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APPLICATIONS AND APPROACHES IN ICHNOLOGY, NEOICHNOLOGY, AND SEDIMENTOLOGY

BY
MURRAY KENNETH GINGRAS ©

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

DEPARTMENT OF EARTH AND ATMOSPHERIC SCIENCES

EDMONTON, ALBERTA

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Degree: Doctor of Philosophy

Year this Degree Granted: 1999

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FACULTY OF GRADUATE STUDIES AND RESEARCH

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Abstract

Detailed analysis of modern and Pleistocene deposits at Willapa Bay, Washington, concentrates on identifying the ichnological and sedimentological characteristics of five estuarine subenvironments, assessing the temporal and paleoecological significance of *Glossifungites* surfaces, and initiating fluid flow studies in bioturbated media. The data collected at Willapa Bay is used to consider the effects burrow-associated diagenesis have on permeability and tortuosity in burrow-mottled carbonates.

Neoichnological studies focused on intertidal flat deposits, tidal creek deposits, fluvially- through tidally-influenced point-bar deposits, bay deposits, and locally channel bar deposits. Each depositional subenvironment has a distinctive sedimentological and ichnological signature. Traces from both modern and ancient deposits display a marked reduction in size and diversity in the upper estuary.

Modern studies pertaining to the *Glossifungites* ichnofacies suggest that the stratigraphic significance of a *Glossifungites*-demarcated discontinuity can be assessed in the rock record. Several criteria that might be used for identifying temporally significant surfaces are suggested, including: the lithology of the palimpsest substrate, the absence of compaction of the *Glossifungites* assemblage; the presence of burrow sculptings; and, planar to gently undulatory erosional surfaces. Several parameters control the nature of bioturbation observed in firmgrounds. These include the firmness, texture, and bathymetric zonation of the burrowed substrate.

The potential permeability enhancement of a *Glossifungites* surface is investigated by using computer simulations and, laboratory- and field-measurements to assess the effective permeability of a *Glossifungites* surface. All the testing methods indicate that the effective permeability of a substrate is enhanced by the presence of *Glossifungites* burrows in a low-permeability substrate. Furthermore, the modified arithmetic mean can approximate the permeability of these burrowed horizons. These formulae can be applied to a variety of burrowed geologic media, as is shown with the example of the Tyndall Stone (Ordovician, Yeoman Formation, Williston Basin).

Tyndall stone is characterized by distinct textural heterogeneity. Physical parameters such as permeability, porosity, tortuosity, and dispersivity are difficult to assess. Mini permeameter readings are compared to experimental assessments of bulk permeability. Also, relative dispersivities of different geological media are experimentally generated and compared to that of Tyndall Stone. These data suggest that burrow mottled carbonates can act as dual permeability systems.

Dedication

I dedicate this thesis to two people, both of whom had a profound and unknowing influence on my life. My Grandmother, Astrid Viker, who taught me that strength of character is derived from loving your friends and family, and from living a life based on principle, not desire. She is the strongest person I have ever known. The other person I would dedicate this endeavor to is my Auntie Ida Gingras. Ida once told me "your smart enough, but it doesn't mean too much if you don't work hard on everything you set your mind to". She knew me all too well. Ida passed away while I was working on my dissertation and I will miss her dearly.

Acknowledgement

Without a means of getting to the field (and sustaining themselves there), a geologist cannot ply his or her trade. The funding that made this research possible was generously provided by the Natural Sciences and Research Council (NSERC) Operating Grant (No. A0816) to S.G. Pemberton, John VanWagoner at Exxon Production Research, Lee F. Krystinik at Union Pacific Resources, and Grant Wach at Texaco Inc.

A little more than five years ago, I was an undergraduate student in the third year of the Bachelor of Science program at the University of Alberta. Part of that term's curriculum included a stratigraphy course taught by Professor S. George Pemberton. Of course George's reputation as an ichnologist, a sedimentologist, and a stratigrapher preceded him, but I was not prepared for the education he was to bestow on me. He inspired me, not only to apply to graduate school, but to become an ichnologist, a sedimentologist, and a stratigrapher. So I stayed at the University of Alberta and worked for the one person who could teach me all three disciplines. Indeed, George is one of the few people who have truly mastered all three fields and my respect for his ability is great.

At a glance you might think George, who we now affectionately call "Jedi", to be gruff (and sometimes he desperately tries to be). However, abrupt observations in such matters are inevitably incorrect. George has a warm and genteel personality. He literally fills the room with his warmth, kindness, and strength. He leads by example, and I have learned and grown from this example. My studies were based on several ideas that might be traced back to George and he has graciously given them to me. I humbly accept these as gifts. I have been indulged intellectually and financially, yet have offered very little in return. Thank you Jedi, for my future.

It is foolish to think that this journey began but five years ago. A long, long time before, my father Garry, taught me how to question perception. When I was a child we had tireless debates regarding the origin of life, the planet, our solar system, and God. Nothing is too sacred for that man. My mother, Sharon, supported all my endeavors, thought I was smarter than Einstein, and loved me more than any other person ever could. I love her, too. Donna, my kid sister, has grown into a fine and beautiful woman. I am intensely proud of her (and her family, Rick and Dallas), and she is now my role model.

There are some people, without whom this thesis simply would not have come to fruition. Vivienne Robertson, my betrothed, tirelessly edited, proofed, corrected, and typed. She felt more anxiety over the process then I did. She also tolerated moody days, short temper, deadline hysteria, and many long days at the lab. Psychiatrists and friends can be hard to find.

Some scientific influences clearly fall into the 'indispensable' category as well. Ed Clifton gave freely of his expertise regarding Willapa Bay (and geology in general). Furthermore, Ed included me as a coleader on several field trips and made every effort he could to enhance my notoriety. Tom Saunders, who is the best artist, scientist, and friend I have known, really got me started on my thesis. Tom, Kevin Brett, Chris Cameron, Stef Zaklan and myself are the original *Nephtys* Warriors. Doctor James MacEachern launched me down the road to academia. Doctor Mike Ranger taught me not to get too high on myself and that you can watch lots of television and still be really smart. Doctor John-Paul Zonneveld (Pancho) led the charge from debauchery to respectability. I'm still trying to figure out how we got this far. Jason Lavigne never heard an argument he did not like. Moreover, he never heard one he never joined (or started). Bo Henk just made me happy by filling me with his own enthusiasm. Suman De is directly responsible for teaching me that it does not matter what you do, but *how* you do it. Mike Caldwell taught me that it does not matter what you do, but *who* you do it with. Arjun Keswani taught me that it does not matter what you do, but that you do it. These are fine learnings, indeed. Others have a special place in my heart as well. The following people have given me their support, emotional or otherwise (commonly at the Powerplant) time and time again. They include Val Slowiak, Leslie Dawson, Brana Brett, Catherine Yuill, 'Arctic' Al Lindos, Cindy Want, Mike Geir, Jeff Peterson, Indraneel Raychaudhuri, 'Grizz' Krpan, Astrid 'Flo' Arts, Karen Fallas, 'Greasy Boots' Roberts, Paul Blanchon, Ted Little, Steve Kelly, Al Kestner, and Leon Halwa, the list goes on.

I would be remiss to not mention the hospitality Theresa and George Pemberton, and their children, Sarah, Erin, and Josh, have shown me on several occasions. They are a special family.

Many thanks to Tom and Mary Robertson, Mark and Marie-Pierre Robertson, and the rest of Viv's family for the kindness and support they have given me in abundance. Also I am indebted to the friends who saw *all the way through university*. These are Kevin and Tina Thompson, and Phil Goldring.

Two very special individuals served as my assistants at Willapa Bay. They are Steve Hubbard and Ian Armitage. Although I have joked that their job title should have been 'Summer Hindrance', I feel nothing but love and respect for them. Ian and Steve made what seemed impossible a doable undertaking. I hope I have influenced them as much as they have me. They will go far. Vivienne deserves an honorable mention for her field assistance as well. For the record, without Sue Fleming, we would never get anywhere, nor would we be able to return. She is amazing and dear.

Many new graduate students have joined the Ichnology Research Group since I've arrived. Each has inspired me in a unique way. These fine geologists include Demian Robbins, Eric Hanson, Glenn Schmidt, Jason Frank, Errin Kimbal, Chad Harris, Jeff Reinprecht, Corrine Bagdan, Yaojun Han, Michelle Spila, and Gladys Fong. I can hardly wait to see what these aspiring academic hooligans can accomplish!

Many people of Bay Center, Washington helped us conduct our research. They include Bill and Sam Pickernell, Leonard and Dave Bennet, Bev Smith, Dick and Jan Wilson, "Shrimper" Terry Rhodes, and especially Linda. Bill passed away in December of 1996, left a gaping hole in mine and Linda's souls.

Final thanks to Stan Rogers, Big Rock Breweries, the inventor of eight ball, Jack Daniels, and Johnny Walker. These made a life of relative austerity much more pleasurable.

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CHAPTER 1: INTRODUCTION

Studies in ichnology are unique in that trace fossils represent the ethology, or behavior of the tracemaker. Ichnology provides a looking-glass through which sedimentologists might observe the survival mechanisms employed by animals to persist in a sedimentary environment. Studies in modern and ancient sedimentary deposits provide geologists with a considerable database that has great utility where applied to the rock record. Relative salinity, salinity fluctuation, oxygenation stress, turbidity stress, substrate consistency, and thermal stress are all parameters that might be elucidated by understanding the ichnological data present in a sedimentary succession. Because all of these parameters can be related to depositional geometry, bathymetry, or hydraulic energy, trace fossils can be used to identify the depositional nature of the sedimentary strata in which they are observed.

Given the utility of ichnofossils, it is surprising that most sedimentologists have not been especially rigorous in combining biogenic- with physical-sedimentary interpretations. Contemporary sedimentary manuals, such as Prothero and Schwab (1996) and Reading and Collinson (1996), treat the field rather cursorily. Ichnologists commonly contribute to the problem by inadequately synthesizing trace fossils with classic sedimentology (Bromley, 1996). It must be emphasized, however, that several papers and theses have served as a model for this type of research. Most notable among these is the body of work directed by George Pemberton, and his associates and graduate students. Focusing on the Cretaceous strata in the Western Canada Sedimentary Basin (W.C.S.B.), they have evolved a model detailing the ichnological characteristics of brackish-water deposits (Pemberton et al., 1982; MacEachern and Pemberton, 1994). Much of their research has also focused on the identification of depositional environments (Saunders, 1987; Ranger and Pemberton, 1992). Finally, their research has led to the recognition that certain trace fossil suites can have sequence stratigraphic significance, in particular, the *Glossifungites* ichnofacies (Pemberton and Frey, 1985; Pemberton and MacEachern, 1995).

Chapter 1 and 2 expand on these concepts, with a decided focus on salinity stressed assemblages observed in modern and ancient brackish-water deposits, drawing on examples from Willapa Bay, Washington. The origin of these studies can be traced back to the 1950's and the early stages of actuopaleontology (Fig. 1.1). This field of study depended on the transfer of observation and deduction from the modern to the rock record. Although this research resulted in the development of the extremely useful ichnofacies concept (Seilacher, 1967), no criteria with which brackish-water deposits might be identified, had yet been proposed. Interestingly, an ichnofacies comprised of traces characteristic of brackish deposits has never been defined. This is true of other physico-chemical stresses, such as oxygenation, temperature, sedimentation, and turbidity (Fig. 1.1). There are a number of reasons this is so. Firstly, substrate control (texture and consistency) most strongly influences the burrowing behavior in a sedimentary environment. The substrate-controlled ichnofacies (*Nereites*, *Zoophycos*, *Cruziana*, *Skolithos*, *Glossifungites*/*Scoyenia*, *Trypanites*, and *Teredolites*) define a baseline and their physical aspect reflects their dependence on this single parameter. Variables such as salinity and oxygenation modify the ichnofacies significantly, however, the resultant trace fossil assemblage , excepting extreme examples, still lends itself to classification by the Seilacherian ichnofacies. For this reason, substrate-controlled ichnofacies had to be developed before other physico-chemical relationships could be addressed (Fig. 1.1).

A great deal of confusion is evident in ichnology because researchers do not generally agree on the significance of ichnofacies. Bromley and Asgaard (1991) contend that the *Skolithos*, *Cruziana*, *Zoophycos*, and *Nereites* ichnofacies are most strongly affected by taphonomic processes. Although taphonomic considerations indelibly alter the preservational guise of a sedimentary rock, these processes tend to *modify* ichnofacies, not define them (Fig. 1.2). The advent of ichnofabrics (Ekdale and Bromley, 1983) has

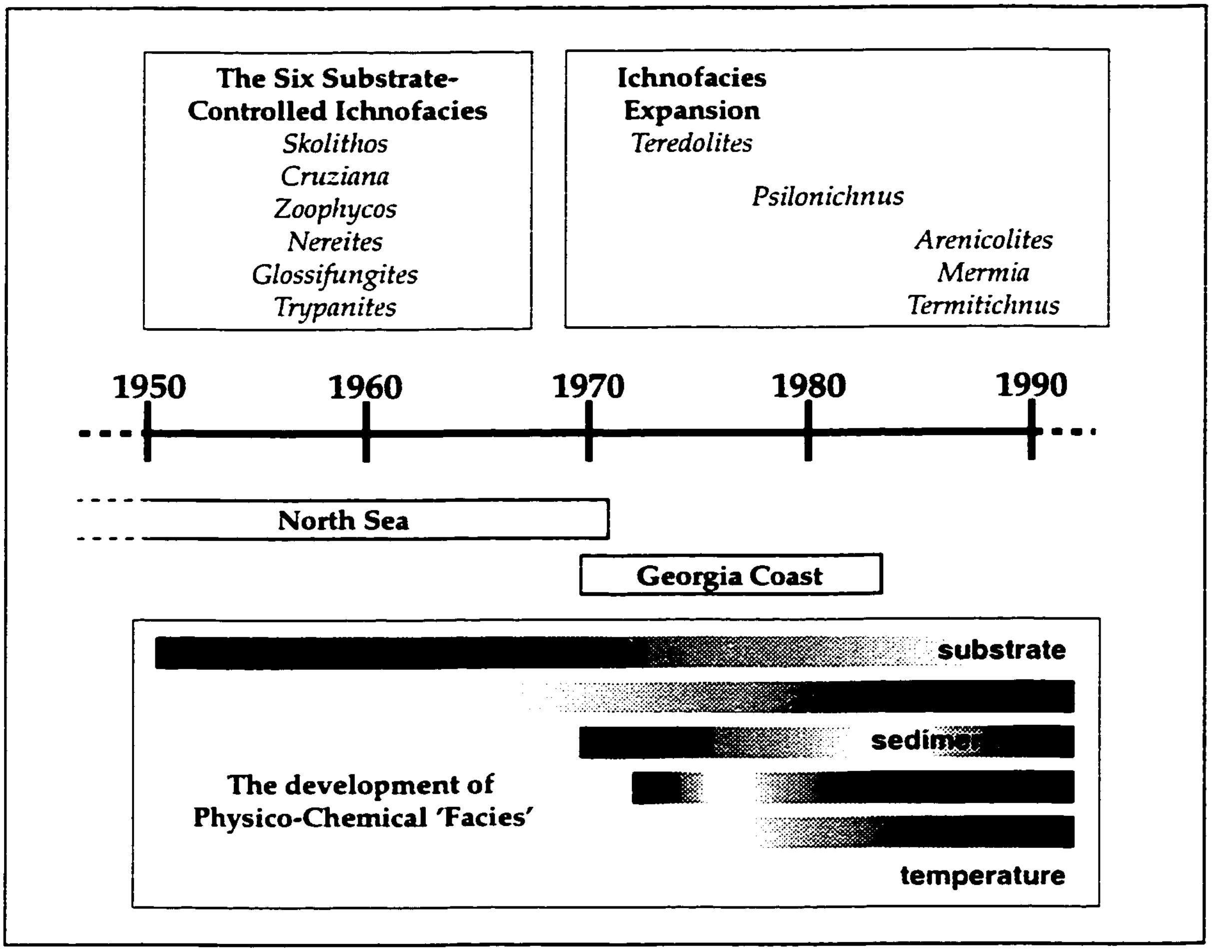

FIGURE 1.1 - The development of modern ichnology was dependant on modern research carried out in the North Sea and along the Georgia Coast. Substrate-controlled ichnofaces formed the basis upon which physico-chemical 'facies' were developed. Many of these parameters are poorly understood.

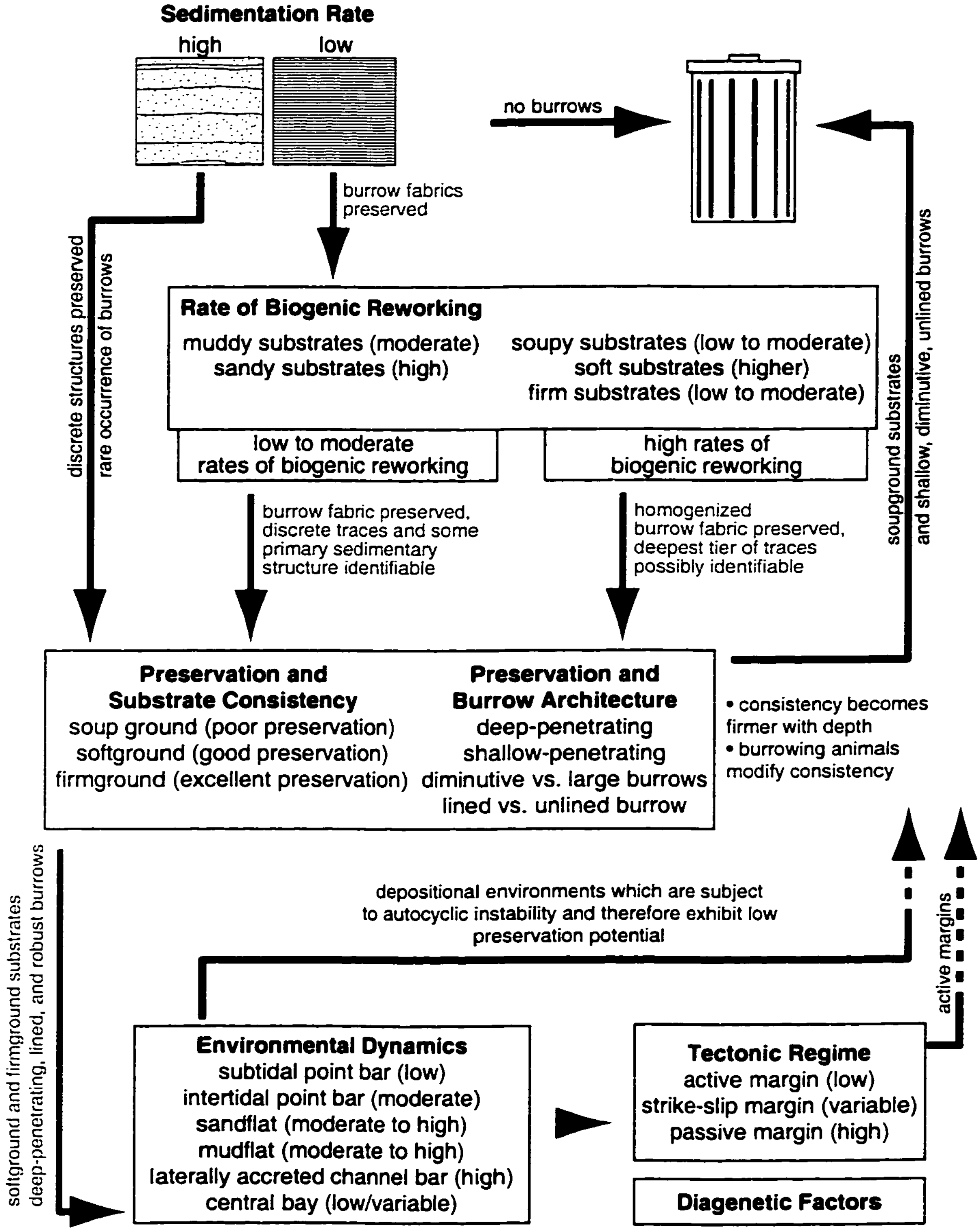

FIGURE 1.2 -Taphonomic processes acting on trace fossil assemblages in marginal marine depositional environments. Note that none of the above processes directly relate to the physical characteristics that define an ichnofacies, such as burrow architecture, and the nature of the trace fossil assemblage.

allowed ichnologists and sedimentologists to discard much of the baggage ichnofacies had accumulated over the past three decades (such as an intrinsic bathymetric connotation; Seilacher, 1967). This liberation has come at a cost though. Most recent publications fail to communicate the role that sedimentologic context and the condition of the substrate plays in determining the preserved trace fossil assemblage. That is not to say brackish-water deposits lend themselves to description by ichnofacies alone. Brackish-water accumulations, particularly in ancient estuarine deposits, are notorious in their complexity and, as Chapters 2, 3, 5 and 6 indicate, they defy categorical definition.

Chapters 3, 4, and 5 explore the temporal and ecological significance of *Glossifungites* assemblages observed in modern and Pleistocene deposits at Willapa Bay, Washington. The *Glossifungites* ichnofacies includes all trace fossil suites that penetrated firm substrate at the time of burrow emplacement. Their sequence stratigraphic significance is derived from the knowledge that firm substrates generally require compaction and dewatering to attain their consistency. Although many allocyclic and autocyclic processes might expose these substrates, it is generally accepted that widespread exposure of a firmground requires large-scale allocyclic processes (Pemberton and Frey, 1985). Although *Glossifungites*-demarcated discontinuity surfaces have been shown to have stratigraphic significance, their paleoecological significance is commonly overlooked. Several examples from the bay illustrate that bathymetry, texture, and substrate firmness play a significant role in determining the resulting ichnofacies. A field technique used to determine the firmness of modern deposits is also presented (Chapter 4).

Glossifungites assemblages are unique in that they 'pipe' sediment from overlying sedimentary deposits into the exhumed firmground. This sediment is discretely packaged into burrow fabrics with textural characteristics that commonly contrast those of the matrix. Sand tubes descending through low permeability, muddy matrix are therefore not uncommon. The bulk physical characteristics of a muddy deposit are significantly altered under such circumstances. Chapter 7 explores the assessment of the bulk permeability of *Glossifungites* surfaces. This data complements that provided in Chapters 4, 5, and 6, as those chapters deal with the delineation, prediction, and morphology of these horizons. Furthermore, this train of thought demonstrates the multidisciplinary approach required to solve ichnological problems.

Chapters 8 and 9 present a shift in focus from trace assemblages in brackish-water, bay settings. They follow the premise introduced in Chapter 7, suggesting that trace fossils can enhance the permeability of a sedimentary deposit. This is important as the common perception in the geological literature is that bioturbation reduces permeability. Chapters 8 and 9 explicitly focus on the development and assessment of burrow-associated textural heterogeneity in carbonate deposits. In pursuing questions regarding the development of such fabrics, diagenesis and its role in producing burrow-dolomite are reviewed in-depth. Together, petrographic and isotopic data provide a petrogenetic framework. Gas flow tests through burrow-mottled Tyndall Stone (Ordovician, Yeoman Formation, Selkirk Member) demonstrate that the permeability of such deposits can be markedly enhanced by burrow diagenesis. Furthermore, these fabrics are complex, profer tortuous fluid flow pathways, and generate dual porosity/permeability networks. The characterization of such deposits has a significant bearing on the reservoir quality of such rocks.

In summary, this thesis focuses on the ichnology of brackish-water bay deposits. This is not limited to bioturbate fabrics emplaced in soft sediments, but explores the geometry, ecology, and predictability of burrowed firm substrates as well. The data presented herein are provided to better resolve geometric configurations, salinity-stress gradients, and the nature of genetically significant stratigraphic surfaces in similar deposits in the rock record. Establishing the nature of these surfaces leads to the assessment and prediction of permeability associated with *Glossifungites*-demarcated discontinuity surfaces. This is considered in the light of conceptual reservoir configurations, and their hypothetical impact on reservoir quality. Conceptually, assessing the permeability of *Glossifungites* surfaces is similar to assessments for all geological media characterized by distinct, burrow-associated textural heterogeneity. Burrow-mottled carbonates are therefore utilized to demonstrate the potential of applying this technology to other deposits. In doing so, key diagenetic models are introduced and discussed.

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CHAPTER 2: THE ICHNOLOGY OF RECENT AND PLEISTOCENE BRACKISH-WATER DEPOSITS AT WILLAPA BAY, WASHINGTON[1]

INTRODUCTION

Ichnology has been employed widely to assist in identifying brackish-water deposits. Several notable core studies underscore the utility of ichnology when applied to ancient estuaries (e.g., MacEachern et al., 1992; Pemberton and Wightman, 1992). However, there is a marked paucity of outcrop- and actualistic studies in the recent literature. This is particularly unfortunate as the recognition of lateral variation and the identification of key subenvironments provide the tools needed for resolving complex geometric problems, predicting compartmentalization of potential reservoirs, and identifying pool-edge indicators in the subsurface. Outcrop-based studies and an understanding of modern estuarine processes may provide some of the solutions to these complex geological puzzles.

Pleistocene outcrops at Willapa Bay present a unique opportunity to integrate ichnologic data into a well-documented sedimentologic and stratigraphic framework (Clifton and Phillips, 1980; Clifton, 1982; Anima et al., 1989), thereby allowing a focus on ichnologic variation in brackish-water deposits. The modern bay provides an excellent analog for comparison to the ancient deposits and reveals complexities inherent to incised valley fills (IVF). These complexities present problems with tractable solutions that can be applied to the rock record.

This paper focuses on the ichnologic characteristics of five subenvironments: (1) intertidal flats; (2) intertidal point bars; (3) fluvially- through tidally-influenced main point-bar deposits; (4) subtidal, laterally-accreted mid-channel tidal bars, and; (5) quiescent central bay deposits. Both modern and Pleistocene examples are utilized, lending insight into the taphonomy of traces in IVF. Studies at Willapa Bay were also designed to test whether archetypal ichnofacies could be consistently applied to ancient

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[1] A version of this chapter has been accepted for publication in PALAIOS as "The Ichnology of Recent and Pleistocene Brackish-Water Deposits at Willapa Bay, Washington", by Murray K. Gingras, S. George Pemberton, Tom Saunders, and H. Edward Clifton.

estuaries and bays. The aim of this research is to establish whether *predictable* exceptions to the ichnological brackish-water model are present in modern bays and how they might enhance the interpretation of the rock record.

The Brackish-water Model

In general, salinity-stressed trace fossil suites are discerned by the identification of a few ichnological characters (Pemberton and Wightman, 1992). The initially observed patterns (Pemberton et al., 1982) include: a low diversity of trace forms and suites dominated by a single ichnogenus; overall diminutive traces; simple *marine* forms, constructed by trophic generalists; vertical and horizontal traces common to the *Skolithos*- and *Cruziana*-ichnofacies; and locally prolific trace densities. These criteria are outlined in Pemberton et al. (1982) and were the result of extensive comparative modern-ancient studies throughout the 1970's.

The origin of these studies can be traced back to the 1950's and the early developmental stages of modern ichnology. Researchers including Schafer, Seilacher, Reineck, Dörjes, and Hertweck developed a framework for ichnological research that was rooted in modern observations (actuopaleontology). Although the original research primarily focused on defining burrow architecture and understanding taphonomic processes, substrate texture was soon recognized as a controlling factor in trace distribution. This recognition translated into the archetypal (substrate-controlled) Seilacherian ichnofacies (Seilacher, 1967). Although much of the North Sea data were collected in brackish environments, a set of criteria to identify brackish deposits had yet to be developed. Seilacher (1963) noted that "the activities controlling trace morphology are related to the sedimentary facies, however, they are independent of salinity." Seilacher also stated that the identification of a species, whose salinity range might be established, would provide the most direct solution towards the identification of estuarine strata. Unfortunately, a (burrowing) taxon that might provide such an ichnological solution has not been put forward.

Early work in the North Sea was supplemented with data gathered from estuaries along the Georgia coast in the early 1970's (Howard and Frey, 1973, 1975; Dörjes and Howard, 1975). Though the significance of estuarine IVF's in the rock record essentially was unrealized at that time, the work of Howard and Frey provided a valuable database from which the brackish-water model evolved. A number of physico-chemical parameters were documented in this earlier work (Howard and Frey, 1973). They included salinity, oxygen content of the water column, substrate textural relationships, temperature, and pH. Of these factors, salinity and texture were consistently associated with particular ichnocoenoses, the physical character of which could be compared to the rock record.

Although this paper focuses on the ichnological signature of salinity stress, it is recognized that other factors influenced the trace fossil assemblage as well. Examples of other stresses include low oxygen contents in the water column, turbidity, and high sedimentation rates.

Setting

Willapa Bay, located in the southwest corner of Washington (Fig. 2.1), is separated from the Pacific Ocean by the North Beach Peninsula, a 27-km-long spit derived from sand transported from the mouth of the Columbia River. Five river systems discharge into Willapa Bay, from the south, east, and north margins, complicating facies distribution within the estuary. The bay is sheltered from oceanic waves by the North Beach Peninsula and Willapa Bar, a set of shoals at the bay mouth. Also, Willapa Bay is a mesotidal estuary with a tidal range of 2 to 3 m. Tremendous water exchange occurs in the bay, and the tidal prism, which exceeds 700,000 m^3, comprises about 45% of the bay's total volume (U.S. Army Corps of Engineers, 1975). This volume is by no means constant. The maximum exchange occurs during spring tides, whereas neap tides proffer a much smaller tidal prism. The bay becomes somewhat 'stagnant' with the neap tides, affecting the food resource, oxygenation, and salinity levels on a monthly and yearly basis (L. Bennet, pers. comm., 1997). Longer term climatic patterns, such as *El Niño,* have a similar effect.

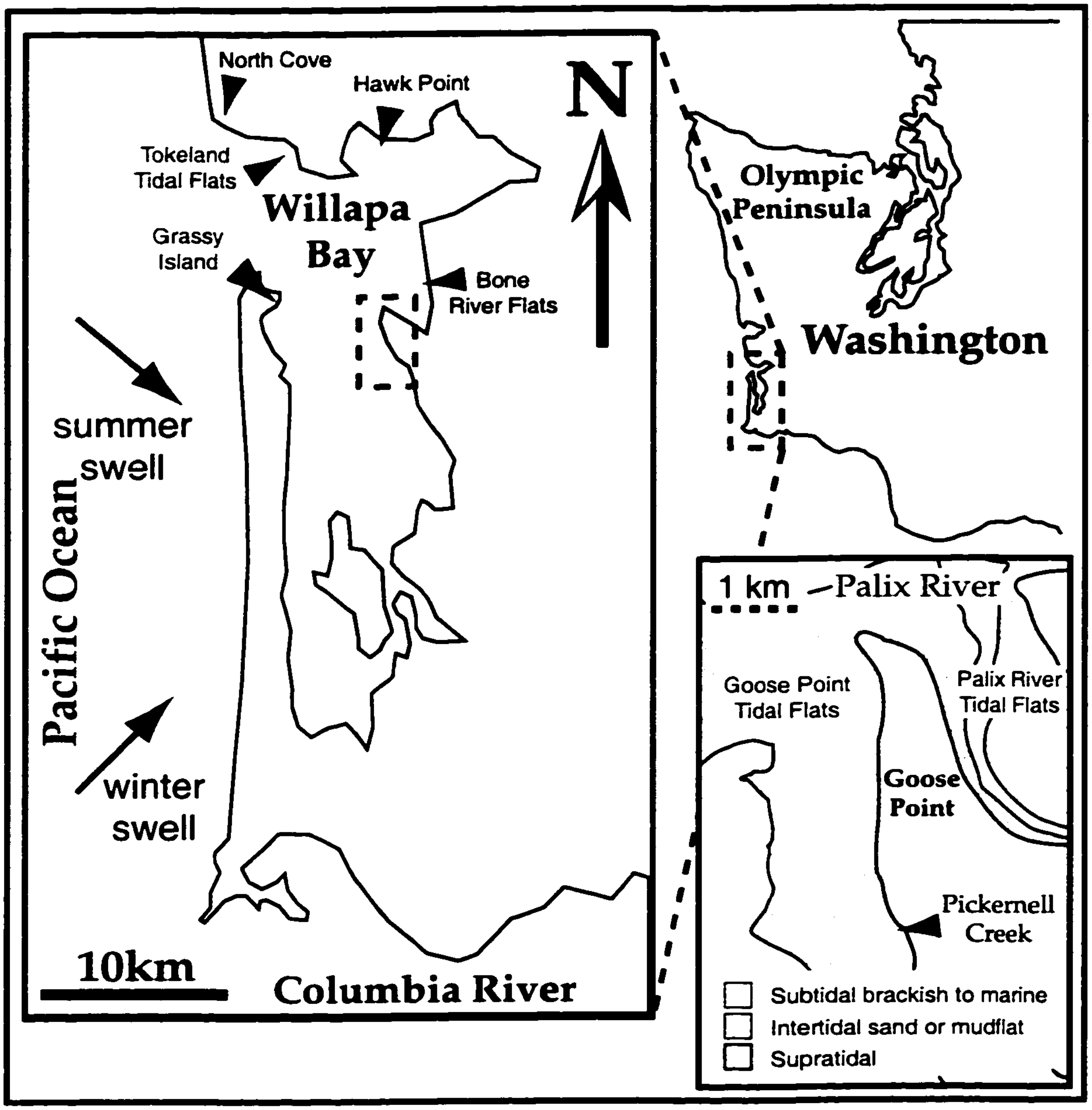

FIGURE 2.1 - Map of Willapa Bay, Washington.

The right frame of Fig. 2.1 details Goose Point and the Palix River, an area of focused modern and ancient ichnological study. Sediment accumulations at Willapa Bay are siliciclastic. The lower estuary is dominated by sandy deposits, generally upper fine- to medium-grain, and the upper estuary is characteristically muddy (80% finer than phi 6). An analysis of the heavy mineral fraction of the modern and Pleistocene deposits was completed by Luepke and Clifton (1983). They found that sediment has been transported into the bay from both fluvial and tidal processes. Pleistocene deposits at the north end of the bay may have originally been derived from glacial outwash (Luepke and Clifton, 1983).

Pleistocene terraces are exposed along the northern, eastern, and southern margins of the bay. The deposits have been informally separated into an "older" and a "younger" terrace set (Clifton and Phillips, 1980). Younger Pleistocene deposits were deposited between 100,000 and 200,000 years before present (Kvenvolden et al., 1979); the older strata have not been reliably dated.

The younger Pleistocene strata have been divided into 5 units (I through V; Fig. 2.2). Unit I is primarily a muddy accumulation that has been interpreted to indicate deposition in intertidal and uppermost subtidal environments (Clifton et al., 1989). Both intertidal flat and intertidal creek point-bar deposits have been identified in Unit I. Unit II, in contrast, is comprised mostly of sand. Clifton et al. (1989) compared this to the central channel of the modern bay. Unit III is typically muddy and contains abundant organic detritus. Locally cross-cutting Units I and II, Unit III has been interpreted as being primarily alluvial and is indicative of a basinwards shift of facies (Clifton et al., 1989). The most widespread interval in the younger Pleistocene deposits is Unit IV. It outcrops almost continuously from Goose Point to Pickernell Creek (Fig. 2.1), except where it is truncated by Unit V. Unit IV is lithologically variable, consisting of two facies types: unstratified fossiliferous muds and stratified mud and/or sand (Clifton et al., 1989). Locally, unstratified sand and fossiliferous sand are observed, particularly in the

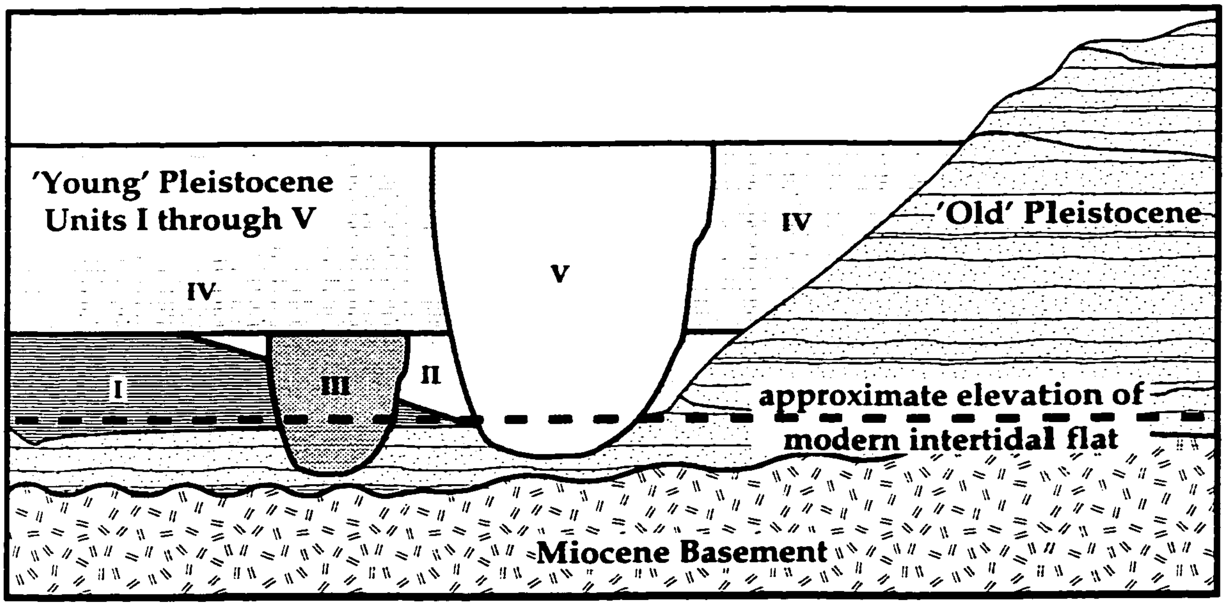

FIGURE 2.2 - The stratigraphy of Pleistocene deposits at Willapa Bay, Washington. An even older, third terrace set is present at the bay (not shown on schematic), the stratigraphy of which is poorly understood. Units I through V indicate the stratigraphic divisions as delineated by Clifton and Phillips (1980). These units are interpreted to represent chronostratigraphic divisions, although they are identified on the basis of lithologic characteristics (lithostratigraphic). Unit I is primarily muddy. Unit II erosionally overlies Unit I and is comprised primarily of sand. Unit III is represented by a woody and muddy channel fill; it truncates Units I and II. Unit IV locally truncates Units I, II, and II. It represents a primarily sandy accumulation of bay deposits. Unit V locally truncates Units I through IV, and is characteristically muddy. Modified from Clifton *et al.*, 1989.

vicinity of Johnstone Beach. The ubiquity of the oyster *Ostrea lurida* in Unit IV reflects that it was deposited subtidally and, based on further sedimentologic and stratigraphic evidence, was probably deposited partly in the trough of a broad bay and partly in tidal channels (Clifton et al., 1989). Unit V is a channelized deposit typically containing gravelly beds and unstratified and stratified mud. Rhythmic sedimentation patterns suggest tidal influence; an absence of burrowing, however, reflects deposition accompanied by extreme salinity stress. Unit V is primarily fluvial (Clifton et al., 1989).

Although the complex stratigraphy of the older Pleistocene terraces has yet to be deciphered, many examples of subtidal through supratidal deposits have been identified in these strata (Clifton et al., 1989). Both the younger and older terraces, then, provide the database with which discrete subenvironments can be characterized. These data are bolstered by research carried out in the modern bay.

Methods

Outcrop data were gathered through detailed logging of 27 sections throughout the Pleistocene deposits. Samples of Pleistocene outcrop were removed and slabbed for detailed analysis. Slabs were polished by rubbing them against a piece of flat, expanded-metal grating while immersed in water, and subsequently radiographed using a Hewlitt Packard cabinet X-ray system (Faxitron series). The ichnologic data, particularly the radiographic plates, were obtained in "core-sized" format, to aid in the subsurface identification of the different depositional environments.

Modern deposits were studied using a variety of methods, including trenching, shallow coring, box coring, resin casting, SCUBA, and radiographic analysis. Resin casts were produced with two media; polyester resin for more robust burrows (> 5 mm diameter) and polyurethane casting resin (Castmaster 2000) for diminutive burrows (generally < 5 mm diameter). The comparatively low viscosity of polyurethane resin allowed penetration of burrows less than a millimeter in diameter.

In the absence of diagenetic processes that emphasize a trace's architecture, burrow architectures in modern and Pleistocene deposits have been interpreted as being indicative of common ichnofossil morphologies. For example, vertical traces are *Skolithos*-like, and large diameter crustacean burrows with thickened pellet-lined walls are *Ophiomorpha*-like. Although largely interpretive, this facilitates communication of this data in a more standard ichnological framework.

MODERN AND ANCIENT DEPOSITS AT WILLAPA BAY, WASHINGTON

Common Trace Makers at Willapa Bay

A number of organisms leave distinctive traces in the sediments of Willapa Bay. Figure 2.3 details some of the most common burrowers, many of which display a strong preference for muddy or sandy substrates, although much overlap is evident in substrate selection (Fig. 2.3). The burrow architectures are varied and many are potentially analogous to common trace fossils. The most common traces include *Skolithos*- and *Gyrolithes*-like burrows, which are made by a number of burrowers including *Saccoglossus* (an entrepneust), maldanid polychaetes, *Heteromastus* (a capitellid polychaete), and more rarely *Nereis* (Fig. 2.3). *Cylindrichnus*-like burrows are also constructed by maldanid worms, whereas terebellid polychaetes commonly construct a *Rosselia*-like structure at the ends of their parchment-lined u-shaped burrows. This latter observation confirms Masakazu's (1995) speculation that terebellids might construct such structures. *Planolites* and *Palaeophycus* structures typically represent the work of the polychaetes *Nereis* or *Nephtys* (Fig. 2.3); sections of *Saccoglossus* or *Heteromastus* burrows may solicit a similar interpretation. Decapod crustaceans, such as *Upogebia pugettensis* and *Callianassa californiensis*, commonly construct *Thalassinoides*- or *Ophiomorpha*-like burrows (Fig. 2.3). *Diplocraterion* and *Arenicolites* structures are utilized by the spionid worm, *Polydora*, and the amphipod *Corophium*.

Figure 2.3 indicates which burrows are transient, or occupied for a short time, and which are used by the organism for much of its life cycle. More transient burrows are relocated often and, although the trace itself may have lower preservation potential, their producers potentially bioturbate the substrate to a higher degree. The illustration therefore relates taphonomic considerations to the burrowing assemblage.

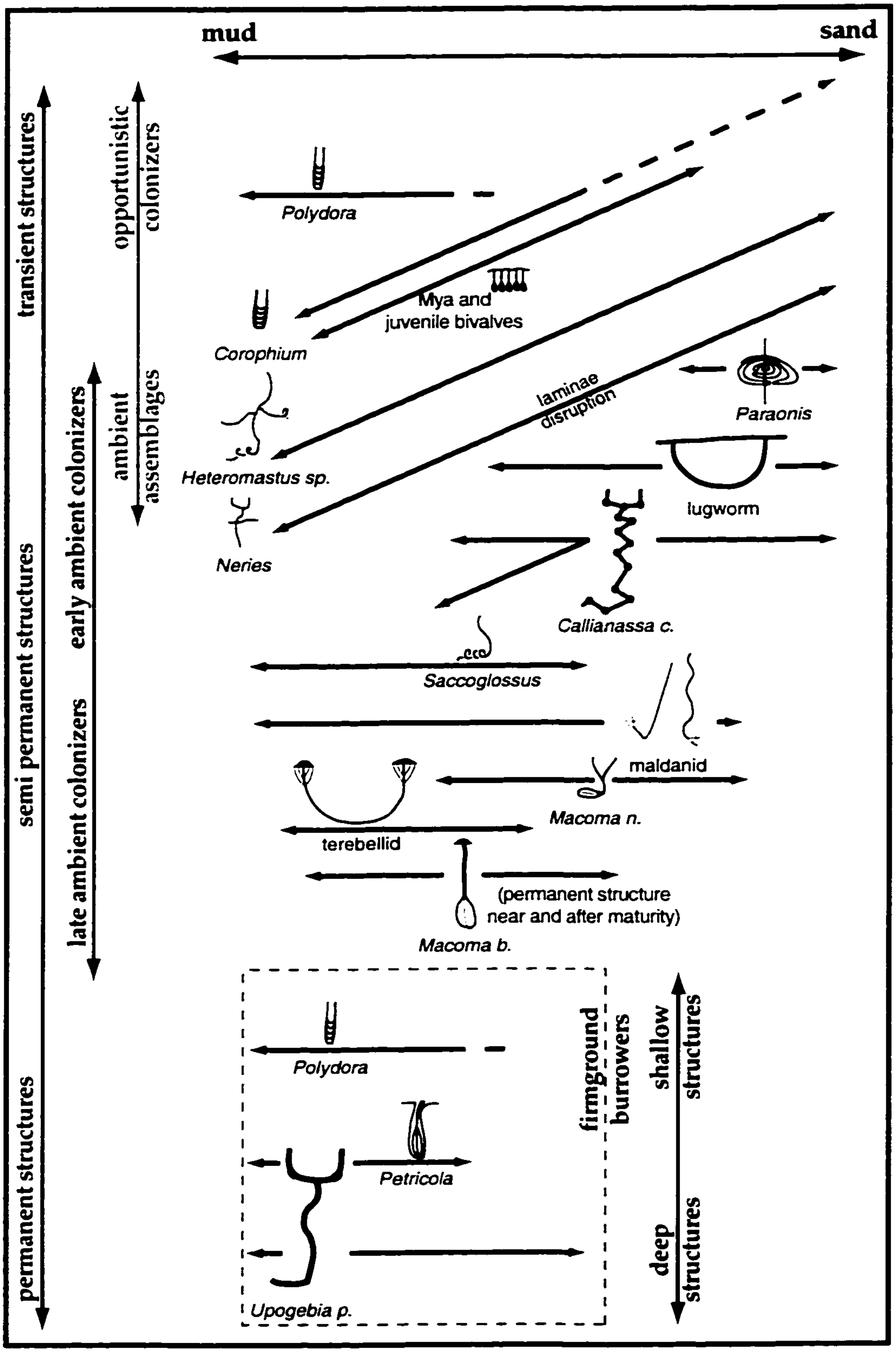

FIGURE 2.3 - Some of the common trace makers of Willapa Bay, Washington. Detailed are general trace configurations and empirical estimates of the substrate texture they inhabit. ---->

(cont.) Classification of ambient versus opportunistic assemblages is based on observations at Willapa Bay and may vary in other locations. The distinction between early and late ambient assemblages alludes to the order in which organisms move into an unexploited substrate. The semi-permanent and ephemeral axis alludes to taphonomic characteristics, such as the presence of a burrow lining and depth in the substrate.

Intertidal Flat Deposits

Modern Tidal Flats

Modern intertidal flat deposits are typically characterized by distinctive ichnocoenoses. *Upogebia-*, *Callianassa-*, terrebellid-, *Saccoglossus-*, maldanid-, and bivalve-dominated communities are common. Inevitably, a host of worms and bivalves, notably *Heteromastus, Nereis, Corophium, Nephtys,* and *Macoma sp.,* are also present in ambient assemblages. A terebellid-dominated assemblage is idealized in Figure 2.4, indicating relative distributions and generalized depths of penetration in these deposits. Exposed, sandy intertidal flats are locally colonized by *Ophelia,* producing fabrics identical to those observed in rocks that contain *Macaronichnus* (Clifton and Thompson, 1978).

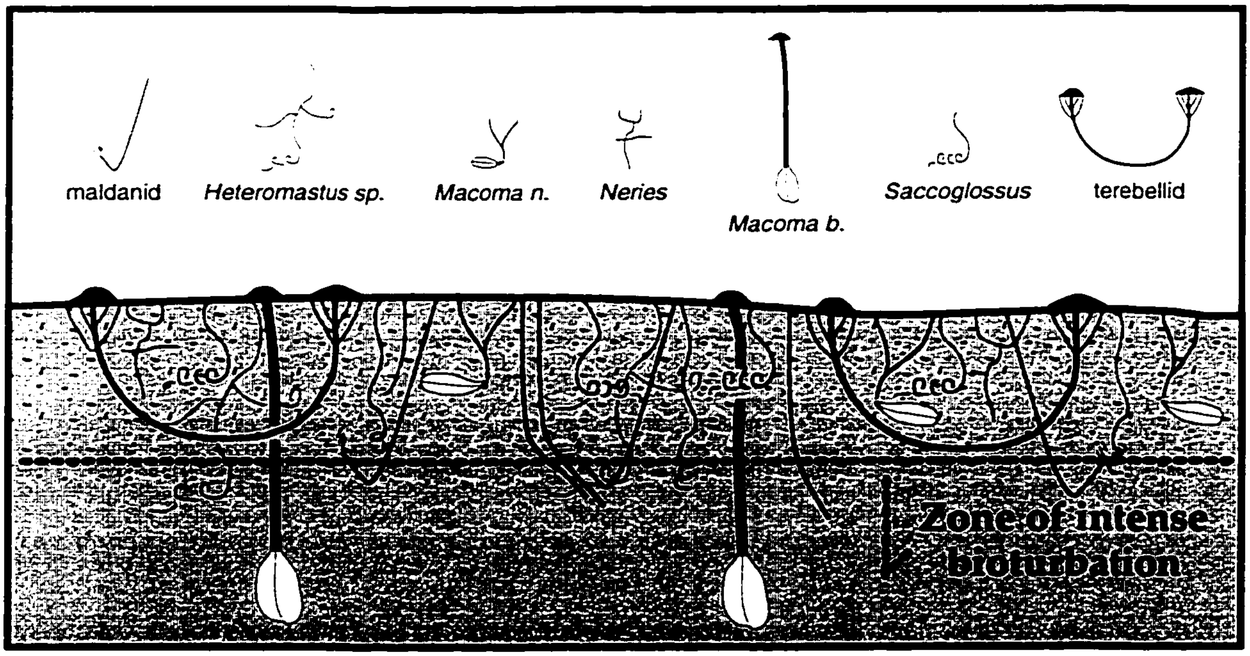

FIGURE 2.4 - Schematic detail of a mudflat-dwelling assemblage at Willapa Bay. The burrowers shown represent the dominant tracemakers present in an ambient intertidal mudflat at the bay. Terebellid polychaetes are shown. However, maldanid polychaetes, mud shrimp, or various bivalves may occupy their niche. The depth to the dashed line is 15-25 cm.

In muddy deposits, permanent and semipermanent burrows are stained orange by a thin oxide coating. Burrows observed in sandflats with a shallow redox discontinuity are similarly discolored. Scanning electron microscopic analysis indicates that Fe, Mg, and Mn are enriched in this zone, and that the degree of enrichment is variable. Oxide burrow halos are not observed in unconsolidated sediments that have passed into the historical record, and no analysis has been carried out to determine whether the metal enrichment associated with the *lebenspurren* persists below zones of active colonization.

Biogenic reworking on the intertidal flat is extensive. Radiographs of cores retrieved from both sandy and muddy intertidal flat deposits show that, as the sediment passes into the historic record, primary sedimentary structures are all but obliterated (Fig. 2.5). In muddier deposits, a vestigial lamination may be preserved (Fig. 2.6). Below sediment depths of 10 to 20 cm, sandflat deposits are characterized by the absence of physical sedimentary structures. An exception to this is the presence of lamination produced by rapidly aggraded run-off channels (Fig. 2.7A). Resulting ichnofabrics are typically dominated by crustacean burrows, or appear massive (ichnofabric index 6) due to extensive biogenic reworking.

Physical sedimentary structures, though rarely preserved, generally include current- and wave-generated ripple lamination, starved ripple lamination (particularly in muddy accumulations), and low angle to horizontal planar lamination. Bedding is horizontal and characteristically thin (cm scale). Organic detritus comprised of terrestrial plant debris, and marine kelp and algae is disseminated throughout muddy deposits; sandflats have very little macroscopic organic material preserved into the historic records (microscopic organic material present interstitially, or adhering to the sand grains was not assessed).

