 of chapter 4) combined with the lack of genuine "black shales" precludes this possibility. Although the agglutinated assemblage usually itself indicates lower oxygen concentration this factor is not of extreme importance to such small fauna (Brasier, 1980).

D. A Brackish Water Column

Wall and Rosene (1977) in their studies of foraminifera from outcrop samples of the Cardium state that, "the rather sparse and agglutinated nature of this microfauna ... suggests that the transgressive sea following deposition of the Cardium Formation was shallow, turbid and perhaps brackish." The agglutinated nature of the foraminifera is the most important factor in labelling the water as brackish (e.g. Brasier, 1980). The recent reporting of more a more diverse content (Wall and Sweet, 1982) thus has little bearing on the gross environmental label.

Wall (1967) also reports that "marine [my emphasis] and non-marine ostracods have been recorded locally ... this [fauna] suggests that the environment of the middle shaly unit probably was lagoonal and brackish." The ostracod fragments discussed above match these Cypridea remains (Wall, 1967) in the Moosehound Member of Stott (1967). This family of ostracods occurs in fresh to brackish settings (Brasier, 1980). The joint occurence of foraminifera and ostracods in 4/7-10-62-6W6/c supports the interpretation of a brackish water column in the marine setting.

Brackish in this sense is used rather loosely to imply a dilution, of uncertain amount, of normal seawater; the dilution is sufficient to affect foraminiferal populations but not sufficient to result in the occurence of the more traditional macrofauna associated with lagoonal deposits (e.g. Lingula). The term is used consistently by micropaleontologists when describing agglutinated foraminifera (e.g. Haynes, 1981 and Brasier, 1980) to indicate reduced salinity. However, no quantitative estimate of the salinity reduction may be made (J.H. Wall, p. comm., 1986).

Given that the 'normal' marine conditions are somewhat brackish, as determined from the agglutinated nature of the tests, the label of brackish in figure 4-4 and in figure 4-3 may imply a much greater fresh water input. The possible increased brackishness is thus relative to the 11-36-63-7W6 standard. It is conceivable that the flatter 'bench' of figure 8-3 (labelled in figure 4-4) was subject to greater dilution by fluvial and pluvial input leading to semipermanent haloclines over its extent. Instability in any haloclines or variation in the relative influences of 'normal' and fresh water may have led to the occasional production of normal levels of foraminifera within the 'bench' setting, as in sample 5/7-10-62-6W6/e. Due to the impossibility of continuous sampling, I cannot tell how much variation may have occurred in such a fashion; given the general lack of 'normal' test levels conditions were probably rather stable. This seems to be confirmed by the samples mentioned above from midway within the Raven River, Dismal Rat and Karr Members. Regardless of the exact mechanism, the stressed levels of foraminifera shown in these samples indicates that these conditions persisted on the 'bench' throughout the time of upper Cardium deposition. Figure 8-3 also indicates that the topography was persistent, so the two are very probably linked.

The occurence of siderite, discussed at length in the next chapter, also supports the likelihood of freshwater dilution of the water column when the depth was shallowest.

The decrease in pyrite present in disaggregated samples, see above, in this 'brackish' region is additional evidence for the idea of dilution of 'normal' marine water. However, the accompanying inverse trend in increasing carbonaceous debris lends credence to the theory of high sediment input possibly helping to increase turbidity in the area described. This idea must also be considered and is discussed below.

E. A Turbid Water Column

The amount of terriginous debris reinforces the idea of a water column which contains vast amounts of mud, silt and terriginous material all swept in from the transgressed shore and maintained in suspension by persistent storms. The widespread flat nature of the 'bench' might also have lead to a damping out of many storm waves and an accompanying increase in suspension of mud as the waves were damped by widespread, shallow, unconsolidated mud. Such a phenomena has been observed on the Suriname coast which is a muddy transgressive to stillstand setting (Rine and Ginsburg, 1985). Such a turbid environment would create the functional equivalent of stress in high energy environments characterized by larger sand contents. Perhaps this is reflected in the difficulty in distinguishing the causes of low test levels in the different facies shown in figure 4-3.

Such a mechanism is slightly preferable to continued extreme fresh water dilution of the water column for several reasons. Marine trace fauna would seem to indicate a relatively marine condition. Moreover, if siderite forms, as argued below, in part due to fresh water dilution during the shallowest phases of deposition, then it might be expected to occur more frequently away from the Horizons. Its absence probably indicates that fresh water stress played a part in controlling foraminiferal populations when the water column was very shallow, but that turbidity formed the primary control. Dr. J.H. Wall, who has extensively studied Late Cretaceous foraminifera, does not consider that fresh water dilution would be a significant factor except in marginal marine environments (p.comm, 1986).

Turbidity exerted its primary control on foraminifera numbers possibly by cutting of light and hindering nutrient accessibility.

F. The Duration of Stress

It is important to realise that the region behind the line of the Kakwa shore maintained this stressed environment during the overall transgression of the Cardium. The stressed environment discussed above occurs at all stratigraphic levels of the upper Cardium. The foraminifera do not return to normal levels until the time of the Wapiabi Formation. The ability to maintain such an environment is related to the topography of the basin (described in greater detail below). Briefly this topography, visible in figure 8-3, consists of an 'offshore basin' east of the Kakwa shoreface and the Kakwa shore which rises into a flat 'bench' initially occupied by the Musreau Member but later covered by shallow, muddy marine sediments during transgression. Figure 4-4 has been labelled with this topography.

The small populations in the 'bench' area make it more difficult to investigate the possibility of pause plane development, but the lack of any relatively large accumulation above the erosive-transgressive members of Plint et al. (1986) seems to preclude such behaviour. Certainly the lack of tests right at the surfaces (SH in figure 4-3) and the occurrence of 'flooded' samples in the silts below the H4 deny the occurence of accumulations of biogenic material offshore during transgression or erosion.

In short, the development of the Cardium event stratigraphy occurred too rapidly for biological systems to leave of record of a time gap.

By the time of the upper Muskiki Member of the Wapiabi, more normal marine conditions prevaled as indicated by the presence of calcareous foraminifera and a greater diversity (Wall and Rosene, 1977).

The full implications of these general environmental interpretations and bulk faunal variations appear only when considered in the context of the sedimentological response of the Cardium to rapid shallowing and the consequent associated chemical changes. These confirm the very rapid nature of the basinal changes and will be discussed next.

6. SUMMARY

The major points of this chapter may be summarized as follows.

A. Most of the muds near Horizons 4-7 contain lower than normal levels of foraminifera.

B. The Horizons examined do not represent pause planes based on the absence of abnormal accumulation of fauna.

C. The Cardium sea was generally of reduced salinity ('brackish').

D. Muds may be depleted in foraminifera for three reasons: fresh water dilution of the water column, the sandy nature of some samples, a probably turbid water column.

E. Turbidity is the primary control of foraminiferal population with fresh water effects being important in the shallowest phases of deposition.

F. Environmental stress was persistant across a topographic bench throughout deposition of the upper Cardium.

CHAPTER 5

EARLY DIAGENESIS

1. INTRODUCTION

Siderite, as determined from its highly birefringent, spherulitic form in thin section and dissolution in only warm HCl, is one of the most immediately visible products of diagenesis in the cores of the Cardium. It has a characteristically tan colour. Siderite is the only mineral which is consistently associated in visible quantities with the Horizons examined. Calcite can occur within sand and conglomerates but is rare in the region studied and will therefore not be considered in detail.

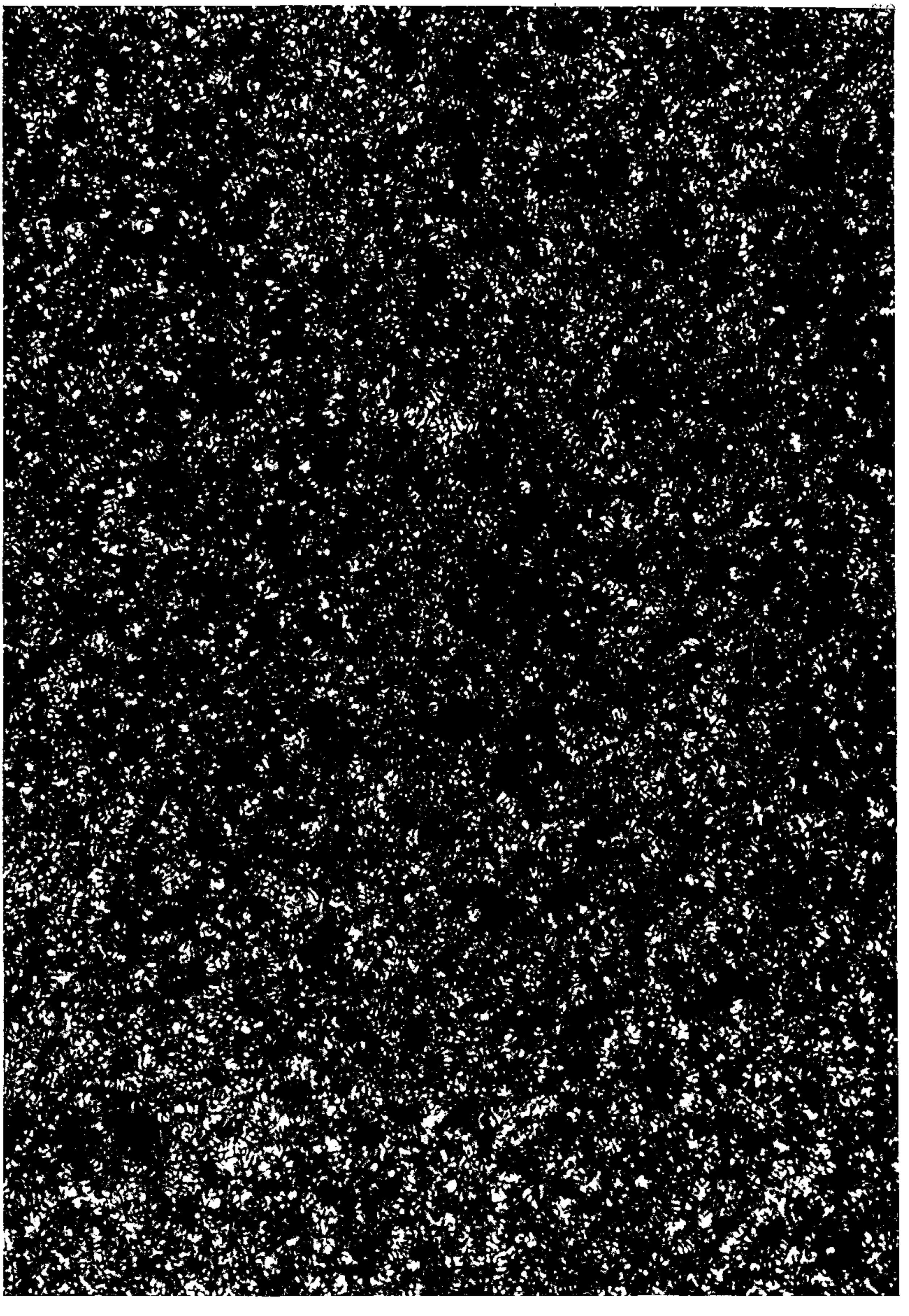
The persistent occurence of siderite at the tops of many of the Cardium sequences may be seen in the sections shown in Appendix 1.

The ubiquitous occurence of siderite raises the question of whether or not siderite directly reflects conditions in either the water or the top of the sediment at or near the time of the sea level changes responsible for the Cardium events. Moreover, does the siderite reflect cementation during a pause in sedimentation? This is particularly important as none of the mineralogical criteria listed by Weimer (1984) for recognizing sea level changes in cratonic basins (e.g. glauconite and phosphate) are present in any amount across the Cardium surfaces. However, the sedimentology as discussed by Plint et al. (1986) demands that such variations in sea level occur. It is thus concieveable that siderite reflects either different environmental conditions or different behaviour of the surfaces (i.e. rapid rather than prolonged erosion) from those mentioned by Weimer.

2. THE OCCURENCE OF SIDERITE

In detail, the siderite does not form an extensive sheet but occurs in close proximity to erosive surfaces or within various Horizons. It typically occurs below distinct surfaces and scattered within gradational seqences. Although very common at the Horizons, it is not restricted to them and can be found in nodular form in deeper marine sediments or in fluvial/lagoonal sediments of the Musreau Member. There is no pattern of occurence corresponding to the 'bench' or 'offshore' division shown in figure 4-4.

The only common type of siderite seen in the rocks studied is the spherulitic to massive type shown in Plate 5-1 although larger rhomohedral siderite has been reported from more porous sandstones in the Cardium (Griffiths, 1981 and K.M. Bergman, p. comm., 1986).



3. THE TIME OF SIDERITE FORMATION

Determining how relevant siderite is to Horizon behaviour requires investigation of the timing of its formation relative to the time during which sea level was changing. The relative timing of the formation of the siderite can be studied along several lines. The most immediately obvious are the textures of the siderite in the core. Analysis of the paleoporosity of the enclosed silts and muds supplements this visual evidence.

3A. Texture

The presence of ripped up clasts of siderite intermixed with mud rip ups some of which may be armoured occurs rather commonly in facies 10 and 15 and may be seen in Plate 3-5B. Pebbles of sideritized mud are also common in facies 8 and facies 6b,c. In some cases, sand and mud laminae have compacted around sideritized regions (incipient nodules).

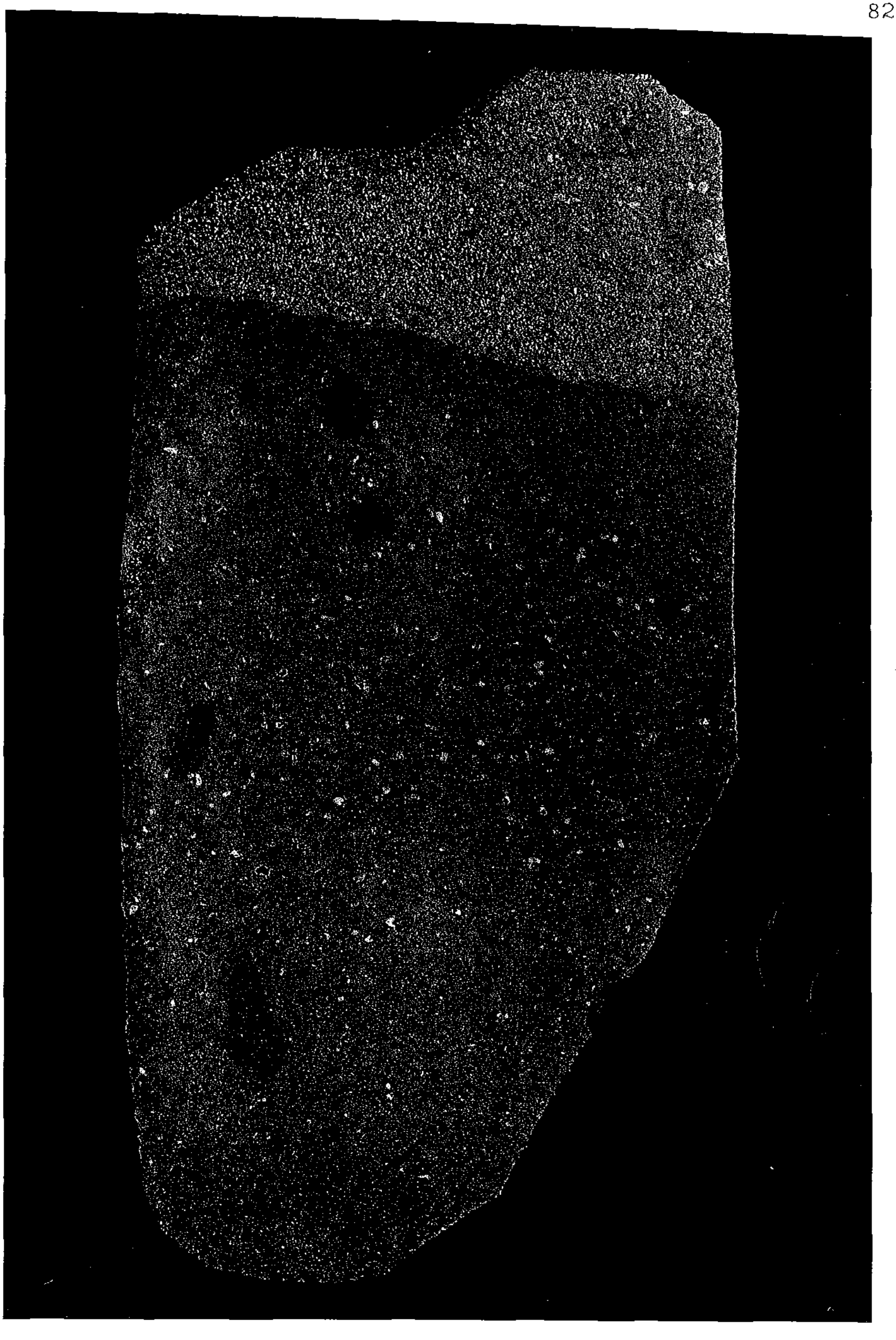
These textures imply that the siderite formed prior to the deposition of the sand bed containing portions that have been torn up. This requires formation at a sufficiently shallow depth that the mechanism of scour could expose the already formed mineral. The presence of occasional armouring sand grains indicates a sufficiently soft body, as does the round shape, to deny the possibility of relatively deep burial prior to the time of erosion.

The compaction of mud and sand laminae around incipient siderite nodules also indicates early formation.

3B. Paleoporosity

Calculation of paleoporosity for the muds which have been sideritized confirms the almost syndepositional nature of the cement. Paleoporosity may be calculated in different ways all of which involve the dissolution of the siderite by an acid. For isotope work, the most common approach is to dissolve it using phosphoric acid (e.g. Weber et al., 1969, Fritz et al., 1971 and Hangari et al., 1980), but for this work I destroyed the siderite using warm HCl (following the work of Franks, 1969).

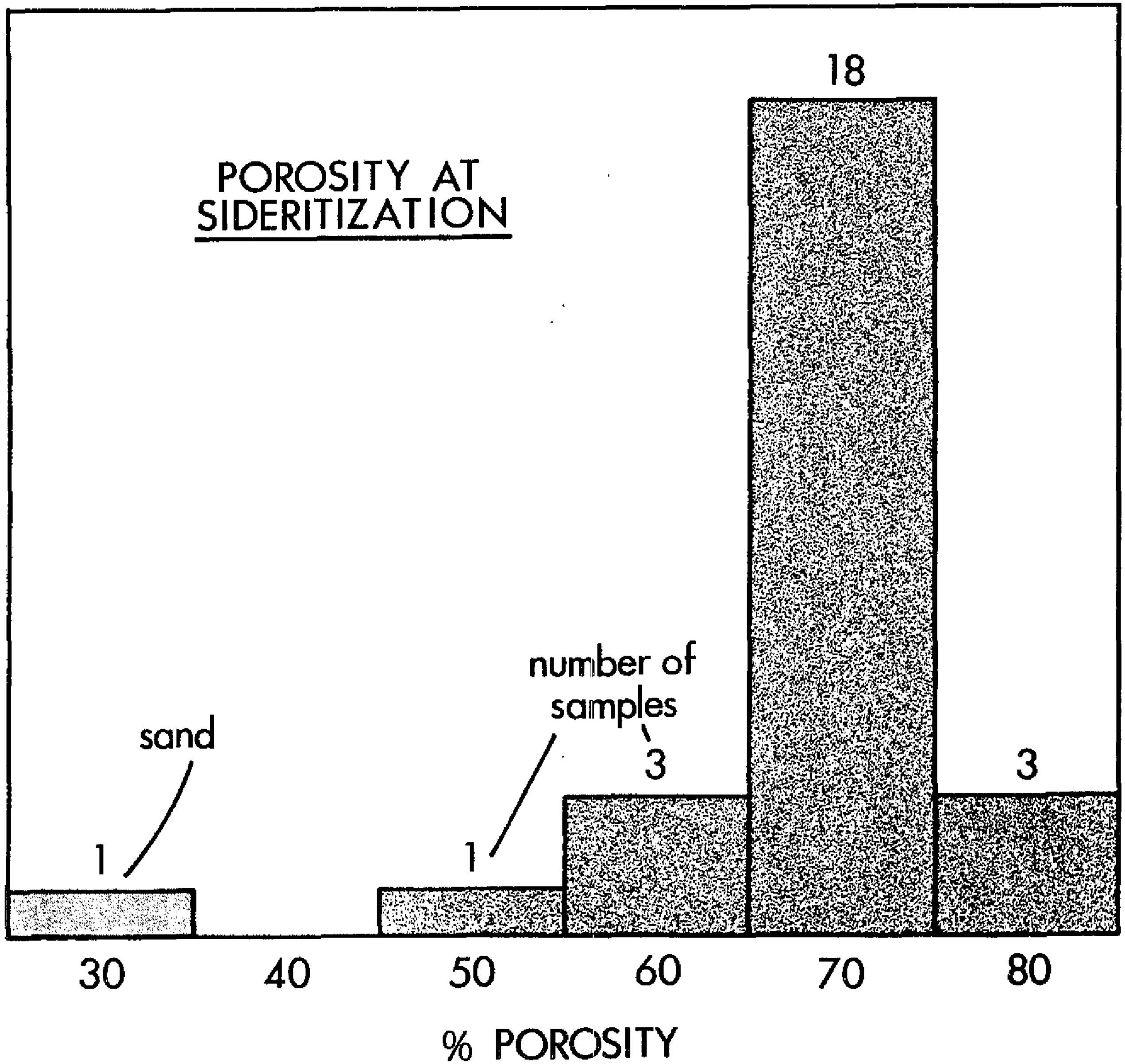
The procedure is as follows. A sample of siderite was ground, weighed and then dissolved in warm (<100C) HCl (10%); the sample was immersed until all signs of dissolution ceased. It was then removed from the hot plate, drained and dried then weighed. Using the final weight, the initial weight, an assumed density for the residual material of 2.65 (a reasonable density given the contents of quartz silt and clay) and the density of siderite, the volume of siderite dissolved can be calculated. I then assume that this volume represents the entire initial pore volume of the siltstone which appears to be the case from thin section studies. Plate 5-2 shows a typical occurence of siderite; massive siderite



dominates the field in the lower 4/5 of the Plate. Implicit in such work is the assumption that no significant amount of non-siderite matrix is dissolved. Tests on non siderite bearing silt samples from core confirm that there is no apparent loss of weight. No visible amounts of calcite or other disolvable minerals occur in the siderite examined. No such loss or bias has been reported in the literature on similar insoluble residue work (e.g. Curtis and Coleman, 1986 and Curtis et al., 1975).

The final calculations show that for silt/mud samples the paleoporosity averages 70% as shown in figure 5-1. The data shows an almost perfect 'normal' distribution. Figure 5-1 does not discriminate between samples from different Horizons or from different positions within cycles because no differences were observed. All siderite studied behaves in this fashion. Note that even in a siderite cemented sand, the sample at 30% (sample 5/2-19-62-20W5/[161]), the paleoporosity is very high.

These high porosities are typical of freshly deposited mud which has undergone little burial compaction (Singer and Muller, 1983). Therefore, the siderite in each case must have formed almost at the sediment-water interface almost immediately after burial. This is the case for all siderite samples analyzed. Values on the order of 70 percent paleoporosity are not surprising and have been


POROSITY AT SIDERITIZATION
18
number of samples
sand
3
3
1
1
30
40
50
60
70
80
% POROSITY

obtained by others working on siderite behaviour (e.g. Curtis and Coleman, 1986 and Curtis et al., 1975).

4. THE ENVIRONMENTAL IMPLICATIONS OF SIDERITE

Having established the early nature of the siderite, it may then be used to discuss the chemical environment at the junction between water and sediment and to speculate, in conjunction with other evidence, on conditions in the water column itself and possible rates of the Cardium events.

Much has been written on the chemical implications of siderite and yet in some cases, it remains a little misunderstood. This is in part due to the difficulty of applying studies of modern chemical regimes to the rock record where the same measurements cannot be made. It can thus be difficult to seperate alternate hypotheses. Some confusion is also due to the consequent emphasis of only one of two different modes of occurence.

