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TRACE FOSSILS AND SEDIMENTOLOGY OF A LATE CRETACEOUS PROGRADATIONAL BARRIER ISLAND SEQUENCE: BEARPAW-HORSESHOE CANYON FORMATION TRANSITION, DOROTHY, ALBERTA

by

THOMAS DONALD ARNOLD SAUNDERS

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF
MASTER OF SCIENCE

GEOLOGY

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THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled TRACE FOSSILS AND SEDIMENTOLOGY OF A LATE CRETACEOUS PROGRADATIONAL BARRIER ISLAND SEQUENCE: BEARPAW-HORSESHOE CANYON FORMATION TRANSITION, DOROTHY, ALBERTA, submitted by THOMAS A. SAUNDERS in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE.

Supervisor

Date February 14, 1989

DEDICATION

To my wonderful parents, Bill and Renie.....

......a small token in appreciation for all that you have done.

By 'emselves they ain't worth shucks. But sneak them rascals up side something else and they's dynamite!

Jethro Bodine (on the ciphering value of noughts)

ABSTRACT

A classic example of a regressive barrier-island sequence outcrops in the Alberta "badlands" along the Red Deer River Valley. The sequence is essentially flat-lying and occurs more-or-less continuously exposed along an extended (20 kilometer) tract, trending roughly perpendicular to the inferred orientation of the paleoshoreline: excellent conditions, therefore, exist in which to observe latero-vertical facies relations in onshore-offshore transect.

In the most landward (northwestern) corner of the study area, where the sequence approaches its depositional edge, only shallow water and subaerial deposits are represented. Here, tidal inlet related facies dominate the preserved record. Seaward (southeast) of this, however, with greater paleowater depths having evidently existed at the onset of progradation, tidal inlet facies vanish altogether from the record and the sequence instead becomes everywhere typified by open ocean beach-offshore facies, arranged in upward-coarsening progradational succession. Detailed sedimentologic-ichnologic analysis of the beach-offshore sequence have allowed for the division into three distinct stratigraphic zones (lower, middle and upper) each, in turn, ascribing to deposition across a specific environmental zone of the paleo-shoreline profile.

The *Lower Zone* comprises a laterally varied assemblage of storm influenced lower shoreface-through-offshore deposits. Sections measured in the northwest of the study area are everywhere dominated by thick beds of hummocky and/or swaley cross-stratified storm sand, either amalgamated or occurring in stacked succession. Sections measured towards the southeast, on the contrary, reveal a much lower overall periodicity of "major" storm events and, as a direct consequence, a great deal more of the background depositional gradient has been preserved. The lower zone, plays host to a wide diversity of exceptionally well preserved trace fossils, whose distribution appears to have been profoundly influenced

by offshore gradients in wave-energy and bottom stagnation, and by the interplay between storm and fairweather processes.

The *Middle Zone*, as dictated by its stratigraphic position between deposits of inferred lower shoreface and foreshore origin, records deposition across the intervening upper shoreface environment. Here, horizontal to low-angle bedding predominates, with sets of small, decimeter and large-scale cross-bedding occurring interspersed throughout but being more prevalent towards the top of the zone. It is a characteristic feature of the upper two-thirds of the zone, that virtually nowhere do biogenically formed structures occur. Perusal of the recent literature on modern sandy beach ecology suggests that this may in turn point towards deposition in an exposed high-energy surf zone setting, as opposed to in a more sheltered, low-energy one.

The *Upper Zone* finally records the progradation of the intertidal-supratidal portion of the shoreline complex. Distinctively planar laminated sandstone of inferred foreshore origin form a distinct zone, above which vertical rhizoliths and associated organics become increasingly abundant, marking the transition into the backshore. One of the most intreguing features of the upper zone involves the occurrence of an intense biogenically disrupted zone that occurs toward the top of the foreshore sequence. The zone consists entirely of intrastratal concentrations of the trace fossil *Macaronichnus segregatis* . Here, modern comparison with a very similar ichnological zone found along surf-stressed Pacific west coast North American beaches, has allowed for inferences to be made concerning the precise morphodynamic state and tidal regime of the beach.

ACKNOWLEDGEMENTS

First and foremost I wish to acknowledge the tremendous support and encouragement offered to me by my supervisor, *Dr. S. George Pemberton.* In addition to helping me develop and sharpen the conceptual framework of this thesis, he has also very patiently over the years instilled in me the "tools of the trade", making available his vast knowledge of the Cretaceous, and of ichnology and sedimentology in general.

Over the past three years, many people have contributed their thoughts and perceptions concerning various aspects of the study. In these regards, I wish to thank: *Dale Leckie, Peter McCabe, Ray Rahmani, Paul Johnstone* and *Brian Jones*; fellow "Pembertonites" *Mike Ranger, Jim Magwood, Andy Fox & Bruce Beynon*; and finally the many people who have participated in past field trips. Many thanks to *Hughie Stewart* for hi invaluable help both in the field and in the lab, and to *Cathy Gendron* for so patiently typing and revising the many versions of this manuscript. Thanks also to: *Sue* and *Belinda Gordychuk* for helping out with the typing on less than spur of the moment notice; to *Shawna Vossler* for assisting with the analysis of *Ophiomorpha borneensis* and to *Ron Stewart* for helping with the photographic reproductions. Financial support for this thesis was generously provided by *Texaco (Canada) Inc.* in the form of a graduate student researc grant.

I feel a sense of great fortune in thinking back and realizing that I might never ha accomplished this thesis, had it not been for the enduring support of my family and some o my closest friends. *Mom & Dad* especially (and to whom I dedicate this thesis); *Mr.& Mr Savitsky; Uncle Dave & Aunt Faye; Lalla, Kunta, Riggy, Joani, Geggy & Pruny*---you gu have all been unbelievable! Lastly, I owe a very special appreciation to my girlfriend *Terry Savitsky*--thanks "bunches & bunches" *Ter,* for all the love and understanding you've give me, and for reminding me that there is more to life than just rocks and fossils.

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I INTRODUCTION

In recent decades, through the continued exploration of the modern record, geologists have grown increasingly aware of the tremendous multiplicity of shallow marine depositional environments. Accordingly, the resolution of clastic shoreline facies models has greatly improved (cf Reading, 1986; Walker, 1984). State-of-the-art interpretations have progressed from the mere recognition of "shoreline sands", to the differentiation of specific depositional shoreline settings and related subenvironmental facies associations, and, given ideal conditions, to the precise calculation of such key paleoparameters as water depth (cf. Klein, 1974; Elliot, 1986), wave climate (cf. Clifton, 1985; Dupré, 1985) and tidal regime (cf. Allen, 1981; Terwindt, 1981; Visser, 1980).

Traditionally , however, geologists have relied heavily on *physical sedimentary structures* in the interpretation of ancient clastic shallow marine deposits, paying little or no heed to their *biogenic* counterparts (i.e., trace fossils). More recently, the potential value of trace fossils as environmental indicators has been repeatedly demonstrated (cf. Howard, 1972; Fürsich, 1975; McCarthy, 1979; Howard and Frey, 1984, 1985; Pemberton and Frey, 1984; Curran, 1985). It remains, however, of fundamental importance that trace fossils, representing both biologic and sedimentologic entities, be viewed in concert with, rather than in lieu of, the associated physical record (Frey and Pemberton, 1984). This study combines the fields of ichnology and sedimentology, in precisely this manner, in an attempt to arrive at the depositional setting of a late Cretaceous shoreline sequence outcropping along the Red Deer River in south central Alberta.

GEOLOGICAL SETTING

An essentially flat lying succession of intertonguing shallow and marginal marine strata is exposed in the valley walls of the Red Deer River between the townsites of East

FIGURE 1

Map of study area. Measured Appaloosa sections occur at EC-5, EC-4, EEB-1, Pipe Rock, Ophimorpha Heaven, Sundance Coulee, Little Big Coulee, Big Coulee, Boot Coulee, and Snake Coulee.

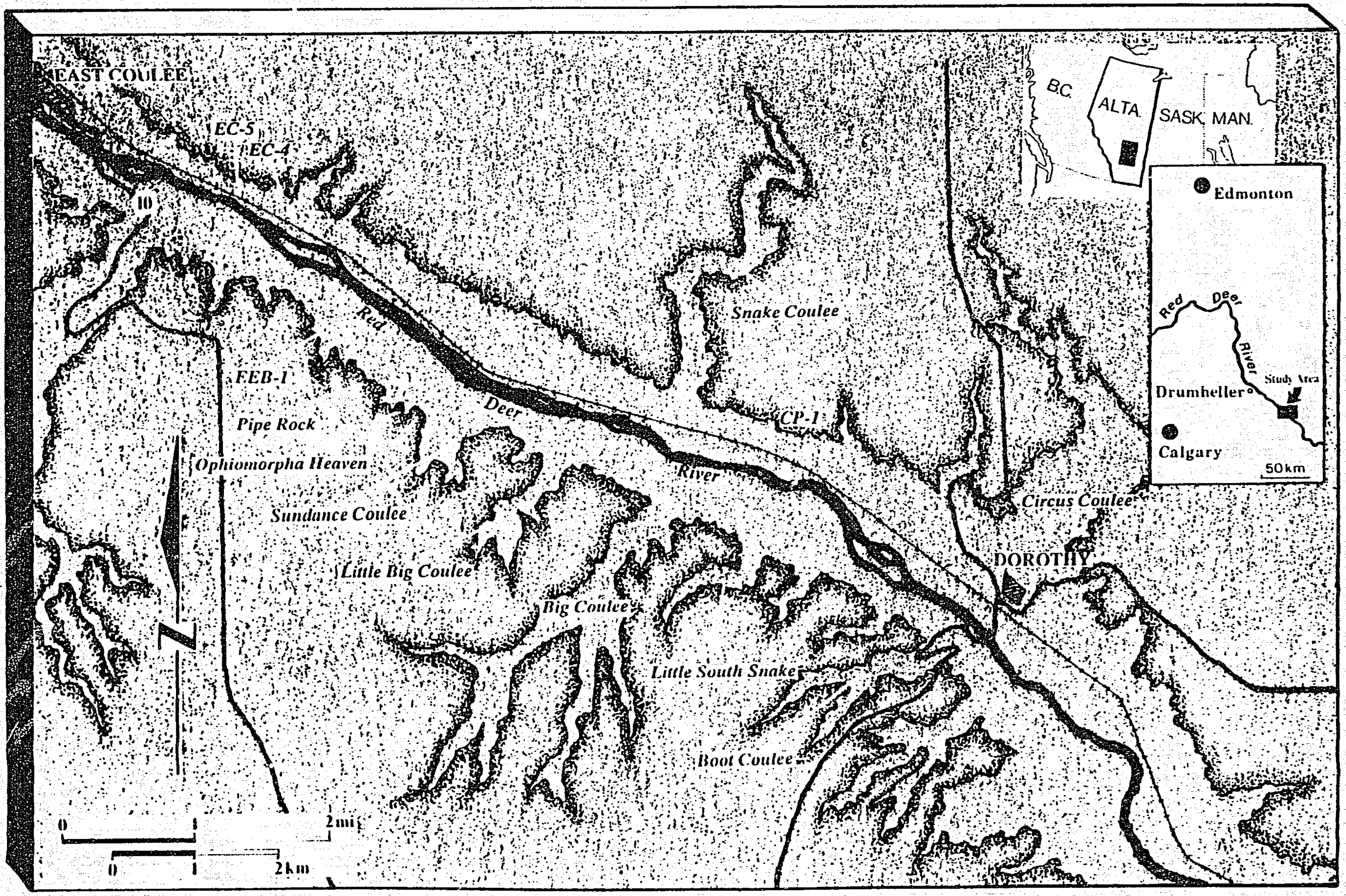

EAST COULEE
EC-5
EC-4
10
Red
Deer
River
FEB-1
Pipe Rock
Ophiomorpha Heaven
Sundance Coulee
Little Big Coulee
Big Coulee
Little South Snake
Boot Coulee
Snake Coulee
CP-1
Circus Coulee
DOROTHY
N
B.C.
ALTA.
SASK.
MAN.
Edmonton
Red Deer River
Drumheller
Study Area
Calgary
50km
0
1
2mi
0
1
2km

FIGURE 2

Onshore-offshore transect of transitional Bearpaw-Horseshoe Canyon strata illustrating depositional history and evolution of shoreline across study area.

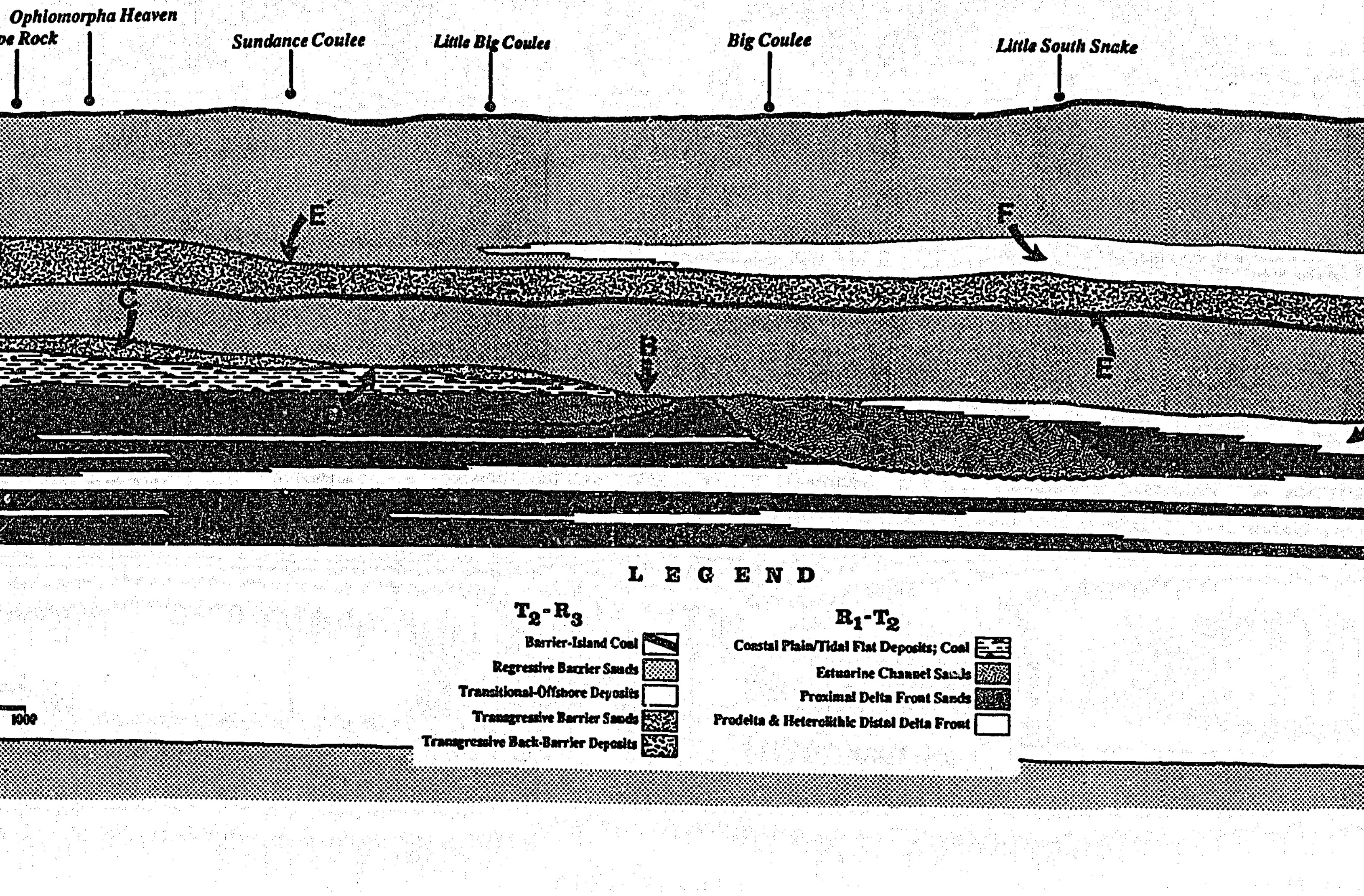
Stage 1 (R1 Regressive Cycle) Southeastern progradation of a tidally-dominated deltaic shoreline.

Stage 2 (T2 Transgressive Cycle) Delta abandonment: (A) Landward encroachment of prodelta facies; (B) erosion of delta headlands and establishment of transgressive barrier bar; (C) transgressive deposit evidencing landward translation of the newly established barrier shoreline by process of 'shoreface retreat', as opposed to 'in place drowning' as envisaged by Rahmani (1983); (D) development of the *Glossifungites* ichnofacies within semiconsolidated R1 delta plain muds exhumed in the process of shoreface erosion.

Stage 3 (R2 Regressive Cycle) Southeast progradation of storm-influenced, barrier beach shoreline; although exact extent of progradation beyond study area is not precisely known, the sequence, complete with backshore sands and coal facies on top, can be traced for 5 kilometers to the southeast of Dorothy,

Stage 4 (T3 Transgressive Cycle): Barrier transgression, again via shoreface retreat; with the exception of the back barrier assemblage preserved to the NW of EEB-1, the depositional record comprises storm-emplaced lower shoreface sands, locally underlain by tidal inlet channel facies. The continuous peat (coal) bed capping the R2 sequence evidently played an integral role in the shoreface retreat process, acting as an erosional stop. (E) development of the Glossifungites ichnofacies below the basal transgressive surface with the shoreface exhumation of the R2 peat; (E') development of the *Glossifungites* ichnofacies beneath the upper transgressive surface.

Stage 5 (R3 'Appaloosa' Regression): Final progradation of the barrier shoreline complex. (F) development of seaward thickening wedge of transitional-offshore facies with increasing paleodepths to the southeast.


Ophiomorpha Heaven
oe Rock
Sundance Coulee
Little Big Coulee
Big Coulee
Little South Snake
E
F
C
B
E
1000
LEGEND
T2-R3
Barrier-Island Coal
Regressive Barrier Sands
Transitional-Offshore Deposits
Transgressive Barrier Sands
Transgressive Back-Barrier Deposits
R1-T2
Coastal Plain/Tidal Flat Deposits; Coal
Estuarine Channel Sands
Proximal Delta Front Sands
Prodelta & Heterolithic Distal Delta Front

Coulee and Dorothy (Figure 1). The succession stratigraphically separates the marine shales of the Bearpaw Formation from the overlying terrestrial coal-bearing strata of the Horseshoe Canyon Formation. It therefore occupies a pivital position within the major regressive wedge of clastic sediments deposited in late Campanian-early Maestrichtian time, as the epicontinental Bearpaw Sea regressed to the southeast on its final withdrawl from the southcentral plains region of Alberta (Shephard and Hill, 1970; Williams and Stelck, 1975; Lerand, 1983). That the Bearpaw paleoshoreline, throughout deposition of the study section, was situated with an overall northeast-southwest orientation, has been convincingly demonstrated by Rahmani (1983). The modern Red Deer River Valley, and hence the main outcrop tract, trends roughly perpendicular to this, i.e. northwest-southeast. Consequently, ideal roadside exposures occur along highway 10 from Drumheller to Dorothy, in which to observe the complete lateral transition grading from terrestrial coal-bearing alluvial facies in the vicinity of Drumheller, through a mosaic of intracoastal and marginal marine facies, finally arriving at fully marine conditions towards Dorothy in the extreme southeast.

Detailed stratigraphic discussions dealing with the *Horseshoe Canyon Formation* specifically and the *Edmonton Group* in general, can be found in papers by Ower (1960), Irish (1970) and Gibson (1977). The most comprehensive stratigraphic treatment of the *Bearpaw Formation* is that of Lines (1963). These relationships will not be reiterated here.

DEPOSITIONAL FRAMEWORK AND PREVIOUS WORK

The study area (Figure 1) adjoins those of Shephard and Hills (1970, 1979) and Rahmani (1981, 1983), all of whom investigated a more "landward" extension of the succession outcropping to the northwest between East Coulee and Willow Creek (Figure 3B). From here Shephard and Hills (1970) established the general depositional framework as that of an easterly prograding deltaic complex, drawing most of their analogies with the modern Mississippi Delta. Rahmani (1981, 1983) re-interpreted the succession, presenting strong evidence which instead favored deposition within a range of estuarine and barrier-island related environments associated with an "embayed" deltaic shoreline; analogies here were drawn with the mesotidal estuaries occurring along the Georgian coast, the estuaries of the Rhone Delta of southwestern Netherlands, and the Willipa Bay estuary on the Pacific Washington coast.

In addition to establishing a working depositional model, within a 50 meter interval of the transitional succession, Rahmani (1983) traced the movements of the paleoshoreline through a series of transgressive-regressive cycles (Figure 3A). His lowermost genetic unit (Unit 1 in Figure 3A) documents the initial southeastern regression of the shoreline (in the configuration of a tidally-dominated delta) into the East Coulee area. A major transgression is then inferred to have occurred, drowning the coastal peat-forming swamps (i.e. as represented by Coal O), leading ultimately to the establishment of a barrier-island complex at the shoreline. Figure 3C depicts the ensuing mode of barrier evolution, as inferred by Rahmani from laterovertical facies relations within his Units 2, 3 and 4.

TRACING RAHMANI'S STRATIGRAPHY INTO THE PRESENT STUDY AREA

Unit 1. Extrapolating each of Rahmani's genetic units into the present study area proved, for the most part, to be a relatively straight forward task (Figure 2). This was particularly true concerning Unit 1 (denoted as the *R1 Regressive Cycle* in Figure 2). The progradational limit of the *R1* delta shoreline, as evidenced by the southeastern extent of the coal-bearing coastal plain lithosome capping the sequence, can be traced to a position southeast of Little Big Coulee. Beyond this, the sequence is represented entirely by subaqueous open ocean facies, locally being erosionally capped by offshore subtidal channels undoubtedly associated with Rahmani's main estuarine complex. Southeast of Little Scuth Snake, subaqueous channel and delta front sands can then be seen to gradually "fizzle out", giving rise to a sequence dominated almost exclusively by prodelta facies.

***Units 2, 3 and 4*.** Although interpretations to be presented here generally agree with Rahmani's "barrier island" model for units 2, 3 and 4, a number of fundamental discrepancies remain; this is especially true concerning the nature of transgressive-regressive cyclicity. In tracing Units 2, 3 and 4 into the present study area, complex interchanneled back barrier facies (see Figure 3A) give way to a more uniformly bedded succession, instead consisting largely of open marine facies; the overall result is a much clearer picture as to the precise nature of shoreline evolution (see caption in Figure 2 for details).

THE APPALOOSA (R3) REGRESSIVE SEQUENCE

The uppermost progradational sequence of Rahmani (1983), to which the remainder of this thesis will be devoted, is represented by a distinctive cliff-forming sandstone that begins near East Coulee and continues right across the present study area, finally disappearing beneath the erosional landscape approximately 8 kilometers to the southeast of Dorothy. The name *Appaloosa* is strictly informal, intended solely as a means of facilitating future reference. The approximate locations of Appaloosa sections measured during the course of field investigations are indicated on the study map (Figure 1). Detailed schematic logs have been included only for those measured sections directly referenced in the course of the discussion.

Throughout the study area, the sequence exhibits a characteristic upward shoaling succession of sediment textures and structures that, when combined with the observed distribution of trace fossils, strongly implies deposition within a prograding barrier island shoreline setting. My interest in this particular sequence was originally spurred by the contained assemblage of exceptionally well preserved lebensspuren. Included are a wide diversity of forms, representing the following ichnogenera: *Ophiomorpha, Macaronichnus, Conichnus, Rosselia, Skolithos, Planolites, Palaeophycus, Gyrochorte, Aulichnites, Cylindrichnus, Asterosoma, Teichichnus, Lockeia, Chondrites, Rhizocorallium,* *Diplocraterion, Thalassinoides and Helminthopsis.*

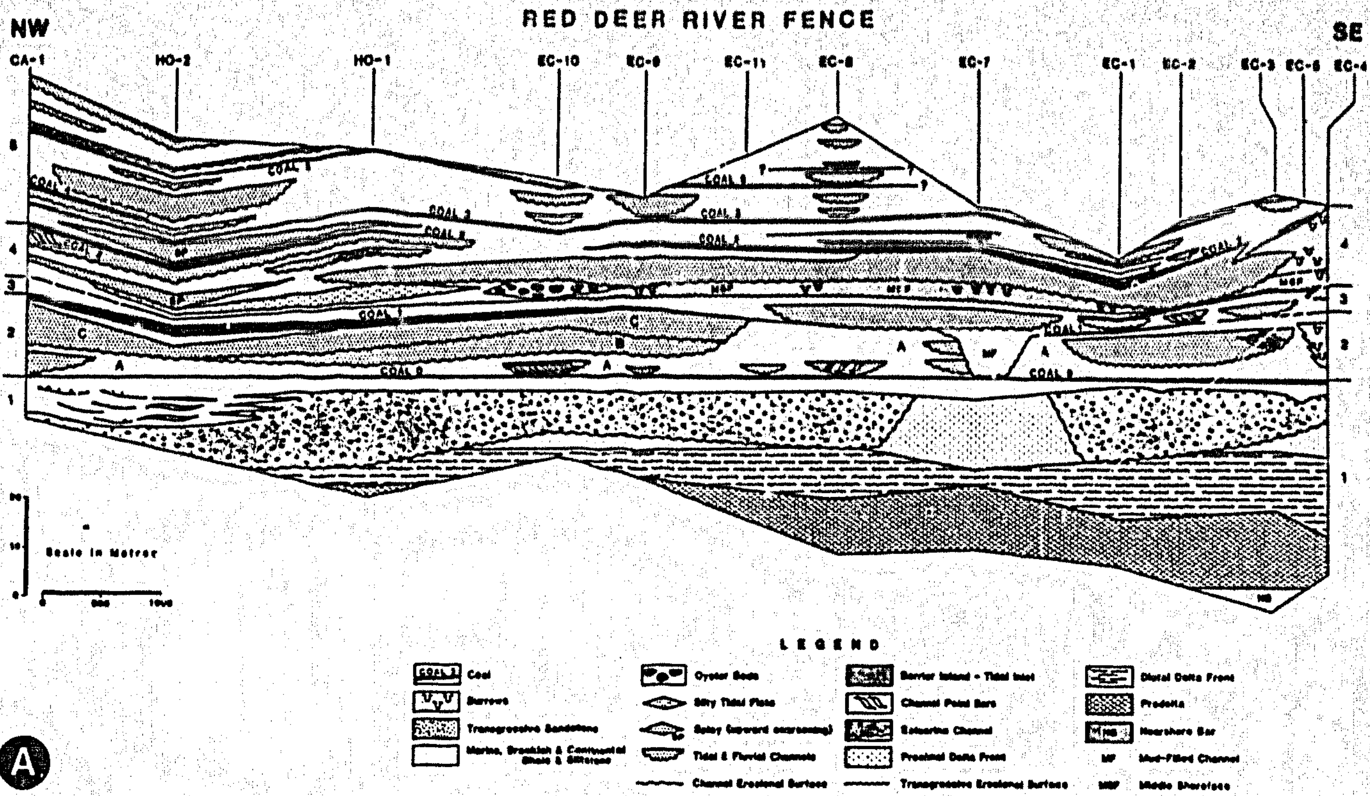
Based on fundamental sedimentologic and ichnologic changes that occur upward through the sequence, at all sections--with the exception of EC-5 -- the Appaloosa can readily be subdivided into three distinct zones, here dubbed the "Lower", "Middle", and "Upper". Correspondingly, each zone can be attributed to deposition within a specific shorezone environment. In the pages that follow, the sedimentological and ichnological characteristics of each zone are recounted. Depositional interpretations are then given based on comparisons with modern systems, as well as with several of the more well established ancient barrier-island sequences displaying features found to be remarkably similar to those described herein.

FIGURE 3

Fence diagram of Rahmani (1981, 1983) extending NW-SE along the Red Deer River. Note that Rahmani's fence overlaps with that of the present study at sections EC-5 and EC-4.

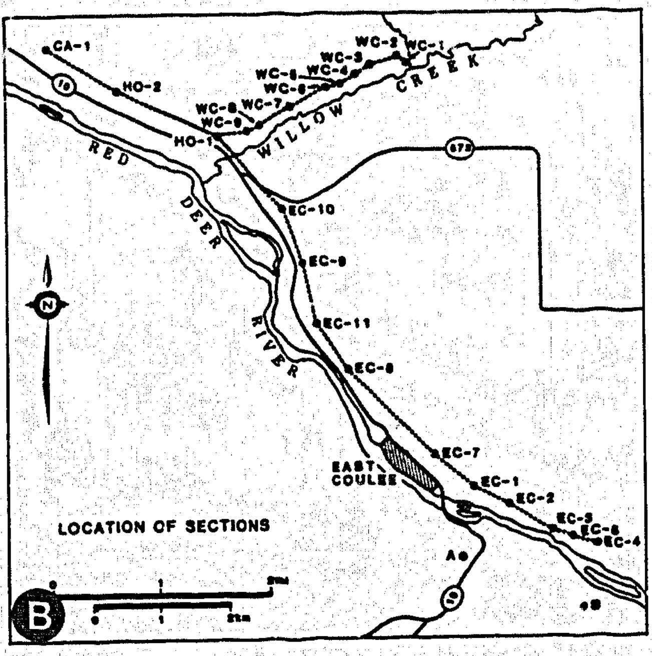
Study area of Shephard and Hills (1970, 1979) and Rahmani (1981, 1983).

Schematic diagram depicting the mode of barrier-island evolution as envisaged by Rahmani (1983), involving: (A) the establishment of a mesotidal barrier complex; (B) progradation of the barrier complex; (C) sudden in plane drowning of the barrier and landward translation of the shoreline; and (D) re-establishment of the prograding barrier complex. This cycle is then thought by Rahmani to have repeated three times as represented by units 2, 3 and 4, respectively. See figure 2 for an alternative explanation.

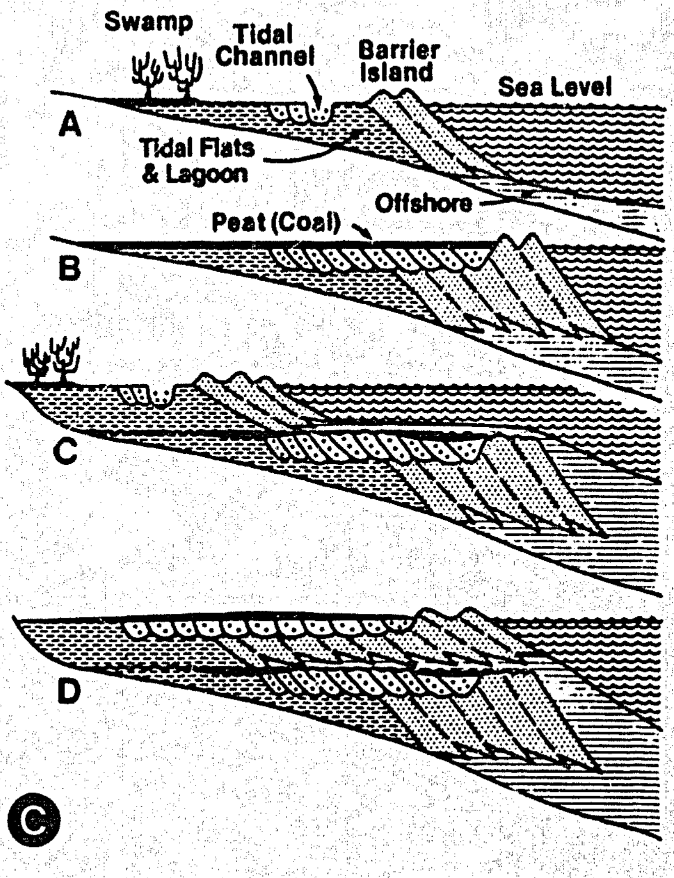


A

RAHMANI'S MODEL



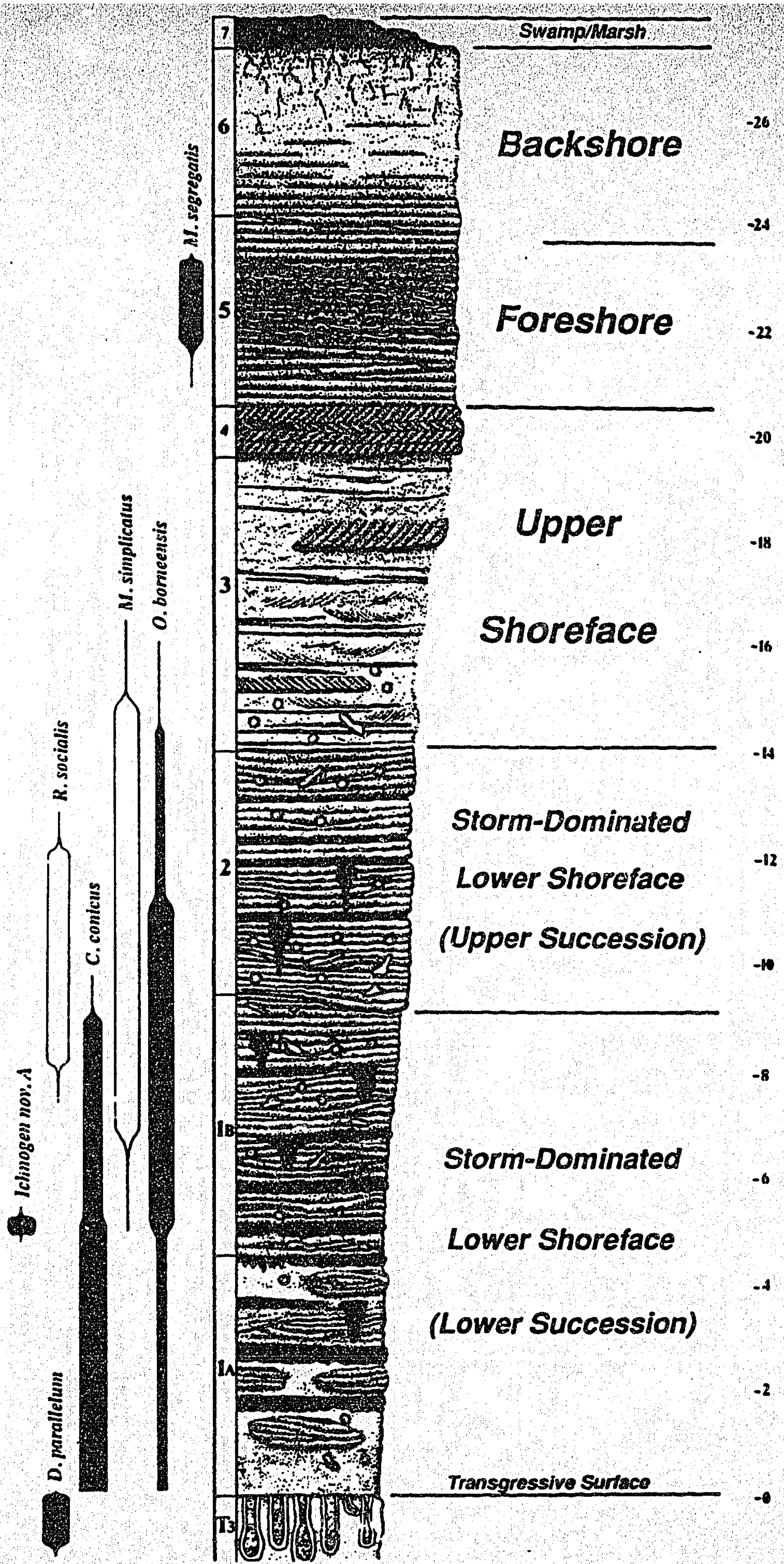
B



C

FIGURE 4

Vertical sequence characterizing the Appaloosa cycle at Sundance Coulee. The LOWER APPALOOSA ZONE corresponds to Units 1-2, the MIDDLE ZONE to Units 3-4, and the UPPER ZONE to Units 5-7. Ichnofossil distributions shown in black denote *characteristic lebensspuren* (*sensu* Dörjes and Hertwerk, 1975) whereas those in white refer to *associated* or more sporadically encountered forms.



APPALOOSA SEQUENCE AT SUNDANCE COULEE

II THE LOWER APPALOOSA ZONE

A. LOWER ZONE SEQUENCE IN THE NORTHWEST SECTOR

Throughout the northwest sector of the study area (i.e., northwest of Little Big Coulee), the Lower Appaloosa Zone comprises an upward-coarsening succession of very-fine to fine-grained sandstone that rests disconformably on the underlying T3 transgressive sequence (Figure 2). The overall thickness of the Lower Zone increases progressively to the southeast, from 4 meters at EC-4 to 13 meters at Little Big Coulee. This is interpreted to reflect the increasing water depths as encountered down the paleoslope at the onset of shoreline progradation and, hence, the southeastern addition at the base of the sequence of the more distally developed facies. As noted in the paragraphs to follow, the sedimentologic and ichnologic characteristics of the Lower Appaloosa, as it exists in the northwest, combine to indicate a *storm-dominated lower shoreface* environment of deposition. Two outcrop exposures, one occurring at Sundance Coulee and the other at 'Ophiomorpha Heaven', have been selected for the purpose of detailed facies analyses (see Figure 1 for section locations).

SUNDANCE COULEE SEQUENCE
(Units 1 and 2 in Figure 4)

At Sundance Coulee, the Lower Shoreface sequence comprises a 13 meter coarsening-upward succession of very-fine to fine-grained sandstone, divisible into two main units (Figure 4).

Unit 1: LOWER STORM SUCCESSION. Unit 1 is characterized by an 8 meter amalgamation of erosively based sand beds that increase upward through the unit with respect to both sand

FIGURE 5

Lower Shoreface (Lower Zone) Deposits at Sundance Coulee

A. Calcite cemented pod within subunit 1B displaying well-developed HCS.

B. Photograph of Lower Zone at Sundance Coulee, taken off line of section; note: (1) resistent sideritic layers; (2) interspersed specimens of *Conichnus conicus* (c); and (3) the distinct color change on transition from subunit 1A into subunit 1B.

C. Calcite cemented pod within lowermost storm bed of Unit 2 displaying well developed HCS.

D. Amalgamated storm beds from subunit 1B; note swaley X-stratified sand bed at top of photo and *Conichnus conicus* (c) immediately subjacent to a major discordant surface towards bottom of photo.