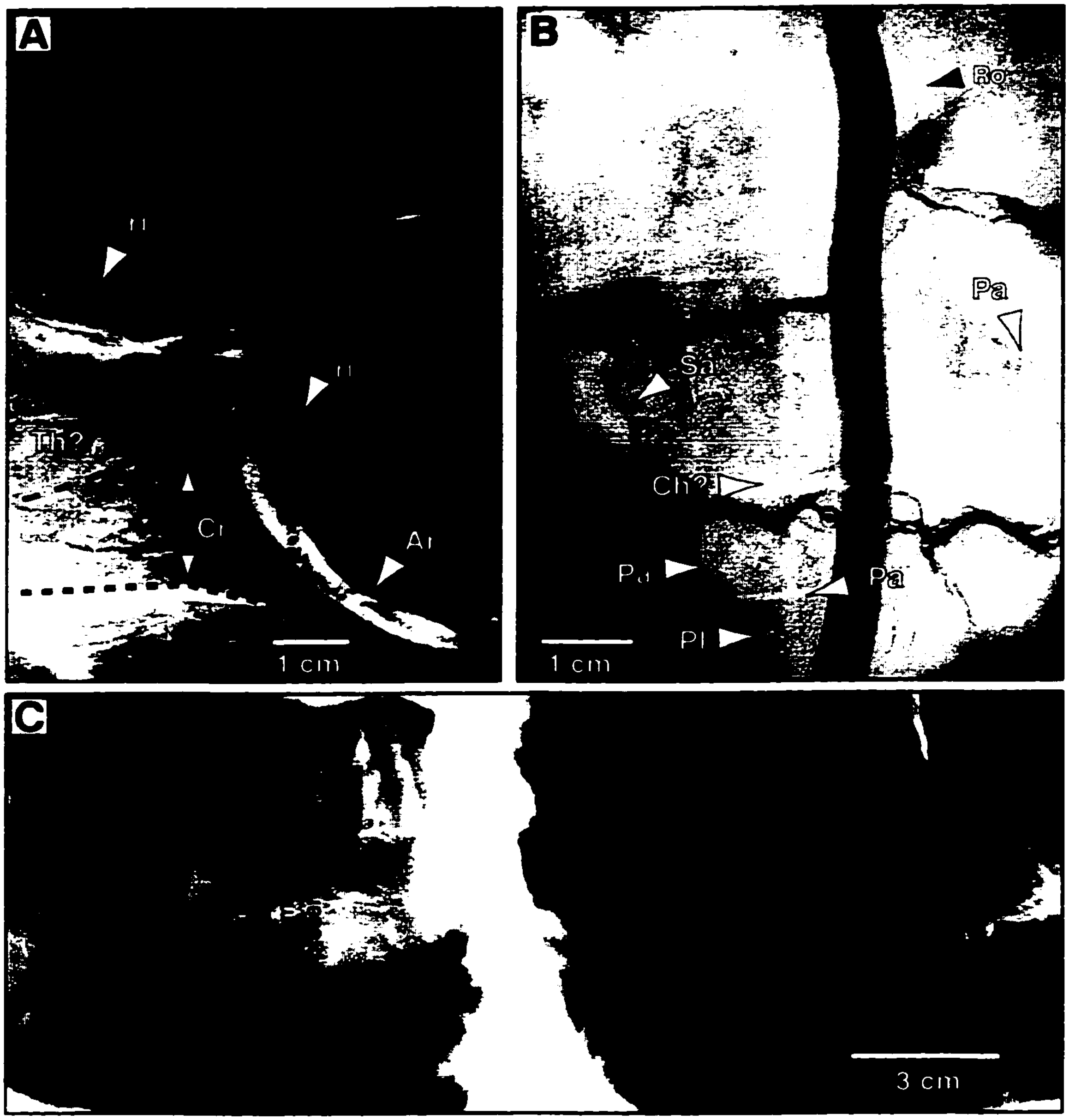

FIGURE 2.5 - Various mudflat radiographs. (A) Radiograph of modern intertidal sandflat. The sand is ripple laminated to a depth of approximately 13 cm. Lamination is destroyed and replaced by a zone of cryptic bioturbation (Cr) at about the depth of the U-portion of the lugworm burrow (Ar). *Thalassinoides* (Th?) is detailed on the left side of the frame. The lugworm, *Aberinicola*, is visible in its burrow. (B) Radiograph of a robust terebellid burrow from a modern mudflat at Willapa Bay. Primary sedimentary structure is absent due to intense reworking. *Rosellia*-like lamination is visible near the top of the photo (Ro), and a *Gyrolithes*-like *Saccoglossus* coil is also present (Sa). Other burrows include *Chondrites* (Ch?), *Palaeophycus* (Pa), and *Planolites* (Pl). (C) Radiograph of an extremely stressed assemblage of mudflat burrowers from Teal Slough, Willapa Bay. Primary sedimentary structure is eradicated below 4 cm depth, even though the bioturbation results from only two burrowers, *Nereies* (the visible burrows) and *Heteromastus* (barely visible vertical threads).

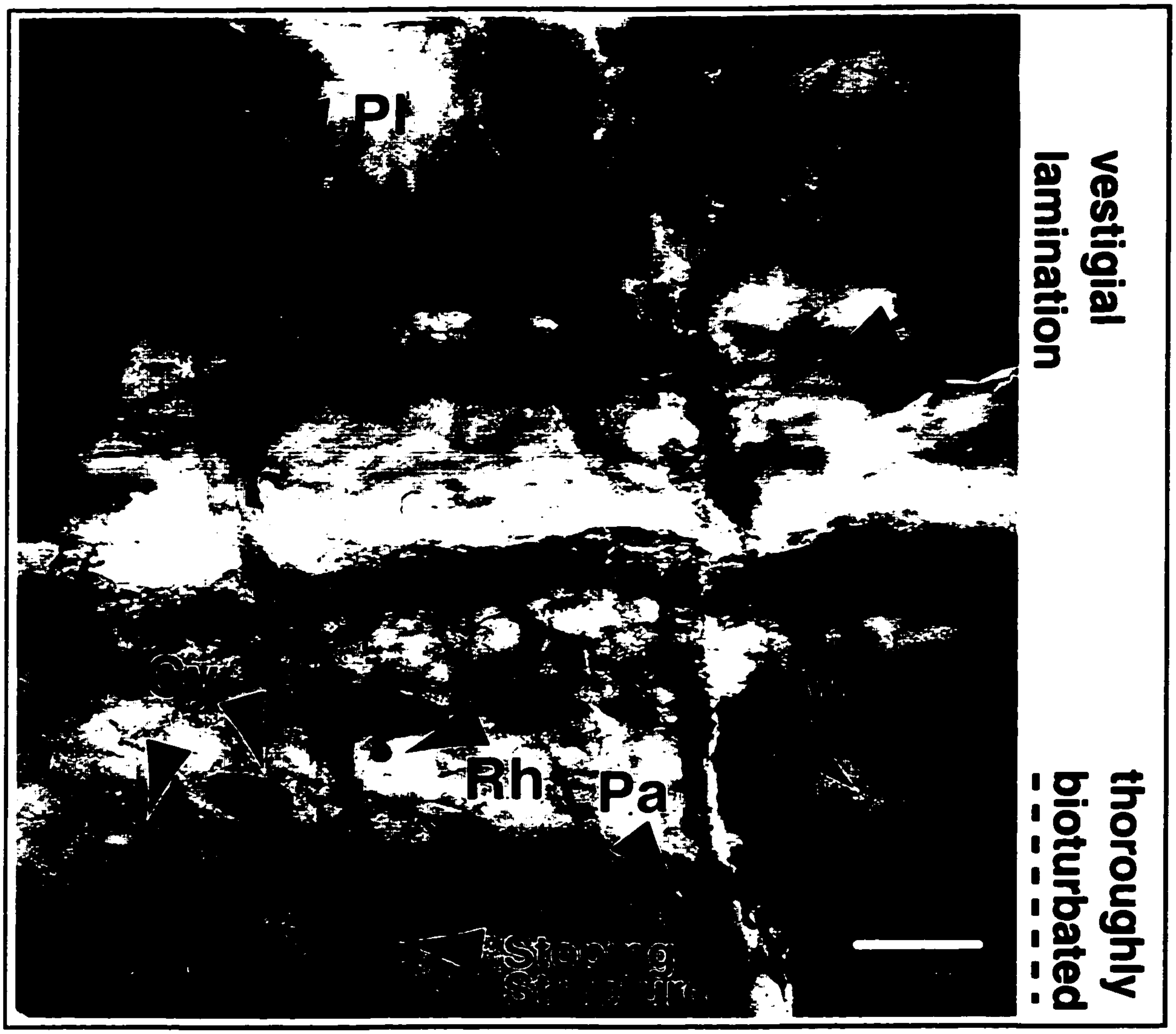

FIGURE 2.6 - Radiograph, interpreted to be representative of Pleistocene intertidal flat deposits, emphasizing the overall degree of biogenic reworking passed into the rock record. Only vestigial lamination, represented by changes in grain size preserved in the bioturbate texture, is present. Trace fossils characteristic of these deposits are labeled. Among them are *Cylindrichnus* (Cy), small *Planolites* (Pl), *Palaeophycus* (Pa), *Rhizocorallium* (Rh), and a stoping structure. The overall fabric is the result of abundant *Planolites*, *Gyrolithes*, *Palaeophycus*, and possibly *Trichichnus* almost completely reworking the sediment. Sample from the Bone River Tidal Flats

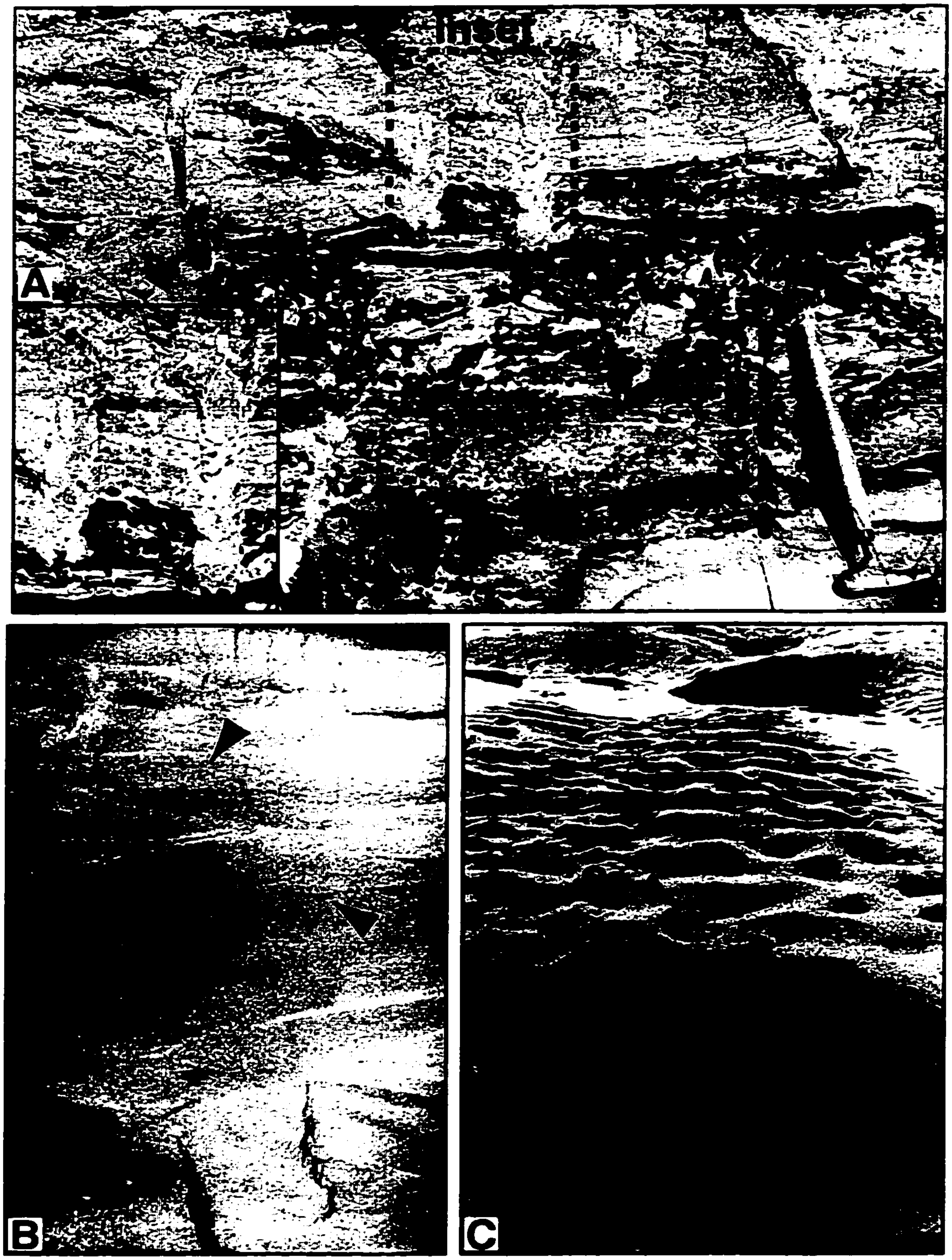

FIGURE 2.7 - Various sandflat perspectives. (A) Pleistocene sandflat deposit intercalated with laminated, lens-shaped, silty runoff channels. Large bivalve traces are present, and locally, the animals siphonate passage is visible. Adjustments to sediment influx are visible below the bivalves indicated by the dashed black rectangle. A magnification of this zone is inset lower left. The bivalves appear to have ascended in pulses, likely in relation to variations in sediment-accumulation rates. The persistence of silty substrate increases upwards, possibly due to --->

(cont.) progradation of the intertidal flat. Location near Bruce Port historical marker on highway 101. (B) Radiograph of ripple cross-laminated sand with abundant *Paraonis* spirals (black arrows). The spirals are connected to the surface with thin vertical shafts, which are visible near the top of the image. *Paraonis* and other thread worms disrupt sands and are capable of generating a form of diffuse, cryptic bioturbation. (C) *Ophiomorpha* eroding out of an intertidal cutbank. These burrows are the result of sand shrimp (*Callianassa californiensis*) colonizing the sand flat. Evidence of their capacity for overturning the substrate is evidenced by the undulatory appearance of the sandflat. Sand ejected from the burrow is reworked into small hummocks and ripples during the high tide. A subaqueous dune is visible in the background. Shrimp burrows are visible on these migrating dune forms as well. The black arrows indicate pelletized burrow apertures (Ophiomorpha) weathering out of the substrate (Op). From the Tokeland tidal flats.

Although striking lateral variability exists between the upper, middle, and lower intertidal zones, they are complex and not easily summarized. In both muddy and sandy intertidal flats, the depth and intensity of burrowing is highest in the lower intertidal zone, which is consistently dominated by burrowing shrimp, most commonly *Callianassa* or *Upogebia*. Other burrowers include thread worms, *Nereis, Nephtys,* and various bivalves, notably *Mya, Macoma,* and *Crypatoma*. Subtidal organisms, such as *Dungeness* and sturgeon, venture into this zone during the high tide. Their search for food is documented by locally abundant feeding pits, which give the lower intertidal a pitted appearance. Traces generated by shrimp commonly extend 60 cm into the substrate and constitute the dominant component of the observed ichnocoenose.

The middle intertidal zone is distinguished by medium- to large-sized burrowing bivalves, including *Macoma balthica* and *Tresus nuttalli*. Burrowing worms such as *Nereis, Nephtys, Saccoglossus, Heteromastus,* lug worms (particularly in sand-dominated flats), and terebellid polychaetes are typically present, generating an array of trace forms. Grazing fauna, such as the barrel snail (*Rictatus punctocaelatus*), are more common, and burrowing shrimp are absent to common (up to 110 individuals / square meter) and are unevenly distributed in this zone.

Trace assemblages in the upper intertidal zone exhibit a lower trace diversity and include notably smaller forms. An exception to this is the presence of raccoon feeding pits. These are holes (15 cm diameter) dug into the substrate in their quest for the small, but abundant bivalves present.

Pleistocene Tidal Flat Deposits

Ancient intertidal flat deposits at Willapa Bay are comparatively scarce. Where complete sedimentary successions are observed, they cap subtidal units, such as estuarine point bar or channel bar deposits.

As with the modern, Pleistocene intertidal flats are reworked extensively and their bedding is massive to crudely defined by continuous horizons of silt- and sand-filled burrows (Fig. 2.6). Primary sedimentary structures are rarely preserved, but may include planar bedding, graded laminae, ripple and starved ripplelamination. Organic detritus is locally abundant, including wood fragments and transported rhizomes. Burrows are typically small (1 to 4 mm in diameter) and biogenic disruption is pervasive. Discrete burrows are locally discernible and are commonly limited to the ichnogenera *Skolithos*, *Arenicolites*, *Gyrolithes*, *Cylindrichnus*, *Planolites*, and *Palaeophycus*. In outcrop, *Skolithos*, *Gyrolithes*, *Planolites*, and *Palaeophycus* are evenly distributed; *Arenicolites* and *Cylindrichnus* are sporadically distributed, generally in closely spaced packages of 2 or more trace fossils along bedding surfaces. Crustacean burrows are present sporadically, attaining notable abundance (> 80/m^2). These traces are comprised of relatively large (greater than a cm in diameter) *Thalassinoides*. Crab burrows also are abundant locally, typically infilled with a crudely laminated, passive infill. Where present, the crustacean burrows overprint the background bioturbate texture and typically represent the deepest tier of mudflat burrows.

Ancient sandflat deposits are most common in the older Pleistocene strata at Willapa Bay. Two examples include the Pleistocene exposure adjacent to the Bruce Port historical marker on Highway 101 and the outcroppings near Pickernell Creek (Fig. 2.1). At these locations, massive to crudely bedded sand is intercalated with rare mm-scale mud beds. The deposit is intensely cross cut by silt- and sand-filled run-off channels (Fig. 2.7). Bioturbation consists primarily of medium- to large-sized bivalve traces (equilibrichnia and *Siphonichnus*), medium-sized *Ophiomorpha* and *Thalassinoides*, passively-infilled crab domiciles, and diminutive *Planolites* and *Skolithos*. As a whole, smaller trace fossils are absent, probably due to extensive reworking of the deposit by larger burrowers and preservational bias in coarser-grained clastic deposits.

In summary, both modern and ancient mudflat deposits are characterized by relatively small burrows and high degrees of bioturbation. The physical sedimentary character is commonly destroyed, although silt- and sand-filled burrows are concentrated along planar horizons and may be indicative of the original bedding surfaces. Pleistocene sandflat deposits are comparatively rare, and are dominated by somewhat larger traces, notably those made by bivalves and crustaceans. This compares favorably with the modern sandflat, which, except in the upper intertidal zone, is almost completely colonized by *Callianassa sp.* and, locally, relatively robust bivalves. As with the modern, Pleistocene sandflats exhibit poor preservation of smaller traces.

Interpretation of Tidal Flat Deposits

Burrowing intensity in intertidal flat environments lends a distinctive aspect to their associated deposits. Strongly burrowed fabrics (i.i. 5 or 6) are the product of low sedimentation rates and high rates of biogenic reworking on the intertidal flats. Lead shot tracer experiments conducted over one year indicate low sediment aggradation rates (< 1 cm / year) are characteristic of the tidal flats. This precludes the possibility that the weakly laminated to burrowed (locally massive-appearing) bedding results from neap/spring tidal cycles; the fabric most likely results from seasonal variations in rates of bioturbation and is akin to the seasonal bundles noted by Dalrymple et al. (1991) at the Bay of Fundy. Thorough bioturbation in sandy deposits suggests the rate of biogenic reworking (by deposit feeders) in sandy deposits is higher than in muddy substrates (Swinbanks and Luternauer, 1987). Measurements of the total organic carbon content are significantly higher in muddy (6.7 to 7.8%) compared to sandy intertidal flats (1.8 to 3.2%). This comparatively limited resource in sandy deposits requires that greater amounts of substrate must be processed more rapidly by the resident infauna. *Callianassa*, for example, is an aggressive deposit feeder present in the sand flats at Willapa Bay. Empirical observations on modern tidal flats, and aquarium studies conducted at Willapa Bay clearly indicate that these shrimp churn great quantities of sand at depths of 10 to 40 cm. as they sieve sand grains through their mouth-parts.

Overall, there is a general trend towards more robust burrows in the lower intertidal flat. This pattern is directly controlled by the duration of inundation, which governs the amount of oxygen available to burrowing organisms. Infauna inhabiting the middle and upper intertidal zones are subject to additional stresses, such as salinity stress from discharging groundwater and rainfall, dessication, and predation (Cadée, 1998). The ichnologic contrasts between the upper, middle, and lower intertidal zones are gradational, but distinct enough that they may be utilized as facies edge-indicators.

Modern and Pleistocene deposits are remarkably similar in many respects. Both are strongly bioturbated and exhibit a paucity of physical sedimentary structures. *Planolites*, *Palaeophycus*, *Arenicolites*, and *Skolithos* in ancient deposits exhibit ichnofabrics similar to fabrics from the modern (Figs. 2.5B, C, and 2.6). Certain trace fossils, such as *Ophiomorpha*, *Thalassinoides*, and *Cylindrichnus*, are morphologically similar to burrows made by the modern trace makers, *Upogebia*, *Callianassa*, and maldanid polychaetes. No example of *Rosselia* has yet been documented from the Pleistocene deposits. Stratal thickness in the Pleistocene is variable, but generally 1-to-2.5-m-thick packages are preserved. The thickness of modern deposits ranges from a few centimeters, above wave-ravined Pleistocene firmground, to more than 2.6 m.

Rare physical sedimentary structures preserved in both modern and Pleistocene intertidal flat deposits are consistent with processes observed in the modern. Ripple and starved ripple lamination result from low- to moderate-energy tidal currents and wind-generated wave action. Winter storm tides are possibly represented by thicker laminae sets. Abundant organic material has been transported from both terrestrial and marine sources. Transportation agents include tide- and wind-generated currents. Terrestrial organic material is delivered to the bay by fluvial transport (Cadée, 1998). Marine kelp and algae are derived from the bay (growing in situ) and come into the bay via the bay inlet (Cadée, 1998).

Rare preservation of intertidal flat deposits may be due to their tendency to be removed by the rapid meandering of intertidal creeks (Clifton and Phillips, 1980), or truncated by channel or ravinement processes due to allocyclic changes in base level.

In the modern, intertidal deposits clearly pass into the historic record. This is particularly true in muddy substrates in which meander rates are relatively slow (Fig. 2.8). Conversely, in somewhat sandy flats, robust intertidal communities are truncated by rapid intertidal creek migration, biasing the intertidal record towards the deepest-tier traces. The rapid meandering of tidal creeks in sandy substrates is, however, countered by high rates of biogenic reworking. Sandy intertidal flat deposits reflect this balance, preserving completely bioturbated horizons intercalated with run-off channels that appear to have rapidly aggraded and thus were spared biogenic eradication (Fig 2.7A).

Ravinement due to changes in base level may also explain the overall paucity of preserved intertidal flats in the Pleistocene deposits. In subducting tectonic regimes accommodation space is gradually reduced due to plate flexure, followed by sudden increases (potentially metre-scale) of accommodation space during megathrust earthquakes (Atwater, 1987; Atwater and Yamaguchi, 1991). Along the Washington coast, tectonic adjustments due to plate flexure have been demonstrated to occur every 300 to 700 years throughout the Holocene (Atwater, 1987; Atwater and Yamaguchi, 1991); no Pleistocene data is available. Gradual relative sea level (rsl) rise followed by a sudden lowering of rsl should have the following effects on intertidal flat deposits: the intertidal and supratidal facies prograde forming a thin, shallowly dipping bed; this bed is increasingly susceptible to erosion as progradation continues; and the thin deposit is easily eroded by first and second order tidal channels following sudden rsl rise. All of these factors markedly reduce the overall preservability of intertidal deposits.

Point-bar deposits

Modern Tidal Creek Point-bar deposits

Modern intertidal flats are commonly truncated by complex networks of meandering intertidal creeks, particularly in substrates with notable silt or mud content. Associated with these channels are numerous point-bar deposits (Fig. 2.8A). Depending on the texture of the intertidal flat sediment, these point bars may have a high preservation potential. Dominantly muddy flats inhibit the rate of channel meandering, limiting the distribution of point bars, whereas sandy substrates are rapidly reworked by the sand-flat biota. Intermediate substrates therefore proffer the greatest likeliehood of passing intertidal point-bar deposits into the geologic record.

Modern intertidal point bars at Willapa Bay typically are burrowed by an extremely low-diversity assemblage of diminutive infauna (Fig. 2.8B). Threadworms, such as the capitellid polychaete *Heteromastus*, are among the most common burrowers. *Heteromastus* burrows consist of vertical shafts 10 to 30 cm deep, with numerous horizontal to subhorizontal branches. The terminus of the burrows generally ends in a *Gyrolithes*-like coil, the axis of which is oriented randomly. Other tracemakers include *Nereis*, the small amphipod *Corophium*, and juvenile bivalves. The resulting trace suite is a low-diversity assemblage composed of diminutive vertical and horizontal burrows. This assemblage grades with the intertidal flat assemblage over 2 m on smaller point bars (fourth-order channels) and up to 8 m on larger point bars (first- or second-order channels). Figure 2.9 illustrates the gradational relationship between the intertidal point bar and tidal flat ichnocoenoses.

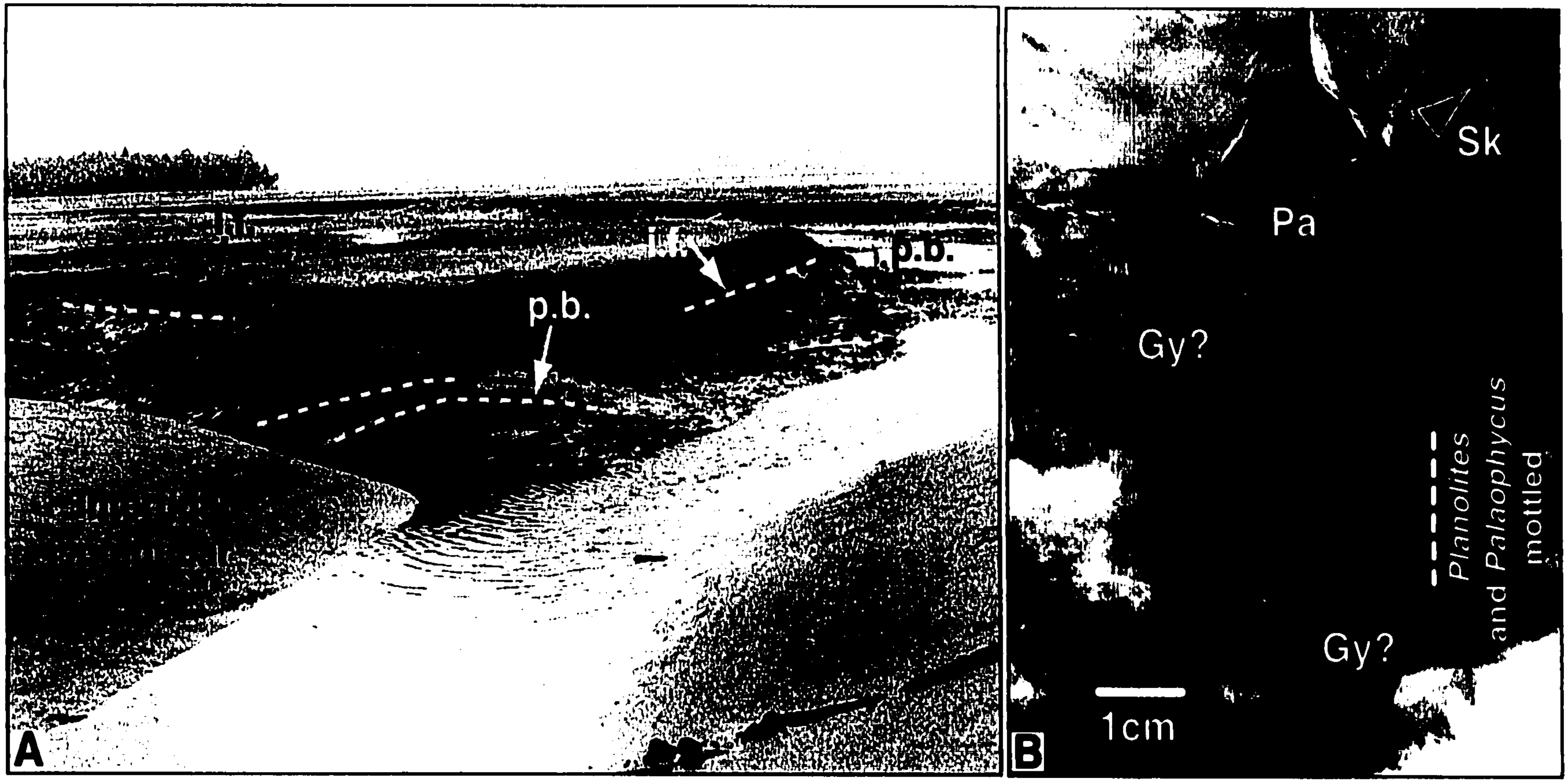

FIGURE 2.8 - Relationships of intertidal point bars to intertidal flats and the radiographic fabric of intertidal point-bar deposits. Both from the Bone River tidal flats. (A) Intertidal flats, cutbanks, and point bars near the Bone River at Willapa Bay. Intertidal flat bedding (i.f.) and point bar bedding (p.b.) are visible in the cutbank. Progradation of the intertidal flat over the point bar allows reworking of the upper portion of the point-bar deposit. The cutbank is about 1.3 m high. (B) Xray image of modern intertidal point bar, from about the middle of the point bar. The degree of reworking may be high, but vestigial lamination is more apparent than in intertidal flat deposits. The burrows are almost exclusively comprised of small *Planolites*, *Palaeophycus* (Pa), *Skolithos* (Sk), and *Gyrolithes* (Gy?). No large burrows are present.

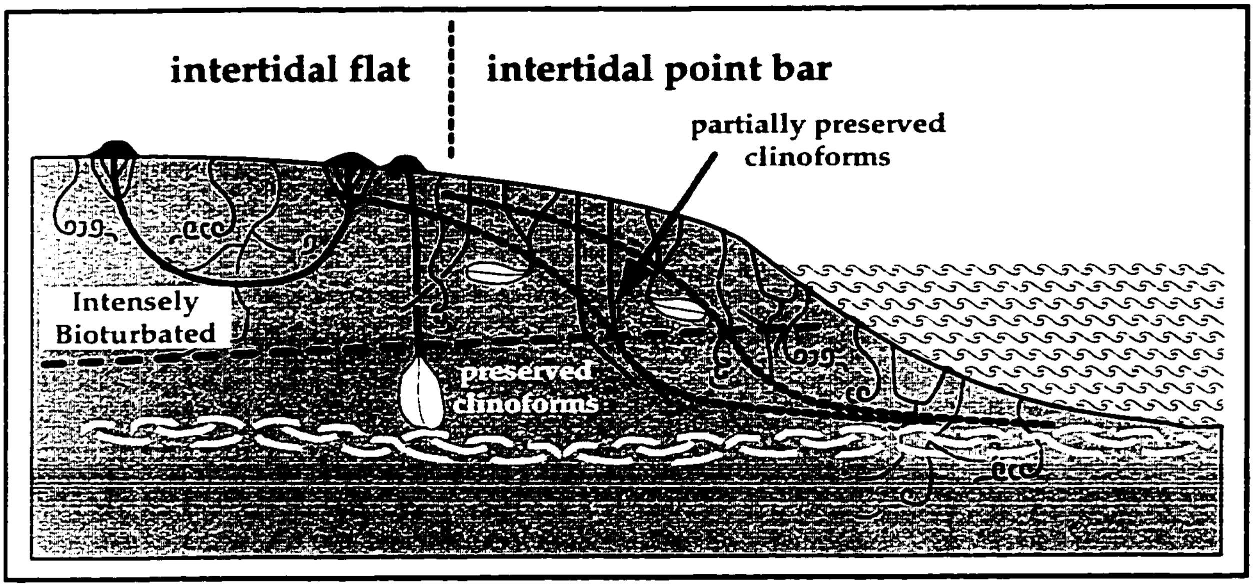

FIGURE 2.9 - Schematic detail of an intertidal point-bar assemblage (substrate is muddy sand to sandy mud) at Willapa Bay. The burrowers shown represent the dominant tracemakers present in an intertidal point bar at the bay. The lower, more stressed portion of the point bar has the highest preservation potential (below the dashed line). A legend for the biogenic structures is present in Figure 2.3. The height from the base of the channel to the top of the intertidal flat is generally abetween 1 and 2.5 m.

The assemblage observed in modern intertidal point bars is superimposed on inclined, relatively well-laminated sediment indicative of cyclic deposition. The degree of bioturbation may be such that laminae are completely disrupted by small traces (Fig. 2.10), although planar lamination, graded bedding, and ripple lamination are observed locally. Bedding is primarily defined by muddy and silty to fine-grained sand laminae. The deposit is rich in organic detritus (TOC between 5 and 8%; 4 samples measured) and, locally, woody debris. Lower contacts in these deposits are always sharp to erosional, and typically a 5-to-10-cm-thick shelly lag has accumulated immediately above the contact.

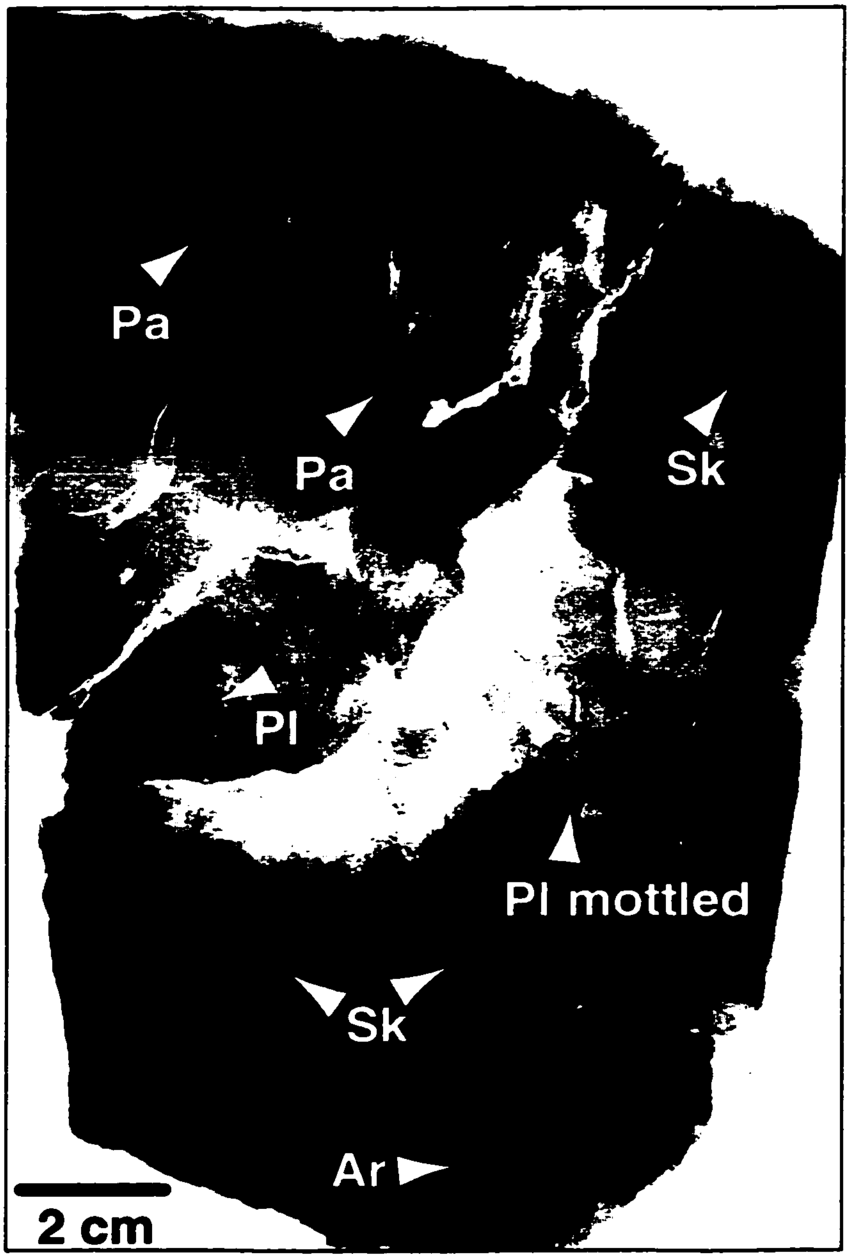

FIGURE 2.10 - Radiograph of Pleistocene silt and mud interpreted as indicative of deposition in an intertidal point-bar environment. Small *Skolithos* (Sk), *Arenicolites* (Ar), *Planolites* (Pl), and *Palaeophycus* (Pa), are present in moderate to high abundance. Some of the mottling is likely due to the presence of small, deformed *Gyrolithes* although none are clearly discernible on this illustration. Original bedding is destroyed by these small burrows. This example may come from higher on the point bar than the modern example detailed in 8B.

Pleistocene Tidal Creek Point-bar Deposits

Ancient intertidal point-bar deposits are present locally in Unit I. Like their modern counterparts, they are commonly burrowed with a diminutive, low-diversity suite of trace fossils. Common lebensspurren observed include *Skolithos, Diplocraterion, Palaeophycus, Planolites,* and *Gyrolithes.* Rarely, passively-infilled crustacean burrows, similar to those made by *Hemigrapsus* in modern deposits, are present. Deformed *Gyrolithes* appear to cross cut the other trace fossils and represent the deepest tier of burrowing, possibly near the basal terminus of longer *Skolithos*-like burrows. Ancient intertidal point bars can be traced approximately 5 to 15 m across the outcrop. However, these exposures provide sections oblique to the channel axis, and rarely exceed one metre in thickness. There is lateral variation, with small *Gyrolithes* and *Skolithos* present near the toe of the point bar, and larger trace forms (*Planolites, Palaeophycus,* and *Skolithos*) more abundant in the upper portions (Fig. 2.10).

The Pleistocene sedimentary structures are comparable to those described herein from the modern tidal creek point bars, except that the overall degree of bioturbation is higher in the Pleistocene strata (Fig. 2.10). Pebbles and wood debris overlie the sharp lower contact of these deposits; disarticulated bivalve shells are present locally, but not with the ubiquity of analogous modern environments.

Pleistocene intertidal point-bar deposits are, therefore, characterized by low-diversity, diminutive trace fossil suites. The degree of bioturbation is low to high (increasing upwards), and primary sedimentary structures are preserved locally. Modern intertidal point bars are analogous in every respect, except that the overall degree of bioturbation in the modern is somewhat lower and a basal shell lag is not typically present in the Pleistocene deposits.

Modern Fluvially- and Tidally-Influenced Main Channel Point-bar Deposits

The main channel point-bar depositional environment is common at Willapa Bay. Due to their association with fluvial tributaries, they exhibit notable ichnological, chemical (most notably salinity), and textural variability. As the major supply of coarser clastic detritus comes into the bay through its inlet, sandy deposits tend to be situated near the lower reaches of the estuary. The upper reaches, on the other hand, are typically characterized by silt and mud. In the upper estuary salinity fluctuations and low background salinities contribute to extreme salinity stress (Fig. 2.11). Figure 2.11 also outlines the different burrowing taxa (diversity) and quantifies dimunition of trace forms, as the point bars are traversed in an up-estuary direction. In the lower reaches of the Palix River (stations 1 and 2), 12 burrowing taxa are commonly observed. Typical burrow diameters range between 3 to 15 mm. At station 4, only 7 taxa are noted, with average burrow diameters falling between 1 and 3 mm. Station 5 is characterized by 5 common burrowers, all of which produce burrows less than 2 mm in diameter.

Muddy point bars typically exhibit low-diversity assemblages that are comprised primarily of diminutive traces. Trace makers include *Heteromastus*, *Corophium*, *Nereis*, juvenile *Mya*, and *Hemigrapsus*. The resulting ichnocoenosis is strongly tiered and consists of shallow *Arenicolites*, moderate-depth (appx, 1- 10 cm) siphonate passages, and deep-penetrating (up to 28 cm) *Skolithos* and *Gyrolithes* (Fig. 2.12). Radiographs of modern deposits indicate that the deepest-tier burrows overprint shallow burrows and are preferentially passed into the historic record (Fig. 2.13).

Physical sedimentary structures include planar lamination, graded bedding, and starved ripple lamination (Fig. 2.13). Bedding is primarily defined by mud and silt laminae, although fine-grained sand laminae are present locally. The deposit is rich in organic detritus with TOC measurements falling between 6 and 9%; wood clasts are abundant throughout the point-bar deposit. In situ, articulated bivalve shells and imbricated, disarticulated valves along bedding planes are rarely present. The lower

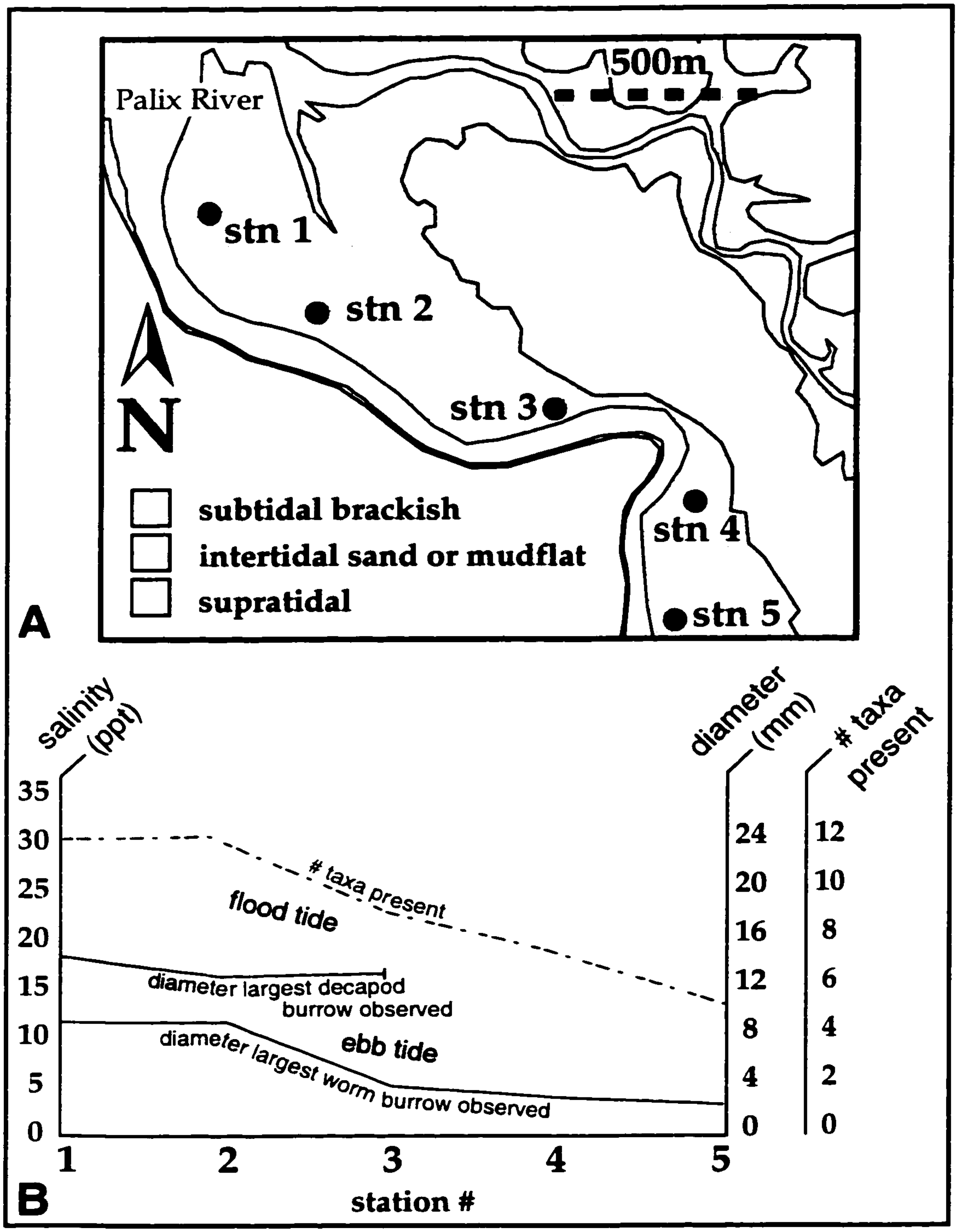

FIGURE 2.11 - Base map of the Palix River showing the location of five observation stations and associated salinity gradients. (A) Base map and location of temporary observation stations along the Palix River. (B) Graph of station number versus salinity (ppt), diameter of largest commonly observed burrows (mm), and the number of common burrowing taxa present. The flood tide and ebb tide are shaded, as they represent a range of values at each station.

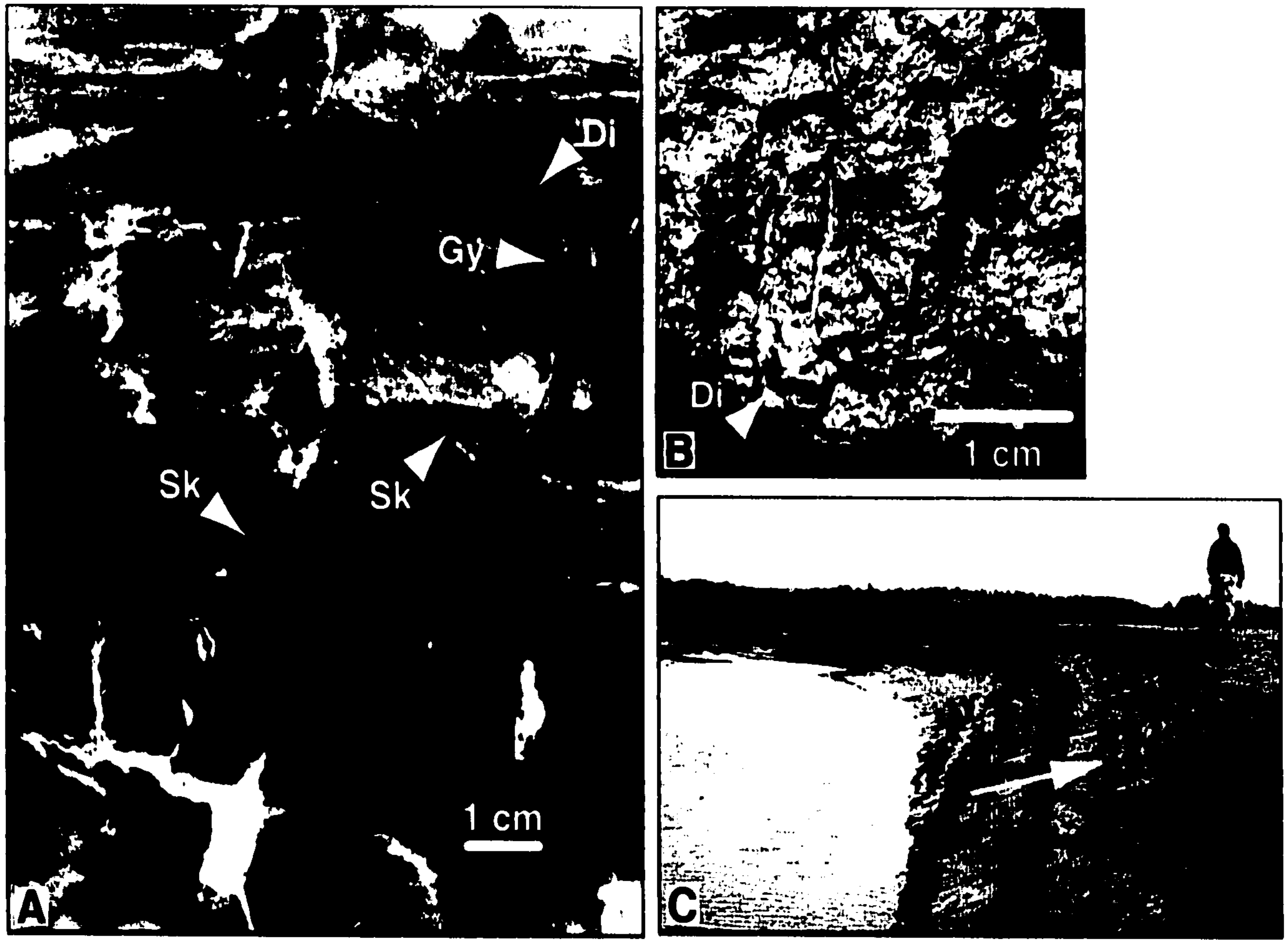

FIGURE 2.12 - Different scales of view for muddy, main channel point bars. All plates are from the Palix River. (A) Radiograph of modern subtidal point-bar lamination and bioturbation in the muddier upper estuary. *Skolithos* (Sk), *Gyrolithes* (Gy), and *Diplocraterion* (Di) are labeled. All of the traces are small and much of the lamination is preserved. (B) *Diplocraterion* (Di) produced by the isopod *Corophium* from core retrieved at the same site as the xray image shown in A. (C) Point bar lamination (inclined heterolithic stratification) exposed during low tide. The upper portion of subtidal point-bar deposits are also subject to reworking upon intertidal flat progradation.

FIGURE 2.13 - Subtidal (modern), sandy point-bar deposits. (A) *Callianassa* -reworked sediment. Very little lamination is preserved, although traces similar to *Thalassinoides* (Th), *Ophiomorpha* (Op), and *Planolites* (Pl) are present. The *Ophiomorpha* on the right appears to have been filled passively by conical infilling. Palix River, station 2. (B) Laminated (modern) subtidal point bar characterized by wavy and planar bedding, expressing inclined heterolithic stratification. Traces are primarily those of burrowing polychaetes (maldanids and capitellids) and include *Skolithos* (Sk), *Gyrolithes* (Gy), and *Palaeophycus* (Pa). Palix River, station 3.

contact is erosional and, commonly, a woody, shelly lag has accumulated in the channel adjacent to the point bar.

Sand to muddy sand deposits exhibit a more diverse assemblage of tracemakers (Fig. 2.13). *Callianassa* colonize the point bar from the middle intertidal zone down to its subtidal toe. Population densities are variable (0 to 247 burrow openings / square meter, the mode in burrowed zones is 80 openings/m^2), although generally the highest densities are present in the upper subtidal. *Nereis, Nephtys,* and various threadworms are present in moderate abundance (no population count), typically extending from the middle intertidal facies down into the subtidal channel facies. Tube-dwelling maldanids (a polychaete worm) are present in subtidal zones, and are most abundant (> 500 individuals/m^2) where a significant component of interstitial mud is present (Fig. 2.13). Locally, robust *Mya* and *Macoma sp.* are present; however, their distribution is patchy. Juvenile bivalves are more common, with population densities ranging from absent to almost 600 individuals per square meter (extrapolated from 25 cm^2). The consequent trace assemblage is variable and shows distinct zonation down to the channel thalweg (Fig. 2.14). Traces include *Ophiomorpha-, Skolithos-, Gyrolithes-, Monocraterion-, Siphonichnus-, Rosselia-, Planolites-,* and *Palaeophycus*-like burrows (Figs. 2.14, 2.15). Some of the traces are relatively large (4-12 mm diameter), particularly the maldanid and terebellid tubes, and *Callianassa* burrows.

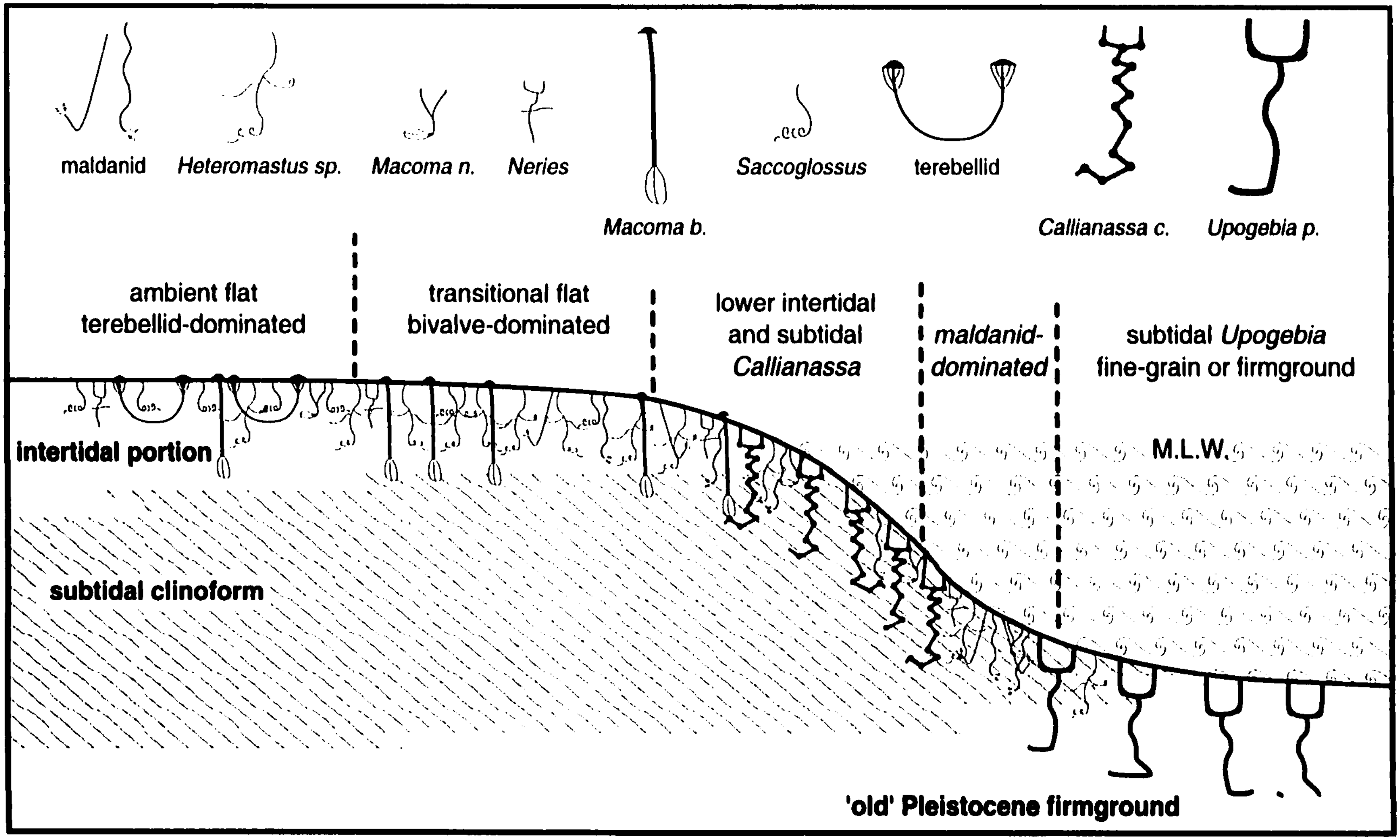

FIGURE 2.14 - A schematic representation of subtidal point bars and their relationship to intertidal flat deposits. This schematic is based on a muddy sand substrate and details a section along the Palix River (approximately at station 2, Fig. 2.11). At this location, the subtidal channel intersects ancient Pleistocene deposits and *Upogebia pugettensis* has colonized the firm substrate. The maldanid zone and *Callianassa* zone are those most observed in Pleistocene deposits at Willapa Bay. This is due to their fortuitous location, which maximizes preservation potential.