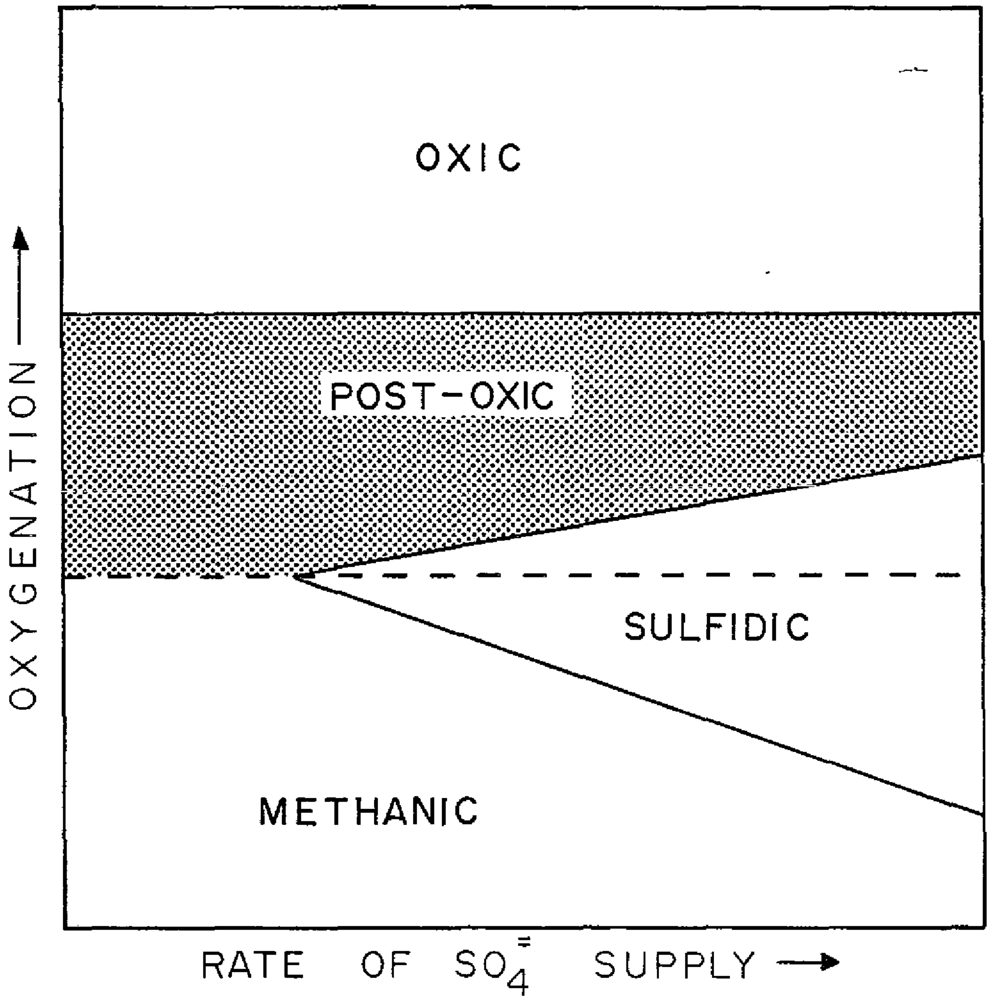
4A. Chemical Stability Diagrams and Environmental Implications (Post-Oxic Siderite ?)

The chemical conditions may be investigated using two different but complementary frameworks, the diagenetic summary of Berner (1981) as modified by Maynard (1982) and detailed, thermodynamically constructed Eh-pH diagrams.

The diagenetic scheme of Berner (1981) as modified by Maynard (1982) is the simplest framework for discussion of siderite formation. This is because it can be readily applied to rocks where only crude estimates of chemical conditions may be obtained by examining bulk mineralogy; it does not require the use of pH and Eh measurements that are impossible on rocks and difficult enough on modern sediments. This scheme is shown in figure 5-2.

To paraphrase Berner and Maynard, in this arrangement, the Oxic field contains sufficient oxygen to lead to the oxidation of iron and the formation of such compounds as hematite; in the Post Oxic field oxygen has been depleted to such a level that reduced iron is available and siderite can form under the right conditions; the Sulfidic field occurs when sufficient sulfate is available to complex with the reduced iron to form pyrite or its precursors; the Methanic field represents the region in which methane producing bacteria produce sufficient carbon dioxide that iron carbonates, particularly siderite become stable, assuming that all sulphur has been used up by transition through the sulphidic field. The latter, methanic, occurence of siderite is the one most often cited.

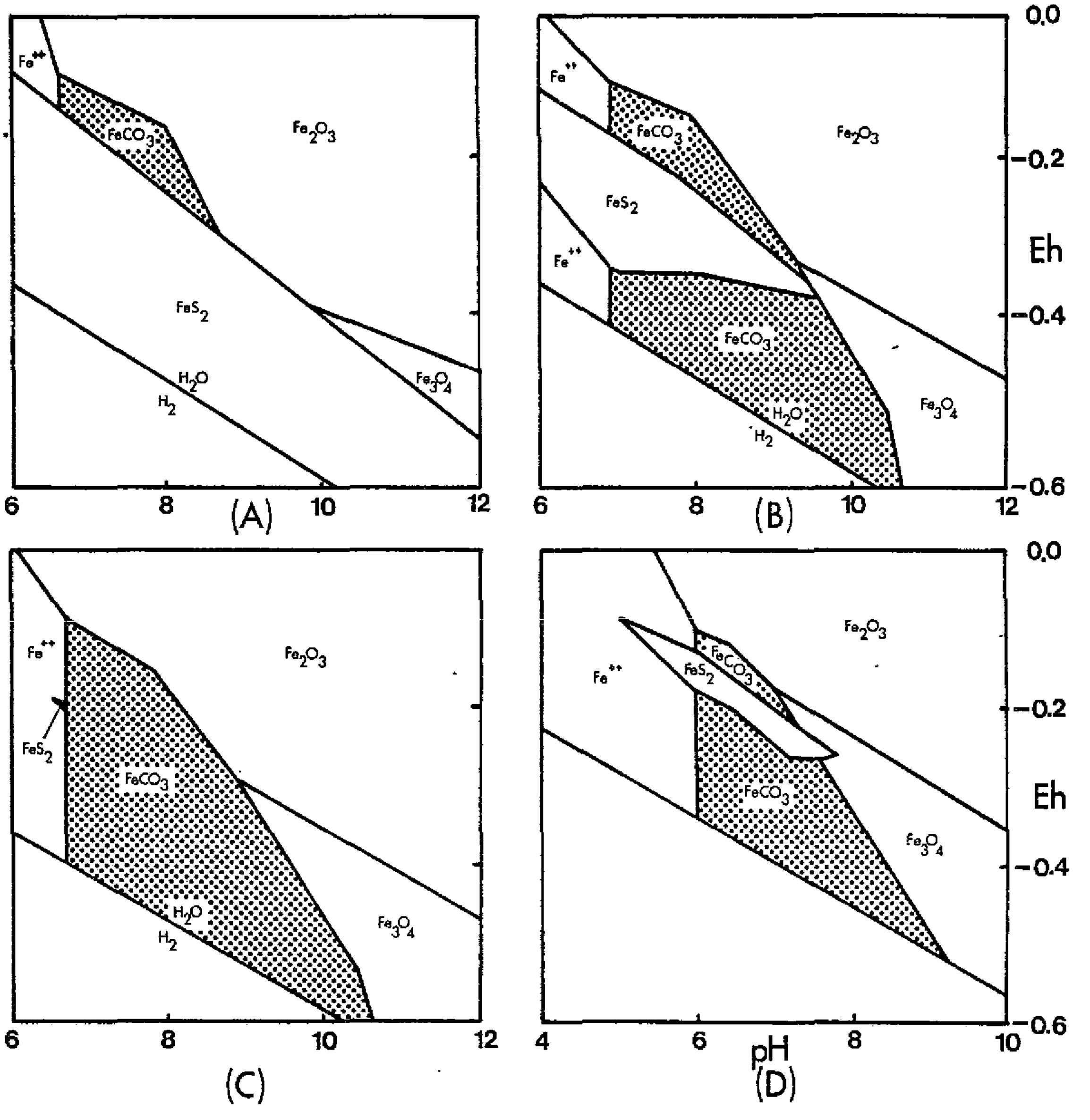
Despite the simplicity of this approach, there are some disadvantages, namely that the diagram glosses over the chemical and biological mechanisms of formation of the various minerals involved. This can lead to some confusion, particularly in the case of the siderite. Its


OXIC
POST-OXIC
SULFIDIC
METHANIC
OXYGENATION
RATE OF $SO_4^{=}$ SUPPLY

simplicity has also led to over emphasis of siderite formation after progression through oxygen depletion and sulfidic fields to the exclusion of other modes of sideritization. This is particularly important given the very early occurence of the siderite in the Cardium.

The simplified model implied and generally quoted (e.g. Gautier, 1985) is that siderite does not form until the sulphate common in marine waters has been used up by transition through the sulphidic field and consequently, siderite is characteristic of the methanic stage of early diagenesis. This argument implies relatively deep burial (see for example Gautier, 1985). However, this model does not account for the formation of all siderite, and, indeed, its overemphasis seems to have led to problems in accounting for some of the isotope results in some cases (e.g. Gautier, 1985). It must be remembered that under some conditions, siderite may form in the post-oxic field. As discussed in more detail below, this may occur regardless of the concentration of sulphate in the water (and hence pyrite in the rock).

The primary flaw of the above diagram is that by simplifying the Eh, pH diagrams for mineral stability some information has been obscured. An examination of any series of such stability diagrams reveals that in all cases, regardless of sulphate concentration, there is a field, of varying size, at Eh values above the field of pyrite stability in which siderite is thermodynamically capable of forming. Figure 5-3 shows such diagrams (taken from Woodland and Stenstrom, 1979). The details of each field shown are discussed in the figure caption. Note that even for sulphate concentrations above those found in sea water (5-3A) there exists a stability region for siderite. This contradicts the most commonly held view that the formation of siderite requires a removal of almost all sulphur from the system. Even in the fields where siderite is unstable relative to pyrite, siderite may form preferentially because of the relative kinetic difficulty in complexing sulphur with iron (Gautier and Claypool, 1984). In fact, the governing controls on siderite formation are Eh and the presence of ferrous iron. Organic material, summarizable as carbon (C), is responsible for the Eh regime, reducing iron (Fe) and generation of CO_2. None of these factors can be readily measured in the rock record. In short, siderite formation does not directly depend on $SO_4^{=}$ concentration. High organic concentration may have led to the precipitation of the siderite in different ways. MicrOrganism activity could have played an unknown part. Sarjeant (1975) states that "some algae have a chemotactic affinity for iron; indeed, several species, mainly members of Cyanophyceae, deposit iron in or upon



Fe++
FeCO3
Fe2O3
FeS2
H2O
H2
Fe3O4
(A)
(B)
(C)
(D)
Eh
pH
0.0
-0.2
-0.4
-0.6
6
8
10
12
4

their phylaments and occur abundantly within iron oolites". Warme (1975) notes that endolithic algae, which are the type which might be expected to have an effect on any of the Cardium rock Horizons, are probably ubiquitous at the shoreline and in shallow depths. The high iron and carbon concentrations could conceivably, therefore, be linked to microbial activity rather than just an idealized relatively passive response to the decay of introduced organic material. Indeed, as an idea which would require much further investigation, it is interesting to postulate the possibility that some of the reaction rims visible around chert pebbles surrounded by siderite might be due to etching by endolithic algae; however, such rims are much more likely due merely to dissolution of the chert due to pH differences wherein the carbonate is stable and the silica unstable.

Indeed it seems that the idea of siderite dependence on reduced sulphate concentration became entrenched in the literature by continued reference to the initial, low sulphur, diagram of Garrels and Christ (1965, e.g. their fig. 6-21). However, another diagram published in this same source relatively clearly summarized the possibility of siderite occuring prior to the occurence of abundant pyrite (figure 7.8 in the above work) due to the difference in the Eh-pH potentials of the two reactions.

The thermodynamic literature thus leaves the possibility of either post-oxic or methanic siderite. It is important to distinguish the two because the methanic occurrence generally implies a depth of burial sufficient to remove the possibility of studying the sediment-water column interaction. Textural evidence is important in discerning the stage of formation. The very high paleoporosity, which argues for depths of formation most uncharacteristic of the methanic stage of diagenesis, implies that the siderite formed in the post-oxic stage due to high organic concentration.

4B. Pyrite and Guessing the Salinity of the Water

In some cases, mineralogy may help to distinguish the different stages of sideritization, but in the case of the Cardium siderite only crude approximations may be made. The presence of pyrite, although problematical in some ways, is the most reliable mineralogical factor for distinguishing methanogenic and post-oxic siderite. In a system with any marine influence, the sulphate contained in the waters trapped in the pores would, indeed, be reduced to form pyrite prior to the generation of methanic siderite. The problem arises in the amount of pyrite so formed. Assuming complete reduction of all sulphate but no further interaction with sea water, sea water of typical ionic composition (e.g. that from Blatt, Middleton and

Murray, 1982) the amount of pyrite expected can be calculated as follows for 2cc of sea water. (2cc yield approximately the amount of pyrite to be expected in a typical core sample.)

$$(.028 \text{ moles } SO_4^{=}/1000\text{gm } H_2O_{sw})(1\text{gm/cc}) =$$

$$.028 \text{ moles } SO_4^{=}/1000\text{cc}$$

$$\rightarrow (2.8 \times 10^{-5} \text{ moles } SO_4^{=}/\text{cc } H_2O)(2\text{cc}) =$$

$$5.6 \times 10^{-5} \text{ moles } SO_4^{=}$$

Assuming complete consumption, this equates to

$$5.6 \times 10^{-5}/2 \text{ moles } FeS_2$$

which equates to

$$2.8 \times 10^{-5} \text{ moles } FeS_2$$

the Molecular Weight of pyrite = 120gm/mole

$$\rightarrow \quad (120)(2.8 \times 10^{-5} \text{ gm } FeS_2)$$

$$= 3.36 \times 10^{-3} \text{ gm } FeS_2$$

the density of FeS_2 = 5gm/cc

$$\rightarrow \quad 3.36 \times 10^{-3}/5 = 6.72 \times 10^{-4} \text{ cc } FeS_2$$

$$\rightarrow \quad (6.72 \times 10^{-4} \text{ cc } FeS_2)(1000\text{mm}^3/\text{cc})$$

$$= \underline{.67 \text{ mm}^3 \text{ FeS2}}$$

Although a rough minimum, this is a very small amount which would be very difficult to detect in comparison to the large amount of siderite present because of the relatively unlimited amount of iron and organic matter present in the same volume of rock. Consequently it would be very difficult to argue for one kind of siderite or the other based solely on the amount of pyrite present if the original water had average or below average $SO_4^=$ concentrations and/or little post depositional circulation of pore fluids.

The problem is made even worse by the very strong possibility of microenvironments leading to changes in Eh sufficient to precipitate pyrite in one small area while siderite precipitation occurs elsewhere. I have seen the results of such microenvironments in the form of small, less than 2mm diameter pyrite filled burrows set in otherwise unaltered or sideritized silts. The subtle variations in such cases are likely due to fecal matter concentrations.

In terms of microenvironments, it is interesting to note that the occasional calcite cementation of sands and conglomerates noted above may also be due to local effects. The lack of muds in these cases probably lowered the concentration of iron because iron is collated onto the clays. Consequently, the system was saturated with respect to carbonates because of the bicarbonate indirectly available from organic decay but had no iron to complex with and so precipitated calcite.

The presence of a somewhat brackish water column, as indicated by the microfauna (chapter 5), makes the problem even more difficult by introducing the likelihood of an initially reduced sulphate content. Moreover, the amount of circulation through the uncemented pores by water containing any amount of sulphate is unknown so, in a reverse argument, even sediments containing relatively large amounts of pyrite cannot be certainly claimed to have arisen from any given type of water.

Conclusions based solely on mineralogical criteria would therefore, be somewhat tenuous at best. However, there is a distinct general lack of pyrite (see the discussion of figure 4-4, above) in the sideritized Horizons of the Cardium. This lack allows for formation from 'brackish' water. This is compatible with low $SO_4^{=}$ concentrations implied by the "brackish" fauna (see the preceeding chapter). In summary, siderite likely formed in brackish to fresh waters very early in the post-oxic field.

5. THE QUESTION OF SUBAERIAL EXPOSURE

The strong likelihood of fresh water influence in the formation of siderite raises the question, briefly mentioned above, of whether any of it is due to subaerial exposure. Proof of non-marine formation, or more specifically 'subaerial' formation, is difficult. With the exception of H5 (E5) (discussed in Chapter 7), textural evidence argues against exposure. The frequent gradational nature of the siderite and interbedding with marine facies on the decimeter scale (discussed in Chapter 3) seems to preclude such formation. This is particularly true for facies such as facies 16 which contains thin beds of siderite alternating with unsideritized marine muds and sandy storm beds containing siderite rip ups on occasion which almost proves a subaqueous formation. Given the formation in waters of lower than 'normal' marine sulphate concentration discussed above, such considerations would require isotope work to distinguish meteoric versus sea water. Thus, the relative importance of meteoric versus sea water in the occurence of the siderite is not definitely known. None of the above analyses can discern between such water sources. Unfortunately, no thorough isotope work is available, to date, on the Cardium. Even the ability to distinguish between meteoric and connate waters may not definitely allow conclusion for or against subaerial formation of siderite because of the possibility of meteoric water entering the 'marine' system through aquifers.

6. THE EXTENT OF SIDERITIZATION

Regardless of the isotopic composition of the waters in which the cement formed, the widespread nature of the siderite poses a puzzle. As mentioned above, this likely fresh-water induced cementation shows no distinct pattern correlatable with the 'bench' and 'offshore' of Figure 4-4 in Chapter 4. Why then does an apparent fresh-water influence extend over the entire basin (where investigated)? The answer is that the entire basin was diluted with respect to standard seawater. This is implied by the agglutinated nature of even the `offshore' foraminifera (discussed in Chapter 4) and the ubiquitous presence of siderite with its implication of reduced sulphate concentration. The foraminifera show a more pronounced pattern than the siderite because they are likely more sensitive to water conditions. It may thus be that the `bench' had either greater fresh water input and/or higher turbidity which would not be reflected in the siderite pattern. Conditions were just as suitable further into the basin as on the `bench' for its formation. The widespread fresher water conditions aiding the formation of siderite were probably induced by repeated shallowing of the basin as discussed by Plint et al. (1986) which made dilution easier. Shallowing may also have led to increased organic and iron input via the arrival of clays from transgressed areas. (In fact, Kumar and Sanders (1976) provide a description of what sounds suspiciously like a modern example of such a setting off the Fire Island barrier; they observed "seaward of wave base, the bottom morphology was irregular. In some places vague traces of large inactive ripples could being reworked by burrowing organisms could be distinguished. In addition, the bottom of seaward wavebase was overlain be a thin (few cm thick) layer of rust-coloured (my emphasis) organic debris which apparently consisted of diatoms, algae and other micro organisms." This sounds very much like a storm bed covered in organic debris reacting with iron which could conceivably lead to siderite precipitation.) Both an increase in organic and iron supply and a decrease in sulphate concentration would account for extensive increased susceptibility to sideritization.

7. POSSIBLE CEMENTATION DURING SEDIMENTATION PAUSES

Widespread cementation of this sort conjures up the image of a pause leading to the development of a hardground analogous to behaviour seen in carbonate rocks. However, the changes in rather subtle chemical conditions could be the only mechanism responsible for such cementation. Rate of sedimentation need not be a factor; if cementation were rapid enough, fluctuating sea level with its concurrent changes in water chemistry could form the only control on extensive cementation. In fact siderite may form very rapidly as indicated by studies in the Atchafalaya Bay of the Mississippi (Ho and Coleman, 1969) where it forms in muds as shallow as 20 ft. It has also been observed to have formed in the Wash in England on WWII age material (brass shells) (M. Coleman, p. comm., 1985). These are minimizing values that may be placed on the events discussed. Obviously the potential for formation over a period of approximately a century makes it difficult to argue conclusively that siderite represents pause cementation. The opposite may be true; siderite may merely reflect rapid cementation due to extensive changes in water and 'substrate' chemistry coincident with proximity to exposure.

8. CONCLUSIONS

Although uncertainties such as discussed under the various headings above remain, the various conclusions of these discussions may be summarized briefly in point form.

1. The siderite in the Cardium Horizons formed very early almost immediately after depostion.

2. The siderite very probably is post-oxic siderite.

3. The formation of the siderite is probably due to increased supply of organic material and iron during transgression in conjunction with basinal shallowing close to the point of emergence which allowed for increased fresh water dilution of the system.

4. Siderite probably does not indicate subaerial exposure.

5. The formation of siderite was probably very rapid and hence the possibility of pause related cementation cannot be discerned. The widespread occurrence may indicate a relative pause in deposition long enough for

extensive cementation to occur but of insufficient duration for the biological community to respond (as discussed in the previous chapter.). It is thus the only indicator of possible delay in sedimentation during formation of the the event stratigraphy. The sediments forming these events, discussed in the next chapter, indicate that any pause was probably of very limited extent.

CHAPTER 6

COMPARISON TO CARBONATE HARD AND FIRMGROUNDS

1. INTRODUCTION

A review of the facies and sequences discussed previously indicates that nowhere is there developed an immediately obvious analogy to the hard or firmgrounds present in carbonate units as summarized, for example by Kennedy (1975). However, a comparison of the characteristics of carbonate firmgrounds with the Cardium events is enlightening and helps constrain the timespan within which the Cardium surfaces formed.

Ichnology is the basis for such a comparison, so it should be noted that information in this field of study is biased. Trace fossils have been particularly well studied in clastics and more or less extended from there to carbonate environments. However, carbonate equivalents exist for the bulk of standard terrigenous clastic sequences (Kennedy, 1975). The current exception to this is the information on hardgrounds in which the predominance is reversed. This is most likely due to greater prominance of carbonate horizons in which early cementation is much more common and more readily achieved.

2. OMISSION SURFACES IN CARBONATES

Understanding interpretations of Cardium surfaces first requires understanding of the better studied carbonate horizons. The surfaces of this kind in carbonate rocks have been divided into several categories by Bromley (1975). These are: discontinuity surfaces, minor erosion surfaces, substitution surfaces, omission surfaces and hardgrounds. The trace fauna have been divided into a pre-omission suite and an omission suite. The omission suite may be the same as the pre-omission suite but denser due to crowding. Members of the omission suite characteristically penetrate those of the pre-omission suite. However, the omission suite most typically envisioned differs from the pre-omission suite due to energy or lithification changes. The omission suite is Seilacher's *Glossifungites* suite. Seilacher's *Glossifungites* ichnocoenoses includes hardgrounds, firm mud and erosion surfaces (see for example Pemberton and Frey, 1984); *Glossifungites* fauna require highly indurated shales. The most important point of comparison for studies of siliciclastic systems is the concept of the omission suite. Many of the other firmground terms are carbonate specific. Some of the common carbonate related criteria are as follows.

Although some longstanding hardgrounds are burrowed to only a slight degree, most carbonate omission surfaces are marked by a predominance of Thalassinoides burrows and faint feruginization of the burrow walls (Bromley, 1975). In fact, Kennedy (1975) claims that Thalassinoides is the only burrow consistently associated with hardground omission suites; other borings occur 'randomly'.

The burrows are typically filled by the overlying sediment. Along with the burrow networks, intraclasts of the syncementational sand occur due to periods of higher energy.

Many of the carbonate surfaces do not represent single events by rather show several suites of boring as sediment pulses infilled lithified burrows which were rebored (Bromley, 1975). This multiple nature, indicates that the surfaces are actually relatively active. Their activity is merely relatively slow compared to the rapid cementation possible in carbonate settings.

The final interesting characteristic of burrows of the omission suite is that they modify in form concurrent with cementation (i.e. a Thalassinoides burrow will curve around regions that are already cemented)(Bromley, 1975).

3. A COMPARISON WITH THE CARDIUM SURFACES

A comparison of the characteristics of the two cases, summarized in Table 6-1 confirms that the Cardium events only crudely fit the carbonate hardground model. E5 is an exception.

TABLE 6-1
A COMPARISON OF CARBONATE FIRMGROUNDS AND THE CARDIUM

Carbonate Firmgrounds	Cardium Horizons
1. *Glossifungites* ichnocoenoses (also characteristic of the known siliciclasitc firmgrounds)	absent
2. Ubiquitous *Thalassinoides*	present
3. Firmgrounds are multiple events	possible
4. Passive infill of burrows with rip-ups of the firmground	equivalent occurs??
5. Modification of burrow path during cementation	yes
6. Rip-ups of cemented material present on the surface	yes
7. Reburrowing of existing burrows	?