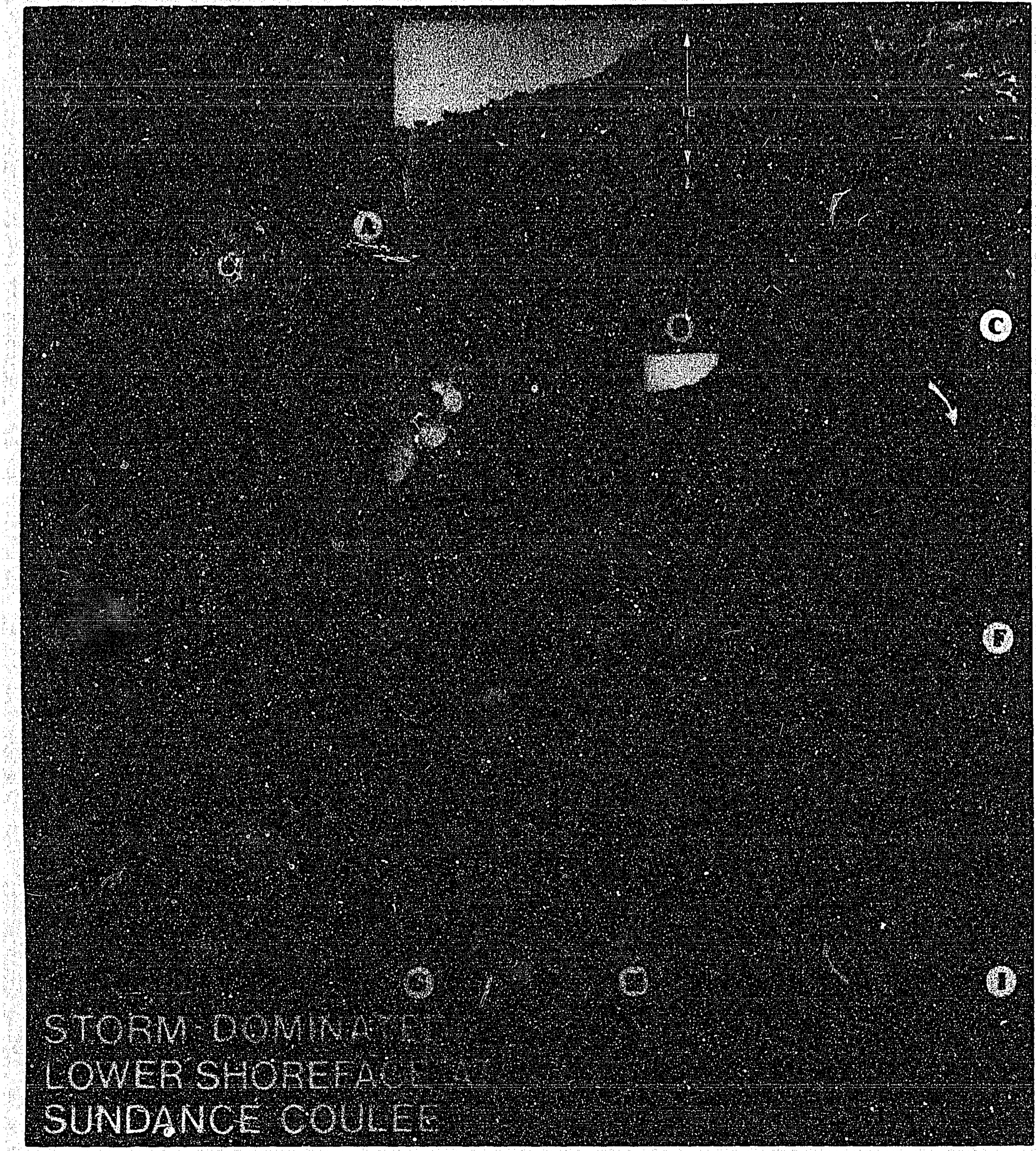
E. Upper bedding surface from subunit 1B displaying well developed parting lineation with a profusion of superimposed *Skolithos linearis* specimens. In bedding plane preservation, *S. linearis* commonly forms distinct epichnial bumps representing the horizontal expression of vertically oriented cylindrical shafts; note distinctly lined specimen at very bottom centre of photo.

F. Amalgamated storm sands from subunit 1B. Note upper right of photo (arrow) where swaley scoured surface has 'bottomed out' upon an internal sideriticed organic rich layer. Processes of very early carbonate cementation would appear to have been involved.

G. *Diplocraterion parallelum* Torell, 1870. Well preserved, closely spaced specimens as characterizing bed X at the bare of the lower storm succession (see text for discussion).

H. *Conichnus conicus* Myannil, 1966. Sideritized specimen from subunit 1B showing typical concentration of fragmentary plant material. These burrows evidently represent the resting/dwelling trace of large anemone or anemone-like organisms.

I. Photo showing thick cross-stratified storm bed at base of upper storm succession. Note network developments of *O. borneensis* towards base of bed (arrow).


C
STORM-DOMINATED
LOWER SHOREFACE AT
SUNDANCE COULEE

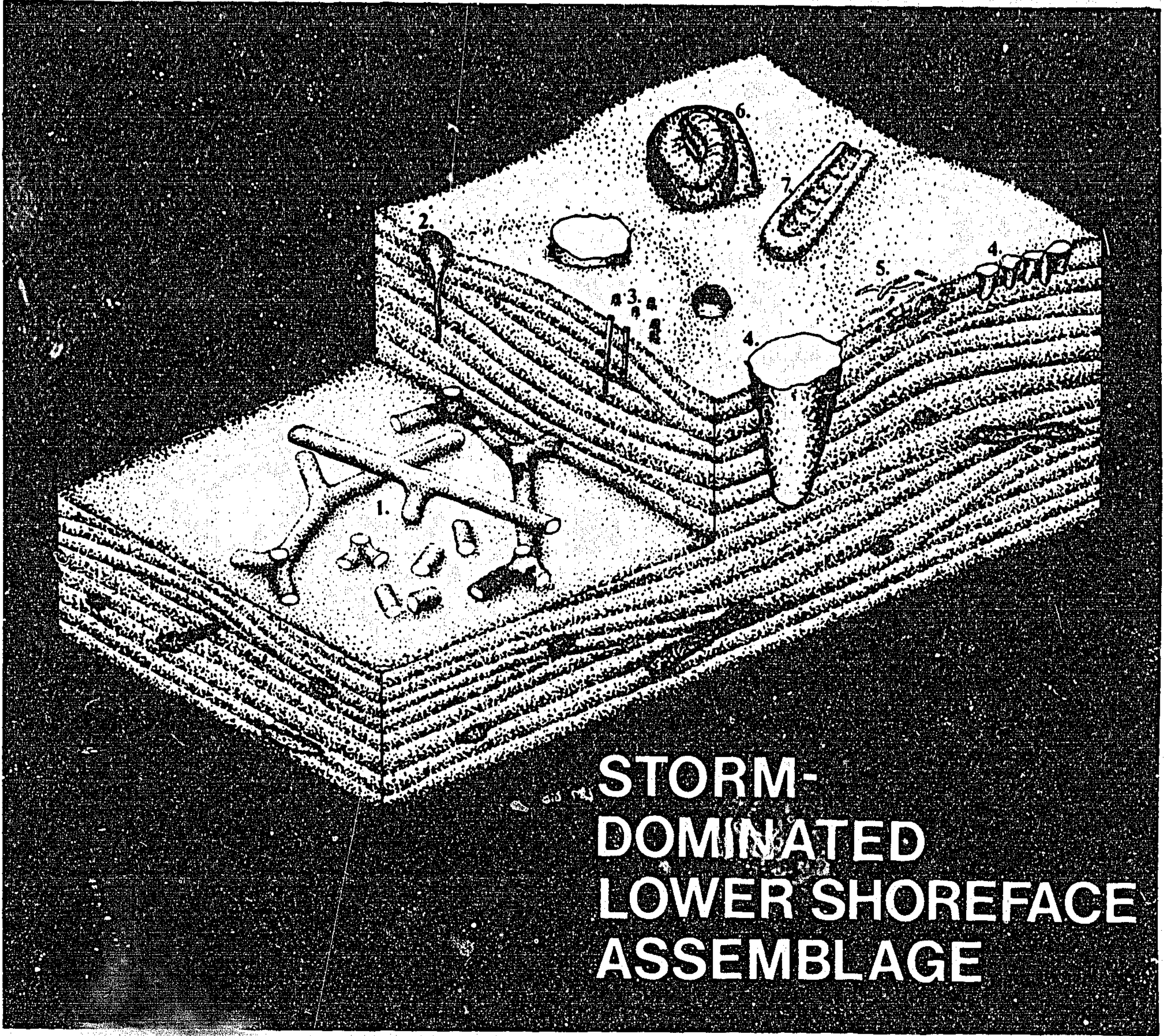
grain size and average bed thickness. Internally, the sands are relatively clean and wherever the nature of bedding can be discerned reveal either planar lamination or, more commonly, low angle undulatory (hummocky) cross-stratification.

The lowermost 5.5. meters of the unit (subunit 1A) consist largely of friable, deeply weathered, drab-colored dark-greyish sandstone occurring in poorly defined beds 0.2 to 1.0 meters thick. Prominent, laterally discontinuous, sideritic iron-stone layers, 20 to 30 cm thick, are common throughout this part of the succession and appear to be exclusive to the very tops of individual beds, often occurring immediately subjacent to major first order erosion surfaces. These resistant ledge-forming layers oxidize a distinctive iron-red color on exposure to the atmosphere, and thus stand out in stark contrast from the surrounding clay-cemented sands (Figure 5B). Although intense surface weathering has greatly obscured internal bedding within this part of the succession, hummocky cross-stratification (HCS) was found to be ubiquitous within isolated calcite-cemented pods.

5.5. meters from the base of Unit 1 (i.e., on transition into subunit 1B) a fundamental change, traceable throughout the coulee, occurs in the color and weathering characteristics of the sandstone. Above this point, the sands become markedly lighter in color from that of the underlying subzone (see Figure 5B) and improved outcrop conditions provide for a much clearer picture of the internal structure of the sand. Here, two morphologically distinct variants of HCS appear to be represented. The first form, referred to here as "classical" HCS (*sensu* Harms et al., 1975), involves both antiformal and synformal laminae sets which conform to internal bed discordances and intersect one another at low angles (< 15). The second variant better complies with the description of "swaley" cross-stratification (SCS) introduced in the literature by Leckie and Walker (1982) in which synformal scours and conformant to slightly divergent laminae sets constitute the dominant bedding element; hummocks or internal convexities of any kind appear to be absent. Within subunit 1B, sideritic ironstone layers persist, but with reduced thickness and

FIGURE 6

Composite block diagram depicting the overall assemblage of trace fossils as occurring within Unit 1 at Sundance Coulee. Included are: *Ophiomorpha borneensis* (1), *Rosselia socialis* (2), *Skolithos linearis* (3), *Conichnus conicus* (4), *Macaronichnus simplicatus* (5), *Rhizocorallium sp.* (7), and *Ichnogen. Nov. form B* (6).



STORM-
DOMINATED
LOWER SHOREFACE
ASSEMBLAGE

frequency from the underlying subunit.

The overall assemblage of trace fossils occurring within Unit 1 is summarized diagrammatically in Figure 6. Not all of the forms illustrated, however, were observed in direct association with one another. *Conichnus conicus* and *Ophiomorpha borneensis* occur sporadically throughout the unit: *Conichnus conicus* is most common within subunit 1A; *Ophiomorpha borneensis* predominates within subunit 1B. *Conichnus conicus* penetrates the tops of beds, and along with the sideritic ironstone layers from which they commonly subtend, these conspicuous burrows provide an excellent means of identifying concealed-bed-junctions on deeply weathered vertical exposures where the nature of bedding cannot readily be determined. Network developments of *Ophiomorpha borneensis*, although somewhat sporadic in extent, can be found at virtually all levels within any given bed. On exposed bed-top bedding surfaces a common sedimentologic-ichnologic association involves parting lineation with superimposed profusions of *Skolithos linearis* (Figure 5E). *Macaronichnus simplicatus* also occurs locally towards the tops of individual beds, within subunit 1B. Finally, *Rhizocorallium sp.* and *N. ichnogen.nov.B* were observed at a single level within subunit 1B, situated within a plateau forming sideritic layer (Plate 7, Figure 1, and Plate 12, Figures 1-3).

Unit 2: UPPER STORM SUCCESSION. Completing the Lower Zone sequence above Unit 2 is a 5 meter interval of relatively clean fine-grained sandstone comprising a succession of sharp, sometimes erosively based beds ranging in thickness from 15 to 70 cm. Rather than being amalgamated, however, most beds are separated by thin (5-10 cm), deeply weathered zones enriched with dense concentrations of carbonaceous laminae. These carbonaceous zones are laterally discontinuous and appear to conform with the tops of beds. Internally, the sand beds themselves are not, in most respects, unlike those in Unit 1. Nowhere within this part of the sequence, however, was classical HCS observed. Instead, thinner beds, where bedding is clearly expressed, appear horizontally stratified. Thicker beds reveal well developed swaley cross-stratification.

Ophiomorpha borneensis constitutes the dominant trace fossil of Unit 3, and is most abundant within the thick sand bed occurring at the base of the unit (Figure 5I). Isolated specimens of *Rosselia socialis* occur within the lower half of the unit, subtending from the tops of sand beds.

"OPHIOMORPHA HEAVEN"

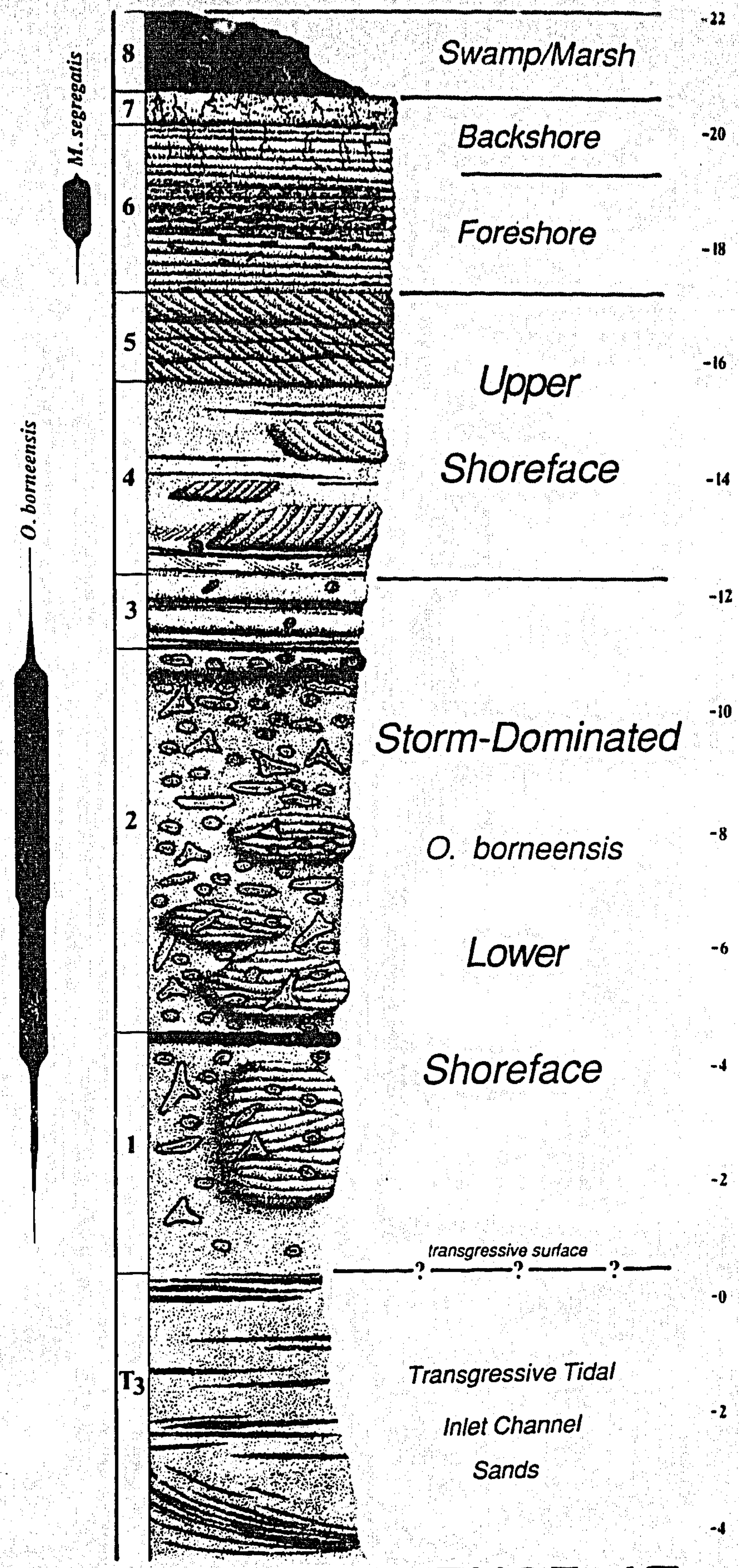
(Units 1, 2 and 3 in figure 7)

The measured section at Ophiomorpha Heaven occurs approximately one kilometer landward (i.e., to the northwest) of Sundance Coulee. Sedimentologically, apart from a decrease in overall thickness and the concomitant disappearance of the prominent sideritic layers at the base of the sequence, the sequential character of the Lower Zone here is very similar to that found at Sundance Coulee: the sequence coarsens upward from very-fine to fine-grained sandstone, and appears structurally to comprise an amalgamation of hummocky-through-swaley cross-stratified sand beds.

Ichnologically, on the other hand, a very pronounced difference exists. Here, in the almost complete absence of any other lebensspuren, a dramatic proliferation in the density of *Ophiomorpha borneensis* occurs (Figure 8). Everywhere, lowershoreface outcrop exposures are riddled with dense networks of *Ophiomorpha borneensis* . This is particularly true within Unit 2, where the great intensity of burrows has rendered the sand completely structureless: remnants of swaley and/or hummocky cross stratification can be discerned only locally.

FIGURE 7

Vertical sequence characterizing the Appaloosa cycle at Ophiomorpha Heaven. The LOWER APPALOOSA ZONE corresponds to Units 1-3, the MIDDLE ZONE to Units 3-4, and the UPPER ZONE to Units 5-7.



APPALOOSA SEQUENCE AT 'OPHIOMORPHA HEAVEN'

FIGURE 8

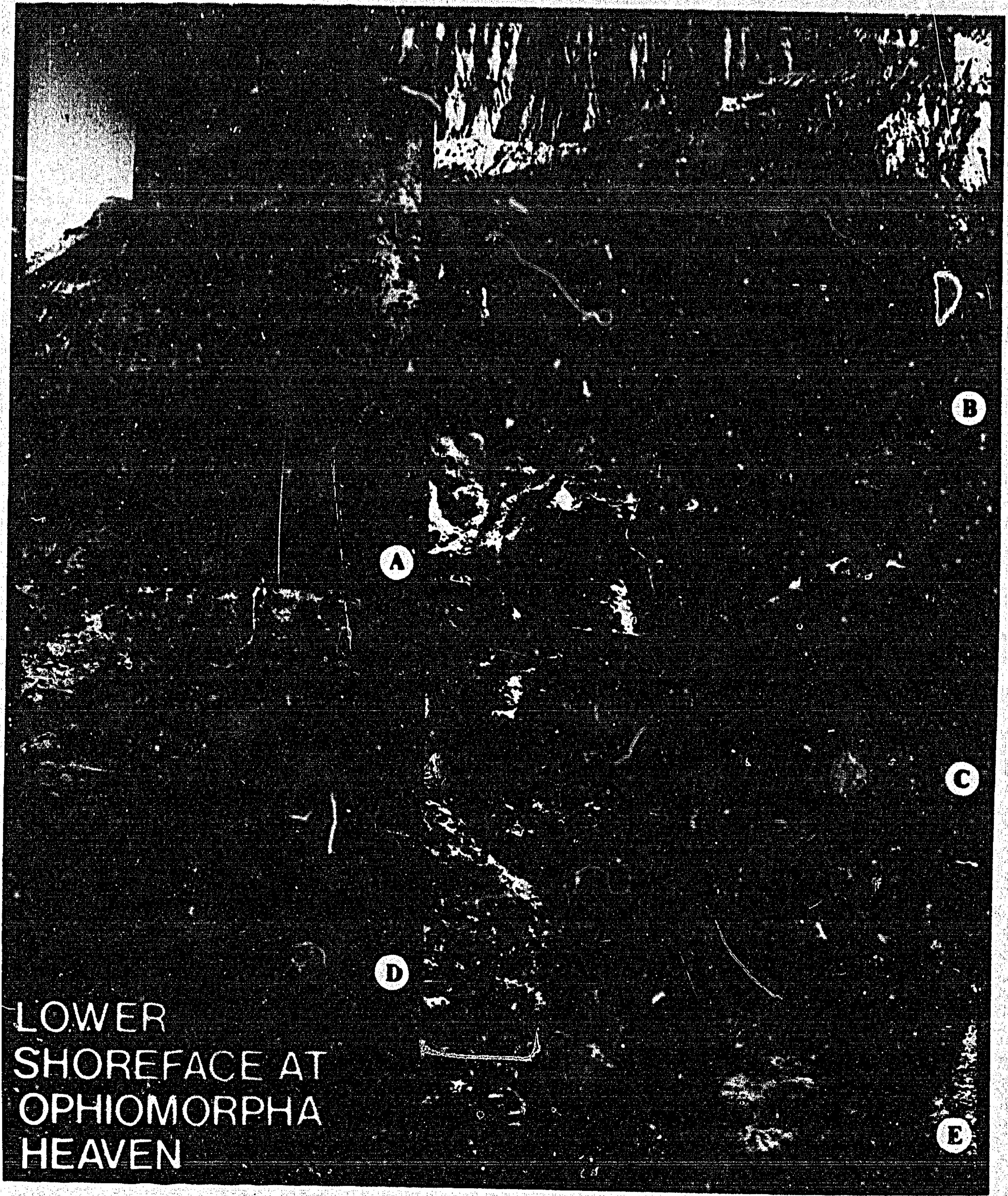
Lower Shoreface (Lower Zone) Deposits at Ophiomopha Heaven

A. Vertical Face showing tremendous intensity of *O. borneensis* burrows.

B. Distance view of outcrop darked by the extreme abundance of both in situ and weathering out burrows.

C. Vertical face showing complexly interwoven three-dimensional 'boxworks' within ammalgamated storm sands.

D, E. Isolated calcite cemented pods showing vestiges of Hummocky Cross-Stratification.



LOWER SHORE FACE AT OPHIOMORPHA HEAVEN

DISCUSSION AND INTERPRETATION OF THE LOWER ZONE SEQUENCE AS OCCURRING IN THE NORTHWEST

Sedimentological Aspects

Many of the shoreline sandstones characterizing regressive hemicycles from the Cretaceous of the Western Interior evidently formed along shorelines subject to major storm disturbances. In virtually all cases, this has been inferred from the lower shoreface-through -offshore depositional record in which relatively thick beds of clean, 'storm' stratified sand, occur either in amalgamation (as is the case here), or superimposed on a background gradient of deposits reflecting fair and minor storm weather conditions.

The sharp-based beds of clean laminated sand dominating the Lower Zone throughout the southwest, strongly resemble storm beds documented from both modern (c.f. Kumar and Sanders, 1976; Howard and Reineck, 1981; Aigner and Reineck, 1982) and ancient lower shoreface deposits (cf. Campbell, 1971 Balsley, 1981; Leckie and Walker, 1982; Howard and Frey, 1984). During intense storms (e.g. tropical hurricanes and mid-latitude winter wave cyclones) shallow marine depositional environments are subject to extreme modification (Reinson, 1984; Duke, 1985; Aigner, 1985). Although depositional processes operative during storms can be highly variable and are not as yet well understood (Niedoroda et al., 1984; Walker, 1984), the general process occurring on the lower shoreface can be summarized as follows: high-energy storm waves will impinge on the seabed, and, if of sufficient magnitude, will scour into and resuspend surficial sediments. At the same time, suspended sand eroded from higher up the beach face may undergo a net seaward transport onto the lower shoreface (Kumar and Sanders, 1976; Bourgeois, 1980; Field and Roy, 1983; Dupre, 1984; Neidoroda et al., 1984). As the storm subsides, suspended sand is then redeposited as a seaward thinning layer of laminated sand. Correspondingly, if the thickness of fair and minor storm weather accumulations between successive major storms is repeatedly less than the depth of bottom scour accompanying these events, amalgamation will result .

A storm interpretation is further supported by the occurrence of hummocky and/or swaley cross-stratification. Although the precise mechanism by which HCS and SCS form is still somewhat conjectural (see Duke, 1985; and Allen and Pound, 1985 for discussions), it is generally agreed that oscillating storm wave action is in whole or in part requisite to their development.

Ichnological Aspects

Ecological Effects of Storm Deposition. In order to better understand the overall assemblage of trace fossils characterizing the lower shoreface storm bed successions at Sundance Coulee and Ophiomorpha Heaven, it is necessary to first consider certain ecological ramafications known to accompany major storm disturbance. During and immediately following a large-scale storm, the lower shoreface benthic environment is drammatically transformed. The sudden impingement of erosive stormwaves on the seabed, followed rapidly thereafter by the deposition of a thick sand layer, would generate levels of physiological stress capable of devastating even the most resilient of infaunal populations. Thus, with the fairweather equilibrium community temporarily abated or displaced, the ensueing post-storm environment becomes wide open for benthic re-colonization. In the present succession, the widespread occurrence of *O. borneensis*, along with the localized occurrence of *C. conicus, S. linearis, Ichnogen.nov.A , Rhizocorallium sp., Rosselia socialis* and *Macaronichnus simplicatus* , as substantiated by various lines of field evidence, are all interpreted as representing the dynamic response of different infaunal species involved in the post-storm re-colonization process.

Opportunistic Tracemakers. Following the criteria as outlined originally in Levinton (1970) and Pianka (1970), and later extended to ichnology by Pemberton (1979), Miller and Johnson (1981), Pemberton and Frey (1984) and Ekdale (1986), both *Ophiomorpha* *borneensis* and *Skolithos linearis* show all the characteristics marking the post-storm recolonizational invasion of opportunistic species[1]. On a related theme, and for reasons to be discussed elsewhere, the locally associated feeding structures *Rhizocorallium sp.* and *Ichnogen.nov.A* may well represent the opportunistic feeding response (cf. Cadee, 1984) of the *O. borneensis* tracemaker, reflecting a switch in trophic behavior from predominantly filter feeding to surface and subsurface deposit feeding, perhaps in response to changing post-storm conditons (see later discussion).

Significance of Conichnus conicus. These conical burrows evidently represent the resting-dwelling trace of anemone or anemone-like organisms (see additional discussion in Systematics). The overall size of the burrow cavity provides a rough approximation of the size of the trace-producing organism and, as such, in all cases appears to indicate the involvement of extraordinarily large adult organisms (Figure 5H). This, combined with the fact that rarely do smaller burrow size gradations occur (i.e. possibly indicating juvenile co-habitation) and the lack of evidence such as laminary wall-linings, vertical retrusions, or ontogenic burrow re-adjustments which would suggest long-term inhabitance, indicates that the *C. conicus* tracemaking populations were probably not initiated by means of larval recruitment. Instead, a more plausible explanation can be found in the modern studies of Dobbs and Vazarik (1983) and Santos and Simon (1980) concerning the effect of storms on infaunal redistribution. These studies show that during periods of large scale storm disturbance, entrained adult infaunal organisms, even large species, are often capable of surviving wide scale storm re-distribution. Accordingly, *C. conicus* may well represent

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[1] the term "opportunist" is applied to certain species of organisms, plant or animal, that have evolved life-history characteristics such as rapid dispersal, high reproductive rates, broad environmental tolerances, and generalized feeding habits that enable them to quickly locate and briefly exploit a new habitat following a physical disturbance such as a storm. As condtions following the disturbance revert to normal, the opportunists will ultimately be displaced by succeeding colonists of the resident equilibrium community (McCall, 1976; Thistle, 1981, Pemberton and Frey, 1984).

post-storm re-settlement of adult organisms entrained within a nearby environment and subsequently transported by storm-driven currents onto the lower shoreface.

SIGNIFICANCE OF SIDERITIC CEMENTATION AT SUNDANCE COULEE

Sideritic Bedtops. The sedimentologic disposition of sideritic layers at Sundance Coulee (i.e. along the very tops of storm beds and often beneath major storm erosion surfaces), suggests that incipient cementation may have been initiated at a very shallow depth of post-depositional burial, and in turn played a major role in delimiting the depth of subsequent major storm scour.

Much has been learned in recent decades concerning the diagenetic conditions under which sideritic layers form in marine environments (for recent discussions see Berner, 1981; Gautier and Claypool, 1986). Virtually all research has been directed towards the study of muddy offshore-type sediments, so the precise mechanisms leading to the formation of sideritic layers in the present succession, remain the subject of much speculation. Figure 9 is an attempt to summarize empirically the inferred role played by early cementation processes during the depositional history of Unit 1, and, how the comparative absence of bed top sideritic developments at "Ophiomorpha Heaven" might partially account for some of the observed ichnological differences.

Diplocraterion at the T3.-Appaloosa Contact.-- Occurring within bed X at the base of the sequence at Sundance Coulee (see Figure 4), is one of the more intriguing ichnofossil occurrences recorded anywhere from within this part of the succession. Here, on the line of section, a vertical face of this resistantly cemented sand bed reveals a monospecific association comprising superbly preserved specimens of *Diplocraterion parallelum* (Text-Figure 5G; plate 1, Figs. 1 - 8). Along this face, complete cross-sections of the burrows can be seen, all of which appear to subtend from a common sedimentological interface corresponding with the top

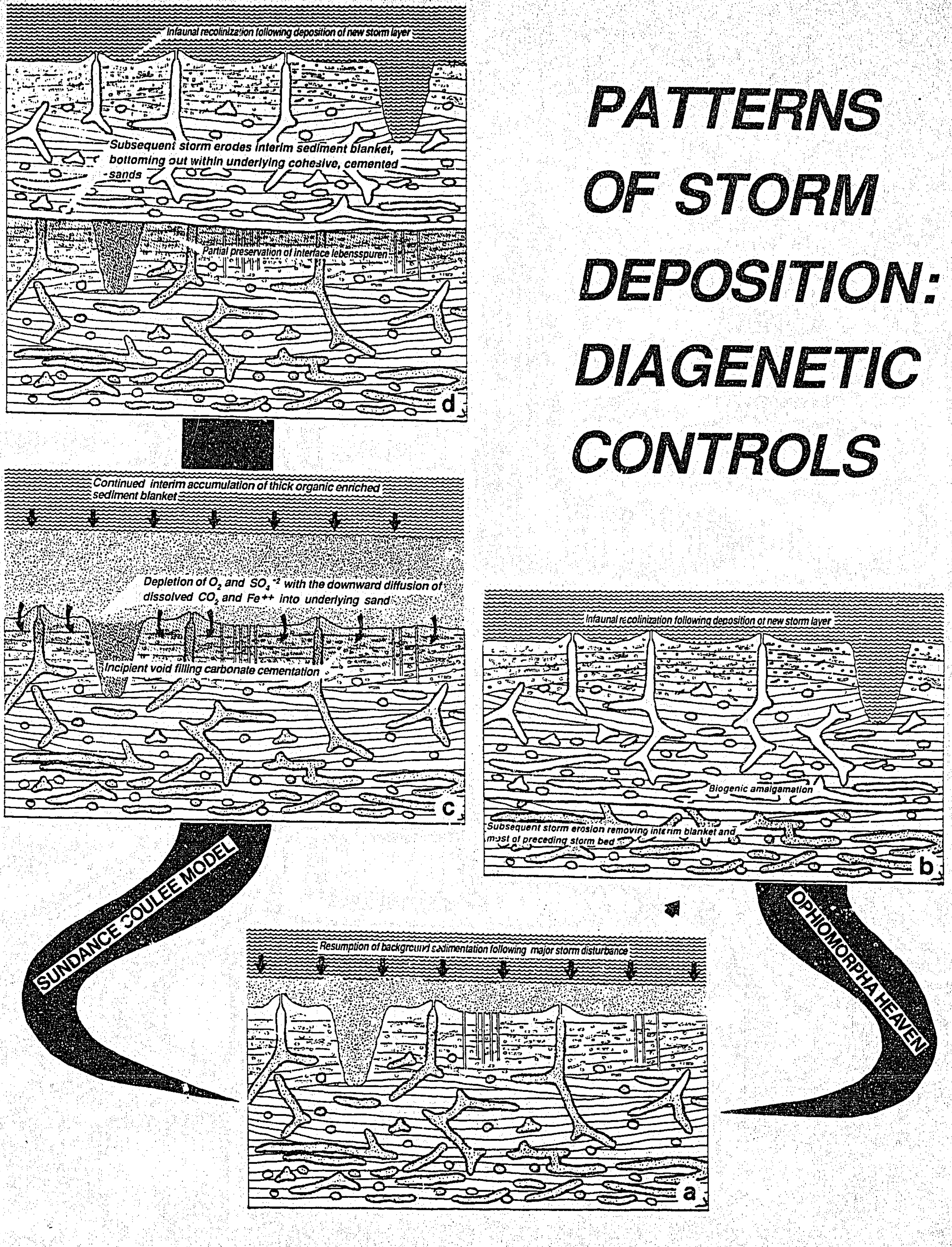
FIGURE 9

Hypothetical model relating presence/absence of lower shoreface storm-top sideritic layers to (1) the relative frequency of major storm events and (2) the thickness and physiochemical character of the interim post-storm sediment blanket.

Sundance Coulee Model: Pathway A>C>D suggests a possible mechanism for the formation of sideritic layers as characterizing the lowermost lower-shoreface succession at Sundance Coulee. Here major storm events are thought to have been separated by prolonged periods of fairweather quiescence leading to the accummulation of thick, organic-rich interim blankets. Development of anoxic-nonsulfidic conditions at depth within such a sediment pile, presumably would have then resulted in the downward diffusion of reduced ions (Fe and CO_2) and incipient sideritic cementation within the porous underlying storm layer (c). Internal cohesion resulting therein, would then have played an important role during the following storm event, acting as a 'barrier' to wave erosion (d). In this way, shallowly tiered, interface related lebensspuren such as *M. simplicatus*, *C. conicus* and *S. linearis* would stand a much greater chance of being preserved.

Ophiomorpha Heaven: Pathway A>B then shows the alternative situation as exemplified by the lower shoreface sequence at Ophiomorpha Heaven. Here, successive storm events are inferred to have occurred on a much more frequent bases, prior to the inception of interim conditions as indicated in figure C. Thus, in the absence of any inhibiting diagenetic factors, storm wave erosion could then have proceeded in a more unconstrained fashion, removing not only the interim blanket but also most of the underlying storm bed (b). In this way, one can account for the seeming proliferation of *O. borneensis* and the absence of all other lebensspuren, as only the most deeply tiered traces would have been apt to be preserved.

PATTERNS OF STORM DEPOSITION: DIAGENETIC CONTROLS



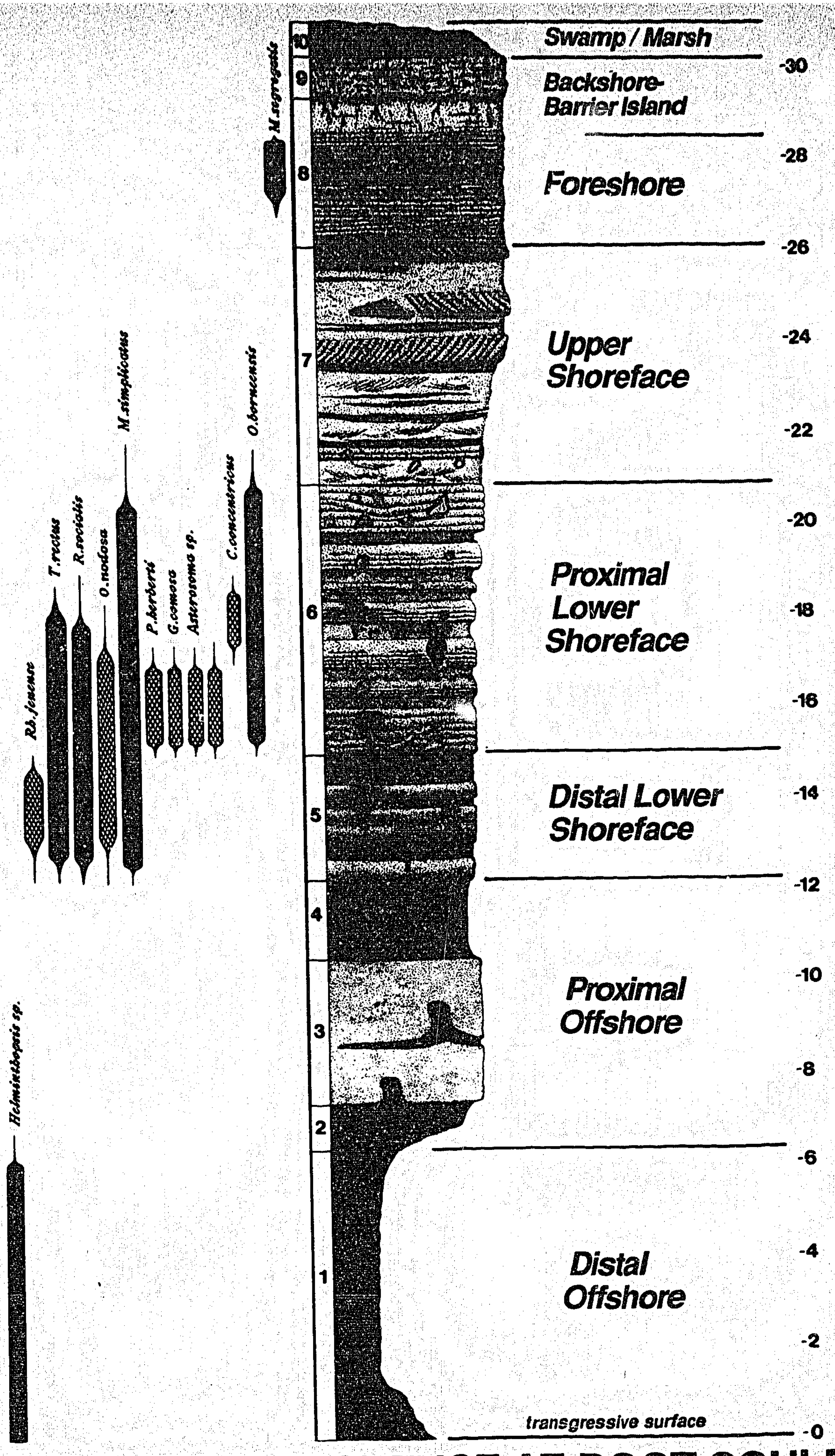
of bed X.