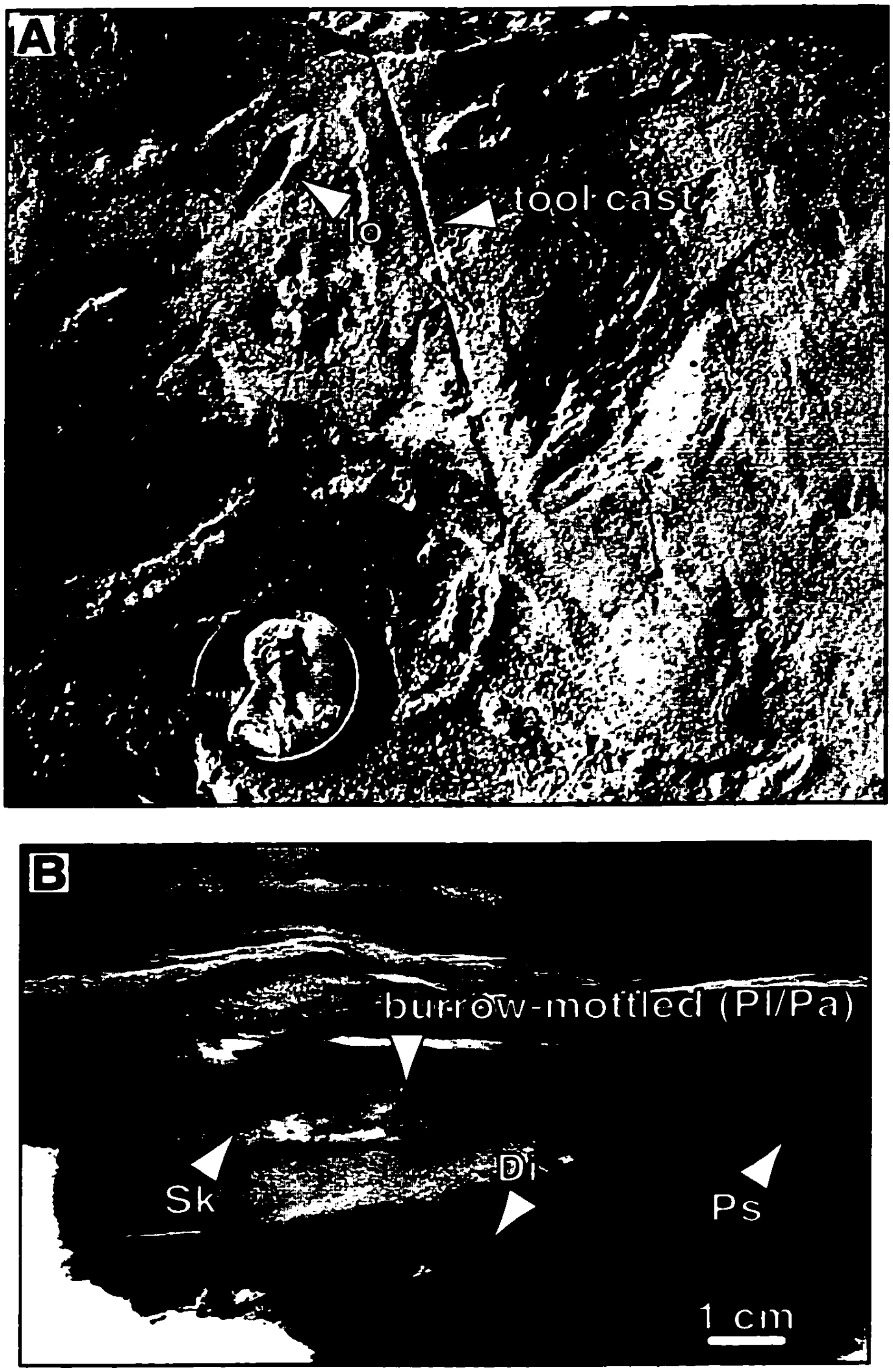

FIGURE 2.15 - Pleistocene sandy, subtidal point-bar deposits. (A) Bivalve resting traces (*Lockeia*) on bedding planes of Pleistocene strata at Willapa Bay. Some sections are very similar to cross sections of the trace fossil *Lingulichnus*. From outcrop near Pickernell Creek. (B) Radiograph of Pleistocene subtidal pointbar deposit at Willapa Bay. Note the overall similarity of this plate to Figure 13B. *Skolithos* (Sk), *Diplocraterion* (Di), *Planolites* (Pl), and *Palaeophycus* (Pa) are present. *Psilonichnus* (Ps) is interpreted to represent the ancient burrow of a *Hemigrapsus*-like tracemaker. From outcrop near Bone River.

Pleistocene Fluvially- and Tidally-Influenced Main Channel Point-bar deposits

Pleistocene subtidal point-bar deposits contain variable trace assemblages that appear to be, at least in part, texturally controlled. Dominantly muddy or silty accumulations are characterized by low-diversity suites of small trace fossils. Most commonly, deformed *Gyrolithes, Skolithos, Planolites, Palaeophycus,* and *Arenicolites* comprise the trace fossil assemblage. Rare *Ophiomorpha* and *Thalassinoides* are present locally. Large, passively-infilled burrows, interpreted to represent the dwelling structures of robust crustaceans (such as crabs), are rare to locally moderate, and are typically observed along the lower portions of the point-bar deposit. Overall, the degree of bioturbation is low, and traces are sporadically distributed. Physical sedimentary structures include planar lamination, graded bedding, starved current-ripple lamination, and local current scours. Organic detritus is abundant, particularly woody debris. Bivalve casts are present locally and some bedding-plane exposures show excellently preserved *Lockeia* (Fig. 2.15A).

Sandy subtidal point bars, such as those present in older Pleistocene outcrops near the Bone River (Fig. 2.15B), contain a more diverse array of *lebensspurren*. The suite is similar to the assemblage in muddy subtidal point bars, with the addition of moderately abundant *Cylindrichnus* and *Monocraterion*. These traces tend to occur in clusters of 3 to 5 shafts. Also, *Ophiomorpha* and *Thalassinoides* are most commonly observed in the sandier units. Passively-infilled, unlined burrows (attributed to a *Hemigrapsus*-like trace maker) are locally common. Physical sedimentary structures include abundant flaser, wavy, and lenticular bedding. Bedding is defined by abrupt changes in grain size (silt to fine- or medium-grain sand), indicative of seasonal changes in sediment supply (Clifton et al., 1989). Organic detritus is comparatively less abundant, although unbored wood clasts are observed locally. The lower contact of these deposits is erosional and is typically demarcated by intraformational rip-up clasts, pebbly lags, and concentrations of woody or shelly debris.

In summary, the ancient deposits at Willapa Bay are comparable to the modern deposits. Sedimentological and ichnological criteria are alike between the ancient and modern deposits, especially when texturally similar deposits are considered.

Interpretation of Point-bar Deposits

Subtidal and intertidal point-bar deposits represent the dominant facies present in the Pleistocene record at Willapa Bay. Trace fossils in these deposits lend insight into the distribution of physical and chemical stresses that were manifest in the ancient bay. Although it is difficult to assess precisely which physico-chemical parameters most influenced the ancient burrowing community, comparison of the Pleistocene deposits to the modern bay deposits provides an analog in which some of the variables are estimable.

Trace fossils in muddy point-bar deposits are sporadically distributed and degrees of bioturbation vary between unburrowed to locally moderate. With the exception of rare *Ophiomorpha* and *Psilonichnus*, the trace fossils are diminutive, ranging between 1 and 3 mm in diameter and include *Gyrolithes-* (relatively abundant), *Planolites-* (abundant), *Palaeophycus-*, *Cylindrichnus-*, *Teichichnus-*, *Monocraterion-*, *Skolithos-*, and fugichnia-like traces in rare to moderate abundance. These traces are are similar to those observed in other brackish-water deposits (Howard and Frey, 1973; Howard, 1975; Pemberton and Wightman, 1992). Several parameters may have played a role in limiting the size and diversity of burrowing infauna. They include lower levels of salinity or fluctuating salinity, oxygenation stress, turbidity stresses, rapid rates of sedimentation, and thermal stresses. Salinity is strongly correlated to dimunition of infauna and overall reductions in diversity (Fig. 2.11). Salinity fluctuation and overall low salinity appear to place limitations on the size of burrowing fauna in this environment. Contrasting burrow assemblages in sandy *versus* muddy substrates are due to two factors; different substrates are exploited in strikingly different manners, and sand and mud present dissimilar taphonomic barriers. This relationship is similar to Dörjes and Howard's (1975) observation in the Ogeechee Estuary on the Georgia Coast. They found that 6 estuarine biofacies exhibited similar distributions as five mapped sedimentary facies. This is *partly* attributable to passive links between salinity and texture. The authors noted "physical energy and the salinity *probably* (our italics) play major roles in determining similarities between the physical and biogenic records." Extracting ancient *relative* salinity stress from the rock record is therefore a daunting, but resolvable challenge. Furthermore, a strong behavioral dependence on substrate texture implies that ichnologic changes within similar lithofacies provide more information than comparing trace assemblages between lithofacies.

Muddy Pleistocene point-bar deposits at Willapa Bay exhibit very similar ichnologic characteristics to their modern counterparts. They are locally unburrowed, although a stressed suite of trace fossils is usually present. The ichnologic suite is indicative of the salinity extremes and sedimentation stress to which the infauna was exposed, and is relative to its location in the ancient estuary. In modern deposits along the Palix River, for example, the trace assemblage changes markedly over just 2 km (Fig. 11), from a relatively robust sand-dwelling assemblage to a stressed, mud-dwelling assemblage. Remane and Schlieper (1971) showed diversity of brackish species is consistently lower with reductions in salinity down to 5 ppt. This concentration represents a trough in the Remane Curve as fresh water species are increasingly abundant below 5 ppt. Extreme lateral variability along the Palix River, characterized by abrupt ichnologic changes, implies the overall aspect of the ichnologic suite can be utilized to assign a particular point-bar deposit to an approximate palaeogeographic position in an ancient estuary.

Taphonomic considerations also are reflected in the preserved trace fossil assemblage. Most of the observable traces are filled with silt or fine-grained sand, and tend to descend from the coarser-grained laminar components of the point-bar deposits.

They are typically deformed due to syn- and post-depositional compaction of the sediment. Deep-penetrating burrows (> 25 cm) descend into somewhat compacted mud, and are less likely to undergo severe post-depositional deformation. These traces overprint the more subtle and deformed shallow traces, lending an even more impoverished appearance to the trace assemblage. This bias is exaggerated because shallowly tiered traces are more vulnerable to erosion and may be removed by scouring currents. The deep burrows have the greatest probability of being passed into the historical record (in this case, the *Skolithos-* and *Gyrolithes*-like burrows of *Heteromastus*, and the *Thalassinoides*-like burrows of *Neotrypea*).

A notable contrast between sandy and muddy point bars is the presence of decapod burrows (*Thalassinoides* and *Ophiomorpha*) in sandy deposits, and their marked absence in muddy deposits. This is due to fundamental behavioral differences between sand shrimp and mud shrimp. Sand shrimp (*Callianassa)* process sand continuously, and its burrow is therefore dynamic, or typically shifting (Swinbanks and Lutenauer, 1987); hence, burrows are maintained easily in environments characterized by rapid rates of sedimentation. Another decapod, the shrimp *Upogebia pugettensis*, prefers muddy environments. *Upogebia* differs from *Callianassa* in that it requires a permanent domicile (Swinbanks and Lutenauer, 1987; Dworshak, 1988). Maintaining a permanent and static domicile in a rapidly aggrading sedimentary environment is comparatively energy-demanding. The presence of mud shrimp on active point bars is therefore mitigated. In other words, the presence of shrimp burrows in a muddy deposit is indicative of colonization *not* on the point bar proper. In fact, decapod burrows in muddy deposits are most likely to occur within tidal flats, tidal channels, or in bay deposits (discussed later). In contrast, shrimp burrows are common in sandy point-bar deposits, as sand shrimp are not necessarily restricted to depositional environments characterized by slower rates of sediment aggradation.

Some of the physical and chemical stresses exerted on runoff-creek (intertidal) point bars have an effect similar to that observed in main channel (subtidal) point bars. That said, intertidal point bars aggrade at a rapid rate and their ichnologic signatures are notably subdued by high sedimentation rates. Differentiating intertidal from subtidal point bars in outcrop is relatively simple, due mostly to the lateral relationship intertidal point bars have with intertidal flat deposits. In cored successions, the correct identification of these facies is more subtle. With respect to intertidal point-bar deposits, key criteria present at the core-scale include: inclined bedding, dipping between 5° and 15°; the presence of a diminutive suite of traces, including *Gyrolithes*, *Planolites*, and *Skolithos*; a sharp lower contact that overlies strongly bioturbated intertidal flat deposits; a trace assemblage that potentially grades upwards into an ambient intertidal flat ichnofacies, characterized by somewhat larger traces, higher degrees of bioturbation, and an increased diversity of trace fossils; and an accumulated thickness of less than 4 m (in mesotidal estuaries). It is equally important to note that intertidal point bars are not likely passed into the historic record if the substrate is primarily muddy or sandy. Intermediate substrates offer a compromise between meander rate and the rate of biogenic reworking that enhances the likelihood of their passage into the rock record.

Sandy, Laterally Accreted Mid-Channel Tidal Bars

Modern Sandy, Laterally Accreted Mid-Channel Tidal Bars

Mid-channel tidal bars are prominent features of the main tidal channels in the lower estuary. They are characterized by rapidly shifting, medium- to coarse-grained sand and are subject to reworking by strong tidal currents. There is an overall paucity of burrowing, although several notable trace makers persist in this energetic environment. Burrowers observed in this environment include: shallowly tiered, thick-shelled cockles; rare deep-burrowing bivalves, such as *Tresus nuttalli*; deep-penetrating, vertical Cerebratulids; sporadically distributed, deep-penetrating *Callianassa*, *Nereis*, *Nephtys*, and various thread worms are also present in variable densities. The resulting trace assemblage consists of bivalve equilibrichnia, *Siphonichnus*, robust *Ophiomorpha* and *Thalassinoides*, *Skolithos*, and rare *Palaeophycus*. The deepest-penetrating burrows proffer the greatest likelihood of preservation in these deposits, which suggests the historical record is dominated by *Ophiomorpha*, *Skolithos*, and deep-seated bivalve traces.

Bedforms include linguoid current ripples superimposed on subaqueous dune forms. The larger-scale bedforms are locally superimposed upon laterally-accreted, clinoform sets. Clinoforms dip gently (up to 10^0) perpendicular to the dominant flow direction. The bedforms observed do not necessarily reverse from flood to ebb tide, as these bars are typically ebb- or flood-dominant (Clifton et al., 1989).

Pleistocene Sandy, Laterally-Accreted Mid-Channel Tidal Bars

Pleistocene mid-channel tidal bar deposits exhibit many of the same sedimentological characteristics noted in the modern deposits. An excellent example is present at the South Bend Section (Fig. 2.16), where the overall degree of bioturbation is low (i.i. 1 to 2). Nevertheless, sporadically distributed *Ophiomorpha*, *Thalassinoides*, *Teichichnus*, *Palaeophycus*, and *Siphonichnus* are present throughout the section (Fig. 2.16B). These are typically about 9 to 15 mm in diameter and are intermediate in size. Also common throughout the deposit are small, branching, sandy tubes of thread worms (Fig. 2.16C), possibly analogous to the central shaft of *Paraonis* spirals observed in the modern bay (Fig. 2.7B).

The physical sedimentary structures include sharp-based, meter-scale clinoforms (Fig. 2.16A), and locally abundant trough crossbedding and ripple lamination (Fig. 2.16). Silt drapes over current-ripple lamination are common locally, forming flaser to wavy bedding. Rare tabular cross bedding and upper-flow-regime planar lamination are also present. Flow directions measured from trough cross-stratified beds are typically perpendicular to the dip direction of the clinoformed master bedding surfaces. Organic

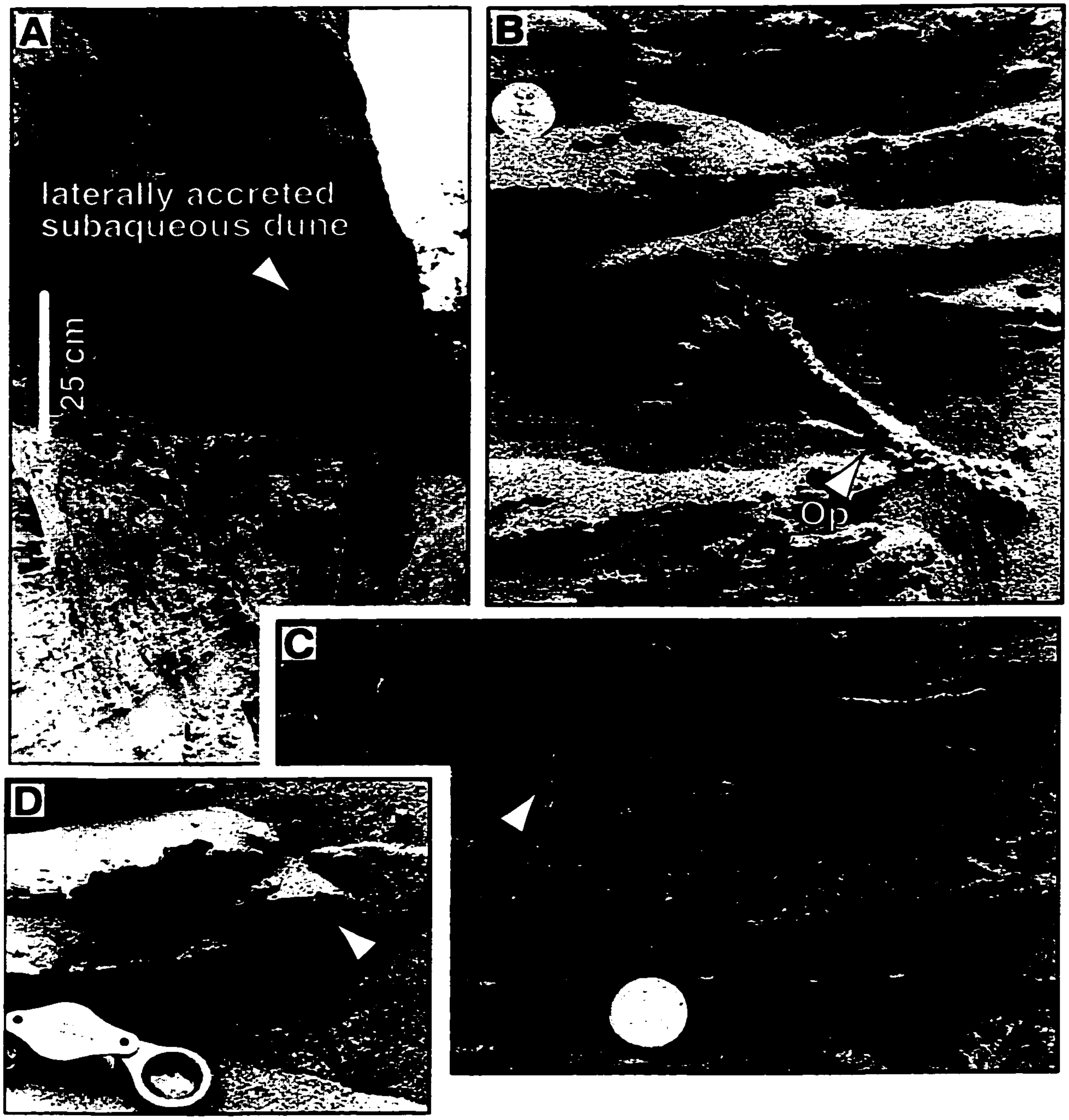

FIGURE 2.16 - The Southbend section, interpreted to represent a succession of migrating tidal mid-channel bars. (A) Outcrop of migrating, sandy clinoforms at the Southbend outcrop. (B) Robust *Ophiomorpha nodosa* (Op) descending from a clinoforn surface. (C) Vertical threadworm burrows, possibly representing the central axes of *Paraonis* spirals (arrow). (D) A horn-shaped polychaete tube (arrow) similar to the ichnofossil *Terebellina* (nomen nudem).

detritus is virtually absent; wood and shell fragments are rare. Rare heavy minerals, usually augite or magnetite, are present along the toesets of the clinoforms. Clinoformed packages have an erosional base and exhibit a gradual fining upwards trend; they range in thickness from 3 to 4.5 m.

Interpretation of Sandy, Laterally-Accreted Channel Bars

Of the Pleistocene deposits present at Willapa Bay, sandy channel bars lend themselves best to an archetypal (*i.e.*, Seilacherian) ichnofacies classification. The presence of *Ophiomorpha*, deep-penetrating *Skolithos*, *Thalassinoides*, *Teichichnus*, and abundant threadworm tubes (Fig.2.16C) are indicative of the *Skolithos* ichnofacies. The *Skolithos* ichnofacies is associated with rapidly shifting substrates in moderate to high-energy hydraulic regimes. This interpretation is supported by the physical sedimentary structures, which include current ripples, trough cross bedding, planar-tabular cross bedding, and upper-flow-regime planar bedding. These structures typically are superimposed on, and are indicative of current directions perpendicular to, the laterally accreted clinoforms.

The energetic nature of this depositional environment strongly biases the trace fossil record towards deep-seated traces. This is due to reworking of the upper portions of the substrate by storm- and tidal-currents, which effectively remove all evidence of biogenic activity in the shallow portions of the substrate. The aforementioned trace fossil suite reflects this taphonomic bias, particularly the preserved *Ophiomorpha*, *Thalassinoides*, and *Skolithos*. In light of this, the pervasive occurrence of threadworm tubes is somewhat enigmatic. Their preservation, however, is typically on aggradational surfaces, and is indicative of a 'conveyer belt' colonization strategy (Bromley, 1996).

The presence of a robust *Skolithos* ichnofacies and the various sedimentary structures present constrain the location of this depositional environment relative to the ancient bay's configuration. The potential subenvironments are further narrowed by the requirement for nutrient-rich (probably marine) water and a paucity of fine-grained clastics. All of the required physico-chemical parameters are most closely met in main tidal channels, in a location more or less proximal to the estuary mouth. In this area, tidal channels are subject to less salinity stress and therefore would be conducive to the development of a healthy *Skolithos* assemblage. Tidal channels are also subject to great variability in flow regime and to significant storm reworking, as is indicated by the suite of physical sedimentary structures. Finally, the strong tidal currents and geographic proximity to nutrient-rich marine water would have the ability to deliver a food resource to bay fauna dependent on marine organics.

Subtidal, Quiescent Bay Deposits

Modern and Pleistocene Subtidal, Quiescent Bay Deposits

The present configuration of Willapa Bay is dominated by large tidal channels. Quiescent deposits, sheltered from tidal currents and wave energy, are rare in the modern bay. An exception is the area just southeast of Grassy Island, informally called the land of the giants (Fig. 2.1). Here, the moderately sorted sandy substrate (u.f.) is completely bioturbated and colonized by dense populations of large *Callianassa* (> 250 burrow openings/m^2). Robust polychaetes (*Nereis, Glyceria, Nephtys*) and bivalves are also commonly observed, although their population densities were not assessed. A number of smaller threadworms are ubiquitously distributed throughout the substrate. The most conspicuous traces include *Ophiomorpha*- and *Thalassinoides*-like burrows, which overprint a mottled fabric comprised of horizontal and subvertical deposit-feeding structures.

Pleistocene deposits are similar in many respects. Large *Ophiomorpha* and *Thalassinoides* are common, crosscutting a suite of smaller deposit-feeding trace fossils, such as *Planolites* and *Teichichnus* (Fig. 2.17). Locally, *Psilonichnus*-like burrows, interpreted to represent the domiciles of burrowing crabs, are the dominant crustacean

FIGURE 2.17 - Radiograph of Pleistocene quiescent bay deposit. Note the large burrows cross cutting the small-burrow-mottled background fabric. Larger burrows include those of shrimp (*Ophiomorpha*, Op) and crabs (*Psilonichnus*, Ps). *Gyrolithes* (Gy), *Planolites* (Pl), and *Palaeophycus* (Pa) are also shown. From Goose Point.

burrows (Fig. 2.17). *Siphonichnus* and bivalve adjustment traces are sporadically distributed and locally absent. The degree of bioturbation is typically moderate to high; primary sedimentary structures are commonly obliterated. Where the physical sedimentary structures are preserved, they consist of horizontal lamination, wavy lamination, and low amplitude ripple forms. These ancient accumulations are generally muddy, although sandy deposits are present in Units 2 and 4. Wood and shell debris is dispersed sporadically. Articulated bivalves may be present; most abundant are the shells of the native oyster, *Ostrea lurida*, which form lenticular beds locally. These in situ oyster beds are most abundant in strata that, uncharacteristically, are rarely bioturbated.

Interpretation of Subtidal Bay Deposits

Although quiescent bay deposits are relatively uncommon in modern Willapa Bay, sheltered accumulations in the present bay configuration are similar to some Pleistocene deposits observed in outcrop. The most distinctive bay deposits are those that are burrowed conspicuously with various crustacean burrows. These include an array of *Ophiomorpha*, *Thalassinoides*, and *Psilonichnus* that are generally (but not always) exclusive of each other. These relatively robust burrows overprint an assemblage of deposit-feeding traces predominantly consisting of *Planolites* and *Palaeophycus*. Bivalve traces and sub-vertical *Skolithos* are also locally present. This mixed trace assemblage does not lend itself to archetypal ichnofacies classification. Rather, it suggests various ethologies are employed in this environment and that food resources are abundant in both the substrate and the water column. The mixed assemblages at Willapa Bay are comparable to ichnocoenoses observed in core by Beynon et al. (1988) in the Cretaceous Grand Rapids Formation of the Western Canadian Sedimentary Basin. Beynon et al. (1988) noted that gross ethologies (suspension- vs. deposit-feeding) occurred together in what they interpreted as a salinity-stressed depositional environment.

The paucity of physical sedimentary structures in quiescent bay deposits indicates sedimentation rates were relatively low. Low sedimentation rates also suggest that the benthic community did not persist in the estuary's turbidity maxima.

Somewhat perplexing is the presence of thin oyster beds in laminated, unburrowed, fine-grained sediment. The oyster, *Ostrea lurida*, is only moderately tolerant of turbid conditions and, compared to certain burrowing polychaetes, is not particularly hardy. Laminated and unburrowed silt and mud reflects mainly turbid conditions. The presence of a turbid water column is contradictory when juxtaposed with *in situ* oyster beds. *Ostrea lurida* (and other oysters) are primarily filter feeders and are overwhelmed by exceptionally turbid water. The absence of trace fossils infers extreme physico-chemical conditions were present when these strata were deposited. Ultimately, the question becomes, if oysters are present, why are the traces of their stalwart invertebrate associates not evident? All of the evidence implies that the deposition of laminated silt and mud was intermittent, allowing lenticular oyster beds to develop in channels and protected bays. Perhaps this is indicative of shifts of the bay's turbidity maxima. Such a shift would likely have to endure several seasons to permit colonial oyster growth. Burrowing might have been inhibited by the development of oyster beds, which precluded the development of an infaunal community below their densely packed shells. This relationship is certainly reflected in the modern bay, where infauna is notably sparse below well-developed mounds of *Crassostrea*.

The protected bay is among the variable depositional environments preserved in the Pleistocene strata at Willapa Bay. Variability results from differing degrees of tidal or fluvial dominance, various bay configurations, the state of bay-fill aggradation, the nature of the sediment supply and decade- or century-scale weather patterns. These observations underscore the problematic nature of identifying similar depositional environments from core and wireline datasets.

DISCUSSION

Variability in Estuary Deposits

Although most researchers agree that the stratigraphy and sedimentology of estuary deposits is complex, little consideration is given to the significance of facies changes in IVF. Both modern and Pleistocene deposits at Willapa Bay show a great degree of variability resulting from changes in sediment supply, magnitude of the tidal prism, and changing chemical conditions in the modern and ancient bay. Many of these factors are linked to climate variability. At San Francisco Bay, historical records show that the shoreline position, salinity, and bay-fauna cycles are remarkably variable (Peterson et al., 1995). This variability is expressed on the annual-, decade-, and century-scale, and might be linked to climatic patterns and recent anthropogenic effects. *El Niño,* for example, can be related to changes in estuary salinity. With each *El Niño* / Southern Oscillation event (ENSO), streamflow along the western U.S.A. changes dramatically (Ely et al., 1993). Fluvial input into estuaries is a function of streamflow and it correspondingly changes with streamflow. Storm activity along the Pacific northwest also increases with ENSO. Salinity measurements in San Fransisco Bay appear to be altered due to ENSO cyclicity (as much as 8 ppt. near the mouth of the bay; Peterson et al., 1995) on short- and long-term trends. ENSO cyclicity has been exceedingly variable historically; Anderson (1990) documents cycles of 90, 50, and 22 to 24 years, during which ENSO events are more frequent. Anderson et al. (1992) suggest the effects of *El Niño* are evident in Pleistocene deposits off the coast of California. In core extracted from this area, 'varved' sediment is punctuated by bioturbated zones. Their interpretation (Anderson et al., 1992) is that bioturbated horizons represent conditions of warmer surface water and increased dissolved oxygen in the water column during *El Niño* events. Laminated zones represent cooler *La Niña* conditions where oxygen levels were decreased due to upwelling and increased oxygen consumption, which was associated with increased planktonic production. The effects on marine biota may, then, be profound. This illustrates that *El Niño* conditions persisted in the Pleistocene, and that its effects on the marine ecology at that time probably influenced marginal marine systems, such as the ancient Willapa Bay.

It is unknown how much climatic variability is necessary to have a significant effect on estuarine biota. Very few long-term studies exist and most focus on seasonal variability. At Willapa Bay, no historical salinity, oxygen, or temperature records exist for the past 30 years. A number of anthropomorphic changes can be noted, however. They include: the damming of the Columbia River, which conceivably reduced the magnitude of the freshwater plume entering the Pacific Ocean just south of Willapa Bay; increasing denudation of the forests adjacent to rivers that empty into the bay; the introduction of east coast species, such as *Spartina* (a round grass); and increased levels of nutrient-rich pollutants from farmland and housing adjacent to the bay. Among other things, these changes influence that amount of sediment influx into the bay, decrease the duration of freshettes (rainwater runoff) in the bay, and alter the distribution of ecospace for the plants and animals living in the bay.

Sudden changes in the rock record result from a natural variability that is inherent to estuarine systems. The sensitivity of biota to subtle changes in bays and estuaries make trace fossils useful indicators of change that is intrinsic and extrinsic to the depositional system. This is only true, however, if facies changes are persistent, mappable, and can be placed in a genetic framework.

Assessment of the Brackish Water Model

The ichnology of brackish-water deposits has been characterized by previous researchers (Pemberton et al., 1982; MacEachern et al., 1992; Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994). Key ichnologic criteria include a diminutive assemblage of traces and a low diversity of ichnogenera. Also, trace fossils such as *Gyrolithes, Skolithos, Planolites, Cylindrichnus,* and *Palaeophycus,* are common in these deposits. Combined with valuable physical sedimentological data, the general model has been applied with notable success in both core and outcrop. One of the finest examples of a Cretaceous brackish-water deposit is the McMurray Formation in the Western Canadian Sedimentary Basin of Alberta, Canada (Pemberton et al., 1982; Mattison et al., 1989; Ranger and Pemberton, 1992; Pemberton and Wightman, 1992). Detailed analysis of its ichnology, sedimentology, and stratigraphy have allowed high-certainty interpretation of this unit as estuarine IVF (Wightman and Pemberton, 1997). Like the McMurray Formation, Pleistocene deposits at Willapa Bay are important because they represent another example of trace fossil assemblages in a probable brackish-water deposit (Clifton and Phillips, 1980; Clifton, 1982; Anima et al., 1989).

Generally, the brackish-water model applies equally well in the modern and Pleistocene deposits at Willapa Bay. Diminutive examples of typical brackish-water forms are present in low-diversity assemblages in every depositional environment, except sandy, laterally accreted channel bars. The notable exception to the aforementioned parameters is the potential presence of robust crustacean traces overprinting typical brackish-water assemblages (Fig. 2.11). These assemblages, which are common to some bay deposits, illustrate that in certain brackish-water subenvironments crustacean burrows may be relatively large. In these situations, it is appropriate to consider the size and diversity of the primarily worm-burrowed background assemblage as being indicative of salinity stress. Why is the worm-burrowed suite apparently more sensitive to fluctuating and lower levels of salinity?

This relates primarily to the evolutionary means by which the animal responds to reduced or fluctuating salinity. Salinity stress is coped with through physiologic, anatomical, morphological, and ecological innovation or through behavioral adaptation (Spaargaren, 1979, 1995). These strategies provide different adaptive landscapes for animals living in brackish-water environments.

Dimunition is an example of morphologic adaptation. Decreasing size in response to salinity occurs for two reasons: it is advantageous for the organism as it allows the animal to change its surface area to mass ratio quickly and 'fine tune' the rate at which osmotic transfer occurs; and, in environments that are characteristically extremely brackish (approaching 5 ppt), animals expend large amounts of energy maintaining a concentration gradient (Spaargaren, 1979), sacrificing growth. An excellent example of dimunition was provided by Remane and Schleiper (1971) with bivalve species from the North Sea. They showed systematic reductions in body length correlated almost linearly with lowering salinity. Five species of bivalve in particular (*Mytilus edulis, Mya arenaria, Mya truncata, Cardium edule,* and *Macoma balthica*) were as much as 35% smaller than their original size where comparing salinity levels of 35 ppt. versus 5 ppt. As with all ideals based on natural systems, there are exceptions to dimunition. This depends on where an animal falls on its brackish adaptive landscape. Some animals actually increase body size slightly with decreasing levels of salinity. Female copepods, for instance, have been shown to respond in such a manner (Miliou, 1996).

Most likely, dimunition of trace fossils as observed at Willapa Bay is a result of population dynamics as opposed to true morphologic adaptation. Powell and Stanton (1996), working at Copano Bay, Texas, separated the size-frequency distribution of bay populations into small- and large-size classes. They noted that under resource-stressed conditions the two size groups responded quite differently. Typically the large size class reached some fraction of their species optimal size (true dimunition). Smaller-size organisms typically attained full growth for the species (Powell and Stanton, 1996) and their biomass was essentially unchanged. Conceivably, this relationship is similar to the salinity-stressed assemblages illustrated in Figure 2.11. The consistently smaller (worm) burrow diameters are species-specific. At station 1 and 2 robust terebellids make the largest annelid burrows; the largest common worm burrows at station 3 are excavated by *Saccoglossus*; and *Heteromastus* perforates the muddy substrate at Stations 4 and 5 (Fig. 2.11). Interestingly, *Heteromastus* is also present at stations 1 through 3 and is identical in every respect (including size) to those observed at Stations 4 and 5 (Fig. 2.11). These data suggest that, although the burrowing population is comprised of increasingly smaller organisms, the individual species are not enduring size reduction.

In contrast, *Upogebia* and *Callianassa* have repeatedly been shown to modulate their burrow environment by irrigating their burrows when chemical conditions in the water column are most amenable (Thompson, 1967; Thompson and Pritchard, 1969; Swinbanks and Luternauer, 1987; Dworshak, 1988). Parameters such as oxygenation, salinity, and pH are buffered by the volume of water in the burrow, which can be sealed during rain and run-off (Spaargaren, 1979, Rickets et al., 1985; Swinbanks and Luternauer, 1987; Spivak et al., 1994). Behavioral innovations make physiological adaptation less relevant. The advantages of deep burrowing and maintaining a volume of water amenable to an organism's respiratory requirements is enjoyed by several burrowers, including *Callianassa*, the fiddler crab *Uca crenulata*, large bivalves, and to some extent *Arenicola* (Rankin and Davenport, 1981; Rickets et al., 1984). Maintaining a stable burrow environment does not completely protect infauna from the rigors of fluctuating physico-chemical conditions. Szedlmayer and Able (1996) studied patterns of habitat use by fishes and decapods in southern New Jersey. They found that seasonal temperature, percent silt, and salinity were the key factors influencing the distribution of several types of fish and the blue crab, *Callinectes sapidus*; no size data were recorded.

Although large crustacean burrows contradict the original tenets of the brackish-water model, their presence in a sedimentary deposit should not alone dismiss the possibility of a brackish-water origin. In fact, large (>1cm diameter) *Thalassinoides* and *Ophiomorpha* cross-cutting a low-diversity suite of diminutive trace fossils can be typical of brackish deposits. Ultimately, the familiar appeal to consider the ichnofabric (or ichnofacies) as a whole is reiterated.

Many studies have successfully integrated ichnofacies into tripartite estuarine models (Pattison, 1992; MacEachern and Pemberton, 1994; Buatois et al., 1997). Other researchers have noted a general mixing of ethologies that are not particularly well suited to classification into Seilacherian ichnofacies (Pemberton et al., 1982; Beynon et al., 1988). Excepting depositional environments proximal to the bay mouth and, locally, in quiescent bay deposits, no excellent examples of the *Cruziana* and the *Skolithos* ichnofacies have been noted in modern or Pleistocene deposits at Willapa Bay. Application of Seilacherian ichnofacies may depend, in part, on the degree to which wave or tidal processes are manifested in the bay. Wave-dominated estuaries, for example, proffer the abrupt energy gradients required to provide discrete, predictable facies segregation (Reading and Collinson, 1996). In contrast, tide-dominated estuaries transmit tidal energy to the upper estuary, distributing energy more evenly in the bay. Willapa Bay exchanges 45% of its volume daily (U.S. Army Corp. of Engineers, 1975) and is best classified as a mixed to somewhat tidally-dominated estuary.

SUMMARY

Both modern and Pleistocene deposits at Willapa Bay are interpreted to have been deposited under primarily brackish conditions. An important exception to this is sediments that were deposited near the bay mouth. The sedimentological and ichnological characteristics of five depositional environments considered are considered in this paper: (1) intertidal flats; (2) intertidal point bars; (3) fluvially- through tidally-influenced main point-bar deposits; (4) subtidal, laterally-accreted mid-channel tidal bars, and; (5) quiescent central bay deposits. Each sub-environment can be discerned from the others on the basis of ichnologic data. Intertidal flat deposits are typically thoroughly bioturbated by a somewhat diminutive suite of shafts and burrows that are locally cross-cut by robust crustacean dwellings. Tidal creek point-bar deposits are sporadically burrowed by minute *Gyrolithes, Skolithos, Cylindrichnus, Planolites, Palaeophycus,* and rare, small, bivalve equilibrichnia. Fluvially- through tidally-influenced main point-bar deposits are sporadically bioturbated with vertical traces that are superimposed upon inclined heterolithic stratification. Moderately to thoroughly bioturbated bay deposits are normally burrowed by relatively robust forms of *Ophiomorpha, Teichichnus, Skolithos* and bivalve equilibrichnia. Finally, mid-channel tidal bar deposits typically display robust bivalve equilibrichnia, rare *Ophiomorpha,* and deep-penetrating *Skolithos;* this assemblage is indicative of the *Skolithos* ichnofacies. The preceding data are summarized in Table 2.1.

Of the environments considered, point bar and intertidal flat deposits are the most variable laterally, and are therefore the most useful paleogeographic indicators at Willapa Bay. Both of these depositional environments are characterized by striking changes (and fluctuations) in salinity and kinetic energy from the lower to the upper estuary. Textural changes can be linked to changes in the hydraulic energy and are generally evident in transects from the lower to upper estuary. At Willapa Bay these deposits in the upper estuary are dominated by mud and sandy mud. Sedimentation in middle and lower estuary is dominated by the deposition of fine- to medium-grain sands. Trace assemblages present in the upper estuary are generally extremely stressed and are dominated by a low diversity suite (less than 5 major burrowing fauna) of small (<2mm diameter) burrows.

Although the brackish-water model applies to deposits at Willapa Bay, it is not archetypal. Furthermore, there is some question whether Seilacherian ichnofacies can be utilized to best describe these deposits. In general, the sedimentological and ichnological characteristics of Willapa Bay are similar to other brackish-water deposits. Also this

depositional environment	common infauna / trace fossils	degree of bioturbation (ichnofabric index)	physical structures	lithology / accessories	contacts / thickness
modern muddy intertidal flat	*Upogebia*, terrebellid, *Saccoglossus*, maldanid, various bivalves, *Heteromastus*, *Nereis*, *Corophium*, *Nephtys*	mod. to complete (4, 5, 6)	typically vestigial horizontal bedding normally	organic detritus, oxide stain, shell debris, 50-60% < phi 4 sand typ fine to v. fine.	gradational / burrowed with intertidal point-bar undetermined tk.
modern sandy intertidal flat	*Callianassa*, *Arenicola*, *Saccoglossus* (r), maldanid (r), *Macoma*, *Heteromastus*, *Nereis*, *Corophium*, *Nephtys*	low or complete (1 or 5, 6)	ripple lamination, low angle lamination, thin bedded, scour and fill runoff channels	rare organic detritus appx 80% phi 1 to 3	abrupt to gradational with intertidal point-bar undetermined tk.
Pleistocene muddy intertidal flat	*Skolithos*, *Arenicolites*, *Gyrolithes*, *Cylindrichnus*, *Planolites*, *Palaeophycus*, *Thalassinoides*, *Psilonichnus* (r)	mod. to complete (4, 5, 6)	typically vestigial horizontal bedding	abundant organic detritus fine sand laminae appx. 60 to 80% < phi 4	gradational / burrowed with intertidal point-bar 1 to 3 m tk.
Pleistocene sandy intertidal flat	*Skolithos*, *Arenicolites*, *Planolites*, *Palaeophycus*, equilibrichnia, *Thalassinoides*, *Ophiomorpha* (r)	low or complete (1 or 5, 6)	locally massive-appearing ripple lamination, low angle lamination, thin bedded, scour and fill runoff channel	abundant organic detritus fine sand laminae f.g. to m.g. sand (visual est.)	gradational / burrowed with intertidal point-bar 2 to 3 m tk.
modern intertidal point-bar	various juvenile bivalves, *Heteromastus*, *Nereis*, *Corophium*, *Nephtys*	absent to mod. (1, 3)	ripple lamination, low angle lamination, inclined bedding, soft sediment deformation	terrestrial organic detritus TOC 5 to 8%, thin sand lam. appx. 50% finer than phi 4	scoured lower contact demarcated by shells and wood, 1 to 3 m tk
Pleistocene intertidal point-bar	*Planolites*, *Palaophycus*, *Skolithos* *Arenicolites*, *Gyrolithes*	absent to mod. (1, 3)	ripple lamination, low angle lamination, inclined bedding, soft sediment deformation, mud couplets, rhythmic bedding	terrestrial organic detritus transported rhizomes (g.s. not measured, appx. Mud	scoured lower contact demarcated by shells and wood, 1 to 3 m tk.
modern main channel point-bar (sandy)	various juvenile bivalves, *Heteromastus*, *Upogebia*, terrebellid, *Callianassa*, maldanid, *Nereis*, *Corophium*, *Nephtys*	low to mod. (2, 3)	ripple lamination, wavey to flaser bedding, inclined heterolithic stratification (IHS), trough cross strat (rare), climbing ripples	terrestrial organic detritus TOC 1 to 6% variable grain size, see text	scoured lower contact demarcated by shells and wood, several m tk.
modern main channel point-bar (muddy)	various juvenile bivalves, *Heteromastus*, terrebellid, maldanid, *Nereis*, *Corophium*, *Nephtys*	low to mod. (2, 3)	starved ripple lamination, pin stripe lam. inclined stratification	terrestrial organic detritus TOC 5 to 11%, thin sand lam. variable grain size, see text	scoured lower contact demarcated by shells and wood, several m tk.
modern sandy laterally-accreted mid-channel tidal bar	*Clinocardium*, various interstitial threadworms *Tresus nuttallii* (?), *Callianassa*, Cerebratula *Nereis*, *Nephtys*	absent to moderate (1, 3)	ripple lamination, low angle lamination, inclined bedding (10 degrees), trough cross strat perp to inclined beds	rare organic detritus rare heavy minerals typically m.g. sand	contacts not observed subtidal
Pleistocene sandy laterally-accreted mid-channel tidal bar	*Ophiomorpha*, *Thalassinoides*, *Teichichnus* (*Skolithos* ichnofacies)	absent to rare (1, 2)	ripple lamination, scour and fill, inclined bedding, local flaser to wavey bed rythmic bedding, trough cross strat	organic detritus, oxide stain rare mm-scale shelly debris concentrations of heavy min	sharp lower contact demarcated by shells and wood, meter-scale thickness
modern quiescent bay deposit	*Callianassa*, various interstitial threadworms *Crassostrea*, *Nereis*, *Nephtys*, *Glyceria* crabs	moderate to thorough (3, 6 locally absent (1)	ripple lamination (vestigial ?) planar lam (vestigial ?)	organic detritus woody debris, shelly debris unconsolodated (g.s. varies)	contacts not observed, subtidal several meters thick
Pleistocene quiescent bay deposit	*Ophiomorpha*, *Thalassinoides*, *Teichichnus* *Ostrea lurida*, *Psilonichnus*, *Planolites*, *Palaeophycus*	moderate to thorough (3, 6	ripple lamination (vestigial ?) planar lam (vestigial ?)	organic detritus, oxide stain rare woody and shelly debris (g.s. varies, typ 60%<phi 4)	variable

TABLE 2.1 - Summary of the physical characteristics of the different depositional environments discussed in the text. Common burrowing fauna are listed for modern deposits whereas common trace fossils are listed for Pleistocene deposits.

work emphasizes that stoping and mining behaviors are relatively common in brackish-water trace assemblages. Although ichnofabrics at Willapa Bay are generally comprised of diminutive ichnofossils, large diameter crustacean burrows locally cross-cut these fabrics. There is some question as to the nature and mechanisms by which dimunition (commonly observed in these deposits) occurs. I suggest this is a reflection of population composition as opposed to true dimunition. If tested and proven elsewhere, these additional characteristics should also be incorporated into the brackish model.

Most importantly, the data presented may help geologists resolve facies distribution and identify depositional environments in the subsurface. A better understanding of these systems from modern- and outcrop-based studies will ultimately help delineate ancient estuaries.

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CHAPTER 3: THE PALEOECOLOGIC SIGNIFICANCE OF PLEISTOCENE *PSILONICHNUS UPSILON* AT WILLAPA BAY, WASHINGTON[1]

INTRODUCTION

Studies of modern burrows associated with the activities of crabs are numerous (*e.g.*, Rice and Chapman, 1971; Hill and Hunter, 1973; Allen and Curran, 1974; Katz, 1980; Robertson and Pfeiffer, 1982), and the environmental significance of these burrows is largely understood (*e.g.*, Chakrabarti, 1981; Frey et al., 1984; Duncan, 1986; Frey and Pemberton, 1987). Studies of modern burrowing activity have helped develop a general understanding of the paleoecology of ancient deposits marked by the presence of crab burrows (*e.g.*, Stephenson, 1965; Frey and Mayou, 1971; Curran and Frey, 1977; Humphreys and Balson, 1988; Pemberton and Jones, 1988; Curran and White, 1991). The ichnogenus *Psilonichnus* was erected by Fürsich (1981) to describe J- and Y-shaped trace fossils from the Upper Jurassic of Portugal. In this report, morphological similarities were noted between *Psilonichnus* and *Thalassinoides*, as well as modern crab burrows.

Two distinct trace fossils are described from Pleistocene deposits that outcrop along the eastern and northern margins of Willapa Bay, Washington (Fig. 3.1). These ichnofossils represent crab domiciles. Although they are normally observed in intertidal and subtidal point bar deposits, the lebensspurren are also common in quiescent central bay deposits (Chapter 2). The crab burrows typically dominate the deposits they are found in. However, they also are observed within low-diversity ichnofossil assemblages that typically include *Thalassinoides* and, less commonly, bivalve burrows. Both trace fossils characteristically contain a distinctive laminated fill comprised of alternating silt and sand laminations. The nature of the burrow-fill, and the geometry of the trace fossils, provide important paleoecologic data. This information is used to interpret the trace-making behaviour associated with these burrows, and to determine certain

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[1] A version of this chapter has been submitted for review by PALAIOS as "The Paleoecological Significance of *Psilonichnus upsilon* at Willapa Bay, Washington", by Murray K. Gingras, Stephen Hubbard, S. George Pemberton, and Tom Saunders.

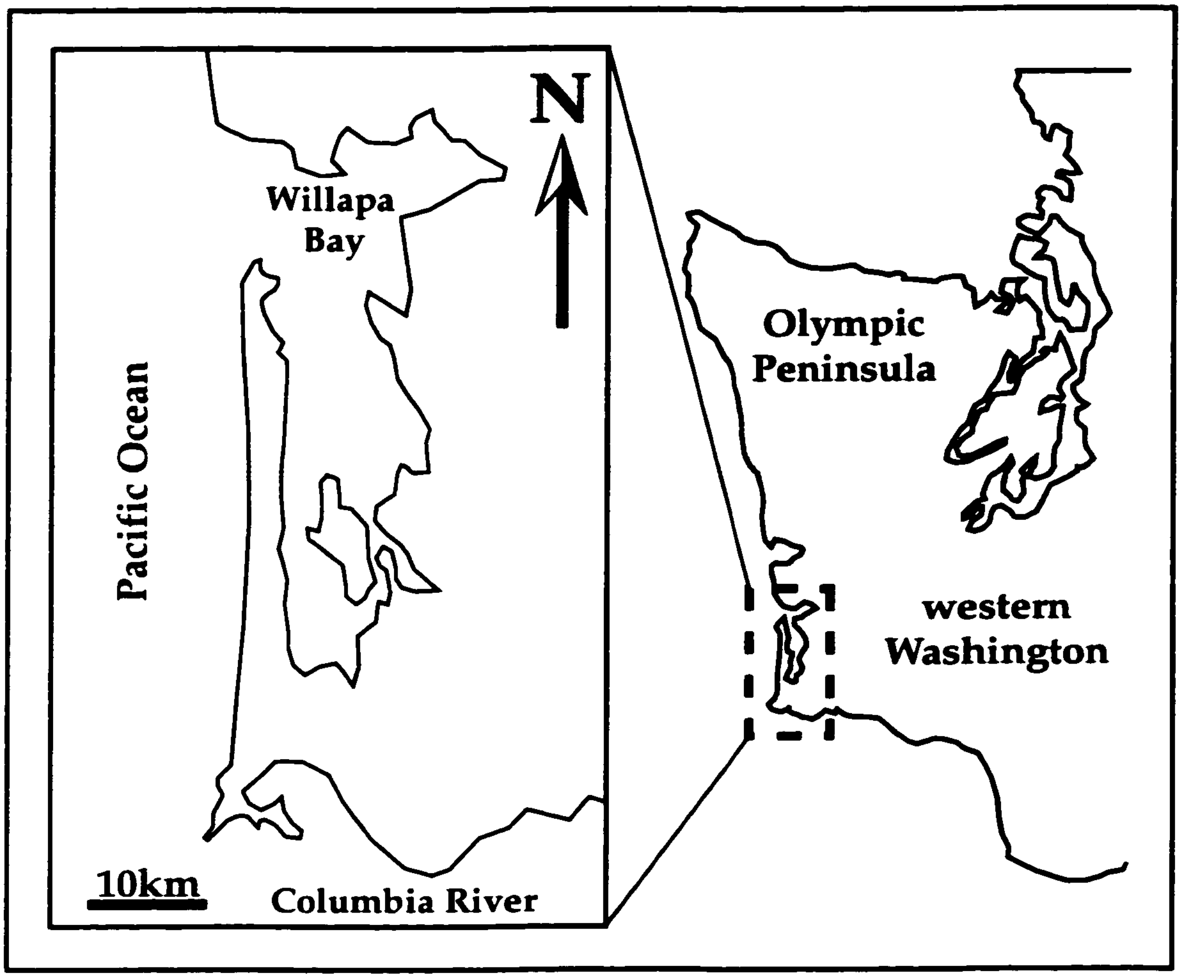

FIGURE 3.1 - Location map of Willapa Bay, Washington.

physical characteristics of the depositional environment. The aim of this study, then, is to describe these particular trace fossils and interpret their paleoecologic and sedimentologic significance.

Setting

Willapa Bay is located in the southwestern corner of Washington (Fig. 3.1). It measures approximately 38 km in length and 8km in width. The bay is sheltered from the open Pacific Ocean by a 30 km-long barrier spit called North Beach Peninsula. The spit is derived from sediments that were discharged by the Columbia River and subsequently redistributed by longshore currents (Ballard, 1964).

Pleistocene deposits outcrop along the modern bay's eastern and northern margins. These strata are interpreted to have been deposited in an estuarine environment similar to that of the modern bay (Clifton et al., 1976; Clifton and Phillips, 1980; Clifton et al., 1989; Clifton and Gingras, 1997; Chapter 2). Previous researchers at Willapa Bay have characterized the sedimentology and stratigraphy of both the modern and Pleistocene sediments (Clifton, 1983; Luepke and Clifton, 1983; Clifton and Phillips, 1980; Anima et al., 1989).

The Ichnogenus **Psilonichnus**

Crab burrows and trace fossils resulting from the activities of crabs have been described in numerous deposits from a wide range of depositional settings, most commonly marginal marine and quasimarine (Frey et al., 1984). Trace fossils recognized as crab domichnia have been reported in backshore deposits (Curran and Frey, 1977; Howard and Frey, 1980; Curran and White, 1991), beach rock (Curran and White, 1991), subtidal marine sands (Humphreys and Balson, 1988), coastal plain deposits (Williams, 1965; Frey and Mayou, 1971; Allen and Curran, 1974), and intertidal marine environments (Fürsich, 1981). Modern occurrences of crab burrows have also been noted in a wide diversity of depositional environments that include salt marshes (Allen and Curran, 1974; Edwards and Frey, 1977; Letzsch and Frey, 1980), backshore (Frey and Mayou, 1971; Allen and Curran, 1974), beach/foreshore (Stephenson, 1965; Chakrabarti, 1980, 1981; Hill and Hunter, 1973), intertidal bar (Chakrabarti, 1993), shoaling estuaries (Williams, 1965), and interdune flats of barrier islands (Hill and Hunter, 1973).

Fürsich (1981) first described *Psilonichnus tubiformis* from the Upper Jurassic (Kimmeridgian/Portlandian) of the Lusitanian Basin in Portugal. He considered the ichnofossil to be related to the ichnogenus *Thalassinoides*, differing primarily in that *Psilonichnus* was considered to be dominated by vertical elements, and characterized by a simpler branching pattern (Table 3.1). Fürsich (1981) noted that the upper portion of *P.*

	Thalassinoides suevicus **(Rieth, 1932)**	***Psilonichnus tubiformis*** **(Fürsich, 1981)**	***Psilonichnus upsilon*** **(Frey et al., 1984)**
Diagnosis	• 3-dimensional networks • smooth-walled • cylindrical section • Y- to T-shape branch	• upper Y- or U-component • predominantly vertical • straight to slightly curved shaft • irregularly spaced, horizontal to oblique dead-end branches	• gently inclined • rarely branched • J- or Y-shaped • inclined shafts that are straight to curved
Modern Analogs	• thalassinid shrimp	• thalassinid shrimp (?), similar to *Upogebia*	• ghost crab (*Ocypode quadrata*) • shorecrab (*Hemigrapsus oregonensis*)
Occurrence	• silts, sands, limestones • common in sheltered bays • common on proximal offshore deposits	• marginal marine to terrestrial • low energy, brackish • intertidal, near shoreline	• foreshore to backshore • intertidal to shallow subtidal in brackish, sheltered bays (this study)

TABLE 3.1 - Taxinomic characteristics and environmental significance of *Thalassinoides suevicus*, *Psilonichnis tubiformis* and *Psilonichnus upsilon*.

tubiformis was frequently Y-shaped and that the form was intermediate between the simpler J- and Y-shaped burrows of modern crabs, and *Thalassinoides*. Another crustacean ichnofossil, *Psilonichnus upsilon*, was described by Frey et al. (1984). In contrast to *P. tubiformis*, *P. upsilon* was originally defined as consisting of inclined, branched or unbranched, J- or Y-shaped burrows (Table 3.1). These trace fossils were primarily attributed to the activities of burrowing crabs.