The comparisons are as follows.

1. The presence of the *Glossifungites* fauna

Members of the *Glossifungites* fauna are absent from the Cardium. The presence of an extensively cemented or indurated substrate generally only occurs in H5, as discussed in chapter 7 and illustrated in Plates 7-1A and B. Thus, it is the only surface which potentially presents a solid analogy to the carbonate surfaces. The high percentage paleoporosity described in chapter 4 and the general biotubation, indicating high initial water content (Rhoads, 1975), of most of the facies described in chapter

3 probably prohibited the occurence of the Glossifungites ichnocoenoses in the Cardium. The events contained therein must have occurred in relatively 'soupy' sediments which in some cases were rapidly sideritized to such a degree and over such a time scale as to prevent colonization and boring by the standard Glossifungites fauna. Such a lack of fauna could also be due to conditions in the water column discussed in chapter 4. According to Kauffman (1969), the order of disappearance of genera with decreasing oxygen levels and temperature is first, specialized epibenthic and infaunal molluscs and echinoderms, then shelled epibionts and specialized burrowing invertebrates, Inoceramus and burrowing arthropods, and finally, by reduction and loss of detritus, detrital feeding polycheates. If, as postulated in the above chapter, the Cardium events are characterized by increasing degrees of brackish stress on the system with increasing shallowing, then it is quite likely that by the time each cycle was sufficiently affected to create the siderite cement, the fauna capable of creating the Glossifungites suite, predominantly molluscs (e.g. mechanically boring bivalves (Bromley, 1975)), had been killed off or inhibited by low oxygen levels and turbidity. Nevertheless, bioturbation by polycheates is possible immediately prior to and following sideritization and is

indeed observed in the form of sideritized indistinctly bioturbated muds overlain by bioturbated muds.

2. The presence of Thalassinoides

The surfaces do show some Thalassinoides burrows. Where the burrows are visible in the erosive surfaces, most notable at the fifth Horizon, they are likely crustacean burrows, possibly Thalassinoides, but the identification is difficult in core. Plates 7-1A and B show two burrows through E5. The `twisted" shape is probably due to such fauna but cannot be claimed with certainty. The burrows do not appear to be borings but have been excavated into material of greater than usual consolidation as discussed in chapter 7. More convincingly, Plate 6-1A shows a passively filled Thalassinoides burrow from E7. In this example, the burrow lies at the base of the Amundson Member.

3. The presence of multiple events

Multiple events are not distinguishable at any Cardium surface but do occur within the conglomeratic members. For example, the pulsed nature of facies 8 was discussed in chapter 3. Plate 6-1B shows a Thalassinoides burrow within the Amundson Member, between E7 and T7, which has subsequently been sideritized. The pulsed behaviour of the conglomeratic members with their attendant burrows might be taken as analagous to carbonate behaviour but probably only


A
16 - 29 - 59 - 1W6
2285'
JJB
B
16 - 29 - 59 - 1W6
2283' 10"
JJB

reflects discontinous sedimentation that would occur normally.

4. Passive infill of firmground burrows

As with the burrowing, passive infill similar to carbonates may occur, albeit the fill is not of rip-up nature but is coarser sand and granules. This type of fill may be seen in the Plates 7-1A and B and 6-1A and B.

5. The presence of burrows modifying in response to cementation

Burrow modification in response to cementation may be observed in outcrop at the Seebe Dam site (see Walker and Wright, 1982 for location). Approximately 1 cm *Planolites* burrows curve around siderite nodules that were developing at the time of burrowing in association with a now exposed erosive surface (thought to correlate with E5 in the subsurface). This is shown in Plate 6-2.

6. The presence of syn-cementational rip-up clasts

Rip-ups of recently cemented material also occur as described in facies 16 and 10B in chapter 3; these correspond to the ripped up clasts of carbonate material common in carbonate surfaces but are not as extensive. the Given the probably rapid rate of cementation (Chapter 5), this probably indicates a rapid transgression of the cemented horizon. This rapid transgression is also reflected in the lack of a pattern of continuous reworking.

The rapid transgression makes it impossible to distinguish a 'normal' rate of bioturbation from reworking of any sort of brief omission surface that might occur at H6 or H7 for example.

7. Reburrowing of existing burrows

The "freezing" of existing burrow forms prior to reburrowing at the same horizon is particularly absent in the Cardium surfaces. This absence is probably due to the very short timespan of the events relative to the rate of cementation and burrowing. Perfectly analagous behaviour in siliciclastics would require slower rates of transgression.

4. SUMMARY

In summary, the Horizons of the Cardium show features that may make them crude siliciclastic equivalents of the firmgrounds in carbonate rocks. However, rapid transgression probably prevented full development of these features. The best analogies exist at E5 where definite erosion is visible in core, but there are sufficient occurences of such criteria as Thalassinoides burrows and early cementation in the form of siderite to make the other Horizons compatible with this model. Their variations stem from their different basinal location and behaviour, as summarized in the next chapter, and the very short time over which the events occurred in generally muddy sediments.

Consideration of sediment behaviour on a more basinal scale also emphasises the short, but unquantifiable, nature of the events.

CHAPTER 7

HORIZON BEHAVIOUR

1. INTRODUCTION

The discussion of the early diagenesis and foraminiferal data and the comparison to carbonate firmgrounds of the above chapters all emphasize the rapid nature of the events that define the Cardium stratigraphy of Plint et al. (1986). This leaves the question of what do the sediments themselves look like in response to very rapid fluctuation of relative sea level and what, in turn, do they tell us about any variations in the nature of the events? The sediments of interest are those in immediate proximity to distinct surfaces and those that compose gradational sequences correlative to E-T events. Study of a few examples will suffice because the facies of chapter 3 are distributed regularly in the vertical sequences that comprise the Cardium members as defined by Plint et al. (1986).

2. THE CARDIUM MEMBERS

Although many of the facies of chapter 3 may be interpreted on the basis of internal characteristics, the most salient information comes from the sequences within which they occur. These sequences have been well described by Plint et al. (1986) and will not be discussed further here apart from a brief summary for the orientation of the reader. Rather, this thesis is concerned with the pattern and truncation of facies within the immediate proximity of the event surfaces, where discernable; the scale is thus on the order of a meter.

The sequences of Plint et al. (1986) in the transgressive phase of the Cardium may be crudely divided into two types, the Karr type cycle and the Raven River type cycle (K-type and R-type). Both sequences show shallowing upwards facies trends and rapid to erosional truncation. The K cycles, those up to Horizons 4 (Burnstick), 6 (Low Water) and 7 (Amundson) usually proceed from offshore muds of facies 1 to 3 up to facies 6 sometimes capped by conglomerates of facies 8. The R cycles, up to Horizon 5 (Carrot Creek) have the same basal sequence of facies 1 and 3 but proceed into the finer sand facies 4, 5, and 7 and in turn are usually capped by 8. Both cycles represent shallowing into storm dominated sands, but the R cycles are finer grained, and the K cycles tend to be more gradational.

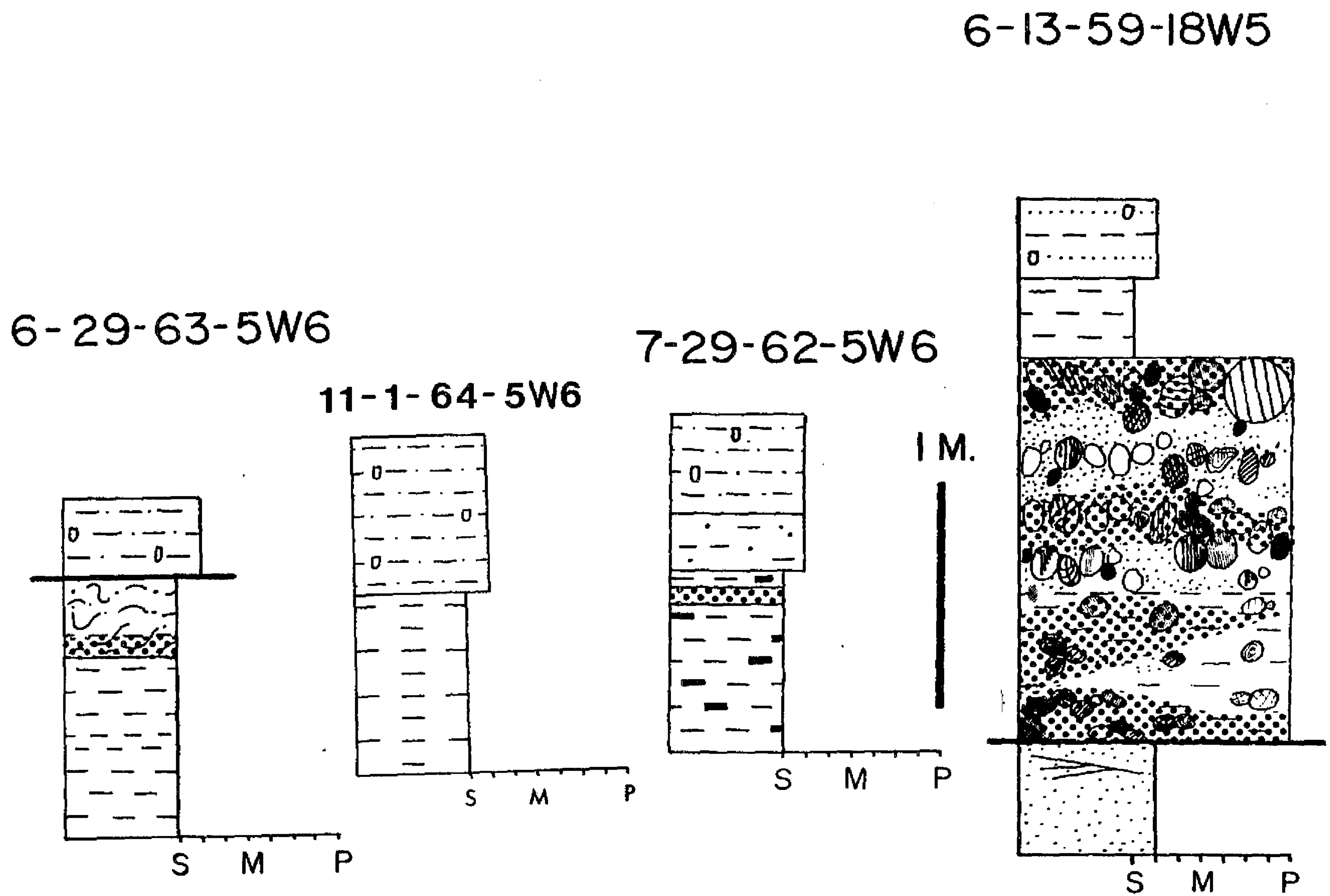
The nature of the Raven River sequence between the fourth and fifth Horizons is a little ambiguous. It could represent either the occurence of a shallowing of the basin into an H.C.S. facies (the most likely interpretation given the behaviour of the other cycles) or the continued transgression of the basin with the H.C.S. portion of the cycle representing siltier/sandier sediments offshore of a transgressive muddy shoreline. The H.C.S. would lie offshore in this case due to depth; waves would be damped out in shallow muddy water and be incapable of forming the structure there.

In keeping with the relative constancy of facies sequences in the various members, the transitions between cycles are also fairly consistent but do show some important variations both within a Horizon and between Horizons. These variations will be discussed Horizon by Horizon in numerical order.

3. BEHAVIOUR OF THE FOURTH HORIZON

The fourth Horizon, between the Hornbeck, Kakwa or Musreau and Raven River members shows a variety of behaviour from gradational "standard" transgression to erosive transgression. Figure 7-1 illustrates four examples of transitions across H4.

The first lithosection, 6-29-63-5W6 shows an example of a sharp, presumably erosive, contact between marine and non-marine muds. Plate 7-1, a thin section from this contact, shows that at the time of erosion the underlying sediment was still soft enough to be burrowed (note the prominent U-shaped amphipod burrow and the small circular


6-29-63-5W6
11-1-64-5W6
7-29-62-5W6
6-13-59-18W5
1 M.
S M P
S M P
S M P
S M P

burrow filled with the fine sand from the overlying facies). The relatively coarser material, in this case fine sand, usually associated with these transgressive Horizons has been thoroughly bioturbated into the over- and underlying material. Thus there may have been sufficient delay before the marine transgression to allow for consolidation of the non-marine muds but insufficient to develope truely indurated mudstones. It is difficult to quantify how long a period this might represent, however. In fact, the non-marine nature of the underlying sediment may even allow for subaerial consolidation completely unrelated to the rate of any basinal events. Qualitative estimates of the timespan of the events thus requires consideration of further examples.

Lithosection 11-1-64-5W6 shows what might be termed a typical marine transgression over a brackish bay where marine muds gradationally overly non-marine muds. There is no visible erosion here implying that whatever caused erosion in 6-29-63-5W6 acted over too short a time or too limited an area to have any influence here.

The next lithosection, 7-29-62-5W6, shows a response transitional between those of the previous two. Here there is a thin layer of dispersed sand that could concievably represent the feeble remains of a retreating barrier. There is no distinct erosion but there is a distinct lithological 'marker' between the marine and non-marine. Whatever the source of this dispersed sand, it was deposited on very unconsolidated ground as witnessed by its scattered nature.

Finally, section 6-13-59-18W5 shows a classic E-T form. In this case, there is visible erosion below the Burnstick Member. However, the transgression to marine muds appears on a scale apparently as rapid as those discussed above.

Note that the pebbles and granules of the Burnstick Member do not always appear in the correlative Horizon over the non-marine muds (this may be seen in Appendix 1).

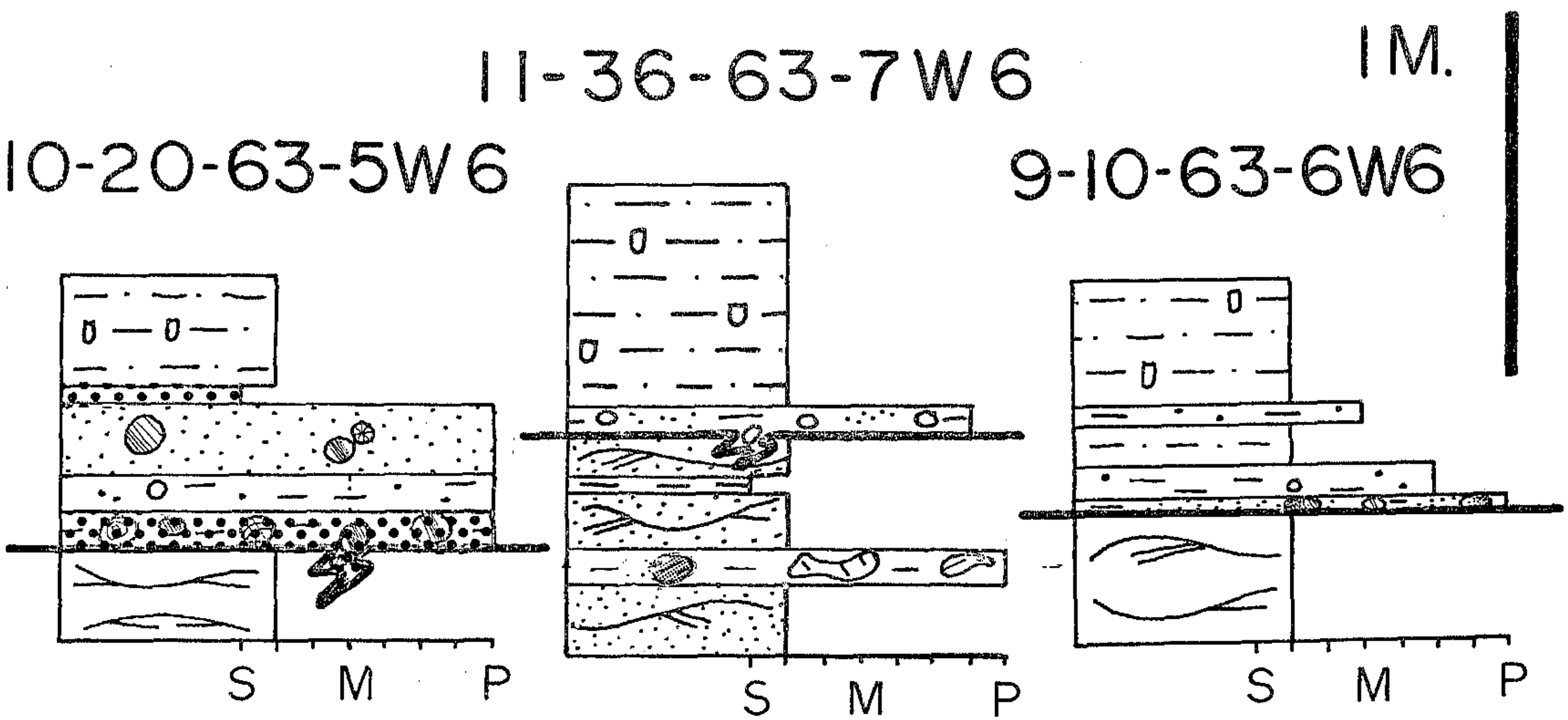
In conclusion, H4 is generally sudden and only occasionally erosive, probably because of very rapid transgression over muddy sediments. The erosion is most distinct below thick accumulations of the Burnstick Member and is probably due to brief stillstand allowing for scouring of lowstand shorefaces (see Plint et al., 1986 and Bergman and Walker, 1986).

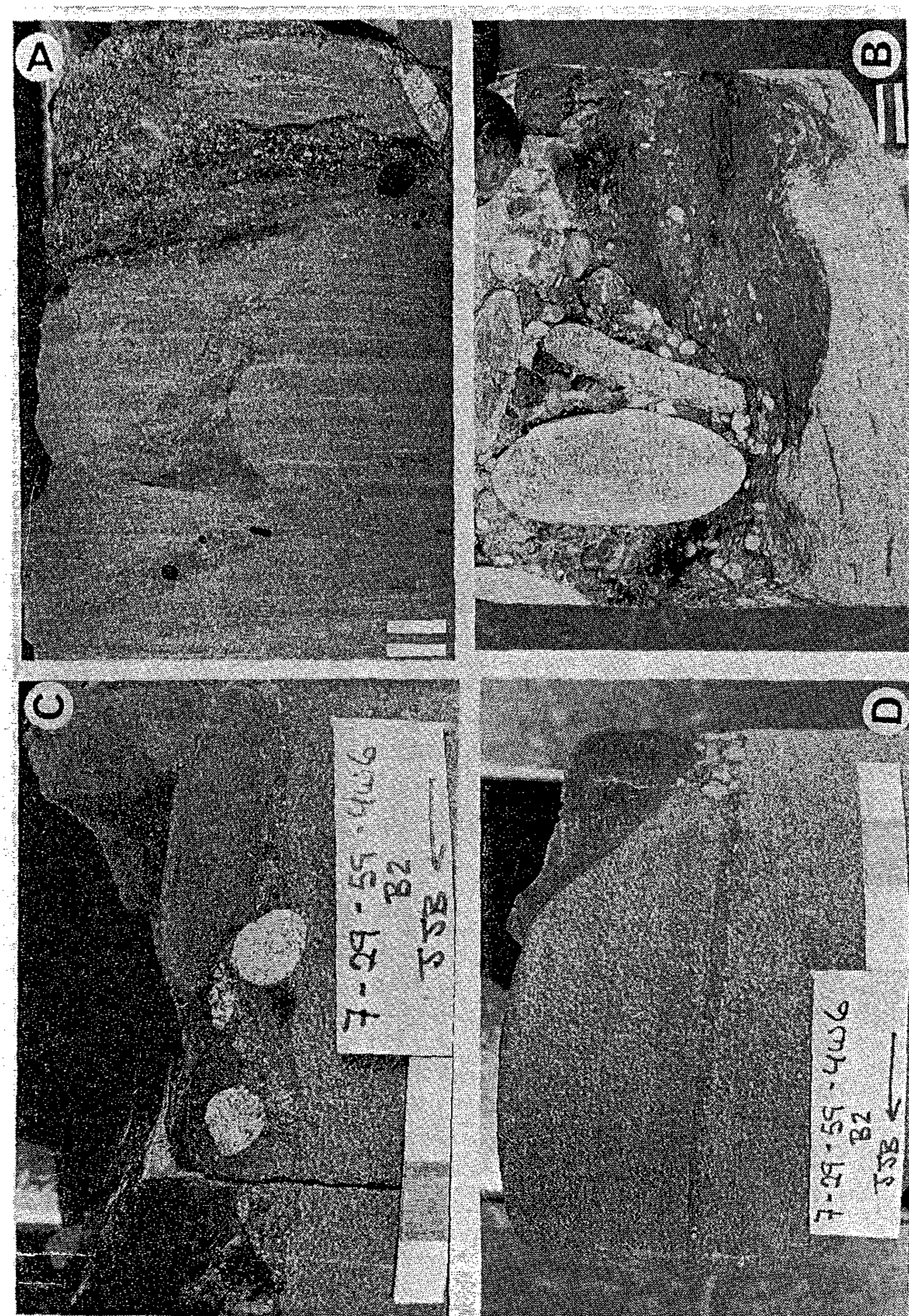
4. BEHAVIOUR OF THE FIFTH HORIZON

The fifth Horizon, between the Raven River and Dismal Rat members is ubiquitously erosional; it is the only surface which has such predominant scour. The erosion is widespread and has been discussed by Plint et al. (1986) and Bergman and Walker (1986). These authors have discussed it on a larger scale where erosion may be demonstrated by preservation of a prior stratigraphy in some locations whereas the same facies sequences may be seen to be removed in other locations (Bergman and Walker, 1986).

As a comparison of the sections in figure 7-2 shows, although the erosion is ubiquitous, burrows may occur. As discussed in chapter 6, it thus forms the best analogy to a carbonate firmground. Plates 7-2A,B,C and D show examples of the erosion and the overlying veneer of the Carrot Creek member. Plate 7-2D shows a large sandstone clast torn up from underlying facies 7 indicating that substantial lithification occurred prior to the erosive event. However, the burrows present (Plate 7-2A and the lower right of 7-2B) indicate that lithification was not complete. It is likely that the burrows occured in areas of lesser lithification as shown in Plate 7-2A. This partial lithification implies that only a relatively short time was available for cementation; it further indicates the very rapid nature of the sea level changes at this time.

The reason for the pronounced erosion at this surface as opposed to the occasional occurrences in the other Horizons is uncertain but may be related to subaerial exposure (Bergman and Walker, 1986). As discussed in the


10-20-63-5W6
11-36-63-7W6
9-10-63-6W6
1M.
S M P
S M P
S M P


A
B
C
D

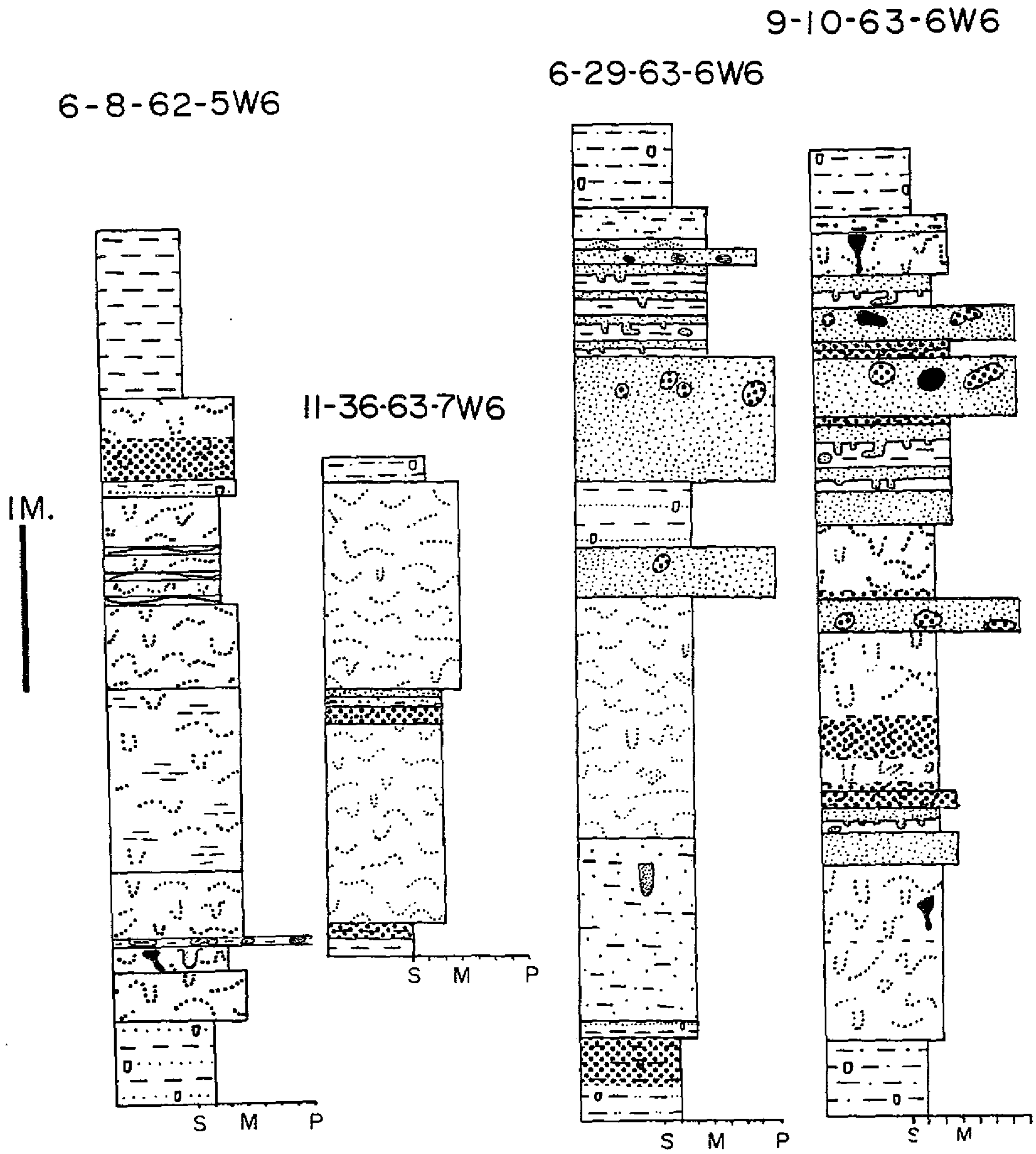
next chapter, circumstantial evidence strongly suggests that subaerial exposure occurred. This may also account for the increased lithification which generally seems to be due to pervasive formation of siderite. However, as discussed in chapter 5, siderite need not indicate emergent conditions.