Superficially, the mass occurrence of *D.parallelum* , the dwelling burrow of a suspension feeding crustacean (see later discussion) might appear to be characteristic, if not exemplary of the *Skolithos* ichnofacies, thus evidencing an environment characterized by loosely shifting sandy substrates with relatively high levels of wave and/or current energy (cf. Seilacher, 1967; Frey and Pemberton, 1984). Instead, however, it is here evident that at the time of burrowing the substrate, was not loose or shifting, but frozen in a semi-lithified or *firm-ground* state, i.e., the requisite conditions for the *Glossifungites* ichnofacies (cf. Pemberton and Frey, 1985). This is directly inferred from several aspects of the burrow morphology: (1) the absence of any form of burrow wall re-enforcement needed to maintain an open dwelling within an unconsolidated sandy substrate--burrow walls instead being unlined and sharp; and (2) the presence of delicate claw markings locally preserved on the external surface of the burrows (see Plate 1).

In argillaceous sediments, internal cohesion results primarily from dewatering and compaction (Pemberton and Frey, 1985). Bed-X, on the contrary, is composed of clean arenaceous sediment, hence, an alternate explanation must be sought. Based on preliminary observations of the diagenetic characteristics of the sand (bed X being cemented by a microcrystalline mosaic of calcite and siderite) I suggest a mechanism, as in the case of the previously mentioned sideritic layers, whereby internal cohesion of the sand had developed through incipient void filling carbonate cementation. Again, the presence of siderite, however, makes it highly improbable that cementation occurred directly at the sediment-water interface (Berner, 1981; Gautier and Claypool, 1985). It is therefore quite likely that firm-ground conditions within bed X had developed through a major cycle of burial and erosion. Subsequent to exhumation, the "firm ground" stratum was then colonized by an opportunistic crustacean fauna, evidently well adapted to life within semi-lithified substrates. Elsewhere within the study area, similar developments of the *Glossifungites* ichnofacies, characterized by profusions of scratch-marked *Diplocraterion parallelum* , occur within inferred back-barrier mudstones and coals that directly underlie major transgressive surfaces (see Figure 2).

FIGURE 10

Vertical Sequence characterizing the Appaloosa Cycle at Boot Coulee in the extreme southeastern corner of the study area. The LOWER APPALOOSA ZONE as referenced in text corresponds to Units 1-6, the MIDDLE ZONE to Unit 7, and the UPPER ZONE to Units 8-10. Ichnofossil distributions shown in black denote *characteristic lebensspuren* (sensu Dorjes and Hertweck, 1975) whereas those in white refer to *associated* or more sporadically encountered forms.



APPALOOSA SEQUENCE AT BOOT COULEE

B. LOWER ZONE SEQUENCE IN THE SOUTHEAST SECTOR

Tracing the Lower Zone seaward across the depositional slope from Sundance Coulee towards Boot Coulee in the extreme southeastern corner of the study area (Figure 2), a number of characteristic sequential stratigraphic changes can be observed to occur. The first, involves the gradual development at the base of the lower shoreface sequence of a seaward thickening wedge of transitional-through-offshore sediment: again, a direct corollary to the increasing paleowater depths as encountered towards the southeast during the early stages of Appaloosa progradation. The second key change occurs within the lower shoreface sequence itself and involves: (1) the progressive decrease in "major" storm event frequency (the thick HCS/SCS storm beds dominating the sequence in the northwest now becoming much more sporadic in distribution); and (2) the associated emergence, between major storm beds, of the interim lower shoreface depositional record.

LOWER SHOREFACE SEQUENCE AT BOOT COULEE

(Units 5 and 6 in Figure10)

A summary stratigraphic column for the entire Lower Zone at Boot Coulee is shown in Figure 10. Here, the *lower shoreface* sequence can readily be divided into 2 units (Units 5 and 6); a discussion of the sedimentologic and ichnologic characteristics of these units follows.

Unit 5: DISTAL LOWER SHOREFACE DEPOSITS (Figure 11)

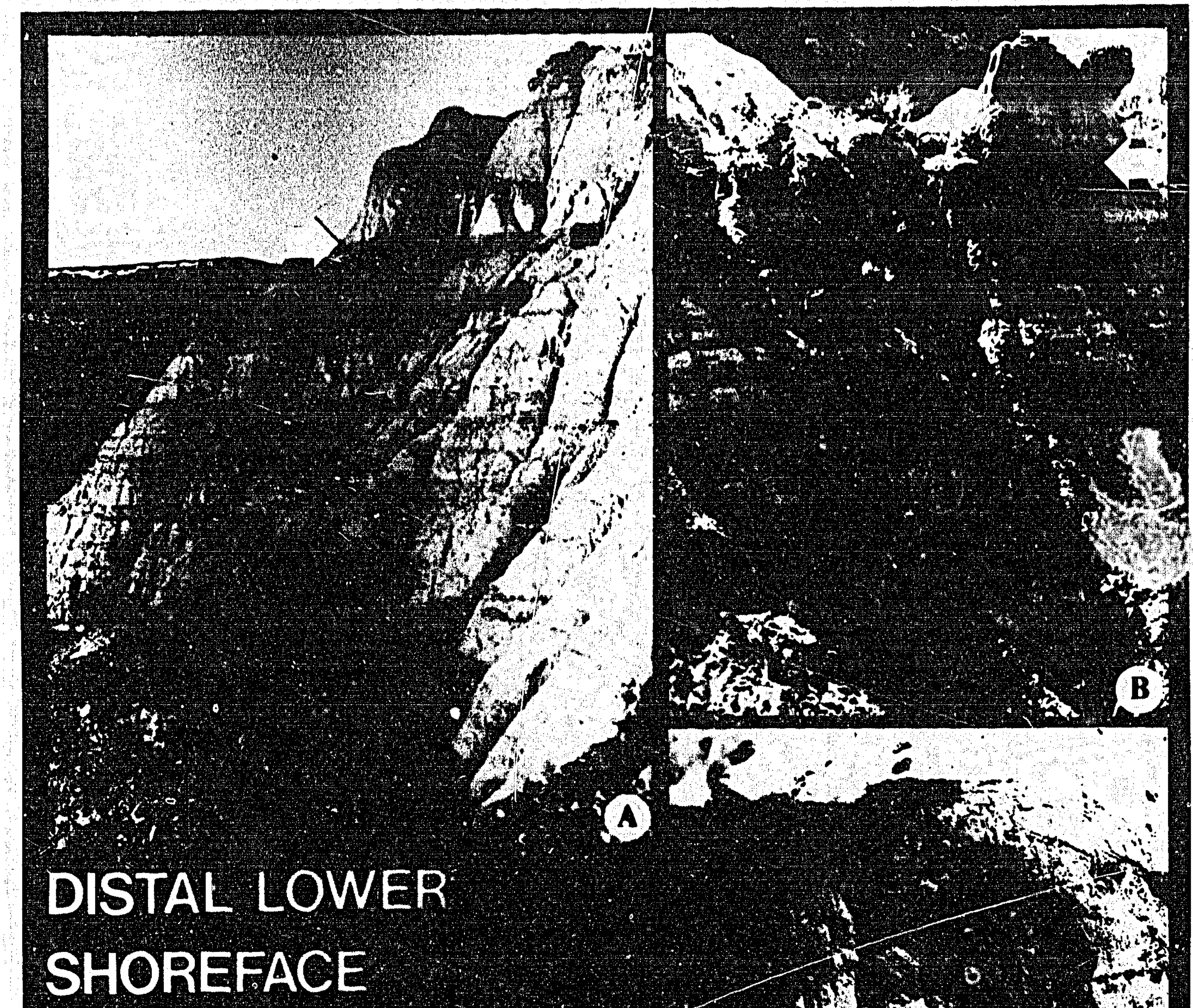
The lowermost facies of the lower shoreface sequence comprises a build-up of friable, intensely weathered, predominantly fine-grained sandstone. A salient feature on the weathered outcrop surface is the facies generally "ratty" and irregular but markedly heterolithic character (Figure 11). Variably thick beds of buff colored, clean, laminated-to burrowed sandstone of

FIGURE 11

Distal Lower Shoreface Deposits at Boot Coulee

A,B. Photograph showing characteristic interbedding of chaotic, dirty appearing background sands (*facies Bd*) and cleaner light colored sand beds of inferred minor storm origin (*facies Sd*). Note double *Rosselia* to right of hammer in figure B. Black arrow denotes unit 5-6 contact.

C. *Rosselia socialis*, Dalmer, 1937. Close up of specimens from Unit 5. Note preserved basal stock in specimen at left (white arrow).



DISTAL LOWER SHOREFACE AT BOOT COULEE

inferred "minor" storm origin (*facies Sd*) occur, intercalated with background deposits of highly impure, chaotically bedded sandstone (*facies Bd*).

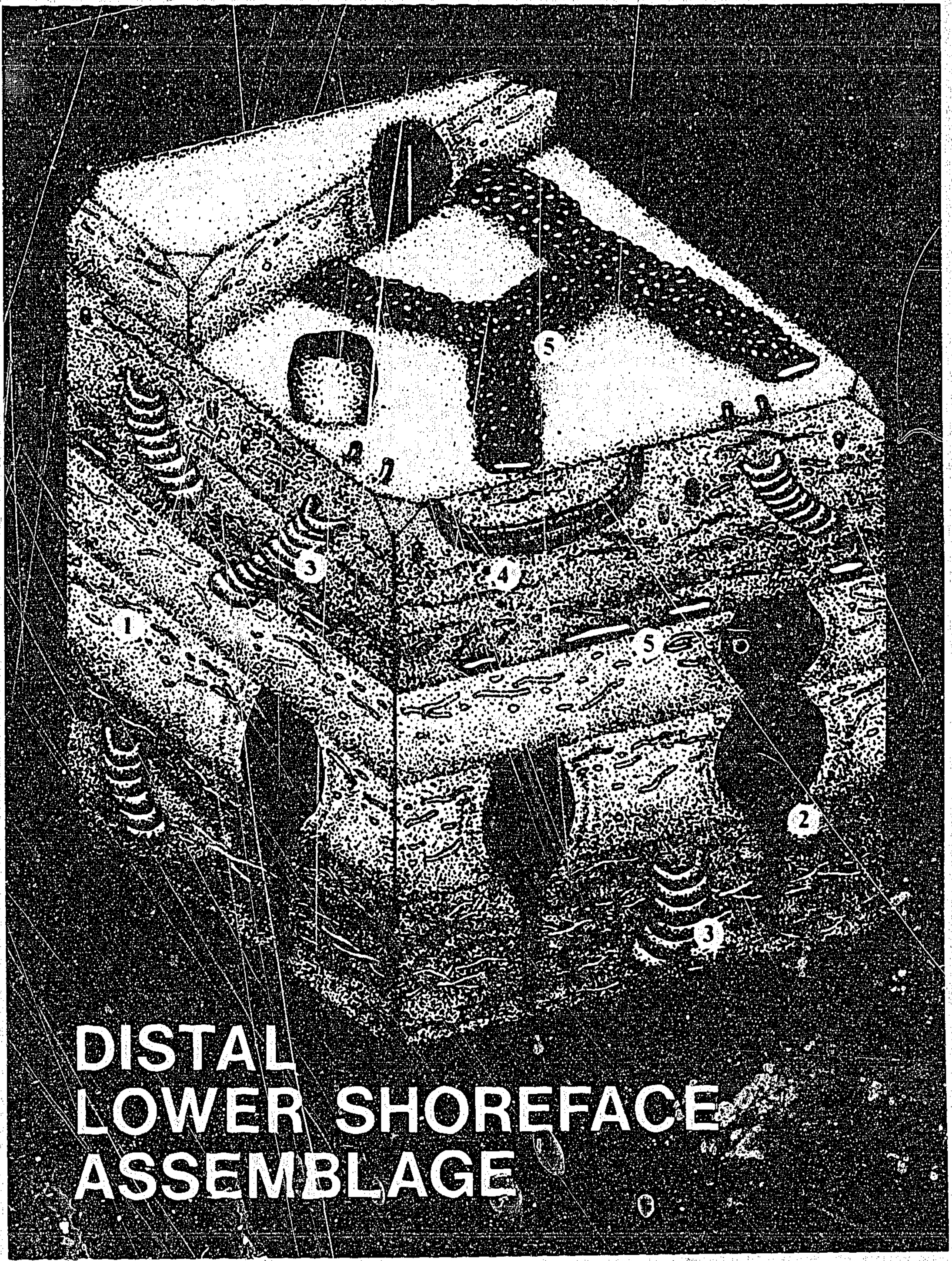
Scraping off the structureless weathered crust of the background sands (*facies Bd*) reveals their "chaotic" appearance to be the product of moderate to pervasive biogenic reworking: in most places the primary structure of sand has been completely obliterated, giving rise to a relatively non-descript admixture of silty fine-grained sandstone and carbonaceous matter. Locally, however, where the degree of bioturbation is less intense, vestiges of primary stratification reveal an irregular stacking of discrete, 1 to 10 centimeter thick, moderately clean sand layers. Interspersed with, and comformingly draping the individual sand layers, are wispy, laminary accumulations of silty sand and carbonitized organics, commonly showing a subtle downward convexity suggesting preferential preservation in topographic lows.

The overall sedimentologic and ichnologic characteristics of Unit 5 are summarized diagrammatically in Figure 12. In the lower half of the unit the locomotary-feeding trace *Macaronichnus simplicatus* constitutes by far the dominant biogenic structure and in many instances appears solely responsible for the 'pervasive' bioturbation mentioned earlier. Within the background deposits (*facies Bd*), dense profusions of *M. simplicatus* pervade the less impure sand layers and, within the upper half of the unit, *M. simplicatus* is joined, and rivalled as the dominant ichnofossil constituent, by the dwelling structure *Teichichnus rectus*. Associated lebensspuren within the background deposits include the dwelling structures *Rhizocorallium jenense* and *Ophiomorpha nodosa*, and the dwelling-feeding structure *Rosselia socialis*. Both *O. nodosa* and *R. jenense* increase in overall abundance upward through the unit.

Within the storm sands (*facies Sd*), *M. simplicatus* again constitutes the dominant lebensspuren, being concentrated toward the tops of thicker beds, while completely pervading beds less than 15 centimeters in thickness. Locally within storm sands, *M. simplicatus* is joined by *Rosselia socialis*; apart from this, no other lebensspuren were observed to occur,

FIGURE 12

Composite block diagram depicting the overall assemblage of distal lowershoreface lebensspuren, including: (1) *Macronichnus simplicatus*, (2) *Rosselia socialis*, (3)*Rhizocorallium jenense*, (4) *Teichichnus rectus*, and (5) *Ophiomorpha nodosa*,



DISTAL LOWER SHOREFACE ASSEMBLAGE

and conspicuously absent from the entire unit is *Ophiomorpha borneensis* .

INTERPRETATION OF DISTAL LOWER SHOREFACE FACIES

In viewing (1) the units overall sedimentologic character, (2) the contained assemblage of relatively diverse and ethologically varied lebensspuren, (3) the pervasive nature of biogenic reworking, and (4) the nature of both overlying and underlying facies, it can be inferred that deposition occurred in a *distal lower shoreface environment* situated below, but in relatively close proximity to, mean fair-weather wave base. Across most modern beach-offshore profiles, it is typically here that infaunal species diversities and individual animal abundances begin to culminate, as sedimentation rates and wave action are low (yet bottom waters are maintained fully oxygenated), and a diversity of food-resource axes exist (Dorjes and Hertweck, 1975). Correspondingly, it is here also that intense biogenic reworking first appears as intermittent periods of prolonged fairweather quiescence allow infaunal organisms colonizing this intermediately stable environment sufficient time in which to rework the substrate (Aigner and Reineck, 1982; Howard, 1975; Howard and Reineck, 1972).

Microdynamics of the Environment. Throughout the depositional history of Unit 4, periods of prolonged quiescence had repeatedly occurred in a below wave-base environment. This is indicated by the presence of silty carbonaceous laminary drapes, the pervasive nature of biogenic reworking, the thick development of individual feeding cones in *Rosselia socialis* and the flat-bottomed horizontal attitude of the dwelling structure *T. rectus* . The thin irregular beds of clean sand comprising the bulk of *facies Bd*, however, instead appear to reflect periods of higher than normal wave conditions, during which times increments of sand entrained higher up the beach face were swept out onto the distal lower shoreface. Ichnological corollaries to this, include (1) the distinctive step-like spreiten retrusions of *Rhizocorallium jenense* (Plate x), reflecting the dynamic response of the tracemaker to the incrementally aggrading substrate, and (2) the pervasive distribution of *M. simplicatus* (see later discussion). Finally as already alluded to, the clean laminated-to-burrowed *Sd* beds, as their relative thickness and stratigraphic disposition would appear to infer, represent periods of somewhat less frequent but clearly more intense storm disturbance. Although the exact ecological impact these higher energy disturbances might have had on the benthic community has not as yet been fully determined, it is, however, relatively safe to assume that the level of severity was still far less than that accompanying the more "major" storm events as discussed earlier. This assumption is based on the fact that specimens of *Rosselia socialis*, where occurring within amalgamated successions of two or more storm beds, often become manifest in vertically stacked feeding cone successions, in which the tops of individual feeding cones coincide with the preserved tops of successive storm layers. This would appear to indicate that the tracemaker was able to escape the initial adversities of the storm by retracting deep within its burrow. Then, following storm cessation and deposition of an increment of sand, the organism re-equilibriated its burrow with the new sediment-water interface. A point worth noting, is that emplacement of the entire storm succession with which the *R. socialis* tracemaker has re-adjusted must have occurred during the life span of a single organism. Thus a scale of "absolute" storm frequency can, in such cases, be reconstructed from the ichnological record.

Unit 6: PROXIMAL FACIES (Figure 13)

Within the underlying distal facies, a very distinctive depositional pattern was established involving the superimposition of clean laminated-burrowed storm layers (*facies Sd*) on a background gradient of deposits instead reflecting the prevailing interim conditions (*facies Bd*). This same pattern of contrasting lithic style and hydrodynamic regime persists upward through Unit 6. Here, however, a number of characteristic sequential changes occur in both the storm and background facies: changes evidently reflecting the upward shoaling into a

FIGURE 13

Proximal Lower Shoreface Sequence at Boot Coulee

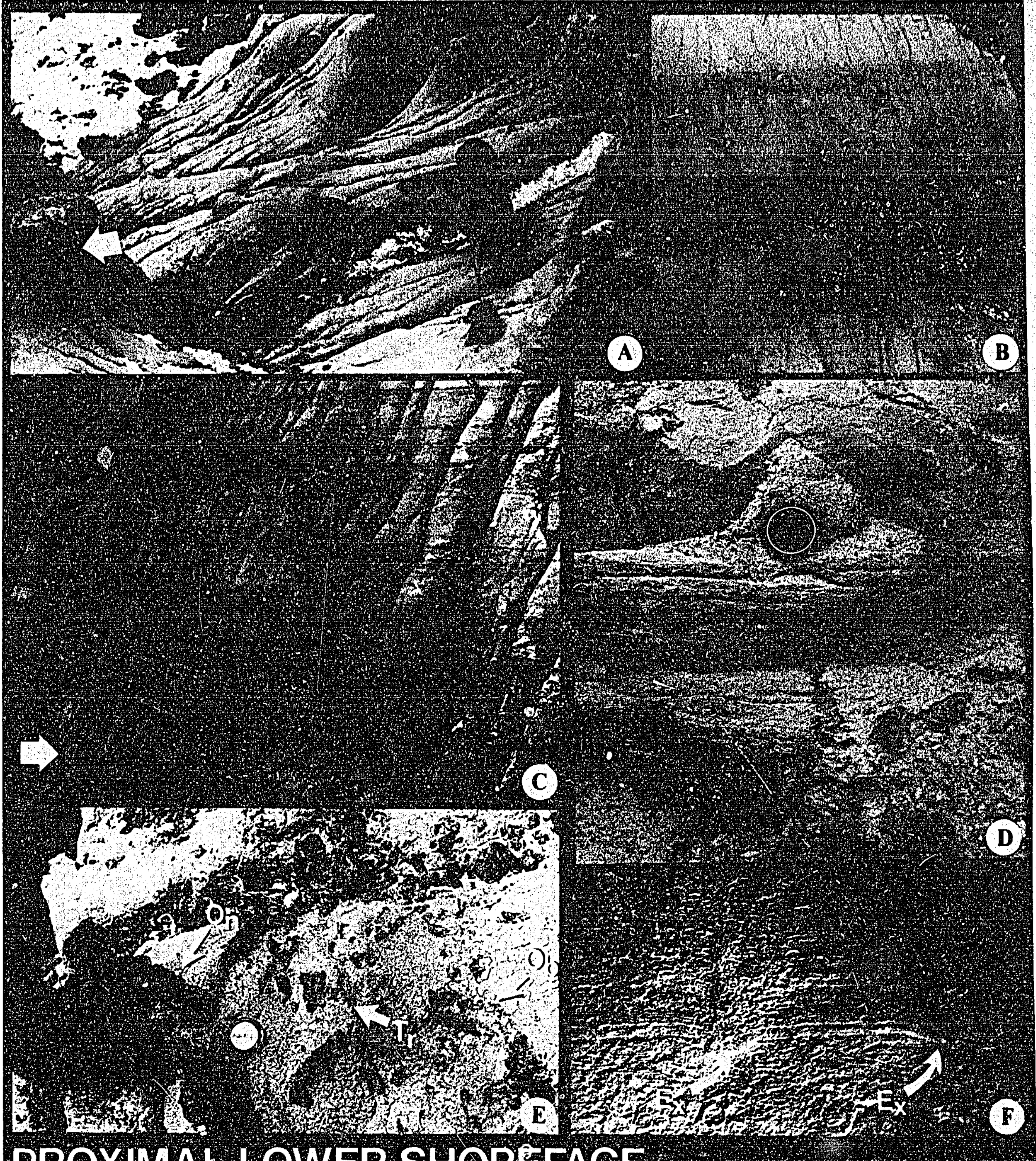
A. Plan view showing sporadically distributed, sideritized specimens of Ichnogen. nov. (A) (large white arrow, as well as off person's left hand), *Asterosoma* sp. (off person's right hand), and *Ophiomorpha borneensis* (small black arrows).

B, C. Vertical faces showing characteristic interbedding of clean, lighter colored storm sands (*facies Sp*) and darker colored bioturbated background beds (*facies Bp*). Black arrows denote preserved Sp bed top wave-ripple topography, draped in swales by carbonaceous laminae. White arrow indicates Unit 5-6 contact.

D. *Ophiomorpha borneensis* Kiej, 1965. Vertical face of calcite cemented bed displaying burrow systems in cross-section as they might be expected to appear in core.

E. Plan view of a background bed (*facies Bp*) containing *O. nodosa* (On), *O. borneensis* (Ob) and *T. rectus* (Tr). Profusions of *M. simplicatus* are also present but unfortunately can not be discerned in photograph.

F. Vertical face occurring towards top of the proximal lower shoreface succession displaying laminated-to-rippled bedding. Note vertical escape structures (Ex) leading up from ripple laminated background sands into the overlying erosively based, horizontally laminated storm bed.



PROXIMAL LOWER SHOREFACE
AT BOOT COULEE

landward adjacent shoreface environment.

Facies Bp: Proximal Background Sands. Background facies of Unit 6 consist dominantly of poorly cemented fine-grained sandstone. On the weathered outcrop they are readily distinguished from their underlying distal equivalents (*facies Bd*) by (1) having a more regular, flat-lying attitude, and (2) having an overall lighter coloration. The latter factor evidently reflects the marked upward decrease in impurities (ie., silt and carbonaceous matter), a trend traceable to the very top of the unit.

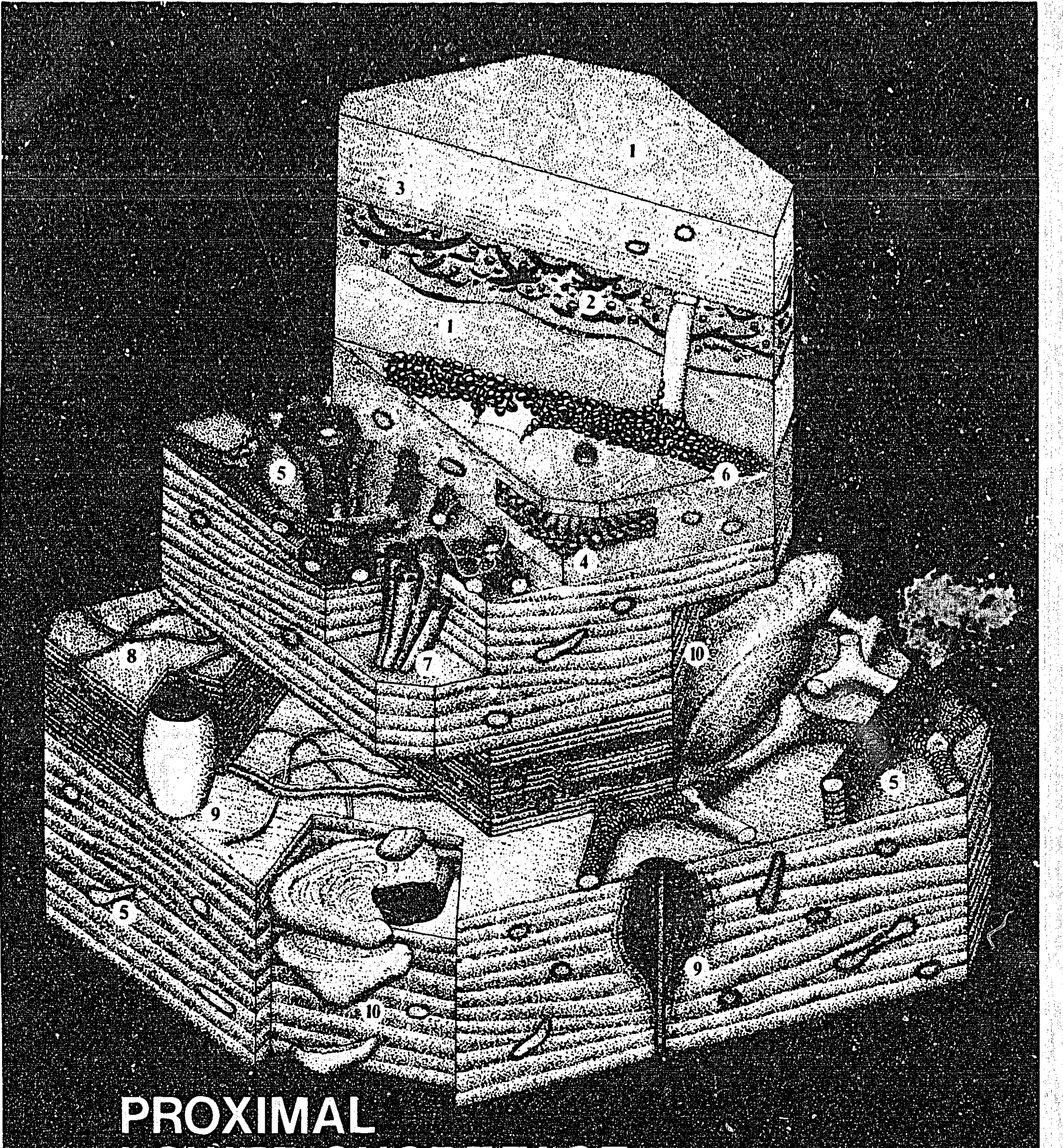
On the whole, the degree of biogenic reworking within the *Bp* beds is somewhat variable. Most beds have been thoroughly reworked; the distinctive bioturbate textures imparted by *Teichichnus rectus* and *Macaronichnus simplicatus* persisting upward from Unit 5. Locally, however, particularly towards the top of the unit, physical sedimentary structures (wave ripple-lamination) can be seen to partially or completely overwhelm the biogenic ones (Figure 13F).

Facies Sp: Proximal Storm Beds . Storm sands of Unit 6, as in Unit 5, comprise clean, buff colored fine-grained sandstone. Here, however, their overall greater thickness, decidedly flat bases and tremendous lateral continuity (many beds being tracable over great distances) readily distnguishes them from their underlying counterparts. Internally, *Sd* beds again display classic laminated-to-burrowed sequence, with well developed planar horizontal lamination (and/or HCS in the thicker beds) giving way to profusions of *M. simplicatus* toward the top of each bed. Locally, vestiges of wave-ripple lamination can be discerned at the top of beds, and several beds occur in which the actual wave-rippled bed top topography has been preserved (Figure 13C). Overall bed thickness increases upward through the unit from an average of 25 centimeters near the bottom to 40 centimeters towards the top, although considerable variation occurs throughout.

Trace Fossil Distributions . In addition to the pervasive occurrence of *M. simplicatus* and *T. rectus* as already discussed, Unit 6 plays host to a wide diversity of other lebensspuren,

FIGURE 14

Composite block diagram depicting the overall assemblage of ichnofossils as characterizing proximal lowershoreface sands at Boot Coulee. Forms shown include: (1) *Macaronichnus simplicatus*, (2) *Teichichnus rectus*, (3) *Palaeophycus herberti*, (4) *Asterosoma sp*, (5) *Ophimorpha borneensis*, (6) *Ohiomorpha nodosa*, (7) *Cylindrichnus concentricus*, (8) *Gyrocorte comosa*, (9) *Rosselia socialis*, and (10) *Ichnogen. nov. C*.



PROXIMAL LOWER SHOREFACE ASSEMBLAGE

including: (1) the dwelling structures *Ophiomorpha borneensis, Ophiomorpha nodosa, Palaeophycus herberti* and *Cylindrichnus concentricus;* (2) the dwelling-feeding structures *Rosselia socialis* , *Asterosoma sp.*, and *Ichnogen. nov. C.*; and (3) the locomotary-feeding structure *Gyrocorte comosa* . The block diagram in Figure 14 summarizes the overall assemblage: actual vertical distributions, however, are perhaps better inferred with reference to Figure 10.

Ophiomorpha borneensis occurs sporadically throughout the unit, reaching its greatest density toward the top of the unit, as well as in association with the thicker storm sands lower down. Both *Ophiomorpha nodosa* and *Rosselia socialis* persist from Unit 4 into the lower half of Unit 5. Along several discrete horizons, one of which is laterally traceable thoughout most of the coulee, tunnel profusions of *O. nodosa* can be observed subtending from isolated vertical shafts. *Gyrocorte comosa, Palaeophycus herberti* and *Asterosoma sp.* are all very localized in occurrence and are confined to the lower half of the unit, whereas *Cylindrichnus concentricus* tends to occur somewhat higher up within the middle portion of the unit. Finally, vertical escape structures (fugichnia) were also frequently encountered throughout the unit and, although not assignable to any particular ichnotaxon, constitute an environmentally significant biogenic structure (Figure 13F).

DISCUSSION AND INTERPRETATION OF PROXIMAL LOWER SHOREFACE FACIES

Sedimentological Aspects

Clues as to the relative bathymetric position of the proximal lower shoreface (Unit 6) are perhaps best inferred with reference to the background depositional gradient (i.e. *facies Bp*). Here, in continuation from the underlying *Bd* beds, the most notable vertical changes involve: (1) the overall upward decrease in the degree of biogenic reworking (i.e. as largely imparted by *Macaronichnus simplicatus* and *Teichichnus rectus*); (2) the concurrent preservation of physical structures (i.e.wave ripple-lamination); and (3) the overall upward cleaning and subtle coarsening of the sand.

Numerous authors (Howard, 1972; Howard and Reineck, 1972; 1981; Dörjes and Hertweck, 1975; Clifton et al, 1971; Kumar and Sanders, 1976; Ainger and Reineck, 1982; Shipp, 1984; Howard and Frey, 1984) have emphasized the importance in detailed beach-offshore facies analysis, of documenting sequential changes in the relative balance between physical and biogenic processes. Here, observed changes in the physical-biogenic balance serve to define a distinct energy-depth gradient. As reflected in the lower parts of Unit 6, as well as within the underlying *Bd* beds of Unit 5, this gradient can be inferred to have extended seaward well **below** modal day-to-day wave base into an environment where endobenthic animal abundances and overall rates of biogenic reworking were high while rates of deposition and physical reworking were comparatively low. As reflected in transition into the more proximal parts of Unit 6, however, the gradient can also be inferred to have extended landward **above** modal wave base into the outermost zone of fairweather wave-build-up. Here, the physical effects of wave surge, although still relatively weak, were sufficient to partially or completely subordinate biogenic processes leaving a record, at least locally, dominated by wave ripple lamination; local variations, including anomolies of both preserved wave-ripple lamination lower in the unit and profusely burrowed horizons higher up, undoubtably reflect dynamic changes in wave climate and hence the relative position of wave base.

Storm Bed Proximality. The overall upward increase in the thickness of inferred storm layers (*facies Sp*) provides an additional line of evidence favoring "shoaling-upward" conditions, reflecting the intensification of storm depositional processes with increasing proximality to the coastline (Aigner, 1985). Following Aigner (1985), the thickness versus stratigraphic position of storm beds can, in a general sense, be taken as a reflective measure of storm strength/duration. For example, a thick HCS sand bed occurring lower down the sequence will reflect a storm event of relatively greater intensity than will a bed with comparable thickness and internal characteristic, but occurring higher up in the sequence. Similarly, *in loco* variations in the thickness of successive storm layers can be taken to reflect dynamic variations in the depositional intensity of successive events.

Ichnological Aspects

In concert with changes in the "physical-biogenic balance" (see earlier discussion), sequential changes occurring in the overall stucture and characterization of trace fossil associations (with specific reference to both syn- and autecologic relations) serve to even further define the lower shoreface gradient. Here, a characteristic gradation of energy-depth related, dynamically interacting biological zones can be discerned (Figure 10).

The Rosselia-Teichnichnus zone.--The most conspicuous ichnological zone of the lower shore face sequence is one defined by the vertical distribution of *Rosselia socialis* and *Teichichnus rectus* . By reconstructing the autecology of the tracemakers, it can be inferred that gradients in physical energy (i.e. increasing wave surge and substrate mobility) played a dominant role in delimiting the upper limit of this zone. The *R. socialis* tracemaker, for example, was evidently preadapted to exploit a surface-deposited food resource. Its landward extent was therefore probably conditioned by the inception of surge regimes too high to have allowed for the preferential settlement of the requisite foodstuffs.

Ophiomorpha borneensis. In an earlier discussion, it was argued that the *Ophiomorpha borneensis* tracemaker may have been an opportunistic species and that its prolific occurrence throughout the northwestern successions was in direct response to the repeated depositional disturbance of the sea bed to extended depths down the paleoslope [i.e. at Sundance Coulee the burrows persist to the very base of the sequence which, using stratigraphic position as a surrogate for paleowater depth (cf. Klein, 1974), can be inferred to have extended to depths in excess of 20 meters].

Toward the southeast, however, where the overall incidence of major storm events was evidently much lower, the vertical distribution of *O. borneensis* changes accordingly. Here, the burrows are confined to a distinct zone extending downward from the distal upper shoreface, terminating abruptly at the proximal-distal lower shoreface boundary (inferred paleodepths here being somewhere in the order of 10 meters). Thus, it would appear that below this point, and in the absence of major storm deposition, interim physiochemical conditions lay outside the tolerance limits of the tracemaker. Alternatively, although somewhat more difficult to assess, competitive/preditorial interactions with the resident community may also have contributed to its exclusion.

That the *O. borneensis* tracemaker was an "opportunist" is corroborated by the fact that, towards the base of its zonal distribution, the trace occurs intimately associated with the feeding structure *Ichnogen. nov.C.* Field relations suggest that both lebensspuren were formed by the same organism which, based on faecal pellet analysis, has been tentatively identified as a species of the extant *Thalassinid* shrimp genus *Palaxius* (see later discussion). Taghon *et al* (1980) and Cadee (1984) noted that organisms inhabiting benthic environments subject to dynamic changes in wave/current energy commonly exhibit opportunistic traits. One of the more common of these involves the ability to switch their feeding behavior from a mode of dominantly filter-feeding to one of dominantly deposit feeding, in response to temporally changing energy levels and concurrent changes in suspended versus deposited food availability. Here, the associated occurrence of *Ichnogen. nov. C* probably represents the adaptive response of the *O. borneensis* tracemaker (whose characteristically mammilated domiciles indicate a dominantly filter-feeding behavior) to an environment in which a deposit-feeding behavior, at least periodically, became more advantageous. Accordingly, the upward disappearance of *Ichnogen. nov. C* would appear to indicate the passage into an above-wave-base environment of consistently higher bottom surge and, hence, preferred filter feeding trophic regime.

The M. simplicatus Zone. That the locomotary-backfill feeding trace *Macaronichnus simplicatus* occurs preferentially concentrated within the "cleaner" sand laminae and beds, and is comparatively absent from the more silt and carbon-rich layers having overall higher organic contents, might at first seem somewhat paradoxical. This is particularly true if traditional trace fossil concepts such as the food resource paradigms of Seilacher (1964, 1967) and Purdy (1964) are to be stringently applied.[2] It is, therefore, important to realize that, because a sandstone appears clean, devoid of fines and "organic detritus", does not necessarily mean that at the time of deposition, it was incapable of sustaining a deposit-feeding mode of existence. We now know, from the study of modern coastal sands, that in such settings bacteria and related microbes tend to colonize, more or less ubiquitously, the surfaces of sand grains, while diverse meiofaunal communities typically inhabit the sediment. Both can, in certain cases, constitute important macrofaunal food resources. It is here inferred, that the *M. simplicatus* tracemaker, as evidenced in the morphology of its burrow, had fed preferentially on an epigranular microbial food resource (see later discussion).