Modern and ancient crab burrows have many characteristics that are generally not shared by other crustaceans (Fig. 3.2). Crab burrows, for example, normally display a relatively rudimentary architecture when compared to the more complex burrows constructed by thalassinidian shrimp. The geometry of crab burrows generally consists of a simple J-, U-, or Y-shape (Fig. 3.2). Apertures are typically the same diameter as the burrow-tunnels, and in some instances the aperture actually has a flared opening (e.g. Atkinson, 1974; Basan and Frey, 1977). In contrast, aperture openings in thalassinid (shrimp) burrows are more commonly restricted over one to several centimetres, as noted by several authors (e.g. Frey and Howard, 1975; Dworshak, 1982; Kleeman, 1884; Griffis and Chavez, 1988).

Crab burrows are ordinarily oval shaped in cross section. An excellent example of this was documented by Humphreys and Balson (1988). Conversely, shrimp burrows have a circular cross section. Lobster and mantis shrimp commonly generate irregular burrows (Fig. 3.2), however, the cross section of these burrows generally approximates a circle (Rice and Chapman, 1971; Farmer, 1974; Myers, 1979). Linings vary appreciably in shrimp burrows, which include pellet-, mud-, and mucous-lined shafts and tunnels (Pemberton et al., 1976; Frey et al., 1978). Occurrences of crab burrows, however, are normally unlined (Atkinson, 1974; Frey et al., 1978; Curran and White, 1991). Although crab burrows are generally limited to a simple sub-apertural architecture, thalassinid burrows may display complex basal structures (Fig. 3.2). These include tiered and boxworked networks. Because crab burrows normally represent domiciles as opposed to combined feeding structures, complex basal geometry is absent. Although the architectures observed in crab traces are more similar to those of lobster traces, lobster burrows commonly display more shallow, sub-apertural branching (Rice and Chapman, 1971; Farmer, 1974).

In summary, the salient physical characteristics of crab burrows include, a vertical to gently dipping J-, U-, or Y-shape, open burrow apertures, a paucity or absence of branches, an oval cross section, unlined burrow walls and, an absence of complex basal architecture. *Psilonichnus upsilon* documented from Pleistocene outcrops at Willapa Bay have many of these characters, as is outlined in the following section.

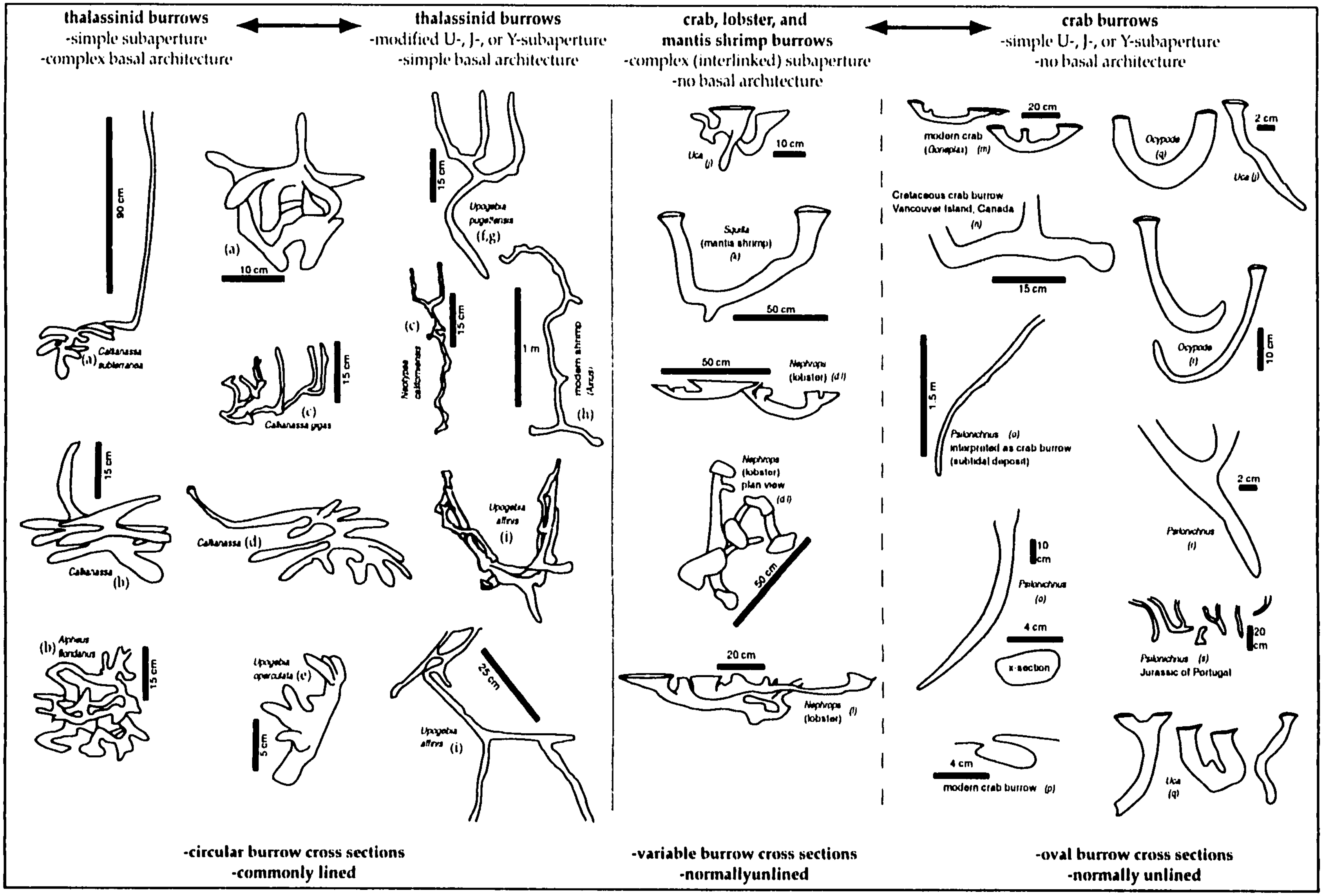

FIGURE 3.2 - Schematic diagrams of resin casts of crustacean burrows and various trace fossils. Thalassinid, lobster, and crab burrows are illustrated, primarily from left to right. --->

(cont.) Important physical characteristics, such as the shape of the burrow cross-section, the absence or presence of a lining, and the overall architectural arrangement, are detailed across the bottom of the diagram. Note the overall higher complexity of the basal portion of thalassind burrows compared to lobster and crab burrows. Lobster burrows demonstrate more complex branching in the sub-aperture portion of the burrow. Crab burrows commonly display the simplest architectures. Sources are indicated by letters beside the burrow schematics and are as follows: (a) Atkinson and Nash, 1990; (b) Shin, 1968; (c) Griffis and Chavez, 1988; (d) Rice and Chapman, 1971; (e) Kleeman, 1984; (f) Dworschak, 1982; (g) Stevens, 1929; (h) Pemberton et al., 1976; (i) Frey and Howard, 1975; (j) Basan and Frey, 1977; (k) Myers, 1979; (l) Farmer, 1974; (m) Atkinson, 1974; (n) Richards, 1975; (o) Humphreys and Balson, 1988; (p) Savazzi, 1982; (q) Farrow, 1971; (r) Frey et al., 1984; (s) Fürsich, 1981.

PSILONICHNUS FROM WILLAPA BAY

Two types of *Psilonichnus upsilon* (Type A and B) have been observed in Pleistocene strata at Willapa Bay. Both occur in unlithified sands and muds that are interpreted to represent deposits similar to those present in the modern bay (Clifton and Phillips, 1980; Clifton et al., 1989). Outcroppings of consolidated Pleistocene sediments are exposed by scraping the outcrop face to a flat surface. Trace fossils are seldom weathered out three-dimensionally. This is primarily due to a lack of cement, which causes the outcrop to weather more or less evenly. For similar reasons, bedding planes are generally difficult to observe. Normally, *Psilonichnus upsilon* Type A and B are both observed in primarily muddy deposits. Type A is normally observed in intertidal flat, intertidal point bar, and subtidal point bar deposits. Type B is typically observed in subtidal central bay deposits and, more rarely, in intertidal deposits. Both types of lebensspurren have a characteristic infill and possess a distinctive architecture.

All the occurrences of *Psilonichnus* at Willapa Bay are observed in intertidal and subtidal deposits. The depth of the ancient water table, then, was probably not a factor that determined burrow depth or geometry. In the modern bay, crab burrows are most abundant in muddy substrates. Even in intertidal sediments, these burrows tend to stay partially filled with water throughout the low tide cycle, mitigating the necessity of intersecting a water table. The modern crab burrows have a similar geometry where they are present in the upper or lower intertidal, or in the upper subtidal.

Psilonichnus upsilon *Type A*

Description

Examples of *Psilonichnus upsilon* Type A are found almost exclusively in mud-dominated units with common sand laminae. Physical sedimentary structures observed in the deposit include lower flow-regime planar, starved ripple, and current-ripple lamination. In some instances, the bedding is comprised of inclined heterolithic strata. Organic detritus is present locally, most commonly as disseminated flakes of terrestrial plant debris; wood clasts are normally present. Fossil remains of bivalves are absent to moderately abundant. The Pleistocene strata are uncemented and other than iron oxide staining, no diagenetic processes are evident. These accumulations previously have been interpreted as point bar and overlying intertidal flat deposits (Clifton et al., 1976; Clifton and Phillips, 1980; Clifton et al., 1989; Gingras et al. in press).

Psilonichnus upsilon Type A are typically unbranched and unlined, and are oval in cross-section (Fig. 3.3A, C). An iron-oxide halo less than a millimeter thick is commonly present. Burrow diameter ranges from 1.5 to 3.5 cm. The orientation of the tunnel is horizontal to slightly inclined with respect to bedding. Tunnel length ranges between 12 and 25 cm long. The burrow aperture, which is usually less than 10 cm long, is more steeply inclined than the tunnel and shows little or no constriction (Figs. 3.3, 3.4). Passively deposited, laminated infills are a commonly observed element of *P. upsilon* Type A (Fig. 3.3A, C). In contrast to the primarily muddy matrix, the fill is typically coarser grained (fine to medium sand). Individual laminae within the fill range from 1 to 5 mm in thickness, and are defined by variations in grain size (sand vs. mud) and lithologic contrast.

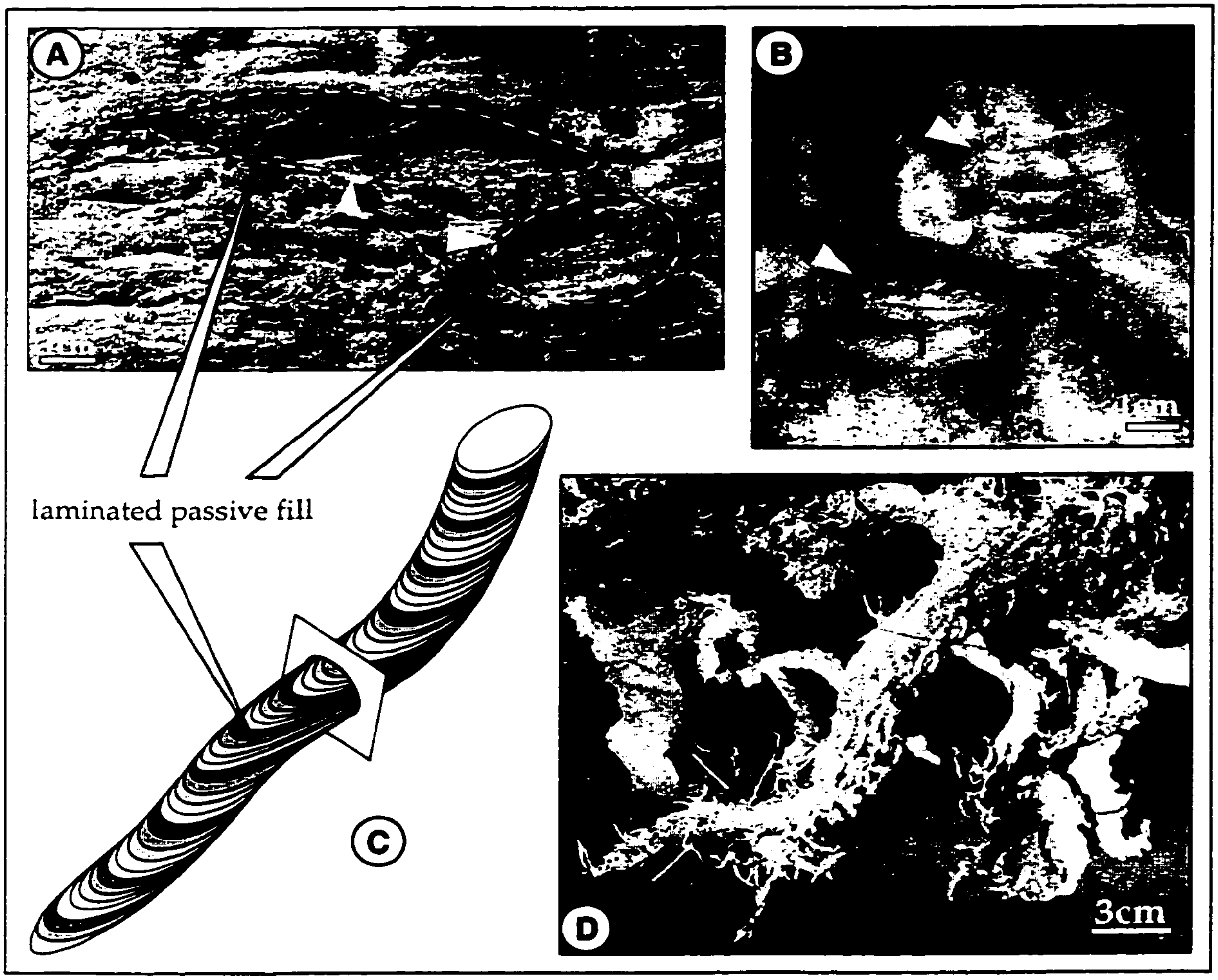

FIGURE 3.3 - Details of *Psilonichnus upsilon* Type A and a similar modern trace. (A) Transverse and oblique sections of *P. upsilon* Type A from muddy point-bar deposits in Pleistocene strata at Willapa Bay. Note the passive infill lamination. (B) Xray of *P. upsilon* Type A from Pleistocene intertidal deposits. In this example, the background fabric is completely obliterated (ichnofabric index 5). (C) Schematic of *P. upsilon* Type A laminae as interpreted from outcrop observations. (D) Resin cast of a crab burrow made by *Hemigrapsus oregonensis* taken from a modern tidal flat at Willapa Bay. The small casted tubes radiating from the *Psilonichnus* were made by the threadworm *Heteromastus*.

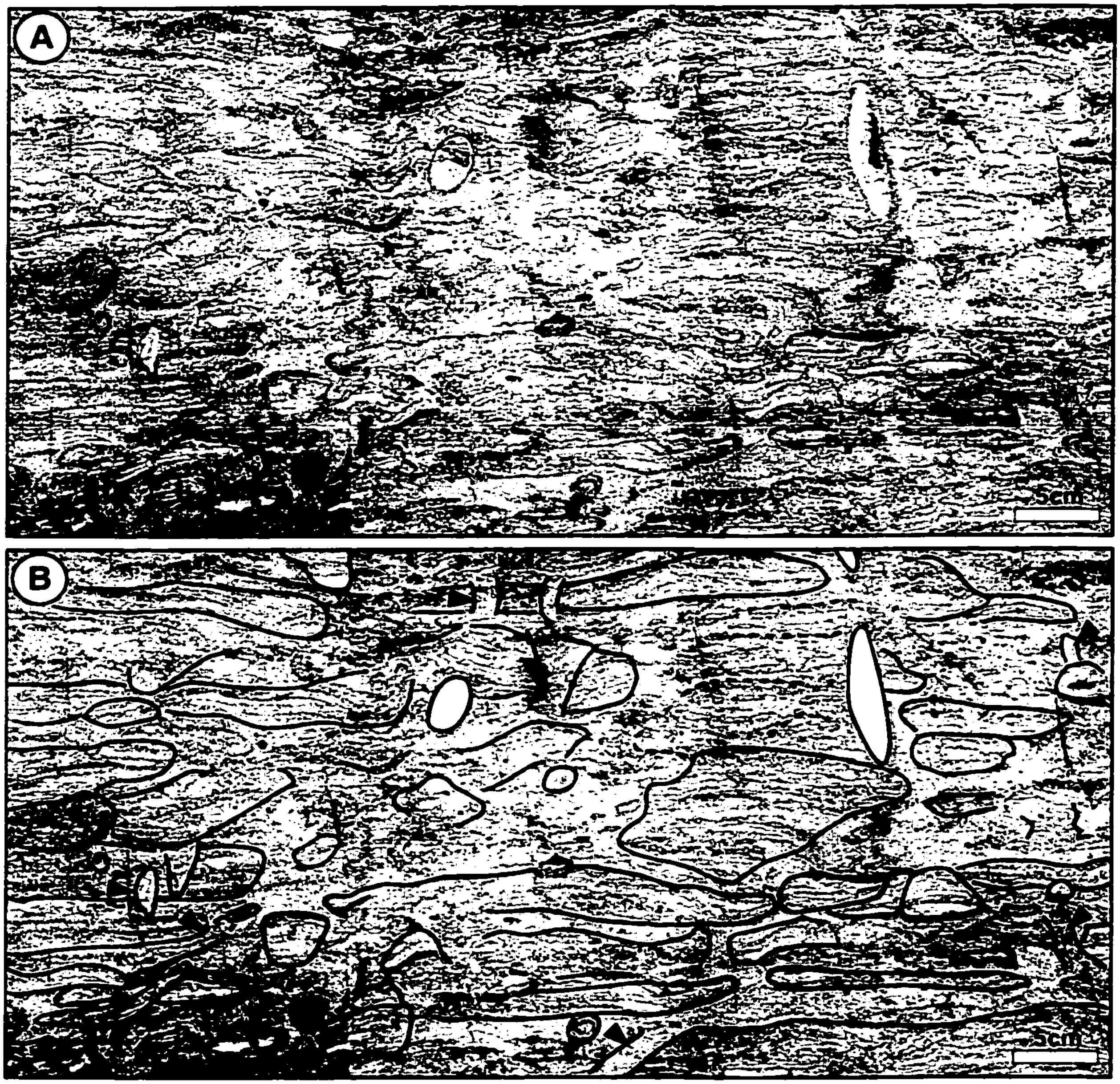

FIGURE 3.4 - Outcrop photograph and interpretation of a subtidal point-bar deposit highly bioturbated with examples of *Psilonichnus upsilon* Type A. (A) *Thalassinoides* (rare) and *Psilonichnus* (abundant) represent the dominant trace assemblage at this location. Fabrics comprised of both these traces are comparatively rare at Willapa Bay. In this photo the high degree of bioturbation, combined with the laminated burrow-fill, make it difficult to discern primary sedimentary structure from the burrow fabric. (B) Solid black lines indicate the location of *P. upsilon* Type A. Dashed black lines show interpretations that are less certain. Burrow apertures are indicated by the black arrows, and *Thalassinoides* are represented by the black lines with a white fill.

Psilonichnus upsilon *Type A*

Interpretation and Discussion

Physical sedimentary structures, such as starved ripple and current-ripple lamination, are indicative of intermittent bedload transport. Fine-grained laminae and lower flow regime planar lamination represent sedimentation primarily from suspension. Episodic alternation from mud to sand deposition may be related to meteorological events (marine and terrestrial storms), neap-spring tidal cyclicity, or seasonal shifts of the turbidity maximum. Based upon comparisons to modern point bars at Willapa Bay, the deposition of mud *versus* sand has been interpreted to largely reflect seasonal variation in sediment supply and stream discharge (Clifton et al., 1989). Undoubtedly, storm events and extreme tides overprint the seasonal record locally.

The absence of common branches and the primarily oblique to horizontal orientation of *Psilonichnus* Type A suggest it is best classified as a variation of *Psilonichnus upsilon* (Table 3.1; Fig. 3.3, 3.4). Other criteria, such as an irregular to ovate cross section, the absence of a lining, and the presence of an open aperture support this interpretation.

The most distinctive characteristic of *P. upsilon* Type A is its passively laminated fill. Where burrow density is high, the infill laminae dominate the observed fabric and the original sedimentary fabric is all but obliterated. In such instances the perceived fabric appears to represent bedding (Fig. 3.4). However, on closer inspection it is apparent that coarser clastic laminae (fine to medium sand) are only present within the burrow fill. The horizontal nature of the laminated burrow fill is partly due to the presence of an unconstricted burrow aperture (Fig. 3.4). The infill is well-laminated and undisturbed (Fig. 3.3A, 3.4) suggesting that the burrows were filled following abandonment. It is probable that the interlaminated nature of the infill is due to deposition under tidal influences. This is important as in many instances the fill of *P. upsilon* Type A provides the only evidence of rhythmic sedimentation at a particular location. Fluctuations in sediment transport related to meteorological events cannot be discounted, however. These processes, in conjunction with passive fill laminae up to 0.5 cm thick, suggest that the burrows filled rather quickly.

Another important consideration is the simple burrow architecture typical of this trace fossil. The oblique to horizontal, unbranching tunnel is typical of modern crab domiciles (Fig. 3.2). Normally, *Psilonichnus upsilon* Type A is present in low-diversity assemblages. Furthermore, in any particular bed, burrow diameters do not vary appreciably (2.0 to 3.4 cm). Although little can be said regarding the population dynamics of the trace-maker, a lack of variation in burrow diameter elucidates certain potential behavioral patterns. Sudden abandonment, coupled with a lack of size variability suggests the traces were evacuated on a seasonal (or at least episodic) basis. This argument is strengthened by the fact that the ichnofossils are dominantly sand-filled, and therefore may record intervals of changing hydraulic conditions. Recolonization of the muddy substrate, by primarily mature burrowers, depended on a return to more amenable conditions.

The burrowing crab, *Hemigrapsus oregonensis* makes similar traces in the modern bay. Burrows of *H. oregonensis* are typically horizontal to oblique, and they incline upwards toward the aperture (Fig. 3.3D). These burrows are typically unbranched, but short branches are present locally near the tunnel opening. The burrow walls are unlined, and passive, crudely laminated fill is sometimes present. Where observed, *Hemigrapsus* burrows normally range from 1 to 3 cm in diameter (Fig. 3.5). Juvenile *H. oregonensis* excavate burrows smaller than 1 cm in diameter. These traces are more commonly observed beneath and inside the shells of dead bivalves.

At Willapa Bay *H. oregonensis* is commonly observed in the intertidal realm, particularly in muddier deposits. Commonly they inhabit cut-banks of intertidal runoff creeks where the substrate is partially dewatered (Fig. 3.5). Unfortunately, the preservation potential of burrows deposited in such a setting is very low and this

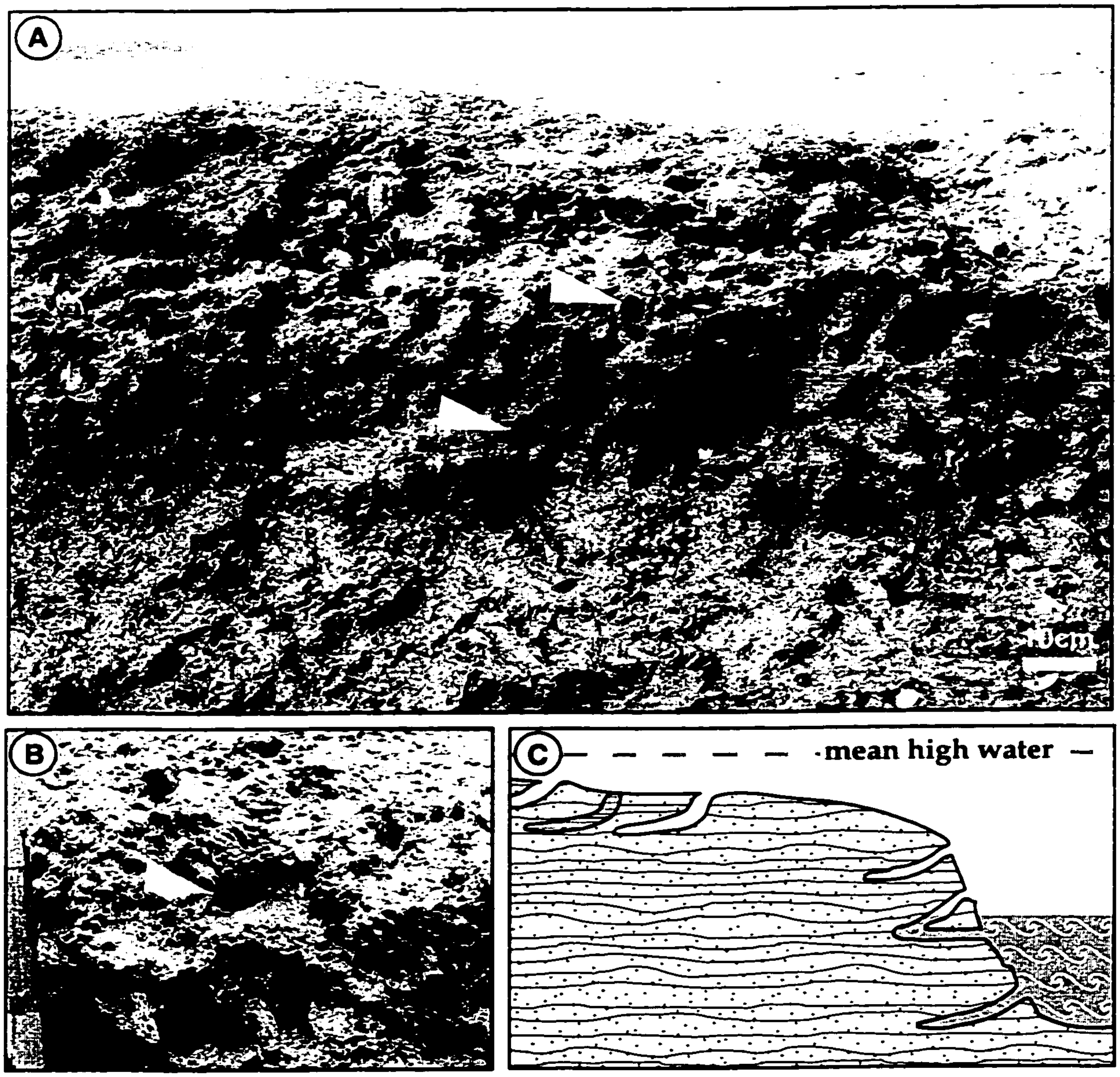

FIGURE 3.5 - Burrows of *Hemigrapsus oregonensis* in intertidal cut-banks at Willapa Bay. These traces are interpreted to be analogous to *Psilonichnus upsilon* Type A. (A) High densities of *H. oregonensis* cross cut intertidal flat lamination. Note the in situ bivalves that are eroding out of the intertidal flat accumulations. (B) Close up of the same deposit. Here burrows of the threadworm *Heteromastus* dominate the background fabric. Apertures to the modern crab burrows are notably robust (arrow). (C) Schematic section illustrating the typical configuration of *H. oregonensis* burrows in cutbank and intertidal assemblages.

relationship is not observed in the Pleistocene record at Willapa Bay. Less commonly, similar traces are observed on modern intertidal point bars, flats, and muddy subtidal point bars. These traces possess a much greater chance of passing into the rock record, and they are considered analogous to the Pleistocene trace fossils described herein.

Psilonichnus upsilon *Type B*

Description

Psilonichnus upsilon Type B is consistently observed in highly bioturbated (ichnofabric index 4 or 5), muddy deposits. Physical sedimentary structures are typically eradicated, although rare wavy lamination, ripple lamination, and decimeter-scale scour and fill structures are sporadically present. Terrestrial organic detritus is common. These deposits have been interpreted as muddy intertidal deposits (Clifton et al., 1976; Clifton and Phillips, 1980; Clifton et al., 1989; Chapter 2), although *P. upsilon* Type B has been observed in quiescent subtidal deposits as well. Quiescent subtidal deposits are sedimentologically similar except for the following criteria: the ichnofabric index of the background fabric is generally higher; the trace fossil diversity is generally higher and is typically comprised of *Gyrolithes, Planolites, Palaeophycos; Cylindrichnus, Thallasinoides* (rare), and *Ophiomorpha* (rare); vestigial sedimentary structures are more rare; and organic detritus is less abundant.

Psilonichnus upsilon Type B is notably larger than Type A (Fig. 3.6, 3.7). Like Type A it contains a fill composed of interlaminated mud and silt/sand. The burrows typically have diameters that range between 10 and 12 cm, and lengths that exceed 50 cm. They are J-shaped, with a long horizontal to slightly inclined, unbranched tunnel. Some burrows have a "notch" protruding from the roof of the burrow with dimensions averaging 2.5 cm across and 2 to 2.5 cm top to bottom (Fig. 3.6A,B, 3.7). The unlined burrows are commonly rimmed by an iron oxide halo (Fig. 3.6A,C).

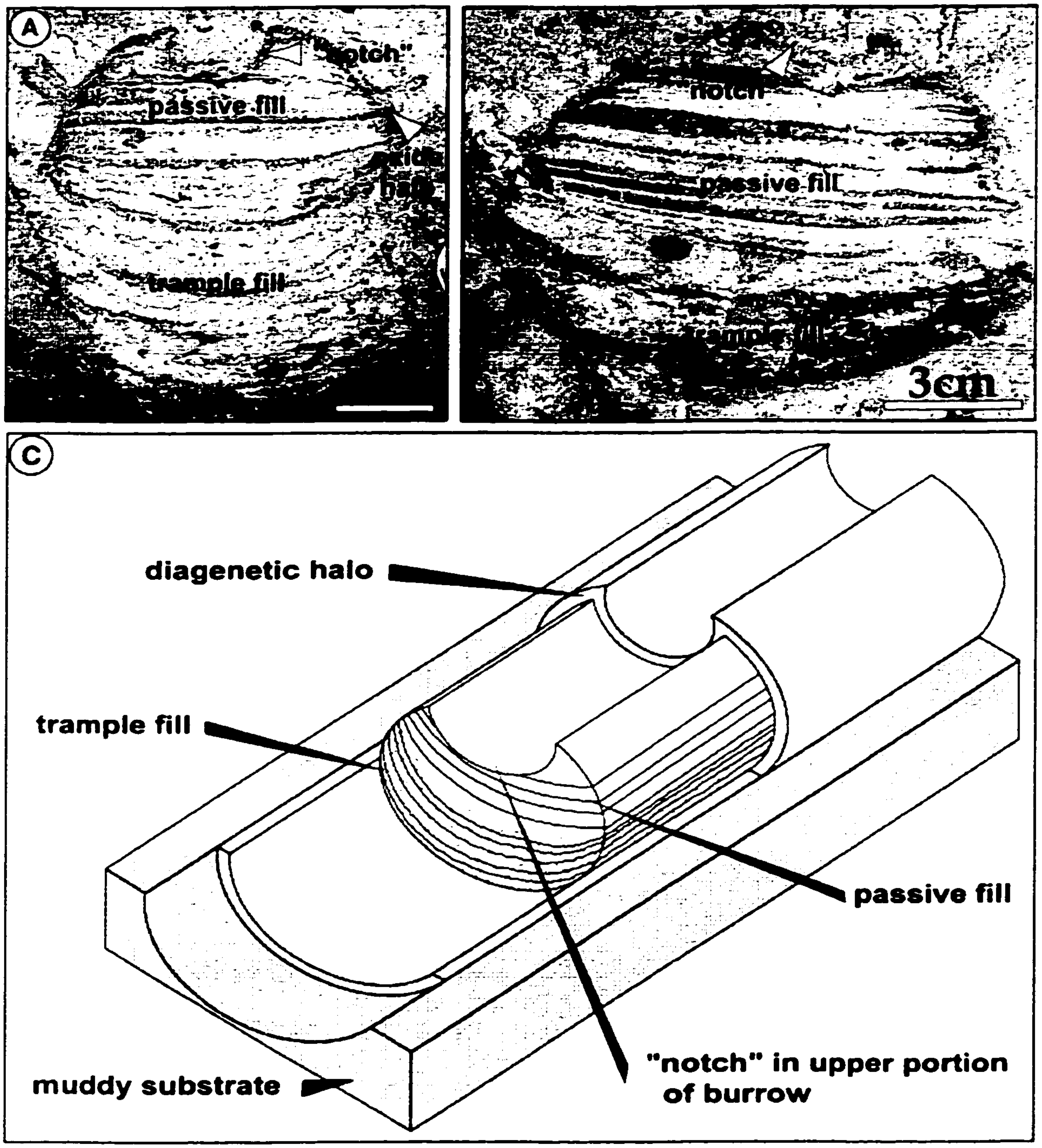

FIGURE 3.6 - Outcrop examples of *Psilonichnus upsilon* Type B. (A, B) Cross section of *P. upsilon* Type B detailing the trample fill, passive fill, diagenetic halo, and notch. (C) Schematic interpretation of the burrows illustrated in 5A,B.

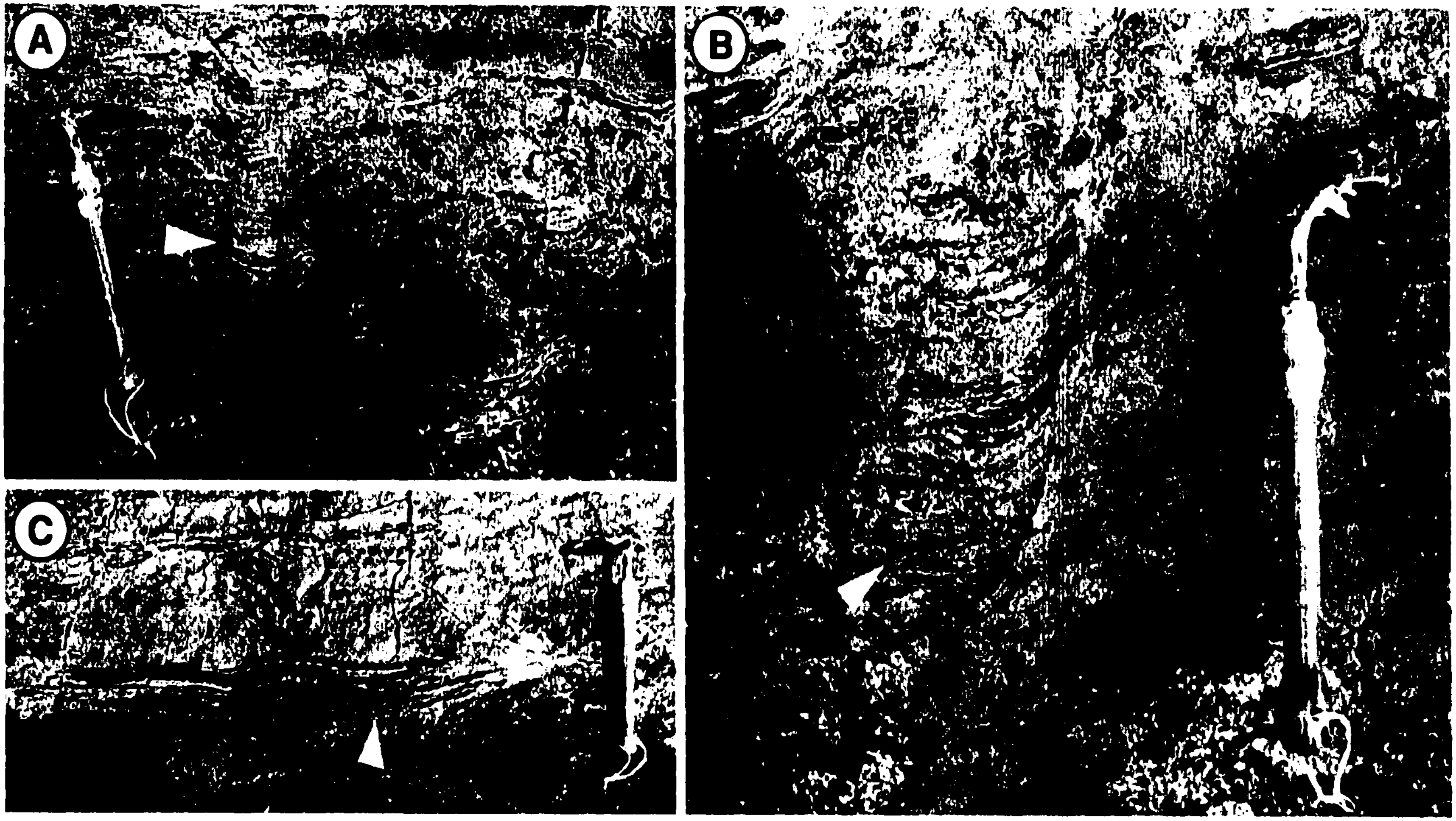

FIGURE 3.7 - Outcrop examples of highly agradational *Psilonichnus upsilon* Type B in cross- and longitudinal section. (A, B) White arrows indicate *P. upsilon*, the black arrow indicates an obliquely-migrating trace fossil. The trowel is approximately 28 cm long. (C) Longitudinal section of the same trace fossil. Note the gently inclined portion (to the right) that is interpreted to represent the area near the apertural opening.

Laminae in the lower portion of the trace fossil are typically spreiten-bearing, lending the appearance of a large *Teichichnus*-like burrow in cross section (Fig. 6). These laminations are considered to be spreite in that they represent sequential demarcations of the burrow wall (albeit the floor). This terminology is consistent with earlier applications (Frey and Seilacher, 1980; Ekdale et al. 1984; Bromley, 1996). The spreite are lithologically defined by thin mud laminae (up to 4 mm in thickness), and coarser-grained fill that is composed of fine- to medium-grained sand and wood fragments (up to 2 cm in thickness). The spreite are crudely defined, concave upwards, slightly wavy, and non-parallel within this portion of the burrow. They are typically disrupted by walking traces, and represent successive (aggrading) floors of the tunnel. Overlying the spreite are planar parallel laminations, 1 to 10 mm in thickness, that are defined by variations in grain size and lithology.

In intertidal flat deposits, this ichnofossil is rare to moderately abundant; it is more common in sheltered subtidal deposits. The degree of bioturbation and the trace fossil diversity of the associated ichnofossil assemblage is notably higher than those associated with *Psilonichnus upsilon* Type A. Both *P. upsilon* Type-A and -B cross cut the burrowed fabric and apparently represent the deepest burrow tier.

Specimens of *Psilonichnus upsilon* Type A are significantly larger than many *Psilonichnus* that have been previously described (Frey and Mayou, 1971; Allen and Curran, 1974; Frey et al, 1984; Curran and White, 1991). However Humphreys and Balson (1988) described unusually large *Psilonichnus* from Pliocene subtidal deposits in eastern England. Pemberton et al. (1984) described burrows of similar proportions from the Cretaceous of Western Canada. Those *lebensspurren* were comprised of branching burrow networks and consequently classified as *Thalassinoides suevicus*. Other burrows of similar proportions, attributed to the work of lobsters, and classified as *Thalassinoides*, have been identified in the in the Lower Cretaceous Atherfield Clay Formation on the Isle of Wight (Wach and Ruffell, 1990).

Psilonichnus upsilon Type B

Interpretation and Discussion

As with *Psilonichnus upsilon* Type A, slightly inclined to horizontal tunnels, an overall J-morphology, and an absence of branching, confirm that ichnofossil Type B is best defined as *Psilonichnus upsilon* (Table 3.1). Furthermore, the burrows are unlined, oval in cross section, and have no complex basal architecture. They share little in common with thalassinid burrows, and lack the shallow networking evident in many lobster burrows (Fig. 3.2).

Quiescent subtidal and muddy intertidal deposits that outcrop around Willapa Bay contain *P. upsilon* Type B in rare to locally moderate abundance (Figs. 3.6A,B, 3.7). Where present, a paucity of other crustacean burrows is normal, suggesting that the trace-maker out-competed others for food or space. Also, they may have preyed on other crustaceans.

Higher degrees of bioturbation associated with this ichnofossil suggest that sedimentation rates were comparatively low. In fact, unlike *Psilonichnus upsilon* Type A, Type B is absent in point bar deposits, which are interpreted to have been deposited under relatively higher sedimentation rates. It seems, then, that the tracemaker could not normally cope with higher sedimentation rates and/or high turbidity.

A distinctive characteristic of these burrows is the vertical juxtaposition of a shifting-upwards burrow floor (forming spreite) and passive fill (Fig. 3.6). Retrusive spreite are common in the lower portion of the burrow fill. Disruptions, interpreted as trample markings, indicate these spreite represent the trace's sporadically aggrading floor. Intermittently, the roof of the burrow presumably collapsed. The tracemaker subsequently re-excavated the domicile in an attempt to maintain a suitable burrow architecture. Alternately, a stable depth in the substrate may have been maintained by scraping material from the burrow roof. These two processes created the series of concave upwards, quasi-parallel laminations observed in the bottom portion of the burrow. The presence of several trampled layers (Fig. 3.6A) indicates successive excavations were required by the burrower. This, along with significant sediment aggradation, suggests these burrows were permanent domiciles that were inhabited for longer time spans than *Psilonichnus upsilon* Type A. Differences in substrate cohesiveness would also account for this observation. Frey and Seilacher (1980) observed similar spreite associated with *Thalassinoides* burrows from the Eocene of Georgia (they noted the same burrow was taxonomically *Teichichnus* in cross section).

The upper portion of the ichnofossil was passively filled after the tracemaker abandoned the burrow. The planar parallel laminations within the upper part of the trace fossil provide no evidence that this occurred while the inhabitant was still residing in the structure. Similar to the infill present in the smaller *Psilonichnus upsilon* Type A, this fill consists of interbedded sand and mud, reflecting alternating bed load transport and deposition from suspension. The burrow fill is interpreted to have been deposited under tidally influenced or episodic conditions. As with *Psilonichnus upsilon* Type A, the laminated fill ordinarily provides the only evidence for rhythmic sedimentation in its associated deposits.

Approximately 30% of *Psilonichnus upsilon* Type B specimens have a distinctive notch that protrudes down from the roof of the structure (Figs. 3.6A,C). The purpose of this conspicuous feature is not clear. This may reflect the functional morphology of the tracemaker, implying the burrower had difficulty reaching the tunnel roof. Thalassinid shrimp (especially *Upogebia* and *Callianassa*) are generally capable of producing burrows with circular cross-sections. In contrast, crab burrows are normally oval in section (Fig. 3.6A, 3.2). This results from the crabs flattened body and the awkward positioning of its front chelae. Their chelae can barely touch to the front of the crab, a situation that is exacerbated when reaching upwards. Of the animals that inhabit the modern Pacific coast, a crab-like morphology is best reconciled with the presence of a notch.

The preservation of the notch above the passive-fill merely indicates that the notch was present at the time of burrow abandonment. Close scrutiny of Figure 3.6A show passive laminae that terminate against the protrusion, indicating it was present before the burrow completely infilled. The portion of the burrow that is passively filled reflects the morphology of the open portion of the burrow as it migrated upwards.

Due to the large size of *Psilonichnus upsilon* Type B and its morphological similarities to modern crab burrows, it is postulated that these structures were constructed by a large crab, shrimp, or similar crustacean. Burrowing crustaceans common in the modern bay include the shrimp *Callianassa californiensis* and *Upogebia pugettensis*, and the crabs *Hemigrapsus oregonensis* and *Cancer magistar*. Of these, only *C. magister* is large enough to produce a burrow of this size. *C. magistar* is known to burrow backwards into sandy substrates, producing temporary resting burrows (Kozloff, 1996). Fishermen in Willapa Bay note that *C. magistar* tends to burrow into the substrate during the winter. Overwintering has been observed with the american lobster, *Homarus americanus* (Thomas, 1968; Cobb, 1971), but this behavior is poorly documented with crabs. Fossil crab burrows, interpreted as subtidal, have been documented from Cretaceous strata on Vancouver Island (Richards, 1975). However, no Pleistocene examples of (subtidal) crab burrows are known from the Pleistocene record along the west coast of North America.

A second potential trace maker for these large *lebenspurren* is the mantis shrimp, *Hemisquilla ensigera californiensis*, which is found in shallow coastal waters off the coast of southern California (Ricketts et al., 1985). Caldwell and Dingle (1976) observed these stomatopods occupying simple subtidal burrows in the Gulf of California. The range of these shrimp, however, is presently far south of Washington. Furthermore, burrows of mantis shrimp are commonly circular in cross-section.

PALEOECOLOGICAL SIGNIFICANCE

The Pleistocene deposits surrounding Willapa Bay are interpreted to have been deposited in a depositional environment similar to that of the modern bay (Clifton et al., 1976; Chapter 2). Despite the overall similarities between the modern and ancient deposits, the analysis of crab traces and trace fossils indicates that the ecology within the estuarine system has varied considerably. Large burrowing crustaceans have not been observed in modern intertidal flat and central bay deposits. In contrast, *Psilonichnus upsilon* are locally abundant in ancient intertidal and subtidal deposits (Fig. 3). In the modern bay, the dominant crustaceans are the burrowing shrimp *Callianassa californiensis* (which has been renamed *Neotrypea californiensis*) and *Upogebia pugettensis*, which typically construct *Thalassinoides*-like burrows. The dominance of *Psilonichnus upsilon* in certain trace fossil assemblages at Willapa Bay indicates that burrowing crabs have, at times, occupied the same ecospace burrowing shrimp maintain today.

Climatic variability and bay-fill history are the dominant factors that controlled paleoecologic changes within the bay. These factors determine, or at least are intrinsically related to such factors as sediment supply, magnitude of tidal prism, and various chemical conditions (Peterson et al., 1995). Crustaceans, which have a robust physiology, are exceedingly tolerant of stressful conditions, particularly salinity- and thermal-stress. However, at Willapa Bay, *Hemigrapsus oregonensis* is present in the upper estuary where *Callianassa* and *Upogebia* are absent. In fact *H. oregonensis* persists where the measured salinity is approximately 10 ppt. In contrast, at Willapa Bay thalassinid shrimp are not present where the salinity falls below 15 ppt (Gingras et al., 1999). Notably, Gingras et al. provided salinity data only. Other factors, such as oxygenation, turbidity, and pollution are not quantified; these factors may also play a role in the distribution of crustaceans.

Competition between populations may also reflect 'random' events. These random factors include larval recruitment, resource type and distribution, habitat fragmentation, and behavioral adaptation (Wilson, 1991; Hopf et al., 1993; Walter and Peterson, 1995; Kidwell and Flessa, 1995). These factors can not be assessed considering the data herein. However, these random events, particularly resource distribution and larval recruitment, are passively linked to physico-chemical changes in the bay (ibid.).

Psilonichnus are typically located within deposits associated with backshore and other predominantly non-marine environments subject to periodic marine influence (Curran and Frey, 1977; Howard and Frey, 1980; Frey and Pemberton, 1987). Pleistocene deposits at Willapa Bay show that forms of this ichnofossil may be well developed in subtidal- and intertidal-depositional environments.

CONCLUSIONS

Two different varieties of *Psilonichnus upsilon* have been observed in Pleistocene strata at Willapa Bay. Each has a distinct fill that provides information about the burrow's history of habitation and the conditions under which they were filled. *Psilonichnus upsilon* Type A is interpreted to have been abandoned seasonally and filled shortly thereafter. *Psilonichnus upsilon* Type B, which is significantly larger than Type A, is characterized by aggraded tunnels that also passively filled following abandonment.

Four notable conclusions are arrived at: (1) *Psilonichnus upsilon* has a more variable architecture then previously discussed in the literature. Both the size and angle of the tunnel vary appreciably. Also *Psilonichnus* may aggrade, forming *Teichichnus*-like structures. (2) In the modern bay burrowing shrimp dominate quiescent subtidal, point-bar, and intertidal deposits. The Pleistocene strata, however, indicate burrowing crabs sometimes occupied similar ecospace in the ancient bay. Their presence suggests physico-chemical parameters, or competition dynamics unlike any in the modern bay (the nature and magnitude of these differences was not characterized). (3) Laminated, heterolithic burrow fills provide evidence of rhythmic sedimentation. These laminae represent tidal or episodic sedimentation and provide the only evidence of such processes in otherwise muddy deposits. The trace assemblages serve to illustrate the paleoecologic flexibility and the variable morphologies inherent to crab burrows. (4) A large burrowing crab that might make *P. upsilon* Type B is probably not present in the modern bay. However, such a trace maker was present when these Pleistocene deposits accumulated. Whether it was an extinct or extant species is not known.

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CHAPTER 4: A FIELD METHOD FOR DETERMINING THE FIRMNESS OF VARIOUS SUBSTRATES[1]

INTRODUCTION

The Sedimentological Significance of Firm Substrates

The firmness of a substrate in modern depositional settings is related to many factors. Some of these include grain size, initial pore water content, drainage of the substrate, previous compaction of the sediment, and (in carbonates) the potential for early cementation of the grains. Notably, physical and biogenic processes are influenced by the overall cohesiveness of the substrate. For example, cohesive substrates resist the erosion and re-suspension of grains (Knighton, 1984; DeVries, 1992; Dade et al., 1995). Furthermore, antecedent topography due to the erosion of surfaces characterized by the patchy distribution of firmgrounds (Huang, 1993), affects sediment distribution patterns on many scales (Sanford and Halka, 1993). It has also been shown that biogenic sedimentary structures are markedly different in firmgrounds where compared to those generated in softgrounds (Seilacher, 1964; Pemberton and Frey, 1985). In fact, the biological response to the cohesiveness of a substrate is recognized in the well-accepted ichnofacies concept. For example, softground suites of trace fossils generally consist of traces that comprise the *Skolithos, Cruziana, Zoophycos,* or *Nereites* ichnofacies. Firmground, woodground, and hardground assemblages represent the *Glossifungites, Teredolites,* and *Trypanites* ichnofacies, respectively.

The dependence of the aforementioned processes on substrate-firmness suggests researchers in modern depositional environments benefit from making detailed observations regarding the distribution of firmness profiles. Most commonly, however, compaction tests are of greater interest to geotechnical researchers. Their studies range from calculating the mechanical resistance of soils (Ohnuki et al., 1997; Smith et al., 1997) to subsurface (borehole) environmental interpretation using penetrometer soundings

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[1] A version of this chapter has been submitted for review by The Journal of Sedimentary Research as "A Field Method for the Determination of the Firmness of Various Substrates", by Murray K. Gingras and S. George Pemberton.

(Nelson et al., 1997). Almost all the previous studies have utilized conical and, less commonly, plate penetrometers. The simplest of these is the drop penetrometer (Levacher, 1985), which consists of a dropped conical apparatus that invades the substrate to a certain depth. With the exception of the drop penetrometer, these devices may not provide the simplest and most portable equipment for use in field applications. Also, measurements derived from such an apparatus are specific, and can be indicative of the sediment firmness over areas less than 1 or 2 mm diameter. This is not necessarily true, however, of measurements taken in relatively soft sediments.

In these regards, sedimentologists might adapt methods from the metallurgical sciences, where the hardness testing of alloyed, heat-treated, and annealed metals has been practiced since the early 1900's. A general overview of these practices can be found in O'Neil (1967). The metallurgical equivalent of the conical penetrometer is the Rockwell hardness tester: a mechanical device that applies a fixed force against a small pyramid that is driven into the metal being tested. The hardness of the metal is inversely proportional to the area of the indentation imposed by the pyramid. Because the application of a fixed force requires a somewhat sophisticated mechanical apparatus, this method is seldom used in field applications. Field measurements are preferentially derived from the Brinell hardness test (Brinell, 1900). In the field, this methodology depends on driving a steel ball into the metal with a dynamic force, usually a three-pound hammer accelerating at the end of a person's arm. In this case, the hardness of the metal is inversely proportional to the area of the indentation created by the ball. The advantages of this method are clear. The equipment is unsophisticated and portable, the procedure can be repeated many times, and the procedure itself is extremely simple. Also, the measurements produced by this seemingly crude method accurately assess the hardness of the metal within half an order of magnitude (hardness in metals varies over several orders of magnitude). Indentations due to Brinell hardness tests are notably larger than those caused by the Rockwell pyramid. The Brinell test therefore takes more general measurements of metal hardness.

This paper suggests that a modified version of the Brinell hardness test is equally appropriate for assessing the firmness of substrates in modern depositional environments. Portable, simple equipment that is capable of providing reproducible results that accurately average the firmness of the sediment provide the opportunity to take a greater quantity of firmness measurements. A somewhat larger area of measurement allows for assessments of the sediment firmness that average small-scale heterogeneities, such as minute burrows or variations in pore water content. Finally, this chapter demonstrates that the calculations utilized to approximate sediment firmness are simple and can be quickly modified to accommodate variations in the methodology applied. These are decided advantages over penetrometer tests where the drop-cone is typically of fixed weight and dimension.