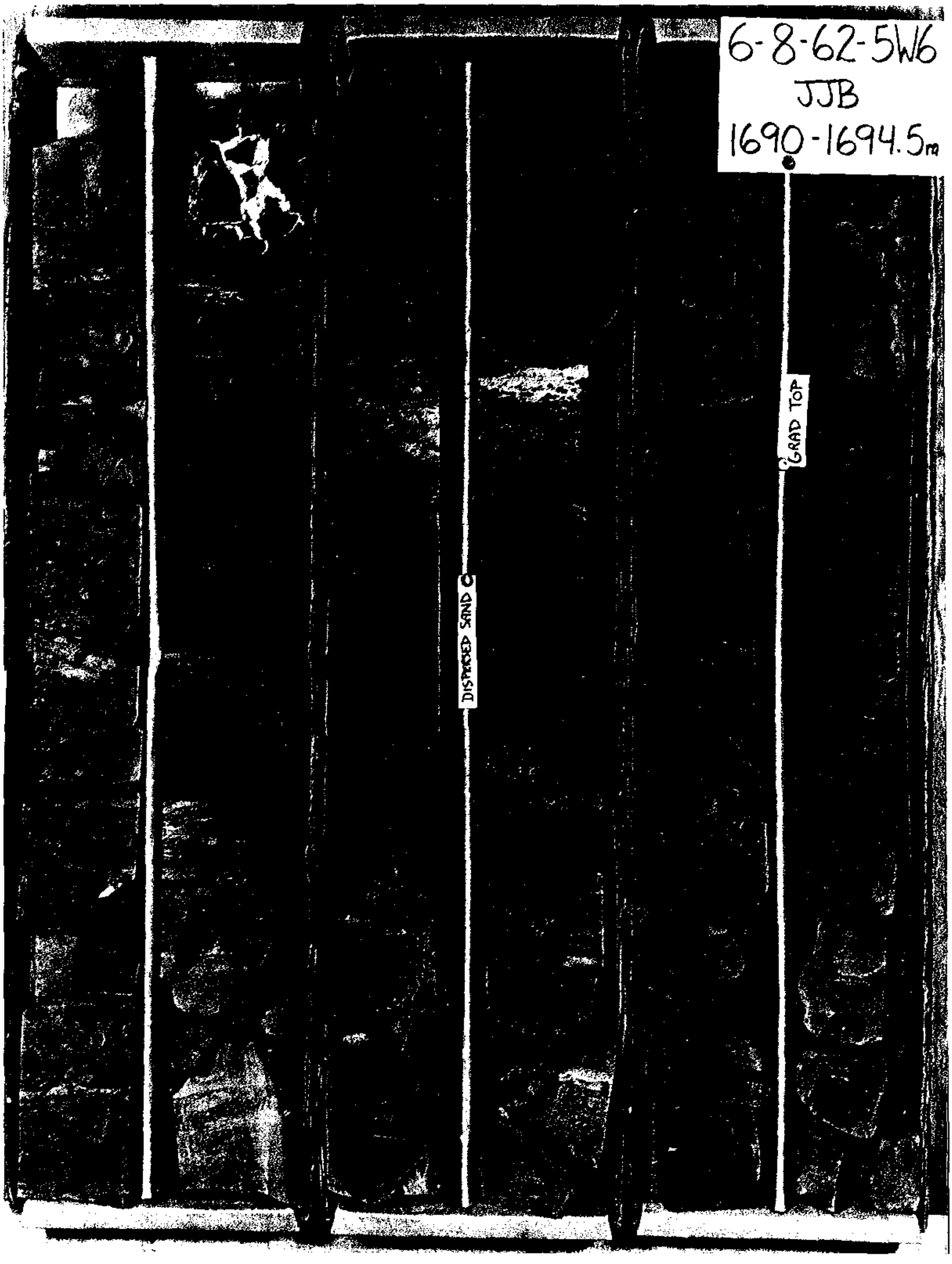
The time and cause of the erosion is difficult to discern because pebbles may lie either on or above the surface and so do not necessarily have to have been directly responsible for scouring the surface. Current action or possibly exposure could have been responsible with the pebbles being deposited later. On the other hand, the pebbles could have scoured the surface and been reworked over and off it during later stages of transgression. The occurence of pebble impressions between facies 7 and an immediately overlying facies 3, shown in section 6-7-63-6W6 (Appendix 1), could fit into either model given the presence of a semilithified substrate. The work of Bergman (Bergman and Walker, 1986) suggests that the pebbles very likely follow the period of erosion.

As discussed in chapter 4, the occurrence of erosion at any Horizon is not linked to accumulations of biogenic debris, particularly not to foraminifera, elsewhere at spots correlative to that surface. Consequently it seems that the erosion must have taken place very rapidly even though it is so extensive. If, as seems likely, subaerial processes contributed to the erosion, then the lack of accumulated marine fauna in the immediate vicinity of the erosion would be nicely explained because they were simply not around to be deposited. This likelihood makes it somewhat more difficult to judge the timespan of the event. But the fact that the surface could be burrowed after erosion implies that exposure was fairly short, assuming cementation can be correlated with exposure.

5. THE BEHAVIOUR OF THE SIXTH HORIZON

In the area studied, the sixth Horizon is the most gradational and in fact gave rise to the use of the Horizon terminology shown in figure 2-6. Figure 7-3 illustrates typical sections showing the general lack of erosion and the predominance of facies 6. Plate 7-3 shows the muddy, subtle nature of the changes in sedimentation. Most of the sections show a gradational base and a comparitively more rapid decrease in sand content upward. This behaviour probably reflects the fact that the sediments in the area examined form the correlative conformity (Vail et al., 1977) of erosive surfaces elsewhere. In fact, up to 38 m of erosion may be demonstrated at this Horizon to the south (A.G. Plint, p. comm., 1986). The rapid transgressions noted by Plint et al. (1986), which show up usually as E-T surfaces give rise, at this Horizon in this location, to a


9-10-63-6W6
6-29-63-6W6
6-8-62-5W6
11-36-63-7W6
1M.
S M P
S M P
S M P
S M

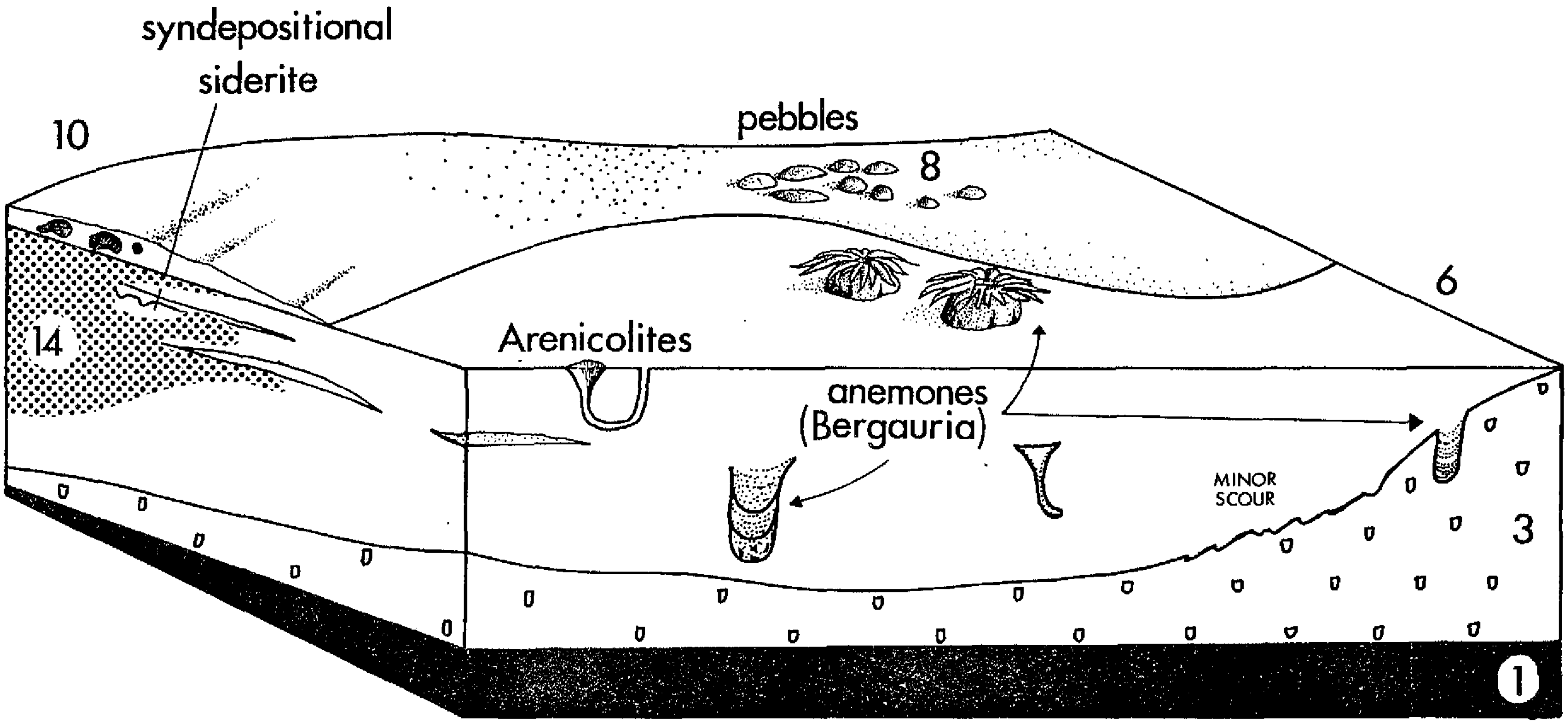

6-8-62-5W6
JJB
1690-1694.5m
GRAD TOP
DISPERSED SAND

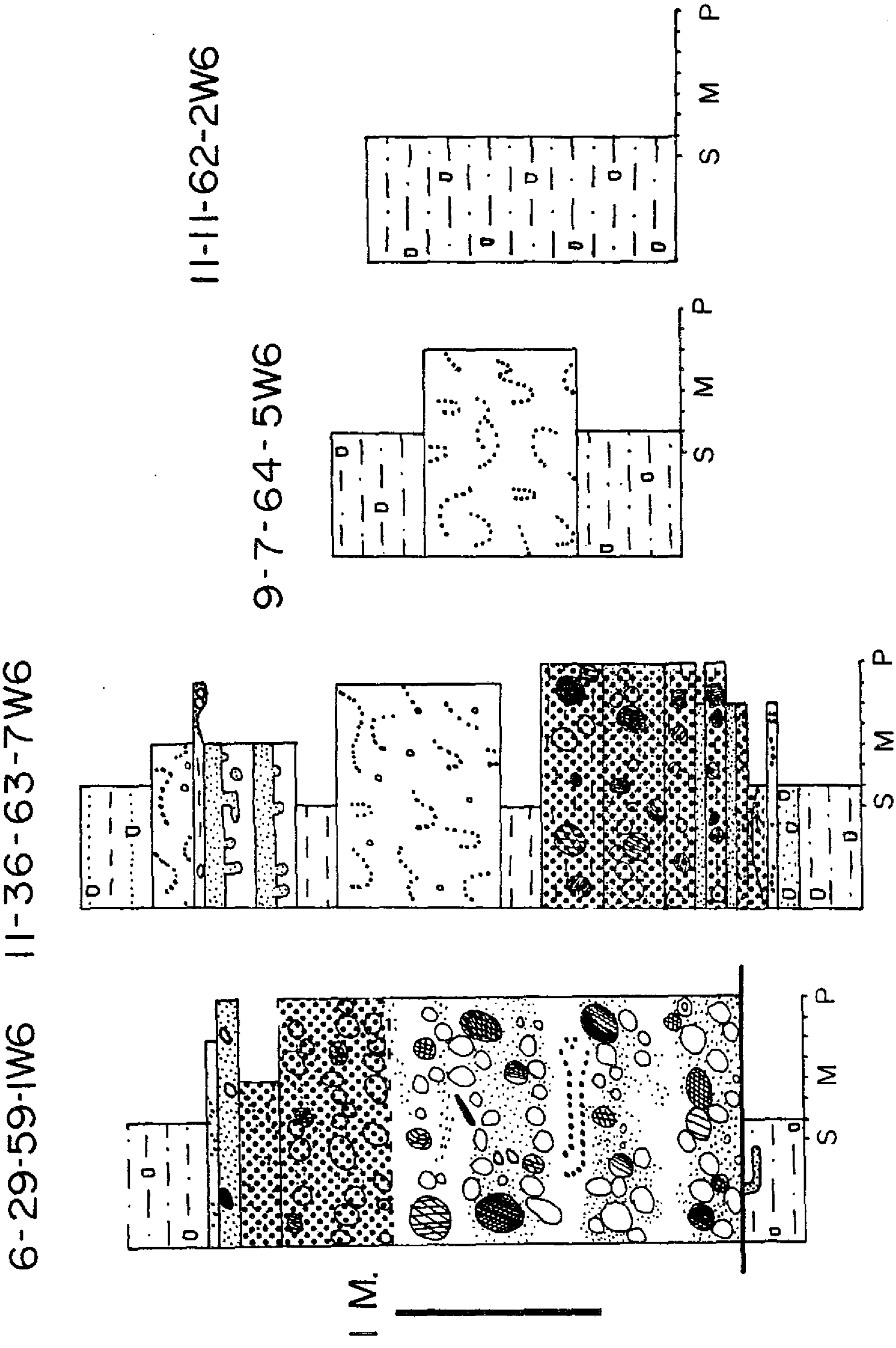
gradational base corresponding to the erosion and a slightly less gradational top corresponding to the transgression. Timewise, this agrees with a possible short stillstand leading to incised shorefaces at another location followed by rapid transgression. Because of the problem of seeing erosion into unconsolidated mud, the relatively soft nature of the substrate in almost all cases could be hiding some erosion. However, relatively flat correlation lines for this surface (see figure 8-2) in this area seem to indicate erosion did not occur. The presence of occasional erosion and conglomerate near the tops of these sequences implies that the scouring and pebble deposition occurred at lowstand, a pattern consistent with the results of Plint et al. (1986).

The gradational nature of the sections is sufficient to allow for crude determination of the environment of deposition of the sands. The lack of foraminifera discussed in chapter 4 gives some information on the environment but this may be refined by considering the facies present. The bioturbation, probable storm beds and distinct traces mentioned in chapter 6 combine to place these sediments in a transition to shoreface setting offshore of a probably muddy transgressive shoreline in a relatively flat 'bench' (see chapters 4 and 8). This setting is also strongly suggested by the regional

TRANSITION TO 'SHOREFACE'

TYPICAL OF 6TH HORIZON



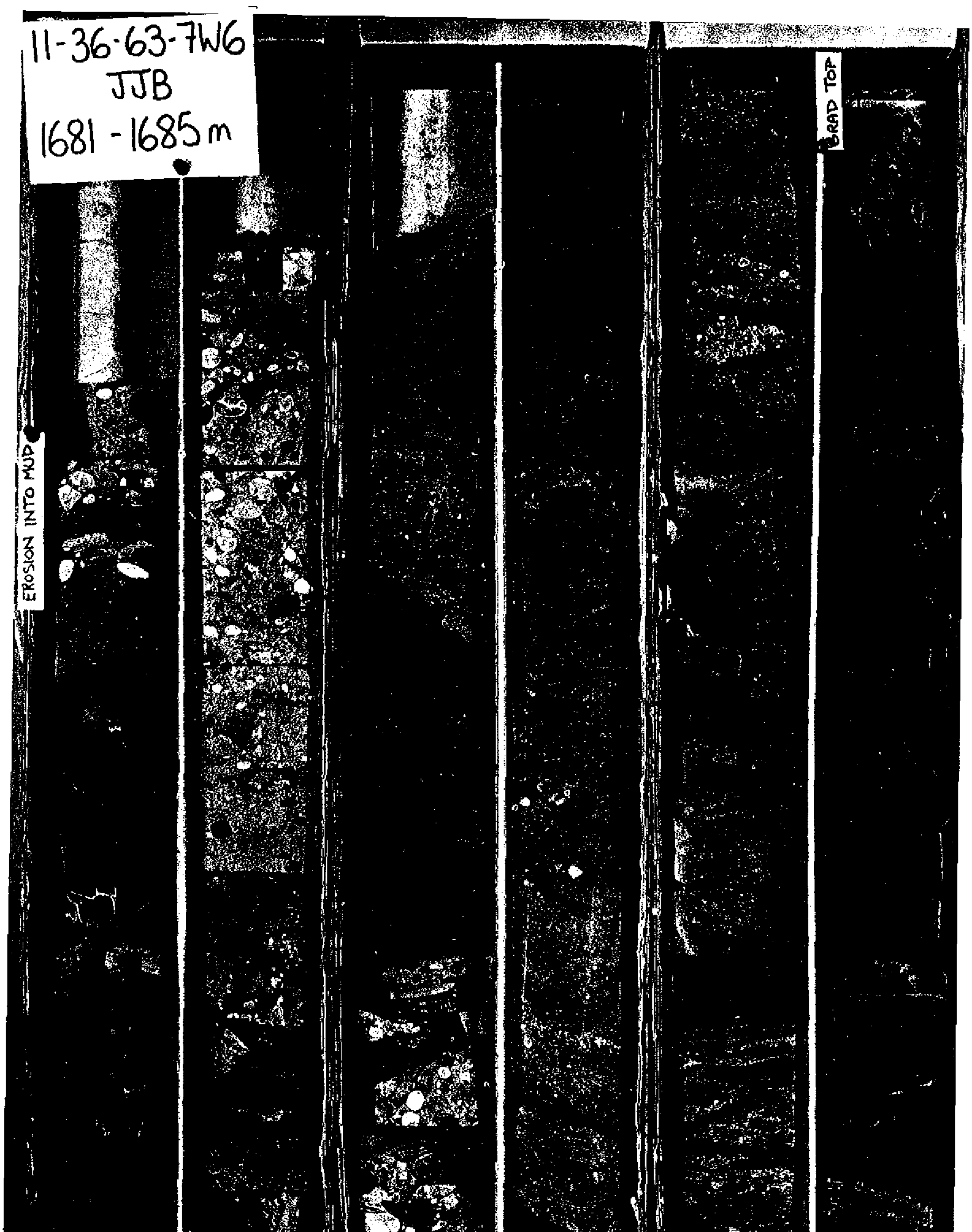

6-29-59-1W6
11-36-63-7W6
9-7-64-5W6
11-11-62-2W6
S M P
1 M.

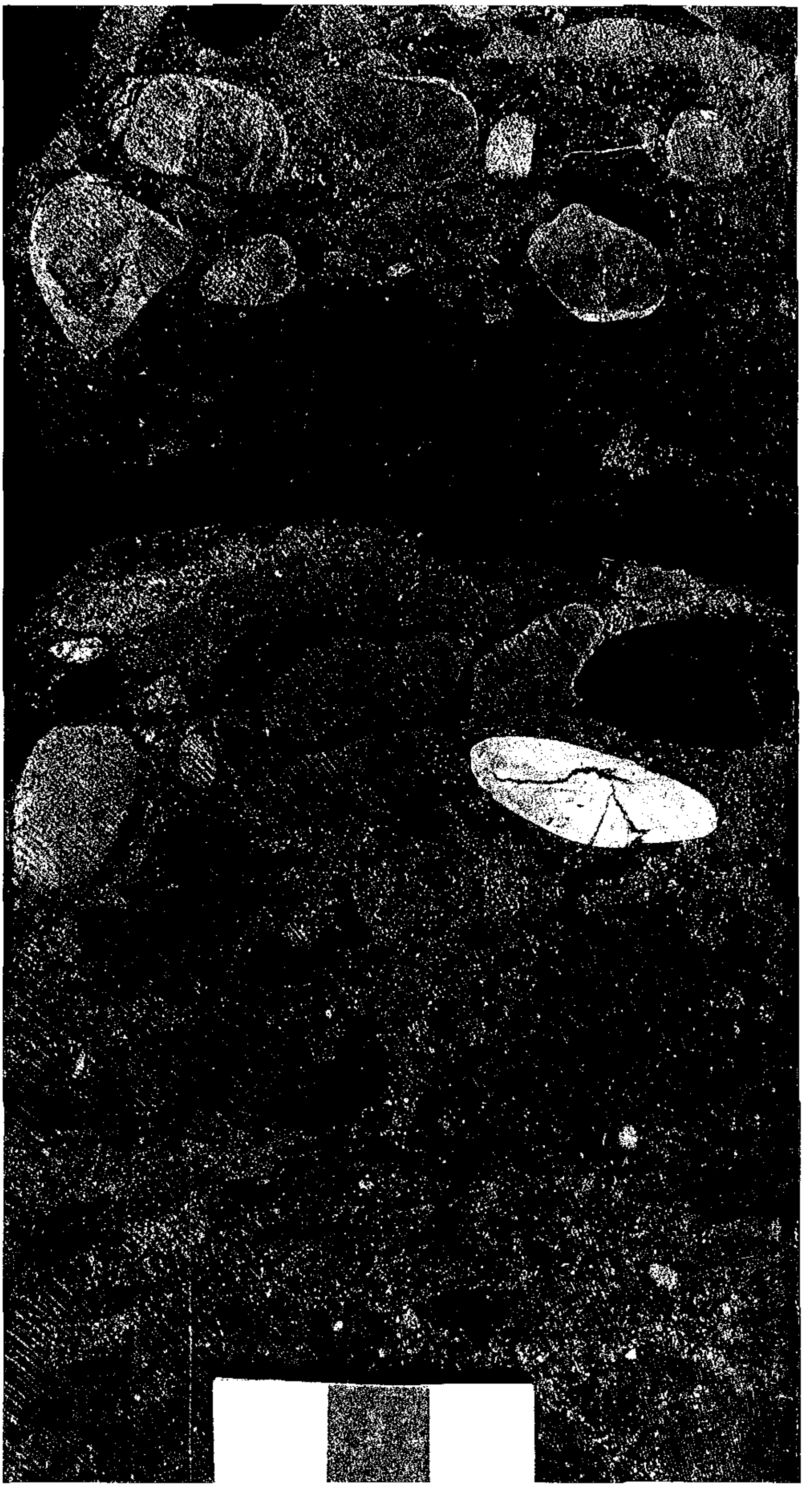
'topography' discussed in chapter 8. Figure 7-4 illustrates this transition to shoreface setting; the numbers are facies numbers. In this interpretation, the mud rip-ups of facies 10B are probably related to storm currents as opposed to the products of erosion following dessication during exposure. This is particularly so given the facies present and lack of E5 like erosion. The interpretation of these sediments as a transition to shoreface lying 'in' a correlative conformity agrees well with the interpretation of Plint et al. (1986) and Bergman and Walker (1986) of erosive regions as shorefaces.