Certain species of sand-loving opheliid polychaetes (eg; *Ophelia limacina, Euzonus mucronata*) serve as excellent modern analogs to the *Macaronichnus* tracemaker (see later discussion). It is a characteristic feature that endemic populations of these species have become narrowly adapted to life within very specific sandy shoreline subenvironments and, consequently, tend to exhibit a high degree of substrate specificity. In particular, it is their feeding behavior that appears to be most closely coupled to the intrinsic character of the sand. Gradients in certain physiochemical properties (ie; interstitial climate, depth of reducing layers,

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[2] A fact that has long been recognized among benthic ecologists, but not as yet fully indoctrinated into trace fossil theory, is that non-living *organic detritus* (or 'food-particles' as it is commonly referred to) does not, *per se*, constitute the primary food resource of most deposit feeding, infaunal organisms. A perusal of the recent ecological literature reveals numerous studies all indicating that such material, which typically comprises fragmentary plant remains, is too refractory for the digestive capabilities of most marine benthos. Instead, deposit feeders evidently derive most of their nutrition from the more readily digested micro-organisms -- primarily bacteria -- that degrade the non-living organics as well as colonize the surfaces of sediment grains (cf. Newell, 1969; Fenchel, 1970; Anderson and Meadows, 1969; Fenchel and Kofoel, 1976; Levinton and Bianchi, 1981; Levinton, 1979, 1982; Yamamoto and Lopez, 1985; Miller, 1985). The common correlation between predominantly deposit-feeding biocoenoses (or fodonichnial/paschinial ichnocoenoses) and stable, organic-rich, fine-grained substrates is, therefore, in part a reflection of the high decompositional and epigranular microbial biomasses typically occurring in such deposits. Most importantly, it does not, as most ichnologists and paleoecologists have in the past assumed, always result directly from the mere partitioning of 'organic food particles' into the substrate (cf. Purdy, 1964; Seilacher, 1964, 1970, 1977; Fürsich and Heinberg, 1983).

mineralogy, grain size and related granulometric properties) govern the distribution of available microbial food, and this in turn ultimately delimits the resultant patterns of larval settlement and adult zonation.

In viewing the overall vertical range of *M. simplicatus* at Boot Coulee, it might be inferred that the tracemaker was pre-adapted to a zone extending from the lowermost reaches of the upper shoreface to the very base of the distal lower shoreface. One must, however, take into account the fact that across this zone conditions would have been continuously changing. Clearly, the dynamic interplay between fair-, rough-, and storm-weather processes would have had a dramatic effect on the zonation of such a specialized organism, whose distribution was so closely tied to the intrinsic character of the substrate. During fairweather periods the seaward limit of the zone would undoubtedly have contracted landward as the depostion of silty organic-rich sands encroached on the distal lower shoreface. Only in response to storms and other high-energy disturbances, after which the distal lower shoreface would have been blanketed by clean fine-grained sand (i.e. the preferred substrate of the tracemaker), would seaward expansion of the *M. simplicatus* zone have occurred.

Additional Comments on the Significance of M. simplicatus. Since its recent introduction into the literature, the ichnogenus *Macaronichnus* (Clifton and Thompson, 1978) has gone from obscurity to become one of the more recurrently characteristic and paleoenvironmentally valued trace fossils in the later Mesozoic of western North America. Unfortunately, however, certain fundamental problems remain inherent in our understanding of these structures and, as a result, continue to greatly inhibit full appreciation of their probable significance.

The main emphasis of interpretation, as expressed in our present state of knowledge, has continued to focus solely on the distributional relations of the ichnogenus as a whole: aspects of paleoecology, although fundamentally important, have been largely overlooked. From this, the general perception has arisen that *Macaronichnus* is an exclusive "beach-nearshore" indicator. Indeed, in accordance with pioneering observations by Clifton and Thompson

(1978), *Macaronichnus* has continued to exhibit an extraordinarily narrow range of facies, recurring exclusively within intertidal and shallow subtidal open marine and estuarine sandstones. Although this pattern of recurrence may indeed be striking, it does not, however, as exemplified here, provide an exhaustive representation of the trace's *full* distributional spectrum. The possibility that with continued exploration the traces distributional boundaries may well be found to extend into *other* environmental associations, must therefore not be dismissed. The fact that it evidentally has is in itself somewhat surprising, considering: (1) the extremely short time-frame and limited extent of past investigations; (2) our presently limited understanding of factors which ultimately govern the trace's distribution; and (3) what, in the final analysis, has proven to be the fate of other, "at first" seemingly restricted lebensspuren as, for example, *Ophiomorpha*. Following the work of Hoyt and Weimer (1963) and Weimer and Hoyt (1964), *Ophimorpha* -- in a manner very similar to *Macaronichnus* -- stood essentially uncontested for over a decade as a seeming indicator of shallow marine, beach conditions. Continued exploration and closer scrutiny of both the ancient and modern records, however, ultimately revealed a much broader spectrum of not only environmental distribution, but also burrow morphologies and phylogenetic origins (Kern and Warme, 1973; Frey *et. al.* 1978; Frey and Seilacher, 1980) In a sense, the work of Frey *et al.* (1978) on *Ophimorpha* marked a major philosophical turning point. Therein, it became apparent that the true paleoenvironmental essence of *Ophimorpha* (or for that matter any other ichnogenus) lies not in the trace's overall range of known distribution but, rather, in the specific autecologic, synecologic and sedimentologic understanding of each separate occurrence. In short, a similar philosophy must now be extended to *Macaronichnus* (Saunders *et al.* in prep).

C. TRANSITION TO THE OFFSHORE

PROXIMAL OFFSHORE (TRANSITION ZONE) DEPOSITS

Throughout southeastern sectors of the study area, the downward transition from distal lower shoreface sand to basinal-offshore mud takes place across a very distinct zone, here designated as the *Proximal Offshore* . The proximal offshore succession is best exposed at Big Coulee, Boot Coulee (Figure 15A) and CP-1(Figure 16).

Internal Characteristics. Proximal offshore deposits comprise an interlaminary build-up of siltstone and very fine to fine-grained sandstone, along with discrete laminae of "mud-free" organics and intercalations of organic-rich mudstone. Sandstone-siltstone laminae occur in tabular, wavy and lenticular geometries, and are often weakly graded. Structurally they display either parallel lamination, ripple cross-lamination or, in the case of thicker layers, parallel-to-rippled 'bouma-like' sequence. Downward through the zone, sand-silt laminae decrease in both thickness and overall abundance, concurrent with an overall increase in the thickness and frequency of mudstone intercalations; locally, however, either of these lithotypes may predominate. Carbonaeous laminae are equally abundant in both proximal and distal portions of the zone and locally may rival the other lithotype as the dominant facies constituent.

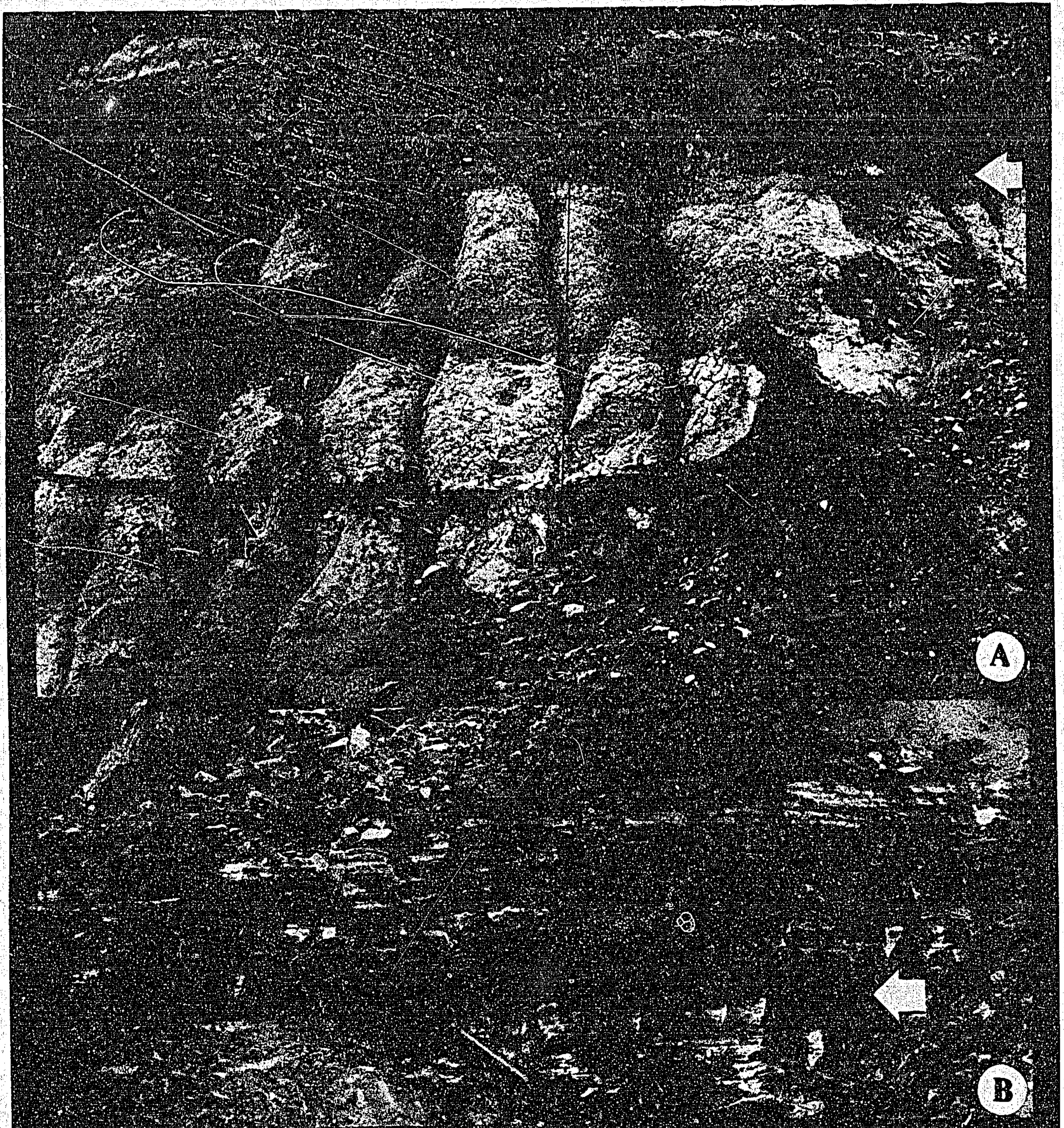
Large-Scale Structure . It is a characteristic feature of proximal offshore deposits that rarely do laminae have a flat lying horizontal attitude. Rather, they occur in discrete sets, each characterized by an undulating scoured basal surface over which the laminae have been conformingly draped. The net result of successive scour and drape cycles is an overall bedding style superficially very similar to the large scale hummocky cross-stratification occurring in the overlying and intercalated storm sand units (Figure 15B). Making the distinction between these two bedding styles is, however, a critical one, considering their different mode of genesis.

FIGURE 15

Proximal Offshore Succession at Boot Coulee.

A. Weathered vertical face showing Unit 3 and the base of Unit 4 (white arrow denotes approximate position of contact). Lense of background proximal offshore deposit (above black arrows) rises diapirically to right of hammer; attributed to instability brought on by rapid storm sand burial.

B. Freshly scraped exposure of Unit 4 showing undulatory nature of laminae and HCS - like bedset intersections: white arrow indicates Unit 3-4 contact.



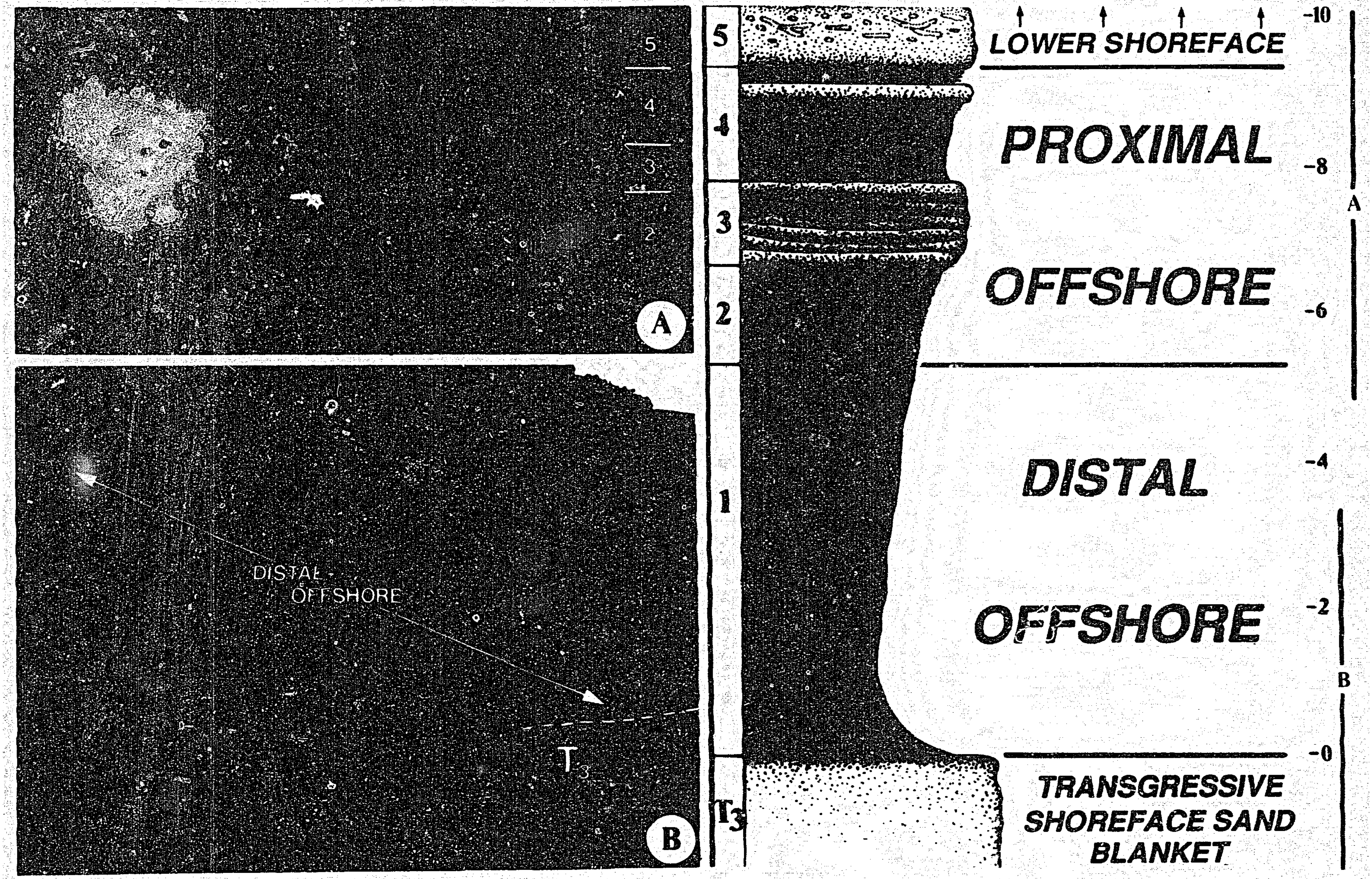
PROXIMAL OFFSHORE AT BOOT COULEE

FIGURE 16

Offshore Sequence as occurring at Measured Section CP-1.

A. Freshly scraped vertical expsure of the proximal sequence.

B. Freshly scraped exposure of the distal sequence along with top of the underlying T-3 transgressive sands.



OFFSHORE SEQUENCE AT CP-I

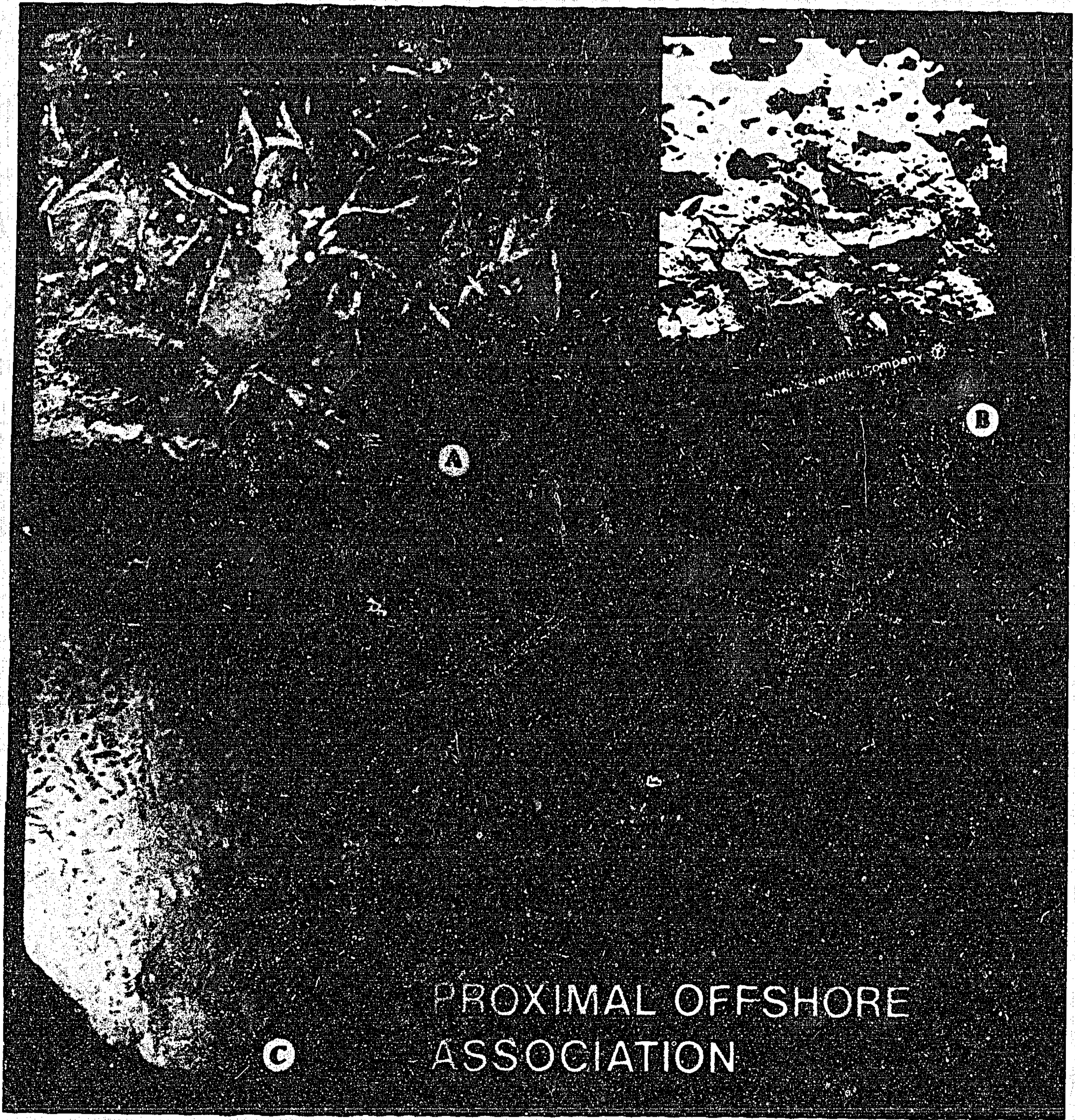
FIGURE 17

Proximal Offshore Trace Fossil Associations as occurring in Unit 2 at Little-Big Coulee.

A. Plan view sideritized mudstone layer containing *Teichichnus* sp. and profuse *Chondrites* sp.

B. *Teichichnus* sp. as occurring sporadically throughout Unit 2.

C. Plan view of same mudstone bed as shown in figure A; here *Chondrites* sp. is seen in association with *Thalassinoides suevicus* .


A
B
sher Scientific Company
C
PROXIMAL OFFSHORE
ASSOCIATION

Trace Fossils. At Little Big Coulee (Figure 22), the re-equilibration structure *Teichichnus sp.* occurs sporadically throughout the fragmentary exposures of the proximal offshore facies and, within an anomolously thick (12 cm) mudstone layer, was found in direct association with *Thalassinoides suevicus* and *Chondrites sp.* (Figure 17). Apart from these localized occurrences, however, proximal offshore facies here, as well as at exposures examined elsewhere throughout the study area, are strikingly devoid of traces. This disparity is most noticable at Boot Coulee where lebensspuren belonging to the diverse distal lower shoreface assemblage vanish on transition into the proximal offshore.

Sedimentologic Interpretation. Proximal offshore deposits document a pivotal shorezone environment, situated transitionally seaward of the main site of lower shoreface storm sand deposition. Here, the overall style of sedimentation appears to have involved (1) the periodic non-depositional disturbance of storm waves, moulding the seabed into an undulatory microtopography, separated by (2) prolonged periods of suspension deposition; mudstone layers accummulating during calm fairweather periods, and intercalated siltstone-sandstone layers reflecting the "feather-edge" of recurrent small scale storm-events. The proximal offshore also evidently served as the preferred site for the deposition of fine-to-intermediately textured detrital organics. The deposition of such matter, particularly as occurring in discrete, relatively thick laminae, is probably a post-storm phenomenon. Following storms, the water column would presumably have become "charged" with organics derived from swamp/marsh areas. The conspicuous dearth of biogenic structures within the proximal offshore also carries important implications, as discussed subsequently.

DISTAL OFFSHORE DEPOSITS

Continuing down-section beneath the proximal offshore sequence, the thickness and frequency of sandstone-siltstone intercalations rapidly diminishes, as does the overall percentage of carbonaceous organics. Grey-weathering mudstone, containing only minor

FIGURE 18

Distal Offshore (*Helminthopsis*) Association

A. Vertical face of silty-mudstone bed displaying characteristic 'verniculate' fabric as imparted by monodominant profusions of *Helminthopsis* sp. (scale bar = 1 cm.)

B. Plain view of sideritized mudstone bed showing *Helminthopsis* sp. in full relief preservation. Burrows characteristically undulate both horizontally and vertically, all the while showing a marked avoidance of interpenetration. (scale bar = 1 cm.)

DISTAL [illegible]
HELMINTHOPSIS
ASSOCIATION

amounts of finely divided organics, is now the dominant lithology. Concomitant with this change in lithology, a dramatic shift also occurs in the physical-biogenic balance, with the "re-appearance" of intense biogenic reworkings, here involving a dense monospecific association of the feeding burrow *Helminthopsis sp.* To the virtual exclusion of all other lebeusspuren, the nature and intensity of *Helminthopsis sp.* gives rise to a very distinct, "vermiculated" fabric, overprinting and obliterating primary stratification (Figure 18). Only toward the top of the sequence can vestiges of millimeter to centimeter thick sand and siltstone intercalations be discerned.

TRACE FOSSILS AND OFFSHORE OXYGENATION GRADIENTS

Across the lower shoreface, gradients in wave-induced bottom turbulence (involving both fair and storm-weather processes) appear to have had an overriding control on the distribution of tracemaking inhabitants. Basinward of the lower shoreface, however, as the "physical control" of waves diminishes, it is then the degree of bottom and interstitial oxygenation that becomes the dominant factor delimiting the structure and overall character of the benthic community.

Oxic Basins. In many of the Jurassic-Cretaceous basins associated with the interior seaways of North America, water movements and circulatory patterns were evidently of sufficient strength that fully oxygenated bottom conditions continued well into the offshore. Here, as a consequence, diverse, normal-marine *equilibrium* offshore communities had developed. Ichnologically, such paleocommunities are manifest in the *Cruziana* ichnofacies (*sensu stricto* Pemberton and Frey, 1984) in which characteristically high ichnospecies diversity reflects the stability of the environment and, hence, the degree to which *biological accommodation* had been allowed to proceed.

Anoxic Basins. There is, however, a growing volume of literature which indicates that during certain times and often across widespread areas of these seaways, *restricted* water circulation had occurred, giving rise to sharp gradients of offshore bottom stagnation. The key to recognizing such conditions in the ancient, derives largely from the study of organism-oxygen relations in modern oxygen-deficient basins. In the Black Sea, the Gulf of California and the borderland basins of Southern California, conditions of increasing offshore anoxia are accompanied by a sequential change in benthic diversity and overall community structure (Rhoads and Morse, 1971). In all modern examples, three distinct, biologically defined zones can be recognized: (1) a shallow water *aerobic zone* (dissolved oxygen concentrations ≥ 1.0 ml/l) in which diverse normal marine bottom communities (including calcified taxa) typically occur; (2) a *dysaerobic zone* (dissolved oxygen levels of 0.3 - 1.0 ml/l) across which a progressive reduction in the diversity and complexity of the community structure occurs, with the gradual dissappearance of the more, equilibrium, *steno-oxic* forms and the persistence and gradual reduction in body size of a small number of soft-bodied opportunistic *eury-oxic* species (the latter typically being dominated by mud-loving infaunal deposit-feeders capable of thriving within low oxygen/high sulphide conditions; and finally (3) an *azoic zone* (dissolved oxygen ≥ 0.1 ml/l), corresponding to basinal conditions lying below the adaptive capabilities of all benthic metazoans (Rhoads and Morse, 1971; Pearson and Rosenberg, 1978; Arntz, 1981).

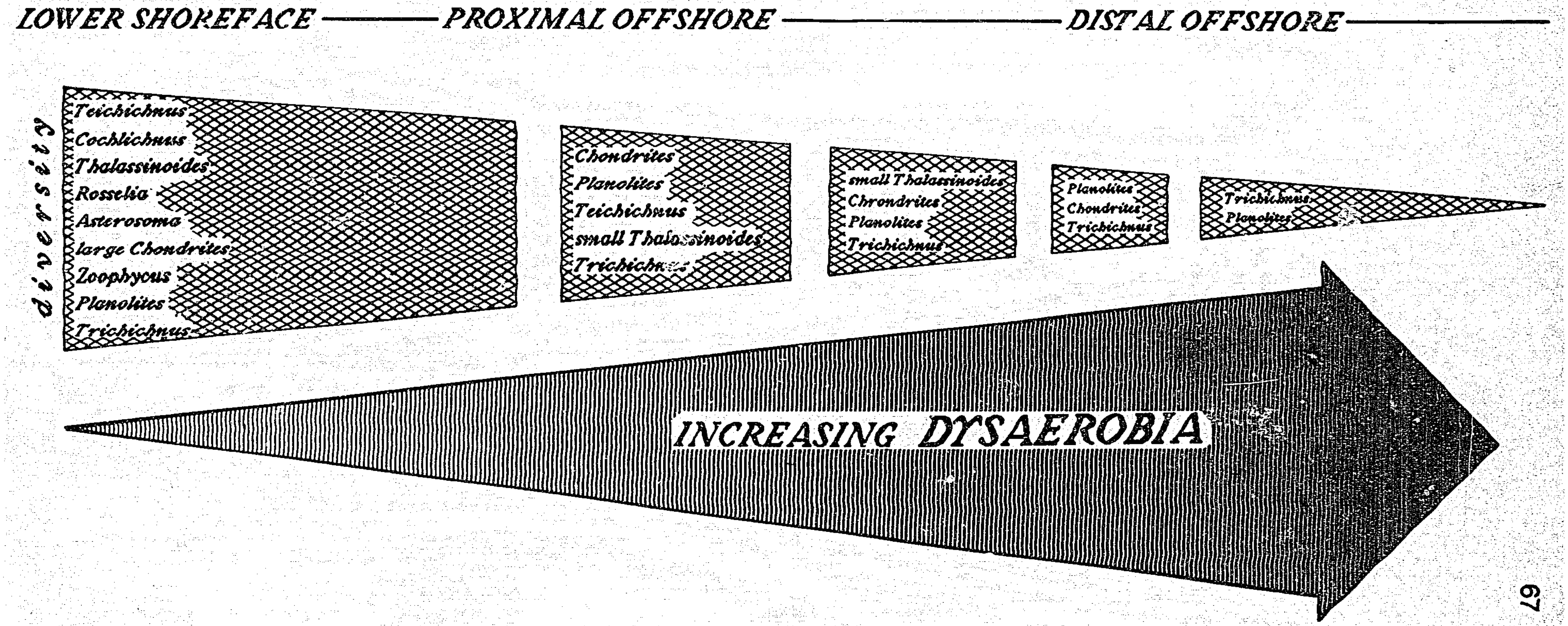
In the ichnological record, strikingly similar trends can be recognized, as manifest in lower shoreface through offshore ichnofacies successions (cf. Frey and Pemberton, 1984; Ekdale et al, 1985). One of the more familar Western Interior examples in which trace fossils have been used to define aerobic-anaerobic gradients, occurs within the Greenhorn and Niobrara cyclothems as summarized by Kauffman (1985). Here, diverse lower shoreface trace fossil associations grade into the offshore through a very distinct succession of ichnofacies: the overall trend being one of sequentially decreasing lebensspuren diversity across the lower shoreface-proximal offshore (Figure 19), followed across the distal offshore by a continued drop in diversity and the concomitant proliferation and domination of certain specific

FIGURE 19

Ichnologically defined aerobic-dysaerobic offshore gradient as characterizing lower shoreface-offshore sequence in the Greenhorn and Niobrara Cyclothems (summarized from Kauffman, 1985).

AEROBIC-DYSAEROBIC ICHNOFACIES SUCCESSION

GREENHORN-NIOBRARA CYCLOTHEM



forms (i.e. the locomotory backfill-feeding burrow *Planolites* and, in the more distal offshore facies, the hair-like vertical tube *Trichichnus*). Such occurrences of *Planolites* and *Trichichnus* evidently reflect the opportunistic proliferation, presumably within the *lower dysaerobic zone*, of a small number of eury-oxic infaunal species. An excellent modern anolog to the *Trichichnus* tracemaker can be found in the cosmopolitan capitellid polychaete *Capitella capitata*, as described by McCall (1977) and Pearson and Rosenberg (1978). Across modern shallow marine oxygenation gradients, *C. capitata* occurs as a subdominant species in the more aerobic environments, then, on transition into environments of increasing dysaerobia, undergoes a dramatic increase in density, becoming the numerically dominant species.

Application to the Present Succession. Viewing the overall transition from the diverse lower shoreface trace associations (Figures 12 and 14), to the monotypic proliferation of *Helminthopsis sp.* characterizing the distal offshore facies (Figure 18) suggests that a similar *anoxic basin model* to that of the Greenhorn-Niobrara can also be applied here. One fundamental difference, however, must first be accounted for: the *anomolous* dissappearance (with the exception of localized occurrences of *Teichichnus* - *Chondrites* - *Thalassinoides*) of virtually all biogenic structures on transition from the distal lower shoreface into the proximal offshore.

Beach-offshore transects measured off Sapelo Island, Georgia (Howard and Reineck, 1972; Dorjes, 1972; Pinet and Frey, 1977), as with numerous other modern examples (Purdy, 1964, Dorjes, 1971), show macrobenthic species diversities and animal abundances to be strongly correlated to the overall percentage of detrital organics occurring within the substrate. For example, off Sapelo Island diversities and animal abundance culminate within the upper offshore adjacent to major inlets where, in response to local hydrographic conditions and suspended concentrations, the substrate becomes greatly enriched in decaying marsh grass (*Spartina alterniflora*) derived from intracoastal areas (Pinet and Frey, 1977).

Consider now, however, the application of such a scenario in interpreting the present succession: within the proximal offshore facies, the overall concentration of visible detrital organics is substantially higher than anywhere else in the succession, yet biogenic evidence of benthic inhabitance is, in most instances, non-existent. Clearly, some sort of paradox would appear to exist.

Recent studies by benthic ecologists, (as summarized in Pearson and Rosenberg, 1978), have shown that under a given hydrologic regime, only to a critical point will organic enrichment of the substrate continue to positively affect (i.e. biostimulate) the resident macrobenthic community (cf. as described by Pinet and Frey, 1977). Beyond this "threshold", further increases then actually begin to have a detrimental affect, as processes of bacterial decomposition/oxygen consumption begin to overwhelm those of bottom-interstitial oxygen renewal, ultimately giving rise to conditions of increasing anoxia: under such conditions the macrobenthic community will of course respond accordingly (Figure 20).What is particularly noteworthy here, in relevance to interpreting the proximal offshore succession, is that the level of organic enrichment can and often does proceed beyond the point at which surficial deposits become "azoic" and, hence, total defaunation occurs. Therefore, in viewing (1) the overall abundance and disposition of organics within the proximal offshore facies (i.e. forming relatively thick, closely spaced accumulations), and (2) the seeming dearth of biogenic structures, it is probably not unreasonable to assume that azoic-lower dysaerobic conditions had occurred as more or less an ongoing phenomena (Figure 21).

FIGURE 20

Universal response of modern shallow marine benthic communities to gradients of increasing organic enrichment, and concomitant changes in bottom oxygen tensions (after Pearson and Rosenberg, 1978).

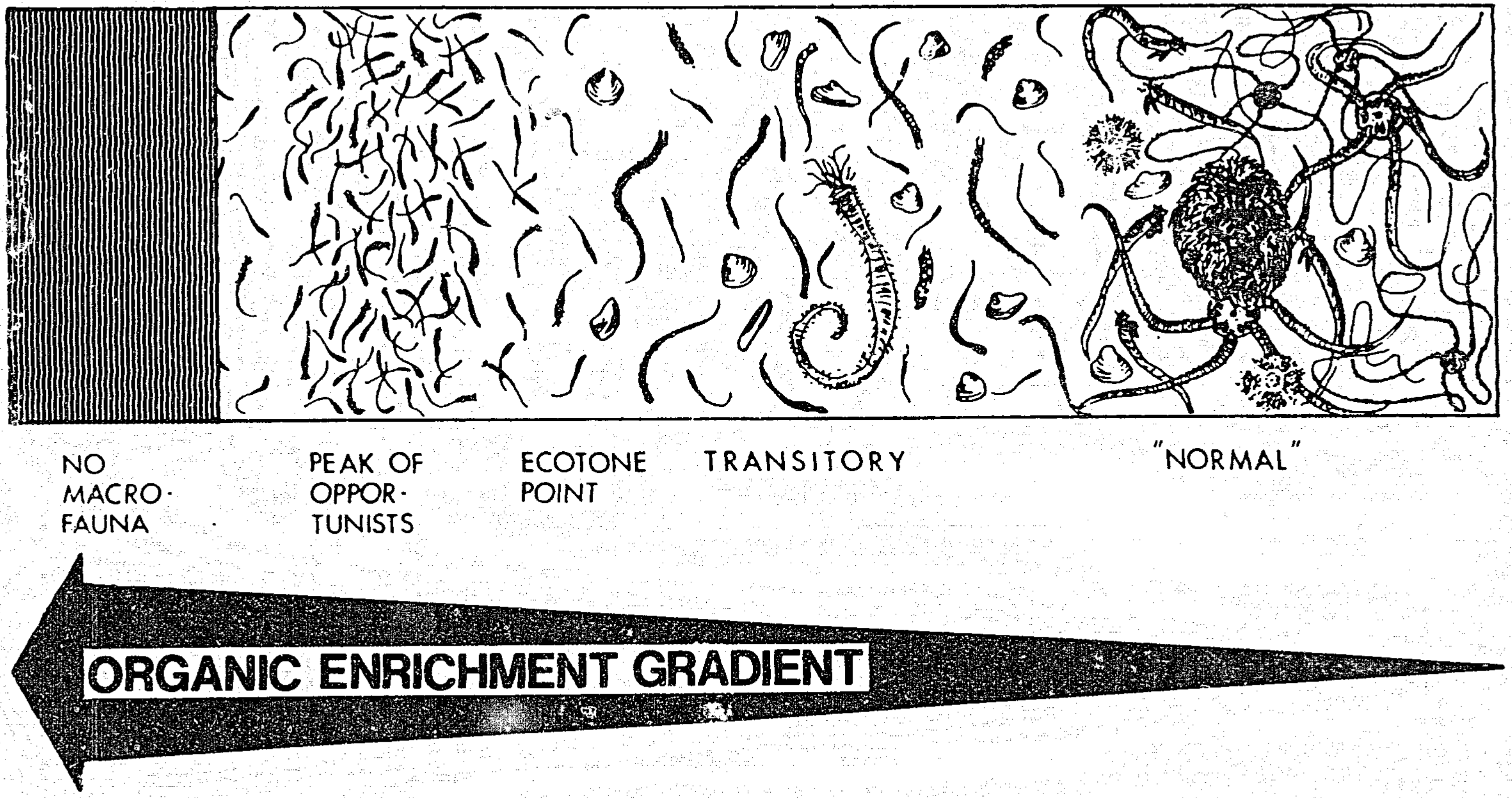

NO MACRO-FAUNA
PEAK OF OPPOR-TUNISTS
ECOTONE POINT
TRANSITORY
"NORMAL"
ORGANIC ENRICHMENT GRADIENT

FIGURE 21

Ichnologically defined oxygenation gradient as characterizing proximal lower shoreface - distal offshore lithofacies in the Appaloosa succession. The overall transition from diverse lower shoreface associations to the mono-proliferation of *Helminthopsis sp.* in the distal offshore, is inferred to have occurred in response to increasing offshore anoxia. What is intriguing is the seeming anomaly in the overall trend that occurs across the proximal offshore; here, as evidences by the dearth of lebensspuren, the extreme abundance of detrital organics occurring within the substrate is thought to have given rise to conditions of complete anaerobisis (see text for detailed discussion).