The Method

A glass or metal indenter, 25 mm in diameter, is dropped from a fixed height of 10 or 100 cm. Calculation of the pressure exerted by the substrate requires equating the potential energy at the top of the indenter's free fall to the energy (or impulse) absorbed by the substrate. This can be calculated as a proxy by calculating potential energy (into the substrate) as a function of mass, acceleration, and depth of penetration into the substrate (Fig. 4.1).

$$PE_1 = PE_2$$

$$\text{mass x gravity x height} = \text{mass x acceleration x penetration}$$

$$m \times g \times h_1 = m \times a \times h_2$$

$$\textbf{(1)} \quad (m \times g \times h_1) / h_2 = m \times a = F_2$$

The force exerted by the substrate (F_2) can be converted to mean pressure by dividing F_2 by the projected area of the indent (Fig. 4.1), a methodology recommended to

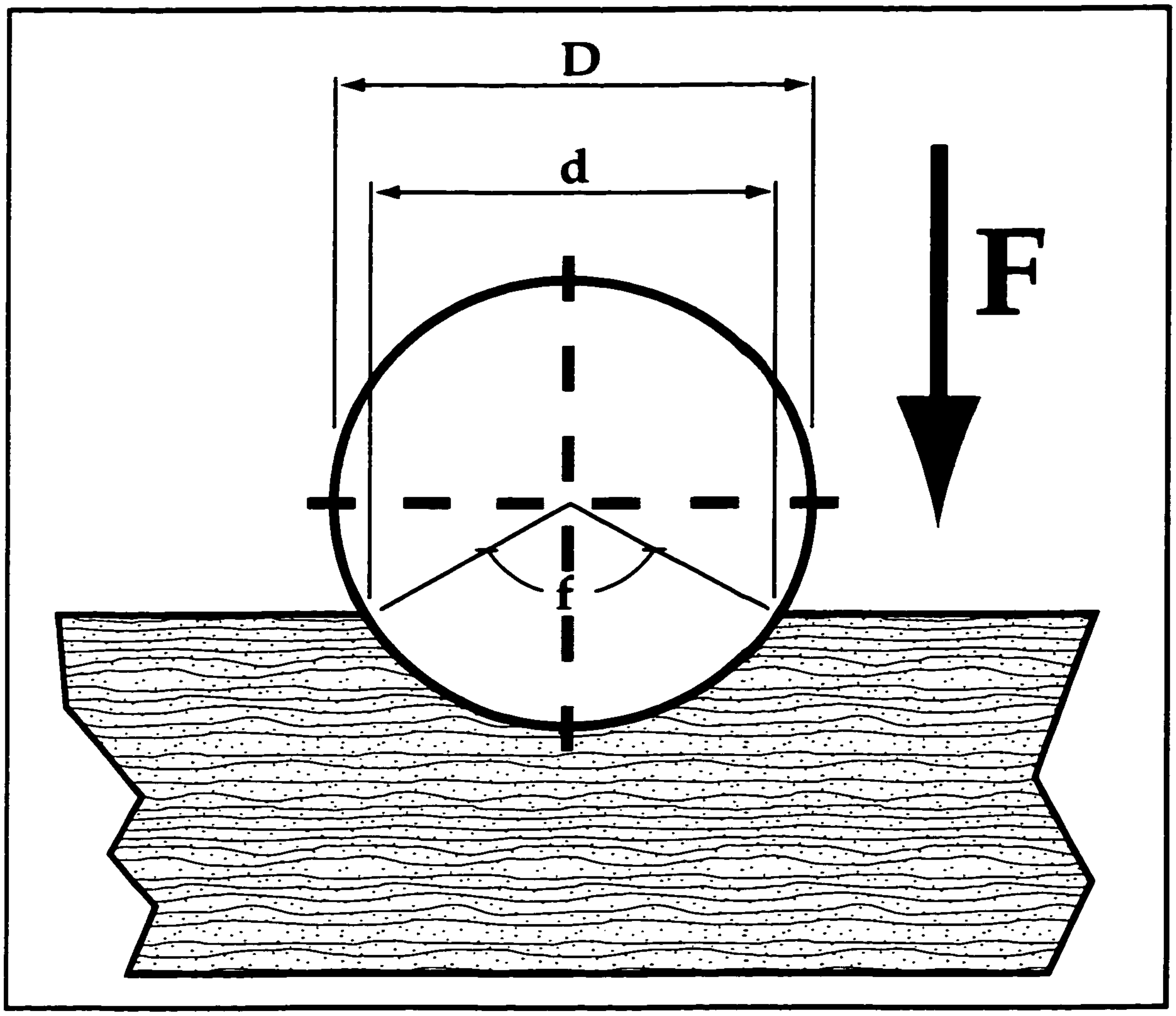

FIGURE 4.1 - Test configuration of the modified Brinell firmness test. The parameters used to calculate the force exerted by the substrate are the diameter of the indenter (D), diameter of the impression (d), and the included angle from the center of the indenter to the edge of the impression (ø).

metallurgists by O'Neill (1967), as it represents the area of substrate resisting indentation. The relationship between the depth of the indent and the pressure exerted by the substrate during impact is non-linear and the practical measurable range, using a 25.4 mm glass ball is between 5.0 kPa and 1.0 x 10^5 kPa (Fig. 4.2).

The simplest means of releasing the indenter is by hand release. A more consistent release is provided by the magnetic release mechanism, in which case a steel ball bearing must replace the glass indenter (Fig. 4.3). In both cases, the indenter's height

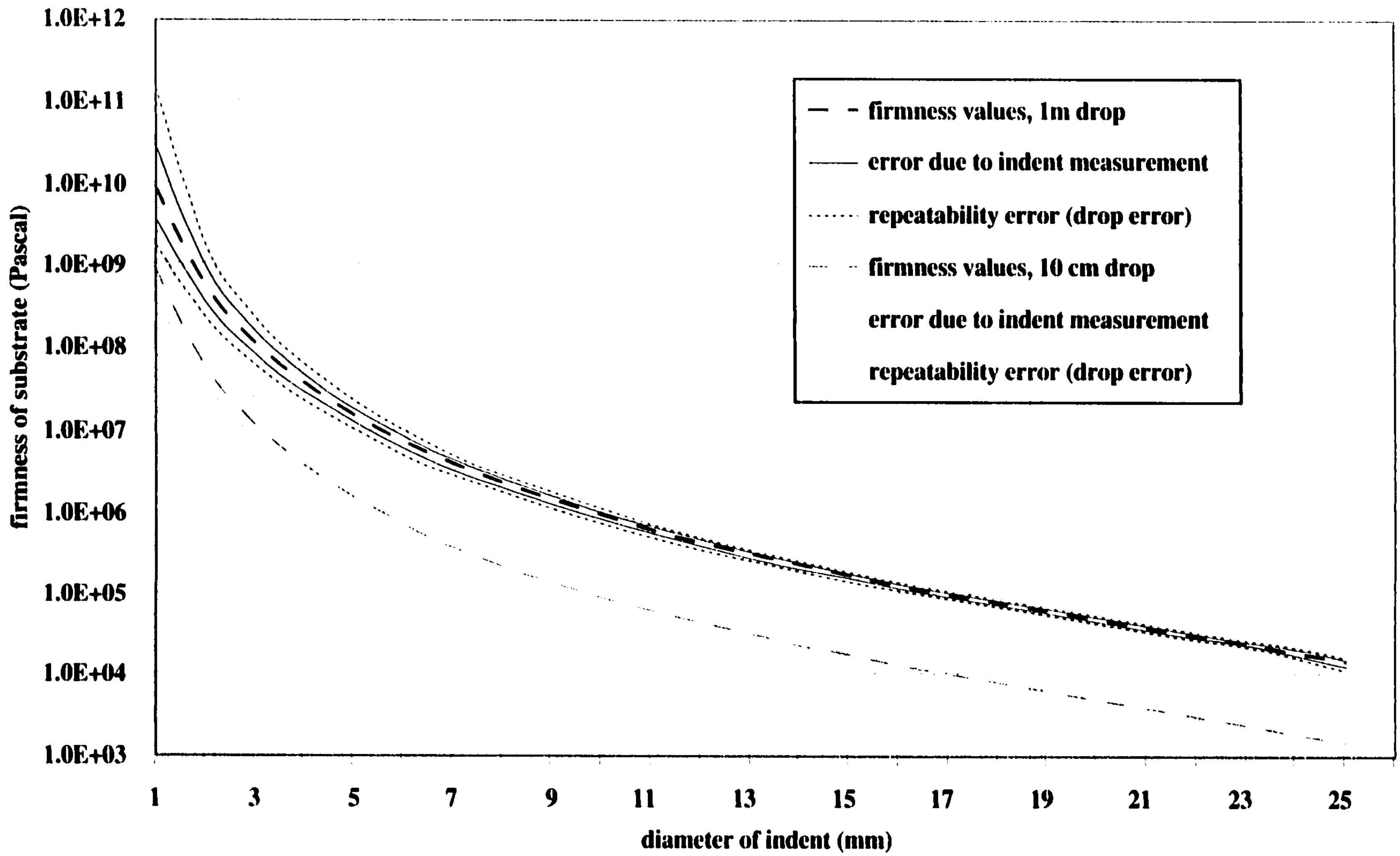

FIGURE 4.2 - Graph of the pressure exerted by the substrate vs. the diameter of the indentation made during the firmness test. The upper (black) curves estimates the pressure produced by an indenter based on a 1m free fall, the lower (grey) curves indicates pressure values produced from a 10cm drop. Thin, solid lines indicate the error due to measurement. Thin dashed lines indicate the error due to the release of the ball; this *includes* the measurement error.

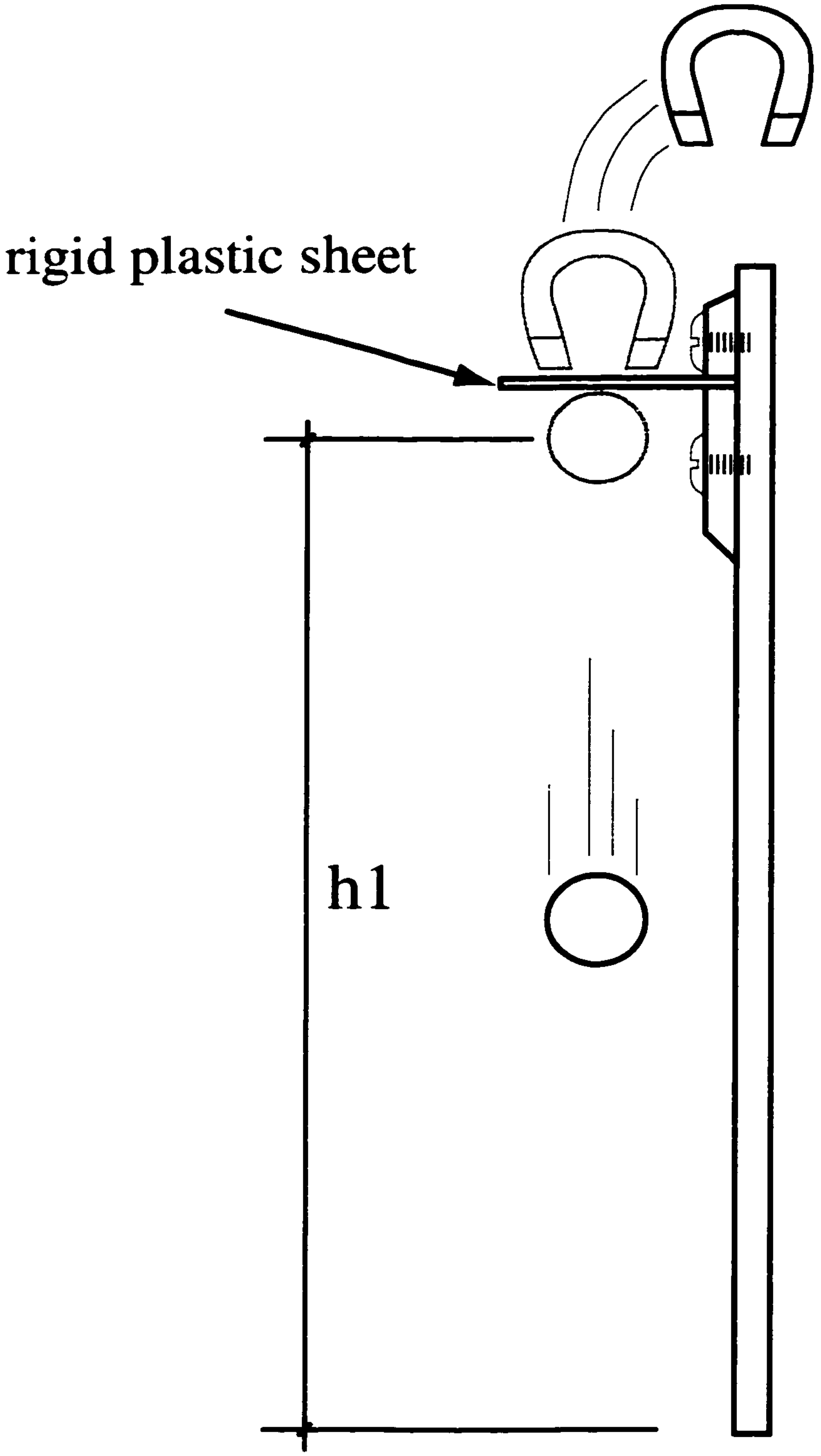

FIGURE 4.3 - Modified Brinell test with magnetic release apparatus.

is calibrated to a decimeter or meter scale. Due to the simple nature of this procedure, firmness tests can be executed on *in situ* substrate or box core samples.

DISCUSSION

Sources of Error and Practical Limitations

Many sources of error are evident in the previously outlined methodology. Most significant among these are errors related to the measurement of the indentation and the variability due to the initial release of the indenter. Normally, the diameter of the indentation can be measured to within +/- 0.25 mm. On firm substrates, where the indent diameter is less than 2 mm, the log error produced due to measurement approaches 10 %. This value represents a range of one order of magnitude about the actual media firmness (Fig. 4.2). If the indent diameter exceeds 9 mm, the log error falls below 4 % (Fig. 4.2).

Multiple trials show that the error due to manual release of the indenter is small. Several repeat runs (n=5) showed that the maximum error about the modal measurement was 0.5 mm (Table 4.1). Given that the error attributed to measuring the diameter of the indent is +/- 0.25 mm, we have assumed that the error due to the release of the indentor is +/- 0.25 mm as well. Therefore, indent diameters approaching 1 mm are inherently inaccurate because the log error approaches 20% (Table 4.1). Where the indent diameter is 2.5 mm, or 10% of the indenter diameter, the log error is an acceptable 8%. Although measurement and release errors are notably small for indent diameters exceeding 20 mm (80% of the indenter diameter), we have found that deformation of the substrate upon removal of the indenter makes these measurements exceedingly inaccurate. It is therefore suggested that this method be utilized where the indent diameter is greater than 10% and less than 80% of the indenter diameter. In the field, drop heights might be adjusted to find an ideal middle range. The adjusted height (h_1) can then be substituted into (1) and the sediment firmness assessed.

All of the above assumes the indenter strikes a horizontal surface from the vertical axis. Indents that are visually out of round are disregarded. Also, the modified Brinell method is inappropriate for dry, unconsolidated sand and extremely thixotropic mud, where indents collapse and cannot be measured. Although these short-fallings are significant, the Brinell method is extremely useful for quickly assessing the firmness of most soft to firmground substrates.

	Indent Measurement (mm)						
Substrate Type	**1**	**2**	**3**	**4**	**5**	**avg.**	**mode**
uncompacted mud a	16	17.5	16	16	17	16.5	16
uncompacted mud b	9	8	10	8	9	8.8	9
uncompacted mud c	18	18	19	19.5	18	18.5	18
uncemented sand a	8	8	8	9	8	8.2	8
uncemented sand b	11	11.8	12	12.5	12	11.86	12
compacted mud a	6	6	6	6	6	6	6
compacted mud b	3.5	3	3	3	3	3.1	3
compacted mud c	2	3	2	2	2	2.2	2

TABLE 4.1 - Summary of test values demonstrating the consistency of data derived from the modified Brinell firmness test.

SUMMARY

Substrate firmness represents a physical characteristic that strongly effects the erodibility and remobilization of sediment. It also creates antecedant topography that may influence sedimentation patterns on different scales. Furthermore, trace assemblages are profoundly influenced by the overall cohesiveness of the sediment. In the light of these observations, it is apparent that a portable, simple, and expedient means of measuring sediment firmness would help establish a more comprehensive database relating to firmness variations in different depositional environments. A modified version of the Brinell hardness test, which is employed by metallurgists to quickly assess the hardness of steel, fulfills these field requirements.

The modified Brinell firmness test assesses the impulse imparted to the sediment by a sphere dropped from a fixed height. The impulse is converted to pressure and is regarded to be representative of the sediment's firmness.

Due primarily to measurement errors, the method is inaccurate where the diameter of the indent imparted to the substrate is less than 10% and greater than 80% of the indenter diameter. If the indent diameter does not fall between these two values, the drop height can be adjusted. In such cases, the simple formulae provided herein can be used to correctly assess the firmness of the substrate. The modified Brinell test is inappropriate for measuring the firmness of dry, unconsolidated sands and thixotropic muds. It is, however, extremely useful where assessing the firmness of most soft to firmground substrates.

In short, the advantages of this testing procedure are simplicity, portability, flexibility of method, ease of calculation, and relative accuracy. The primary disadvantages include substrate limitations, and constraints regarding indent to indentor ratios.

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CHAPTER 5: FIRMNESS PROFILES IN TIDAL CREEK DEPOSITS: THE TEMPORAL SIGNIFICANCE OF *GLOSSIFUNGITES* ASSEMBLAGES[1]

INTRODUCTION

The Glossifungites *Ichnofacies*

Many concepts in ichnology have focused on the identification of key environmental parameters to bolster physical sedimentologic data for the interpretation of sedimentary facies in the rock record. Some of the variables that ichnologists have successfully characterized include oxygenation, salinity, and sedimentation rates. Though trace fossils were thought to be useful in delineating the internal architecture of sedimentary accumulations, their utility regarding the identification of key stratigraphic horizons was limited to trace-fossil stratigraphy (Crimes, 1968; Seilacher, 1970). The evolution of genetic stratigraphic models forced a shift in focus from the resolution of facies geometry to the correlation of genetically significant surfaces. This emphasis led to the recognition that certain horizons, such as transgressive surfaces of erosion, may be demarcated by the presence of a suite of trace fossils characteristic of the *Glossifungites* ichnofacies (Pemberton and Frey, 1985; MacEachern et al. 1992; Pemberton et al., 1992; and Pemberton and MacEachern, 1995).

The *Glossifungites* ichnofacies consists of traces that were emplaced into a firm substrate. Due to their cohesive nature, firmgrounds support open, unlined burrows that would otherwise relax and collapse in a softer substrate. Firmgrounds in clastic substrates are typically derived from sediment that has undergone burial, compaction, and dewatering or are the result of subaerial exposure. The exhumation of buried substrates, through autocyclic or allocyclic processes, is required to expose *compacted* firmgrounds to the activities of burrowing animals. Linking *Glossifungites*-demarcated discontinuities (hitherto referred to as *Glossifungites* surfaces) to potential changes in base level provides the basis for the sequence stratigraphic significance of the

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[1] A version of this chapter has been submitted for review by The Journal of Sedimentary Research as "Firmness Profiles Associated with Tidal Creek Deposits: The Temporal Significance of Glossifungites Surfaces", by Murray K. Gingras, S. George Pemberton, and Tom Saunders.

Glossifungites ichnofacies. This is because the presence of a *Glossifungites* surface evidences a break between erosion and deposition across a surface (Pemberton and MacEachern, 1995). Unfortunately, this concept can be misapplied, as the presence of a *Glossifungites* surface alone divulges no information of stratigraphic value (Pemberton and MacEachern, 1995). Like other sedimentary facies, the *Glossifungites* ichnofacies must conform to Walther's Law and have identifiable, mappable extents.

Seilacher (1964) originally described the *Glossifungites* ichnofacies as a primarily littoral assemblage of trace fossils emplaced in cohesive substrates. These are markedly different from the *Skolithos* ichnofacies that is characterized by shifting substrates. Frey and Seilacher (1980) restricted the *Glossifungites* ichnofacies to firmgrounds in marine environments, though the essential components of Seilacher's original (1964) definition remained intact. Working along the Georgia coast, Pemberton and Frey (1985) provided numerous examples of burrowed firmgrounds in a variety of modern settings. Moreover, their study was the first to link processes, such as wave erosion, to the development of *Glossifungites* surfaces. These observations ultimately led to the integration of ichnology and genetic stratigraphy (MacEachern et al., 1992; Pemberton et al. 1992; Pemberton and MacEachern, 1995).

Although firmground assemblages are well understood, the *Glossifungites* concept generates a great deal of confusion amongst researchers. This is because firmgrounds represent an intermediate and gradational state between soft- and hard-grounds. No 'rule of thumb' exists with which one can determine the degree of compaction and dewatering a substrate has endured in the transformation from a softground to a firmground. Although the stratigraphic significance of *Glossifungites* surfaces is well recognized, their dependence on physical parameters such as grain size, water content, and sedimentation rates have yet to be reviewed in the geological literature. Admittedly, establishing acceptable criteria from which the compactional parameters of a firmground might be derived is an all but impossible task. In addition to the aforementioned parameters, organic content, grain sorting, grain shape, and initial pore pressure undoubtedly have a notable effect on the kinetics of the compaction process (Krumbein, 1959; Hoyt and Henry, 1964; Tokunaga et al., 1994; Dewherst and Aplin, 1998).

This research attempts to profile firmness changes in a dynamic depositional environment that is characterized by the presence of soft- and firm-substrates. The measurements and observations procured from the field are interpreted in the light of their temporal significance and provide a basis for application to the rock record. In other words, can we distinguish significant *Glossifungites*-demarcated discontinuities from less significant ones? This paper also details sedimentological and biological relationships, as they relate to firmness changes across a tidal creek deposit. A tertiary objective is to provide conceptual and empirical bases for future research directed towards understanding the stratigraphic significance of *Glossifungites* surfaces. An intertidal creek and point-bar depositional environment was chosen because substrate consistency changes notably from the point-bar to the cut-bank. Also, the intertidal creek cuts into the intertidal flat, allowing deeper sampling of the intertidal flat deposits. This data is contrasted with *Glossifungites* surfaces associated with wave erosion along the eastern margin of Willapa Bay.

Study Area

Willapa Bay is located in the southwest corner of Washington (Fig. 5.1). The bay is separated from the Pacific Ocean by the North Beach Peninsula, a 27-km-long spit derived from sand transported from the mouth of the Columbia River (Clifton and Phillips, 1980). The bay is sheltered from oceanic waves by the North Beach Peninsula and Willapa Bar, a set of shoals at the bay mouth. Willapa Bay is a mesotidal estuary with a tidal range of 2 to 3 m. The tidal prism, which exceeds 700,000 m^3, comprises about 45% of the bay's total volume (U.S. Army Corps of Engineers, 1975).

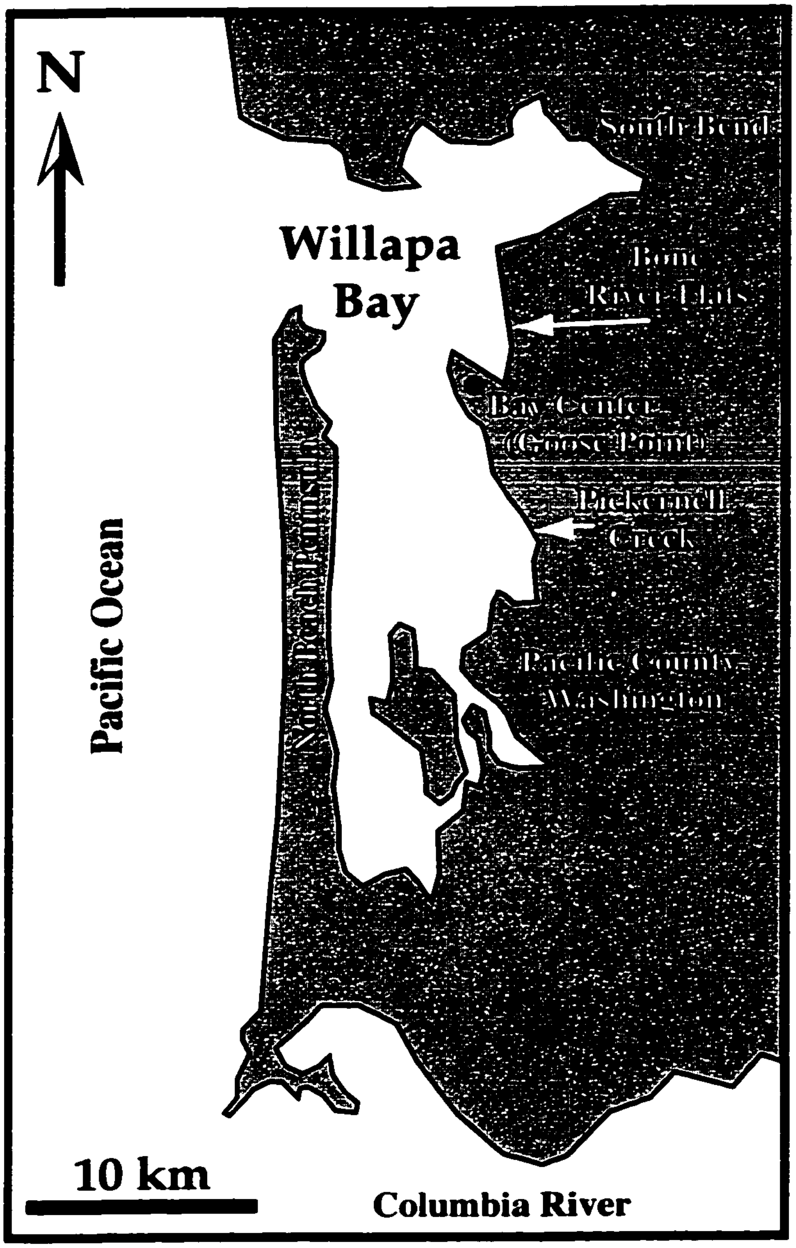

FIGURE 5.1 - Map of Willapa Bay, Washington.

The data presented in this study was primarily collected from the extensive sand- and mud-flats adjacent to the Bone River and Goose Point (Fig. 5.1). At these locations the intertidal flats are easily accessed from Highway 101, and they afford many excellent exposures of modern intertidal creek deposits.

Methods

Detailed descriptions of modern intertidal-creek and -flat deposits were compiled from different datasets. These include manual trenching, box coring, and tube coring. Several resin casts of modern traces were also poured to aid in the interpretation of the biogenic structures.

The firmness test methodology was derived from the standard Brinell hardness test, a metallurgical technique (Brinell, 1900). The modified Brinell firmness test is simple, and the procedure provides consistent results. These characteristics are particularly well suited to the collection of field data.

Firmness tests were taken from cylindrical cores extracted from the intertidal-flat, cut-bank, channel, and point-bar subenvironments. The core was subsequently split, and the center, least-disturbed sediment, was firmness-tested. In an effort to extract core from greater depths, small holes were dug and coring commenced from the bottom of the hole. In such cases the upper 10-20 cm of the core were not considered in the firmness testing.

RESULTS

Intertidal Creek Deposits

Extensive networks of meandering intertidal creeks commonly dissect the modern intertidal flats. This is particularly true of substrates with high mud content. Point-bar deposits, channel lags, and cut-bank exposures are associated with these channels. Modern intertidal point-bars at Willapa Bay are typically burrowed by an extremely low-diversity assemblage of diminutive infauna. Threadworms, such as the capitellid polychaete *Heteromastus*, are among the most common burrowers in this environment. *Heteromastus* burrows consist of small diameter, vertical shafts 10 to 30 cm deep, with numerous horizontal branches. Although the overall trace geometry is *Skolithos*- or *Trichichnus*-like, the termini of the main vertical shaft and many of the branches are commonly demarcated by *Gyrolithes*-like coils. Other trace-makers present in intertidal point-bars include: *Neries*, a polychaete that produces *Palaeophycus*- and *Planolites*-like burrows; the small amphipod *Corophium*, which makes *Diplocraterion*-like traces; and juvenile bivalves whose siphonate trace most resembles *Skolithos*, *Siphonites*, or fugichnia. This assemblage grades with the intertidal flat suite over 2 m on smaller point-bars and up to 8 m on larger point bars. Open burrows present in the point-bar- and intertidal flat-deposits have small diameters, and are generally mucous- or mud-lined. Unlined traces collapse following the passage of the trace maker. Several large diameter (>7 mm) shafts are present in the intertidal flat deposits. These are normally thickly lined, as with the *Rosselia*-like burrows of terebellid polychaetes, or are constantly re-excavated or reamed, such as those traces produced by large bivalves (such as *Tresus nuttallii*). In both intertidal flat and point-bar deposits, no large, open, unlined burrows are present; a *Glossifungites*-like ichnocoenosis is therefore not developed in these accumulations.

Deposition in the channel is restricted to a 5 to 10 cm thick shell lag overlying a sharp, erosional contact. Very few burrowers are present below the shelly accumulation, except rare numbers of *Neries*, *Nephtys*, and *Heteromastus*. Although the substrate at the channel base is relatively consolidated, no large burrows that might constitute a *Glossifungites* assemblage are present. Shifting of the channel lag may preclude the construction of such semi-permanent domiciles.

The cut-banks along the intertidal creeks at the Bone River location expose intertidal flat lamination, point-bar stratification, basal channel scours, and channel lag deposits (Fig. 5.2). Drainage along the cut-banks is enhanced and the partially dewatered substrate supports large, unlined, open, *Psilonichnus*-like burrows of the crab *Hemigrapsus oregonensis*. This ichnocoenosis is of a limited extent and is confined to the exposed portions of the cut-bank and the adjacent intertidal flat. It displays, however, all the salient characteristics of a *Glossifungites* assemblage.

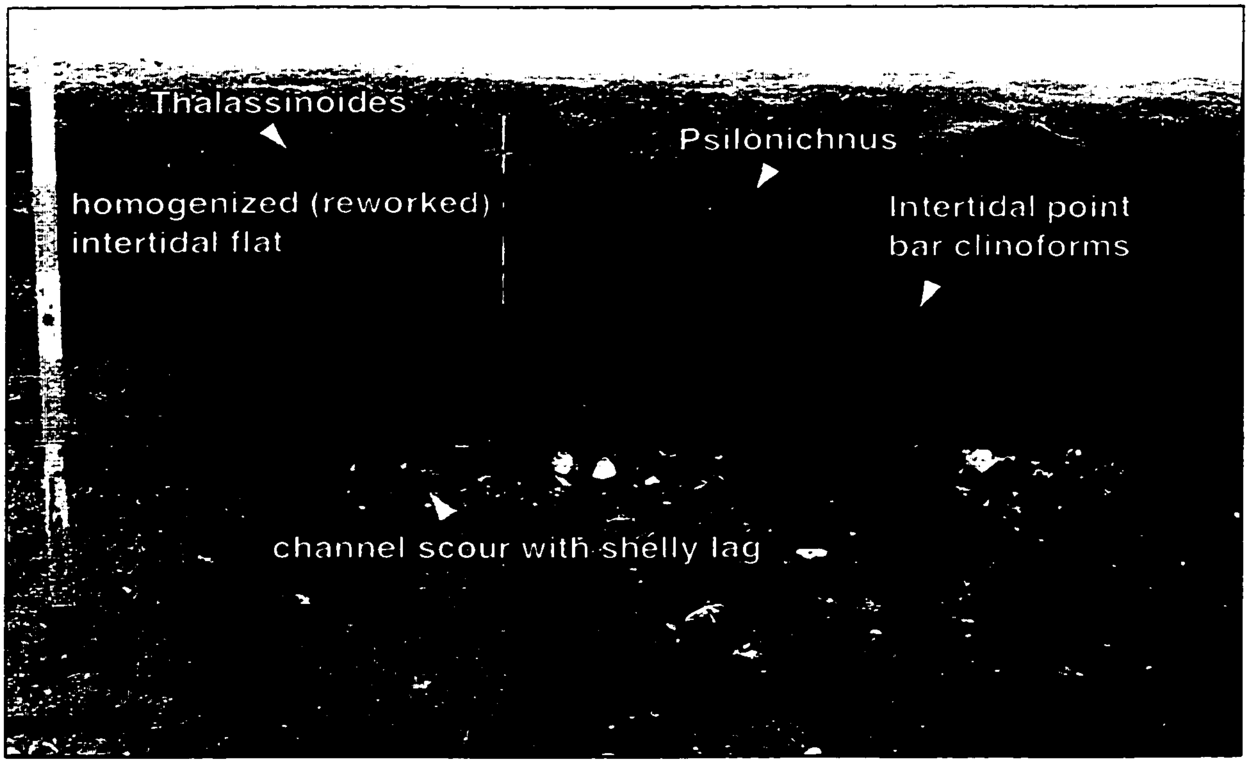

FIGURE 5.2 - A cut-bank exposure associated with an intertidal runoff creek. In this section a channel scour overlain by laminated point-bar deposits is visible. The poorly bedded sediment results from bioturbation associated with the intertidal flat deposit; facies characteristic of intertidal deposits normally prograde over intertidal point-bar accumulations. The *Psilonichnus-* and *Thalassinoides*-like traces are related to colonization of the dewatered cut-bank, as opposed to the intertidal flat depositional environment. Scale bar to left shows 10 cm divisions.

The firmness measurements associated with the intertidal creek depositional environment range from approximately 8 kpa to 178 kpa (Fig. 5.3, 5.4). The contoured firmness profile (Fig. 5.3) shows that zones of relative firmness persist along the intertidal cut-bank and the channel base. Streaks of comparatively soft substrate approximately follow the clinoform geometry of the point-bar. The maximum firmness (178 kpa) is typically intersected almost 2.4 m below the mean intertidal flat elevation. This horizon, though only intersected in 4 of the 9 cores due to the sampling constraints, is presumably present throughout the study site. Some anomalous soft zones are present in the intertidal deposits adjacent to the cut-bank (Fig. 5.3), possibly the result of uneven

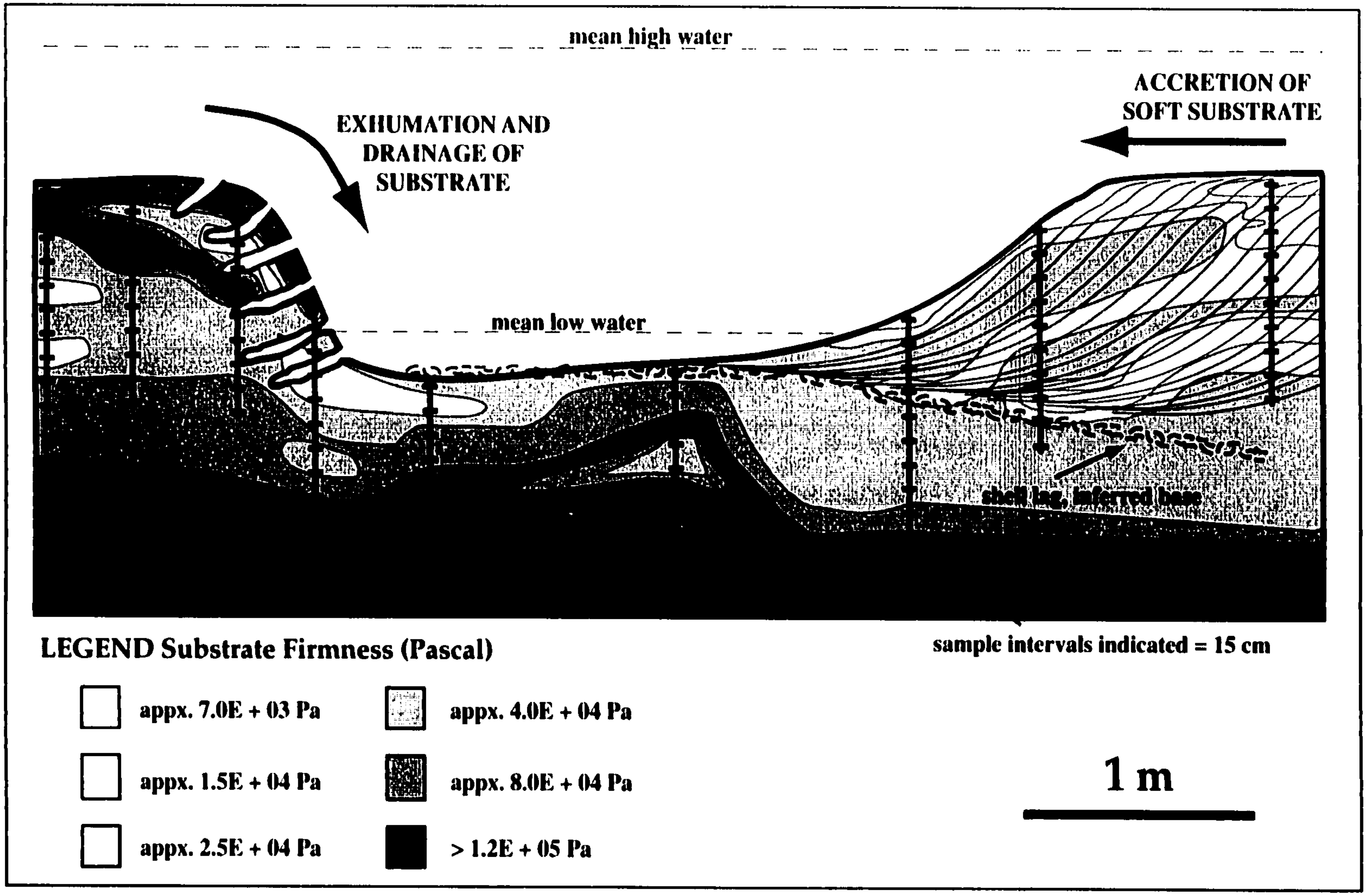

FIGURE 5.3 - Schematic cross section of firmness profiles from an intertidal runoff creek at Willapa Bay. Notable features of this diagram include the following: a strong correlation between the subenvironments (intertidal flat, point-bar, channel, and cut-bank) and cohesiveness of the substrate; marked heterogeneity of firmness profiles, and; the presence of a *Glossifungites* ichnocoenose in the area of the cut-bank.

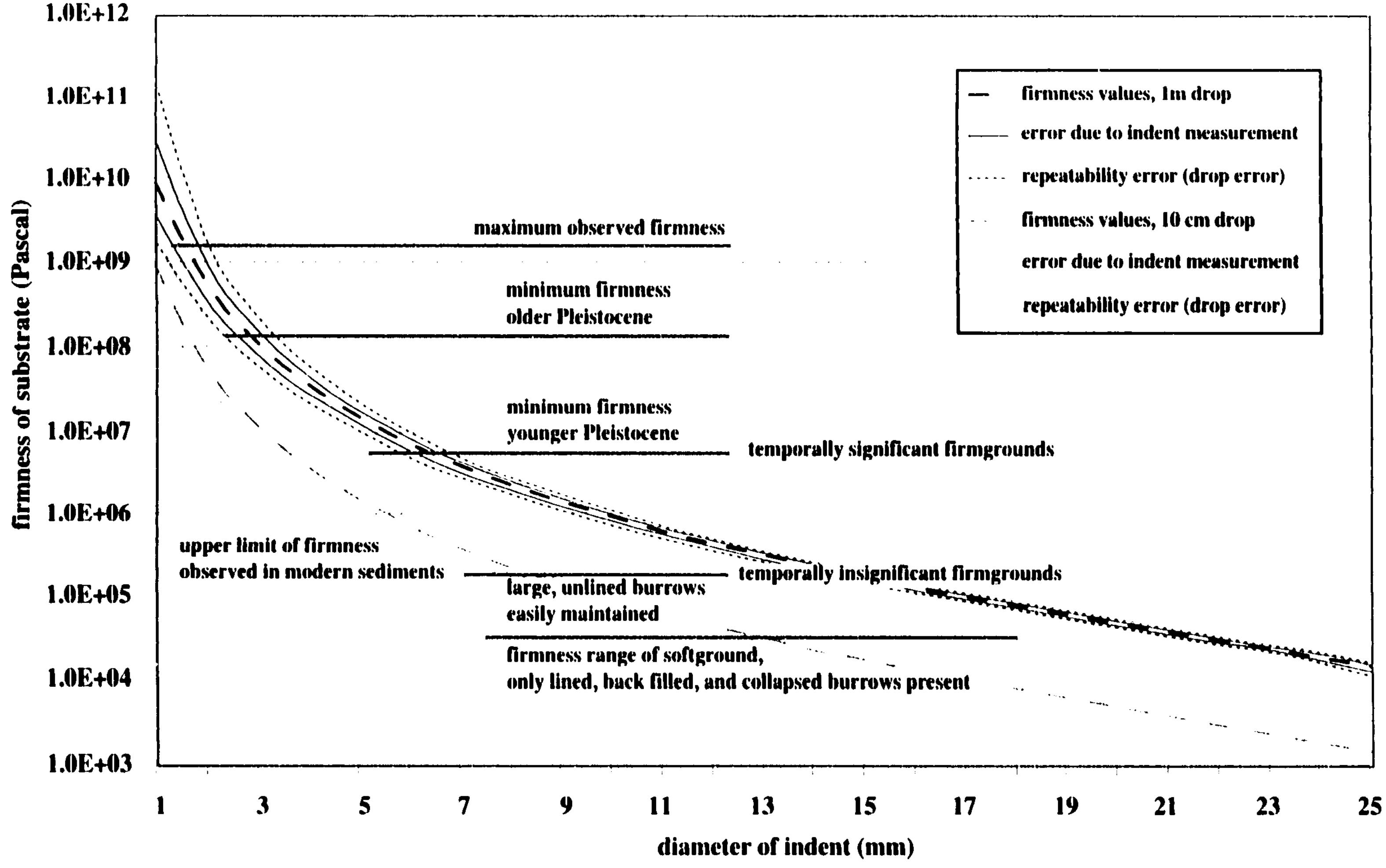

FIGURE 5.4 - Graph of the pressure exerted by the substrate vs. the diameter of the indentation made during the firmness test. The upper (gray) curve estimates the pressure produced by an indenter based on a 1m free fall, the lower curve indicates pressure values produced from a 10cm drop. Error margins are indicated by the thinner lines. Values for exhumed Pleistocene substrates generally exceed 10^7 Pa; *Glossifungites* burrows into modern sediments can be maintained where the substrate cohesiveness is greater than 6 X 10^4 Pa. Firmness values between 10^5 and 10^7 Pa are not recorded at Willapa Bay. They represent the temporally significant gap for sediments that are not dessicated. Modified from Figure 4.2.

drainage. Otherwise, the contoured data is remarkably consistent with the depositional architecture of this subenvironment. The firmness measurements can also be compared favorably to the empirical observations outlined in the previous section.

Wave-Eroded **Glossifungites**-*Demarcated Discontinuities*

Along the eastern margin of Willapa Bay, exhumed firmground is generally present from Goose Point to Pickernell Creek (Fig. 5.1). Unlike the firm substrates associated with the cutbanks of intertidal creeks, the wave-eroded sediments are composed of Pleistocene mud. These muds are comparatively firmer than any modern firm substrates observed, as they are commonly firmer than 10^7 Pa and locally exceed 10^9 Pa. The maximum firmness of modern sediments is about 10^5 Pa. Although the range of firmness values spans several orders of magnitude, the firmness is largely substrate-specific. They are contingent on the texture of the sediment, and the age of the Pleistocene deposit. Older Pleistocene strata, which have not been reliably dated, exhibits firmness values on the order of 10^8 to 10^9 Pa (Table 5.1; Fig. 5.4). Younger Pleistocene strata was deposited approximately 100 000 bp (Kvenvolden et al., 1979), and its firmness is generally closer to 10^7 Pa (Table 5.1, Fig. 5.4).

Locally, the firmness profiles are remarkably homogeneous. Indent diameters in fresh surfaces of the compacted Pleistocene sediment generally vary within 0.5 mm . In fact, measurements taken within texturally similar deposits of similar age show little variability overall.

In the lower intertidal zone, relatively softer Pleistocene muds are generally colonized by the burrowing mud shrimp, *Upogebia pugettensis*. Their traces are decidedly *Thallasinoides*-like (Fig. 5.5), and the burrow density can be notably high (commonly exceeding 100 individuals/m^2). In the upper intertidal, *Polydora* is the dominant burrower (Fig. 5.5). These small spionid worms reside in diminutive *Diplocraterion*-like structures and are present in very high population densities (up to 300 individuals/100

Pleistocene Substrates Substrate Type	indent avg. (mm)	firmness (Pa)
Young Pl mud a	6	9.0 e +06
Young Pl mud a (burrowed)	11.5	6.0 e +05
Young Pl mud b	7	7.0e +06
Young Pl mud c	5.2	1.5e +07
Young Pl mud d	5.5	1.0e +07
Young Pl mud e	6.8	6.0e +06
Old Pl mud a	2.8	2.0e +08
Old Pl mud b	3.1	1.0 e +08
Old Pl mud c	2.2	7.0e +08
Old Pl mud c (burrowed)	2.3	6.0e +08
Old Pl sandy mud c	1.9	1.0e +09

TABLE 5.1 - Summary of firmness data for exhumed Pleistocene mud. Indent averages are based on a minimum of 5 drop tests. Maximum deviation from the mean is 0.5 mm, however most measurements fall between +/- 0.25 mm from the mean.

cm^2). Where the *Polydora* burrow density is extreme, the exposed firmground is softer (≈ 10^5 Pa; Table 5.1). This is thought to be due to mechanical weakening of the burrowed sediment. Bioturbation related to the mud shrimp does not lower the firmness of the substrate at the scale measured.

Older, firmer Pleistocene substrates are generally not burrowed by crustaceans. In the middle intertidal zone, the bivalve *Petricola pholadiformis* is the dominant tracemaker (Fig. 5.5). Their traces have a clavate shape and are most similar to the hardground trace fossil, *Gastrochaenolites*. *Polydora* dominantly colonizes the upper intertidal, generally in lower population densities than with the younger Pleistocene substrates (0 to 70 individuals/100cm^2). Encrusting anenomes and barnacles are also common in this zone.

Little relief has been observed on exhumed Pleistocene firmgrounds. They are generally planar to the sea cliff edge, where they abruptly and smoothly ramp upwards (Fig. 5.5). Topography on these surfaces most commonly results from the weathering of stratification or wood clasts.

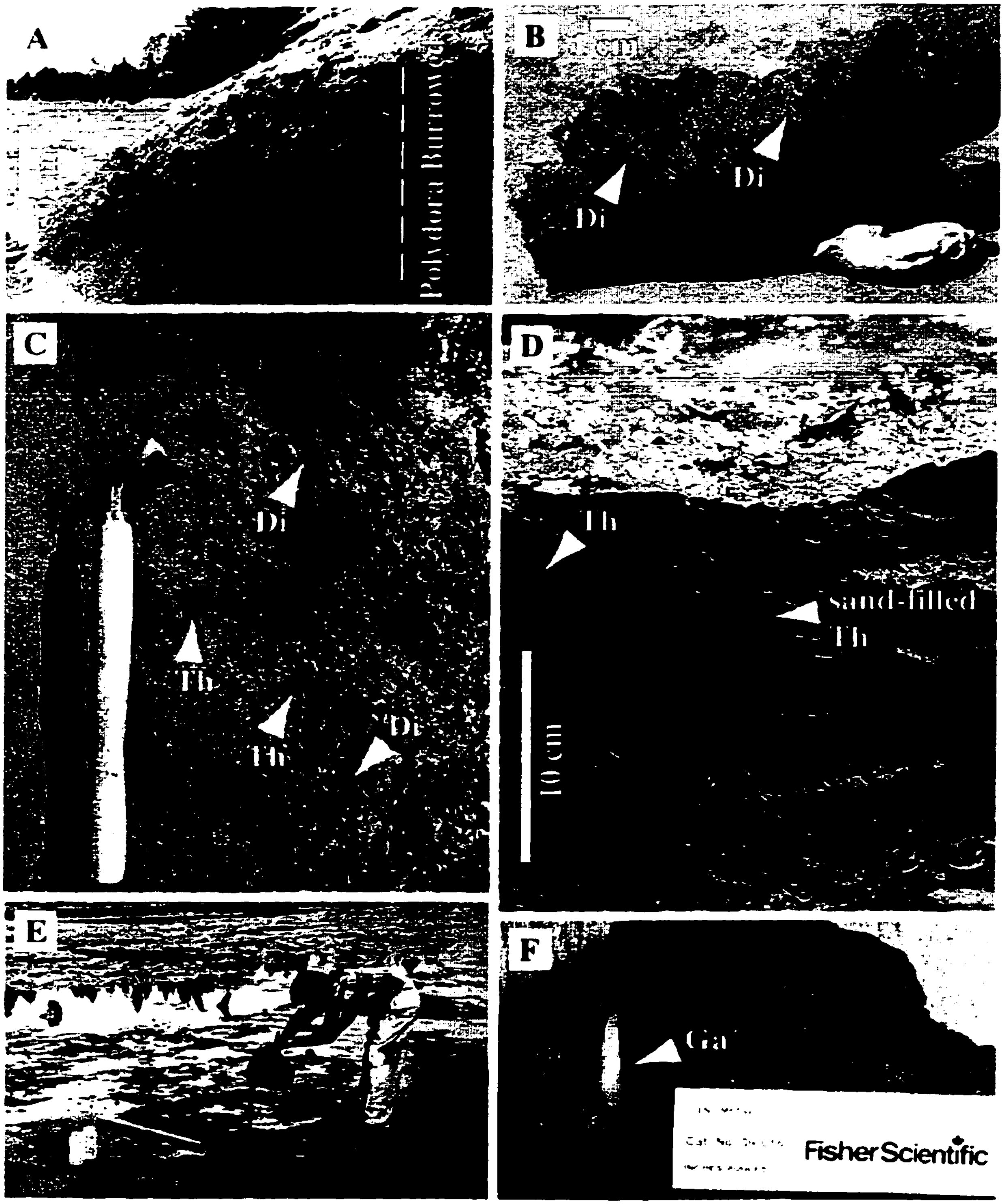

FIGURE 5.5 - A) Younger Pleistocene firmground that is intensely burrowed by *Polydora*. B) A sectional view of the small *Diplocraterion*-like burrows (Di) that are constructed by *Polydora*. In this case, the causative burrows are filled with fine sand, and the spreite are not apparent due to the scale of the photograph. C) Large diameter *Thalassinoides* (Th) excavated in firmground by *Upogebia*. Plan view of the burrows of *Polydora* (indicated by Di) are also apparent. --->

(cont.) D) Sectional view of the *Thalassinoides*-like trace shown in 5C. The primarily vertical shaft is sand-filled. E) A *Petricola*-dominated firmground in the middle intertidal zone. Note the extremely low relief of this surface. F) Clavate, *Gastrochaenolites*-like burrow of *Petricola pholadiformis*.

Traces observed in these substrates are unlined or very thinly lined. Sculptings are generally exquisitely detailed and have a high preservation potential. Several burrows were revisited over three seasons and were essentially unchanged from previous years. The sediment shows no sign of relaxation and collapse. All observations in the modern suggest that these burrows would pass into the geological record with essentially no taphonomic disturbance.

DISCUSSION

Animal / Sediment Relationships

Empirical observations of burrow architecture and substrate consistency across the intertidal creek closely match the data collected using the modified Brinell firmness tests (Chapter 4). Sediments on the point-bar and transitional intertidal flat are relatively soft (approximately 7 to 15 kpa; Fig. 5.3). Here the only open traces present include small- to moderate-sized, mucous lined shafts and burrows. In the intertidal flat, some larger burrows, such as those of terebellid polychaetes, are present; these require a cohesive, thickened lining to remain open in the relatively soft substrate. Other large-diameter burrows, such as those excavated by robust bivalves, require regular reaming to maintain an open conduit to the sediment-water interface.

Point-bar deposits represent the 'softest' accumulations of sediment from the substrates tested. High sedimentation rates, which are characteristic of point bar deposits, may promote elevated pore water content. Abundant bioturbators, such as *Heteromastus*, contribute to the overall soft consistency of this depositional subenvironment. Intertidal flat deposits are characterized by lower sedimentation rates than adjacent point-bar accumulations. Their softness, however, is greatly enhanced by abundant burrowing fauna which significantly increase the pore water content of the substrate (Cadée, 1998).

Those most familiar with intertidal flats have probably noted that the cut-banks adjacent to intertidal creeks proffer the easiest *wadlopen* (following the Dutch enthusiasm for mud-walking). This is reflected in the firmness measurements collected from the channel and cut-bank. Measurements within the channel are typically between 50 and 65 kPa (Fig. 5.3). Firmness assessments from the cut-bank are similar, although they locally approach 89 kPa (Fig. 5.3). Large, open burrows that would have the taphonomic characteristics of the *Glossifungites* ichnofacies are present where the firmness exceeds 50 to 60 kPa. Although the channel base appears firm enough to support similar, unlined burrows, very few traces are present. This may be due to a shifting detrital veneer on the exhumed substrate that precludes the construction of semi-permanent domiciles. Another explanation is that the shelly channel lag acts as a barrier to larger burrowing organisms.

The firmness profiles derived in and around the intertidal creek indicate that patterns of deposition and drainage associated with the intertidal creek strongly control the firmness of the associated substrates. Along the cut-bank, where the best drainage is afforded, the substrate is significantly firmer. Reduced pore pressure in the area of the cut-bank is accentuated as the cut-bank is virtually devoid of bioturbating infauna. The absence of these organisms is the result of higher current energy removing resuspendable, nutrient-rich surface detritus (Whitehouse and Michener, 1998), as well as enhanced drainage of the substrate. Ultimately, the paucity of effective bioturbators precludes the introduction of additional pore water into the substrate.

The patchy distribution of infauna is strongly controlled by the firmness of the substrate, and the rate of sedimentation or erosion (Bromley, 1996; Cadée, 1998). Cut-bank, channel, point-bar, and intertidal flat each exhibit strikingly different trace assemblages: the cut-bank is characterized by *Psilonichnus*- and *Skolithos*-like burrows; point bar deposits commonly contain small *Gyrolithes-*, *Planolites-*, *Palaeophycus-*, *Arenicolites-*, and *Skolithos*-like traces; and, intertidal flat accumulations are distinguished by larger diameter *Thalassinoides-*, *Rosselia-*, *Planolites-*, *Palaeophycus-*, *Arenicolites-*, and *Skolithos*-like architectures. Channel deposits are essentially unburrowed. These distribution patterns demonstrate the dependence of bioturbate texture on certain sedimentological parameters (cohesiveness and sediment agradation rate, in this case).