The cases illustrated above once again emphasize the rapid nature of these events. Even though gradational, transgression is usually relatively rapid. As discussed in Chapter 5, brief chemical changes allowed siderite to form extensively but did allow it time to cement throughout the sediment package.

6. BEHAVIOUR OF THE SEVENTH HORIZON

H7 is very similar to the H6 except, as visible in figure 7-5, it contains more conglomerate and more convincing signs of erosion and sudden deepening. It is also the last occurence of the Cardium Horizons before the basin becomes more stable and more 'marine' (as indicated by foraminiferal content (chapter 4)). The sections shown in figure 7-5 range across the spectrum from correlative conformity to E-T surfaces. The most striking section in figure 7-5 is 11-11-62-2W6. The core has been carefully correlated to the well log based on continuous underlying core but shows no variation in facies indicative of any event. However, the well log response correlates to H7 elsewhere. This section shows the ultimate correlative conformity discussed above. Section 11-36-63-7W6 shows the transition from erosion to gradational sedimentation. It is also shown in Plate 7-4. The relatively rapid appearance of the conglomerate is visible along with the gradational disappearance of sand, but it takes a closer view, shown in Plate 7-5, to see the nature of the basal conglomerate contact. Plate 7-5 shows that although the conglomerate appears rapidly, it overlies a bioturbated mud containing medium to coarse sand and granules, and there is no distinct erosion. Compare this plate to Plate 7-2. The coarse sand is a precursor to the conglomerate but like the conglomerate itself was deposited in soft, faunally rich sediment and bioturbated. Any possible scour here is erosion into soft mud and poorly visible. This pattern indicates that the arrival of the conglomerate, associated with relative sea level changes (Plint et al., 1986), is rapid because the mud would be expected to consolidate and show signs of scour if the change occurred slowly. The


11-36-63-7W6
JJB
1681 - 1685 m
EROSION INTO MUD
BRAD TOP



substrate usually has no time to respond significantly to the final stages of change in sea level.

7. SUMMARY

The information gathered from the behaviour of the sediments may be summarized in point form.

1. H4 is rapidly gradational from transgressed non-marine mud or erosive shorefaces into transgressive marine muds and does not indicate significant consolidation prior to transgression.

2. H5 (E5) is ubiquitously erosional but its base is only partially lithified suggesting possible brief exposure and rapid transgression.

3. H6 is usually rapidly gradational and is a correlative conformity; even the correlative conformities change rapidly.

4. H7 shows behaviour between that of H6 and H5 again indicating sudden changes.

In all cases, whether erosional or gradational, the sediment indicates that the changes in relative sea level occurred very rapidly. The timespan may be close to that of siderite formation, perhaps on the order of tens to hundreds of years as a minimum; it is certainly much less than the 140,000 years equitably assigned to each sequence in Chapter 2. The faunal and diagenetic data agree with the behaviour implied by textures visible in core.

Chapter 8 discusses larger scale Horizon behaviour relative to possible causal mechanisms.

CHAPTER 8

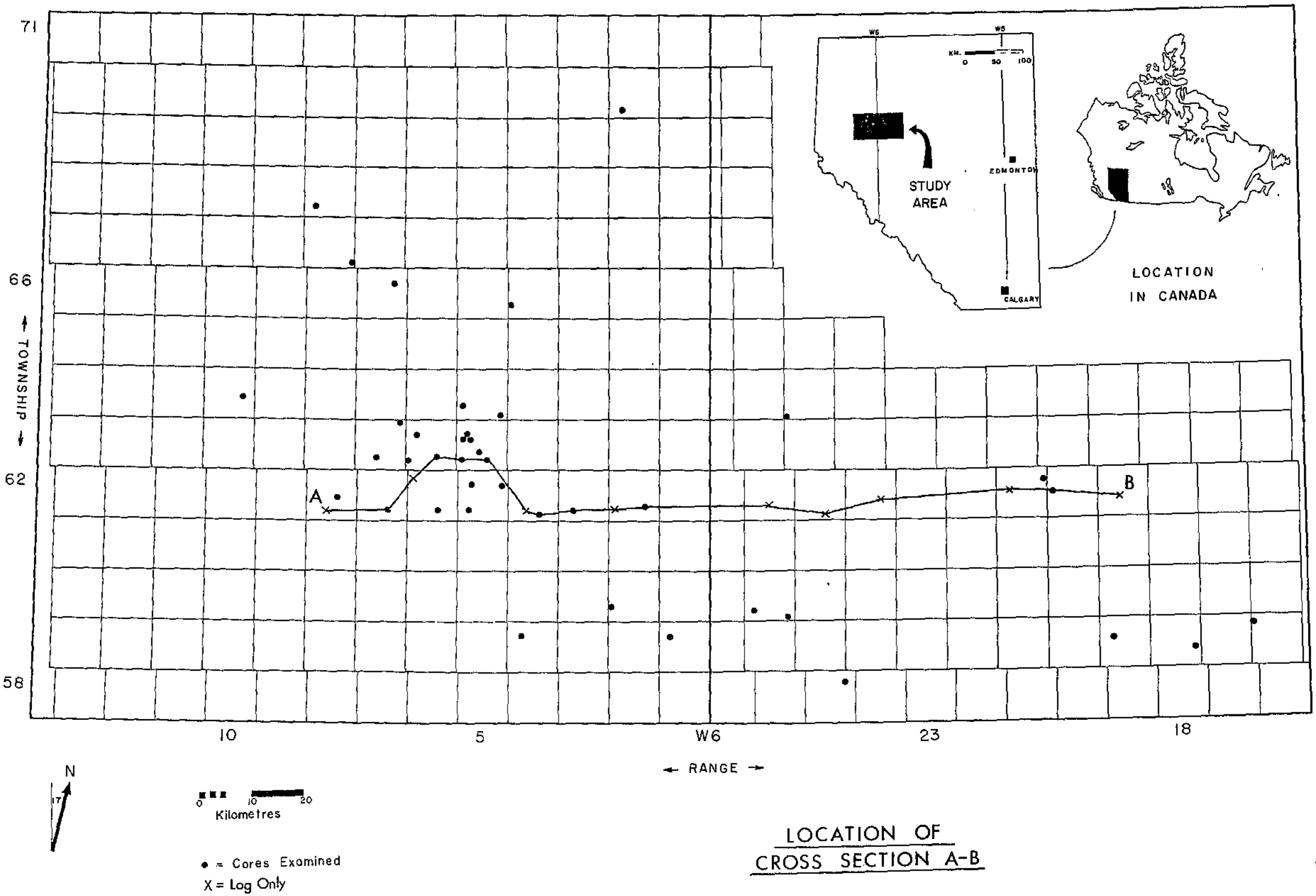
BASIN SETTING

1. INTRODUCTION

In order to consider the cause of the apparently rapid events discussed in the above chapters, it is necessary to analyze the behaviour of the basin in the area studied. This requires construction of a cross-section perpendicular to edge of the basin. In addition to allowing for more informed speculation on the mechanism behind the relative sea level changes, such a cross-section reveals a basinal topography which supports interpretations discussed above.

2. THE BASIN CROSS SECTION

Figure 8-1 shows the location of the cross-section A-B discussed below; the line runs roughly perpendicular to the trend of the Kakwa shoreline (Plint et al., 1986) which is parallel to the most pronounced variations in sediment thickness. The line is designed to contain as much core control through as many Horizons as possible within as straight a line as possible. The kink through blocks 5 and 6W6 does not appear to affect the pattern of the resulting section but does make for better core control. Where necessary, well-log only control has been incorporated to maintain tight control on unit geometry.



LOCATION OF
CROSS SECTION A-B

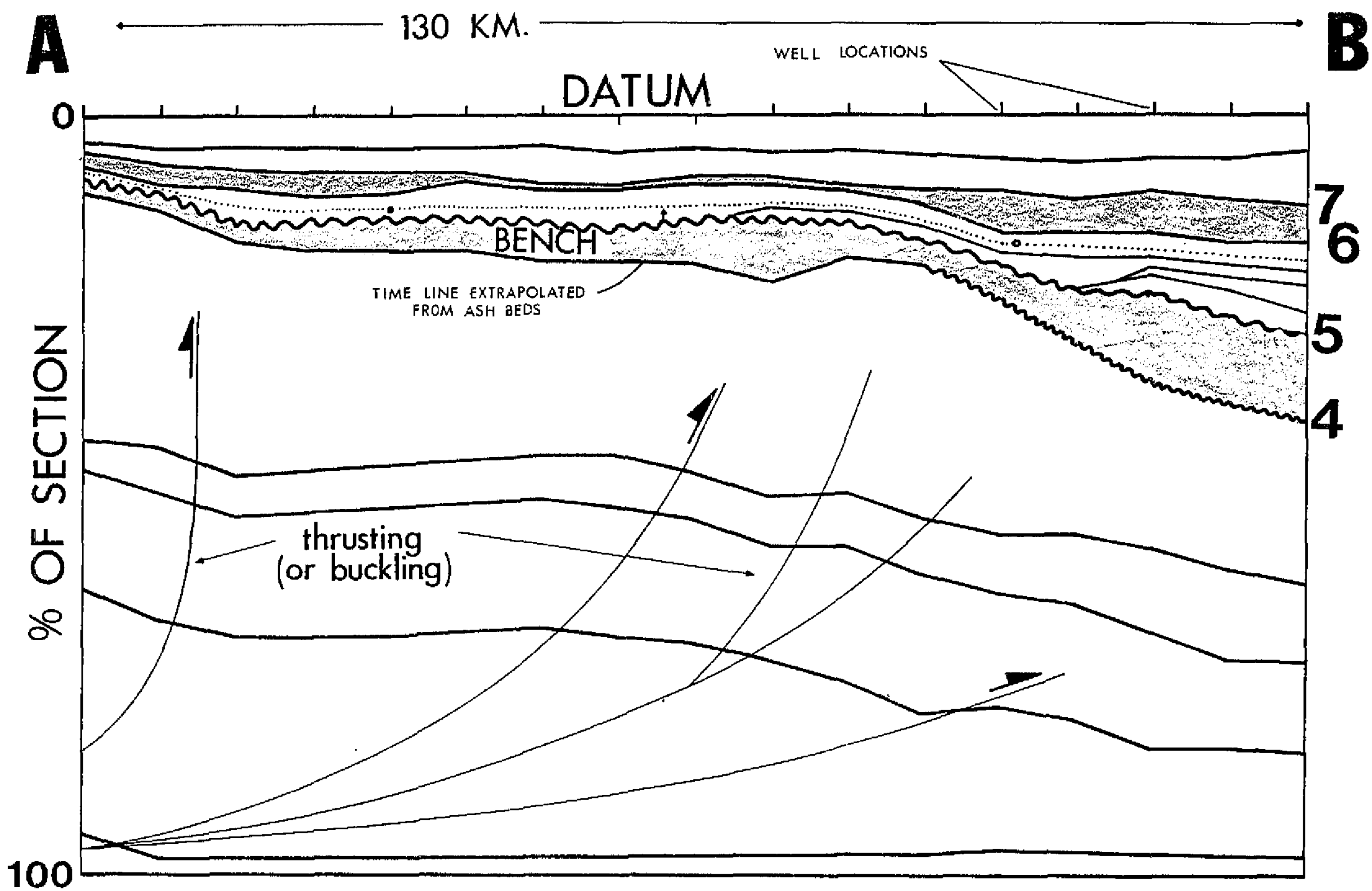
Figure 8-2, located behind figure 8-3 for purposes of comparison, shows the unaltered cross-section. It has been constructed by correlation of gamma and resistivity logs. The resistivity log is the primary tool for correlation while the gamma log has been used to accurately position the core. The deep response of the resistivity is the one most commonly used but the intermediate or shallow ones are sometimes substituted when no response is visible on the former. All logs were expanded or contracted to fit a common scale; hence, any offsets are probably genuine. Correlation of the eastern well-logs that have no core available was checked for accuracy with the more extensive work of Dr. A. G. Plint (p. comm., 1986). Where possible, responses well below the Cardium interval have been correlated in order to investigate any sub-formational disturbance that may have influenced Cardium depostion. Because this is one of the prime objects of the correlation, the logs have all been hung relative to an upper datum, labelled DATUM in the section. The linear response of lines above and below (almost parallel for the line below) indicates that this is a good datum and is not affected by any post Cardium warping. The divergences visible are due to subsidence. The intervals of concern for this thesis have been colour coded for clarity, red separates H4 and H5, yellow separates H5 and H6 and blue separates H6 and H7.

The subsidence related divergence that is clearly visible in figure 8-2 between the very upper and lower markers tends to obscure original topography so it has been removed in figure 8-3. Its removal assumes a linear subsidence rate, which is reasonable over the area examined. The procedure is as follows. Each log was measured from the DATUM to the lowermost commonly visible marker; distances between each marker shown in figure 8-2 were then converted to percentages of the length between the end markers. The markers for each well were then located along the % of section axis of figure 8-3. The tick marks on the horizontal axis of this figure locate each well. Although the spacing is more regular than in the original cross- section, little exaggeration of topography occurs; the area of erosion, indicated by wavy lines, at H4 and the lines above would stretch out a little showing a slightly flatter form. The colour coding is identical to that of figure 8-2. Decompaction of muds has not been carried out in this section primarily because the 'muds' are actually silty and the trace fauna show little signs of compaction. Any compaction that may be unaccounted for would, in fact, only enhance the topography displayed because the topography appears due to thickening and thinning of the muddier members. Consequently, the results may be discussed reliably as they stand.

Figure 8-3 shows several features more clearly than does 8-2. The most obvious feature is the persistent thinning of members back over the Kakwa member; this member extends to the begining of erosion in H4 under the words WELL LOCATIONS. However, within this generally persistent trend there is a slight tendency for the members to pinch out a little over the bulge at the maximum extent of the Kakwa member. This trend appears to die upwards. The next feature is the behaviour of markers above E5. No other inter-Horizonal markers are visible. In this case, the markers die out (onlap) against E5 and as soon as the surface is covered show a flatter trend. This flat trend is demonstrated by an ash bed visible in two cores that has been projected onto the section and marked in figure 8-3 by a finely dotted line. The last feature of importance is the upward 'warping' of sub-Cardium markers between H4 and the lowermost markers.

Each of these features has important implications for the behaviour of these surfaces. The generally thin portions of the member in the West implies that a topographic 'bench' persisted after transgression of the Musreau member. This bench influenced the pattern of sedimentation and probably also determined faunal distribution (as discussed in chapters 4 and 7). It may also have exerted some control on the tendency toward siderite formation by allowing for increased dilution of sea water; the shallow nature of the waters here would make it easier for both pluvial and perhaps fluvial water to exert an influence.

The onlap of the markers in the Karr member onto E5 imply that the surface was probably subaerially exposed. Figure 8-2 shows that when the lowermost of these markers was deposited, E5, or its landwards equivalent, was at least ten meters higher, greater if significant amounts of material have been eroded. The steeper, and in this case lower, parts of the eroded surfaces may be explained by wave erosion at a shoreface (e.g. Bergman and Walker, 1986), but given the height of typical shoreface waves the upper reaches would then be exposed. This upper level of erosion could then either be subaerial or due to eventual transgression by an erosive shoreline. Recognizable beach deposits are probably not extensively preserved because of a combination of very rapid transgression over a very shallow slope (the diagram contains great vertical exageration) and erosion of shoreface sands in a mobile longshore drift system. None of the other Horizons which are all generally apparently subaqueous shows this pattern.



SECTION A–B NORMALIZED
FOR SUBSIDENCE
SHOWING IMPLIED STRUCTURE

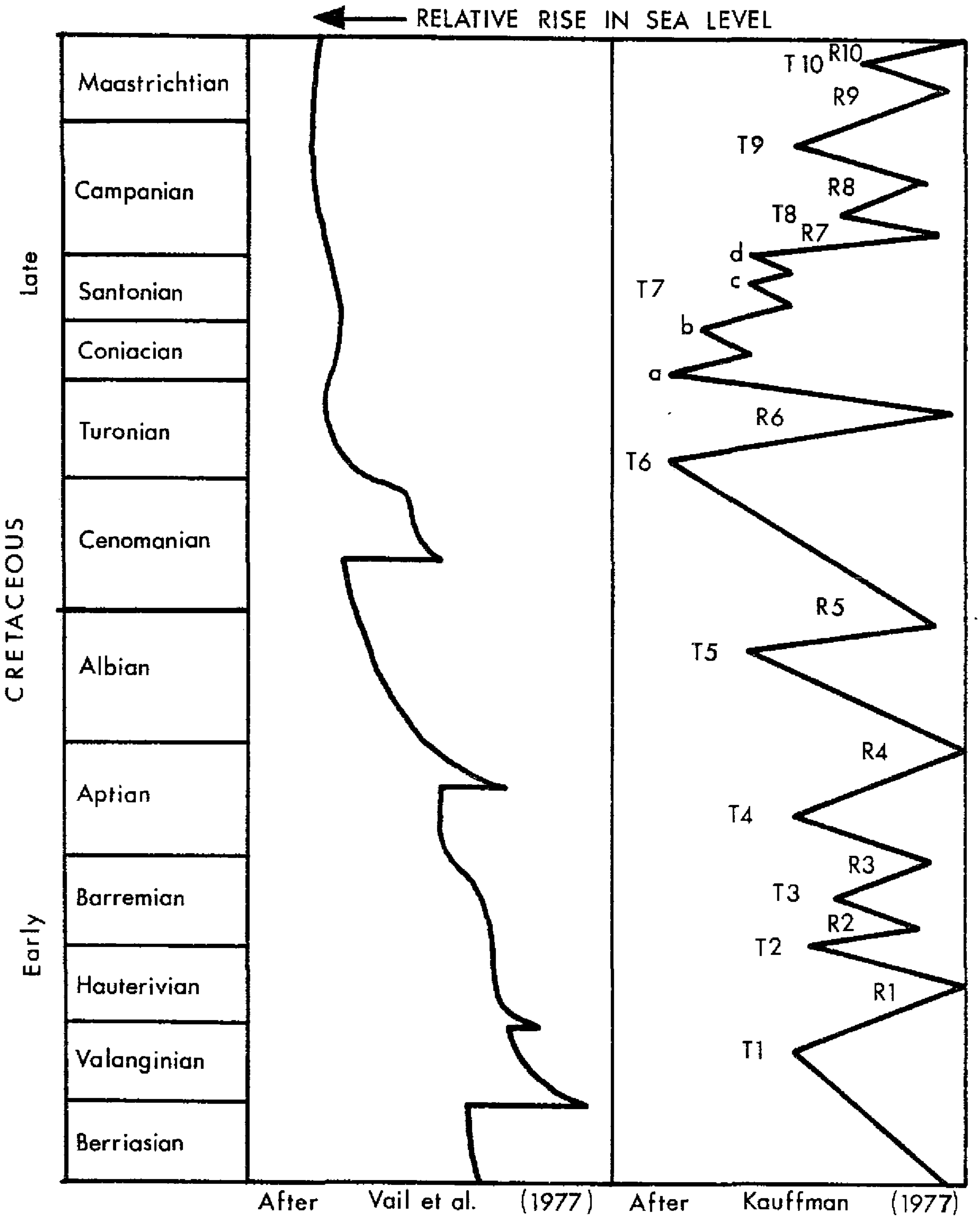
The last two features, the warping of the underlying marker and the pinching of the upper members, are related and may indicate a dying structural activity under the Cardium. It must be emphasized that these features are very subtle and interpretations are therefore somewhat tenuous. The implied structure shown in figure 8-3 has been drawn to reflect the hypothesis of underlyng minor thrust faulting. This is because the lowermost markers show no offset compared to those above and westwards as would be expected in normal faulting. It is difficult to confirm any faulting because repetition of sequences is not visible in the noisy gamma response of pure shale and there is no core available at these depths. Moreover, seismic data probably would not reveal such subtle faulting. On the other hand such behaviour does fit the general structural style of the basin and helps to explain the slight pinching of the upper members. This pinching might conceivably be due to dying activity on thrust faults lying under the edge of the Kakwa member. Thrust activity might also explain the regular occurrences of these events as judged by their approximately equal thicknesses. But this control must be weighed against the possibility of eustatic control.

3. TECTONIC VERSUS EUSTATIC CONTROL

The mechanism controlling the timing and magnitude of the Cardium events remains unknown but consideration of the current knowledge of eustacy and tectonic behavior allows some speculation on such controls.

The possibility of eustatic sea level controlling sand body deposition has become quite popular recently with many references being made to the pioneering work of Vail et al. (1977). Vail et al. (1977) divide eustatic cycles into different scales, or cycles of various orders. The second order cycles contain events of between 10 to 100 million years duration, the third order cycles contain events between 1 and 10 million years duration and the fourth order cycles events between 100 and 1 thousand years duration. The time taken for deposition of the Cardium may be taken as approximately 1 million years. When divided by 7, the number of cycles,this gives a maximum of 140,000 years for each cycle which puts the Cardium into the following framework: the formation as a whole represents a third order cycle and the cycles therein are fourth order ones.

For purposes of comparison, the Cardium may be plotted on exisiting sea level curves, (see figure 8-4) the best known of which are those of Vail et al. (1977) and Kauffman (1977). The Cardium fits quite well into Kauffman's curve in the R6 position which is satisfying given the development of this curve in the Western interior of the United States (Kauffman, 1977). Unfortunately,


RELATIVE RISE IN SEA LEVEL
CRETACEOUS
Late
Early
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
T 10
R10
R9
T9
R8
T8
R7
d
c
T7
b
a
R6
T6
R5
T5
R4
T4
R3
T3
R2
T2
R1
T1
After Vail et al. (1977)
After Kauffman (1977)

insufficient detail has been published for the Cretaceous period by Vail et al. (1977) to allow for a meaningful comparison. The most established "eustatic" curve thus reveals insufficient detail or a possible slight drop in sea level during Cardium time. Moreover, although Hancock and Kauffman (1979) claim to correlate many of the larger cycles (e.g. the Greenhorn-Niobrara) into Europe, the Cardium formation might only reflect tectonic activity also present in equivalent formations in the United States. Positioning the Cardium Formation on these curves therefore does not prove a eustatic origin and raises a couple of questions.

Firstly, is eustatic sea level change a possiblity. Secondly, are the smaller cycles and their events, like those of the Cardium event stratigraphy of Plint et al. (1986) which show up on neither curve, eustatic?

The first question has been dealt with by many researchers, and their comments and criticisms are best referred to in Miall (1984) and Jeletzky (1978). Objections to current eustatic curves include a lack of discussion of dating errors for the micropaleontological data, a strong uncertainty for many of the magnetostratigraphic correlations, and correlations based on sudden sea level falls, an unlikely occurrence world wide, and, above all, the fact that differential subsidence gives different depths at different locations. This latter objection is particularly important since most of the sections used by Vail and his coworkers (1977) come from passive margins and many are restricted to North America. It could therefore be possible that the North American data has beeen imprinted into a 'eustatic' model.

On the scale of the events within the Cardium, which do not even appear in any of the published sea level curves, it is probably impossible to prove a eustatic control without extremely closely spaced rock body correlation over continental size areas. In fact, the local dominance of tectonic events makes it much more likely that such activity was responsible for their generation. Even on the larger second and third order scale, there is some question as to the cause of possibly correlatable events. Sloss (1984) has argued that most large scale cycles are tectonically controlled on a worldwide basis, the amplitudes of erosion in large events always involving greater amplitudes than possible through eustatic mechanisms.

The possibility of eustatic change therefore relies heavily on the known mechanisms of sea level change and their magnitudes and rates. Indeed, the most important problem in eustatic control of events within the Cardium Formation is the mechanism for such control. The only plausible mechanism in non-glacial periods is ridge volume variation (Donovan and Jones, 1979) which can provide an approximate maximum rate of sea level change due to alteration of the geometry of the mid-ocean ridge system of 1 cm per 1000 years (Pitman, 1978). Donovan and Jones (1979) claim that the speed with which these ridge fluctuations occur is about three orders of magnitude slower than that of variation in polar ice cap volumes which timewise are on the same order of magnitude as the Cardium events. In answer to the second question posed above, this means that the second and possibly third order cycles, such as the Cardium, could be eustatic but that it is unlikely that the events contained therein are. The time frame described above for eustatic mechanisms cannot apply to the events of the Cardium. Repeated stillstands, the only causal mechanism which would fit within a purely eustatic model, cannot explain adequately the repeated shallowing of a basin (as opposed to progradation) demostrated by Plint et al. (1986) for the Cardium.