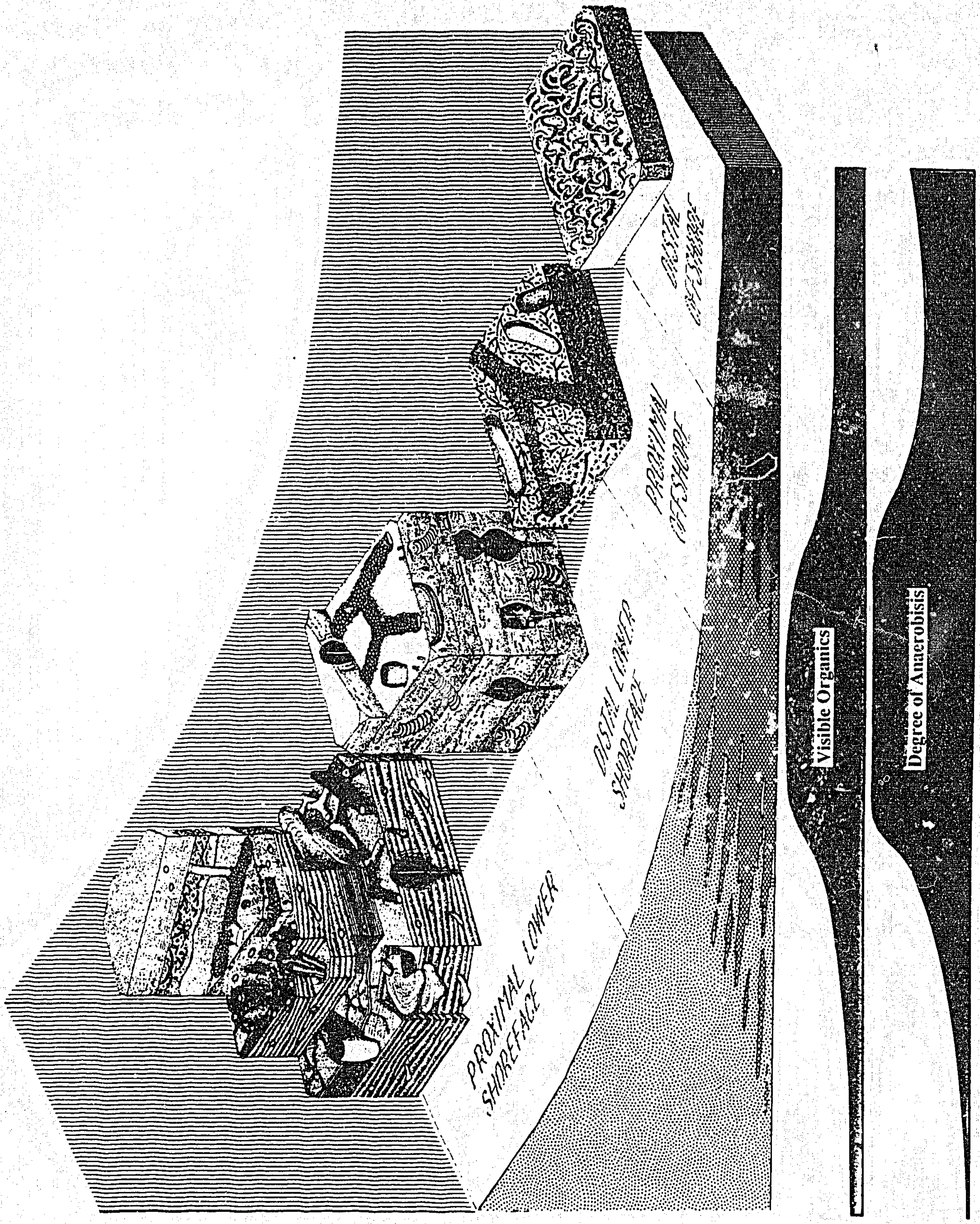
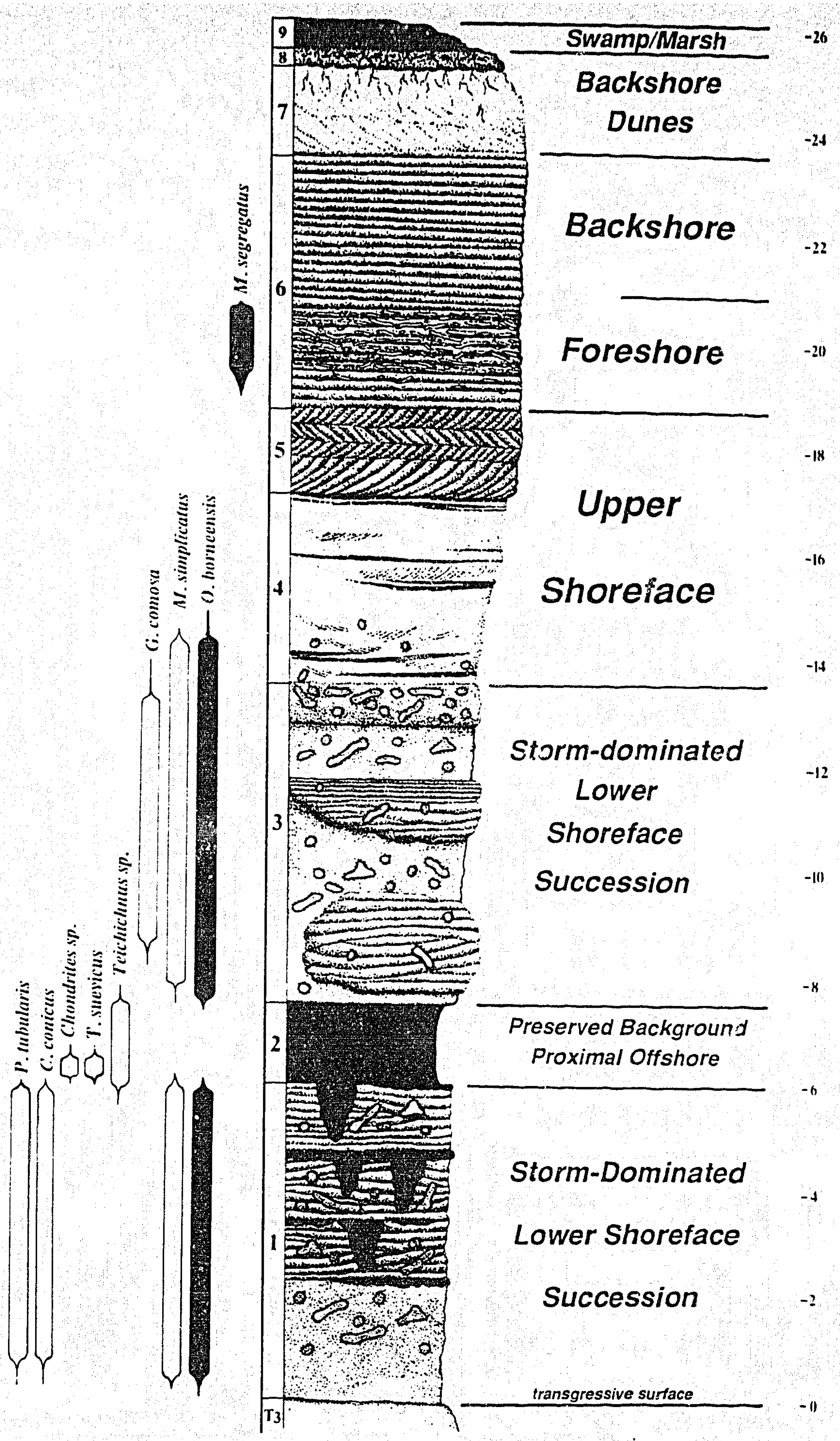

PROXIMAL LOWER SHOREFACE
DISTAL LOWER SHOREFACE
PROXIMAL OFFSHORE
DISTAL OFFSHORE
Visible Organics
Degree of Anaerobisis

FIGURE 22

Vertical sequence characterizing the Appaloosa Cycle at Little Big Coulee. The LOWER APPALOOSA ZONE corresponds to Units 1-3, the MIDDLE ZONE to Units 4-5, and the UPPER ZONE to Units 6-9. Ichnofossil distributions shown in black denote *characteristic lebensspuren* (*sensu* Dörjes and Hertweck, 1975), whereas those in white refer to *associated* or more sporadically encountered forms.



COMPOSITE MEASURED SECTION AT LITTLE-BIG COULEE

III THE MIDDLE ZONE

(Upper Shoreface Sequence)

With the exception of localized calcite-cemented nodules, Middle Zone sands are clay cemented and extremely friable. Consequently, outcrop exposures at most sections are, as a rule, more intensely weathered than either the Lower or Upper Zones. This of course greatly inhibits any form of detailed surficial description. Instead, wherever possible, during the course of field investigations vertical trenches were excavated from which the general sedimentological characteristics could be ascertained. Unlike the Lower Zone, the Middle Appaloosa, with the exception of sections EC-5 and EC-4 (see later discussion), appears to maintain more or less the same overall facies signature throughout most of the sequences progradational extent. Accordingly, discussion in terms of an idealized sequence becomes somewhat more warranted. Admittedly, however, of the three zones the middle still remains the least understood.

DESCRIPTION

Middle Zone sands are relatively clean, yellow to buff in color, and typically coarsen upward from fine-grained at the base of the zone to fine-medium or medium grained at the top. The zone ranges in thickness from a minimum of 5 meters to an estimated maximum of 8 meters. Bedding throughout most of the zone appears horizontal to low-angle (*albeit* sometimes irregular and uneven), and although superficially similar to, is easily distinguished from the storm bedding pervading the underlying Lower Zone sands. Often, laterally discontinuous zones of concentrated carbonaceous laminae--a characteristic feature throughout the lower two-thirds of the zone--provide the only means by which the nature of the bedding can be discerned. Sets of small, decimeter and occasionally large scale cross-beds occur interspersed with the more prevalent horizontal/low-angle bedding, and at a

FIGURE 23

Middle Zone 'Upper Shoreface' Deposits

A. Close-up view of carbonaceous lamination showing coarse fragmentary nature of the organics. (shown at actual size).

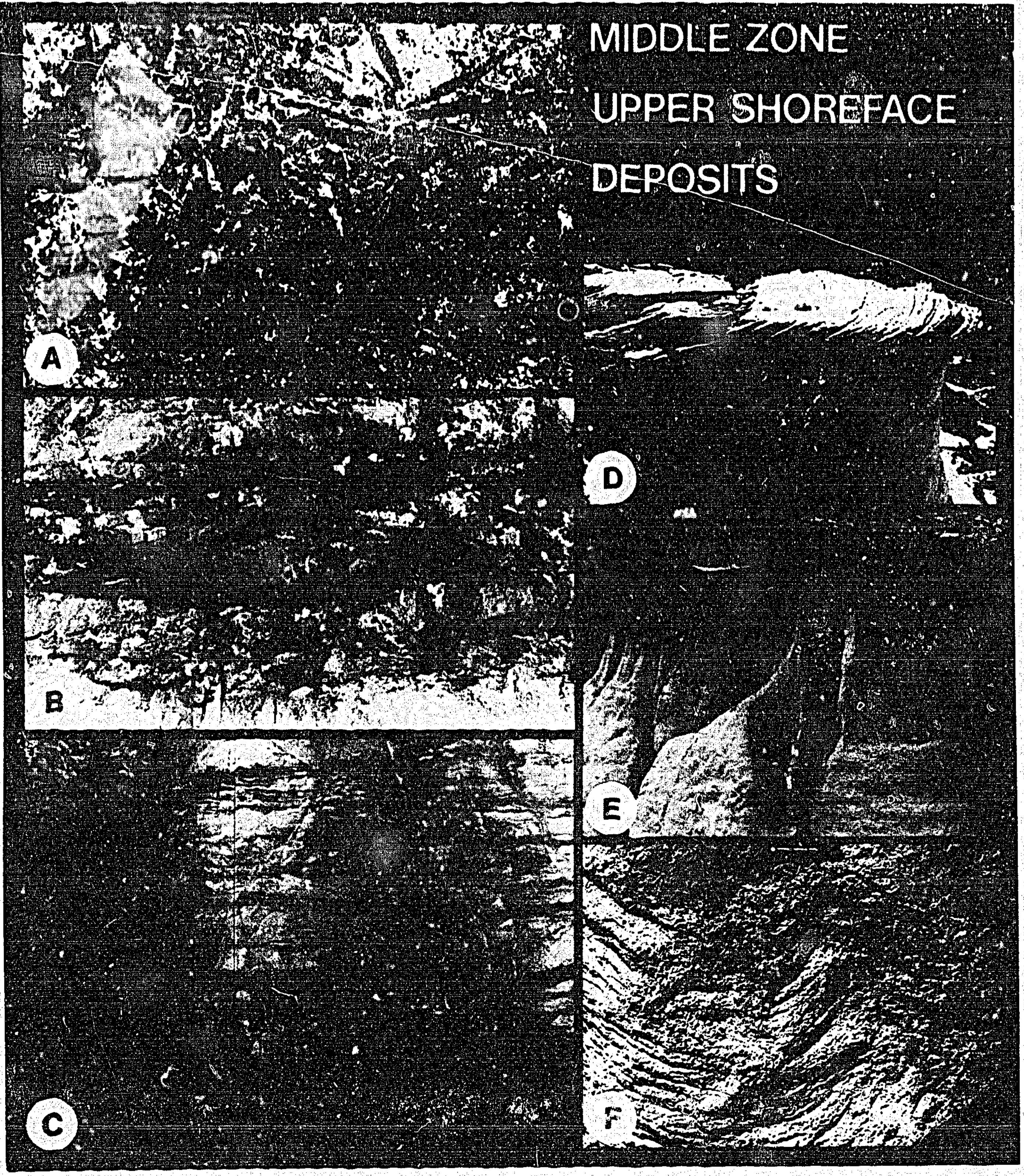
B. Freshly scraped vertical face of the lowermost Middle Zone showing small-medium scale cross-bedding. Toeset-foresets defined by drapings of carbonaceous plant debris.

C. Freshly scraped vertical face of the lower third of the Zone at Boot Coulee displaying characteristic laminary concentrations of organics with interspersed sets of small-medium scale cross-bedding.

D. Aerial view of strata in figure E highlighting calcite cemented set of planar tabular cross-bedding capping the sequence.

E. Stacked succession of tangential, medium scale trough cross-bedsets in upper shoreface-foreshore transition zone at Ophiomorpha Heaven.

F. Plan view of troughs within lower third of middle zone at Ophiomorpha Heaven.


MIDDLE ZONE
UPPER SHOREFACE
DEPOSITS
A
B
C
D
E
F

number of sections (e.g. "Ophiomorpha Heaven", Little Big Coulee and Sundance Coulee) a stacked succession of multi-directional, decimeter scale trough and tabular cross-bedding forms a discrete subzone, 1 to 1.5 meters thick, situated immediately subjacent to the Middle-Upper Zone discontinuity (Figures 23 D & E). Unfortunately, owing to the nature of the outcrop, only in rare instances could reliable paleocurrent measurements be obtained. Within the lower half of the zone, foreset-toeset bedding surfaces are profusely draped by millimeter thick laminae of carbonaceous plant detritus, here notably coarser than that associated with the lower shoreface sands (Figure 23A). Above this, the overall abundance of organic matter greatly diminishes, although at a number of sections, isolated laminary accummulations were found in the upper third of the zone as well.

INTERPRETATION AND DISCUSSION

The observed textural/structural sequence within the Middle Zone, combined with a stratigraphic position between inferred lower shoreface and foreshore deposits (cf. Basley, 1981) implies deposition across the intervening *upper shoreface* or zone of fairweather wave build-up and surf. In contrast to the lower shoreface, during fair weather periods the substratum here will remain in more or less continuous motion under the influence of waves and wave induced currents (Howard and Reineck, 1981). This is reflected in the resultant deposits in which physical sedimentary structures predominate over biogenic ones, particularly in the more landward reaches of the environment. At a number of sections, mud-lined or silicified *Ophiomorpha* tunnels, lacking the characteristic iron-carbonate mineralization of the Lower Zone specimens, may be occassional to common within the lowermost beds of the zone (Figure 23). Here, profusions of *M. simplicatus,* persisting upwards from the lower shoreface, may also occur. Elsewhere, particularly higher within the Upper Shoreface sequence, biogenic structures are conspicuously absent.

In short, the sequence of textures and physical structures characterizing the Middle Zone, when considered along with the almost complete absence of biogenic structures, seems consistent with an upper shoreface interpretation for these deposits. Using stratigraphic thickness as a surrogate for water depth (cf. Elliott, 1986; Klein, 1974), the upper shoreface paleoenvironment can be inferred to have extended seaward of the low water line to depths of 5 to 8 meters, further inferring deposition within an *intermediate to high-wave energy* coastal regime (cf. Howard and Reineck, 1981; Short, 1984). Although little can be said at this stage concerning the precise morphodynamic setting, the common occurrence of angle-of-repose cross-bedding confirms the existence of unidirectional currents and/or bottom wave surge within the environment. Furthermore, the discrete zone of cross-bedding found locally at the top of the Middle Zone compares closely with the foreshore-shoreface transition facies documented by Howard and Reineck (1981) and the Inner-Rough facies described by Clifton et al. (1971). Along topographically simple high wave energy shorelines, this facies typically developes in the plunge zone or position of breakers at low tide (Howard and Frey, 1984). Its recognition in ancient sequence, therefore, may be important in approximating the actual shoreface-foreshore boundary, with respect to the present sequence, this would presumably coincide roughly with the top of the Middle Zone.

Absence of the Skolithos Ichnofacies. The characteristic absence of lebensspuren within the upper two-thirds of the zone, although somewhat tenuous, may provide additional insight favoring deposition in a more high-energy or *exposed* upper-shoreface setting (Saunders and Pemberton, in preparation). In modern low-energy or *sheltered* shoreline settings (e.g. the Georgian Coast, Gulf Coast of Texas, Gulf of Gaeta), infaunal trace making communities of the surfzone-uppershoreface invariably include hemisessile suspension feeding forms which, as a means of escaping the instability at the sand-water interface, construct deeply penetrating, wall re-enforced vertical domiciles (Frey and Pemberton, 1984). Because burrows are characteristically constructed to depths well below the zone of active physical reworking, the long term potential for at least partial preservation of the resultant ichnocoenose will be relatively high. Now, however, contrast this with infaunal tracemaking communities of the beach-upper shoreface habitat as it is known to exist in more exposed, high-energy settings. It is a characteristic feature of modern high-energy sandy open ocean beaches that, owing primarily to enhanced levels of wave induced physiological stress, hemisessile, burrow-dwelling infauna do not occur (McLachlan, 1977, 1980a, 1980b, 1983, 1984; Oliver et al., 1980). Instead, the infauna is characteristically dominated by tough, *highly motile* forms (e.g. certain species of the bivalves *Donax, Venus,* and *Cardium*), whose superficial record of repichnial and fugichnial activity stands little chance of preservation under the prevailing high energy physical regime. Thus the key to differentiating exposed vs. sheltered beach-related settings in ancient sequence may at least partially, lie in the nature of the preserved ichnofacies. Most importantly, the perception amongst ichnologists that conditions requisite to the development of the *Skolithos* ichnofacies extend throughout the entire nearshore spectrum of sandy wave stressed environments (i.e. in both high and low energy beaches alike) would now appear to have been more a product of hypothetical extrapolation than of empirically based modern observation.

IV UPPER APPALOOSA ZONE:

(Foreshore-Backshore-Barrier Island Sequence)

The uppermost sedimentologic zone of the Appaloosa disconformably overlies the Middle Zone sands (upper shoreface sequence), and is, in turn, disconformably capped by a thin seam of coal or carbonaceous shale. This zone averages 5.0 meters in thickness ranging from a maximum of 8.0 meters at Little Big Coulee to a minimum of 3.5 meters at Ophiomorpha Heaven. Compositionally, it comprises moderately well sorted fine-medium to medium grained highly feldspathic sandstone, and at most sections a slight upward fining can be detected through the zone. At a number of sections, particularily those where the underlying shoreface-foreshore transitional zone of cross-bedding is well developed (e.g., Sundance Coulee, Little Big Coulee and Ophiomorpha Heaven), a sharp decrease in grain size also occurs upward on transition into the upper zone.

A. FORESHORE SANDSTONE

SEDIMENTOLOGICAL ASPECTS

The lowermost 2 to 3 meters of the Upper zone is characterized by clean, moderately well sorted sandstone, internally displaying well-developed horizontal to low-angle planar lamination. Laminae typically occur in large scale wedge sets 10 to 50 cm thick which intersect one another at extremely low angles. Associated sedimentary structures, although only locally observed, include low amplitude wave ripples, parting lineation, swash marks and landward dipping decimeter scale tangential cross-bedding.

The distinctive planar lamination pervading these sands strongly resembles "beach lamination" described from modern foreshore deposits (cf. Thompson, 1937; Clifton, 1969), developing in response to wave swash processes on the exposed beach surface. Coarse-to-fine laminae couplets resembling the swash-backwash grain segregations

FIGURE 24

Foreshore - Backshore - Barrier Island Sequence (Upper Zone)

12A. Uppermost foreshore--backshore--barrieri sland transition at Ophiomorpha Heaven; note faint horizontal to low angle planar lamination throughout and resistantly cemented carbonaceous and rooted sand bed disconformably overlying relatively clean laminated backshore sands.

12B. Vertical face of upper foreshore sands at Big Coulee showing zonal development of *Macaronichnus segregatis*; differential weathering serves to illustrate the pervasive nature of burrowing.

12C. Northwest - southwest oriented (shoreline perpendicular) face at Little South Snake displaying seaward dipping depositional surfaces cross-cutting the backshore-foreshore; note also tidal channel (TC) erossionally overlying the Appaloosa coal seam.

12D. Southwest-northeast oriented face (shoreline parallel; looking northwest from OH-1) showing characteristic undulations of upper surface; note large scale X-beds within ridge at left of photo, and also pronounced thickening of overlying coals within swales

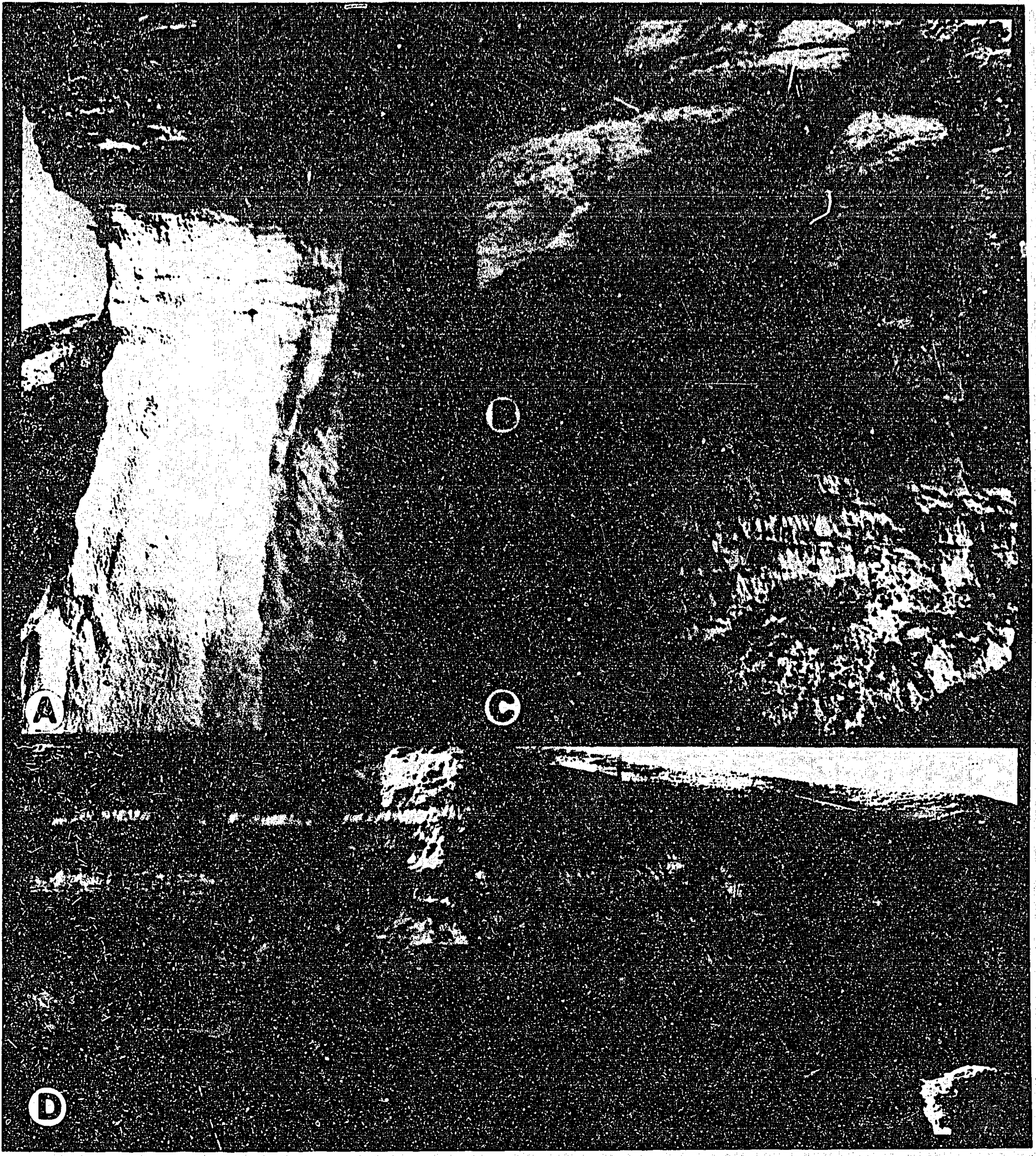
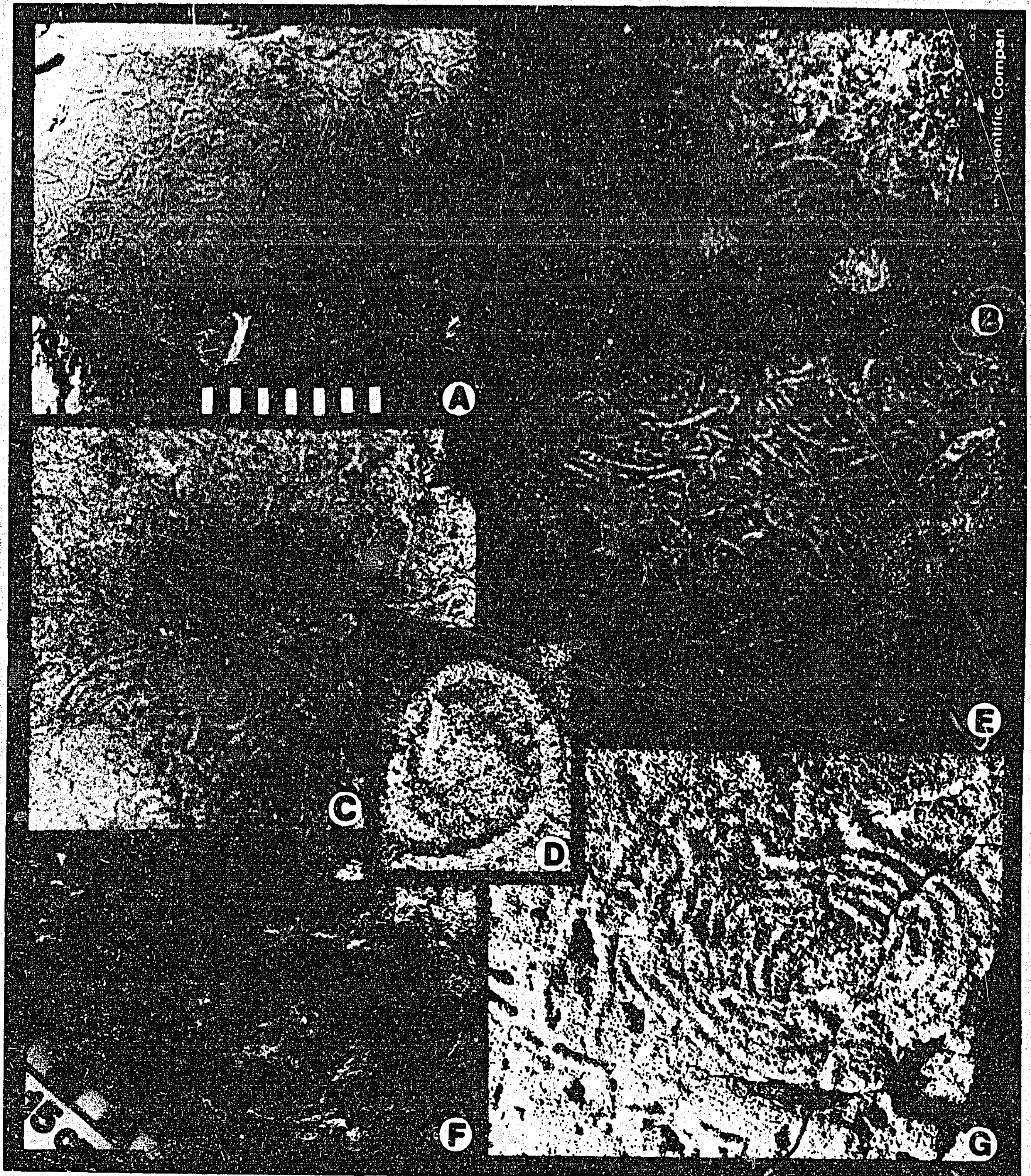

A
B
C
D

FIGURE 25

Macaronichnus segregatis Clifton and Thompson, 1978

A,B,C & E. Profusely burrowed bedding surfaces displaying characteristic 'random avoidance' pattern of burrowing; in figure **(B)**, intergradation between *M. segregatis segregatis* and *M. segregatis spiralis* can be seen. Note also the directional allignment of burrows occurring in **(C)**.

D,F & G *Macaronichnus segregatis spiralis.* Bedding surface views of specimens displaying distinctive spiral configurations; **(F)** well developed near circular tightly coiled spiral; **(D)** incipient spiral; **(G)** specimen showing distinctive but less well developed spiral configuration.


A
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entific Compan

described by Clifton (1969) are also a common feature of Appaloosa foreshore sandstones. The predominance of planar lamination and relative absence of landward dipping foresets suggests that the foreshore surface, at least during the more reflective accretionary stages (cf. Wunderlich, 1972; Hunter et al., 1979), was topographically simple and devoid of ridge /runnel systems. The occurrence of low-angle wedge-like set intersections reflects subtle changes in the slope of the beach, presumably in response to fluctuating wave conditions (cf. Reinson, 1984; Howard and Frey, 1984).

ICHNOLOGICAL ASPECTS (the *M.segregatis* Zone)

While elements of the *Skolithos* ichnofacies are everywhere conspicuously absent from the foreshore succession (a relationship also characteristic of the subjacent upper shoreface-surfzone deposits), virtually every outcrop examined instead revealed a very distinct zone of intense biogenic reworking, invariably beginning 0.7-1.2 meters above the basal foreshore discontinuity and continuing upward for 0.6-1.2 meters before terminating abruptly. This relationship not only holds true throughout the exposed progradational extent of the Appaloosa, but also within the preceeding *R2* hemicycle as well. The zone is composed entirely of intrastratal bedding concentrations of *Macaronichnus segregatis* (Figures 24B, and 25). Within the main zonal concentration, burrows herein assigned to *M. segregatis segregatis* constitute the prevalent morphology. Below this, burrow densities drop off radically, and *M. segregatis segregatis* is sometimes joined by isolated occurrences of *M. segregatis spiralis* ; burrows commonly persist downward to, but never below, the basal foreshore discontinuity. At most sections, particularly where the mafic content of the ambient sand is low, the traces are extremely subtle in appearance, and often are made visible only by scrutinizing freshly scraped vertical faces.

The West Coast Blood Worm *Euzonus mucronata* : (Modern Analog to the *M. segregatis* tracemaker)

Clifton and Thompson (1978) documented the locomotary-feeding behaviour of the opheliid polychaete, *Ophhelia limicina,* demonstrating it to be a close modern analogy to the *Macaronichnus* tracemaker. Both the worms and their burrows were observed in intertidal and shallow subtidal sands flanking the Willipa Bay estuary on the Washington coast. Recently, however, it was suggested (D.A. Lechie, pers. comm. December, 1986) that perhaps an even more exacting analog, particularly concerning the Bearpaw-Horseshoe Canyon *M.segregatis* specimens, might instead be found in the opheliid species, *Euzonus mucronata*, as occurring intertidally along the surf-stressed Pacific Coast beaches of Vancouver Island. Field observations undertaken the following summer at Long Beach, Pacific Rim National Park, have subsequently confirmed this theory (Saunders et. al, in prep.).

Intrastratal feeding burrows of *E. mucronata*, were analysed on planar bedding surfaces exhumed by winds during low tide (Figure 26). Contrasting these with similarly preserved specimens of *M.segregatis* (Figure 25) shows that certain elements of morphologic difference do, in fact, exist. What is important to recognize, however, is that in both situations strikingly similar adaptations of *optimal foraging behaviour* (cf. Taghon, 1978; Pyke, 1984; Hughes, 1980) appear to be represented.

Similarities of Modular Feeding. It has been convincingly shown by Clifton and Thompson (1978) that the *Macaronichnus* tracemaker -- just as *E. mucronata* has long been known to do in the modern (Fox et.al., 1948; Dales, 1952; McConnaughey and Fox 1949; Eikenberry, 1966) -- subsisted largely on a food resource of epigranular bacteria. Within *clean* sand, in comparison to finer-grained organic rich substrates, however, the overall abundance of microbial food will of course be greatly reduced. One might therefore expect deposit feeding organisms specifically adapted to life in sandy substrates, to show some form of adaptation towards maximizing the efficiency in which they go about feeding. In other words, on such a resource, it seems highly improbable that any organism could feed completely indiscriminately and still obtain the energy required to fulfill its metabolic needs. In the case of both *E. mucronata* and the *Macronichnus* tracemaker, the primary *behavioural* adaptation in these regards, as can be inferred from the modular structure of their burrows, was evidently that of *grain selective feeding* (i.e. selectively removing, prior to ingestion, those sand grains that in effect reduce the organisms net energy gain per unit time feeding). In short, the ability to detect subtle inhomogeneneites in the granular partitioning of microbial food and routinely make the distinction between *more* and *less* energetic grains, appears to have been the primary adaptive innovation allowing for the radiation of *Macronichnus* -making polychaetes into the clean sandy shoreline biomere (Saunders et al in prep.).

Similarities of Pathway Configuration.. In the case of *M. simplicatus* as characterizing the finer-grained lower shoreface/distal upper shoreface sands, *grain selectivity* was evidently enough to ensure the tracemaker with an adequate supply of food, with no further measures of optimization needed. In terms of pathway efficiency then, the tracemaker was able to forage at random, without having to worry about overcrossing other burrows and the energy losses that might result in so doing (Figure 25).

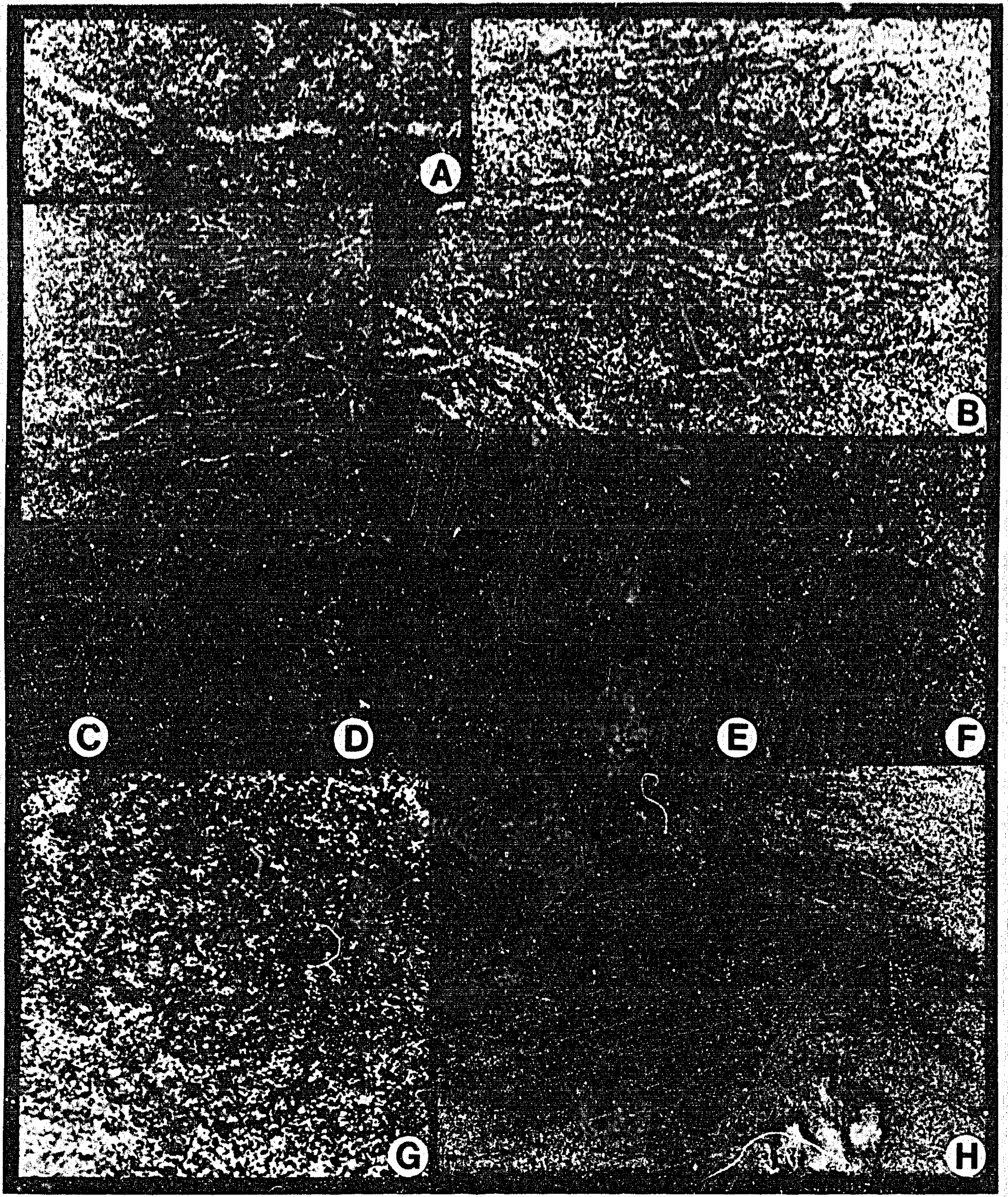
In the case of both *Euzonus mucronata* and the *M. segregatis* tracemaker, however, this grain selectivity was evidently not sufficient to afford the animals enough of an advantage, and additional means of foraging optimization had to be invoked. This involved a step towards higher pathway efficiency. By exercising strong *phobotaxic* and *thigmotaxic* response mechanisms these organisms offset costly energy expenditure losses resulting from path interpenetration. The result is a random but *non-duplicating* coverage of the food bearing horizon. Finally, the transition from a random avoidance pattern of exploitation (*M. segregatis segregatis)* to a compact spiral configuration (*M. segregatis spiralis*) represents yet another step towards reaching an optimal foraging strategy. By spiraling, the total path

FIGURE 26

Locomotary Feeding Burrows of *Euzonus mucronata*

A.	Close up bedding plane view of burrow demonstating its modular similarity to *Macaronichnus*.
B,C,D, E&H.	*Type A Burrows.* Exhumed bedding durfaces showing typical random avoidance pattern of burrowing. Pronounced parallel allignment of burrows invariably occurs in a shorenormal direction, hence similar relationships observed in M. segregatis segregatis (figure 27c) may have implications concerning paleoshoreline orientation.
F&G.	*Type B Burrows.* Exhumed bedding surfaces revealing distinctive planispiral configurations. Identical in form to *M. segregatis spiralis* (figure 27 D, F and G).

** Due to extreme winds at time of photography, scale bar could not be fastened. For reference, however, all burrows are roughly 2mm in diameter.