Far from being homogeneously distributed, firm 'patches' are sporadically present in vertical profile (Fig. 5.3). In deposits passing from the modern to historical record this heterogeneity is pronounced. Hydraulic erosion of the modern deposits at Willapa Bay therefore produces notable decimeter-scale topography (Fig. 5.6). In contrast, older deposits, such as the Pleistocene mud exposed at Willapa Bay, have strikingly

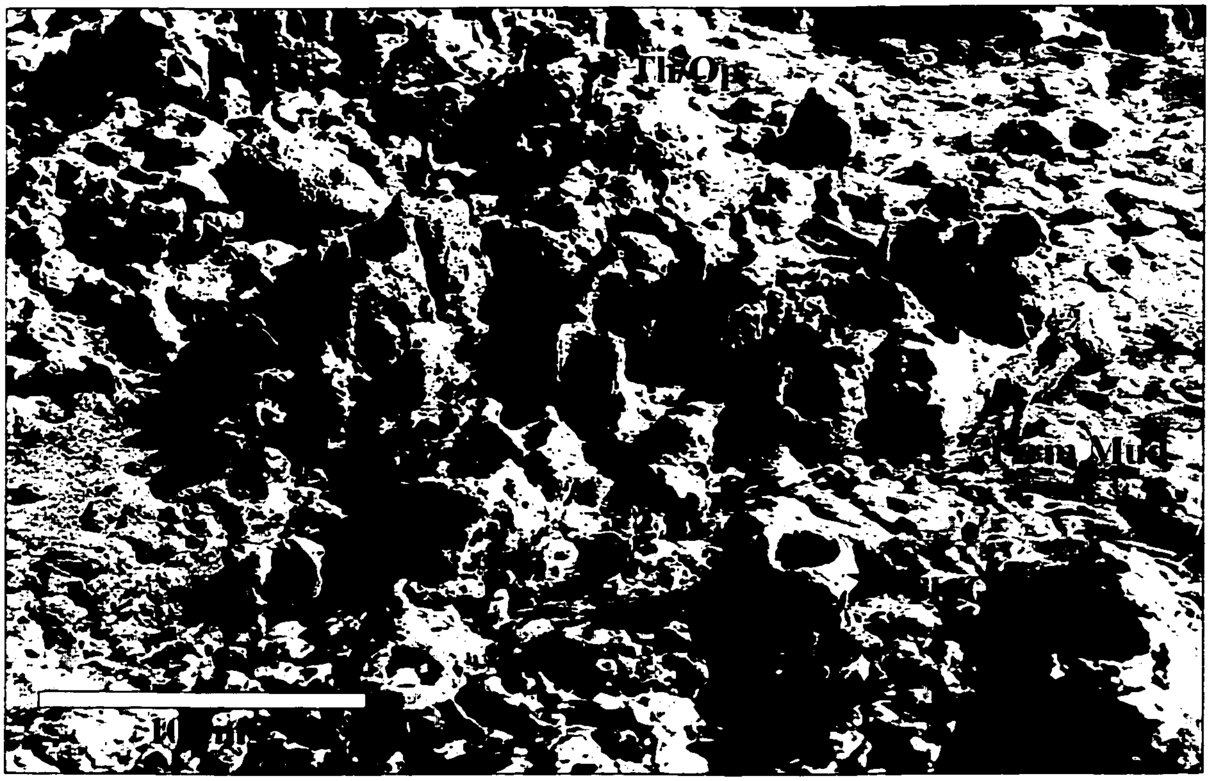

FIGURE 5.6 - Undulatory topography in a burrowed, exhumed, muddy interbed. The mud is recent and has a firmness of approximately 10^5 Pa.

homogeneous firmness profiles. At the bay, wave erosion of Pleistocene muds typically produces a planar surface (Fig. 5.5F). Homogeneity of firmness may be the best indicator of burial and compaction. Substrate that is subjected to drainage or desiccation tends to dewater in an uneven manner. Undulatory (decimeter-scale) *Glossifungites* surfaces are therefore best attributed to minor erosive surfaces; planar to undulatory (meter-scale) horizons are more indicative of longer burial histories and significant erosion.

STRATIGRAPHIC SIGNIFICANCE

The *Glossifungites* ichnofacies is increasingly recognized as being indicative of diastems or surfaces that may have stratigraphic significance in the rock record (Pemberton and Frey, 1985; MacEachern et al., 1992). Although there is general agreement regarding how these surfaces form, the depth of burial required to compact the sediment enough to produce a firmground is uncertain. In fact, the depth required varies with sediment texture, the initial pore water content, the sedimentation rate, and the length of time that the substrate was buried (Fig. 5.7).

Consider, for example, the contrasting permeabilities of muddy versus sandy deposits. The permeability range of muddy substrates at Willapa Bay falls between 10^{-7} and 10^{-4} cm/sec (measured with a standard Darcy laboratory experiment). Sandy substrates, on the other hand, generally measure between 10^{-2} and 10^{-1} cm/sec. The permeability contrast, then, is between 2 and 8 orders of magnitude. Darcy's Law dictates that the volumetric flow rate is directly proportional to the permeability of the matrix. Potentially, the dewatering of muddy substrates takes *2 to 8 orders of magnitude longer* than sandy examples (Fig. 5.7B). Surf-pounded beaches, which are typically cohesive enough to support the weight of an automobile, provide an excellent example of how quickly firm substrates can be developed in sandy deposits. Conversely, well-indurated muds, such as the Pleistocene muds at Willapa Bay, (e.g., exceeding 10^{7} Pa; Fig. 5.4) probably take centuries or millennia to compact and dewater. This temporal

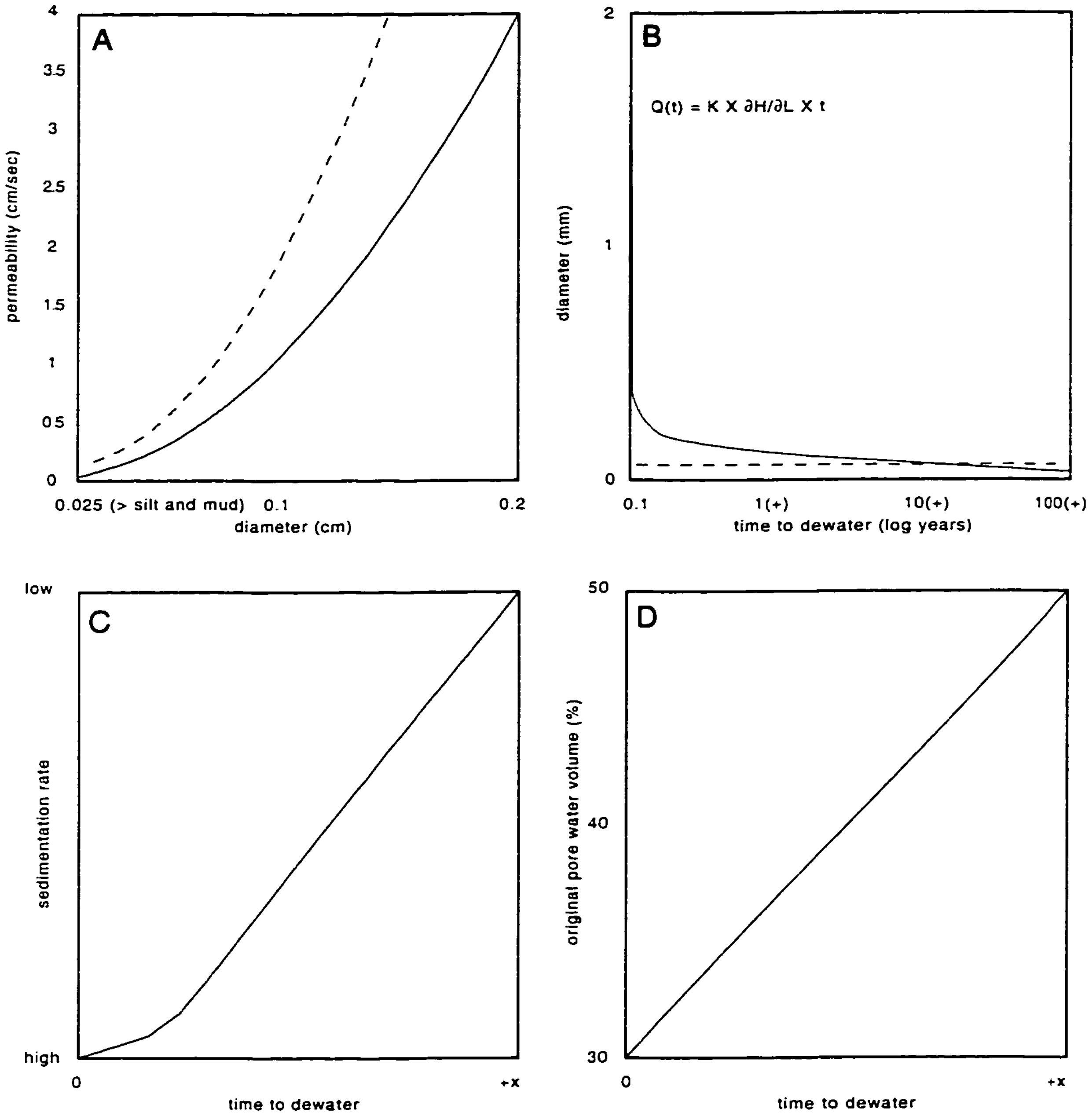

FIGURE 5.7 - Graphs illustrating the relationship between effective grain size, sedimentation rate, initial pore water volume, and the time required to dewater a substrate. A) Permeability versus effective grain size. Permeability was calculated using Hazen's method (Hazen, 1911) for sand and was estimated from charts for silt and mud. The dashed line approximates the potential error due to initial compaction (from Tokunaga et al, 1994). Note that this relationship is logarithmic. B) Time to dewater the substrate based on a fixed compactional drainage with a hydraulic gradient of 0.001 m/m. The formula used to generate the curve is inset into the graph and is based on an initial pore water volume of 50% and permeability from Figure 5.6A. The dashed line shows upper silt grain size. --->

(cont.) Although there is a great deal of error intrinsic to this graph it adequately demonstrates the profound variance in the dewatering times of sands and muds. C)The sedimentation rate forms an almost linear relationship with dewater time and is therefore a subordinate consideration to grain size. D) The original pore water volume develops a linear relationship with compaction time as well, although it may strongly increase the initial permeability (Dewherst and Aplin, 1998).

scale is consistent with the observations of Pemberton and Frey (1985) at St. Catherine's Island, where the exposed firmground was dated to 1500 bp.

The results of this study show that sandy mud is firm enough to preserve open burrows with surface sculptings where the firmnesses exceeds approximately 80,000 Pa. Although these traces are characteristic of *Glossifungites* assemblages, the plasticity of the substrate suggests these traces are subject to some compaction following burial. Exhumed Pleistocene mud is comparatively firm. Because these substrates were previously dewatered and compacted, they are subject to far less compaction upon passage into the historical record. Excellently preserved sculptings, and undeformed burrow architectures are strongly indicative of burrows that were excavated in completely dewatered and compacted sediment. It should be noted that dessicated substrates may also be firm to hard. In such sediments, sedimentological evidence, such as the presence of desiccation cracks and salt casts, must serve to differentiate subareally-exposed sediments from those that were exhumed. Also, sediments that are prone to subareal exposure are commonly inhospitable to softground burrowers. A palimpsest suite of trace fossils is therefore not expected in dessicated substrates.

Although this study demonstrates many of the mechanisms associated with the development of *Glossifungites* assemblages, it does not directly address the problem of generating a widespread *Glossifungites*-demarcated surface. The cutbank is areally restricted and has a low preservation potential. For these reasons it is unlikely that a cutbank-associated suite of traces could produce a mappable *Glossifungites* surface. The firmest substrate observed at the Bone River location, however, is present 2 to 2.5 m below the surface of the intertidal flat (Fig. 5.3). At this depth, the firmness exceeds 120 000 Pa. Therefore, erosion to a depth of 2 m would be required to produce a mappable *Glossifungites* surface. This could be accomplished either by rapid tidal creek migration, or by wave ravinement, possibly in conjunction with base level change. Burrows into this surface would be susceptible to post-depositional compaction and therefore discernible from those emplaced in Pleistocene deposits. At the bay, mappable *Glossifungites* surfaces typically occur in Pleistocene strata that has been exposed by intertidal wave erosion. These include many examples of uncompacted (temporally significant) *Glossifungites* assemblages that are present in the Pleistocene sediment. Common burrows in these deposits include *Thalassinoides-*, *Skolithos-*, *Diplocraterion-*, and *Arenicolites*-like traces. In less cohesive deposits, such as on intertidal cut-banks, *Psilonichnus-* and *Skolithos*-like burrows are most common.

In summary, not all *Glossifungites* demarcated discontinuities represent significant omission surfaces. This observation is well documented by previous researchers (Pemberton and Frey, 1985; MacEachern et al., 1992; Pemberton and MacEachern, 1995). Undeformed trace fossil assemblages that descend into compacted, muddy substrates are more likely to be temporally significant and probably represent century- to millennia-scale burial histories. Somewhat deformed *Glossifungites* assemblages more likely denote decade- to century-scale histories. Sandy firmgrounds, on the other hand, have indeterminant temporal significance. As noted earlier, undulatory (decimeter-scale) *Glossifungites* surfaces are most commonly associated with minor erosion, whereas planar to gently undulatory horizons are suggestive of long burial histories and significant erosion. This conclusion is evidenced in the modern deposits at Willapa Bay, and is due to homogeneity of firmness profiles following prolonged sediment compaction.

Glossifungites-demarcated discontinuities must be laterally extensive and mappable if they are to provide improved stratigraphic resolution. At Willapa Bay, a 2 m lowering of base level would be required to expose mudflat deposits firm enough to develop a mappable *Glossifungites* surface. This surface would probably be subject to post-depositional compaction and be characteristically undulatory and, by the criteria outlined in this paper, not temporally significant. More indurated firmgrounds consist of exhumed Pleistocene muds. These exhumed deposits form more or less planar surfaces, and can be mapped for several kilometers along the bay's eastern margins. The temporal significance of the depositional hiatus represented by these surfaces, spans at least 100 000 years (Kvenvolden, et al., 1979), and is the result of large fluctuations of relative sea level (Dupre et al., 1991).

CONCLUSIONS

Firmness measurements derived from the modified Brinell hardness test provide profiles that are consistent with empirical observations along the tidal creek. As a simple field method it provides the opportunity to compare other occurrences of modern *Glossifungites* surfaces. The firmness profile associated with the tidal creek deposit strongly correlates with changes in burrowing behavior. Dewatered substrates adjacent to the cutbank are most commonly occupied by crustaceans, in this case *Hemigrapsus oregonensis*. Burrowing worms are generally rare, although small *Heteromastus* and spionids successfully colonize this zone. Soft substrates along the point-bar typically contain a low-diversity assemblage of burrowing worms, whereas the soft- to intermediate-substrates of the intertidal flat support diverse assemblages of polychaetes, crustaceans, and bivalves. The resulting ichnofacies are quite distinctive and variable. The cut-bank is characterized by *Psilonichnus*- and *Skolithos*-like burrows. Point-bar deposits contain small *Gyrolithes-*, *Planolites-*, *Palaeophycus-*, *Arenicolites-*, and *Skolithos*-like traces. The intertidal flat contains *Thalassinoides-*, *Rosselia-*, *Planolites-*, *Palaeophycus-*, *Arenicolites-*, and *Skolithos*-like architectures. Complex and predictable lateral relationships underscore the dependency of bioturbate texture on substrate consistency.

Although the stratigraphic significance of *Glossifungites* surfaces is well recognized, their dependence on physical parameters such as grain size, initial pore water content, and sedimentation rates have yet to be reviewed in the geological literature. The temporal significance of such surfaces is therefore unknown. Lower permeabilities in mud *versus* sand suggest that muddy substrates take much longer to dewater and are therefore indicative of more significant erosional events. Criteria such as the degree of compaction of *Glossifungites* ichnogenera, the type of ichnofossils preserved, and the scale of topographic relief on the erosive surface, can help discern the relative importance of firmground assemblages. These observations are evidenced in the modern deposits. Exhumed Pleistocene deposits are generally planar. Modern *Glossifungites* assemblages in these substrates are undeformed and have excellent sculptings preserved (Fig. 5.5). Exhumed, modern, substrates exhibit decimeter-scale topography (Fig. 5.6) and contain burrows that relax if not maintained. This primarily results from a relative patchiness of firmness profiles and an overall difference in the plasticity of modern *verses* Pleistocene substrates.

Temporally insignificant *Glossifungites*-demarcated discontinuities (in muddy substrates) are indicative of at least 2 m of erosion, if the substrate is not prone to widespread desiccation. At the bay, more significant surfaces consist of exhumed Pleistocene mud that represent a depositional hiatus of at least 100 000 years and are the result of large changes of relative sea level (Dupre et al., 1991).

A much larger database will be required to adequately assess the significance of *Glossifungites*-demarcated discontinuities. Data collection should focus on the nature of bioturbation, age relationships, burial histories, and firmness tests. The most valuable information might still be derived from locations in the modern where these deposits are being colonized.

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CHAPTER 6: THE PALEOECOLOGICAL SIGNIFICANCE OF *GLOSSIFUNGITES* SURFACES AT WILLAPA BAY, WASHINGTON[1]

INTRODUCTION

Applying ichnology to the rock record generally focuses on using trace fossils to approximate the physico-chemical parameters at the time of sediment deposition. These variables include fluctuating or suppressed salinity, low oxygenation, variable sedimentation rates, and turbidity stresses. In general, trace-makers are sensitive to these aforementioned parameters. Furthermore, it has been shown that epifaunal and infaunal organisms modify their behavior to cope with environmental stresses. These behavioral modifications are commonly evident in the preserved trace fossil assemblage observed in the rock record. Salinity fluctuations and suppressed salinity, for example, have been linked to a lowering of diversity, trophic generalization, and dimunition in trace fossil assemblages (Howard and Frey, 1973; Pemberton et al., 1982). Also, lowered oxygen levels are commonly associated with *Chondrites*- and *Zoophycos*-dominated ichnofacies (Ekdale and Mason, 1988; Savrda and Bottjer, 1987).

Trace fossils have been utilized to resolve stratigraphic problems as well. Seilacher (1970) and Crimes (1969) demonstrated that certain lebenspurren, notably several ichnospecies of *Cruziana*, were temporally restricted and could therefore be used in biostratigraphic applications. However, ichnofossil stratigraphy is not commonly utilized as several trace fossil forms span significant amounts of geological time.

More recently, substrate-specific trace fossil assemblages have been used to identify genetically significant surfaces. Substrate-specific assemblages include the *Trypanites*, *Teredolites*, and *Glossifungites* ichnofacies. *Trypanites* assemblages are specific to cemented substrates, or hardgrounds. Fürsich et al. (1982), working in the Jurassic of west India, considered hardgrounds (and nodular lags) to be indicative of reduced sedimentation, erosion, and early cementation in carbonate substrates. Although bored

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[1] A version of this chapter has been submitted for review by Palaeogeography, Palaeoclimatology, and Palaeoecology as "The Palaeoecological Significance of *Glossifungites* Assemblages at Willapa Bay, Washington", by Murray K. Gingras, S. George Pemberton, Tom Saunders, and H. Edward Clifton.

and encrusted hardgrounds are most characteristic of carbonate deposits (Bromley, 1996), trace assemblages are locally observed in cemented siliciclastic rocks as well. The *Teredolites* ichnofacies refers to colonized wood substrates. These include peat-grounds (Bromley et al., 1984) and log-grounds (Savrda et al., 1993), both of which have been linked to transgressive deposits (Bromley et al., 1984; Savrda et al., 1993). However, this paper focuses on the *Glossifungites* ichnofacies, which consists of burrows that were emplaced in firm (compacted) substrates. Generating a compacted substrate generally requires that sediment be buried and dewatered. Subsequent erosion is required to expose a firmground to its burrowing tenants. Arealy significant *Glossifungites* surfaces are therefore associated with widespread erosion and have been repeatedly linked to base level change in marginal marine environments (Pemberton and Frey, 1985; MacEachern et al. 1992; Pemberton et al., 1992; Pemberton and MacEachern, 1995).

Seilacher (1964) defined the *Glossifungites* ichnofacies as a primarily littoral assemblage of trace fossils emplaced in cohesive, non-shifting, substrates. Later, Frey and Seilacher (1980) restricted the *Glossifungites* ichnofacies to firmgrounds in marine environments. Modern *Glossifungites* assemblages have been observed in association with wave ravinement, and channel erosion in intertidal deposits (Pemberton and Frey, 1985). These observations have emphasized the link between ichnology and genetically significant surfaces.

Trace fossils present in *Glossifungites* assemblages are characterized by several diagnostic criteria, these include: sharp walls that are generally unlined; cross-cutting of the palimpsest trace fossil assemblage; burrow infill that consists of sediment that is texturally distinct from that which comprises the firmground, the infilling sediment is commonly identical to the sediment present in the overlaying package; the presence of simple burrow architectures, such as *Skolithos*, *Thalassinoides*, *Diplocraterion*, and *Rhizocorallium* (Fig. 6.1); relatively high burrow densities; and, the presence of scratch marks in the burrow walls (Fig. 6.1).

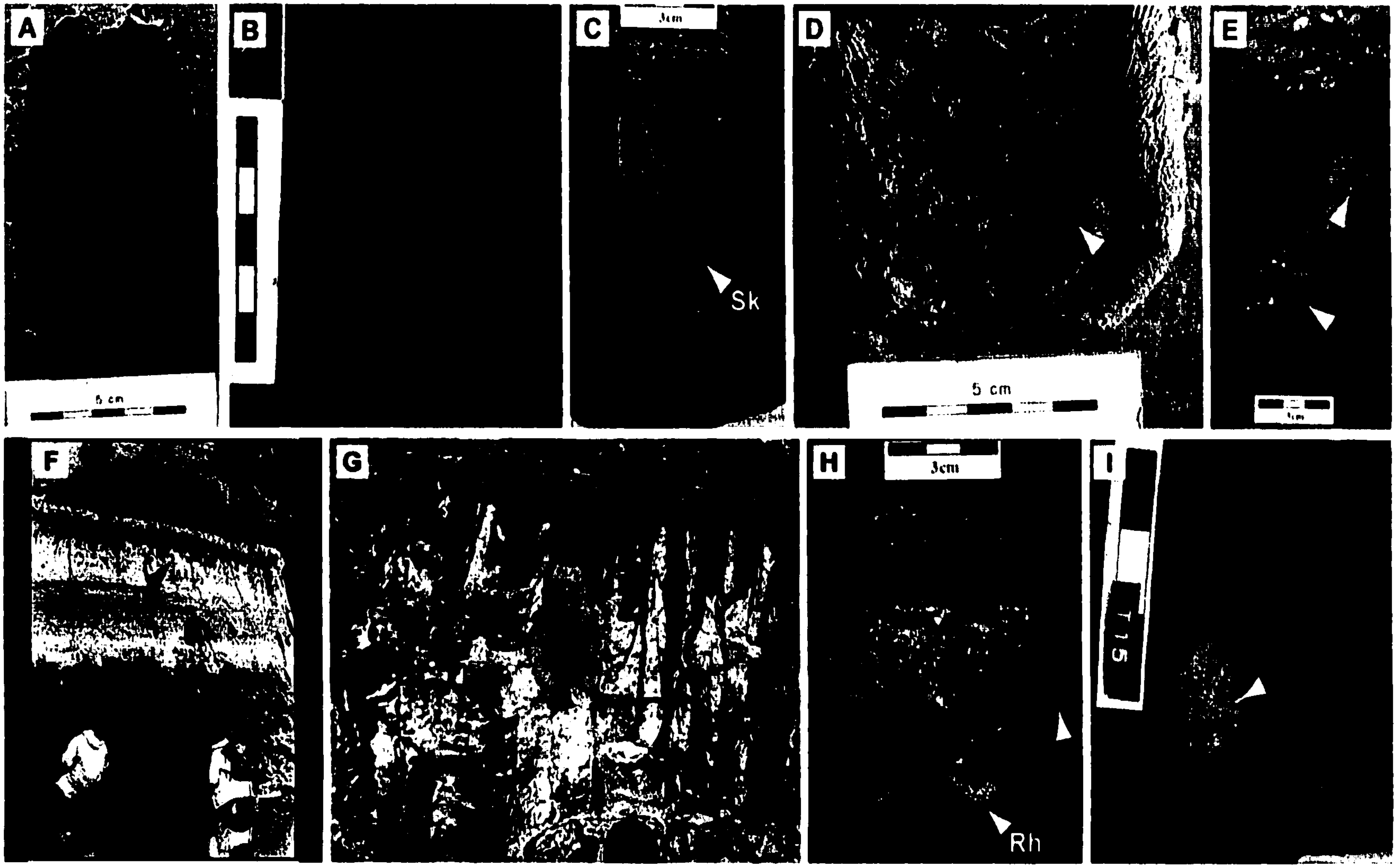

FIGURE 6.1 - Various ancient Glossifungites-demarcated discontinuites. (A) Diplocraterion from the Horseshoe Canyon Fm., Drumheller, Alberta. (B) Sucrosic, dolomitic burrow fill in fine matrix from Saudi Arabia (Hawiya Field). (C) Skolithos descending through a sideritized firmground from the Viking Fm., Kaybob Field. (D)Scratch mark Diplocraterion from the Horseshoe Canyon Fm. (E) Pebble-filled Thalassinoides, Cardium Fm., Pembina Field. (F) Complex modern and ancient relationships, Willapa Bay, Washington.(F)Diplocraterion from the Horseshoe Canyon Fm., Drumheller, Alberta. (H) Rhizocorallium from Viking Fm, Willesdon Green. (I) Bivalve trace (Gastrochaenolites?) in ancient firmground. Thebeud Field, Scotian Shelf.

Beyond their stratigraphic applications, *Glossifungites* surfaces may impart paleoecologic information as well. The nature of burrowing into these surfaces, which includes the type of trace fossil, burrow density, and the depth of burrow penetration, is related to the physico-chemical conditions dominant at the time of firmground colonization. Partly due to their stratigraphic utility, this aspect of the *Glossifungites* surfaces is commonly overlooked. For this reason, the *Glossifungites* ichnofacies has not been subdivided (Bromley et al., 1984). Studies at Willapa Bay, Washington indicate that the potential for better understanding of these surfaces exists and, although no formal subdivisions are recommended herein, there is an opportunity to better resolve the *Glossifungites* ichnofacies.

Study Area

Willapa Bay is located in the southwest corner of Washington (Fig. 6.2). The bay is separated from the Pacific Ocean by a 27-km-long spit (North Beach Peninsula). Willapa Bay is a mesotidal estuary with a tidal range of 2 to 3 m. The tidal prism exceeds 700,000 m^3, comprising about 45% of the bay's total volume (U.S. Army Corps of Engineers, 1972). Data for the modern component of this study were collected from three locations along the eastern margin of the bay (Bone River, Goose Point, and Pickernell Creek; Fig, 6.2). Pleistocene data were collected from outcrops that rim the east and north bay margins.

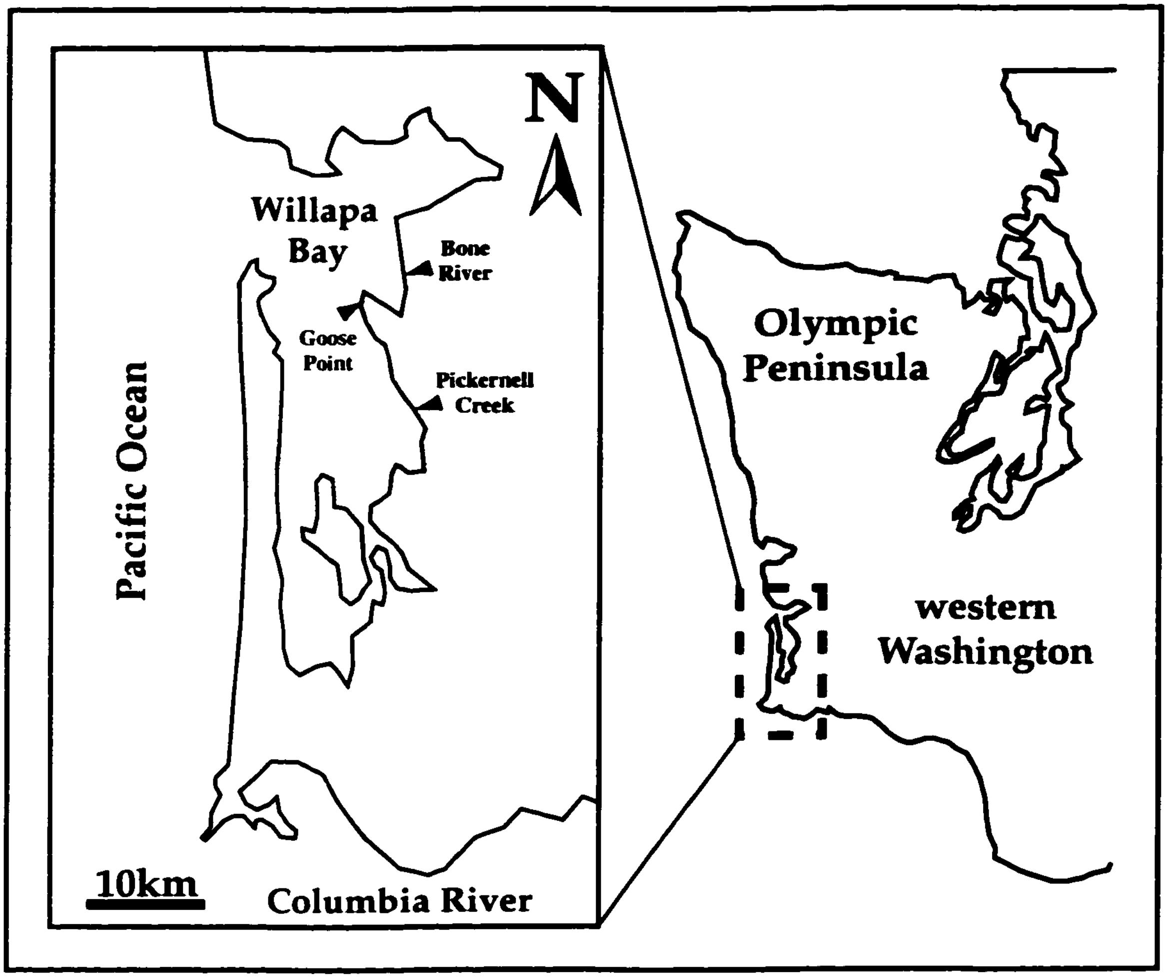

FIGURE 6.2 - Location of detailed modern and ancient Glossifungites studies at Willapa Bay. Goose Point, Pickernell Creek, and Bone River all exhibit examples of modern and ancient surfaces.

Methods

A number of methods were used to collect data from the modern, including manual coring, trenching with a shovel or grub-hoe, slabbing of samples, and x-radiographic analysis of samples. This data was supplemented with subtidal data procured with SCUBA, and resin casting of burrows. Burrow densities were assessed using a 1-m grid for large diameter burrows, such as those produced by thalassinid shrimp, and a 10-cm grid for small diameter burrows (less than 2 mm in diameter). These data were plotted and contoured. Depths to sediment-veneered firmgrounds were procured using a 1.5-m long, 10-mm diameter steel probe (Fig. 6.3). These data were also mapped and contoured. Firmness profiles for exposed firmgrounds were generated using an indentor and a modified Brinell hardness test (see Chapter 4). A standard Brinell configuration consists of a ball (the indentor) which is pressed into a deformable medium with a consistent force. The force with which the substrate can resist deformation is inversely proportional to the distance the indenter penetrates the medium. Pleistocene data were obtained through the detailed logging and analysis of Pleistocene cliff exposures.

FIGURE 6.3 - A probe marked with 10-cm bands is used to measure the depth through soft substrates to firm substrates.

RESULTS

At Willapa Bay, most modern occurrences of *Glossifungites* surfaces are observed in exhumed Pleistocene strata. The strata are present in two distinct terraces, in which two ages have been recogonized. Relatively younger Pleistocene deposits have been dated utilizing amino acid racemetization, the results of which indicate that these strata were deposited between 100,000 and 200,000 years before present (Kvenvolden et al., 1979). The older strata have not been reliably dated. These outcroppings are comprised of mud- and sand-dominated units, allowing documentation of the development of *Glossifungites* surfaces in sediments characterized by both textures.

Three distinctive biological associations can be recognized in the modern deposits at Willapa Bay. These are the *Polydora* Association, the *Petricola* Association, and the *Upogebia* Association. Each association exhibits a strong preference for substrate firmness, substrate texture, and bathymetric zonation (Table 6.1). All three assemblages produce ichnocoenoeses that are strikingly dissimilar from each other. Similar patterns are noted in the Pleistocene deposits that are present at the bay.

Contoured maps of the veneered firmground surface show that beneath the sediment veneer the modern firmgrounds locally develop pronounced steps. The morphology and nature of these surfaces are discussed in detail later in this paper.

	substrate texture	**substrate firmness**	**occurrence**	**common tracemakers**	**common biogenic structures**
Polydora Association	primarily muddy	10e +5 to 10e +7	upper intertidal	*Polydora. Corophium. Hemigrapsus*	*Diplocraterion-. Arenicolites-* and *Psilonichnus* -like
Petricola Association	muddy to sandy mud with sandy laminae	> 10e +8	middle intertidal	*Petricola. Polydora.*	*Diplocraterion- and Gastrochaenolites* -like
Upogebia Association	primarily muddy	10e +6 to 10e +7	subtidal to middle intertidal	*Upogebia. Polydora. Corophium*	*Diplocraterion-. Arenicolites-* and *Thalassinoides* -like

TABLE 6.1 - Summary of the characteristics of the three different *Glossifungites* assemblages observed at Willapa Bay.

The Polydora *Association*

The *Polydora* Association primarily consists of small *Diplocraterion*-like traces that are produced by the spionid worm *Polydora proboscidea* (Fig. 6.4, 6.5). The traces are generally 3 to 4 mm wide and have been observed to descend 1 to 6 cm below the surface of the firmground. The causative tubes that generate these structures are approximately 1 mm in diameter. These burrows are oriented perpendicular to the firmground surface regardless of its steepness. Burrow densities commonly exceed 150 individuals / 100 cm^2, however, this value ranges from 20 to 244 individuals / 100 cm^2 (Fig. 6.6). Where the burrow density of *P. proboscidea* exceeds 100 individuals / 100 cm^2, burrows of the amphipod, *Corophium volutator* are relatively common. These traces have an *Arenicolites*-like geometry, are somewhat broader than the burrows generated by *Polydora*, and have a burrow diameter of approximately 2 mm (Fig. 6.7A).

Larger burrows are present locally, particularly those of the crab, *Hemigrapsus oregonensis* and the bivalve *Petricola pholadiformis*. Their burrows are *Psilonichnus*- and *Gastrochaenolites*-like respectively (Fig. 6.5).

The *Polydora* association is most commonly observed in the upper intertidal zone (inundated 2 to 4 hours every tide cycle; Fig. 6.6). Substrate that is submersed for less than 2 hours or is exposed only to the spray zone, is dominated by the barnacle *Balanus glandula* (Figs. 6.5, 6.6). Data plotted in Figure 6.5 illustrates the strong correlation between tidal zonation and the population densities of *Polydora* and *Balanus*, particularly on exposed intertidal cliff faces. Population densities plotted along the intertidal flat also show a similar distribution pattern. Intertidal flat data are somewhat variable due to the sporadic presence of a sediment veneer that correlates to a reduction of Polydora burrow density (Fig. 6.5).

Substrate texture and firmness are also important factors regarding the distribution of this association. Where the sediment firmness is approximately $1 \bullet 10^9$ Pa, burrow densities do not exceed 30/100 cm^2. In contrast, the firmness of highly populated

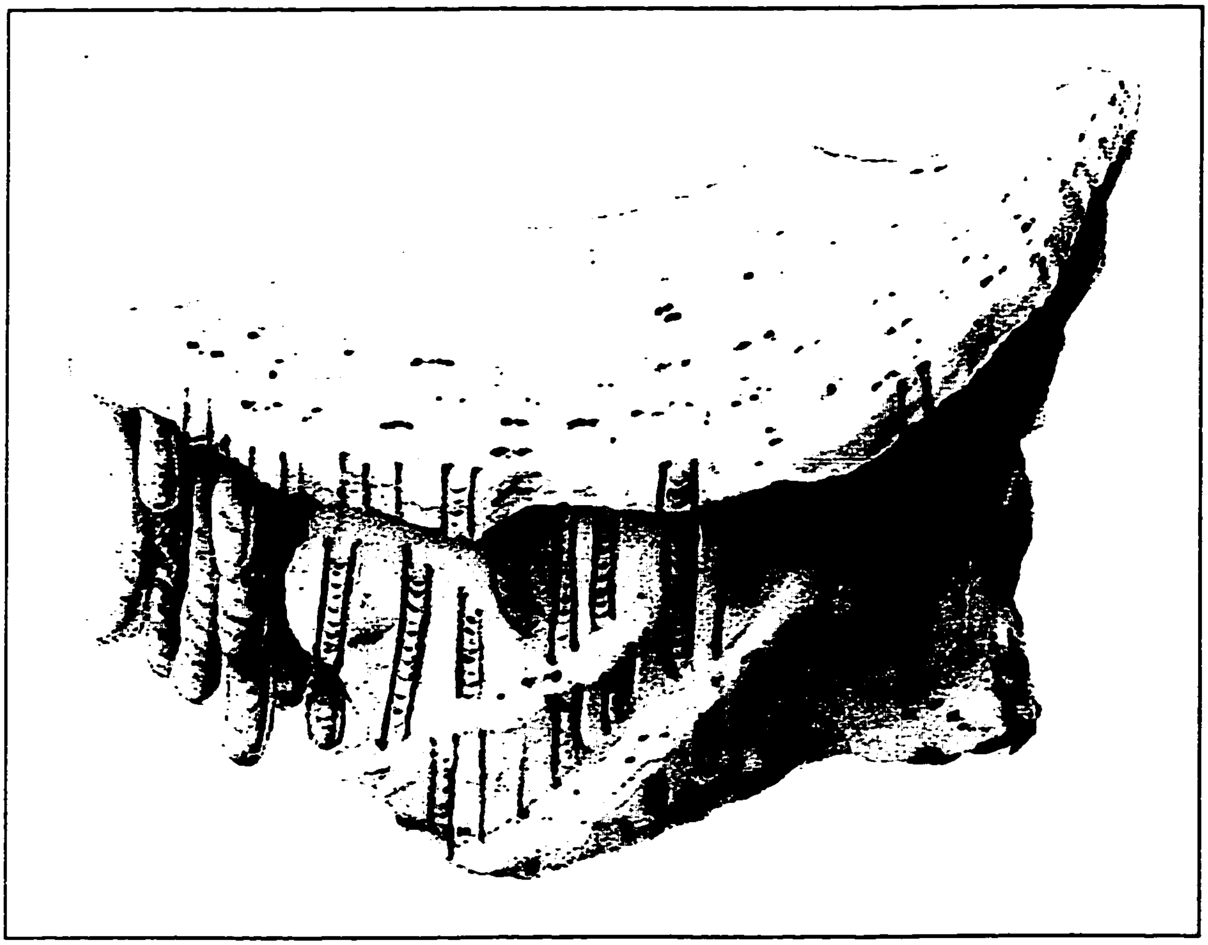

FIGURE 6.4 - Summary diagram of the *Polydora* Assemblage. Small *Diplocraterion*-like traces are the most common biogenic structure, although broader *Arenicolites*-like traces are locally common. Illustration by Tom Saunders.

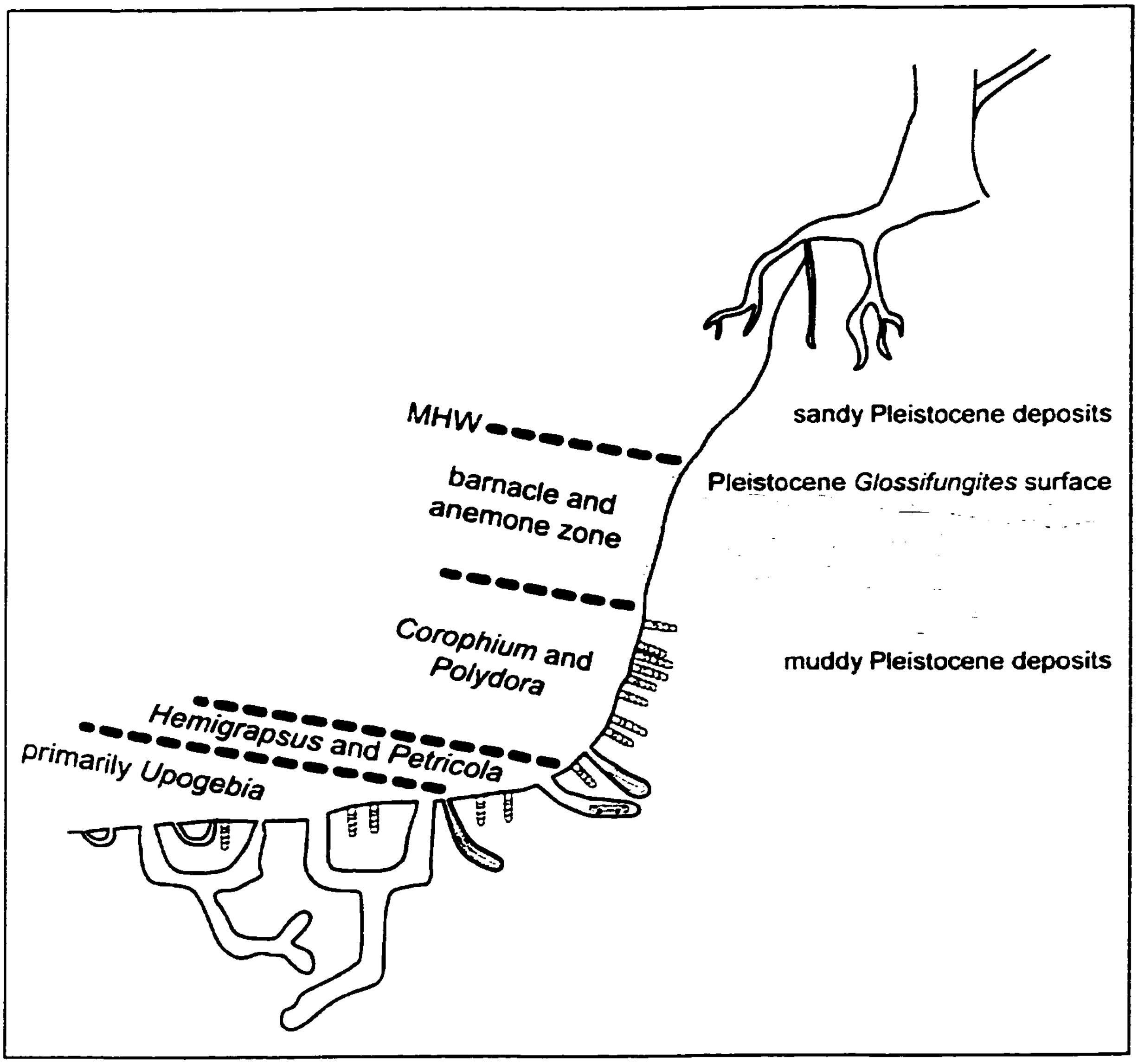

FIGURE 6.5 - Schematic of biological distribution commonly observed with the *Polydora* Association. The zonation is primarily controlled by the duration of tidal inundation.

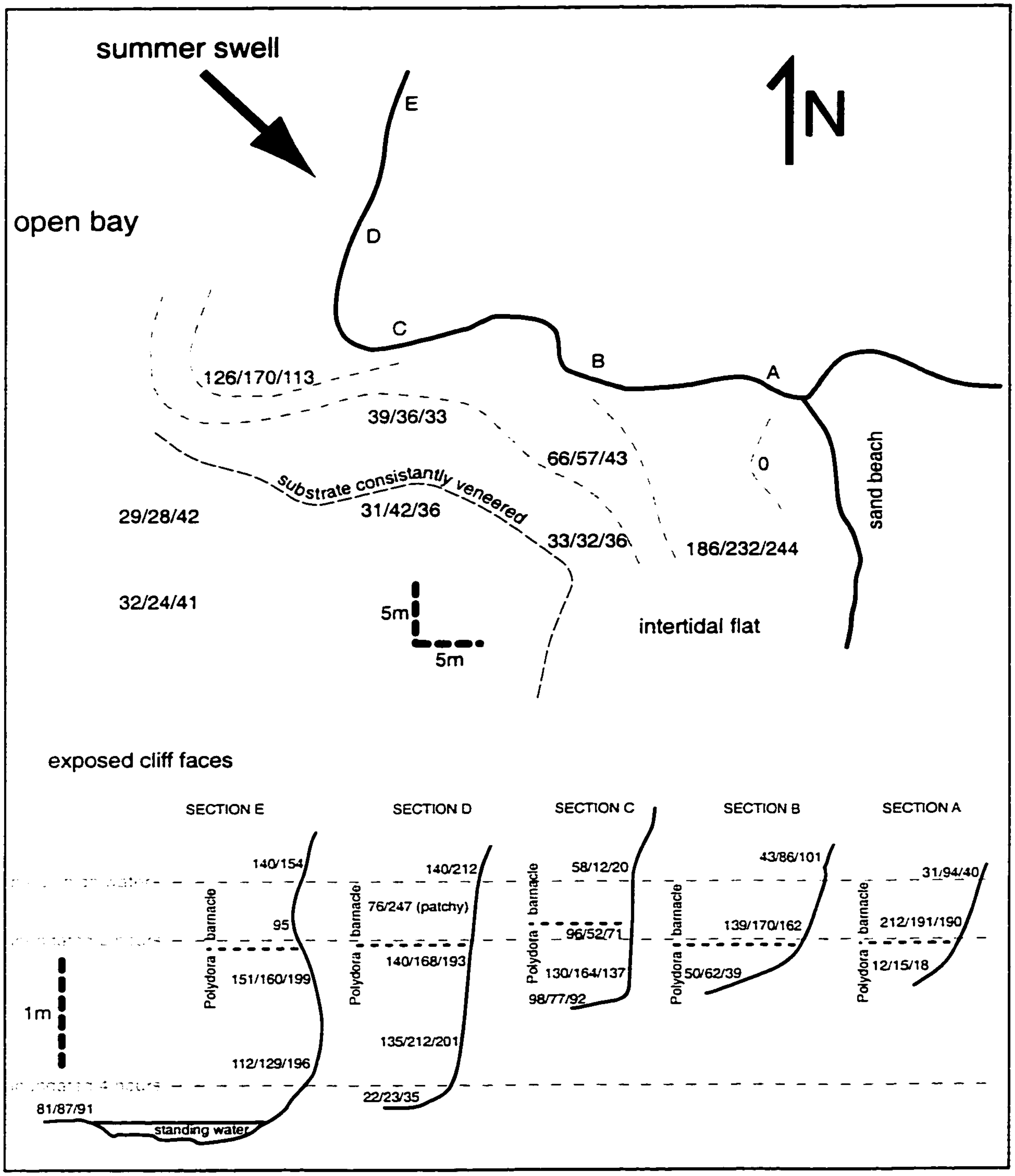

FIGURE 6.6 - Schematic plan and vertical views of *Polydora*-burrowed firmground at Goose Point. In the top plan view, burrow density is contoured. All burrow densities were approximated by counting the burrows in a 10 cm square. Three counts are shown for every data point. The plan view shows a strong shore parallel trend in the burrow distributions. The lower portion of the diagram shows side views of burrowed cliff faces. In section, population distributions strongly correlate to the duration of tidal inundation.

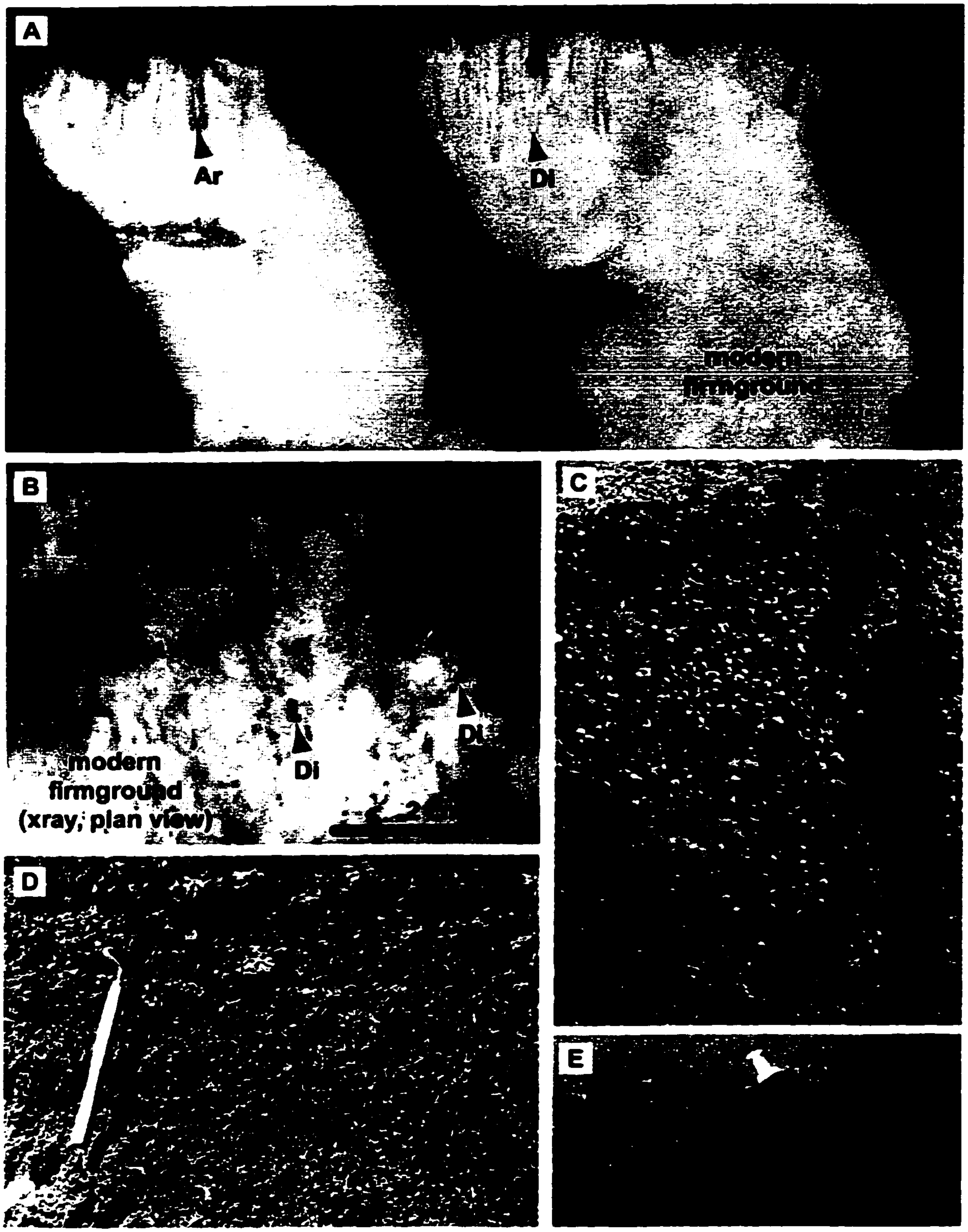

FIGURE 6.7 - Various photographs and radiographs of *Polydora*-burrowed firmground. (A) Sectional view of *Polydora* burrows in a compacted Pleistocene substrate. *Diplocraterion-* (Di), *Arenicolites-* (Ar), and *Thalassinoides*-like (Th) traces are indicated. --->

(cont.) These burrows were made by *Polydora*, *Corophium*, and *Upogebia*, respectively. The plate is approximately 16 cm wide. (B) Plan view of the same surface shown in A. Note the relatively high burrow density (approximately 100 burrows / 10 cm square). (C) The barnacle encrusted zone in the area of brief tidal inundation. (D) Zone of intense *Polydora* colonization in firmground that is inundated for approximately 4 hours. (E) Close up of sand-filled Polydora burrows in cross section.

substrates is only about 1 • 10^7 Pa. Extremely firm substrates (>1 • 10^9 Pa) are generally unburrowed. Grain size analyses of colonized firmgrounds indicate the *Polydora* Association is most common in mud-dominated firmgrounds. These data revealed that in all *Polydora*-colonized (firm) substrates, the silt and clay fraction comprise between 81 and 96 % of the sample mass (four samples measured). At the bay, firmgrounds that are comprised of laminated silt and mud, or are dominantly sandy, are simply not colonized by *Polydora*.