Given the lack of any known mechanism for such frequent relative sea level changes and considering the basinal setting, the most reasonable assumption is that such events are tectonically produced. Work in progess in the Rockies of the United States (Dr. M. Krause, p. comm., 1986) indicates that thrusting occurs in pulses affecting fluvial sediments on the scale of 100,000 years, a scale similar to that of the Cardium events.

In summary, the Cardium Formation may represent a response to a eustatic sea level change upon which tectonic activity has been superimposed.

CHAPTER 9

CONCLUSIONS

The results of the various avenues of investigation of the questions listed in the introduction may be summarized briefly in point form.

1. The foraminiferal data indicates that the Cardium Horizons do not represent pronounced pauses in sedimentation significant enough to allow accumulation of biological debris. They may represent a break in time sufficient for the formation of siderite cement. The relative timing of the erosion visible at most Horizons (and the lack of proof for pauses) indicates that erosion was relatively 'active'.

2. All the events are qualitatively very rapid, but may occur from within hundreds to a hundred thousand years. Timespans nearer the shorter end of this spectrum seem more likely.

3. Lateral changes may be observed in several variables.

Horizons may vary from pronounced erosion to gradational sequences (e.g. H4) but, generally, behave similarly within any Horizon over the extent of the study area (e.g. H5 (E5) is everywhere erosive). The most important lateral difference is the change from erosion to correlative conformity, as implied in H6, but this is on a larger scale than generally emphasized here.

Faunal content may vary from normal to flooded but is universally poor in the immediate proximity of event surfaces or Horizons because of turbidity and fresh water stress.

4. The sea level changes do indirectly influence the pattern of early diagenesis as indicated by the extensive occurence of siderite. However, the exact influence is a little uncertain. It may cause either dilution by fresh water related to shallowing or it may cause increased organic accumulation in the same setting. Possibly both mechanisms operated. It is impossible to say exactly how this relates to the time of formation of the Horizons.

5. Sediments respond very rapidly to the changes in sea level. They have no time to develop into true hardgrounds. Facies generally show a 'rapidly gradational' transition across the Horizons, in some cases being eroded at likely lowstand shorefaces or subaerial exposure surfaces. The common 'erosion' into mud and frequent bioturbated bases reflects the inability of the sediment to cement before the rapid change in sea level.

6. The rapidity of the events is probably due to a generally tectonic driving mechanism superimposed on a slower eustatic rise in sea level.

7. In a subtle sense, the events show some behaviour analogous with that of carbonate hard and firmgrounds. E5 is the closest siliciclastic analog for such surfaces.

8. In answer to one of the most important questions, only H5 shows signs of subaerial exposure. The evidence is all indirect.

Generally speaking, the sediments of the Cardium Formation contain a series of probably tectonically controlled events that occurred so rapidly that sediments could respond only by creating temporary regions of erosion across which few gross environmental changes occurred prior to the next change in sea level. The primary environmental changes induced by the fluctuating sea level seem to have been variations in (1) the salinity of an already 'brackish' sea, (2) the turbidity of the water column and (3) probably the input and temporary accumulation of organic matter.

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APPENDIX ONE

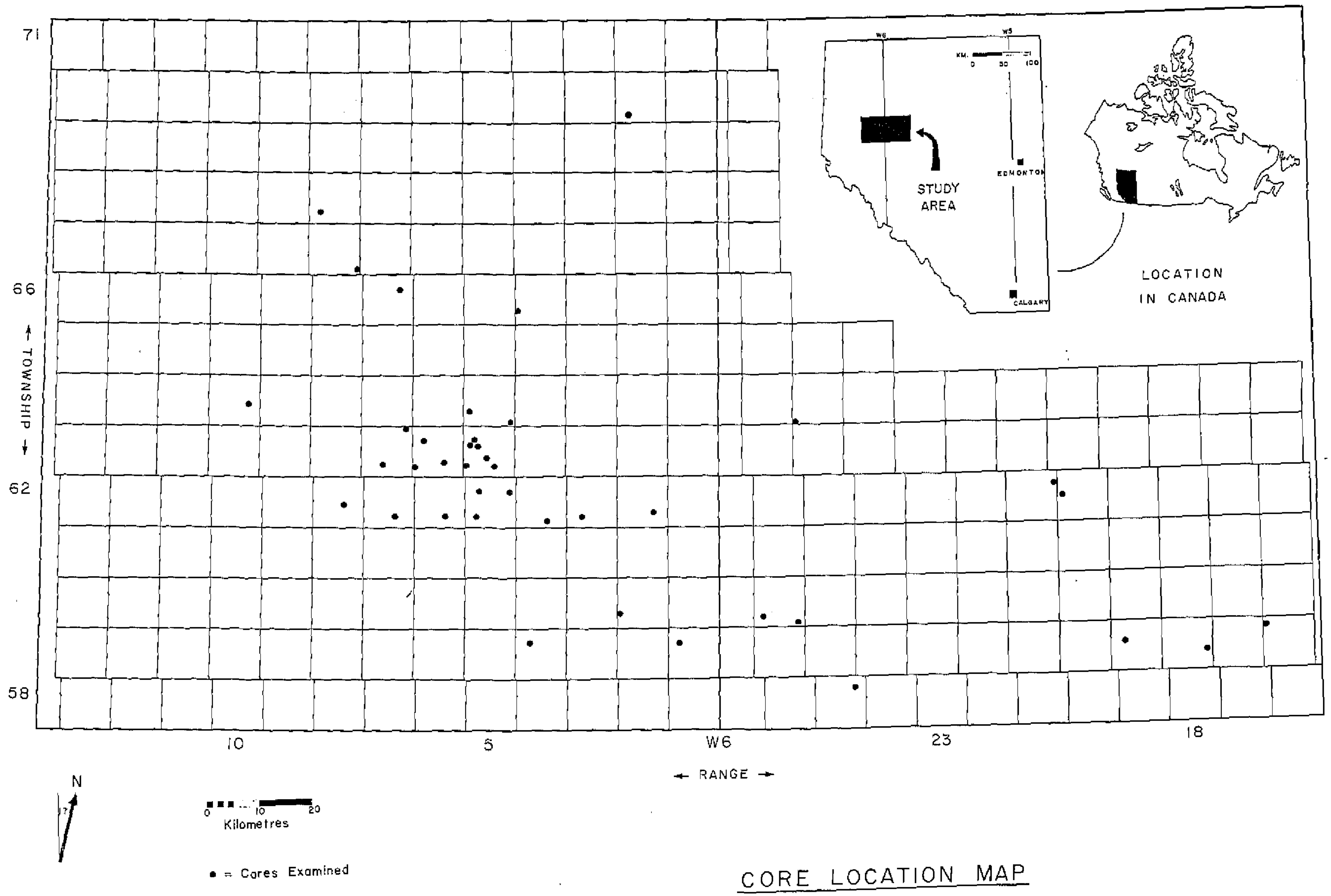
LOCATIONS OF WELLS, CORES AND SAMPLES

WITH LITHOLOGICAL COLUMNS

The following map (p.167) shows the sites of all cored wells examined. Wells with logs only are not illustrated. The Horizons penetrated by each well are as follows:

Well Number	4TH	5TH	6TH	7TH
16-27-48-11W5			X	
4-29-51-11W5			X	
10-26-58-25W5	X			
4-31-59-16W5	X			
6-13-59-18W5	X			
10-20-59-19W5	X			
6-29-59-1W6	X	X	X	X
7-29-59-4W5	X	X		
11-1-60-26W5		X	X	
5-8-60-26W5	X			
14-7-60-2W6	X			X
2-19-62-20W5		X		
10-25-62-21W5	X			
11-11-62-2W6	X	X	X	X
8-8-62-3W6	X	X	X	
10-3-62-4W6	X		X	
6-8-62-5W6	X	X	X	

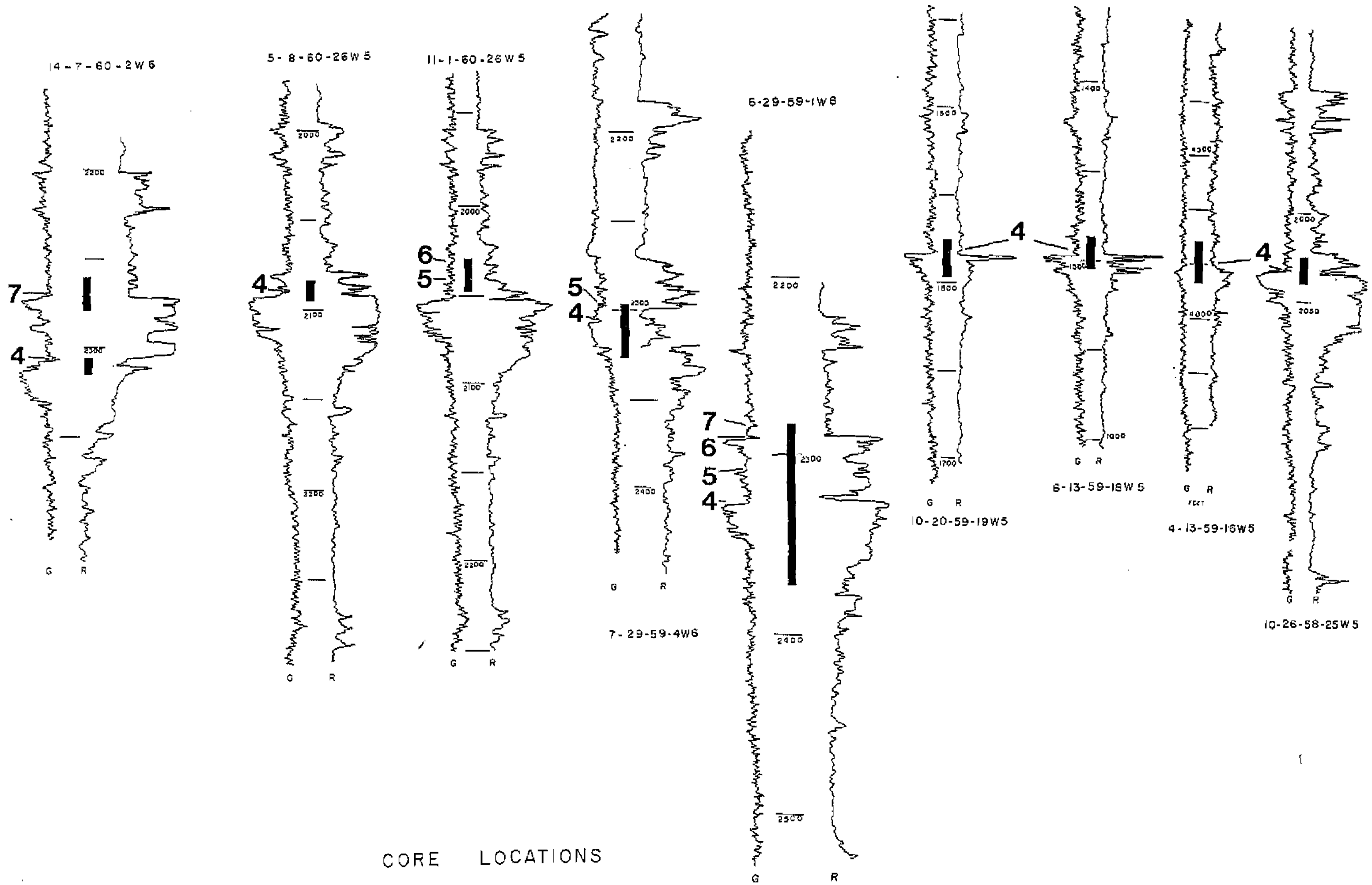
4-25-62-5W6	X	X		
7-29-62-5W6	X	X		
7-10-62-6W6	X	X	X	
7-10-62-7W6	X	X	X	X
10-15-62-8W6	X			
3-3-63-5W6	X	X	X	
11-7-63-5W6	X	X	X	X
2-16-63-5W6	X	X	X	
16-19-63-5W6	X			
10-20-63-5W6	X	X		
6-29-63-5W6	X	X		
6-7-63-6W6	X	X		
9-10-63-6W6	X	X	X	X
6-29-63-6W6		X	X	
10-9-63-7W6	X	X		
11-36-63-7W6	X	X	X	X
6-6-64-25W5	X			
11-1-64-5W6	X	X	X	
9-7-64-5W6	X	X	X	X
10-14-64-10W6		X	X	
11-7-64-4W6	X			
3-26-66-8W6	X			
10-1-67-8W6	X			
6-8-68-8W6	X			
15-5-70-2W6	X			



CORE LOCATION MAP

On pages 170-175 each core has then been tied to its appropriate gamma (G) and resistivity (R) log with the depths listed in meters, or when noted, feet. The cores appear in order of increasing Township, Range (westwards) and section. For reference, the erosional-transgressive Horizons examined (numbers 4, 5, 6 and 7) have also been located next to the logs at the spot they appear in core.

Detailed lithological sections across each Horizon follow the core location illustrations. A facies legend precedes these sections and relates them to the facies described in the text. Sections are listed by increasing Horizon, Township, Range and section. Sample locations, explained in the legend also accompany each section; every sample, where there are more than one, has a small case letter assigned to it for easy reference. The size scale on the bottom of the section corresponds to the divisions on the American-Canadian Stratigraphic grain size card (availbable from the Canadian Stratigrapic Service, 3613 33 St. N.W., Calgary, Alta.) S=silt, M=medium sand and P=pebbles; the grain sizes Very Fine, Fine, Medium, Coarse and Very Coarse correspond to 4-3Ø , 3-2Ø , 2-1 Ø, 1-0 Ø and 0-(-)1 Ø respectively. Granules are between 2-4 mm and pebbles are greater than 4 mm. The extent to which a given facies is drawn to the right along the size scale corresponds to the maximum size clast within that unit and does not imply that all grains are of the size indicated. I take this approach in order to demonstrate, as best possible, the maximum energy and/or size of supply available at any point. Because of the high degree of bioturbation present in almost every unit, descriptions such as sorting would have little meaning and have been ignored. The lines for erosion show only erosion unequivically visible in the core. Major amounts of siderite appear a "overprinting" on existing facies rather than as a seperate facies in order to emphasize the relation of early diagenesis to facies. Sample locations where numbered refer to the distance in centimeters above or below the prior sample (whether numbered or unnumbered).



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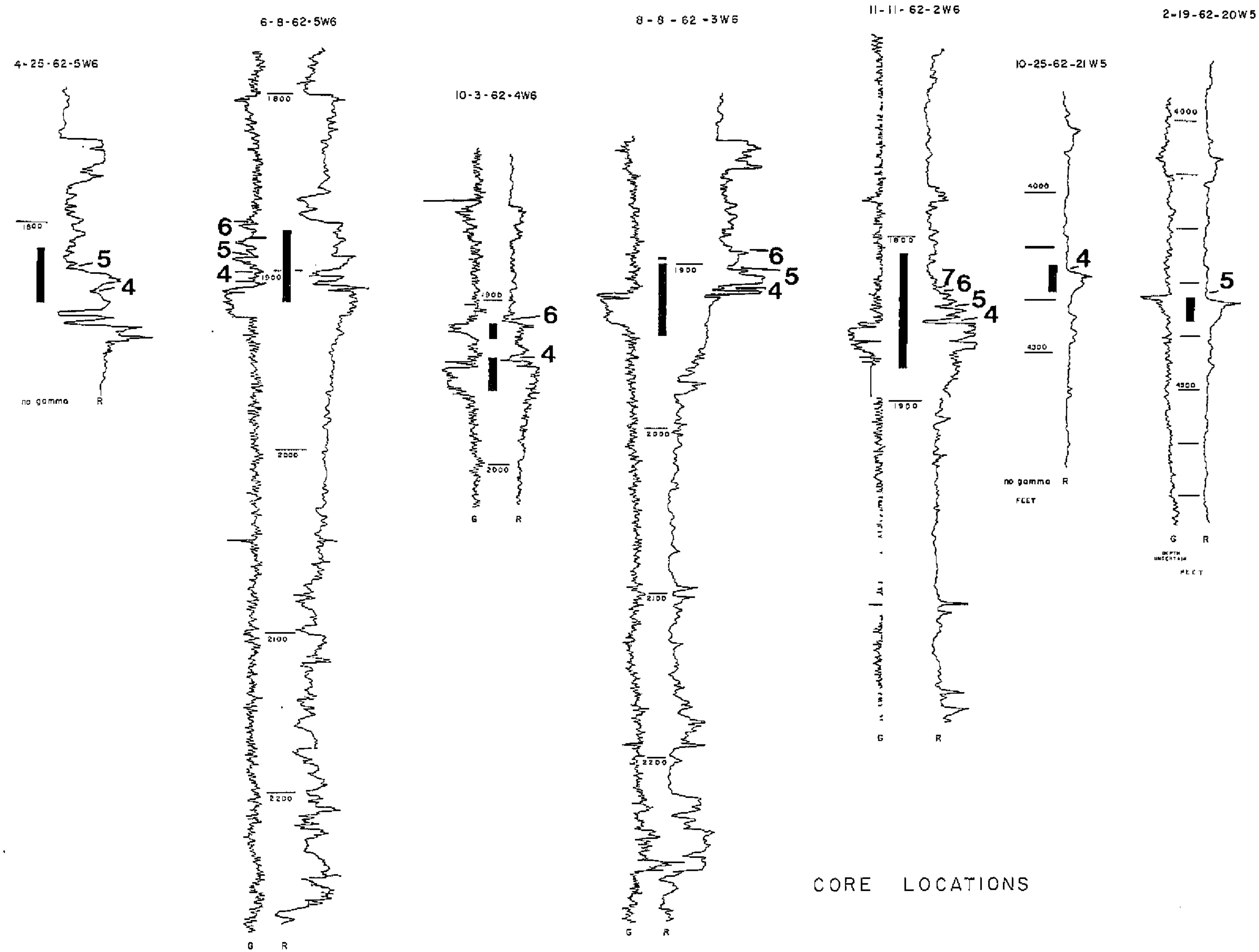

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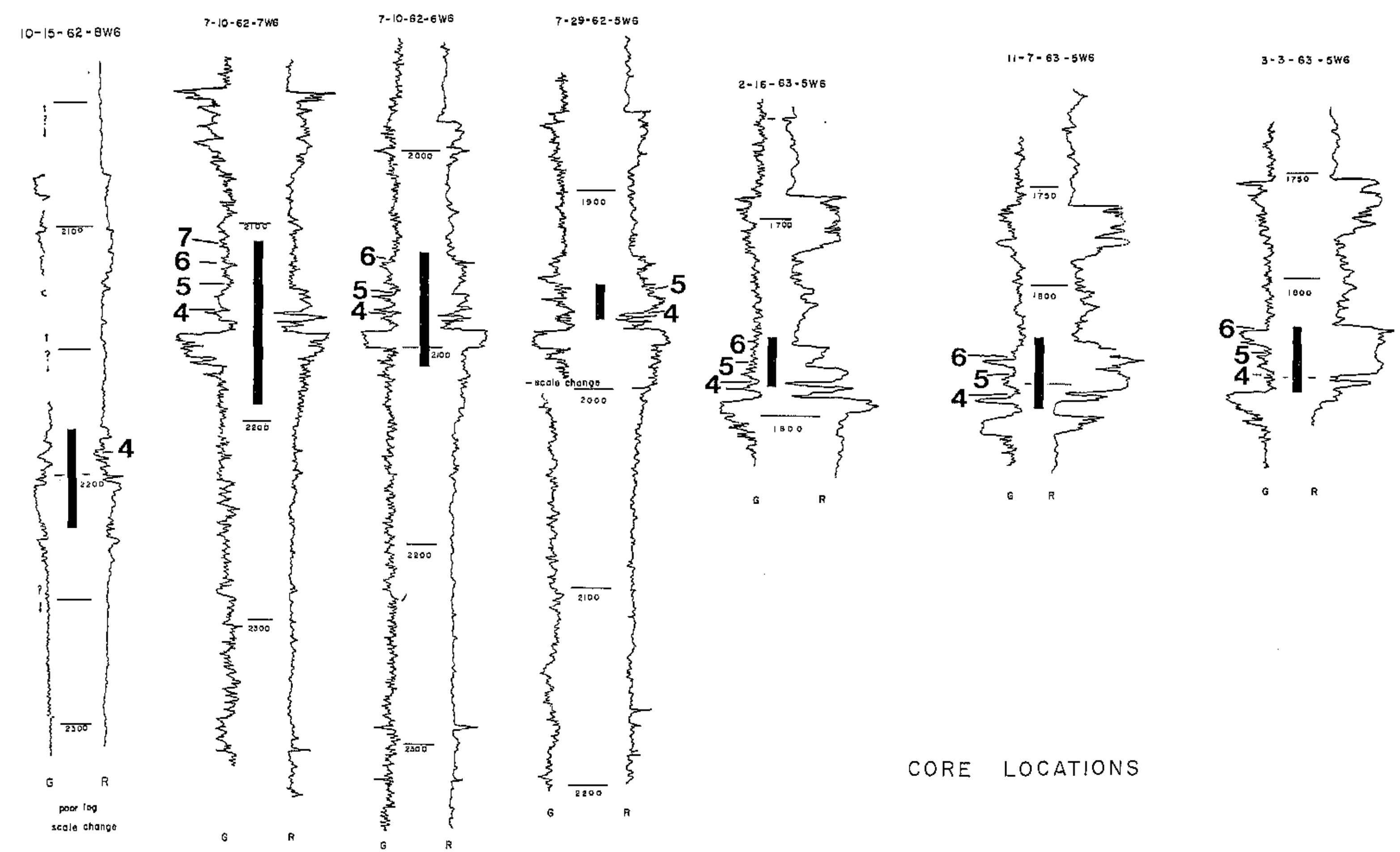

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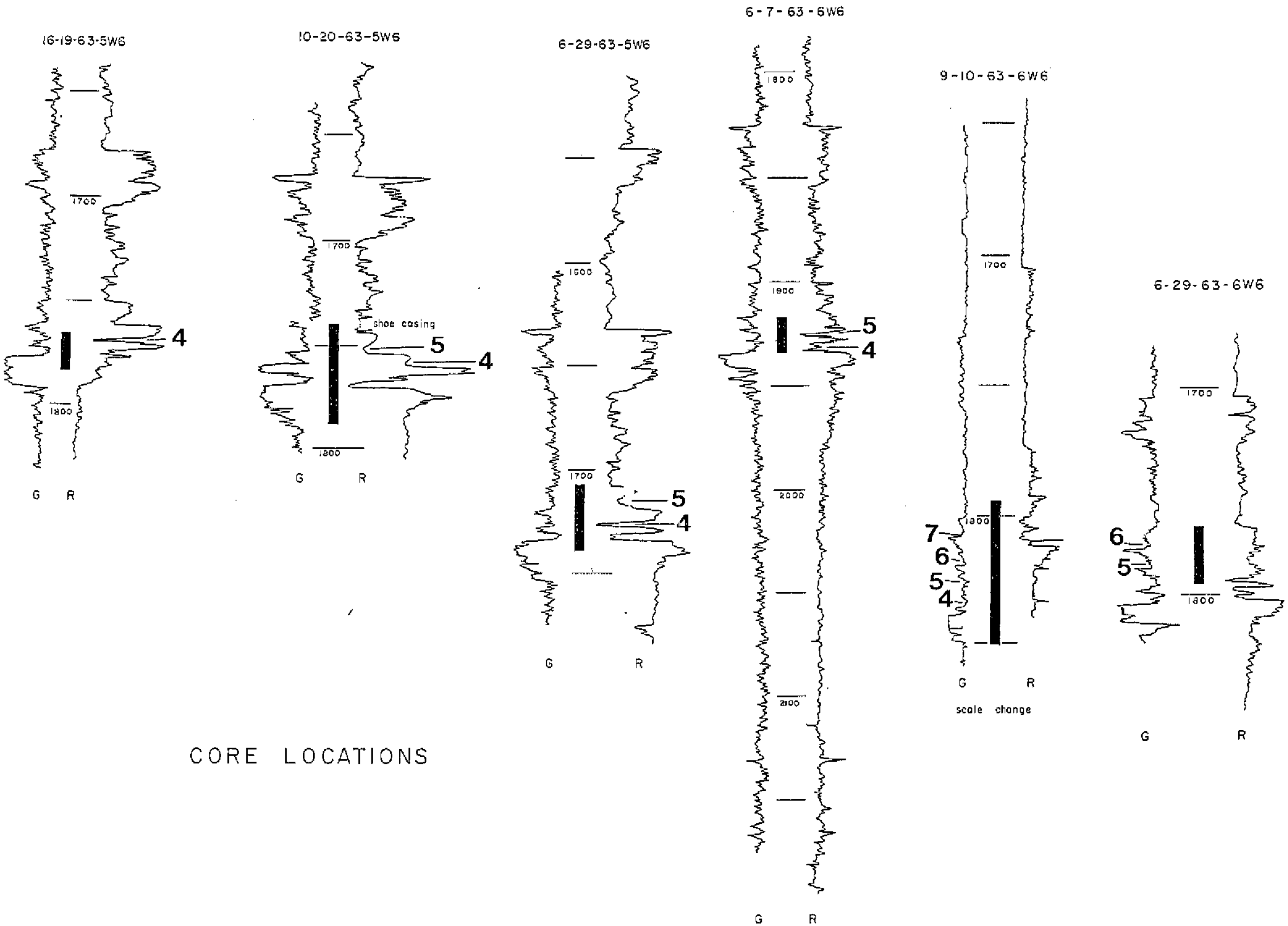