A
B
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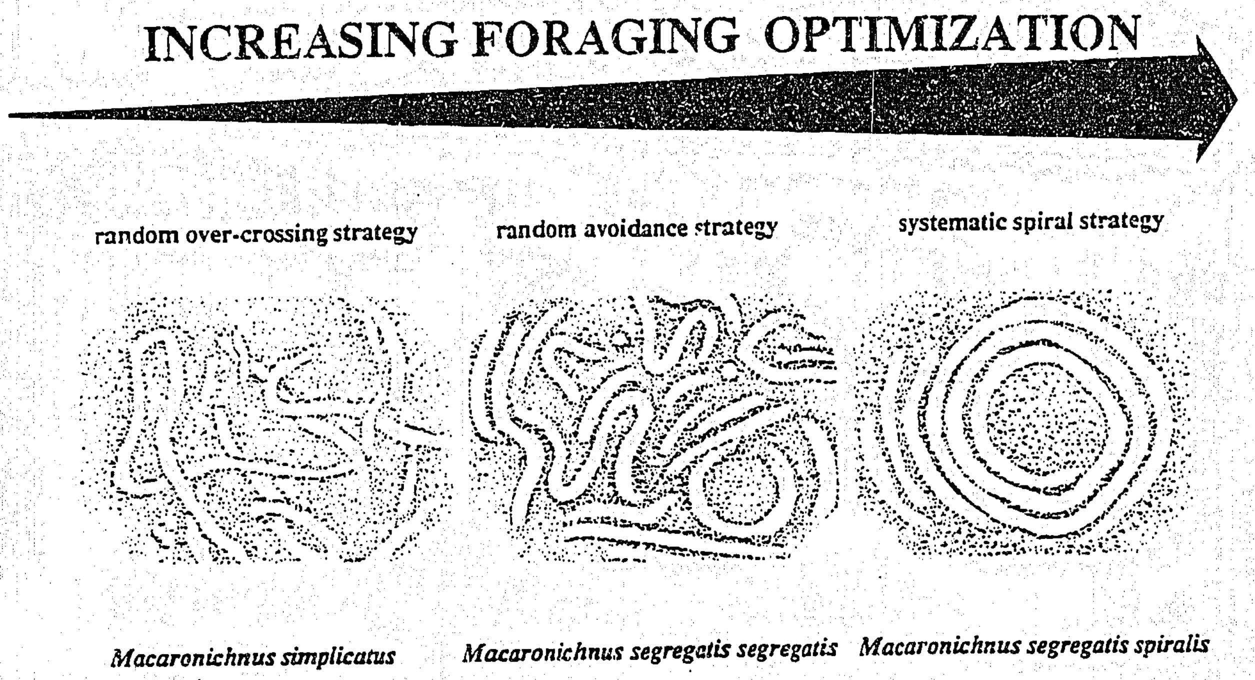
G
H

FIGURE 27

Three distinct levels of foraging systematization represented along a continuum between *Macaronichnus simplicatus*, *M. segregatis segregatis* (=*E. mucronata form A*) and *M. segregatis spiralis* (=*E. mucronata form B*). In all cases the tracemaker was exploiting an epigranular microbial food resource uniformly distributed about a planar bedding surface.

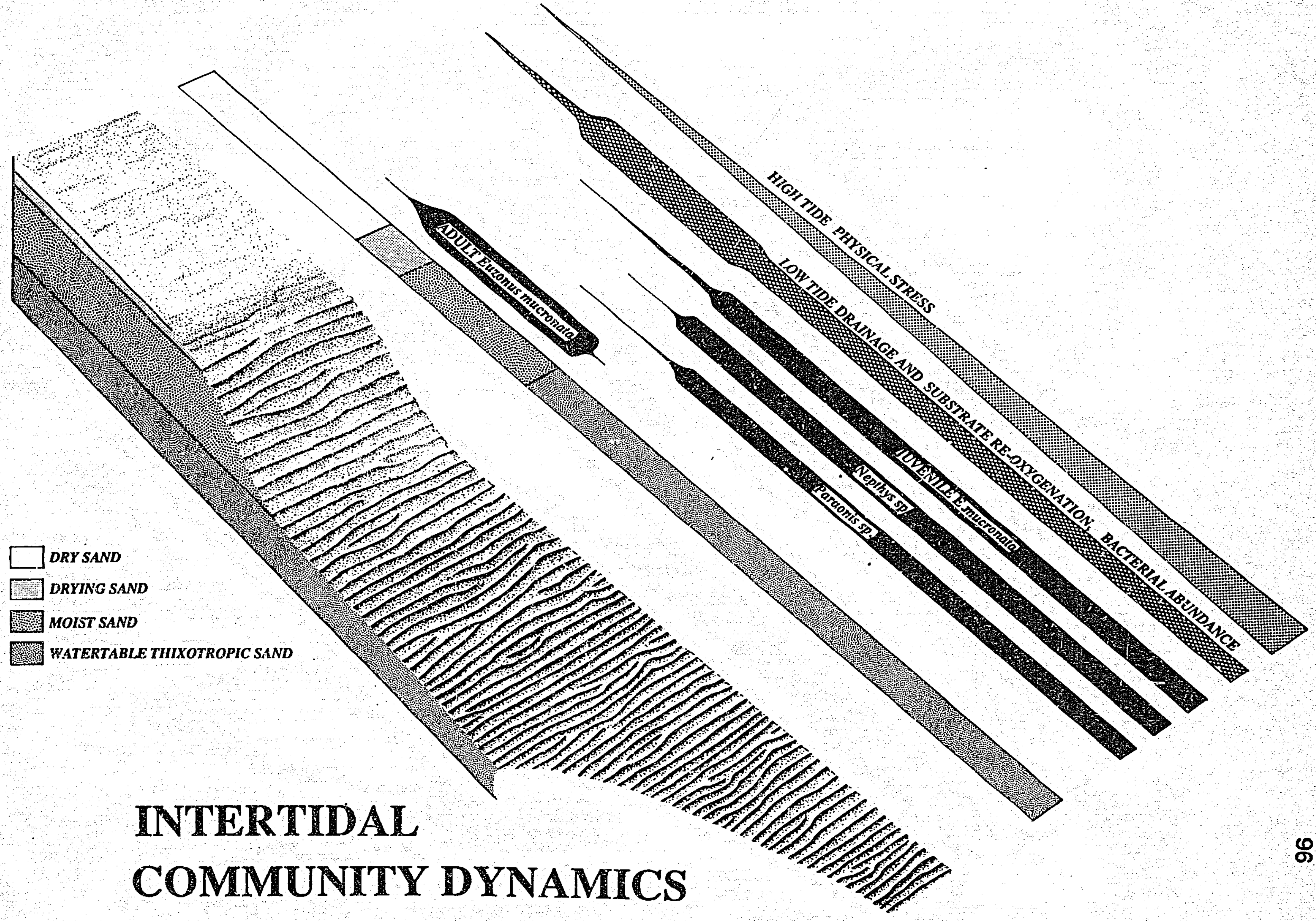

INCREASING FORAGING OPTIMIZATION
random over-crossing strategy
random avoidance strategy
systematic spiral strategy
Macaronichnus simplicatus
Macaronichnus segregatis segregatis
Macaronichnus segregatis spiralis

length is maximized while the total areal utilization is reduced to a minimum. The apparent advantage here is that the tracemaker greatly minimizes its chances of encountering other burrows: energy that otherwise would have been expended in having to react phobotaxically, is therefore conserved. The absence of fully developed spirals from crowded bedding surfaces (eg. Figure 27B) is probably the result of intraspecific competition for available space; an increase in the density of tracemaking individuals simultaneously exploiting the same horizon, would result in a concomitant increase in the number and frequency of animal-burrow and animal-animal encounters.

Environmental Zonation . The analogy between the West Coast blood worm *Euzonus mucronata* and the *M. segregatis* tracemaker can be even further strengthened by taking aspects of environmental zonation into account. As already indicated, it is a striking feature that the *M. segregatis* zone occurs with such tremendous lateral persistence and within such a narrow and seemingly unvaried stratigraphic position (i.e. always perched high within the foreshore sequence). Interestingly enough, the zonal distribution of *E.mucronata* , as occurring at Long Beach, appears to show precisely the same relationship (Figure 28). Here, thriving populations of *E.mucronata* (conservative estimates being somewhere in the order of 2,500 to 3,000 worms per square foot) occur confined, to the almost complete exclusion of all other macrobenthos, in a very distinct, continuous shore-parallel zone situated high within the intertidal. A visual account of the various factors thought to be involved in governing this relationship is given in Figure 28; a more comprehensive discussion will form the subject matter of a forthcoming paper (Saunders et al, in prep).

FIGURE 28

Diagramatic representation of animal-environmental relations across the transitional foreshore-backshore low tide profile at Long Beach, Vancouver Island. (from Saunders et al, in prep).



INTERTIDAL
COMMUNITY DYNAMICS
Long Beach, Vancouver Island

B. BACKSHORE-BARRIER ISLAND SANDSTONE

Above the *Macaronichnus* zone, planar lamination may persist for several meters before dissappearing altogether. Here, however, the distinctive wedge-like set intersections of the underlying foreshore sands do not occur, and instead lamination takes on a more horizontal aspect. At the Sundance Coulee section (Figure 4) this transition appears to take place across an irregular diagenetic boundary: moderately well cemented foreshore sands below give way to resistant, ledge-forming calcite-cemented sand above. At all sections, carbonized plant fragments, woody imprints, and veritcal rhizoliths become increasingly abundant upward, usually culminating at the top of the zone in an irregular, cemented layer of extremely carbonaceous and extensively rooted sand (Figure 24A).

The vertical transition from clean laminated sandstone to carbonaceous root-penetrated sand towards the top of this zone records the final stages of shoreline progradation, marking the passage of the sub-aerial backshore-barrier-island land surface. The upward increase in vegetable matter implies that the density of plants colonizing the barrier increased progressively landward away from the shoreline. Furthermore, the presence of coal or carbonaceous shale capping these sands testifies to the existence of a peat forming swamp or marsh environment flanking the landward side of the barrier. At most localities, the coal/carbonaceous shale facies is in turn overlain by dark grey-brown carbonaceous mudstone of inferred back-barrier lagoonal origin; elsewhere, tidal channel sands have eroded through lagoonal muds and rest directly on the coal (Figure 24C). Nowhere, however, were these channels observed to have eroded through the coal and into the underlying barrier-island sands.

The thickness of the backshore-barrier island sequence may vary tremendously, and along southwest-northeast trending coulee walls (shoreline parallel) the upper surface typically reveals large scale undulatory ridge and swale topography (Figure 24D). Within the ridges sets of root -penetrated large scale cross-bedding can usually be discerned overlying the planar laminated backshore sands. In such cases, these ridges are thought to represent small incipient backshore dune fields.

V RAHMANI'S TIDAL INLET COMPLEX

INLET SEQUENCE AT EC-5

(Units 2 and 3 in figure 29)

Description.: At section EC-5 in the northwesternmost corner where the study area overlaps that of Rahmani (1981, 1983), the sequential-stratigraphic character of the Middle Appaloosa undergoes a fundamental change. Here, a "classic" fining upward *tidal inlet* sequence occurs incised into the lower shoreface, replacing the pre-existing record of upper beachface deposits (figure 29). A tidal inlet interpretation for the sequence follows essentially that of Rahmani (1983). An overall reassessment of ideas is here given, however, in light of the fact that Rahmani had based most of his observation on an exposure (section EC-4) occurring approximately 500 meters to the southeast. As will be discussed subsequently, the sequence at EC-4, although genetically related, bears fundamental differences to the sequence as occurring at EC-5, and in my estimation does not represent a true tidal inlet sequence.

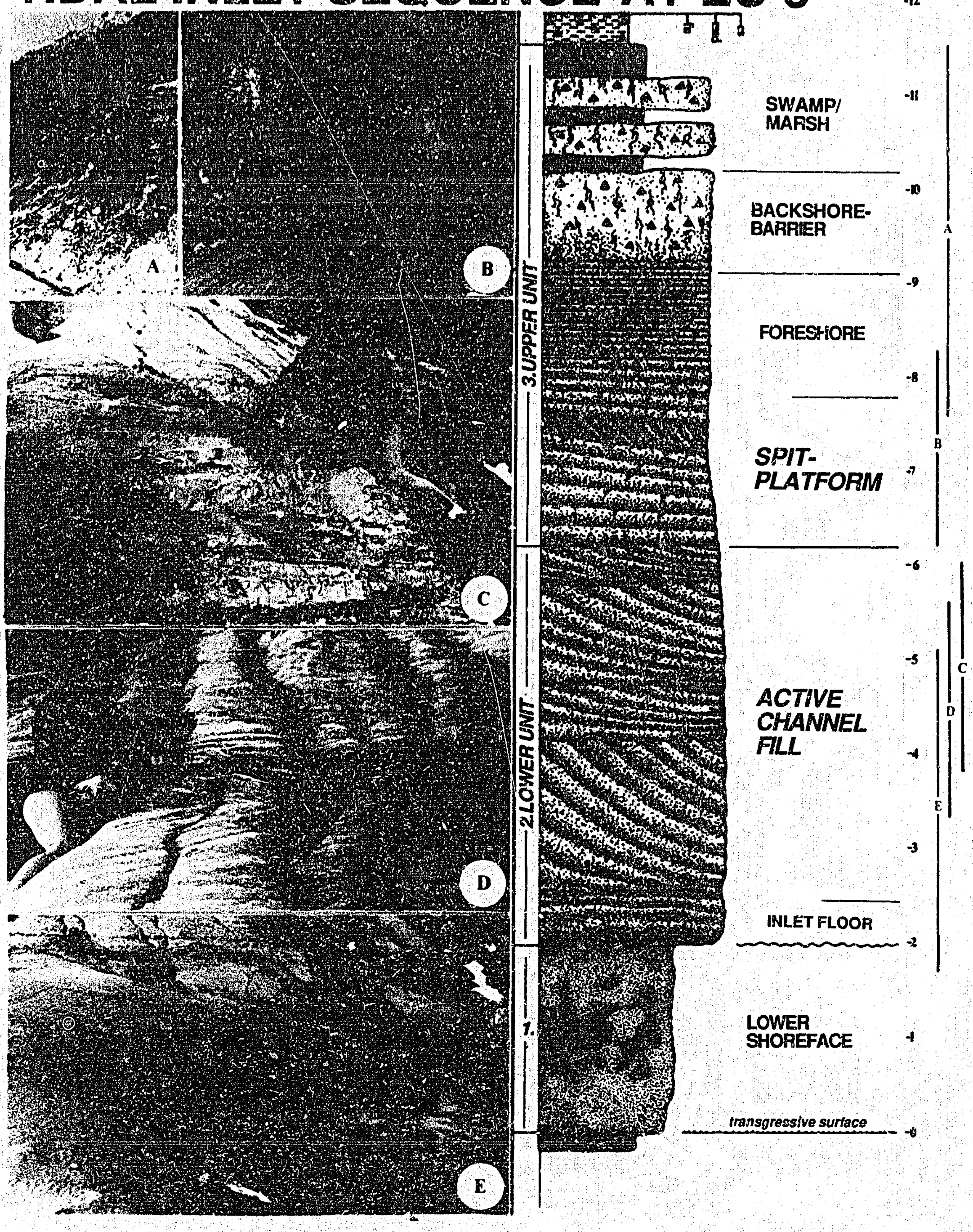
The inlet sequence fines upward from medium-coarse to fine-medium grained sandstone, and is structurally divisible into two main units. The lower unit or *active channel fill* begins with a basal lag of coalified wood, followed by a 4.2 meter succession of large-scale trough cross-stratified sandstone. Here, individual cross-bed sets commonly show a discordant toeset-foreset couplet arrangement, and decrease upward thickness from 1.5 meters to 0.5 meters at the top. Laminary drapes of coarse carbonitized plant debris occur locally in the lower parts of foresets, becoming increasingly concentrated in the underlying toesets. Paleocurrent observations, in accordance with previous measurements by Rahmani (1983; figure 32), indicate dominant flow in a southeastern or *offshore* direction.

Passage into the*upper unit* of the sequence is marked by the dissappearance of large-scale cross-bedding, and the concomitant appearance of dominantly planar laminated

FIGURE 29

Vertical sequence characterizing the Appaloosa Cycle at EC-5; stratigraphic extent of photographs is shown to the right of column.

TIDAL INLET SEQUENCE AT EC-5



sandstone along with rare interspersed sets of small scale cross-stratification. In the lower meter of the unit, planar stratification dips gently to the southeast (apparent dips of 5 - 10 degrees). Above this, laminae gradually "flatten-out" and the remaining sequence becomes very similar to that as described for the Upper Zone elsewhere in the study area. One fundamental difference worth mentioning, however, involves the anomalous thickness of the *Macaronichnus* zone. Here, rather than being restricted to a discrete zone within the upper foreshore sequence, burrow profusions persist right to the base of the unit, a vertical distances of 2.8 meters.

Interpretation.: In the past two decades, tidal inlets, and in particular those occurring along the Atlantic seaboard of the United States, have become widely studied for their sedimentologic significance (for recent reviews see Hayes and Kana, 1976; Hayes, 1980; Barwis and Makurath, 1978; and Moslow and Tye, 1985). Kumar and Sanders (1974) have speculated that owing to the migratory nature of these systems, as much as 20-40% of all modern barrier islands may be underlain by inlet-filling sands.

Moslow and Tye (1985) have summarized the overall sedimentological spectrum of tidal inlets into *wave-dominated* and *tide-dominated* end member extremes. Comparing the sequence at EC-5 to wave-dominated inlet sequences, such as that formed through the lateral migration of Fire Island Inlet, New York (Kumar and Sanders, 1974), reveals a striking analogy: in both the modern and ancient, large-scale, ebb cross-stratified *active channel fill* sands are seen to give way vertically, with decreasing grain size and bedset thickness, to dominantly planar laminated sands of the spit-platform/beachface complex.

Reddering (1983) warned that the recognition of ancient inlet sequences may be obscurred by the fact that within the lower part of the sequence palecurrent patterns are largely unidirectional. The "true key" to identifying the tidal inlet signature may, therefore, lie instead in the nature of the associated overlying facies: with regards to the present succession, the overlying association of planar laminated, *Macaronichnus* -bearing foreshore sands makes an inlet interpretation seem virtually unequivocal.

LATERAL FACIES RELATIONSHIPS

The measured section of the inlet sequence at EC-5 forms part of an extended northwest-southeast trending outcrop tract along which the Appaloosa sands are more/less continuously exposed. Consequently, the rare opportunity is afforded in which to walk-out, almost through its entirety, a complete latero-vertical mosiac of intracoastal through open-ocean tidal inlet related barrier island facies. Progressing first in a landward (northwestern) direction away from EC-5, the inlet sequence can be seen to grade, almost imperceptably, into the channel fill sands of an associated back-barrier tidal channel complex; the most notable sedimentologic change here involves the dissappearance at the top of the sequence of the *Macaronichnus* -bearing beachface sands. The underlying channel fill sands, on the other hand, undergo little in the way of noteworthy change (see Rahmani, 1983 for detailed account of tidal channel facies).

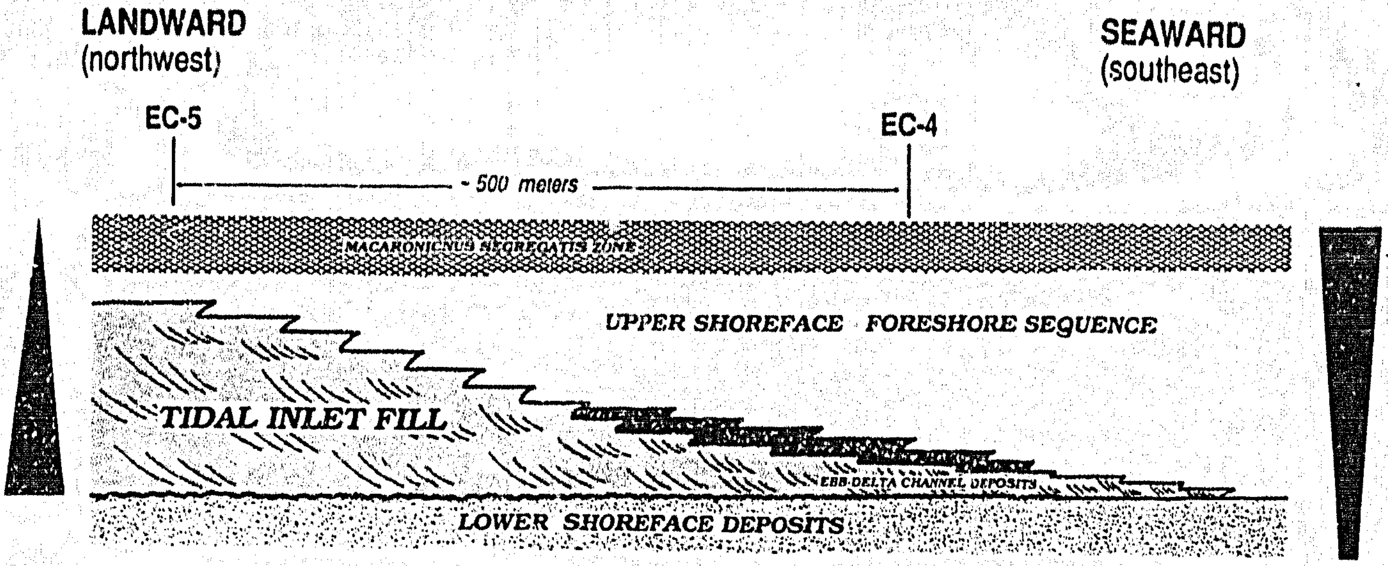
Now consider the seaward (southeast) progression going from EC-5 towards EC-4 and beyond (Figure 30A). While the foreshore sequence, apart from a marked thinning of the *Macaronichnus* zone, persists essentially unchanged, the underlying fining-upward tidal inlet-spitbar sequence undergoes a fundamental transition, passing laterally (again by process of gradual replacement) into a coarsening-upward upper shoreface sequence. As shown in Figure 30A, progressing to the southeast, more and more of the upper shoreface sequence appears at the expense of the underlying inlet fill. At the same time, the basal inlet sands trace seaward into an erosional tongue of medium-coarse grained sandstone displaying ebb-oriented decimeter scale cross-stratification. In the vicinity of EC-4 (Figure 31) the vertical transition from these basal ebb cross-bedded sands (Unit 2) into the overlying upper shoreface sequence (Unit 5), takes place across a bed of *O. borneensis* riddled, fine-grained sandstone (Unit 3) which, in turn, capped by a thin unit of wavy and lenticularly bedded

FIGURE 30

Dynamic stratigraphy of tidal inlet complex occurring in the northwesternmost corner of the study area.

A. (Upper Diagram). Interfingering laterovertrical relations between intracoastal tidal inlet facies to the northwest and open ocean shoreface facies to the southeast.

B. (Lower Diagram). Idealized model of Barrier Island tidal inlet dynamics demonstrating how rapid inlet migration coupled with and, followed by, net shoreline progradation, can be used to account for the observed laterovertical relations as shown in figure A. White arrows denote the pathway of environments as reflected in vertical sequence at EC-4 and EC-5.



TIDAL INLET COMPLEX

dynamic stratigraphy

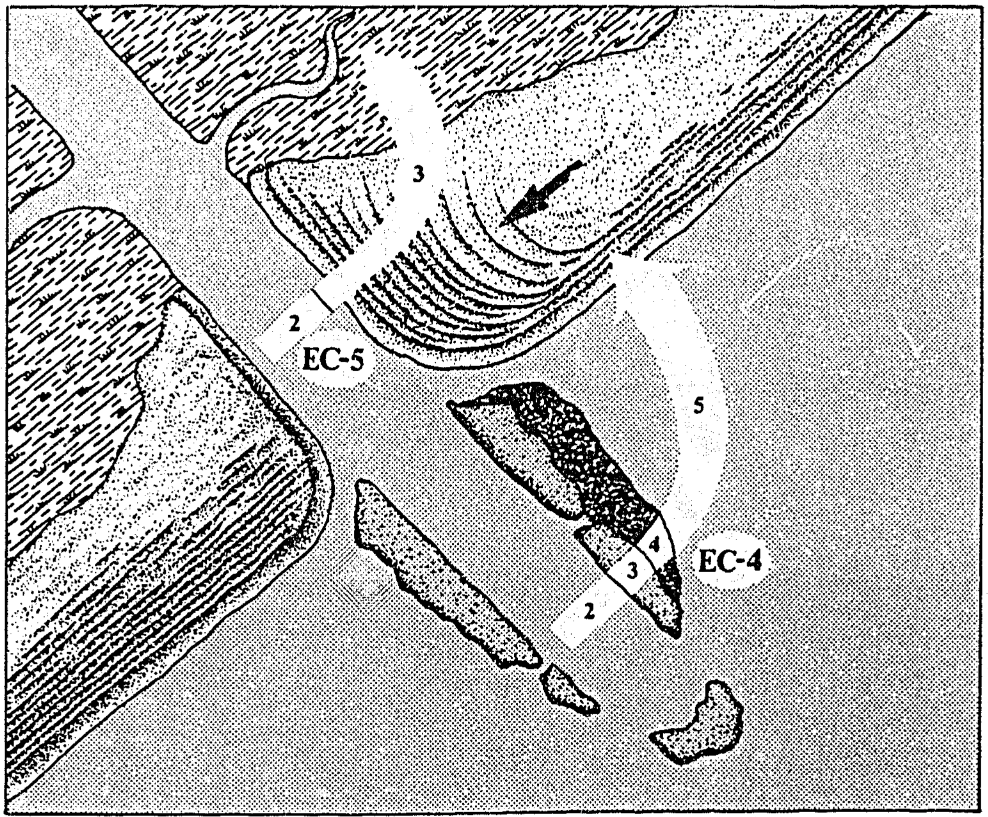
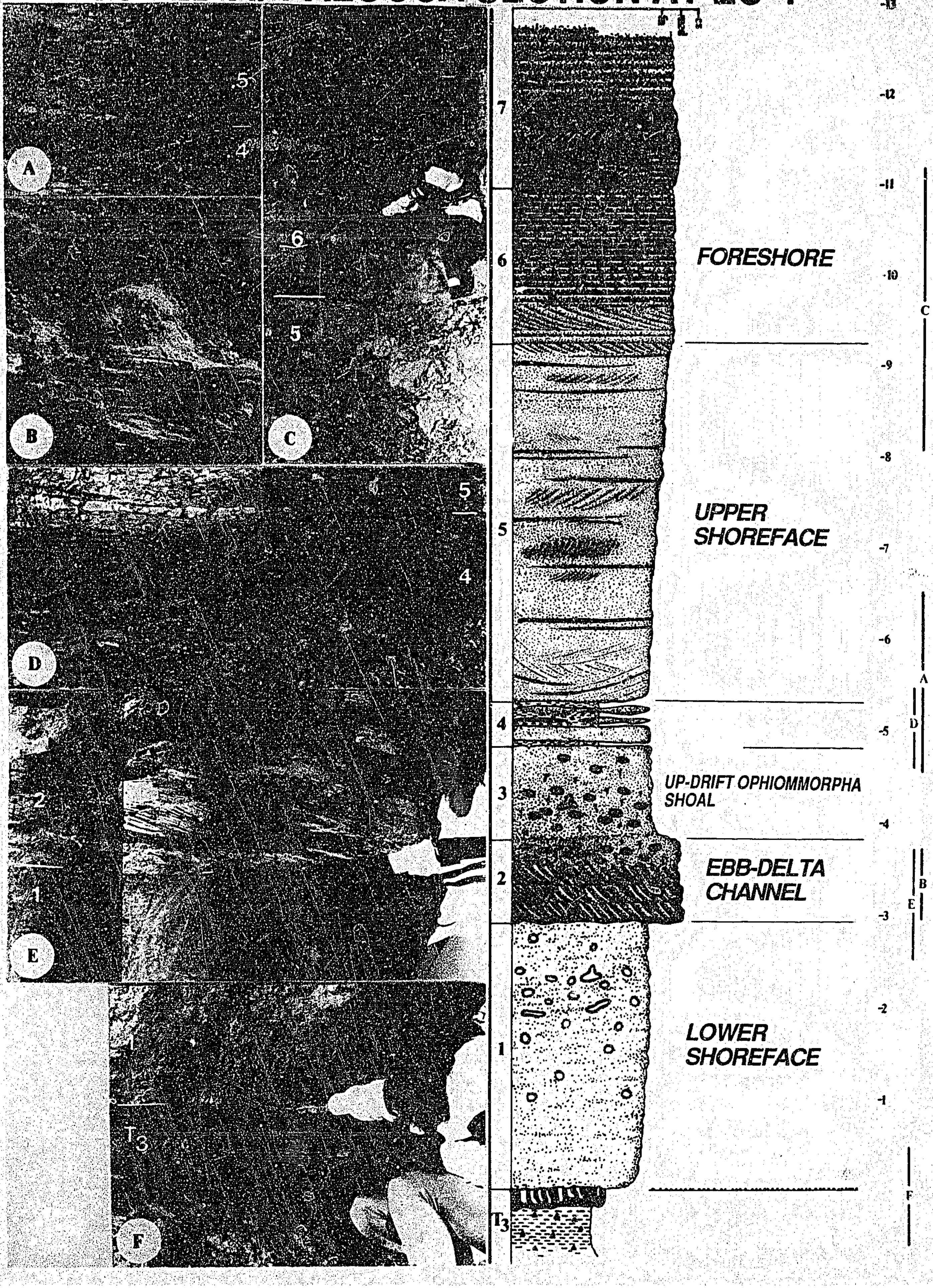


FIGURE 31

Vertical sequence characterizing the Appaloosa Cycle at EC-4; stratigraphic extent of photographs is shown to the right of column.

MEASURED APPALOOSA SECTION AT EC-4



ripple laminated sand and mud (Unit 4).

In light of the above, it is thought that as the inlet channel complex entered the line of section, in the vicinity of EC-5, it was accompanied to the southeast by a seaward extending ebb-delta channel complex (as recorded in the scouring and deposition of Unit 1 at EC-4). Figure 30B is an attempt to summarize this relationship diagramatically. At EC-5, continued migration of the inlet complex led to the establishment of progressively shallower channel and, ultimately, contiguous updrift inlet margin environments (i.e. the *Upper Unit* in Figure 29). At the same time, in the vicinity of EC-4, with the associated migration of the seaward-extending ebb-channel complex, the adjacent updrift ebb-shoal environments (Units 3 and 4 in Figure 31) were then carried into and across the line of the section; Unit 3 at EC-4, undoubtably marks the passage of an environment in which turbulance levels were sufficiently attenuated in order to have allowed the*O.borneensis* tracemaker to proliferate (see earlier discussion). Paleoecologically, Unit 3 might therefore be contrasted to the lowermost upper shoreface deposits occurring elsewhere in the study area. Finally, the vertical transition at EC-4 into the overlying wavy-lenticular beds of Unit 4 records the passage of an up-drift ebb delta-related environment within which turbulence levels were even further reduced and/or suspended mud fractions occurred in anomolously high concentrations, thus allowing for preferential settlement and preservation: as referenced in an earlier discussion, the incorporation of mud accumulations within a succession of otherwise high-energy sandy deposits does not always necessitate the need to invoke prolonged periods of suspensionate quiescience (cf. Oertel, 1973; McCave, 1970, 1971).

VI SYSTEMATIC ICHNOLOGY

Ichnogenus *Diplocraterion* Torell, 1870

Diplocraterion Torell, 1870, p. 17, Fürsich, 1974a, Hantzschel, 1975, p. W67

Diagnosis. Vertically oriented cylindrical U-shaped spreiten burrows.

Remarks. Fürsich (1974) revised the taxonomy of vertical, U-shaped spreiten burrows to include a single valid ichnogenus, *Diplocraterion.* Based primarily on burrow outline and the directional growth of the spreite, 5 distinct ichnospecies are currently recognized: (1) *D. parallelum* - diplocrateria having parallel walls and unidirectional spreite; (2) *D. helmerseni* - diplocrateria exhibiting a markedly expanded base; (3) *D. biclavatum* - diplocrateria in which the arms hyperextend the base of the U-tube forming two blind pouches; (4) *D. habichi* - diplocrateria with upward divergent arms; and (5) *D. polyupsilon* - diplocrateria possessing spreite that are partially or completely bidirectional (Fürsich, 1974).

Diplocraterion parallelum Torell, 1870

Pl. 1, fig. 1-8, Pl. 2, fig. 1-5

Description. (Bed X specimens) Vertically oriented tubular burrows embodying full length unidirectional protrusive spreite. U-tubes are circular to sub-circular in cross-section, and possess sharp, *unlined*, sometimes irregular walls; infill, where preserved, are composed of fine sand containing abundant admixed plant detritus and rod-shaped facal pellets. Two distinct size associations occur: (1) relatively large specimens with tube diameters, widths, and lengths (sensu Knox, 1973) averaging 12 mm, 70 mm, and 250 mm, respectively; and (2) comparitively small specimens with corresponding average measurements of 3 mm, 15 mm, and 40 mm. Among the larger size class, burrow arms characteristically remain straight and near parallel throughout the full length of the structure, although minor lobate expansion and contractions do occur in a number of specimens: in the smaller burrows, the arms, although remaining parallel, begin with a vertical orientation then deflect horizontally into the plane containing both arms. In specimens paralleling the plane of preservation, erosion of the main spreiten body locally reveals uniform patterns of well preserved scratch marks incised into the rock adjacent to the burrow wall. Individual scratch-marks form relatively continuous, uniformly sized and spaced furrows (average width 1mm) that roughly parallel one another and conform to the overall curvature of the spreite. Tube diameter to spreiten width ratios average 1:5.

Discussion. In many cases, reconstructing the ethology and identity of a tracemaker solely from the morphologic characteristics of its lebenssperen leads to a considerable amount of speculation. Quite often, however, the ethology will be clearly expressed, and by applying a working knowledge of the range of organisms producing similar lebenssperen in the modern, the general trophic level and gross identity of a tracemaker can be assumed (Osgood, 1975; Dorjes and Hertweck, 1975).

In the case of *D. parallelum*, the vertical aspect and distinctive U-shaped spreiten morphology readily identifies these structures as the domichnia of suspension feeding organisms (cf. Pemberton and Frey, 1984a; McCarthy, 1979; Fürsich, 1974a). Among modern marine benthos, certain species of suspension feeding Polychaetes, Echiuroids, and Crustaceans are known to construct U-burrows that bear spreite and thus closely approximate the *Diplocraterion* structure (see Fürsich 1974a for a complete discussion).

Ichnogenus *Teichichnus* Seilacher, 1955

Teichichnus rectus Seilacher, 1955

Pl. 3, fig. 1-4

T. rectus Seilacher 1955, p. 378, Pl. 24, fig. 1; Fürsich, 1974, fig. 27b, 33, p. 40; Howard and Frey, 1984, p. 211-212, fig 21.

Diagnosis. Vertical blade-like spreiten structures consisting of several closely concentric, horizontal or inclined, longitudinally nested individual burrows adjoining single parent trunks; spreiten typically retrusive but may be protrusive (Howard and Frey, 1984).

Description. Straight horizontal, vertically retrusive, cylindrical burrows, commonly displaying a slight longitudinal complexity and where fully preserved are adjoined at either end by an upward reaching aperatural shaft; the overall structure, therefore, approximates a broad, flat bottomed "U" having a length/depth ratio in the order of 3-5: 1. Final tubes, when present display circular cross-sections with a diameter range of 6 - 12mm. Most specimens, however, preserve only the spreite, which characteristically thicken towards the longitudinal axis, and usually record relatively short retrusions, averaging 1 cm, with a recorded maximum of 3.5 cm. Individual burrows commonly interpenetrate but never branch.

Discussion. Fürsich (1974) described specimens from the Corallian of England and Normandy characterized by an extensive spreiten wall, and suggested that the most probable tracemaker was a vermiform deposit-feeding organism systematically exploiting the substrate for food. The specimens described here, however, record relatively short retrusions, strongly resembling the recent burrows of *Nereis diversicolor* figured by Seilacher (1957). In this case, the spreite probably represent an equilibrium response of the tracemaker in attempt to maintain the bottom of its burrow at an optimal depth below the sediment-water interface within an incrementally aggrading substrate.

Ichnogenus *Gyrocorte* Heer, 1865

Gyrocorte comosa Heer, 1865

Pl. 3, fig. 5-8

Gyrocorte Heer, 1865, p. 142; Hallam, 1970, p. 190-195; Heinberg, 1973, p. 228-231; Häntzschel, 1975, p. W65.

Diagnosis. Predominantly horizontal, unbranched, blade-like, vertically penetrative bilobate trails.

Description. Straight to tortuous, distinctly bilobate horizontal bedding trails that commonly interpenetrate but never branch. Modular morphology of epichnial specimens consists of twin, parallel hemi-cylindrical lobes, tangentially adjoined creating a narrow median furrow; better preserved specimens reveal the characteristic oblique biserial transverse lobe segmentation. The penetrative nature of these structures was confirmed by scrutinizing specimens which, along their length, transect a succession of bedding surfaces. Trail widths vary from 2 to 15 mm; lengths commonly exceed 30 cm with a recorded maximum of 52 cm. Corresponding hypichnia comprise twin furrows and a median ridge.

Discussion. At present *Gyrocorte* encompasses a single ichnospecies, *G. comosa* . Heer (1877) in his original description, interpreted *Gyrocorte* as Algae, or alternatively, the egg strings of Molluscs. Later interpretations included (1) trails formed by *Corophium* (Nathorst, 1981); (2) the repeated impressions formed through the collapse of a plant in beach sediment at successive low tides (Funcini, 1936); and (3) amphipod collapse tunnels excavated just beneath the sediment-water interface (Hallam, 1970). It has since, however, been convincingly demonstrated based on an analysis of exceptional specimens from Greenland (Heinberg, 1973), that *Gyrocorte* represents a crawling-feeding structure formed by an elongate Polychaete-like organism which fed while moving obliquely through the sediment; this was interpreted by Heinberg as an adaptation towards better exploitation of the sediment for food.

Ichnogenus *Ophiomorpha* Lundgren, 1891

Ophiomorpha Lundgren, 1891, p. 114-118; Häntschel, 1975, p. W85-W86; Frey, Howard and Prior, 1978, p. 199-275; Howard and Frey, 1984, 204-206.

Diagnosis. Simple to complex burrow systems distinctly lined with agglutinated pelletoidal sediment.

Remarks. The morphologic, taxonomic and environmental significance of the ichnogenus has been reviewed by Bromley and Frey (1974) and Frey et al (1978). In the modern, thalassinidean shrimp, including certain species of *Callianassa*, *Upogebia*, and *Axius*, construct complex burrow systems identical in fabrication to *Ophiomorpha* (Frey et al, 1978). At present, four distinct ichnospecies, differentiated primarily on the bases of wall construction, are recognized: *O borneensis*, *O. nodosa*, *O. annulata* and *O. irregulaire.*

Ophiomorpha borneensis Keij, 1965

Pl. 4, fig. A-J

Diagnosis. Burrow walls consisting predominantly of dense, regularly distributed biobate pellets.