The Petricola *Association*

The *Petricola* Association is comprised of clavate burrows produced by the bivalve *Petricola pholadiformis* (Fig. 6.8). These burrows normally measure 10 to 25 mm in diameter near the base, tapering to approximately 10 mm at the aperture. They typical range between 5 and 10 cm in length. Burrow densities range from less than 10 to 87 burrows / m^2. Sporadically distributed patches of *Polydora proboscidea* are present as well. As with the *Polydora* Association, these trace makers generate small *Diplocraterion*-like structures, however, burrow density seldom exceeds 30 individuals / 100 cm^2. Small cup-shaped structures are also present locally (Fig. 6.9). These measure between 5 and 8 cm in diameter, and are generally 8 to 10 cm deep. Two to three small shellfish (*Tapes japonica*) are always present at the base of these features but it is speculative to suggest these are biogenic structures. Barnacles and small anenomes are commonly found attached to the firm substrate, commonly in population densities less than 20 individuals / 100 cm^2. If either type of organism is pried free, a small circular indentation is

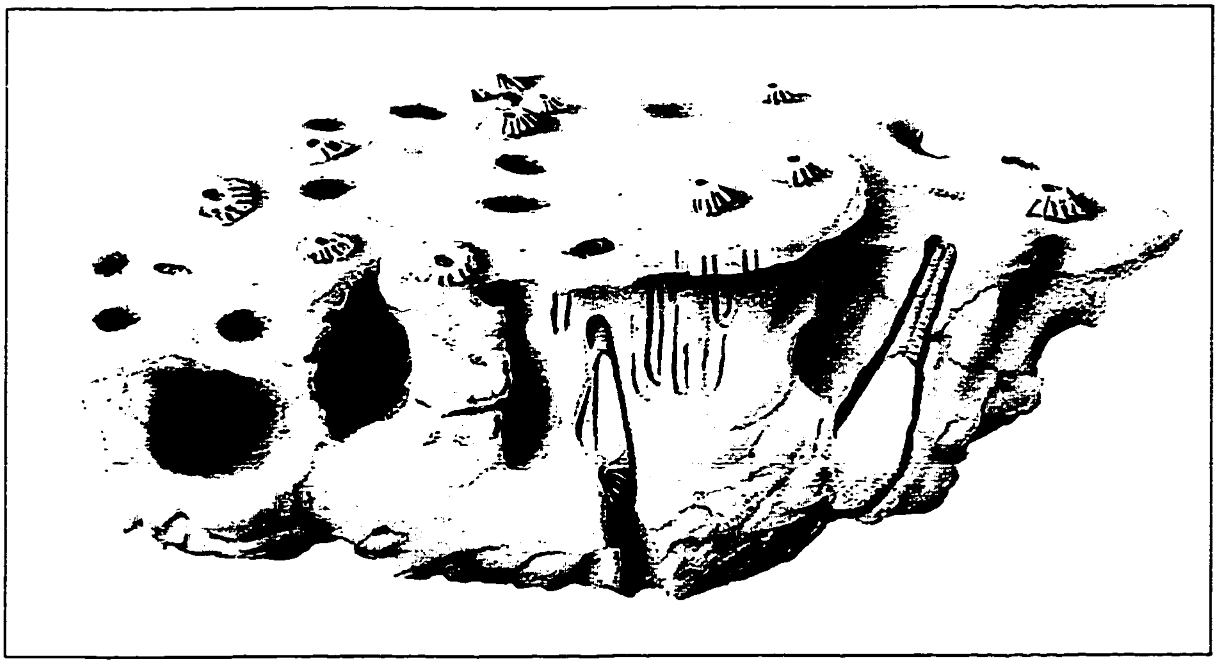

FIGURE 6.8 - Summary diagram of the *Petricola* Assemblage. *Gastrochaenolites*-like traces are the most common biogenic structure. *Diplocraterion*-like traces are locally common. Illustration by Tom Saunders.

FIGURE 6.9 - Detail of shell nests observed locally within the *Petricola* Assemblage. The bivalves that lay at the bottom of the cup-shaped structures are *Tapes japonica* (the Japanese littleneck). Illustration by Tom Saunders.

revealed. The indent is less than 1 mm deep and is normally less than 4 mm in diameter.

This ichnocoenosis is more commonly observed in the lower to middle intertidal zone and is inundated at least 4 hours per tidal cycle. Kozloff (1996) noted *Petricola* was present from the 0.0 to the 0.6 m tide line at Willapa Bay. The observations indicate that this assemblage is locally present up to the +1.0 m tide line.

The *Petricola* association is generally observed in comparatively firm substrates (Purchon, 1955). In situ firmness values are approximately $1 \bullet 10^9$ Pa, which is about one to two orders of magnitude higher than firmness values measured in intensely burrowed *Polydora*-dominated firmgrounds. The *Petricola* Association is limited to mud-dominated substrates, and the percent fines (by mass) varies between 67 and 89 %, based on three samples. These values are sand-rich compared to those generated from *Polydora*-dominated substrates. Like the *Polydora* Association, the *Petricola* Association is rarely developed in firm substrates that are characterized by heterolithic lamination (intercalated sand and mud).

The **Upogebia** *Association*

This association primarily consists of *Thalassinoides*-like burrows excavated by the mud shrimp *Upogebia pugettensis* (Fig. 6.10). These traces have a Y-shaped architecture, although a short branch is commonly observed near the base of the burrow. Burrow cross sections are circular and their diameters commonly vary between 9 and 21 mm in diameter. Depths of penetration are variable, commonly ranging between 40 and 60 cm. It is unknown, however, what the maximum depth of penetration into the firmground is. This is due to difficulties associated with excavating and retrieving resin casts from intertidal firmgrounds.

Unlike the *Polydora* and *Petricola* Associations, the *Upogebia* Association is present in uncovered and sediment-veneered firmgrounds (Fig. 6.10). Where the firmground is exposed, or only thinly veneered, *Upogebia* burrows extend fully into the consolidated

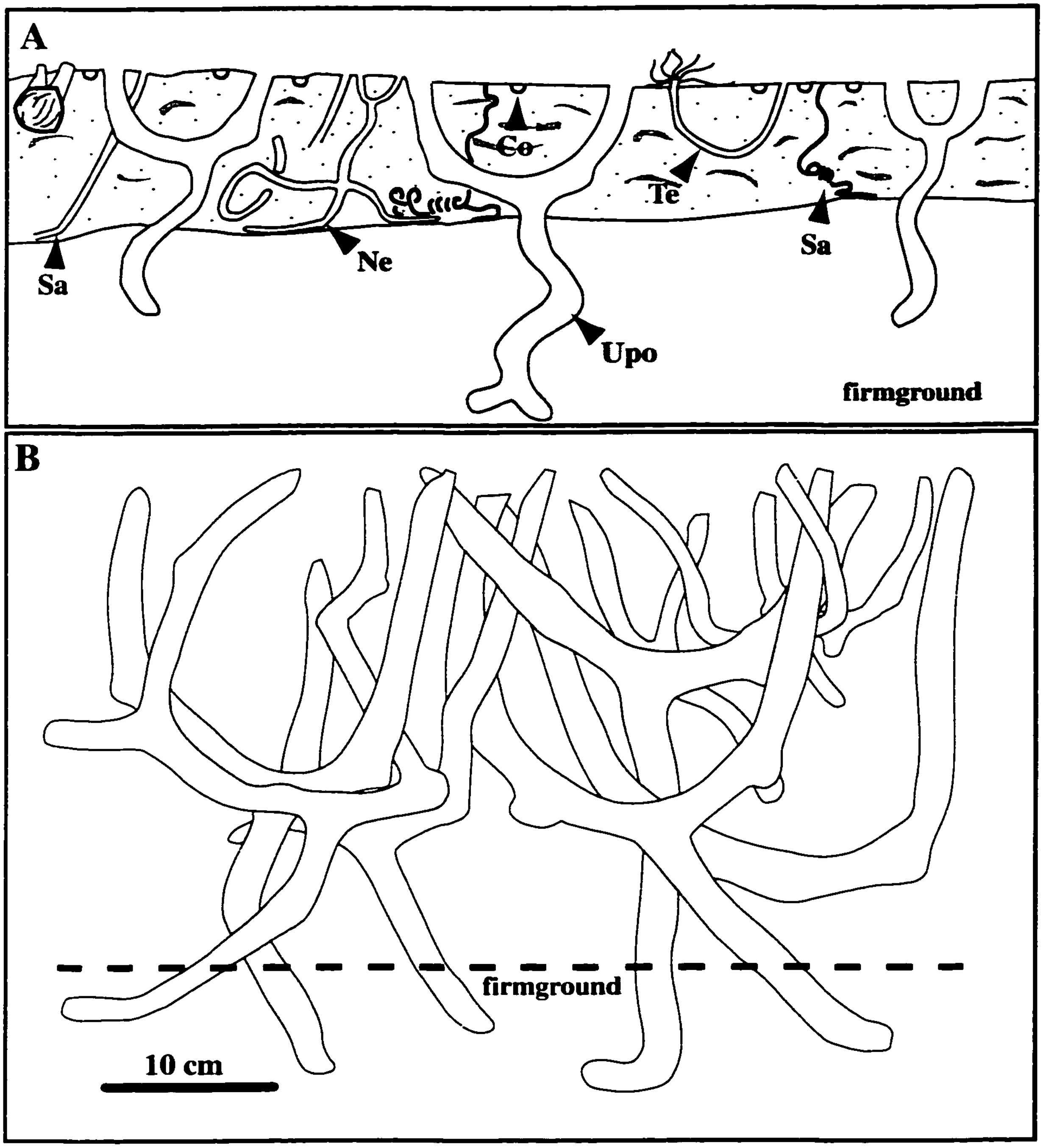

FIGURE 6.10 - Summary schematics of *Upogebia*-colonized substrates. (A) *Upogebia pugettensis* most commonly burrows into a firmground through a soft sediment veneer. Although the soft ground assemblage may be quite diverse, the only burrows that penetrate the firmground are those made by the mudshrimp. Burrows illustrated here include those constructed by *Nereis* (Ne), *Saccoglossus* (Sa), *Corophium* (Co), terrebellid polychaetes (Te), and *Upogebia* (Upo). (B) Schematic representation of *Upogebia*-burrow casts removed from the mud near Goose Point.

sediment. Surprizingly, the overall architecture, size, and penetration depth of these traces are identical to *Upogebia* burrows observed in uncompacted mud. These burrows are generally observed with rare to moderately abundant burrows of *Polydora* and *Corophium*. Less commonly, *Petricola* is present, lending rare clavate burrows to this association.

Where the firmground is covered with a thicker veneer of soft sediment (> 10 cm), *Upogebia* burrows are normally the only biogenic structures that penetrates that firmground (Fig. 6.10). This occurs in sediment veneer that is up to 60 cm thick, in which case only the basal terminus extends into the firmground. *Upogebia* is a persistent burrower, and its burrows generally show no attempt to run horizontally along the contact between the firm and soft sediment. Removing the sediment veneer from the firmground reveals several abandoned burrows, evidencing the activities of previous (crustacean) generations. Generally, the soft sediment hosts several trace-makers that do not burrow into the firmground. Notable burrowers include *Nereis*, *Saccoglossus*, *Heteromastus*, *Cirriformis*, *Nephtys*, and *Corophium*. They would generate an assemblage that would be comprised of *Arenicolites*-, *Planolites*-, *Palaeophycus*-, *Gyrolithes*-, *Rosselia*-, and *Diplocraterion*-like trace fossils (Fig. 6.10). Most of these lebensspuren tend horizontally where they encounter the firmground, although locally they reburrow abandoned shrimp traces that descend into the firmground.

Burrow densities normally vary between 10 and 100 burrows/m^2 (Fig. 6.11). Like the *Petricola* Association, this association is most common in the lower and middle intertidal zones. The burrows are inundated by the high tide for at least 4 hours per tidal cycle, and they are present in the highest densities where this time exceeds 6 hours (Fig. 6.11). Population densities are lowest where the firmground is exposed, especially at the higher tide levels (Fig. 6.11). The *Upogebia* Association has also been observed in subtidal channels at Willapa Bay (this volume, Chapter 2). In these instances, it resembles its intertidal counterpart in most respects.

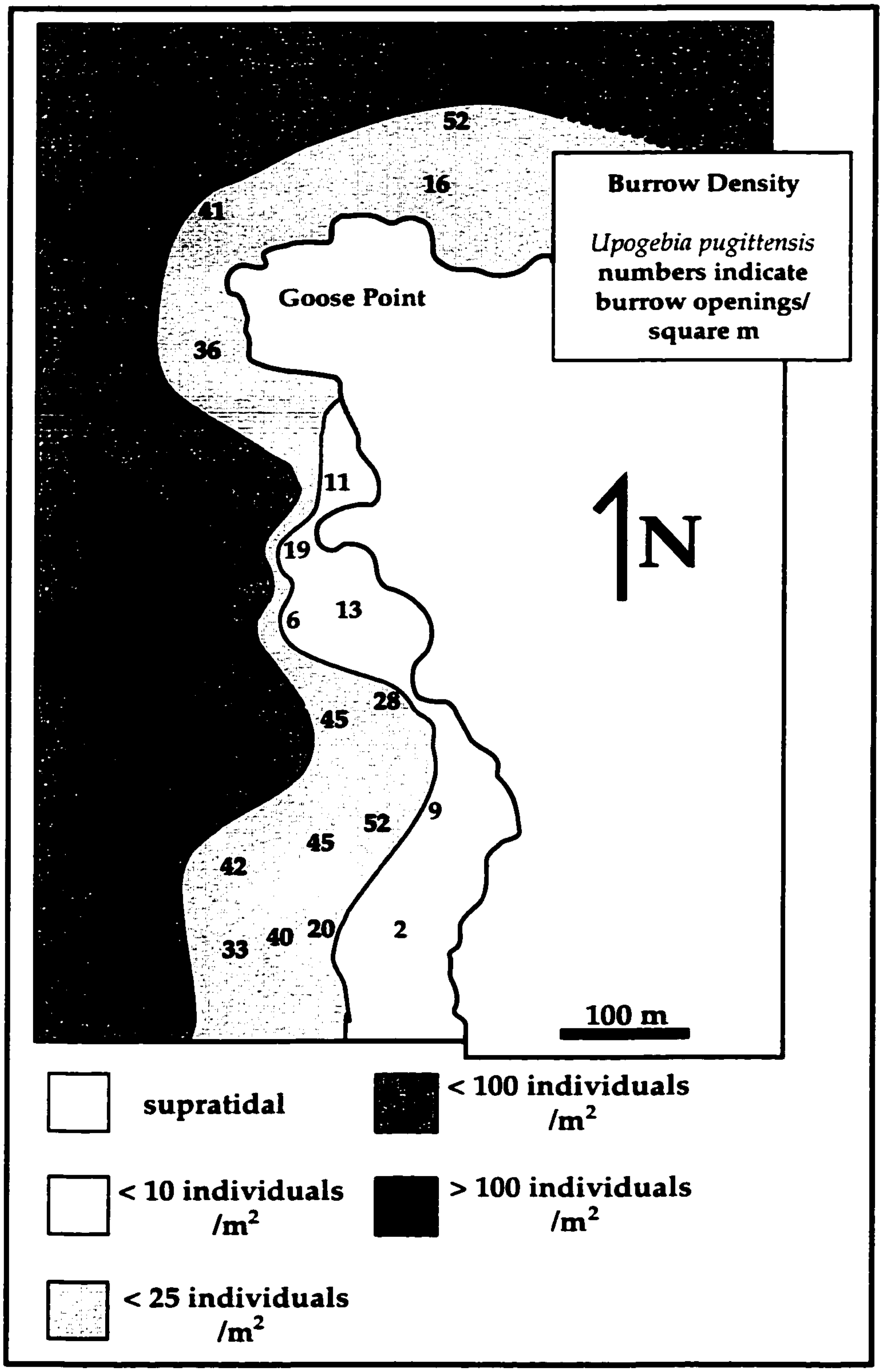

FIGURE 6.11 - Mapped burrow densities of *Upogebia pugettensis*. Note the shore parallel trend and the mappable extent of this surface. The thickness of sediment veneer is variable, but is generally zero near the supratidal, increasing to > 60 cm in the zones of highest population density.

Upogebia-colonized firmgrounds are characterized by firmness measurements similar to those generated from *Polydora*-colonized firmgrounds (1 • 10^7 to 1 • 10^8 Pa). It is not observed in substrates firmer than 1 • 10^9 Pa. Also, the *Upogebia* Association was not observed where the sand constituent of the firmground exceeded 10 % (by mass), or where sand was interlaminated with mud.

The Morphology of Modern Firmgrounds at Willapa Bay

The topography of the firmground beneath the sediment veneer was mapped at three locations at Willapa Bay (Bone River, Pickernell Creek, and Goose Point; Figs. 6.1, 6.12). The veneer thickness was measured to a depth of 150 cm, which was the length of the probe. At Bone River, the firmground abruptly passes below this depth within 100 m from the shoreline (defined by Pleistocene bluffs; Fig. 6.12). Approximately 600 m from the shore a small pod of firm substrate was mapped at a depth of 90 to 150 cm. The lateral extent of this isolated firmground is unknown, however, it was mapped to a length of 120 m.

At Pickernell Creek the firmground topography is characterized by two distinct steps. The first occurs about 220 m from the present shoreline, and is represented by an abrupt 50 cm drop (Fig. 6.12). The second step descends below 150 cm deep; it was mapped 400 m from the shore. Depth measurements from three lines of traverse indicate that these steps are laterally continuous (Fig. 6.12).

The firmground topography near Goose Point is similar to that observed at Pickernell Creek. Two steps are apparent at 75 and 480 m. Each step represents a drop of approximately 50 cm and is laterally continuous (Fig. 6.12). Around the northern tip of Goose Point, the steps are no longer evident. Here the firmground has a consistent slope in the direction of the Palix River.

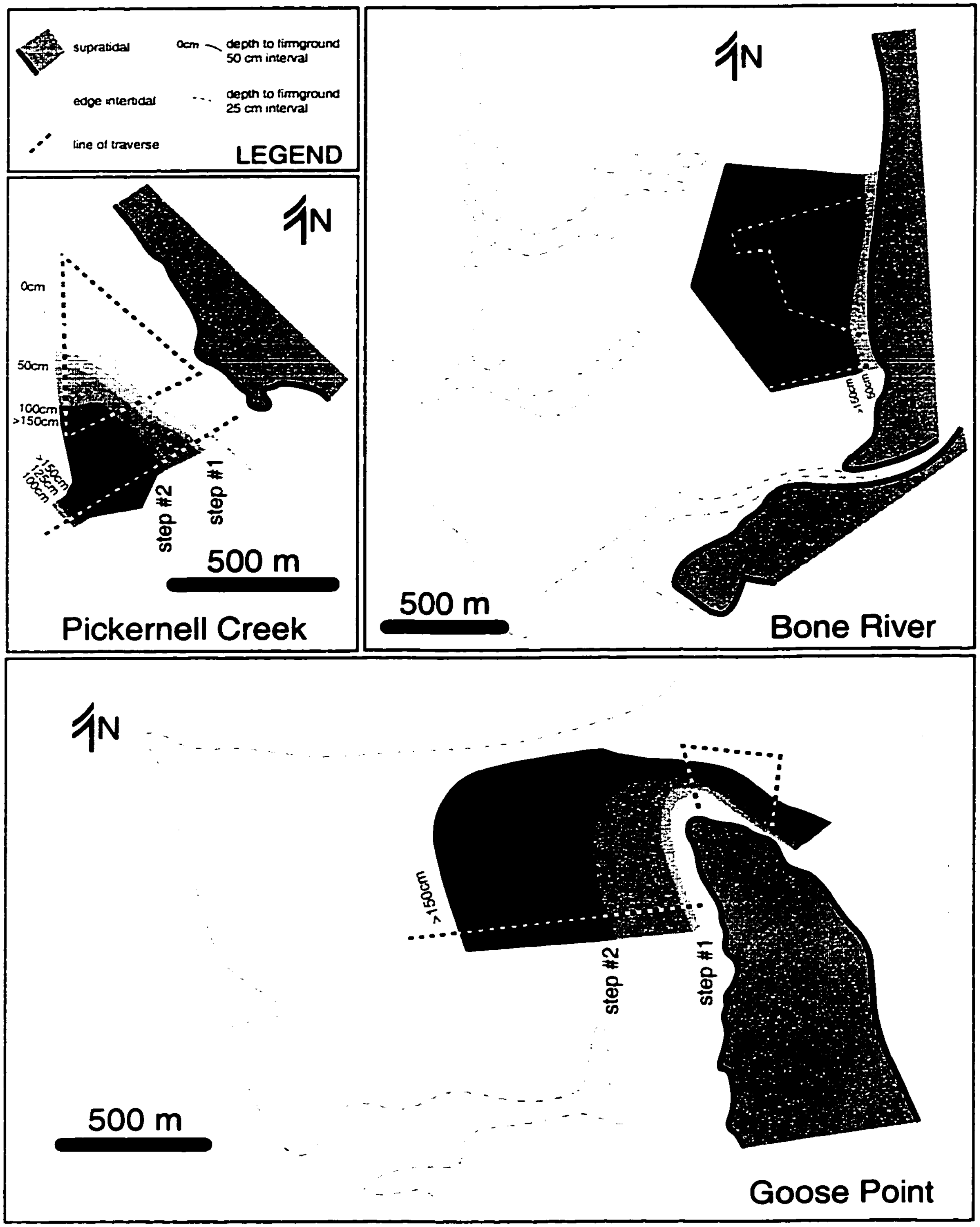

FIGURE 6.12 - Contour maps showing the topography of firmground surfaces beneath soft sediment veneer. At Goose Point and Pickernell Creek, steps are discernible on the surfaces. The firmground at Bone River drops off more abruptly.

At all three locations, exposed to shallowly veneered firmgrounds are present near the shoreline, which is defined by Pleistocene bluffs. Close to the cliffs, the firmground is generally flat to slightly undulatory, except where it slopes up to the Pleistocene outcrop.

Pleistocene Glossifungites *Surfaces at Willapa Bay*

Three types of *Glossifungites* surfaces have been observed in the Pleistocene outcrop at Willapa Bay. The first, and most commonly observed type of *Glossifungites* surfaces at the bay, consists of *Thalassinoides*-dominated horizons (Fig. 6.13). These trace fossils have a large diameter (normally exceeding 20 mm), penetrate deeply below the erosive surface, and locally branch and interpenetrate each other. The lebensspurren are typically unlined to thin walled (up to 2 mm thick), although a thick diagenetic halo comprised of iron oxide cement is normally present. This assemblage is mostly observed at the base of tidal channel and intertidal flat deposits where the underlying strata is particularly muddy (Fig. 6.13).

The best examples of these surfaces are present at Goose Point. Clifton et al. (1989) commented on the stratigraphic significance of these *Glossifungites* horizons. Here, muddy accumulations are unconformably overlain by relatively sandy strata interpreted to have been deposited in a tidal channel. A shelly layer of variable thickness (5 to 170 cm) lays directly on top of the erosional surface (Fig. 6.13). The shell deposit consists of both articulated and disarticulated oysters (*Ostrea lurida*) and has been previously interpreted as a more or less *in situ* bioherm (Clifton, et al., 1989). The fossils are locally supported by a silty sand matrix. Shelly sand from the channel base is present in almost all of the crustacean burrows, even those that extend 2 m below the erosional surface. This particular surface is sporadically present over 3 km and highly burrowed sections are commonly continuous for 150 to 200 m.

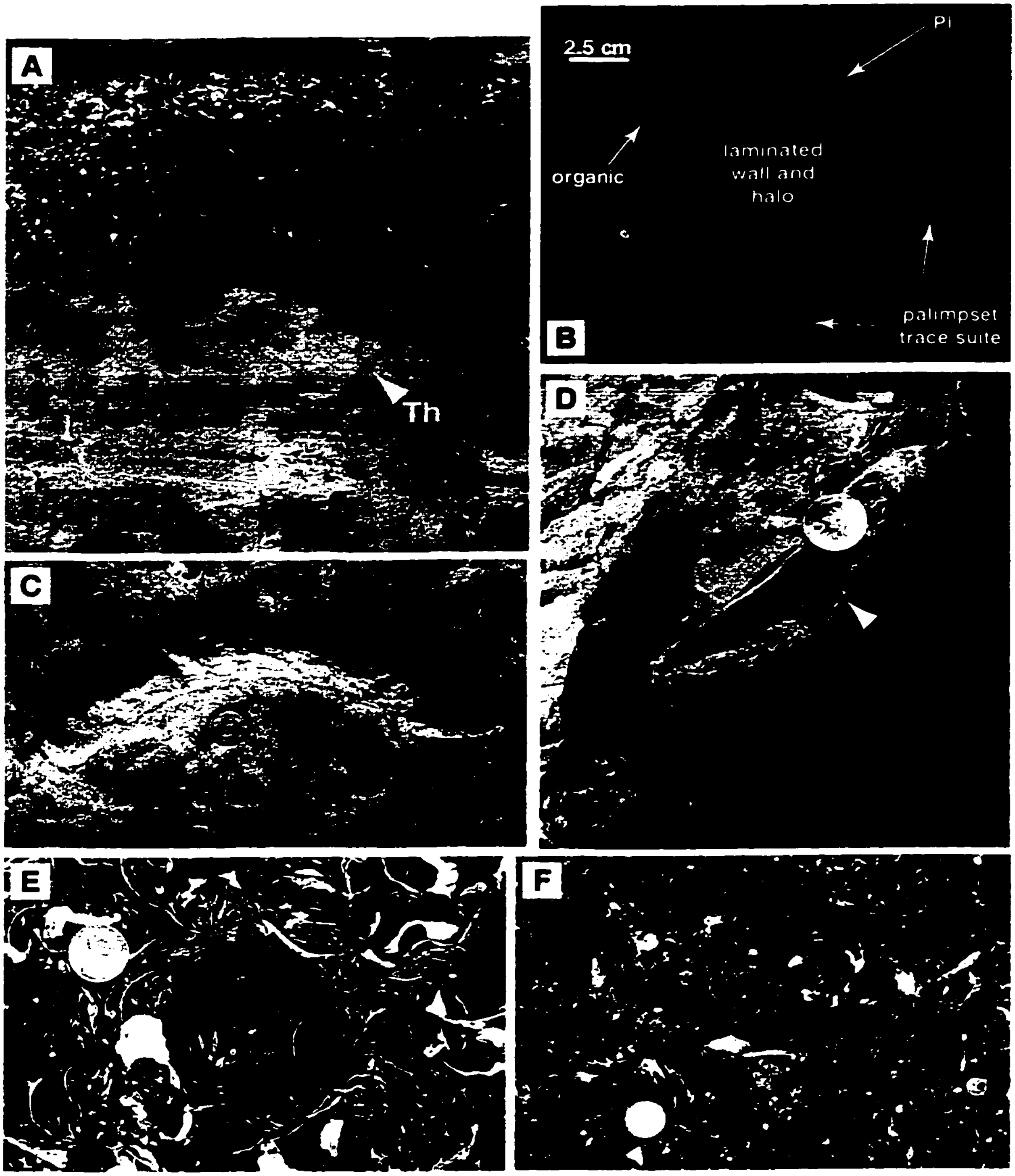

FIGURE 6.13 - Several examples of burrow fabrics observed in Pleistocene outcrop at Goose Point, Willapa Bay. (A) Large diameter *Thalassinoides* descending from a shell-lag demarcated erosional surface. The burrows descend up to 1.5 m below the erosional surface. (B) X-ray of a thin slab across a burrow excavated from A. Here an oxide halo, organic material, and a cross-cut palimpsest trace assemblage are shown. (C) Almost horizontal basal portion of the ancient shrimp burrow. An American quarter is the scale. (D) Obliquely tending *Thalassinoides*. (E) In the shell hash, shell fragments are reoriented, evidencing that these deposits were uncompacted at the time of burrowing. (F) Branching *Thalassinoides*.

Shell nests provide another type of locally observed *Glossifungites* surface. These are similar to those illustrated in Figure 6.9, however, the Pleistocene examples are decidedly less regular and are normally larger (up to 14 cm; Fig. 6.14). The trace fossils tend to have a circular cross-section and normally constrict to about 10 cm diameter near the top. All the Pleistocene occurrences observed are present in deposits interpreted as having an intertidal nature (i.e. highly bioturbated, thin, with evidence of rooted horizons; Chapter 1). These surfaces have little lateral continuity, although they can be traced over 30 m.

Finally, the least common *Glossifungites* surface observed at Willapa Bay consists of small *Skolithos* and *Arenicolites*. The burrow diameters are generally less than 2 mm and they are less than 20 mm long; they are therefore difficult to see in the weathered outcrop. This ichnofacies is also associated with deposits interpreted as intertidal. Their small size and extremely sporadic distribution make lateral tracing of these surfaces all but impossible.

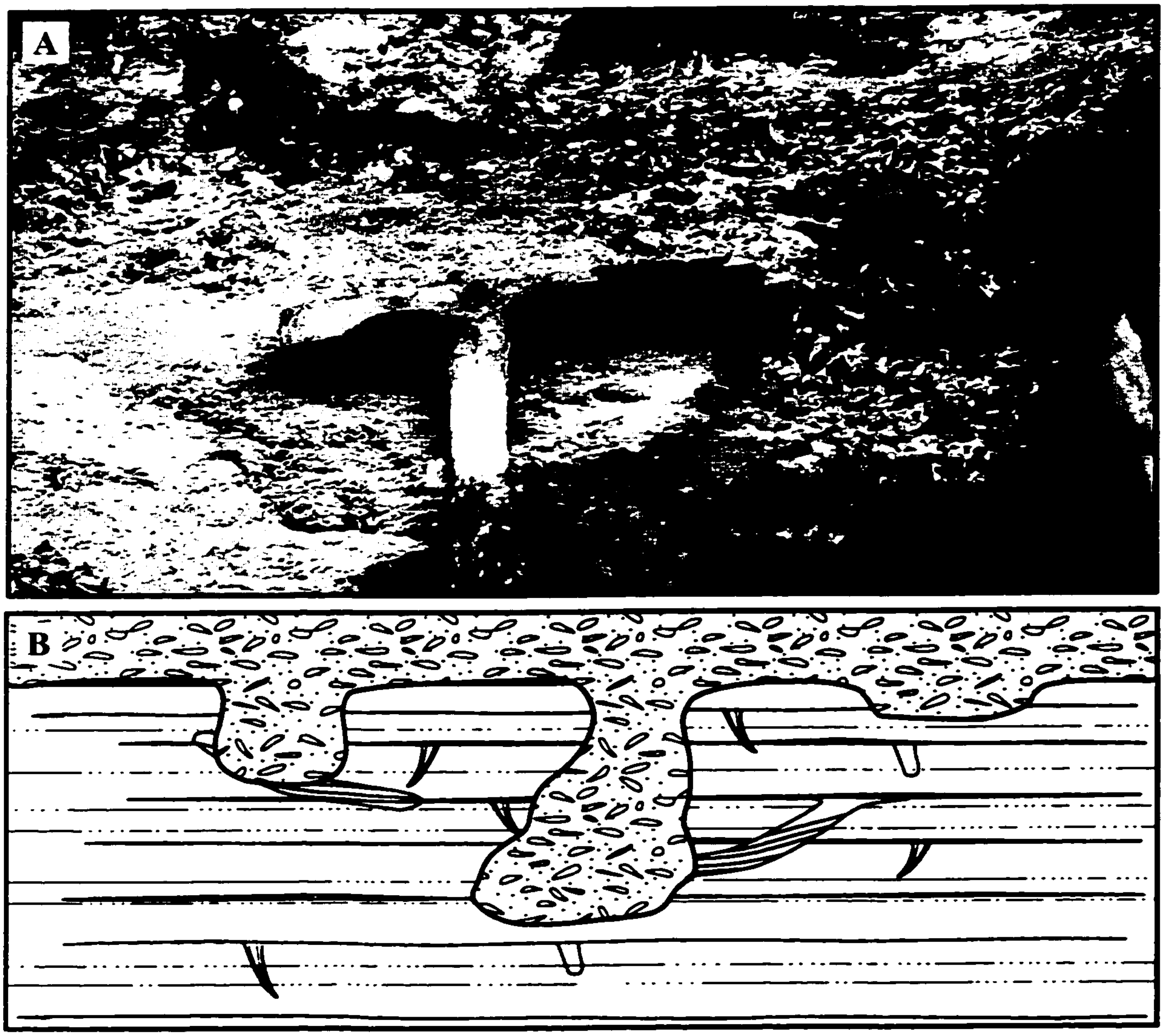

FIGURE 6.14 - Pleistocene shell nest similar to that represented in Figure 6.9. (A) Irregular, cup-shaped structure filled with shelly debris Photo from near Hawk Point (Fig. 2.1). (B) Schematic interpretation of A.

DISCUSSION

Trace Associations

Firmness, textural, and bathymetric data all indicate that the *Polydora, Petricola,* and *Upogebia* Associations each develop on substrates characterized by unique physical parameters. Each of the parameters measured present different burrowing obstacles or stresses that the trace-maker must overcome. The duration of tidal inundation contributes a number of physico-chemical stresses that have been assessed by previous researchers. These include salinity fluctuation due to surface runoff and ground water discharge, temperature variation, desiccation, and oxygenation stress (Fig. 6.15). Of these, salinity and oxygenation stresses are potentially lethal to burrowing organisms. Salinity fluctuations are effectively dampened by the substrate, however, reducing the stress on infauna (Knox, 1986). Oxygen stress has been well characterized in the literature (Rhoades and Morse, 1971; Savrda and Bottjer, 1987). Generally, low oxygen levels result from aerobic respiration in the burrow during the low tide. The availability of replenishing oxygenated water is strictly a function of the time period between tidal flooding. For this reason, animals at higher tide levels are subjected to greater oxygen stress. Some animals are notably tolerant to these stresses. For example, the sand shrimp, *Neotrypaea californiensis,* has been shown to be sufficiently tolerant of low oxygen levels for up to 12-14 hours (Thompson, 1967). Certain worms, such as the lug-worm *Arenicola,* are also oxygen-stress tolerant. Like many animals that live in unwalled burrows, the lug-worm enthusiastically irrigates its domicile during high tide, and, because its burrows are commonly unlined, it potentially benefits from somewhat oxygenated interstitial water during the low tide.

Stresses related to bathymetry and tidal zonation suggest variation in the *Glossifungites* assemblages will normally occur along shore-parallel trends. This is partly confirmed by Figures 6.6 and 6.11. These diagrams indicate changing population densities approximately follow intertidal zonation. The faunal distribution represented

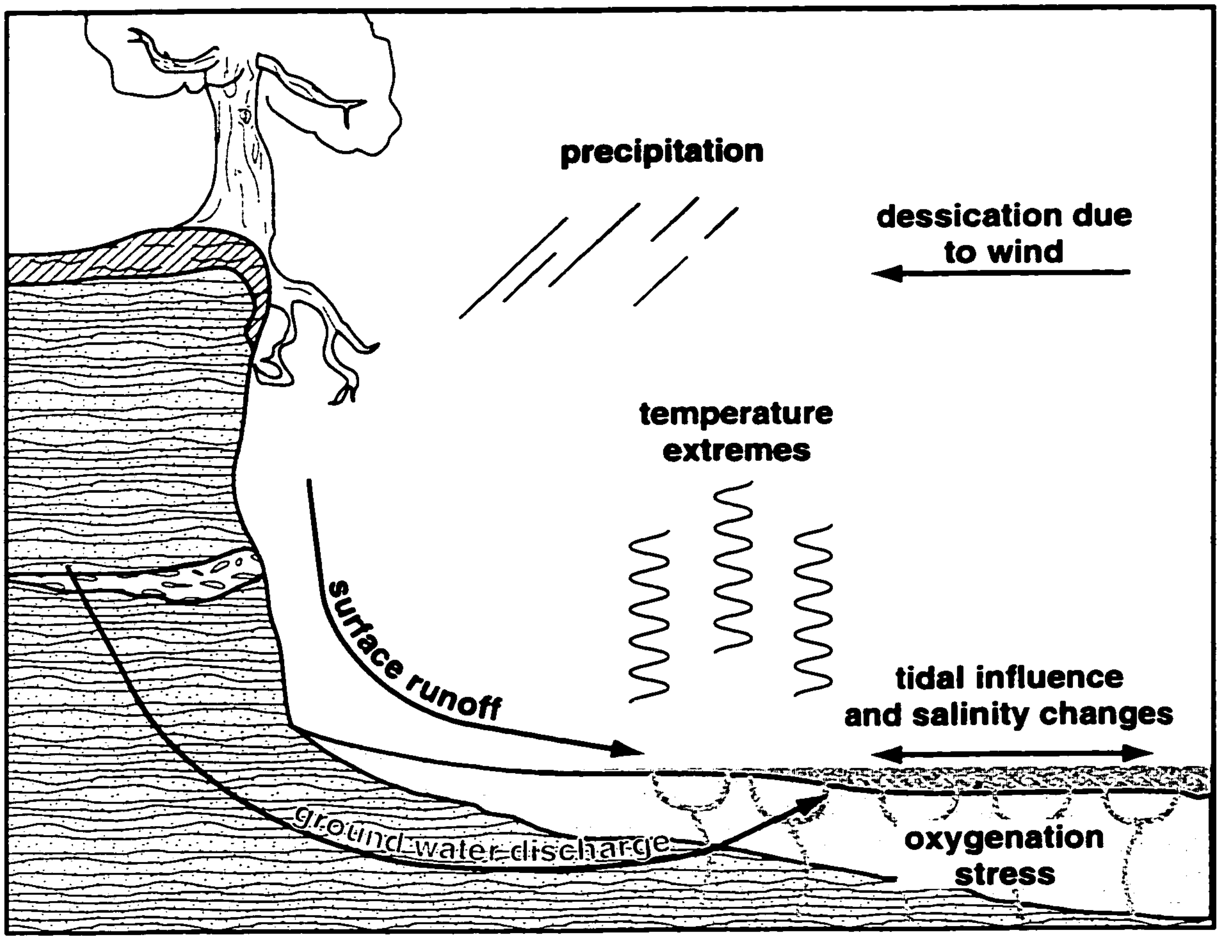

FIGURE 6.15 - Schematic summary illustrating the various stresses that strongly influence bioturbating infauna in the intertidal zone. The stresses tend to increase as time of exposure increases.

in Figure 6.5 illustrates the most common firmground succession observed at Willapa Bay. This succession is attributed to intertidal zonation (duration of inundation; Fig. 6.6) and is specific to relatively softer firmgrounds ($< 10^8$ Pa). Lateral variations in trace assemblages demonstrate the effects of textural variability and changes in firmness.

Higher sand contents apparently reduce the likelihood of colonization of that substrate. This is especially true if sand is interlaminated with mud. Heterolithic substrates require the burrower to be proficient at excavation in muddy and sandy substrates. This is exacerbated in firm substrates as mud can be pushed aside, but sand, because it is already compacted, must be excavated. Further to this, a greater energy expenditure must be associated with burrowing/boring in sandy firmgrounds. Firmgrounds characterized by interlaminated sand and mud are rarely burrowed at Willapa Bay. Those that have been colonized are populated primarily by *Petricola*. No thalassinid burrows have been observed in such substrates at the bay. However, this may be idiosyncratic to Willapa Bay, as many crustaceans, notably species of *Callianassa*, effectively burrow in sand and muddy sand.

Also, sediment texture influences the nature of the burrowing assemblage present in a substrate. Marine ecologists have repeatedly noted that similar groups of organisms are consistently found in texturally-specific substrates (Ricketts et al., 1983). This is due to differing requirements regarding larval recruitment, functional morphology, and behavioral ecology in different substrates (Craig and Jones, 1966). These factors are related to parameters such as porosity, permeability, oxygen content, and organic resource; all of which are passively linked to grain size (Craig and Jones, 1966). Furthermore, Peterson (1991) showed that intertidal zonation of invertebrates was primarily related to two factors, bathymetry and texture. Although this oversimplifies the complexities of natural systems, it serves us well to consider texture and bathymetric disposition to be dominant controls in marginal marine environments. The effects of textural variation remain unclear; however, the observations presented support the following conclusions: boring bivalves cope with heterolithic substrates better than burrowing polychates or crustaceans; as sand content in mud increases, the activity of crustaceans and polychaetes decreases; polychaetes (in this case *Polydora*) are more tolerant of a higher overall sand constituent than certain thalassinid shrimp (*Upogebia*), in this study 19 versus 10% sand represents the respective maximum values.

The textural variation present in firmgrounds is inherited from its original depositional environment. For this reason, variability in the grain size of firm substrates does not normally reflect the geometry of the sedimentary environments exhuming those substrates. Textural changes are not necessarily shore-parallel or –perpendicular and an overprinting control, independent of tidal zonation or absolute bathymetry, may be present in modern and ancient *Glossifungites* assemblages.

Like textural variation, the absolute firmness apparently plays an important role in determining what animals might exploit certain substrates. Both the *Polydora* and *Upogebia* assemblages are found in substrates less indurated than those dominated by *Petricola*. This is not surprising given that boring bivalves excavate firmer sediment primarily by drilling and rasping. Bivalve borings are, in fact, common elements of the *Trypanites* ichnofacies. In contrast, polychaetes burrow into firmgrounds mostly by advecting, or pushing aside the substrate. It is important to note, however, that polychates commonly bore into hard substrates (Gripp, 1967; Bromley, 1972; Lagadeuc, 1991; Guenther, 1996; Sato-Okoshi and Okoshi, 1997). Crustaceans have the ability to remove *and* advect firm substrate, however, it is unclear how effective their chelae might be used to burrow in unusually firm (or hard) substrates. *Upogebia operculata*, for example, is known to bore into coral by drilling with specialized mouth parts (Kleeman, 1984). Also, several examples of apparently thalassinid burrows have been associated with ancient hardgrounds (Bromley, 1967; Bromley, 1968; Fursich and Palmer, 1975). Notably, these are generally interpreted as having been emplaced in the sediment prior to lithification. In short, excepting *U. operculata*, no modern crustaceans are known to bore into hard substrates.

Admittedly, Willapa Bay represents a small database to which the ancient record may be compared. At the bay, however, no notable exceptions to the firmness relationships previously outlined have been observed. Some of the reasons for preferential colonization of relatively softer firmgrounds are intuitive. The energy expenditure dispensed in excavating a burrow, for example, increases with firmer substrates (in already consolidated sediment). Larval recruitment may also be affected by the firmness of a substrate.

These factors (energy expenditure and larval recruitment) do not necessarily explain the field observations already outlined. The apparent preference of *Polydora proboscidea* for slightly softer firmgrounds is unclear. Other species of *Polydora* (*P. giarda, P. convexa, P. pygidialis, P. limicola, P. ciliata* and *P. ligni*) have been observed in substrates that range from mud, to wood, to shell, to rock (Lagadeuc, 1991; Guenther, 1996; Sato-Okoshi and Okoshi, 1997). Sato-Okoshi and Okoshi (1997) note, however, that in Barkley Sound there are boring and non-boring species of *Polydora*.

Upogebia pugettensis has been observed burrowing into consolidated mud at other locations along the coast of Washington. The earliest documentation of this phenomenon was provided by Stevens (1929). Despite a number of similar reports, no database of relative or absolute firmness has been accumulated; speculation regarding global firmness preferences is therefore impossible. Similar inadequacies apply to the database of *Petricola* occurrences.

At Willapa Bay, firmness is predominantly controlled by the relative age of the Pleistocene unit exposed in intertidal and subtidal zones. 'Younger' Pleistocene deposits (100 000 to 200 000 y.b.p.) are normally characterized by firmness measurements of 10^7 to 10^8 Pa. Relatively older strata (not reliably dated) commonly exceed 10^9 Pa. Other factors include the rate of erosion into Pleistocene strata and the length of exposure to modern processes. The duration of this study was not long enough to assess these factors.

Because firmness measurements reflect crosscutting relationships in the ancient strata, their distribution is not related to the geometry of the modern depositional system. Like textural variation, firmness variability overprints the aforementioned intertidal zonation and bathymetric relationships. In general, the effects of relatively firmer substrate include an absence of burrowing by crustaceans, more common bivalve colonization, the presence of sporadically distributed polychaete burrows, and more abundant encrusting epifauna, primarily consisting of barnacles and small anemones.

In summary, various *Glossifungites* surfaces at Willapa Bay are characterized by certain associations of trace-making organisms (Table 6.1). Subtidal occurrences are dominated by the *Upogebia* Association. Depending on the firmness and texture of the exposed substrate, firmgrounds exposed in the lower and middle intertidal zones are characterized by either the *Upogebia* or *Petricola* Association. Upper intertidal zones are most commonly colonized by the diminutive burrowers that comprise the *Polydora* Association. Intermediate between the middle and upper intertidal, a transitional *Petricola* Assemblage may be present (Fig. 6.5). Lateral variation overprints bathymetric and intertidal zonation and is attributed to variations in grain size and firmness. Other factors, such as wave energy, salinity and salinity fluctuations, and oxygen content must play a role as well. These parameters have not been characterized for the different associations outlined in this paper.

Recognition of these spatial variations should help interpret lateral variation of *Glossifungites* surfaces in the rock record. Variation in the burrow architectures present will aid in discerning *Glossifungites* surfaces generated in different intertidal zones from those produced in subtidal deposits. Some ancient examples of *Glossifungites* surfaces are provided in Figure 6.1. Although these examples have been taken out of context, the interpretations provided in the figure captions demonstrate the potential utility of this data.

Pleistocene **Glossifungites** *Surfaces*

The majority of the *Glossifungites* assemblages observed in the Pleistocene deposits at Willapa Bay are comprised of *Thalassinoides*. In the modern bay, similar traces are produced by *Upogebia pugettensis*. Ancient examples of similar assemblages include several Cretaceous examples from the Western Canadian Sedimentary Basin (MacEachern et al. 1992; Pemberton et al., 1992; Pemberton and MacEachern, 1995; Fig. 6.1) and occurences of *Glyphichnus* observed at the Cretaceous to Palaeocene unconformity in southern England (Bromley and Goldring, 1992). Modern intertidal analogs have been observed at Willapa Bay, Puget Sound (Stevens, 1929), and along the Georgia coast (Pemberton and Frey, 1985).

Pleistocene *Glossifungites* surfaces are generally subtidal, mostly occurring at the base of tidal channels (Fig. 6.13). Intertidal examples have also been documented. As observed with the *Upogebia* Association, these burrows descend through a shelly sediment veneer that is situated immediately above the erosional surface. Two taphonomic biases explain the overall abundance of this association in the rock record: firstly, subtidal channels tend to migrate laterally, allowing estuarine point-bars to prograde over *Glossifungites* assemblages; and, large, deep-penetrating crustacean burrows are protected from complete eradication if erosional processes continue.

Glossifungites surfaces more akin to the *Petricola* and *Polydora* associations are locally present in ancient intertidal deposits at the bay (Fig. 6.14). These consist of large, open excavations that are commonly filled with shelly debris, rare *Thalassinoides*-dominated assemblages, or stressed assemblages comprised of minute *Skolithos* and *Arenicolites*. The more robust assemblages are interpreted to represent surfaces developed in the lower to middle intertidal, whereas the diminutive assemblages, which are analogous to the *Polydora* Association, are interpreted as being characteristic of the upper intertidal. The poor lateral continuity of these surfaces probably reflects the firmground's susceptibility to erosion in upper intertidal zones.

In short, *Glossifungites* surfaces are commonly preserved in outcrop at Willapa Bay. Modern analogs support the paleontological and sedimentological information gathered from outcrop observations, illustrating the potential for application of this data to more ancient rocks. Taphonomic biases are also considerable, a factor that may not be uniformitarian where considering *Glossifungites* assemblages in more ancient rocks.

TOPOGRAPHY OF THE MODERN GLOSSIFUNGITES SURFACES

At Goose Point and Pickernell Creek, the topography of the modern firmground is characterized by two steps. These are present below a sediment veneer and are locally mappable (Fig. 6.12). The origin of these steps is somewhat uncertain, however, two hypothesis are most likely. The first suggests that the stepped topography results from changes in base level due to plate flexure associated with mega-thrust earthquakes. A second thesis relates each successive step to different orders of tidal creek erosion. It is also possible that both processes contribute to the morphology of this surface.

In subducting tectonic regimes, particularly those characterized by sporadic (sticky) plate movement, accommodation space is reduced due to upwards plate flexure. This is followed by sudden subsidence (potentially metre-scale) during mega-thrust earthquakes (Atwater, 1987; Rogers, 1988; Atwater and Yamaguchi, 1991; Atwater and Hemphill-Haley, 1997). Along the British Columbia and Washington coasts, mega-thrust earthquakes have been demonstrated to occur every 300 to 700 years, probably throughout the Holocene (Rogers, 1988; Atwater and Yamaguchi, 1991; Atwater and Hemphill-Haley, 1997). Although no Pleistocene data is available, it is proposed that fluctuations of base level due to the aforementioned processes could generate stepped firmground surfaces (Fig. 6.16). Tsunamis generated from megathrust earthquakes might rapidly alter the bay configuration as well. Such changes may induce stepped erosion in the firmground as well.

Unfortunately, no reliable means of dating the successive steps is known to the author. Furthermore, no obvious analogs are present in the Pleistocene outcrop. A notable exception to this is a sandy intertidal deposit at Goose Point (Fig. 6.17). This deposit is characterized by a *Thalassinoides*-dominated *Glossifungites* surface. These trace fossils are interpreted to have colonized the ancient firmground following an earthquake. Evidence for this is based upon the following: semi-brittle disruption of otherwise continuous mud beds; locally contorted sedimentary structures and trace

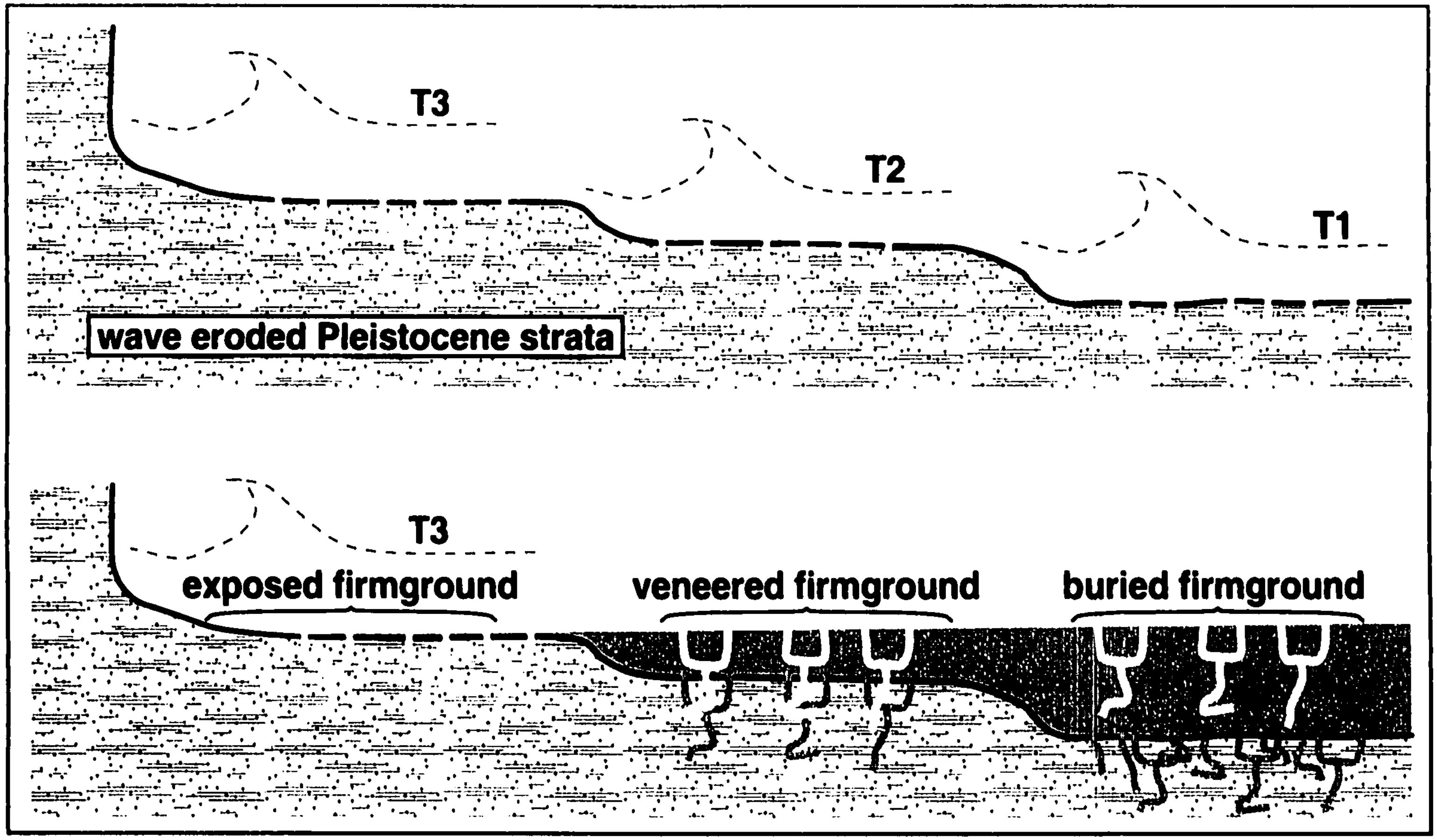

FIGURE 6.16 - Schematic representation outlining the development of a steppedfirmground/*Glossifungites* surface. Different base levels during T1, T2, and T3 might result from post seismic subsidence. Following each subsidence interval, Pleistocene sediment is truncated by a wave-erosion surface. Lower wave cut notches are concurrently covered by a sediment veneer.

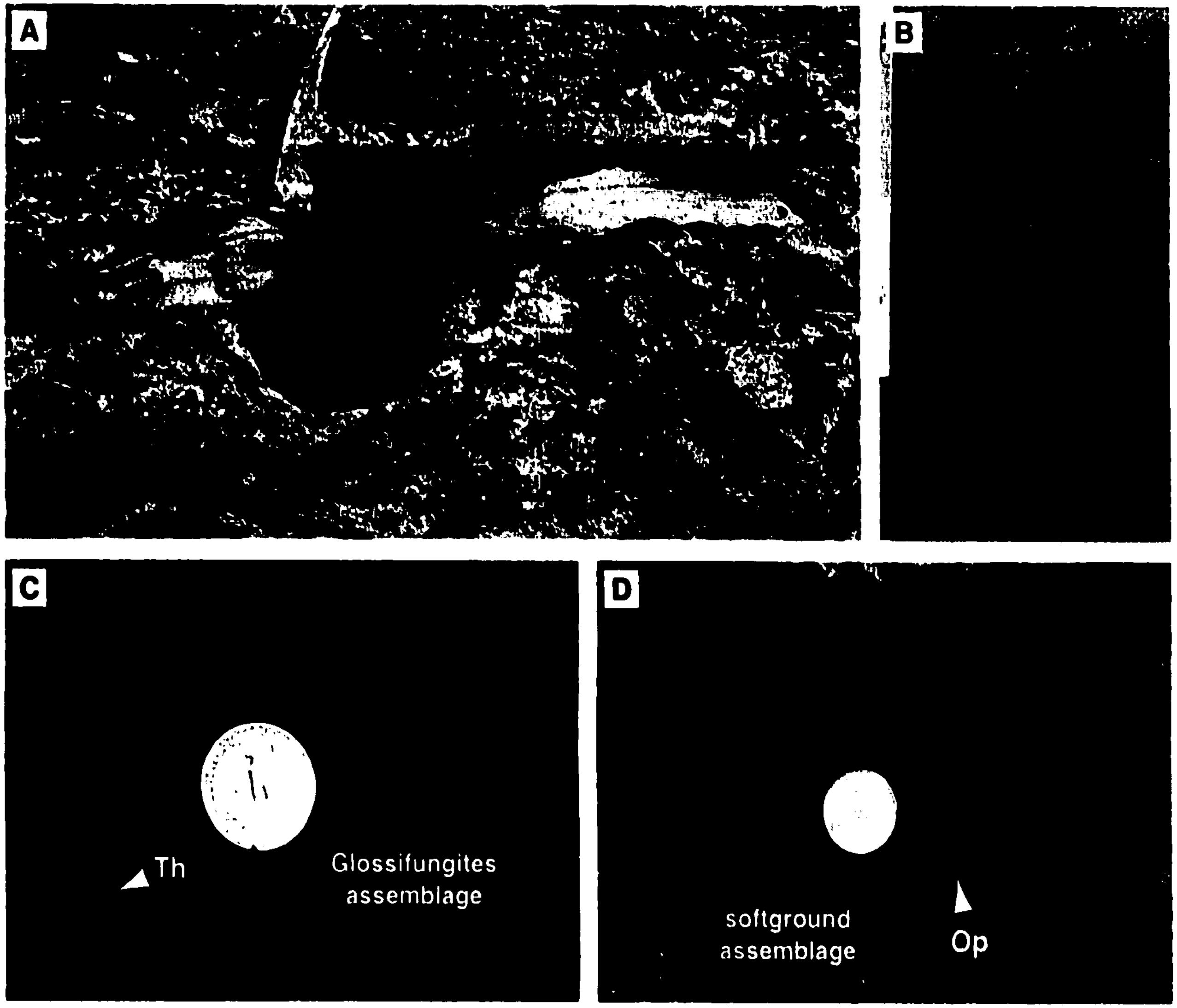

FIGURE 6.17 - Evidence for tectonic disturbance of Pleistocene sediments at Goose Point. (A) Disrupted and convolute laminae in a sandy intertidal flat deposit. Muddy interbeds are broken and disrupted as opposed to convolute. (B) The softground assemblage, like the disrupted mud interbeds, are chaotic and locally deformed. --->

(cont.) (C) Muddy interbeds are reburrowed by robust *Thalassinoides* (Th) that are filled with sand derived from 35 cm above. These burrows are unlined and are undeformed. These are interpreted to have been emplaced following seismic disruption. (D) Where the softground suite of trace fossils is preserved, the burrows are commonly lined and filled with sand identical to that present in the matrix.

fossils; and, a sharp upper bounding surface overlain by undeformed and burrowed sand (Fig. 6.17).