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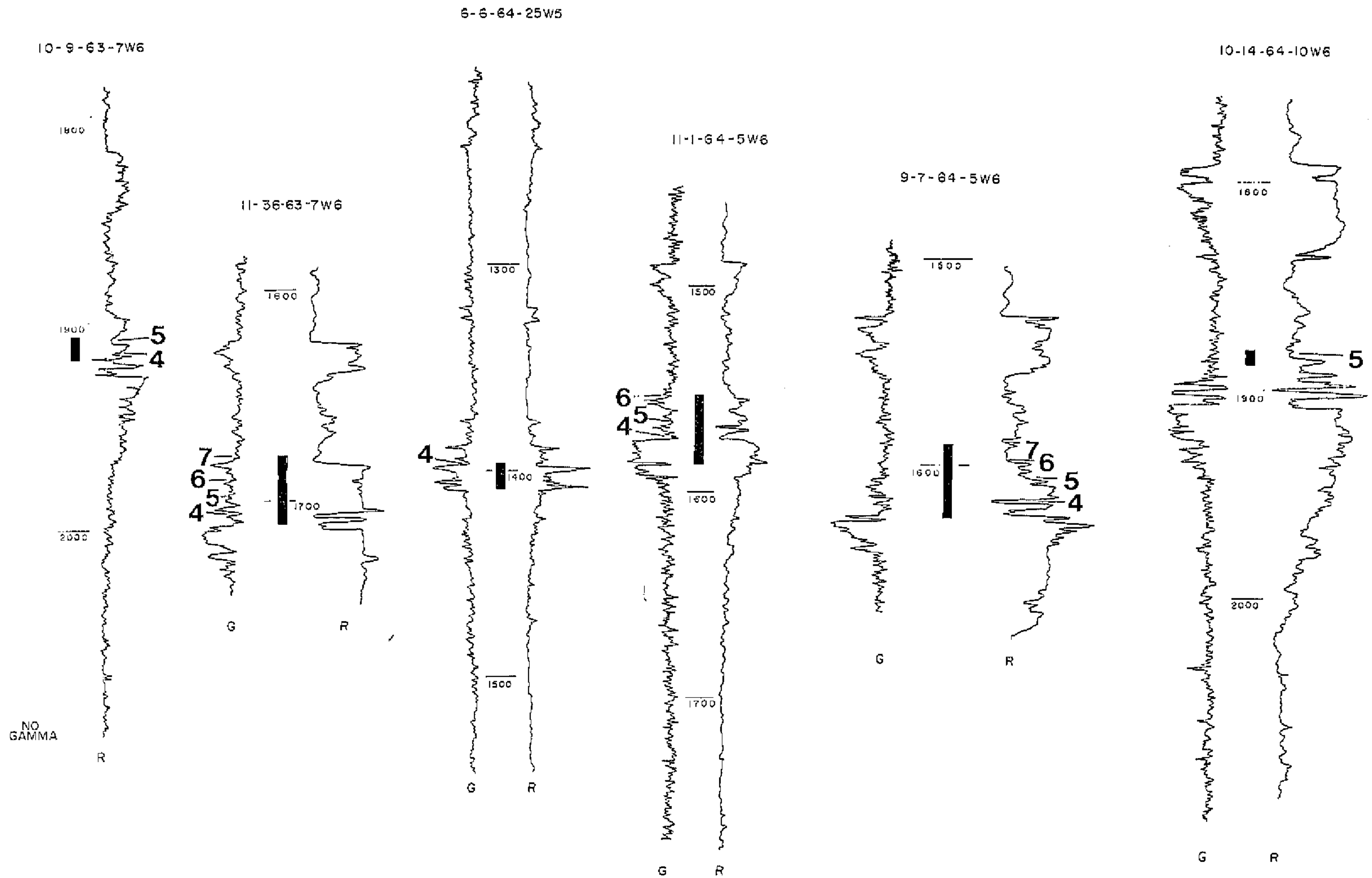
10-9-63-7W6
1800
1900
5
4
2000
NO GAMMA
R
11-36-63-7W6
1600
7
6
5
4
1700
G
R
6-6-64-25W5
1300
4
1400
1500
G
R
11-1-64-5W6
1500
6
5
4
1600
1700
G
R
9-7-64-5W6
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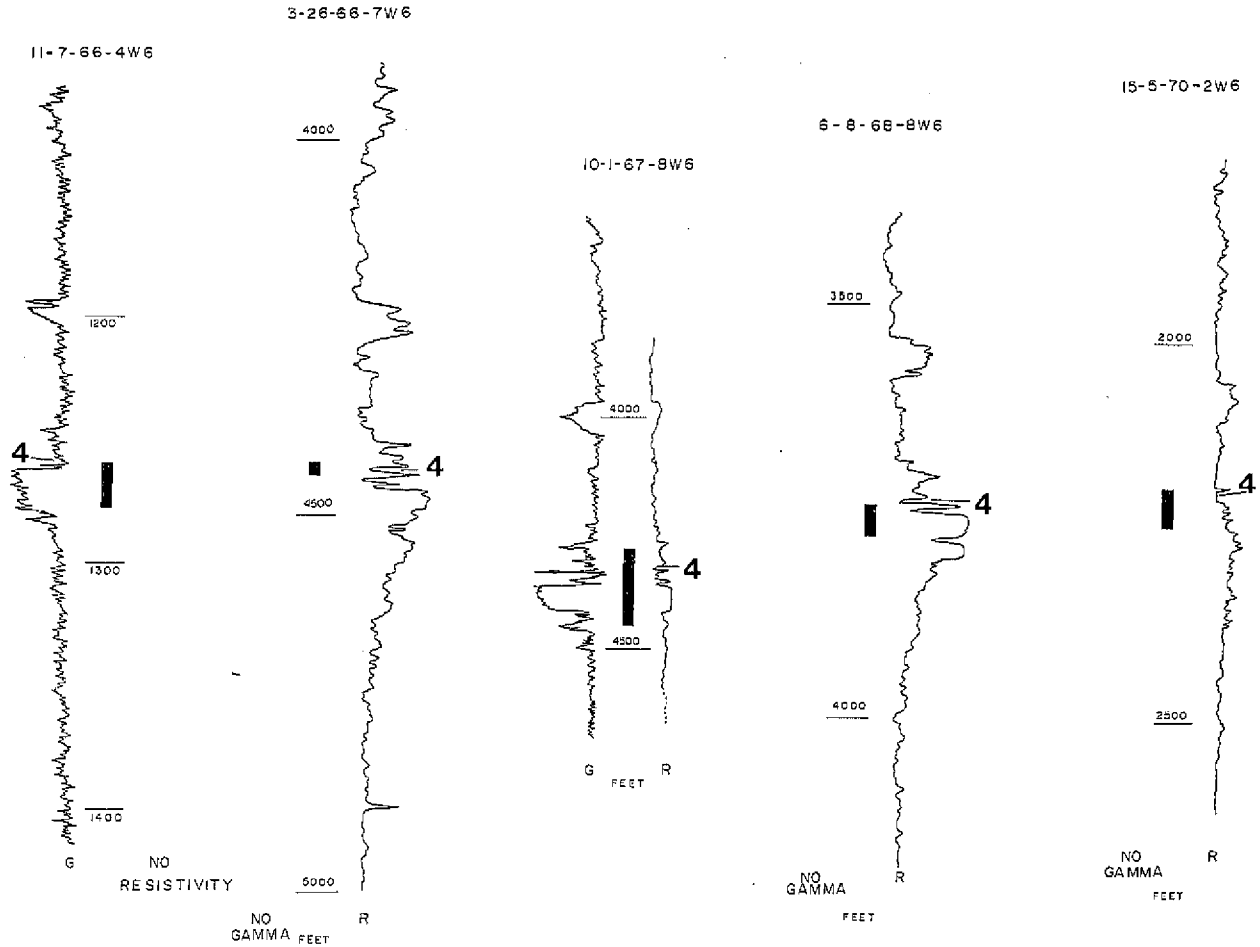
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3-26-66-7W6
10-1-67-8W6
6-8-68-8W6
15-5-70-2W6
1200
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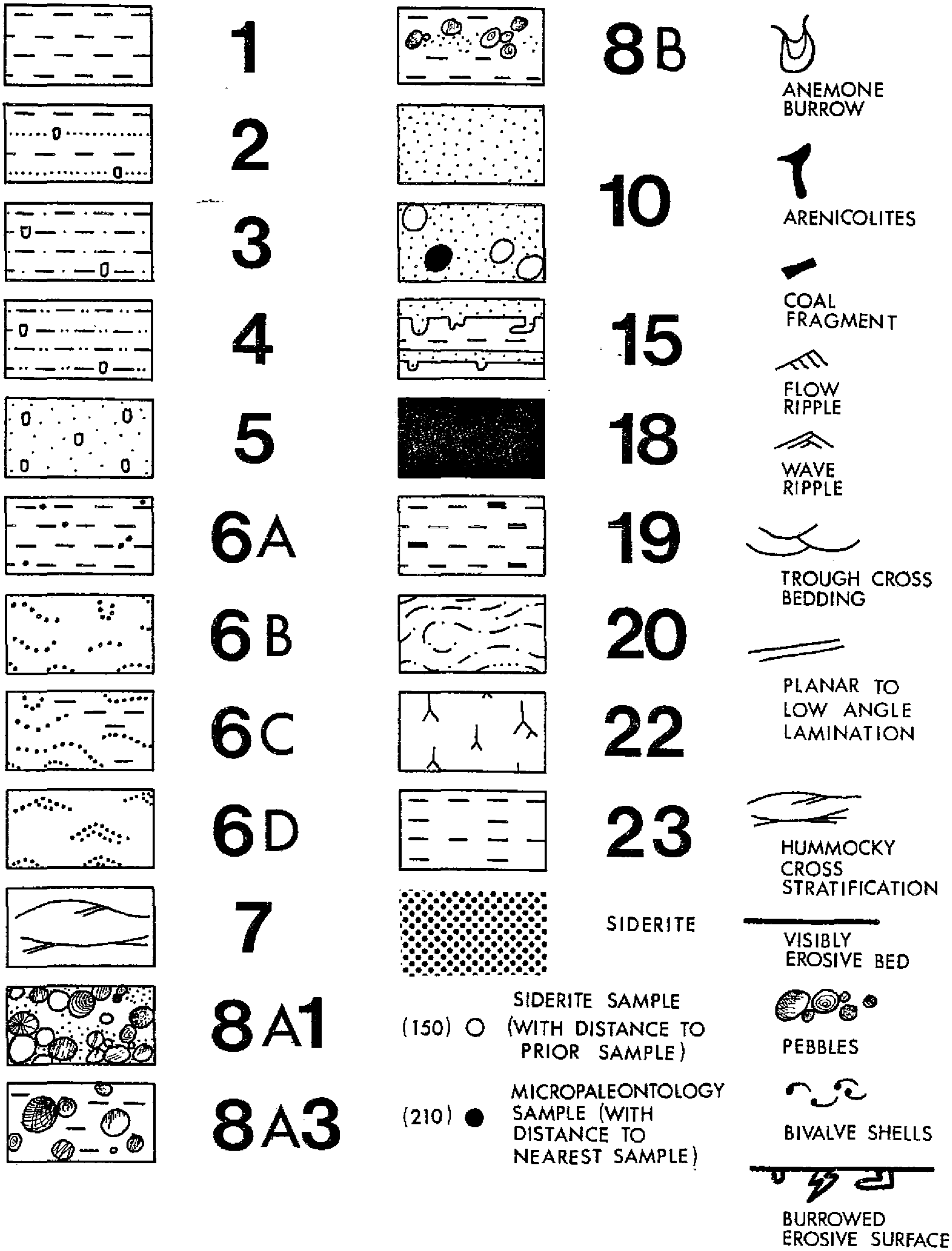
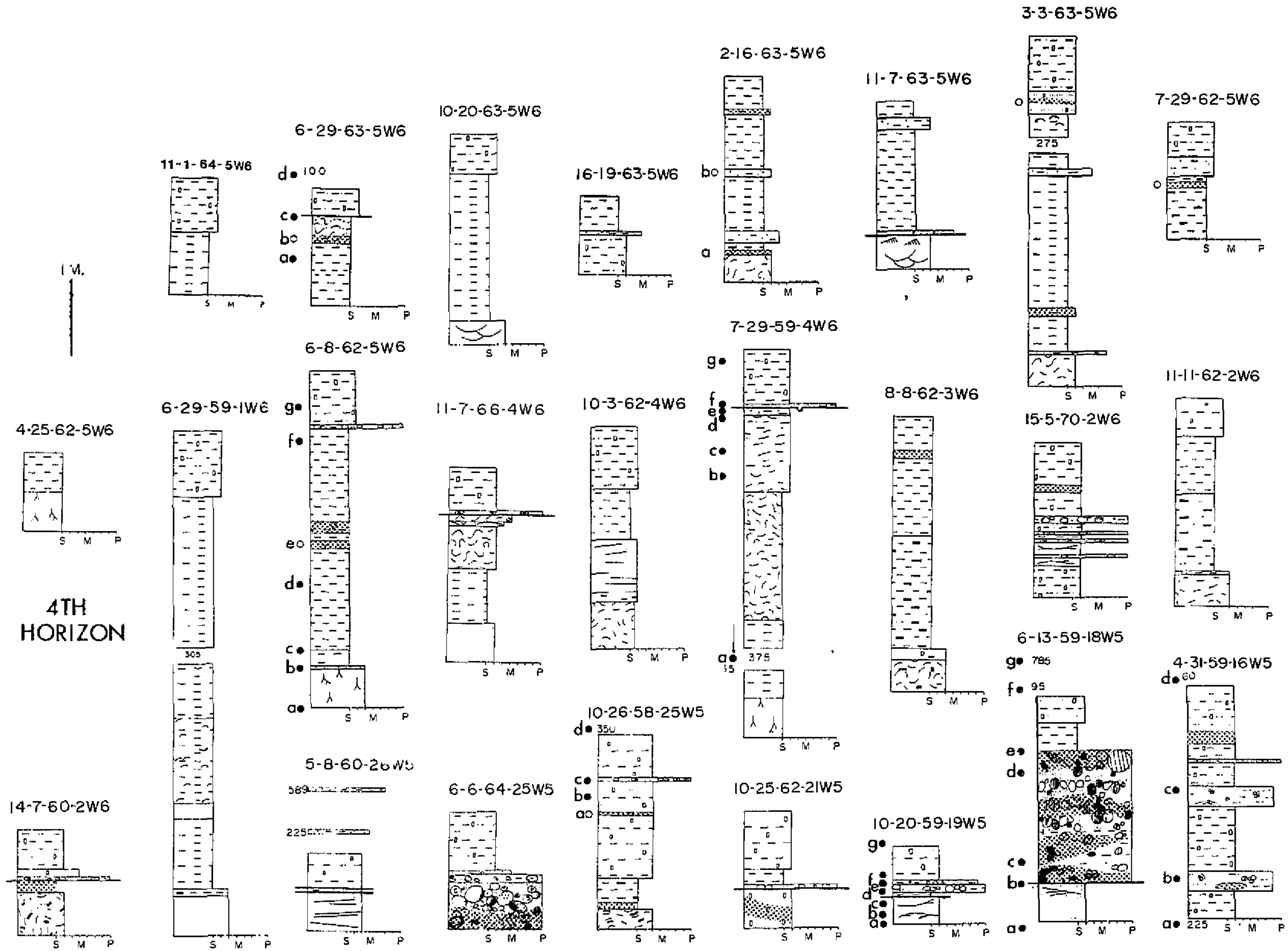
1400
4000
4500
5000
4000
4500
3500
4000
2000
2500
4
G
NO
RESISTIVITY
NO
GAMMA
FEET
R
G
FEET
R
NO
GAMMA
FEET
R
NO
GAMMA
FEET
R

FACIES LEGEND





1 M.
4TH HORIZON
11-1-64-5W6
6-29-63-5W6
10-20-63-5W6
16-19-63-5W6
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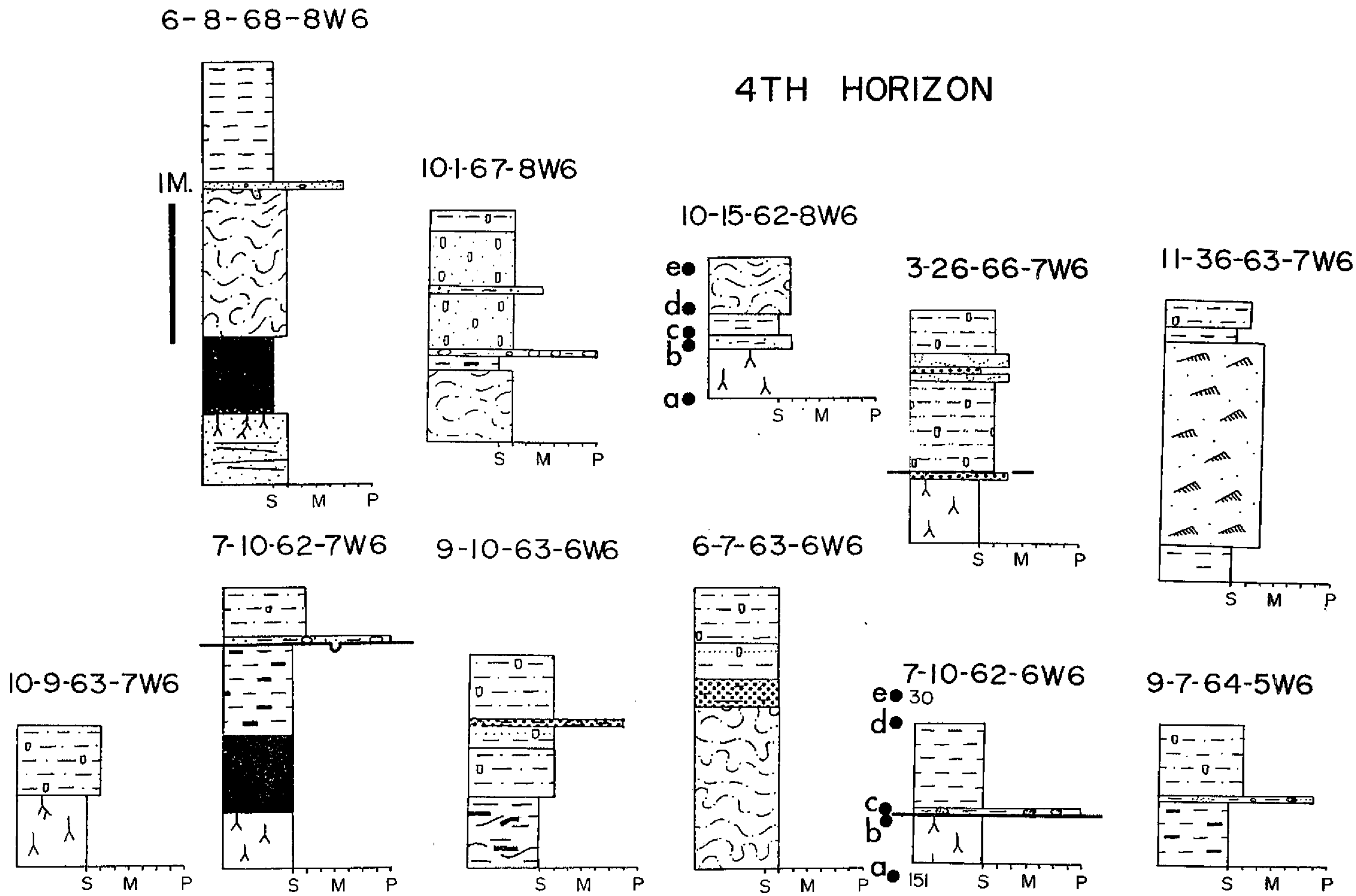
11-7-63-5W6
3-3-63-5W6
7-29-62-5W6
4-25-62-5W6
6-29-59-1W6
6-8-62-5W6
11-7-66-4W6
10-3-62-4W6
7-29-59-4W6
8-8-62-3W6
15-5-70-2W6
11-11-62-2W6
14-7-60-2W6
5-8-60-26W5
6-6-64-25W5
10-26-58-25W5
10-25-62-21W5
10-20-59-19W5
6-13-59-18W5
4-31-59-16W5
S M P