Description. Large, complex burrow systems, with overall configurations ranging from (1) predominantly horizontal maze-like tunnel networks having only minor vertical components (figure), to (2) irregularly branched three-dimensional boxworks involving all of vertically through horizontally oriented components (figure). Cross-sections vary from circular to elliptical (tunnels only); component diameters range from 0.4 to 4.0 cm, becoming markedly enlarged at points of branching. Burrow walls characteristically display a mammilated outer lining, and most when viewed in cross-section, reveal an inner somewhat irregular lining, 0.5 to 6.0 mm thick, consisting of sideritized mud with varying amounts of admixed sand: here, a concentric layering may be evident. External pellet morphologies of the outer wall are dominantly bilobate --1.5 to 6.0 mm in height, 2 to 5 mm in width, and 3 to 13 mm in length--with pellets almost always oriented transverse to burrow axis; in most burrows, single, ovoid to polygonal pellets occur interspersed with the doubles, and locally may constitue the dominant pellet morphology. Internally, pellets are composed of agglutinated, concentrically laminated sand and mud. Usually, tunnel roofs and walls are densely mammilated with well developed, uniformly distributed pellets; towards tunnel bottoms, however, pellet morphologies and distributions become increasingly irregular, and pellets are commonly either sparse, or are altogether absent. Burrow infills consist predominantly of structureless sand identical to host stratum; occasionally, isolated burrow components may reveal distinct meniscate backfill, or inclined to horizontal laminary infills. Of 29 thin sections cut, most revealed superbly preserved ellipsoidal fecal pellets, occurring randomly distributed throughout both burrow infills and the inner and outer wall linings; pellets consist of either sideritized or calcified clay sized material, and some appear to contain traces of collophane; diameters average 2.5 mm, with a maximum recorded length of 5 mm; internal pellet structure reveals a distinctive bilaterally symmetrical configuration of x-sectionlly cresentic canals; four inward facing marginal pairs, along with an outward facing central pair.

Discussion. On the basis of internal fecal pellet morphology the *O. borneensis* tracemaker for the Appaloosa specimens has been tentatively identified as a species of *Axius*, an extant species belonging to the tribe Thallasinidae. Modern "*Ophiomorpha* "-like burrows of Axius serratus were investigated from the Strait of Canso, Nova Scotia (Pemberton et al., 1976).

Ophiomorpha nodosa Lundgren, 1891

Pl. 10, fig. A-F

Diagnosis. Burrow walls characterized by a dense mosaic of regularly to irregularly distributed discoid, ovoid or polygonal pellets (*sensu* Frey and Howard, 1985)

Description. An extraordinarily large, prevasively sideritized form of *Ophiomorpha* characterized by sprawling, highly irregular tunnel networks interconnected with isolated, near vertical shafts. Tunnel diameters display a high degree of variability within any given system but are consistently larger than *O. borneensis* (averaging ~ 6 centimeters). Locally tunnels expand into irregular, sheet-like chambers; blind tunnels with tapered, rounded terminations, are relatively common; tunnel sides and roofs are heavily re-enforced with thick (up to 1 centimeter) linings of irregularly sized and shaped pellets: here, multiple pellet layers can usually be discerned; average pellet diameter 0.5 centimeters. Tunnel bases are decidedly flat and sparsely pelleted. Vertical shafts are characteristically smaller in diameter than tunnels (average 3.5 centimeters) and exhibit near circular cross-sections. Maximum observed length of shafts 42 centimeters: actual sub-interface depth of horizontal tunnel networks not determined.

Ichnogenus *Arenicolites* Salter, 1857

Diagnosis. vertically to sub-vertically oriented spreitenless U-burrows.

Arenicolites variabilis Fursich, 1974

Pl. 6, fig. D & E

A. variabilis Fursich, 1974, p. 5-9, fig. 4, 5b, and c; Howard and Frey, 1984, p. 201-202, fig. 4.

Diagnosis. Simple, unlined to thinly lined, vertical to slight oblique, cylindrical U-shaped tubes having no spreiten; outline geometry of U-tube highly variable.

Description. The vast majority of the Appaloosa specimens are know only from bedding surfaces, preserved as either (1) conspicuously paired hemi-spherical to sub-hemispherical ridges, or (2) endichnia made visible from the surrounding matrix either by having a contracting color and/or composition , or by possessing a thin (<1mm) fine-grained, commonly sideritized wall lining. Tubes are circular to sub-circular in x-section with diameters ranging from 1.5 to 17.0 mm, and inter-opening spacings from 1 to 12 cm; no correlation between diameters and spacings was recognized. In addition to the more common bedding surface preservation, a small number of vertically exposed burrows were observed, revealing a full range of U to V-shaped x-sectional geometries, most being somewhat irregular and asymmetric in outline; perfectly symmetric U-bends were not observed; maximum observed burrow length was 28 cm.

Although in most specimens the two burrow openings are identically sized, a number of the larger specimens display one aperature that is grossly enlarged with respect to the rest of the burrow, forming an upper expanding funnel with top diameters 1.2 to 1.5 times that pervading the rest of the structure; such burrows may also reveal a subsidiary trunk branching off the main U-structure at one end.

Remarks. The individual burrow openings of *A. variabilis* , when viewed on bedding surfaces, are indistinguishable from *S. linearis* , and can therefore only be indentified by the conspicuous occurrence of burrow pairs. Consequently, where densities are moderate to high, individual *A. variabilis* entities may become impossible to discern; in the absence of longitudinal sections this problem is unavoidable.

Ichnogenus *Palaeophycus* Hall, 1847

Diagnosis. Distinctly lined, horizontal to sub-vertical, straight to gently curved, cylindrical burrows. Wall linings range from very thin to relatively thick, and are either smooth, longitudinally striated, or longitudinally striated and transversly annulated. Infills typically are of the same composition as the host stratum.

Discussion. *Palaeophycus* is differentiated from the superficially similar ichnogenera *Planolites* and *Macaronichnus* primarily by the presence or of absence of a wall-lining, and the character of the burrow infill; lined burrows infilled with sediment more or less identical to the host stratum are assigned to either *Planolites* or *Macaronichnus* (Pemberton and Frey, 1982; see also discussion on p. 00). It is of fundamental importance, however, that the mantle concentration of mafic grains characterizing burrows assigned herein to *Planolites sp.* and *Macaronichnus* (ethologically reflecting a specialized deposit feeding behavior), not be taxonomically confused with the true burrow linings of *Palaeophycus* (ethologically representing a fabricational wall re-enforcement of an open burrow).

Palaeophycus tubularis Hall, 1847

Pl. 11, fig. 3, 6 & 7

P. tubularis, Hall 1847, p. 7-8; Pemberton and Frey, 1982; Pemberton and Frey, 1984

Diagnosis. *Palaeophycids* possessing thin, unornimented wall linings.

Description. Horizontal to sub-horizontal, cylindrical burrows possessing a thin, dark organic mud wall lining up to 1 mm thick. Cross-sections are circular to sub-circullar, with diameters of 4 to 8 mm recorded; known solely from relatively short, straight, unbranched, poorly preserved endichnia, and epichnia.

Palaeophycus herberti Saporta, 1872

Pl. 6, fig. A-C

Palaeophycus herberti Pemberton and Frey, 1982, Plate 4; fig. 4.

Diagnosis. Smooth, unornamented, thickly lined cylindrical burrows (sensu Pemberton and Frey, 1982).

Description. Predominantly vertical to subhorizontal, gently curved to J-shaped, thickly lined cylindrical burrows. Diameters range from 0.8 to 2.3 centimeters and are constant along burrow length. Wall linings range from 2 to 4 millimeters in thickness and consist of clean, sorted sand markedly depleted with the darker grain constituents of the ambient sand. Vertical burrow components exhibit near perfectly circular cross-sections while sub-horizontal components often show minor compaction. Maximum observed length was 23 centimeters.

Ichnogenus *Macaronichnus* Clifton and Thompson, 1978

Macaronichnus Clifton and Thompson, 1978, p. 1293 - 1294, fig. 1 - 3; Curran, 1985, p. 263, Pl. 1, fig. B,D, Pl. 2, fig. A; Fursich and Heinberg, 1983; Dupre, 1984.

"Curved non-branching bedding plane burrows" Tillman and Martinsen, 1985, p. 17, fig. 17.

Planolites Heinberg, 1974, p. 15; Chisholm, 1970, p. 24, Pl. 1, figs. 1, 2, 3, 4.

"Horizontalschliff Hantzschel and Reineck, 1968, Tafel 14, fig. 1.

"Haustoriid Amphipod Burrow " Radwanski et al, 1978, p. 237 - 239, fig. 10.

Type species. *Macaronichnus segregatis* Clifton and Thompson, 1978, from the Painted Rock Sandstone Member of the Vagueros Formation, Santa Lucia Range, California.

Origin of Name. From the Italian "*macaroni* " in general reference to size and shape.

Emended Diagnosis. Predominantly horizontal, unlined, tubular burrows of small to moderate size and variable configuration. Infills comprise clean, structureless to weakly backfilled, lightish colored sand showing a marked depletion in the darker grain constituents as occurring in the ambient sediment; an overabundance of such grains occurs at the infill periphery, giving rise to a distinct though often subtlely expressed "mantle"; infill/mantle junction sharp; mantle/ambient sediment junction gradual. Preserved as endichnia and less commonly as epichnia.

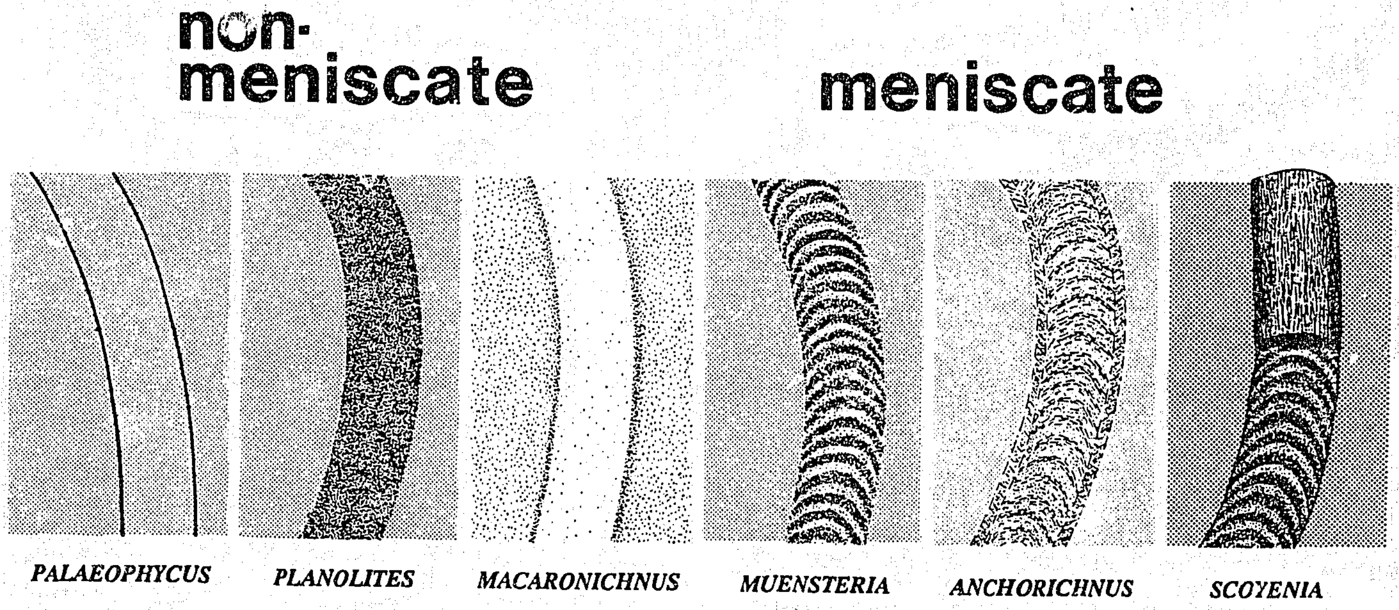
Discussion. The combination of infill character and wall structure (modular morphology) has proven invaluable in establishing a working taxonomy for the group of ichnofossils encompassing horizontal to inclined cylindrical burrows (cf. Pemberton and Frey, 1982; Frey et. al. 1984). In terms of modular morphology, burrows presently included in the concept of *Macaronichnus* are best diagnosed as being: (1) unlined but distinctly walled [the characteristic mantle concentration of mafic grains not constituting a true burrow lining (sensu Pemberton and Frey, 1982) as suggested by Curran (1985)]; and (2) infilled with clean, mafic deficient sand, either structureless or faintly backfilled. In this way, *Macaronichnus* can readily be distinguished from morphologically similar forms such as *Planolites, Palaeophycus, Muensteria, Anchorichnus, and Scoyenia* ; all of which share in common the same basic predominantly horizontal, quasi-cylindrical plan morphology; all, with the exception of *Palaeophycus* , reflecting the locomotory - backfill feeding activity of highly motile infaunal organisms (figure 34).

Known Occurrences . Although equivalent burrows were originally described from the Jurassic Pecten Sandstone, East Greenland (Heinberg, 1974; see also Fursich and Heinberg, 1983), virtually all subsequent reportings of *Macaronichnus*, have been confined to North America, the vast majority of which being from the Cretaceous of the Western Interior. The oldest confirmed occurrence is presently credited to the Permo-Pennsylvanian Fountain Formation of Colorado Springs (H.E. Clifton, pers. comm. 1986). It is however, worth mentioning that *Macaronichnus* has also been tentatively identified from the Mississippian Borden Formation of Kentucky (Chaplin, 1980; Figure 25), and the late Visean of Scotland (Chisholm, 1970, figure?). Both these occurrences, however, are based solely on my own identification of burrows from published photos accompanied by very little in the way of descriptive clues.

In retrospect, it is somewhat difficult to conceive that such burrows could have gone so long undetected in the rock record. One must consider, however, that only in recent times, with the advent of the ichnofacies concept (Seilacher, 1958, 1964, 1967), has trace fossil research in North America been directed toward the in-depth study of potential *Macaronichnus* -bearing geological successions. The other major factor to consider, as previously pointed out by Clifton and Thompson (1978), is that the trace itself is often extremely subtle in appearance. Where outcrop or even core conditions are less that ideal, the burrows could easily be overlooked by the non-specialist, particularly where the ambient sand contains low dark grain

FIGURE 32

Comparative diagram isolating the modular relationship between *Macaronichnus* (Clifton and Thompson, 1978) and morphologically related forms such as *Palaeophycus, Planolites, Muensteria, Anchorichnus* and *Scoyenia.*


non-meniscate
meniscate
PALAEOPHYCUS
PLANOLITES
MACARONICHNUS
MUENSTERIA
ANCHORICHNUS
SCOYENIA

percentages.

ICHNOSPECIES DESIGNATIONS

As outlined by Pemberton and Frey (1982), many of the taxonomic inconsistancies and ambiguities still plagueing certain groups of ichnofossils, stem from the inadequate description and diagnosis of the type material. Clifton and Thompson (1978), although giving a relatively concise description of *Macaronichnus segregatis* , unfortunately did not include a proper synonomy and, moreover, failed to communicate - via a formal diagnosis - exactly what morphologic features are considered as diagnostic. The problem is further compounded by the fact that specimens from a number of different geologic units were described collectively. Such a practice can be justified only if material from all occurrences is first carefully examined on a separate basis, hence assuring that no significant inter-sample taxonomic differences exist. Unfortunately, however, while the integrity of the ichnogenus in terms of its *modular concept* (figure x) can readily be extended to all known occurrences, aspects of *pathway configuration* can not. Clifton and Thompson (1978) appear to have inadvertantly included together two seemingly distinct ichnospecific forms: (1) *M. segregatis* as typified by specimens occurring on the Miocene Age Painted Rock Sandstone Member of the Vaqueros Fm (see Clifton and Thompson, 1978 fig. 1 p. 1294) and (2) what I have referred to here to as *M. simplicatus n.ichnosp.* as typified by specimens described by the authors from the Miocene Branch Canyon Sandstone (see Clifton and Thompson, 1978; figs. 2 and 3 p. 1294). I am suggesting that these two forms be given ichnospecific status in light of fundamental differences in grazing configuration: where bedding plane concentrations are moderate to high, *M. simplicatus* will characteristically interpenetrate; whereas *M. segregatis* , owing to a strong phobotaxic/thigmotaxic behavior exercized by the tracemaker, will not (see earlier discussion).

Macaronichnus segregatis Clifton and Thompson, 1978

Text fig. 27 A-G

Macaronichnus segregatis Clifton and Thompson (1978), p. 1294, Fig. 1 "Curved non-branching bedding plane burrows" Tillman and Martinsen, 1985, p. 17, fig. 17.

Emended Diagnosis. Predominantly horizontal burrows displaying random non-systematic to distinctly spiraled pathway configurations; burrows characteristically exhibit a strong tendency towards the avoidance of interpenetration.

Holotype. Sample collected by D.L. Durham on repository at U.S. Geological Survey, Menlo Park, California.

Decription of Appaloosa Specimens. Unlined, distinctly walled, cylindrical burrows preferentially oriented along horizontal planes with minor subhorizontal to sub-vertical components. Burrow infill noticeably lighter in color than host sand resulting from the almost complete absence of mafic mineral grains; a thin, but distinct mantle concentration of such grains (pseudo-lining) commonly occurs immediately exterior to wall, further excentuating burrows from host sand. At a glance, infills appear structureless, however, upon close examination faint sand-on-sand backfills are often, but not always discernable. Burrow cross-sections are circular to eliptical showing a pronounced horizontal flattening; diameters measured horizontally range from 1.5 to 3.0 mm (commonly 2.0 - 2.5), are extremely constant along burrow length, and at any given outcrop a common diameter usually prevails amoungst all burrows.

Subspecies variety M.segregatis segregatis. Along bedding surfaces where densities are moderate to high, individual burrows are seen to follow smooth but randomly curving and meandering paths. In spite of high burrow densities, interpenetrations and close contact cross-overs are extremely rare; instead, where one burrow converges on another, the typical response is to either curve sharply away, coming within a finite distance (phobotaxic behavioral response), or to swing parallel maintaining a more-less constant separation for a short distance before again diverging off (thigmotaxic behavioral response). On crowded bedding surfaces, the repetition of such responses imparts what is herein referred to as a "random avoidance" pattern of exploitation.

Subspecies variant M.segregatis spiralis. On bedding surfaces characterized by low burrow densities, individual burrows were on occasion found displaying distinctive planispiral bedding configurations of varying levels of perfection. Where well developed, burrows spiral outwards, in either dexral or sinistral fashion, from an initial circular to sub-circular coil 1.5 to 2.5 cm in diameter, with an observed maximum of 12 coils. In most specimens, an open but close and relatively constant spacing is maintained between successive coils (commonly 0.5 to 2.0 mm), although minor irregularities do occur in all specimens.

Macaronichnus simplicatus n.ichnosp.

Pl. 11, fig. 1-5 & 7

Macaronichnus segregatis Clifton and Thompson, 1978, p. 1294 fig. 2 and 3; Curran, 1985, p. 263, Pl, fig. B, D, Pl. 2, fig. A.

Planolites Chisholm, 1970, p. 24, Pl. 1, figs. 1, 2, 3, 4.

Diagnosis. Variably oriented but predominantly horizontal burrows that, upon burrow-to-burrow encounters, will characteristically interpenetrate.

Description of Appaloosa Specimens. Distinctly walled, unlined, predominantly horizontal, straight to randomly curving and meandering, cylindrical burrows that characteristically interpenetrate. Burrows exibit circular to sub-circular cross-sections, with constant along-burrow diameters of 1.5 to 8.0 mm; bimodal size distributions commonly occur within a given population.

Ichnogenus Thalassinoides Ehrenberg, 1944

Thalassinoides suevicus Rieth, 1932

Text fig. 17 C

Diagnosis. Large burrow systems consisting of smooth-walled, essentially cylindrical components. Branches are Y to T-shaped and are enlarged at points of bifurcation. Burrowdimensions may vary within a given system. Some systems are essentially horizontal whereas others are irregularly inclined (Pemberton and Frey, 1984).

***Description* (*Little Big Coulee, Unit 2 Association*).** Predominantly horizontal to sub-horizontal, cylindrical burrows, and Y-branched burrow systems. Diameters range from 18 to 35 mm and, within a given system, can show considerable along length variation, typically becoming somewhat enlarged at branchings. Burrow walls, although somewhat irregular, are unlined and decidedly sharp. Infills comprise a poorly sorted admixture of siditized fine-grained sandstone and organic matter (contrasting markedly with the host mudstone), and subsequently being reburrowed by *Chondrites*. Preserved as Endichnia.

Ichnogenus *Skolithos* Halderman, 1840

Skolithos linearis Halderman, 1840

Pl. 6, fig. F-H

S. linearis Halderman, 1840, p. 3; Alpert, 2974, p. 661-663; McCarthy, 1979, p. 360 fig. 3i; Pemberton and Frey, 1984, p. 297-298, fig. 7a.

Diagnosis. Simple, vertically to sub-vertically oriented cylindrical shafts possessing a distinct, unlined to thinly lined wall structure.

Description. Predominantly vertical, unlined to thinly lined, straight to gently curved, circular to sub-circular cylindrical shafts. Linings, where present, seldom exceed 1 mm, and consist of either: (1) dark organic mud; or (2) clean agglutinated sand lighter in color than both the casting medium and burrow infill. Diameters range from 1to 9 mm with lengths up to 14 cm recorded.

Discussion. Preserved as epichnial ridges, and less commonly as endichnia. Interpreted as the dwelling structure (domichnia) of suspension feeding annelids, ie.; certain polychaetes and phoronids (cf. Pemberton and Frey, 1984). Unlined forms probably represent temporary dwellings of itinertant organisms (cf. McCarthy, 1979), whereas the presence of a distinct wall lining, albeit thin, implies a more permanent residency allowing sufficient time for burrow re-enforcements to be made.

Ichnogenus *Cylindrichnus* Howard, 1966

Cylindrichnus concentricus Howard, 1966

Pl. 5 fig. 1, 3 & 5

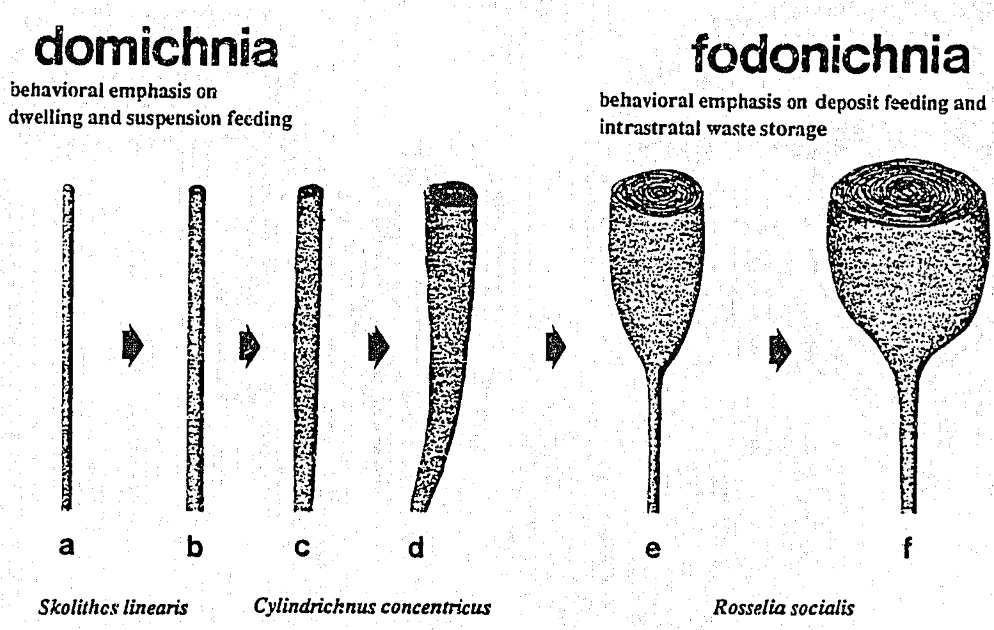
C. concentricus Howard, 1966, p. 45, fig. 10; McCarthy, 1979, p. 361, P1.1, fig. 8; Pemberton and Frey, 1984, p. 289, fig 12b; Howard and Frey, 1984, p. 203, fig. 7.

Diagnosis. Relatively long, subcylindrical to subconical burrows, straight to gently curved, vertical to horizontal, having concentrically layered walls (Howard and Frey, 1984).

Description. Relatively large, deeply penetrating, vertical to subvertical, straight to gently curved, cylindrical burrows possessing a central core surrounded by a thick, downward tapering, concentric to slightly excentric laminary wall. Burrows occur either in solitary form, or more commonly comprise 2 or more (maximum 4) equally sized branches all extending to a common interface from a single parent stock; point of branching typically occurs 25 to 30 cm below the inferred apertural interface; maximum recorded length for total structure is 50 cm.

FIGURE 33

Diagram illustrating the morphologic intergradations and behavioral changes along an ichnospecific continuum from *Skolithos linearis* to vertically oriented *Cylindrichnus concentricus* and *Rosselia socialis*. Burrow A (unlined *S. linearis*) represents the temporary dwelling of an itinerent suspension feeder; development of a distinct wall lining in burrow B (still *S. linearis*) represents a step towards a more permenant inhabitance in which wall re-enforcement was of primary importance; development of a thin to moderately thick laminary wall in burrow C reflects, in addition to wall re-enforcement, the maintainance of an open domicile, in falling sediment being pressed directly ;into the burrow wall. Finally, burrows E and F (*R. socialis*) show the development primarily the outward reworking of sediment involved directly or indirectly in the process of feeiding; note downward gradation of funnels to a basal stem indentical in fabrication to burrow C (*C. concentricus*); burrow D (thickly lined, conically tapering *C. concentricus*) may overlap with this behavioral catagory.


domichnia
behavioral emphasis on dwelling and suspension feeding
fodonichnia
behavioral emphasis on deposit feeding and intrastratal waste storage
a
b
c
d
e
f
Skolithos linearis
Cylindrichnus concentricus
Rosselia socialis

Ichnogenus *Rosselia* Dahmer, 1937

Diagnosis. Conical to irregular bulbous structures, vertical to inclined, consisting of a small central burrow surrounded by broad, concentric, funnel-like laminae, tapering downward to a concentrically walled stem (Pemberton and Frey, 1982).

Remarks. At present, three ichnospecies of *Rosselia* are recognized, based on fabricational differences of the upper feeding structure: (1) *R. socialis* - formed by the outward laminary growth of a more or less stationary tube (Dalmer, 1937); (2) *R. rotatus* - formed by the back-filling of a tube which moved in a rotational pattern about a central axis (McCarthy, 1979); and (3) *R. chonoides* - a somewhat abberant form in which the sediment has been reworked in spreite-like helicoid swirls (Howard and Frey, 1984).

Rosselia socialis Dahmer, 1937

Pl. 9, fig. A-H

R. socialis. Dahmer, 1937, p. 532-533; Frey and Howard, 1970; Hautzschel, 1975, p. w101.

Diagnosis. Coniform to funnel-shaped *Rosselians*: central tube surround by concentric laminations of biogenically processed sediment.

Description. Relatively large, vertically oriented, bulbous, protuberant structures comprising a simple, deeply extending, sharp walled, curcular to subcircular core ranging in diameter from 6 to 12 mm; upper portion of core centrally encapsulated within an upward expanding, coniform to funnel-shaped sediment body consisting of concentric laminae nested convexly downward; laminae consist dominantly of sideritized mud with thin, somewhat irregular interlaminations of less intensely sideritized sand; burrow core infilled with sand identical to host stratum. Funnel diameters range from 10 to 35 cm, with diameter/length ratios of 1:1-3. Downward, funnel structure tapers to a thin, concentric wall lining, 1-5 mm, about the basal core.

Discussion. In addition to the basic solitary cone morphology, burrows commonly comprise a vertically stacked succession of two or more individual feeding cones (recorded maximum 4): others comprise a single feeding cone with 2 or more upper burrow openings (Plate). These structures evidently reflect a post-storm burrow re-adjustment response on behalf of the trace maker (see earlier in text discussion).

Ichnogenus *Conichnus* Myannil, 1966

Ichnospecies *Conichnus conicus* Myannil, 1966

Pl. 7, fig. 2-6

C. conicus: Howard 1966, fig. 15; Frey and Howard 1970, fig. 8b; 1981, figs. 1A, 2A-E; Howard and Frey, 1984, fig. 7.

Diagnosis. Conical to acuminated subcylindrical structures, vertically oriented, thinly lined, having a smooth, sharply rounded basal apex (Howard and Frey, 1984).

Description. Large, vertically oriented, unlined, conical, plug-shaped burrows terminating downward in a smooth, well rounded base. Basal cross-sections are typically circular to subcircular, becoming increasingly oval and irregular towards the top of the structure; upper diameters range between 5 and 29cm, with corresponding lengths of 7 to 46 cm; width to length ratios vary from about 1:1.5 to 1:3. Burrows are infilled with sideritized sandstone in which fragments of petrified woody material are both ubiquitous and abundant, often rivalling the sand as the dominant infill constituent (see text figure 9F).

Discussion. The preferential siderite cementation causes the burrows to weather out from the surrounding weakly cemented host sands, forming conspicuous nodular protuberances, the distinctive iron-red coloration and mere size of these structures adds to their prominence on the outcrop. *C. conicus* evidently represents the resting-dwelling trace formed by itinerant anemone or anemone-like organisms.

Ichnogenus *Asterosoma* v. Otto, 1854

Asterosoma, v. Otto, 1854, p. 15; Hantzschel, 1975, p. W43; Fursich, 1974b, p. 38.

Diagnosis. Relatively large, fan to star-shaped burrows with bulbuous, spreitenless, outward tapering rays extending from a central shaft.

Asterosoma sp.

Pl. 5, fig. 4, 6 &7

Description. Relatively large, fan-shaped burrows comprising numerous (15 to 50) outward thickening, finger-like horizontal elements all radiating from a common vertically inclined shaft. All radial elements are morphologically alike, possessing cylindrical exteriors, and distinctly rounded distal terminations. In cross-section, individual elements are circular to horizontally elliptical, and consist of a central core 3 to 5 mm in diameter, mantled by a distally thickening, concentrically laminated wall 1 to 5 mm thick. Constituent elements are tangentially arrayed with minimal interpenetration occurring between neighboring elements. Distinct horizontal planes occur in most specimens, along which a small number of radial elements are aligned; elsewhere, constituent elements are distributed and stacked in a more irregular fashion. The axial shaft, preserved from a single specimen, extends an indeterminate distance both above and below the radial elements and possesses a circular 7 mm diameter core, surrounded by a 5 mm thick concentrically laminated wall; a slight horizontal shift of the axial shaft towards the radial fan, is inferred by the excentricity of the core.

Discussion. These burrows evidently represent combined feeding-dwelling structures formed by a vermiform organism which fed by systematically exploiting the substrate in a radial fashion about a vertically oriented tube (Chamberlain, 1971; Fursich, 1974). The tracemaker evidently possessed a strong phobotaxic behavioral sense, as evidenced by the tangential arrangement of individual feeding probes. These specimens, although clearly belonging to *Asterosoma* , resemble in size an overall plan geometry, specimens of *Dactyloidites ottoi* figured by Fursich and Bromley (1985), but differ by lacking the distinctive spreiten morphology of the radial elements.

Ichnogenus nov.

Tentative Diagnosis. Large, distinctive sideritized spreiten structures formed through the combined lateral migration and outward concentric laminary growth of an unbranched, geometrically varied causative cylindrical tube.

Remarks. Based on the overall configuration of the causative burrow, taking also into account the morphology of the spreiten body, three distinct morpho-ethologic forms, tentatively referred to as A, B, and C, can be recognized. Full intergradation between these forms can be expected to occur. Based on the nature of internal fabrication, *Ichnogen. nov.* is interpreted as a combined feeding-dwelling structure. Although the biological affinities of the tracemaker have not as yet been positively determined the intimate association between *Ichnogen. nov.* and *O. borneensis* may suggest a genetic link.

Ichnogen. nov. type A.

Pl. 8, fig. 7-9

Description. Essentially horizontal, broadly U-shaped forms; spreite can be either protrusive or retrusive.

Ichnogen. nov. type B

Pl. 7, fig. 1

Description. Causative burrow forms a relatively compact, inward and upward spiralling, more-less parallel armed "U"; successive whorls are nested inwards.

Ichnogen. nov. type C

Pl. 8, fig. 1-6

Description. Characterized by a solitary, upward and openly spiraling causative burrow; spreiten always protrusive.

Ichnogenus *Rhizocorallium* Zenker, 1836

Rhizocorallium Zenker, 1836, p. 219; Fürsich, 1974b, p. 18; Hantzschel, 1975, p. W101.

Diagnosis. U-shaped spreiten-burrows, parallel or oblique to bedding planes; limbs more or less parallel and distinct; ratio of tube diameter:diameter of spreite >1:5 (Pemberton and Frey, 1984)

Remarks. At present, the ichnogenus *Rhizocorallium* encompasses three ichnospecies; *R. jenense, R. irregulaire,* and *R. uliarense.* The first species, *R. jenense* is interpreted as the domichnia of a suspension feeder (see discussion below), where as the latter two forms, *R. irregulaire,* and *R. uliarense*, owing primarily to their distinctive plani - and trochispiral burrow configurations and preferred horizontal orientation, are best interpreted as fodonichnia (Fusich, 1974c).

Rhizocorallium jenense Zenker, 1836

Pl. 12, fig. 4 & 6-8

Description. Obliquely oriented , relatively narrow Rhizocorallia displaying discontinuous, step-like retrusive spreite; each successive retrusion displaces the vertex of the burrow, both vertically and horizontally, by up to 5 mm. All specimens are closely sized, with tube diameters ranging from 9 to 12 mm, and spreite varying between 3.5 and 5.5 mm in width. Maximum observed length was 30 cm. Burrows display smooth exterior wall surfaces; most of the internal characteristics, including wall structure and infill composition, were evidently de0stroyed in the sideritization process. The final causative U-tube, preserved in a single specimen, arches with parallel arms upward into the vertical; overall dimensions include a length of 20 cm, a width of 5 cm, and a constant tube diameter of 1.1 cm; this specimen also revealed the presence of a relatively thick (2 mm) laminary wall lining.

Discussion. The following morphological aspects combine to indicate that the *R. jenense* tracemaker was a suspension feeder rather than a deposit feeder (cf. Fursich, 1974):

(1) the oblique orientation and relatively short burrow length.

(2) the presence of a relatively thick laminary wall lining.

(3) the retrusive nature of the spreite, evidently reflecting an equilibrium response to an incrementally agrading substrate.

Rhizocorallium sp.

Pl. 12, fig. 1-3 & 5

Description. Horizontal, planiform, U-shaped, protrusive spreiten burrows up to 20 cm in length. Burrow arms, although relatively straight, diverge symmetrically towards the closed end of the structure resulting a gradual widening of the spriete in that direction [from 5 to 8 cm in one specimen]. U-tubes display circular cross-sections with constant along burrow diameters of 18 to 20 mm. Distinct external *Ophiomorpha* -like discoid, and hemi-spherical pellets (4-7 mm in diameter) were observed on all specimens, scattered about the upper spreite, although also somewhat obscured by diagenisis, do appear to conform with the curvature of the final U-tube.

Discussion. In addition to establishing a genetic link between *Rhizocorallium sp.* and the *Ophiomorpha* tracemaker, the presence of isolated pellets on the wall exterior indicates that the feeding process, rather than continuous, was periodically halted during which time minor wall re-enforcements of the causative burrow were made. Hence, these burrows are perhaps best interpreted as combined feeding dwelling structures, and along with *N. ichnogen A* , may represent opportunistic feeding responses of the *Ophiomorpha* tracemaker.

Ichnogenus *Chondrites* von Sternberg, 1833

Chondrites sp.

Text fig. 17A & C

Diagnosis. Dentritic, smooth walled, regularly but asymmetrically ramifying small burrow systems that normally do not interpenetrate or interconnect. Diameters of components within a given system remains essentiall constant (Pemberton and Frey, 1984).

Description. Relatively small, subhorizontal to sub-vertical, branched, cylindrical burrow systems characteristically displaying ramiform plant-like configurations. Irregularly spaced offshoot tunnels stem from a main trunk and may in turn support further ramifications. Individual branch components vary tremendously in length, and are either straight or, more commonly, gently curved. Burrow diameters range from 1.0 - 2.0mm but remain constant within a given burrow system. Cross-sections are near circular; walls are decisively sharp and unlined. Infills are passive, consisting of fine-grained sand.

Ichnogenus *Helminthopsis* Heer, 1877

Helminthopsis sp.

Text fig. 18A & B

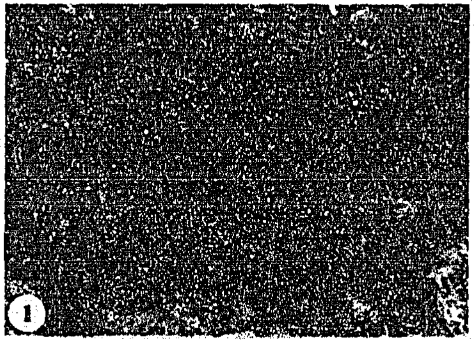
Diagnosis. Predominantly horizontal, unlined, unbranched, cylindrical, highly meanderous burrows. Overall, pathway configuration is irregular in nature, not involving any strictly developed style of undulation.

Description. Predominantly horizontal, unbranched, unlined, tubular burrows characterized by wandering strings of variable but more or less regularly sized, tight, elongate meanders. Although burrow are overall predominantly horizontal, individual meanders occur vertically as well as horizontal. Consequently, in plane preservation the burrows appear discontinuous, consisting largely of short hooked segments, circular dots, and/or strings composed of relatively few meanders. Burrow cross-sections, although near circular, show a subtle horizontal flattening; diameters range from 0.3 - 4.0mm, are constant along burrow length, and within any given burrow population, one diameter typically prevails. Burrows typically occur in dense intrastratal concentrations; it is a characteristic feature, however, that burrows seldom interpenetrate one another. As a result, bioturbation never truly proceeds to 100 per cent. Preserved as endichnia and epichnia. Interpreted as pascichnia.

VII. TRACE FOSSIL PLATES

PLATE 1

Figs. 1 - 8 *Diplocraterion parallelum* Torell, 1870 All specimens from bed X of section S.D.-1. **Figs. 1, 5 & 6** give an indication of tremendous density of burrows. **Figs 7 & 8** relatively small specimens showing pronounced sideways deflection. Scratch marked burrow exteriors can be found by closely examing figures 1,2,4,5 and 6.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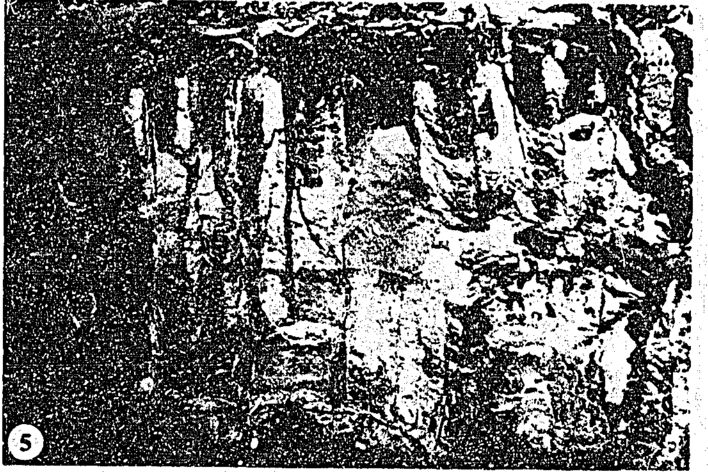
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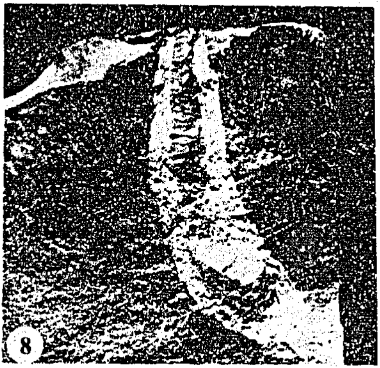
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PLATE 2

Trace fossils from the Appaloosa Sequence

Figs. 1 - 5	*Diplocraterion parallelum* Torell, 1870. Figs. 1 & 2 specimens from base of Appaloosa at EC-4. Here burrows subtend from the transgressive surface, and are excavated into a back-barrier coal seam evidently exhumed during transgressive shoreface erosion. Figs 3, 4 & 5 scratch marked specimens preserved within tidal flat muds capping R, deltaic sequence at Little Big Coulee; here burrows subtend from transgressive surface at R 1 and R2 boundary.

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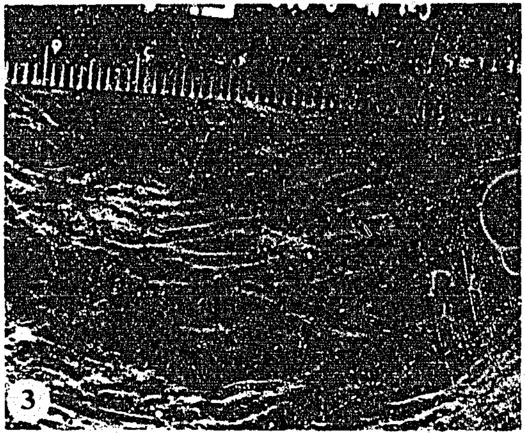
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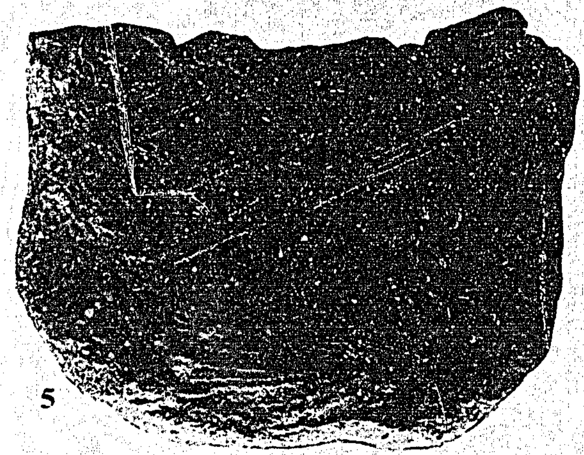
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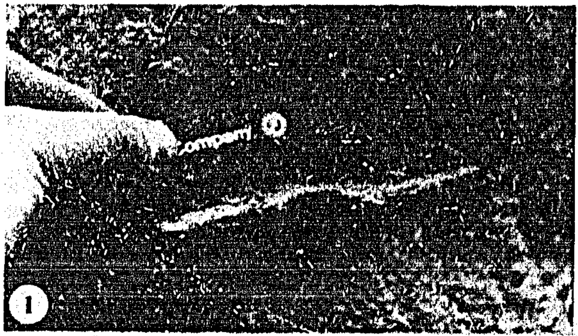
PLATE 3

Trace fossils from the Appaloosa Sequence

Figs.1 - 4	*Teichichnus rectus* Seilacher, 1955. **Fig. 2** plan view of interpenetrating burrows. **Figs. 1, 3, & 4** of vertical outcrop faces; **Fig. 3** dense profusion of burrows. **Fig. 4** exceptionally well preserved specimen showing full U-structure including aperatural arms.
Figs. 5 - 8	*Gyrocorte comosa* Heer, 1865. **Fig. 5** epichnial specimens from BC-1 preserved on upper surface of a Swaley X-stratified storm sand: note tremendous size variation. **Figs 6-8.** hypichnial specimens from L.B.C.-1 preserved on the base of a resistant parallel laminated storm sand.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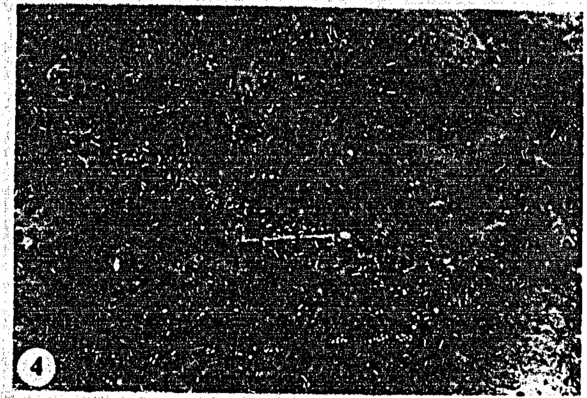
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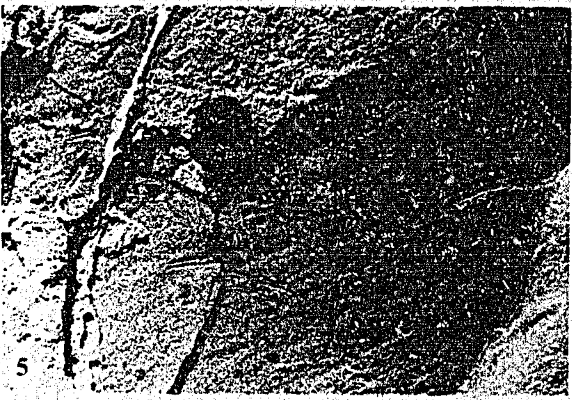
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PLATE 4

Fig. A-J. *Ophiomorpha borneensis* Kiej, 1965. **Fig. A** Triple junction from Unit 6 at Boot Coulee: note of branching **Fig. B.** oblique view of well-exposed 'maze-like' system. **Fig. C.** silicified specimen from Unit 3 at EC-4 showing well preserved double-pellets. **Fig. D.** plan view of gently meandering tunnel with well preserved double pellets. **Fig. E, G & I.** Vertical to subvertical exposed system; note *Teichichnus*-like retrusive spreiten migration of tunnel situated above ruler. **Fig. H.** horizontal plan view of branched tunnels with well preserved wall structures. **Fig. J.** Burrow segments isolating pelletal structure of wall.

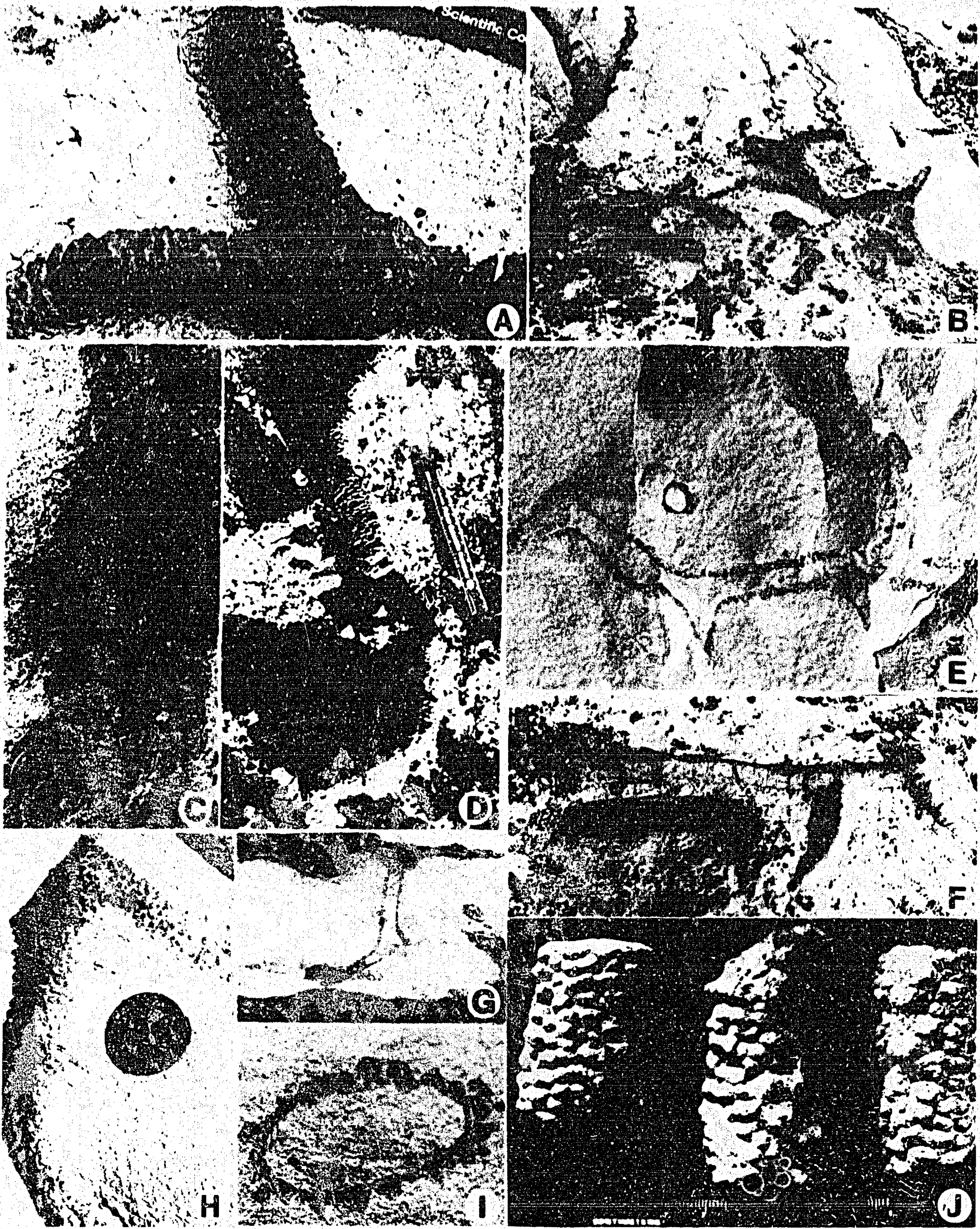
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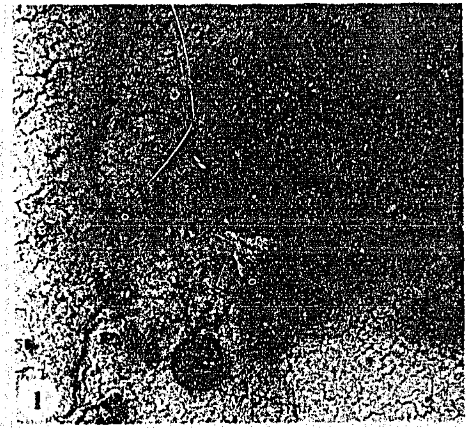
PLATE 5

Trace Fossils from the Appaloosa Sequence

Figs.1, 3 & 5	*Cylindrichnus concentricus* Howard, 1966. Figs. 1 & 3 specimens from Unit 4 at DOR-1 displaying upward branching of basal stock into 2 and 3 separate elements. Fig. 2 top view of specimen in figure 5. Fig. 3 multiple specimens within lower shoreface at EC-5.
Figs.4, 6 & 7	*Asterosoma sp.* Fig. 7 plan view of specimen from unit 4 at DOR-1: note concentrically laminated central shaft. Fig. 4 x-section of specimen in figure 6: note tangential arrangement of radial elements. Fig. 6 specimen showing characteristic outward branching of radial elements.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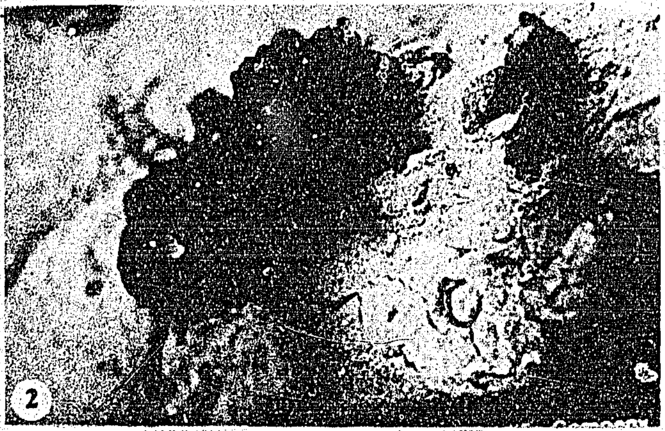
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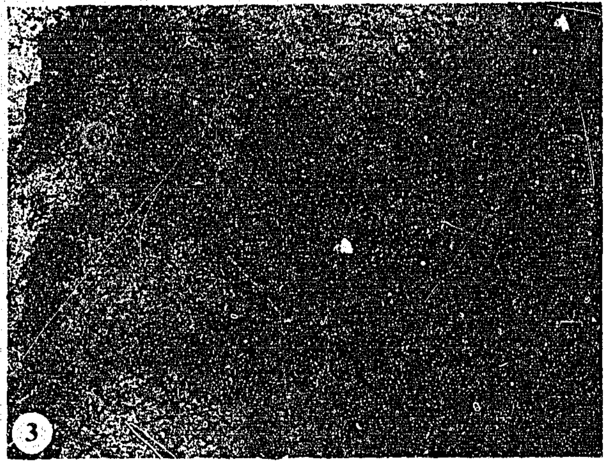
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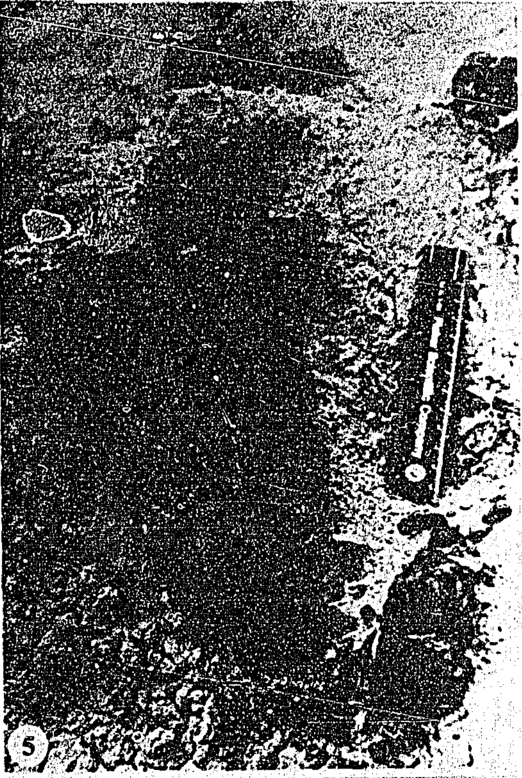
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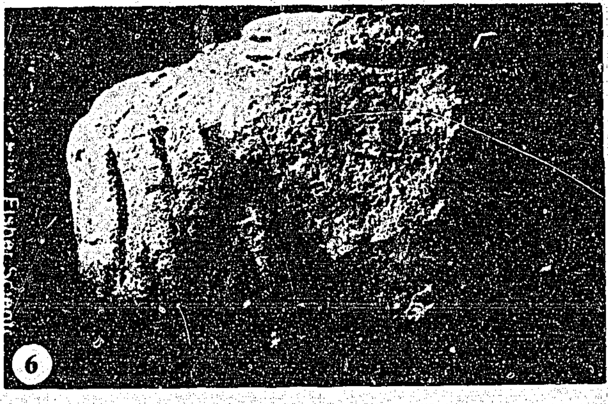
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PLATE 6

Figs. A-C. *Palaeophycus herberti* Saporta, 1872. **Fig. A.** Gently curved specimen in near vertical exposure. **Fig. B.** Vertical face showing partially collapsed subhorizontal components (black arrows) in association with *Teichichnus rectus*. **Fig. C.** Close-up bedding view of specimen displaying near circular x-section and characteristic color contrast between infill and wall.

Figs.D & E. *Arenicolites variabilis* Fürsich, 1974. Both photos taken from bedding surfaces near the top of the Appaloosa sequence at EC-4; note size differential of individual openings comprising paired associations.

Figs.F-H. *Skolithos linearis* Halderman, 1840. **Fig. F.** x-sectional view of specimens occurring within laminated-to-rippled lower shoreface sands. **Fig. G.** specimen displaying thick lining. **Fig. H.** bedding plane profusion on upper surface burrow of HCS bed at Sundance Coulee.

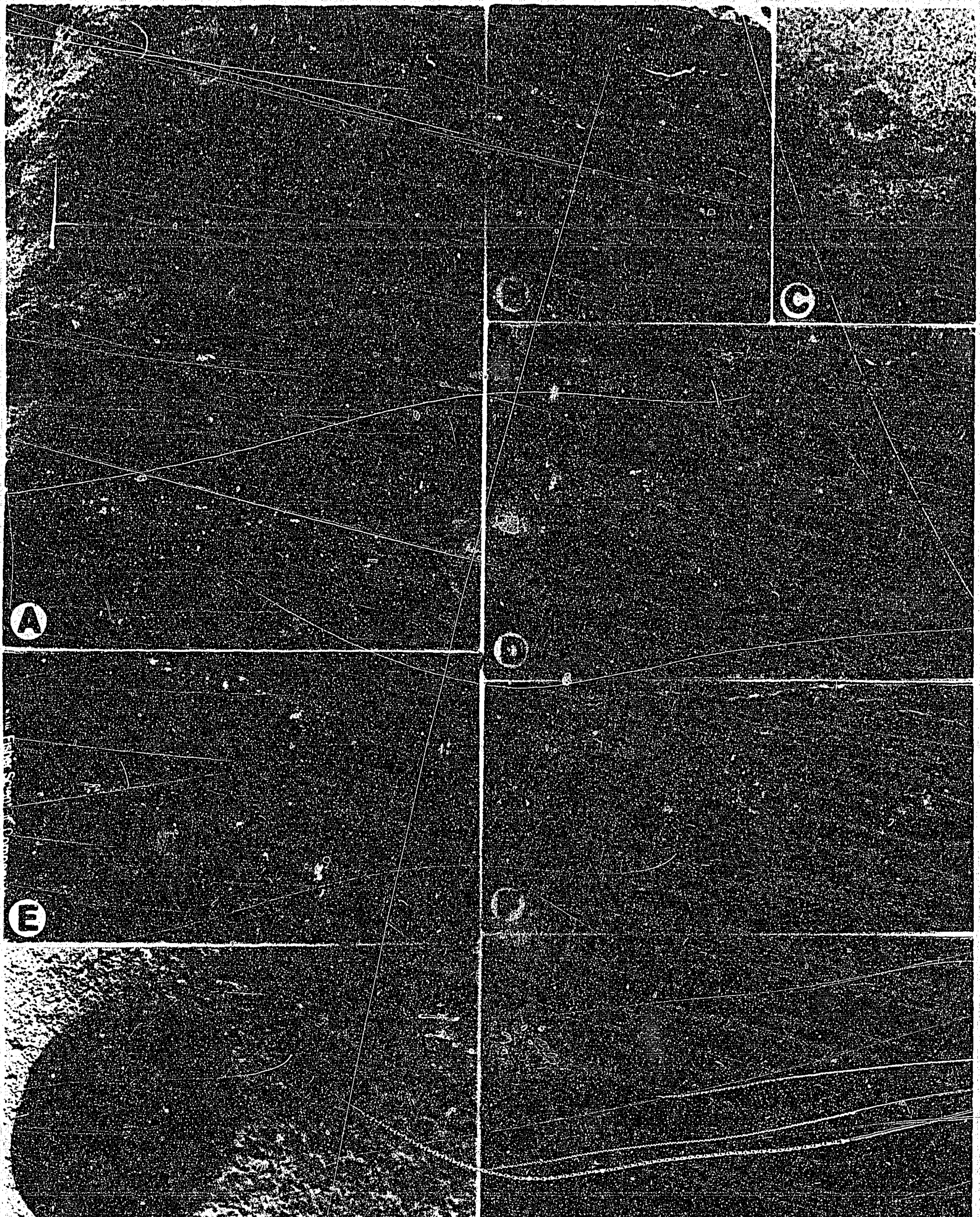
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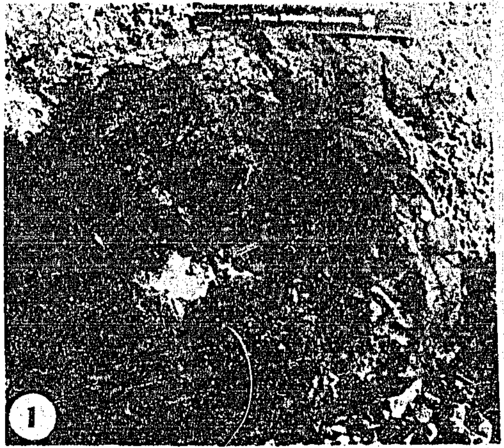
PLATE 7

Fig. 1 *Ichnogen. nov. B*. plan view of type specimen from Unit 1B at S.C.-1: note characteristic upward and inward nature of coiling; although resembling Rhizocorallium in overall geometry (see Fürsich, 1974), this burrow is made distinct by the presence of a thick laminary wall structure.

Figs. 2-6 *Conichnus conicus* Myannil, 1966. Protuberant sideritic specimens from Unit 1 at Sundance Coulee. **Fig. 3** cluster of relatively small specimens, indicating the trace maker, at least during juvenile stages of development, exhibited "gregarious" behaviour -- a characteristic common amongst certain species of modern Anemones. **Fig. 6** large specimen (note scale at base of photo) showing characteristic rounding of basal apex.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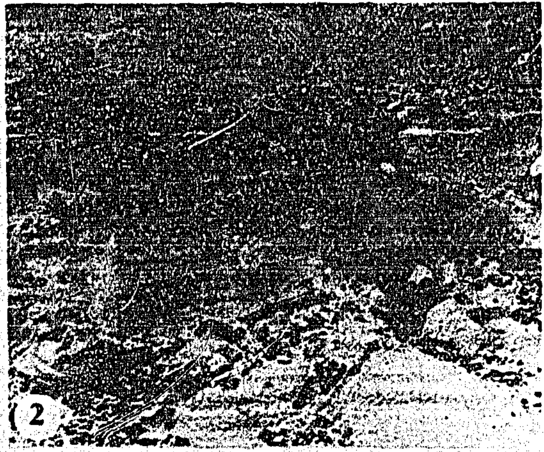
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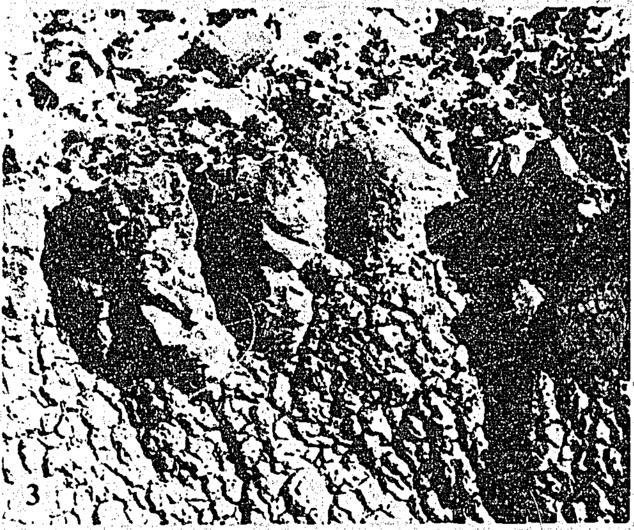
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PLATE 8

Trace fossils from the Appaloosa Sequence

Figs. 1 - 6	*Ichnogen. nov. C.* Specimens from unit 5 at DOR-1 **Fig. 1** oblique view of type specimen showing three successive levels within spiral: see figure 2 for top view of this specimen. **Figs. 3 - 6** side views of specimens showing the range of possible morphological variation.
Figs. 7 - 9	*Ichnogen. nov. A* **Fig. 7** partially preserved specimen from Unit 5 at DOR-1. **Fig 8** photo (taken later) showing internal structure of specimen in Figure 7; note sand fill tube coursing through centre of structure and overall similarity in mode of fabrication with *R. socialis*.


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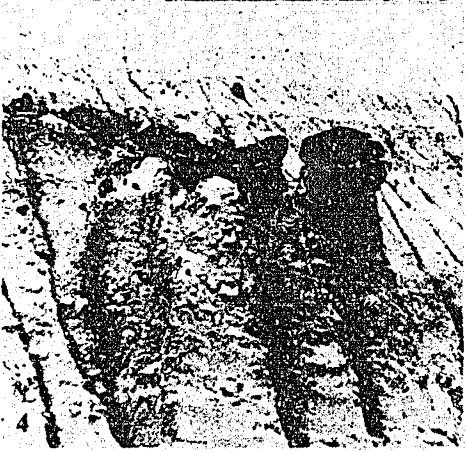
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PLATE 9

Figs. A-H	*Rosselia socialis* Dalmer, 1937. All specimens shown are from Units 5 & 6 at Boot Coulee. **Fig. A & G.** specimens displaying preserved basal stock. **Fig. B.** outcrop view of specimens elucidating concealed bedding surfaces. **Fig. D.** close up of double-funnel in center of figure B.**Fig. E & H.** longitudinal sections of specimens showing central sand filled tube and internal nature of laminae comprising feeding cone. **Fig. F.** specimen displaying re-equilibriation response of the tracemaker. **Fig. C.** top view of relatively large specimen.


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PLATE 10

Figs. A-F. Ophiomorpha nodosa Lundgren, 1891. **Fig. A-C.** specimens exposed on vertical coulee wall displaying ramose, sprawling nature of tunnel systems: note preserved vertical shaft in figure B. **Fig. D-F.** Plan views of tunnels showing irregular nature of wall mammillations.


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PLATE 11

Trace fossils from the Appaloosa Sandstone

Figs.1-5 & 7 *Macaronichnus simplicatus n. ichnosp.* Figs. 3 and 7 specimens displaying characteristic randomly interpenetrating pattern of burrowing; all bedding views. Fig. 4 epichnial specimens occurring on upper surface of storm sand in Unit 1B at S. D. -1; note distinct parting lineation.

Figs. 3, 6 & 7. *Palaeophycus tubularis* Hall, 1847. Fig. 6 side view of endichnial specimen displaying relatively thick mud lining: note similarity between infill and matrix. Figs. 3 and 7 epichnial specimens co-occurring with *M. simplicatus* ; both bedding views.

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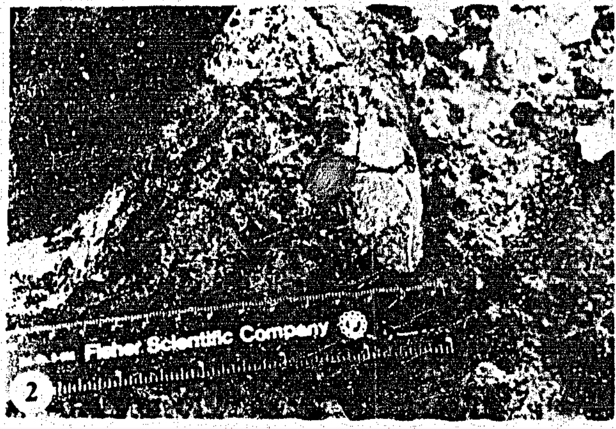

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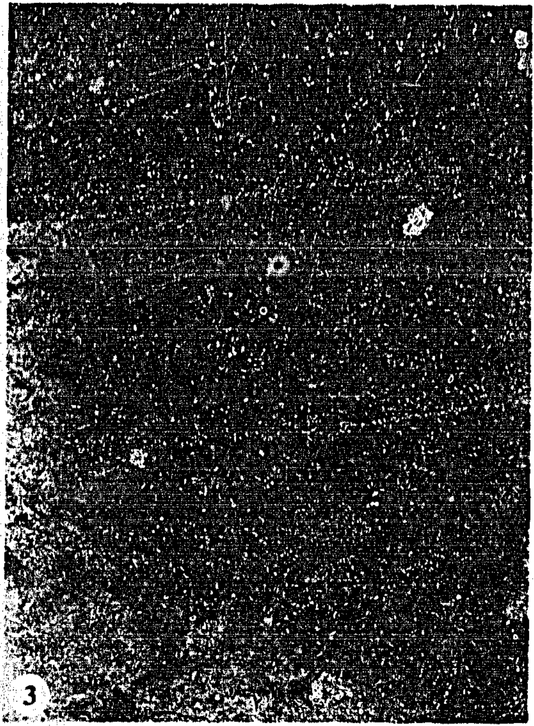

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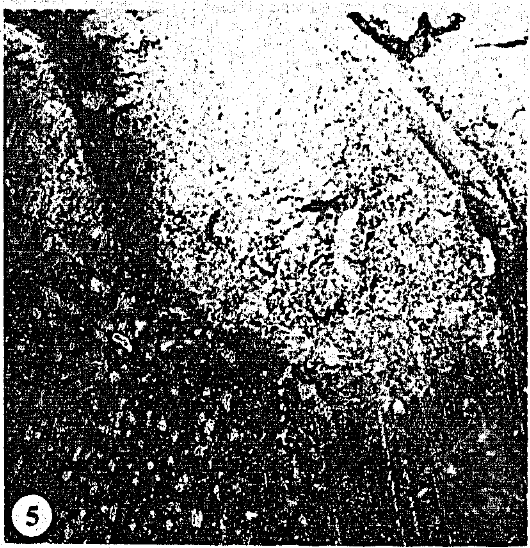

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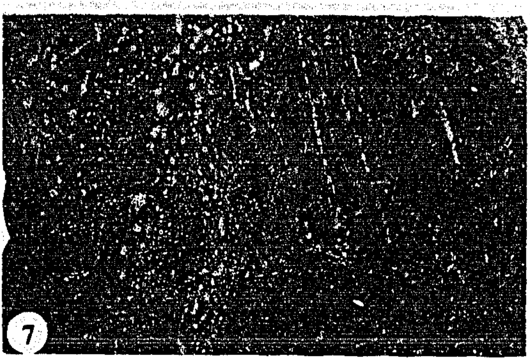

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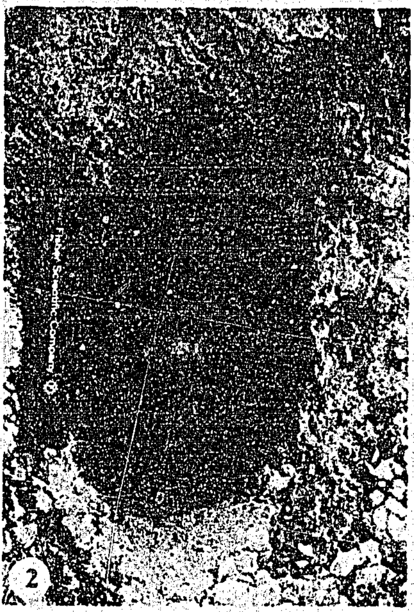
PLATE 12

Trace fossils from the Appaloosa Sequence

Figs. 1-3 & 5.	*Rhizocorallium sp.* Bedding views of specimens co-occurring at top of unit 1B storm bed at Sundance Coulee; note single *Ophiomorpha* - like pellets scattering the surfaces at all specimens.
Figs. 4 & 6-8	*Rhizocorallium jenense* Zenker, 1876. Specimens from Unit 4 at DOR-1 showing characteristic step-like retrusive spreite. Fig. 4 side view of specimens shown below in Figure 6. Fig 8. oblique view of specimens co-occurring with *R. socialis*.


1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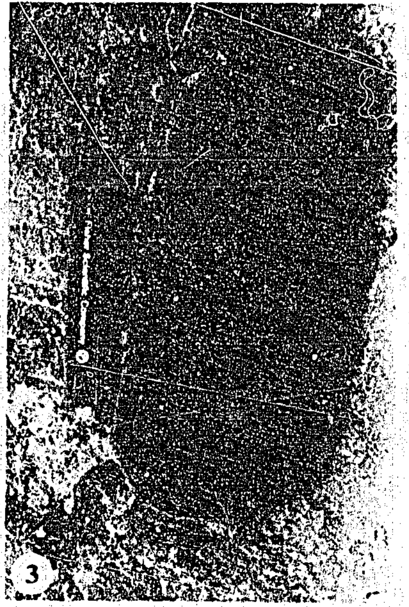
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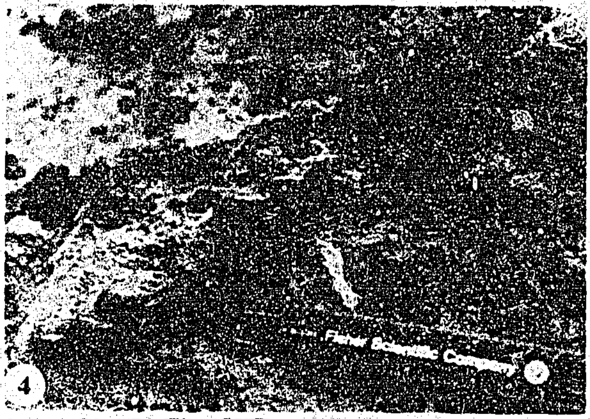
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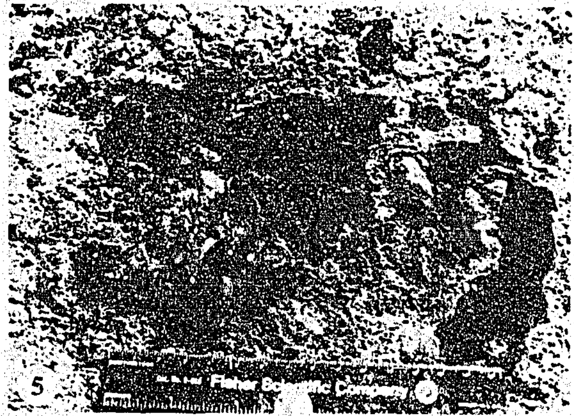
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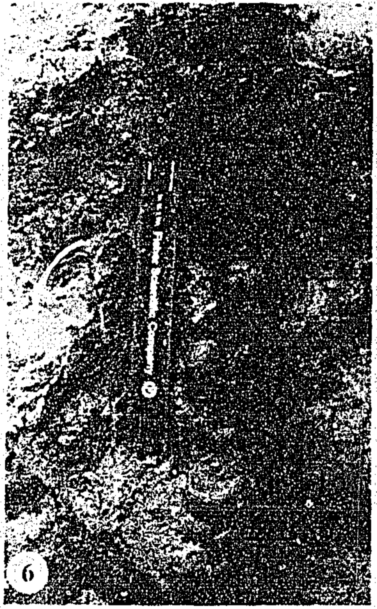
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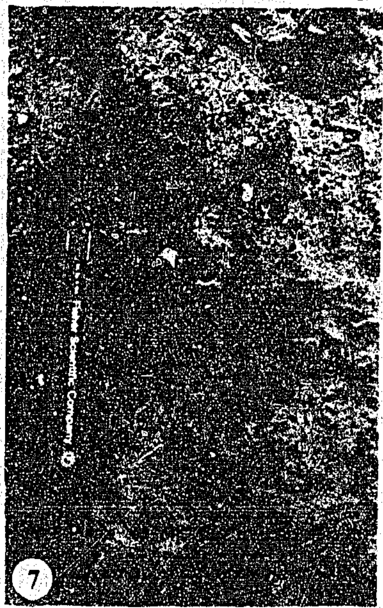
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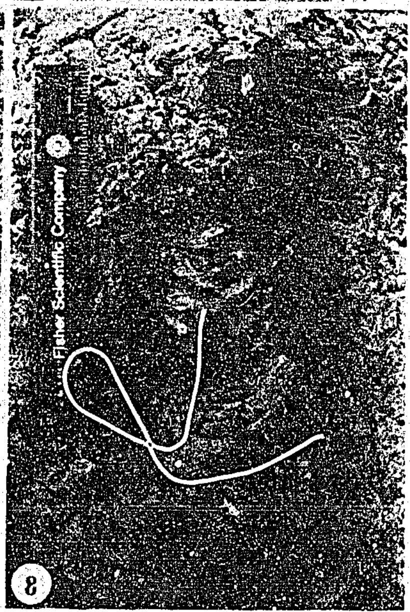
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VIII. CONCLUSIONS

Progradational barrier island sequences are well represented in the geologic record, particularly in the Cretaceous of the Western Interior of North America (cf. Masters, 1967; Land, 1972; Asquith, 1974; Cotter, 1975; Ryer, 1977; Rautman, 1978; VanHorn, 1979; Flores and Espenbeck, 1981; McLane, 1982; Lerand, 1983; Howard and Frey, 1984; Lechie, 1985; Madden, 1985; and Matheny and Picard, 1985). An excellent example, which formed the basis of this study, occurs within the transitional strata of the Bearpaw and Horseshoe Canyon Formations exposed along the Red Deer River Valley near Dorothy, Alberta. Here, spectacular three dimensional outcrop exposures, replete with a wide diversity of exceptionally well preserved trace fossils, have provided ideal conditions from which to apply an integrated sedimentologic-ichnologic analysis in the interpretation of these deposits. The results, I hope, clearly demonstrate how trace fossils, when analysed in concert with the physical characteristics of the rocks, can be used to strengthen a depositional interpretation.

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