4TH HORIZON
6-8-68-8W6
1M.
10-1-67-8W6
10-15-62-8W6
e
d
c
b
a
3-26-66-7W6
11-36-63-7W6
10-9-63-7W6
7-10-62-7W6
9-10-63-6W6
6-7-63-6W6
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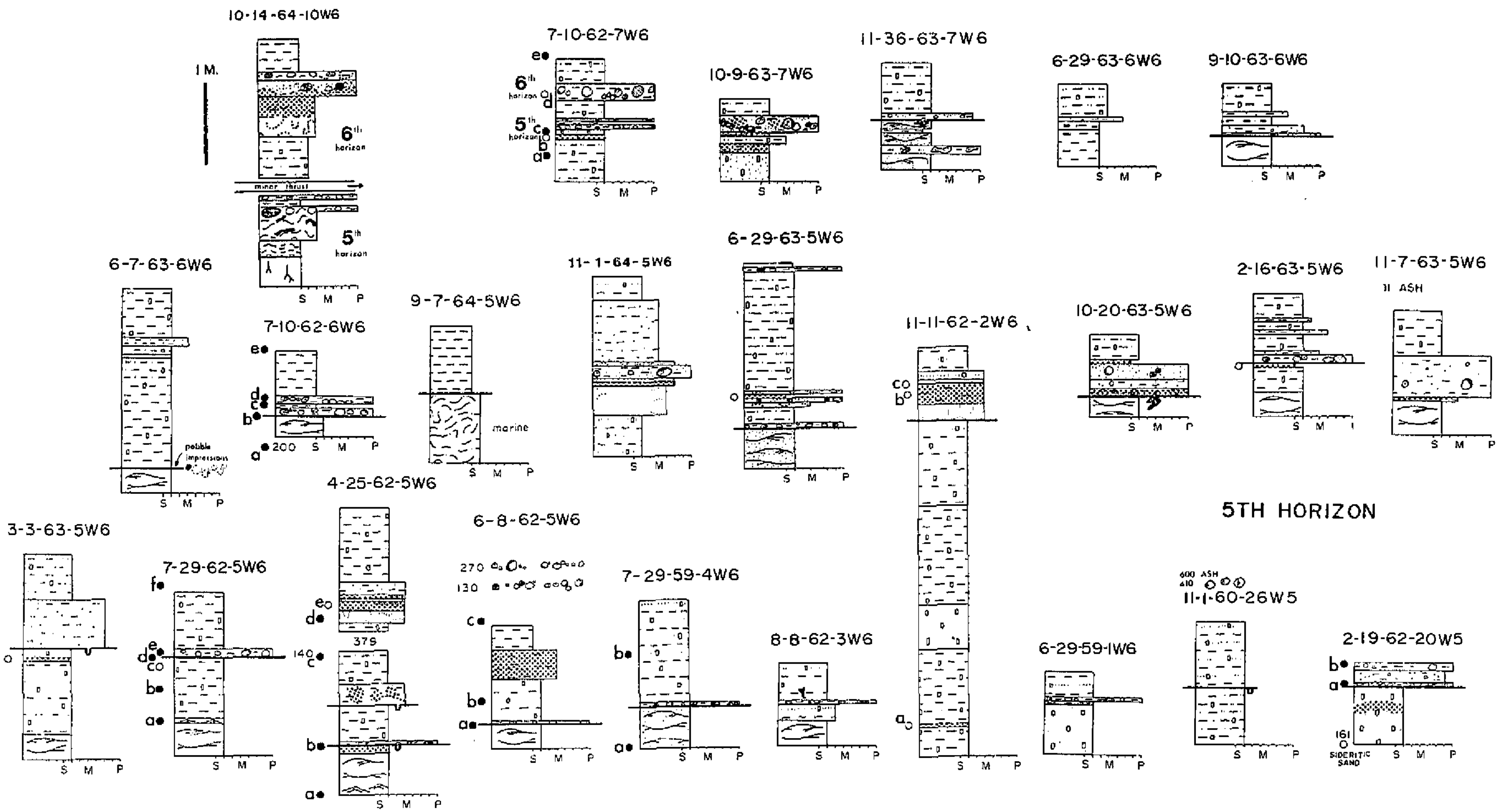
30
151
9-7-64-5W6
S M P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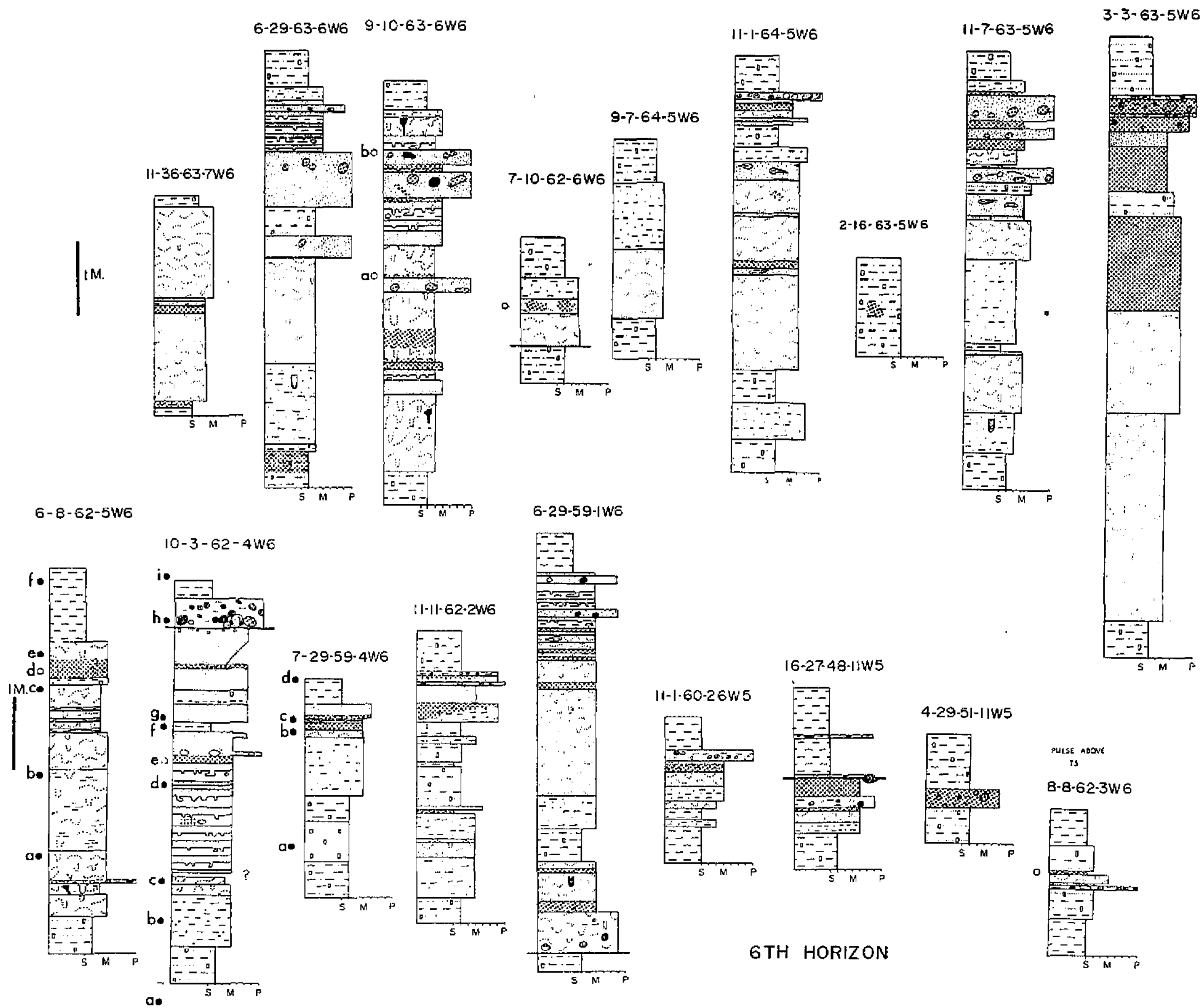
1 M.
6th horizon
minor thrust
5th horizon
7-10-62-7W6
10-9-63-7W6
11-36-63-7W6
6-29-63-6W6
9-10-63-6W6
6-7-63-6W6
pebble impressions
7-10-62-6W6
9-7-64-5W6
marine
11-1-64-5W6
6-29-63-5W6
11-11-62-2W6
10-20-63-5W6
2-16-63-5W6
11-7-63-5W6
ASH
4-25-62-5W6
6-8-62-5W6
3-3-63-5W6
7-29-62-5W6
7-29-59-4W6
8-8-62-3W6
6-29-59-1W6
11-1-60-26W5
2-19-62-20W5
SIDERITIC SAND
S M P
5TH HORIZON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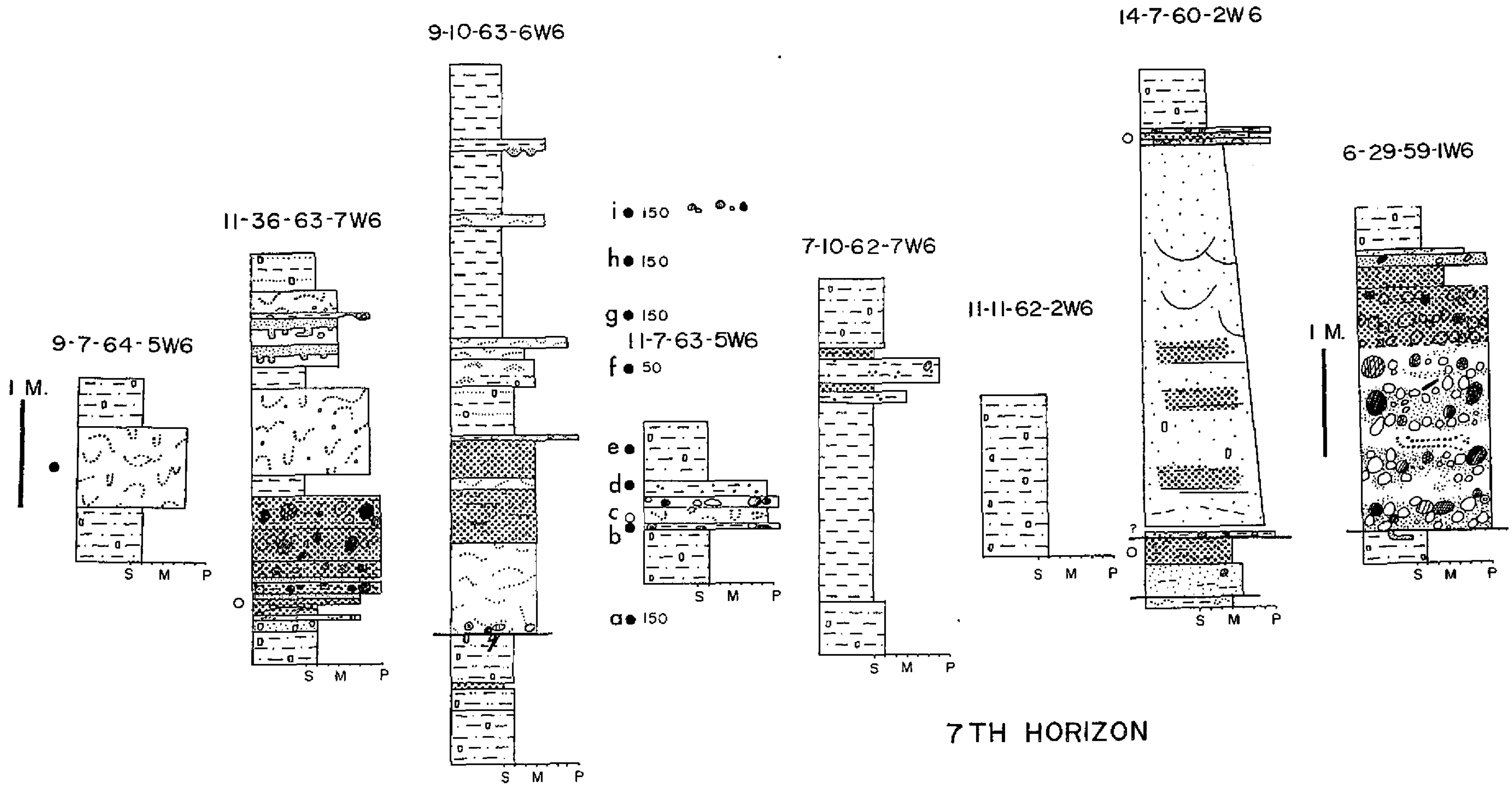
9-10-63-6W6
11-36-63-7W6
7-10-62-6W6
9-7-64-5W6
11-1-64-5W6
2-16-63-5W6
11-7-63-5W6
3-3-63-5W6
1M.
6-8-62-5W6
10-3-62-4W6
7-29-59-4W6
11-11-62-2W6
6-29-59-1W6
11-1-60-26W5
16-27-48-11W5
4-29-51-11W5
PULSE ABOVE TS
8-8-62-3W6
S M P
6TH HORIZON


9-7-64-5W6
I M.
S M P
11-36-63-7W6
S M P
9-10-63-6W6
S M P
i 150
h 150
g 150
f 50
e
d
c
b
a 150
11-7-63-5W6
S M P
7-10-62-7W6
S M P
11-11-62-2W6
S M P
14-7-60-2W6
?
S M P
6-29-59-1W6
I M.
S M P
7TH HORIZON

APPENDIX 2

MICROPALEONTOLOGICAL

SAMPLE DISAGREGATION PROCEDURE

The following shale disaggregation technique is essentially identical to that used at the I.S.P.G. (G.S.C.) in Calgary by Dr. Wall and coworkers and was passed on to the author by Miss K. Bergman. Where indicated the time involved in each step should be followed as closely as possible. The process preserves a wide variety of material from calcareous tests to moderately delicate plant remains.

STEPS:

1. Crush the shale sample (ideally greater than 50 grams) until the debris will pass through an approximately -1.5 Ø seive. In order to better preserve larger forameniferal tests (etc.), the sample as a whole should not be crushed significantly smaller than this.
2. For quantitative work weigh the sample.
3. Place the weighed sample into a 2 liter glass beaker (do not use a smaller size or some sample will be lost due to boil over).
4. Just cover the sample with H_2O_2 stirring it with a glass rod (use rubber gloves and goggles as H_2O_2 is

extremely caustic), and immediately place the beaker in a fume hood.

5. After about 10 minutes, the mixture will react vigoruously and then subside as the H_2O_2 oxidizes the organic material and starts to break down the shale. Let the mixture stand for about 1 hour.
6. Remove the beaker, fill it with water and flush the sample through a 4 Ø seive. Wet seive thoroughly to remove as many disaggregated fines as possible and to dilute the effect of caustic material on the seive.
7. Transfer the greater than 4 Ø residue to a smaller glass beaker (600 ml is usually sufficient) and add 200 ml of NaOH solution (made by dissolving 1 tablespoon of NaOH tablets in 1 liter of water) and 100 ml of household bleach.
8. Stir the contents and place the beaker in an ultrasonic cleaner or on a rotating hot plate for between 1 to 2 hours, stirring occasionally.
9. Repeat step 6 for wet seiving.
10. Return the greater than 4 Ø residue to the small beaker and add 4 parts "Quaternary O" solution to one part sample (Quaternary O solution is made by dissolving 10 ml of the 'solid' detergent, "Quaternary O", in 1 liter of water). (Note "Quaternary O", previously manufactured by CIB GEICY Canada Ltd., is

no longer produced by that firm, and supplies for this research were provided by Dr. Wall to whom the author is gratefull. Supplies may now be obtained from

Chemonics Scientific Ltd.
2020r - 32nd Ave. N.E.
Calgary, Alberta, T2E 6T4
(403) 250-1142 .

11. Place the mixture in an ultrasonic cleaner or on a rotating hot plate for 1 to 2 hours, stirring occasionally.

12. Repeat step 6 for wet seiving examining the residue under low power magnification for remnant shale fragments. Repeat steps 11 and 12 until only sand grains and tests etc. of interest remain. Step 12 will frequently have to be repeated 3 times to completely break down the sample and may have to be done as many as 6. However, samples taking longer than this are frequently too well cemented to disaggregate further.

13. Before seiving the next sample, stain any residual particles in the 4 Ø seive to detect contamination of the following material. This is accomplished by soaking the seive briefly in a toluidine blue solution made by dissolving sufficient toluidine crystals in

water to turn it a dark blue.

14. Weigh the final sample.
15. Pick and mount dead things of interest.

In this research, foraminifera were picked from sieve sizes greater than 2.5 Ø in size, and a greater than 4 Ø size was examined briefly without picking in the cases of samples that were barren in the larger sizes.

Figure 2-1. Oil and gas fields producing from the Cardium Formation (from Walker, 1986). The area of this study is around the Kakwa field in the northwest.

Figure 2-3. The Late Turonian extent of the Western Interior Seaway (after Obradovich and Cobban, 1975).

Figure 2-4. Proposed correlation of the Cardium Formation in subsurface and outcrop (from Walker, 1986).

The figure shows a tentative correlation of the outcrop stratigraphy of Duke (1985) and Stott (1963) with the subsurface stratigraphy of Plint et al. (1986). The nature of the event stratigraphy is more fully discussed in the text with reference to figure 2-5.

Plate 3-1

Letter directions indicate the way up on the photographs.

A. Massive Dark Mudstone (Facies 1). The photograph is from well 6-13-59-18W5 at 4795 feet; the scale is in centimeters.

B. Laminated Dark Mudstone (Facies 2). The example is from well 7-10-62-7W6 at 2129 meters. The bar represents one centimeter.

C. Dark Bioturbated Muddy Siltstone (Facies 3). This example is taken from well 9-10-63-6W6 at 1782m. The bar represents one centimeter.

D. Pervasively Bioturbated Muddy Siltstone (Facies 4). Although this example is slightly sandier than usual, it shows the intense bioturbation. The photograph is from well 7-29-59-4W6 at 2315 meters, and the bar is a one centimeter scale.

Plate 3-2

The letters are oriented to show the way up of the photographs.

A. Bioturbated Sandstone (Facies 5). The photograph shows the greater preservation of beds than in facies 4 and is taken from well 10-1-67-8W6 at 1274.5 meters. The bar represents one centimeter.

B. Dispersed Sandy Mudstone (Facies 6A). This photograph emphasizes the brief, scattered nature of the sand; it comes from well 6-8-62-5W6 at 1899 meters, and the scale is in centimeters.

C. Speckled Sandy Mudstone (Facies 6B). Note the gross similarity to facies 3. This example is from well 6-29-59-1W6 at 2308 meters; the bar represents one centimeter.

D. Mud Speckled Sandstone (Facies 6C). The style of bioturbation is similar to that of facies 6B. The photograph is from well 6-8-62-5W6 at 1884 meters, and the scale is in centimeters.

Plate 3-3

A. This is an excellent example of an Arenicolites burrow in facies 6A immediately overlying H6. The burrow has been lined by medium to coarse sand. This example is from well 9-10-63-6W6 at 1785 meters depth; the scale is in centimeters.

B. The photgraph show several interpenetrating burrows. The first is a Bergauria burrow filled with medium to coarse sand. The sand shows spreite and the base of the burrow contains ripped up angular siderite clasts. Centrally penetrating the sand fill of this burrow is an Arenicolites burrow curving to the right at its base. These two burrows are then penetrated by a centimeter diameter mining structure. The example comes from well 6-8-62-5W6 at 1885 meters in facies 6B. The bar represents one centimeter.

Plate 3-4

The letters indicate the way up orientation of the photograph.

A. Structured Speckled Mudstone (Facies 6D). This photograph show the bedform draping nature of the coarser sand; other, less photogenic, examples have more sand and closer spacing of the sand-mud laminae. This example is from well 11-7-63-5W6 at 1841 meters; the bar represents a centimeter.

B. Non-Bioturbated Sandstone (Facies 7). This photograph is from well 9-10-63-6W6 at 1795 meters, and the bar represents one centimeter.

C. Sandy Interbedded Pebbles, Sand and Mud (Facies 8A1). The example is from 1398 meters in well 6-6-64-25W5. The bar is one centimeter.

D. Muddy Interbedded Pebbles, Sand and Mud (Facies 8A3). The photograph is of well 6-13-59-18W5 at 4698 feet; the bar is one centimeter.

Plate 3-5

The letters are arranged to show way up for each photograph.

A. Pebbly Mudstone (Facies 8B). Note the slight scour which the larger clasts lie in. This example comes from well 14-7-60-2W6 at 2265 meters, and the bar is one centimeter.

B. Massive Sandstone (Facies 10). This photograph shows and example containing mud rip-up clasts. The lighter ones are sideritized. The photograph is from well 9-10-63-6W6 at 1786.5 meters. The bar is a centimeter.

C. Interbedded Sandstones and Black Mudstones (Facies 15). This example shows the short Skolithos and Planolites burrows. It comes from well 9-10-63-6W6 at 1787 meters. The bar is one centimeter.

D. Coal (Facies 18). This example is from well 7-10-62-7W6 at 2145 meters. The bar is one centimeter.

Plate 3-6

The letters indicate way up for the photographs.

A. Black Non-Marine Mudstone (Facies 19). Note the fissility imparted by the high organic content. This photograph is of well 6-8-62-5W6 at 1907 meters. The bar is one centimeter.

B. Carbonaceous Black Mudstone and Sandstone (Facies 20). This is an excellent example of typical slumping. It comes from well 10-1-67-8W6 at 1284 meters; the bar represents one centimeter.

C. Rooted Mudstone (Facies 22). This photograph is from well 6-8-62-5W6 at 1903 meters. The bar is one centimeter.

D. Grey Non-Marine Mudstones (Facies 23). This facies is comparable to facies 19 but lighter due to its lower organic content. The photograph is of well 6-8-63-5W6 at 1888.8 meters and the bar is one centimeter.

Figure 4-2. Common _Textularina_ Genera of the Foraminifera of the Upper Cardium.

The species illustrated are as follows, begining with _Dorothia sp.1_ and moving clockwise: _Dorothia sp.1_, _Trochamminoides (?)_, _Halpophragmoides Recurvoides_, _Reophax Sp.1_, _Pseudobolovina Pepperensis_, _Haplophragmoides Sp.1_, and _Trochammina Sp.1_.

Table 4-1. Grams of Cushed Sample and Final Grams of Processed Sample.

The table is explained in the text.

Table 4-2. Foraminifera per Gram of Sample and Percent of Sand per Sample.

See text for details.

Figure 4-3. Foraminiferal Content as a Function of a Sample's Percent Sand and Facies.

The graph in the upper tight shows the dependence of forams on the percentage of sand in a sample. The limiting line is an assumed trend indicating the variation expected if sand content were the only conterolling factor. Sample belwo this line therefore indicate other repressive mechanisms. One dot is one sample.

The graph in the lower left shos foram content as a function of facies. The 'normal' area is the normal marine content. The excesses or depletions relative to this are discussed in the text. One line is one sample.

Figure 4-4. Distribution of Environments Implied by Foraminiferal Analysis.

The heavy line labelled maximum extent of the Kakwa shoreline is equivalent to the edge of a topographic bench. (This topography is discussed more extensively in chapter 8). The line also marks the division between most of the 'flooded' and 'normal' samples which lie offshore and the majority of 'stressed' samples which lie in the bench region. This line is approximate because of the relatively small number of samples involved.

Plate 5-1. Massive Siderite.

The photograph is at 400 times magnification. It is of a sample from well 2-16-63-5W6 at 1780m. Note the complete lack of any structure and the very fine grain size.

Plate 5-2

A Typical Occurence of Siderite. This is a photograph of a thin section one and a half centimeters across in cross polarized light. The section is from well 10-9-63-7W6 at 1909 meters and cuts across E5, the break dividing the upper fifth from the lower area of the section.

The lower portion of the thin section is completely sideritized resulting in the absolutely homogenous light appearance. Note that the spherulites are so small that they do not appear at this scale.

Figure 5-1. The Paleoporosity of Sideritized Muds.

This figure shows the results of the insoluble residual analysis discussed in the text. The horizontal axis shows the calculated paleoporosity of the mud (or sand in the case of sample 5/2-19-62-20W5/[161] on the far left). The vertical axis is the number of sample with the indicated paleoporosity. The histogram divisions are centered around paleoporosity values in increments of ten.

Figure 5-2. The Geochemical Scheme of Maynard (1982) for Sedimentary Environments.

The division of this diagram are discussed in the text. Siderite may form in either the Post-Oxic or Methanic regions. The stipples pattern emphasizes the likely realm of formation of most of the siderite found in the Cardium Horizons. The vertical axis is a qualitative measurement of oxygenation of the system (more accurately considered as increasing reducing capacity downward), and the horizontal axis is a qualitative measurement of the amount of dissolved sulphate available for reaction.

Figure 5-3. Eh-pH Diagrams Showing the Stability of Siderite (from Woodland and Stenstrom, 1979).

The stipple pattern in each diagram highlights the stability field for siderite. The varying conditions for each field are as follows.

A. $\Sigma aS = 10^{-1}$, $\Sigma CO_3^{-2} = 1$, $PCO_2 = 1 atm$ and $a\Sigma Fe^{+2} = 10^{-6}$.

B. $\Sigma aS = 10^{-4}$, $\Sigma CO_3^{-2} = 1$, $PCO_2 = 1 atm$ and $a\Sigma Fe^{+2} = 10-6$.

C. $\Sigma aS = 10^{-8}$, $\Sigma CO_3^{-2} = 1$, $PCO_2 = 1 atm$ and $a\Sigma Fe^{+2} = 10^{-6}$.

D. $\Sigma aS = 10^{-8}$, $\Sigma CO_3^{-2} = 10^{-2}$ and $a\Sigma Fe^{+2} = 10^{-2}$.

Σ = the sum of

a = the activity of

P = the partial pressure of

Plate 6-1

A. A <u>Thalassinoides</u> burrow at the base of the Amundson Member in well 6-29-59-1W6 at 2995 meters. The scale is in centimeters. Note that the label is <u>incorrect</u>.

B. A <u>Thalassinoides</u> burrow within the Amundson Member also from well 6-29-59-1W6 at 2993 meters. Again the label is <u>incorrect</u>. The scale is in centimeters. Note that the surrounding mud has been sideritized.

Plate 6-2

Planolites Burrows Curving Around a Siderite Concretion.

Numerous *Planolites* burrows, as indicated by the arrow, have curved around this siderite concretion where other traces such as a *Zoophycus* (not visible) penetrate the pre-sideritized mud. This eroded surface is probably equivalent to E5 in the subsurface; the location is given in Walker and Wright (1982).

Figure 7-1. A Typical Variety of Sections Across H4.

The black bar is one meter. The stipple represents sideritized areas and the dark horizontal lines indicate erosion visible across the core. The horizontal scale shows the maximum size of clast within the facies shown; it ranges from silt to pebbles. The facies are described in the facies legend in Appendix One where all of the H4 measured sections may be seen.

Plate 7-1

A Thin Section Across H4.

The thin section is from well 6-29-63-5W6 at 1726.3 meters across H4 (E4 in this case). The section is one and a half centimeters across. The sharp but bioturbated division between the marine mudstone above and the carbonaceous non-marine mudstone below is clearly visible. The burrow on the left is probably an amphipod burrow.