Differential depths of down-cutting may also be attributed to erosion by different orders of tidal creek down-cutting (Fig. 6.18). Although this might explain the firmground topography, a number of observations do not support this concept. Firstly, there is generally little correspondence between the location of runoff channels and the location of the steps. Also, the steps tend to be more or less shore-parallel, which is best explained by prolonged wave-erosion. Finally, firmground surfaces are generally not present at the bases of intertidal runoff creeks.

The presence of the curious, stepped topography suggests that *Glossifungites* assemblages produced in intertidal environments develop complex (ichnological) crosscutting relationships (Fig. 6.18). Sudden subsidence (or rapid retrogradation) of the bay's shoreline, allows the sediment veneer to increase in thickness, subjecting the firmground to different levels of burrowing activity. Also, the transition from exposed to veneered firmground, if induced suddenly, can allow overprinting of different *Glossifungites* Associations.

Steep firmground profiles at Bone River might reflect different erosional processes than those considered for Goose Point and Pickernell Creek. It is also possible that the surface is stepped, but the length of the probe was inadequate to establish this. The abrupt passing of the firmground below 150 cm provides little information regarding the overall morphology of that surface. Therefore, no interpretation regarding it's origin is provided.

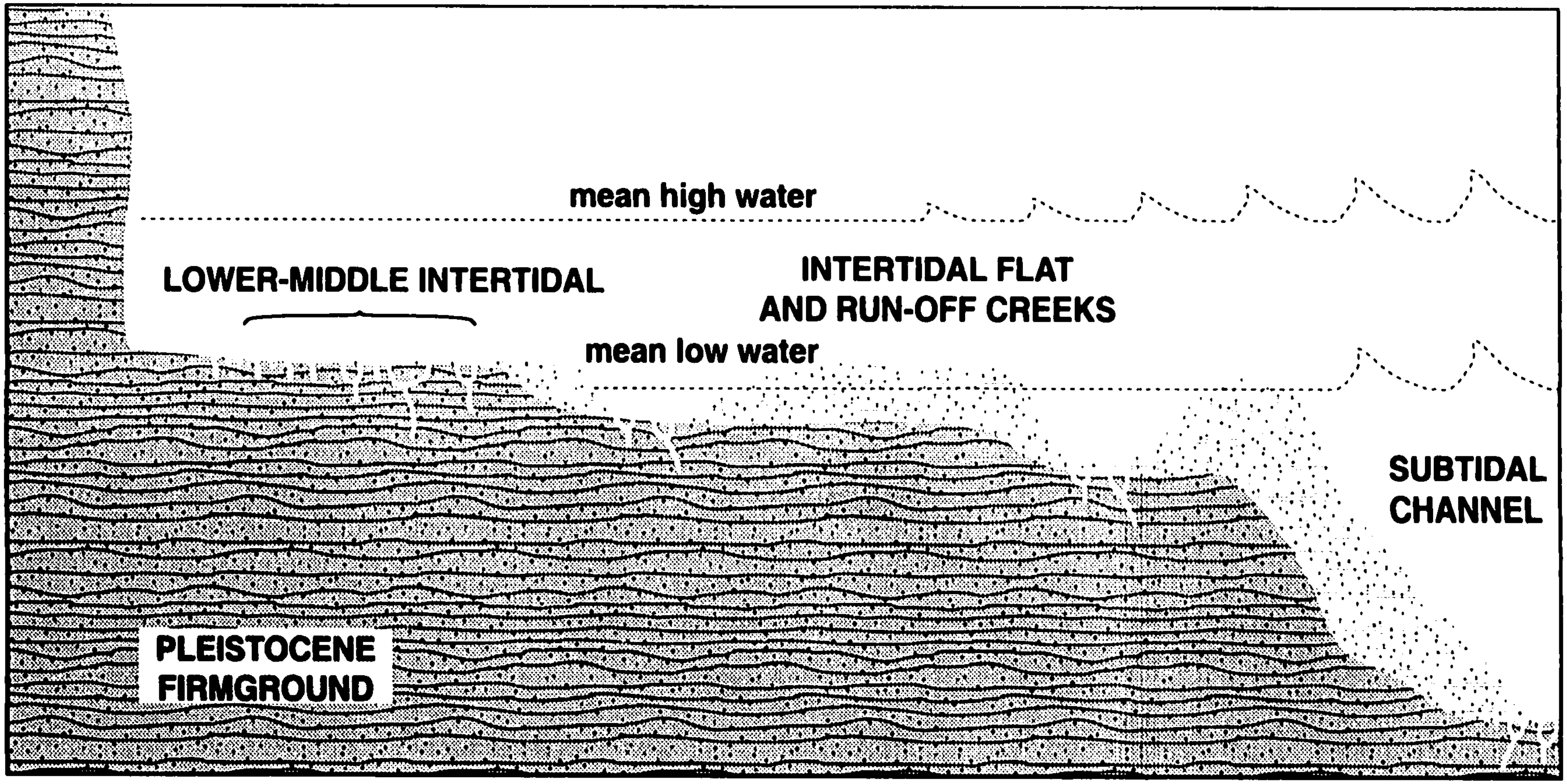

FIGURE 6.18 - Erosion due to different orders of tidal run-off channels might also induce the stepped topography shown in Figure 12. In this case down-cutting due to tidal channel erosion increases baywards, as the size of drainage creek also increases in that direction. *Glossifungites* assemblages are shown developing at the base of these channels. This diagram illustrates that a single *Glossifungites*-demarcated discontinuity can have an extremely complex history, and is commonly correlative to discontinuity surfaces that were exhumed by entirely different erosional processes.

Generally, mapping the structure of an erosional feature is utilized in determining the nature and geometry of a depositional system. Examples of this include incised valley fills (Boreen et al., 1991; Ranger and Pemberton, 1997), and incised shorefaces (Bergman and Walker, 1987; Smith and Jacobi, 1998). These are regional surfaces, however, and the scale of relief detailed in this study would be impossible to map in the subsurface. Regardless, mapping the topography of an ancient *Glossifungites* surface should, in itself, reveal much information regarding the genesis of that surface. Erosional surfaces generated by ravinement, channel erosion, and superimposed tectonic/base level adjustments conceivably impart different morphologies to those surfaces. Provided adequate exposure, the morphology of these surfaces should be discernible in outcrop.

CONCLUSIONS

Glossifungites surfaces impart a great deal of information regarding the rock record. They are extremely useful in stratigraphic applications, especially for the identification of ancient firmgrounds that may have stratigraphic significance. However, due to their stratigraphic utility, the palaeoecological and sedimentological information preserved in *Glossifungites* surfaces is commonly overshadowed. This research focuses on the causes of lateral variability inherent to *Glossifungites* surfaces and their potential subdivision, which is primarily related to intertidal zonation.

Striking variability is evident in *Glossifungites* Assemblages at Willapa Bay. Variation is consistently related to intertidal zonation, sediment texture, and the absolute firmness of the firmground. The presence or absence of a sediment veneer also strongly affects the observed assemblage. Intertidal zonation results from prolonged exposure of the substrate during low tide. Generally, subtidal and lower to middle intertidal firmgrounds are colonized by crustaceans and, more rarely, the bivalve *Petricola*. These surfaces are therefore dominated by the *Upogebia* association, and are characteristically burrowed with *Thalassinoides*- and *Gastrochaenolites*-like traces. The upper intertidal is dominated by the *Polydora* assemblage, the burrows of which include diminutive *Diplocraterion* and *Arenicolites*-like traces. Boundaries between these zones are somewhat gradational, with a poorly developed *Petricola* assemblage locally serving as an transitory element.

At the bay, sandy substrates are avoided by burrowing crustaceans and polychaetes alike, although *Polydora* is observed in deposits that are sandier than those associated with *Upogebia*. Heterolithic substrates, that is, where sand is intercalated with mud, are not burrowed by either. In contrast, *Petricola* is observed in both muddy and sandy-mud substrates, and, more rarely, in heterolithic substrates. These substrates are commonly characterized by the clavate, *Gastrochaenolites*-like burrows produced by these bivlaves.

The absolute firmness of exhumed firmgrounds is quite variable. At the bay, the firmness of younger Pleistocene strata typically ranges between 10^7 and 10^8 Pa, whereas older Pleistocene strata normally exceed 10^9 Pa. The *Upogebia* association is absent in substrates that exceed 10^9 Pa. *Polydora*-dominated assemblages are poorly developed in similar firmgrounds. The *Petricola* association, however, is well-developed in relatively firm substrates, and therefore represents the most common burrowing assemblage in such substrates. Therefore, more robust *Thalassinoides*-like traces are absent in sediment that is characterized by firmness values exceeding 10^9 Pa, as these substrates are dominated by small *Diplocraterion*- and *Gastrochaenolites*-like burrows.

Where sediment veneer exceeds 1 cm, it is generally detrimental to the development of a *Polydora*-dominated assemblage. The *Petricola* association is generally inhibited where the veneer exceeds 10 cm. Only the *Upogebia* association is unaffected by the presence of a thick sediment veneer, however, the presence of soft sediment sharply overlaying firm sediment influence which part of the burrow might be preserved in the firmground. The presence or absence of certain burrow architectures in ancient firmgrounds should reveal whether or not a sediment veneer was present above that firmground at the time of burrow emplacement. Furthmore, it is worth noting that the entire burrow is commonly not neccessarily preserved in an a fossil firmground, rather some portion of it existed in the sediment veneer above. Taphonomic considerations indicate that only the portion of the burrow that descends into the firmground might pass into the historical record.

Textural and firmness characteristics are inherited from other, older depositional configurations. They therefore cross-cut intertidal zonation and perturb the predictable succession attributed to the duration of tidal inundation, which normally exhibits a shore-parallel orientation. This data may be useful in determining the degree of induration an ancient firmground exhibited at the time of exposure to burrowing fauna, and it should also help better resolve palaeogeographic issues in ancient estuaries.

The Pleistocene examples illustrate that ichnofossil assemblages, similar to the trace associations presented herein, can be identified in the rock record. They also show that there is a decided taphonomic bias towards those assemblages that are deep-penetrating. Occurrences of *Glossifungites* surfaces dominated by *Thalassinoides* provide the most commonly observed trace fossil assemblage present in the Pleistocene outcrop. Subtidal assemblages are more commonly observed in the outcrop, these are generally ichnologically similar to the *Upogebia* association. However, many examples of intertidal *Glossifungites* surfaces are present as well. More ancient analogs demonstrate that similar *Glossifungites* ichnofacies are present in the rock record and are, to a degree, amenable to the interpretations derived from this modern study.

Finally, the morphologic characteristics of exhumed firmgrounds show that *Glossifungites* surfaces are dynamic. They are exposed to different physico-chemical conditions as they are exhumed, colonized, and pass into the rock record. Also, they are potentially re-exhumed due to auto- and allocyclic processes. The small-scale topography present on a surface is related to the processes that exposed it, in this case tectonic adjustments, ravinement, and potentially channel erosion. However, a comprehensive study regarding the morphology of similar surfaces below sediment veneer is required before this data can be applied to the rock record. Such an endeavor should consider different sedimentary environments, particularly those related to shorelines and bays.

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CHAPTER 7: ASSESSING THE ANISOTROPIC PERMEABILITY OF *GLOSSIFUNGITES* SURFACES[1]

INTRODUCTION

Ichnology, the study of the 'tracks, trails and burrows' made by animals in various substrates, has provided insight into the way sedimentary accumulations are interpreted by Earth scientists. Ichnologists recognize that a number of factors influence the trace assemblage observed in a depositional environment. An understanding of ichnology therefore provides insight into the nature of sedimentary deposits not possible through a strictly physical interpretation.

The utility of trace fossils is not limited to paleoenvironmental interpretation. For example, recent work has shown that ichnology is important in delineating surfaces that may have stratigraphic significance (Pemberton and Frey, 1985; MacEachern and Pemberton, 1992; Pemberton and MacEachern, 1995). In particular, the *Glossifungites* ichnofacies is used to demarcate burrowing into firm substrates (firmgrounds) which may be exposed where sediment accumulations are exhumed during erosional changes in sea level. Detailed discussions regarding the development of *Glossifungites* surfaces are presented by Pemberton and Frey (1985), and MacEachern and Pemberton (1992).

Because of their discretely packaged permeable fill, *Glossifungites* surfaces can enhance the permeability of a relatively impermeable substrate. Permeability enhancement occurs where open burrows emplaced into a firmground are infilled with sediment exhibiting textural characteristics distinctly different from the matrix. In such instances *Glossifungites* surfaces potentially alter the physical character of subsurface hydrocarbon reservoirs. The ability to characterize the resulting effective permeability provides a reservoir development tool that may be applied in a predictive or qualitative framework. However, the problem of determining effective flow parameters (such as permeability) in such highly heterogeneous media is difficult. This is an especially important consid-

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[1] A version of this chapter has been accepted for publication by Petroleum Geoscience as "Assessing the Anisotropic Permeability of *Glossifungites* Surfaces", by Murray K. Gingras, S. George Pemberton, Carl Mendoza, and Floyd Henk.

eration when heterogeneous elements, such as sand-filled burrows, are discrete and continuous. Such conduits essentially bypass the groundmass, controlling virtually all of the fluid flow parameters. The aim of this chapter is to employ different testing and modeling methods to propose a set of simple criteria that can be used to evaluate the impact that a 'typical' *Glossifungites* surface might have on effective permeability. Key to this is the determination of the effective vertical permeability (k_v), and the effective horizontal permeability (k_h). Assessment of the effective permeability should be based on quantifiable characteristics of the bioturbated media, including the permeabilities of the matrix (k_m) and the burrows (k_b), trace fossil connectivity, and burrow density.

The field portion of this study included outcrop mapping, sampling, studying modern burrows, and slug testing at Willapa Bay. The bay lies on the southwest coast of Washington state, just north of the Columbia River delta. Willapa Bay was chosen because extensive Pleistocene- and modern-*Glossifungites* surfaces are present in and around the bay (Clifton and Phillips, 1980).

The mud shrimp *Upogebia pugettensis* colonizes modern *Glossifungites* surfaces at Willapa Bay. Their burrows are similar to those observed in Pleistocene outcrop at the site (Fig. 7.1). *U. pugettensis* colonizes the modern intertidal mudflats and portions of the northernmost Palix channel (Fig. 2.1) where firmground has been exposed. The firmground extends over a large area (2 km^2) that is comparable in size to a small clastic reservoir. It is important to note that this ichnofacies is typically channel- and shoreline parallel and therefore has a predictable geometry depending on its sedimentary facies association. Ancient and modern deposits at Willapa Bay demonstrate the persistence of *Glossifungites* surfaces, their potential for preservation in the rock record, and the overall extent to which burrowed firmgrounds may be present in the subsurface.

Firmground development below transgressing beaches has also been documented (Pemberton and Frey, 1985). In such instances, burrowing crustaceans aggregate in linear pods in the middle to lower intertidal environments (Granberg, 1995). These elongate

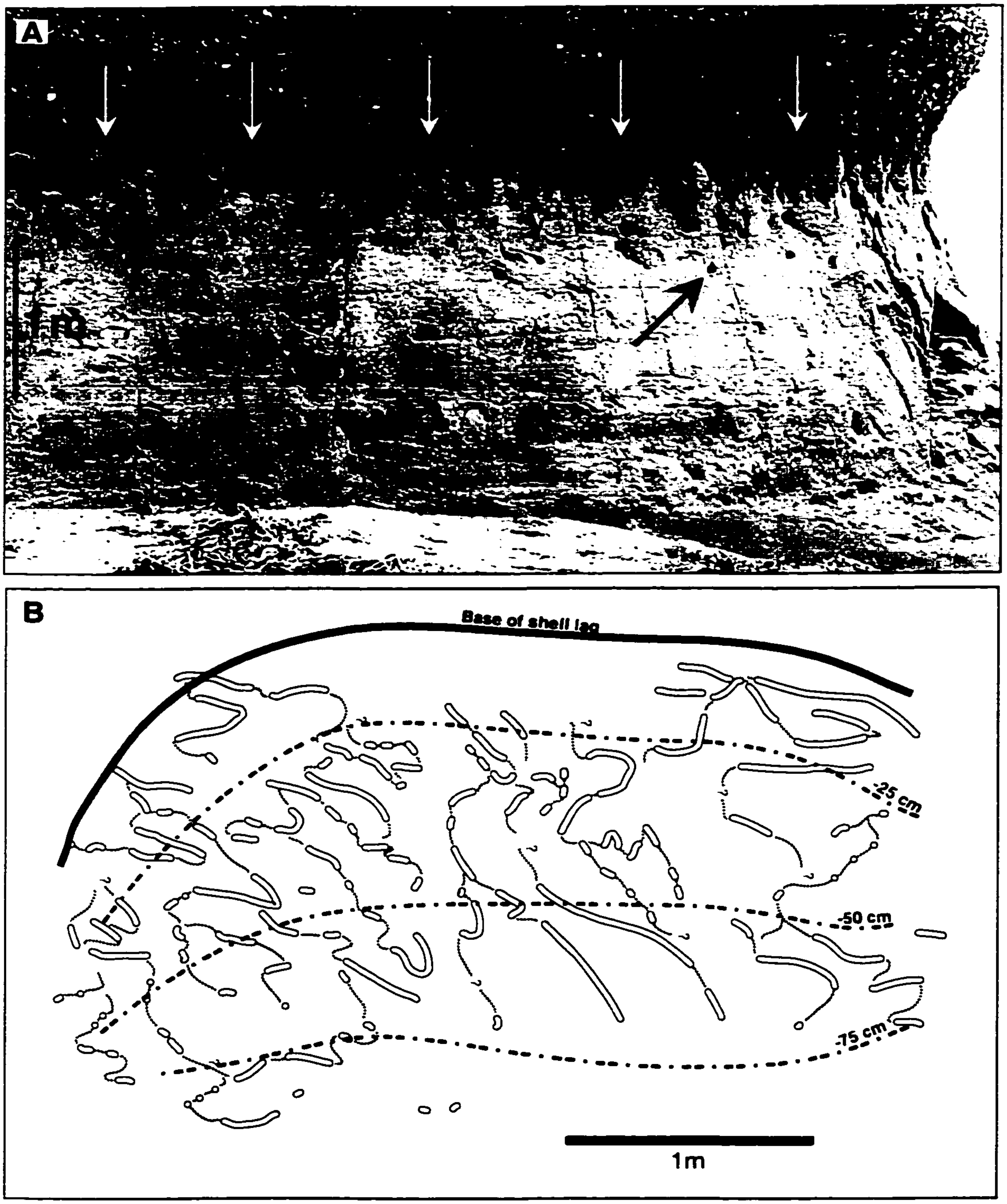

FIGURE 7.1 - Pleistocene examples of *Glossifungites* surfaces from Willapa Bay. (A) A Glossifungites surface demarcated by large diameter crustacean burrows which are filled with sand from the overlaying shelly deposit. (B) Schematic illustrating the degree of interconnectivity present in these burrowed substrates.

pods are aligned parallel to the shoreface; thus, both their location and geometry are predictable.

Method

This study consists of three components: characterization of trace fossils and burrow systems in three dimensions; assessment of the effective permeability using computer, laboratory, and field techniques; and, conceptual modeling of stratigraphic and reservoir configurations to illustrate the potential importance of these surfaces.

Burrow Characterization

The geometry of the shrimp-burrow systems (i.e., *Upogebia pugettensis*) was spatially resolved by integrating outcrop data with resin casts and field observations of modern burrows. The Pleistocene outcrop at Willapa Bay provides excellent two-dimensional data which was utilized to generate burrow maps (Fig. 7.1). Resin casts of burrows from modern environments provided three-dimensional data to supplement the outcrop observations. These databases formed the basis for the simplified models that were integrated into the hydrogeologic model.

Computer Simulation

Effective permeability characteristics of *Glossifungites* surfaces were assessed using a finite difference fluid flow model (MODFLOW) written at the United States Geological Survey (McDonald and Harbaugh, 1988). A three-dimensional grid was constructed with dimensions of 1.0 x 1.0 x 0.8m and was discretized such that each finite-difference cell was 0.02 m on a side. As discussed later, various burrow networks were defined within this grid and then the effective vertical and horizontal permeabilities (k_v and k_h) of the block were determined by assigning a known head difference across the grid (Fig. 7.2), calculating a gross flowrate, and then applying

Darcy's Law to back-calculate the effective k_i for the block. This procedure is conceptually analogous to that used for determining effective permeabilities for packages of layered porous media (Freeze and Cherry, 1979). An underlying assumption was that all the burrow fills had similar permeabilities. This is normally true with *Glossifungites* surfaces because they are filled with sediment derived from the overlaying sedimentary package. All the burrows therefore share lithologically identical fill.

Three variables were considered to effect significant changes in horizontal and vertical effective-permeability: burrow morphology and the degree of connectivity; the degree of contrast of permeability between the substrate and burrow fills; and, burrow density in a bioturbated horizon. All of these parameters were varied with the exception of burrow morphology, which was modeled after burrow architectures consistently observed in modern and ancient deposits at Willapa Bay. A total of 104 simulations were executed. Eighty of these tested systematic changes in connectivity, burrow-fill permeability, and burrow density. The remaining 24 simulations tested extremes, such as the degree of bioturbation.

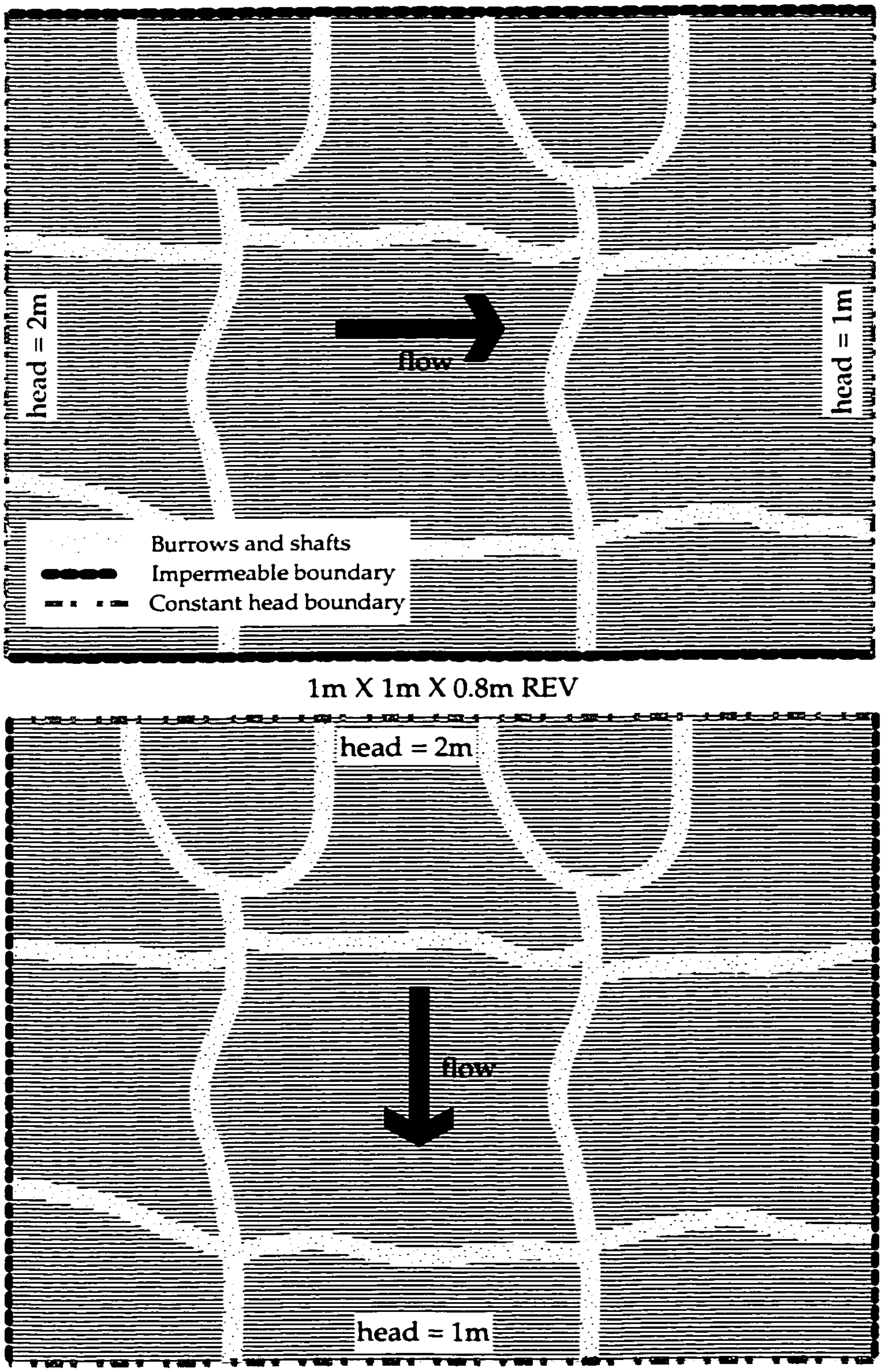

FIGURE 7.2 - A schematic representation of the computer model's configuration and boundary conditions.

Laboratory Flow Experiment

A block (25 x 18 x 20 cm after trimming) was cut from the Pleistocene *Glossifungites* surface at Willapa Bay. Water-distribution flanges were attached to the top and bottom of the block, which was subsequently cast in fiberglass resin. Inlet and outlet tubes were tapped into the flanges and piped into the laboratory tap-water. Steady-state flow under a constant head gradient was attained in approximately 24 hours. Measured parameters were such that Darcy's Law could be applied to calculate k_v.

Independent values for burrow fill- and matrix-permeability were determined using a constant head permeameter. The samples of porous media for these tests consisted of either burrow or matrix sediment that had been mechanically separated and repacked into columns. Fractional burrow volumes (V_b) for the lab sample were estimated visually.

Slug Test

Five separate slug tests were conducted on an exposed Pleistocene *Glossifungites* surface. The exposure contained ancient sand-filled burrows that descended approximately 2m into a silty clay substrate, and was not burrowed by modern animals. Slug tests are a common hydrogeologic tool for estimating in situ permeabilities of porous media. The basic method involves rapidly adding a slug of water to a piezometer and then monitoring the rate at which this imposed head decays over time as water bleeds into the formation. To implement the method at the site boreholes were drilled to a 1.3m depth and stand pipes were installed. Clay packing was tamped into the boreholes to provide a seal. Although the packing typically exceeded 30 cm depth, it failed on two of five tests. The stand pipe was filled with salt water and the elevation head was measured and recorded for 2 to 4 hours. Tests were conducted at low tide. The resulting data were analyzed using the Bouwer-Rice solution (Bouwer, 1989) which is suitable for an unconfined aquifer. Burrow volumes were estimated in the field by placing a metre/ decimetre-grid on the firmground and calculating the areal burrow density.

RESULTS AND DISCUSSION

Burrow Models

Resin casting methods proved to be an effective means of gathering dimensional data for modern burrow systems. *Upogebia* burrows from the modern mudflats at Willapa Bay are comprised of a U-shaped burrow, extending from the sediment-water interface, connected to a single vertical shaft, which descends down from the center of the U-tube (Fig. 7.2). The basal portion of the vertical shaft typically runs oblique to horizontal at the basal terminus, which generally occurs at 50 to 80 cm depth. Both soft and firm substrates may be colonized by *U. pugettensis*, in either case the burrow geometries are similar. The burrow configurations observed at Willapa Bay are similar to *Upogebia* traces from Mud Bay, near Tsawassan, British Columbia, as described by Swinbanks and Luternauer (1987).

Although active *U. pugettensis* burrows are typically isolated from one another (Swinbanks and Luternauer,1987), trenching of the firmground indicated a high degree of interpenetration between active and abandoned burrows. Connectivity primarily occurs in two zones, the basal horizontal sections of the burrow and the upper 'U' portion of the burrow. Figure 7.1B illustrates the degree of connectivity of burrow systems at Willapa Bay. In this obliquely eroded section two zones of branching are apparent at about 25 cm and between 50 and 75 cm depth. Plotting the trace fossil distribution from other outcrop data showed that interpenetration was most common between 15 to 25 cm and 65 to 75 cm below the palimpsest horizon. The volume of burrow fill compared to matrix is approximately 2%. Complete assessment of the true degree of connectivity was not possible from the two-dimensional outcrop data. For this reason, the model was designed to simulate isolated, partially-, and fully-connected burrow systems.

The diameter of modern *Upogebia* burrows observed at Willapa Bay normally ranges from 12 to 23 mm. In contrast, Pleistocene occurrences have a mean diameter of 22 mm. For modeling purposes, an equivalent diameter of 22.6 mm (20 mm square) was used.

Computer-Simulated Flow Through Glossifungites *Surfaces*

Fluid-flow models were simulated by methodically altering three variables: the extent of burrow connectivity; the degree of contrast between the permeability of the burrow fill (k_b) and that of the matrix (k_m); and the burrow density in the block.

Burrow Density

Five different burrow densities were simulated in the model (1.0, 2.0, 10, 25, and 50%). The lower values were based on modern and ancient observations, whereas 25 and 50% examine extreme degrees of bioturbation. Changes in burrow density can have a significant effect on the effective permeability. This factor generates the most variability in effective horizontal permeability measurements (k_h), but causes discernible and systematic changes in k_v as well.

Vertical permeability is predictably enhanced by increases in burrow density. As more vertical shafts are introduced into the burrowed horizon, more fluid-carrying channels can be used by ascending or descending fluids. Weaver and Schultheiss (1983) showed that k_v can be strongly dependent on burrow-density if extreme values are used. Their results indicated that open burrows into a clay substrate increased the permeability of the substrate by as much as eight orders of magnitude. The data presented herein do not account for the possibility of open burrow systems and instead focuses on *bioturbated* horizons. Accordingly, the model results indicate that increases in k_v due to increases in burrow density are small. For example, expansion of the number of fluid conduits by 45% only increases the effective permeability by 0.1 to 0.2 orders of magnitude. This difference is measurable, but not of great utility when considering the variability of natural systems. Several simulations showed that k_v values for 1.0% and 2.0% burrow density are essentially equivalent, however, significantly higher degrees of bioturbation (up to 50% by volume) notably increase effective permeability (Fig. 7.3).

As with k_v, values of k_h are similar between burrow densities of 1.0 and 2.0%. Notable enhancement of permeability occurs when extreme values for burrow density are used (25 and 50%; Fig. 7.4).

Burrow Connectivity

Burrow connections within the model were configured in four ways: isolated vertical shafts, vertical shafts connected to one neighbour, vertical shafts connected to two neighbours, and vertical shafts connected to three neighbours.

Determinations of k_v through computer simulations reveal that very little differentiation exists between the k_v's of surfaces dominated by either isolated or connected burrows (Fig. 7.3). In fact, all the calculated values for k_v are co-linear for each population density considered (1 and 2%). This behavior is due to extensive channeling between the upper and lower surfaces inherent in the vertical shaft model.

The degree of connectivity plays a significantly greater role when considering k_h. Unconnected models and those connected to one neighbour exhibit only very small increases in k_h, even when k_b/k_m exceeds six orders of magnitude. However, increasing the degree of networking has a dramatic affect on values of k_h (Fig. 7.4). Fully connected burrows result in an effective k_h that is comparable to k_v. Decreased amounts of burrow networking, however cause the effective horizontal permeability to decrease significantly: surfaces with shafts connected to the two nearest neighbours develop an effective permeability one order of magnitude below k_v, and those connected with one nearest neighbour are characterized by a k_h approaching that of unconnected systems (Fig. 7.4).

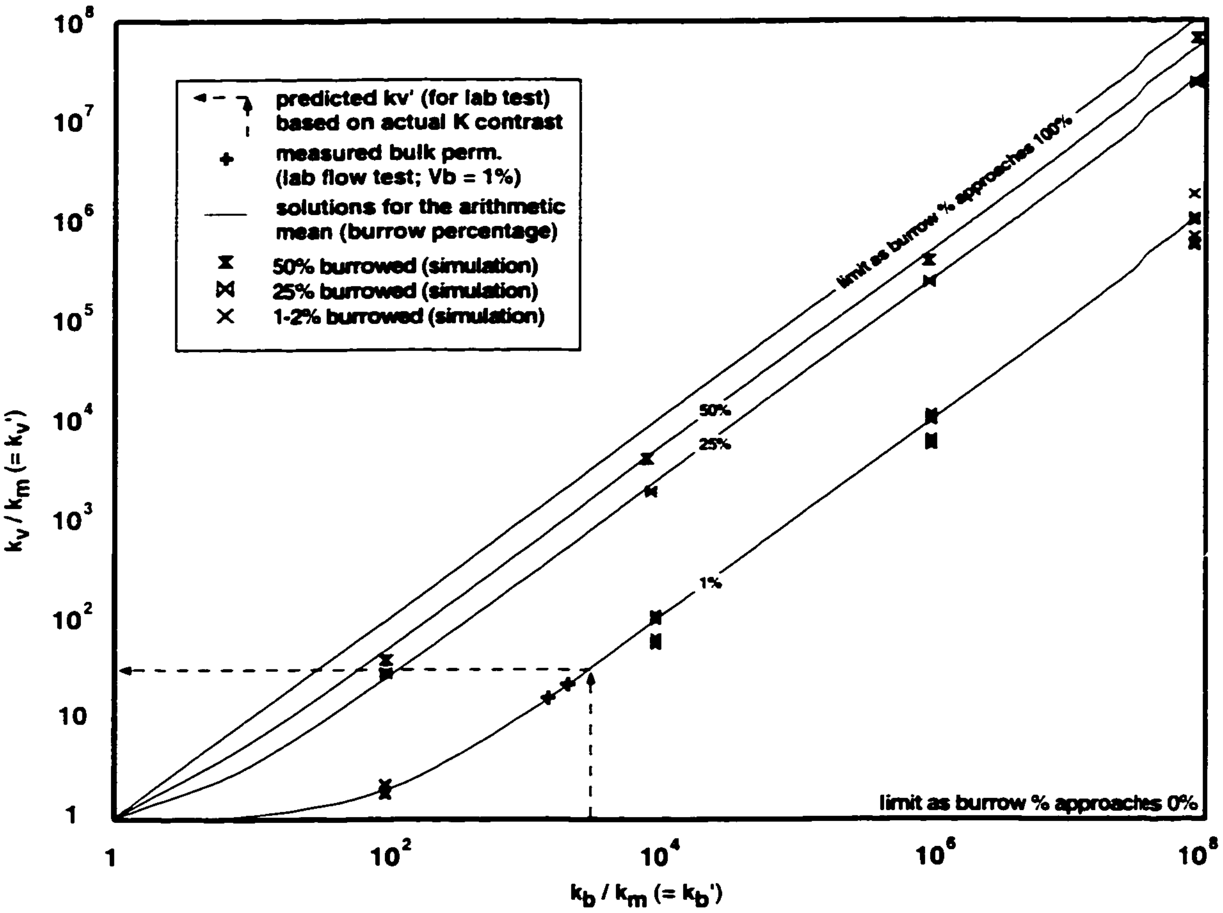

FIGURE 7.3 - Graph of k_v' versus k_b'. These values are normalized by k_m, so that only the permeability contrast is considered. The data shown here indicates that k_v' is reasonably approximated by the arithmetic mean of k_m and k_b. Also plotted on this graph are predicted (dashed lines) and actual k_v' (heavy crosses) based on actual lab experiments.

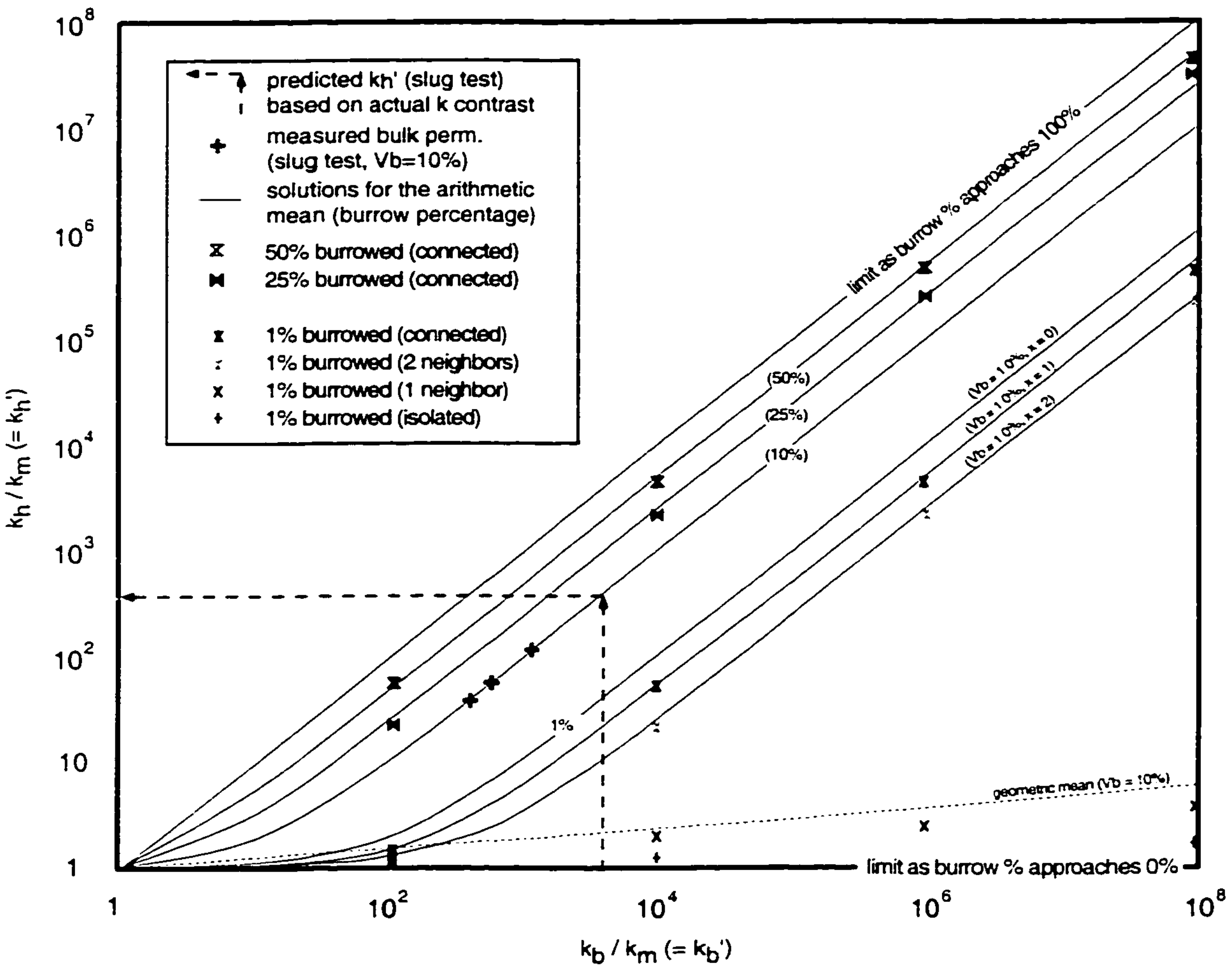

FIGURE 7.4 - Graph of k_h' versus k_b'. As with Figure 3, these values are normalized by k_m. The data shown here indicates that k_v' is reasonably approximated by modifications of the arithmetic mean of k_m and k_b. Also plotted on this graph are predicted (dashed lines) and actual k_v' (heavy crosses) based on actual slug tests.

Permeability Contrast

Various methods of calculating effective permeability can be applied to heterogeneous media. Weighted arithmetic and harmonic means best describe effective k's for flow along and across layering, respectively, in perfectly stratified media (Freeze and Cherry, 1979). Geometric means best describe the effective k for uniformly random media (Gelhar, 1986).

Values of k_v increase proportionally with increases in k_b (Figs. 7.3, 7.5). Analysis of the numerical simulation results demonstrates that for the field-based morphologies considered here, k_v are reasonably represented by the volumetrically-weighted arithmetic mean of the matrix and burrow permeabilities:

(1) $\log k_v = \log [(1-V_b)\, k_m + V_b k_b]$

where V_b is the fractional volume of burrows within a block.

The correspondence between this relationship and the model results is shown in Figures 7.3 and 7.5. The general applicability of (1) is expected because of the excellent burrow connectivity between the top and bottom boundaries of the block. That is, fluid flow will be dominated by preferential flow through the vertical burrow conduits. In vertical drainage experiments Edwards *et al.* (1990) and Trojan and Linden (1992) showed that earthworm burrows markedly improved soil conductivity, demonstrating a similar phenomena with minute, open burrows.

Horizontal flow, however, is not necessarily aided by extensive links between the sides of the sample, and thus (1) does not always approximate k_h. Plotted values of k_h vs. k_b indicate that although burrow permeability does play a role in determining effective permeability, k_h is strongly influenced by the degree of burrow interconnection. Figure 7.4 shows that for the end-member case of unconnected burrows even extreme permeability contrasts do not favor development of a significantly enhanced k_h. Alternatively,

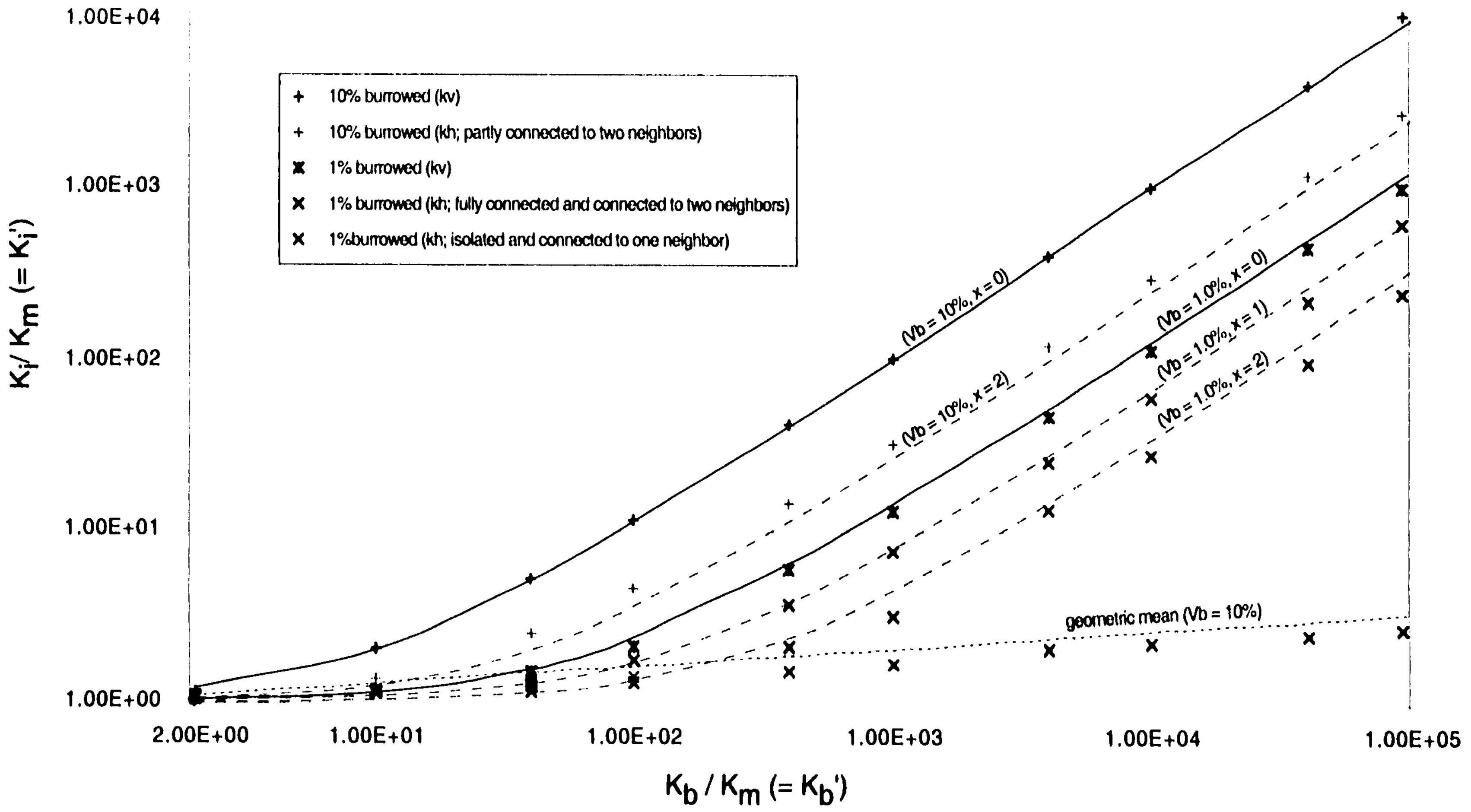

FIGURE 7.5 - Detailed data fitted to the curves generated by Formulae 1, 3a, and 3b. Unconnected and 1-neighbour systems are fitted to the geometric mean where V_b = 10%.

the other end-member case of fully-connected burrows is better-represented by (1) because the connections permit significant lateral flow through the sample, particularly where V_b exceeds 25%.

The horizontal permeability of connected and partly connected simulations best follow the arithmetic mean if the burrow volume is adjusted according to the model's degree of connectivity (Figs. 7.4 and 7.5):

(2) $\log k_v = \log [(1-V_b^*)\, k_m + V_b^* k_b]$

where V_b^* is an effective fractional volume of burrows that actively conduct flow. This factor is given by:

(3) $V^*_b = 2^{-x}\, V_b$

where x = 1 for fully connected systems and x=2 for cases where burrows are connected to two neighbors. Note that (2) collapses to (1) for x=0.

The rationale for (2) is that increased burrow connectivity exponentially increases the number of continuous flow conduits. In burrow systems connected to two neighbours, the likelihood of the presence of continuous flow paths is significantly higher than in 'one-neighbour' systems; one-neighbour systems are by definition characterized by no continuous flow paths and can not be characterized with variations of the arithmetic mean. Somewhat continuous, tortuous conduits are inevitably present in two neighbour systems. Fully connected systems are characterized by box work conduits, all of which may contribute to flow and exhibit a less less tortuous flow path than partially connected systems.

One-neighbour and unconnected systems cannot be characterized in the same way, because burrow pathways do not form continuous channels across the sample or model. In these types of burrow systems, k_h is always strongly dependent upon k_m. Plotted values of k_h for these burrow networks bear this out: no significant enhancement of permeability is developed (Fig. 7.4). The k_h in horizons dominated by low densities of unconnected burrows is poorly characterized by the arithmetic- and harmonic-means. However, the geometric mean (calculated with $V_b = 10\%$) closely describes their behavior (Fig. 7.5). The utility of this relationship is uncertain, given that the enhancement of k_h is almost negligible, even with notable permeability contrasts. Fortunately, surfaces characterized by higher degrees of bioturbation (> 10%) are typically partially connected because of the increased likelihood of chance interpenetration. This is to say the degree of burrowing and the degree of interconnectedness are passively linked. In these instances the arithmetic mean (1) should be considered valid.

Laboratory Flow Tests

Steady-state flow tests were analyzed using Darcy's Law to assess the effective vertical permeability (k_v) of the lab sample. Results from the permeameter tests are presented in Table 7.1:

Description	**k(md)**
burrow fill (k_b; l.med. sand)	$1.2 \bullet 10^4$
burrow fill (k_b; l.med. sand)	$1.1 \bullet 10^4$
matrix (k_m; silty clay)	$2.0 \bullet 10^0$
matrix (k_m; silty clay)	$2.3 \bullet 10^0$
bulk sample (K_v; $V_b = 1.0\%$)	$1.1 \bullet 10^2$
bulk sample (K_v; $V_b = 1.0\%$)	$1.4 \bullet 10^2$
bulk sample (K_v; $V_b = 1.0\%$)	$1.4 \bullet 10^2$

TABLE 7.1 - Calculated values for permeability of burrow fill, matrix, and the bulk sample. All alike tests represent repeat runs.

The laboratory flow test results are plotted against values predicted by the computer model in Figure 7.3. A value for the burrow volume was visually estimated to be 1.0% (by comparison to other measured samples). Values of replicate runs for k_b and k_m provided an average k_b^* (=k_b/k_m) of 5.3 • 10^3 (dashed line, Fig. 7.3), which maps to a k_v^* (=k_v/k_m) equal to approximately 25. Measured effective hydraulic conductivities are about one order of magnitude lower than the predicted values (Fig. 7.3). This small discrepancy is probably due to the small size of the laboratory sample: it is likely that heterogeneities are poorly represented in a block of this size. Overall, however, the data suggest the computer model provides a reasonable prediction of k_v.

Slug Tests

Elevation head-decay curves were analyzed using the Bouwer-Rice Solution for unconfined aquifers (Bouwer, 1989). A number of assumptions had to be made to implement this solution:

1) The saturated thickness of the aquifer is approximately 2m. Other runs varying the thickness between 1 and 2m yielded results within 10% of those using a 2m aquifer thickness.

2) An anisotropy ratio of 1 ($k_v = k_h$) was used. This assumption is supported by the previously discussed computer model if the burrows are partially to fully connected.

3) Smearing effects on the inside of the borehole were negligible.

Of the five slug tests, only runs 2, 3 and 5 were completed without leaking through the clay packing. The results are summarized in the following table;

Run #	**k(mD)**
2	$1.4 \bullet 10^3$
3	$5.1 \bullet 10^2$
5	$7.6 \bullet 10^2$
mean	$8.9 \bullet 10^2$

TABLE 7.2 - Results of slug test curve analysis using the Bouwer-Rice Solution for unconfined aquifers

Slug tests best measure horizontal permeability. Thus the field results are plotted against k_h values predicted by the computer model in Figure 7.4. Measured effective hydraulic conductivities are less than one order of magnitude lower than the simulated values. Sources of error include estimation of V_b^*, heterogeneities in the substrate, and measurement errors. Regardless, the slug test data presented here appear to support the computer model and indicate it's usefulness for characterizing values for k_h in similarly bioturbated horizons.

Conceptual Models

Both primary and diagenetic processes potentially alter or preserve higher porosity and permeability in and adjacent to trace fossils. This is contrary to the commonly held belief that bioturbation in clastic rocks reduces overall permeability (Weber, 1982; Simones and Martin, 1992), and is the result of trace fossils locally introducing heterogeneities to the rock matrix which improve the overall flow characteristics of that rock. *Glossifungites* surfaces provide a striking example of bioturbated substrates that potentially alter the flow characteristics of a reservoir.

Glossifungites surfaces are preserved in many sedimentary environments and hydrocarbon systems. Stacked channel and marine shoreface sand packages provide likely stratigraphic architecture for implementing *Glossifungites* cross-flow. Many of these horizons are situated at the base of channel incisements and shorefaces where compacted, unlithified sediments have been exposed (Pemberton and Frey, 1985; MacEachern and Pemberton, 1992; Pemberton and MacEachern, 1995; Fig. 7.6). In these instances, burrows into the firmground are commonly filled with coarse clastic sediment derived from the channel bed load. Traces descending from the channel bottom may, in certain instances, intersect underlying coarser clastic facies. The coarse clastic unit and burrows may then provide a charging zone for the potential hydrocarbon reservoir. In the absence of a *Glossifungites* surface, the reservoir sand could be bypassed by hydrocarbons. Ultimately, laterally accreted reservoir sands typically pass into a fine grained channel plug, providing a stratigraphic seal for the reservoir. Even if the descending burrows are not in communication with another coarse clastic unit, they may focus local fluid flow beneath the reservoir sand and assist in allowing migration of hydrocarbons into the reservoir. The rate of charge or recharge could be significantly increased by burrowed horizons.

Like an incising fluvial system, a transgressing shoreface may also remove unconsolidated sediment, exposing a firmground. Where a *Glossifungites* assemblage occupies this exposed substrate, robust sand-filled burrows are preserved upon progradation of the shoreface facies (Fig. 7.6). Flooding surfaces overlaying the potential reservoir provide a vertical seal whereas lateral facies changes may provide lateral seals. It is important to recognize that shoreface assemblages are typically oriented parallel to the shoreline and channel assemblages are oriented perpendicular to the shoreline; the *Glossifungites* surfaces therefore have a predictable geometry related to the original depositional environment.

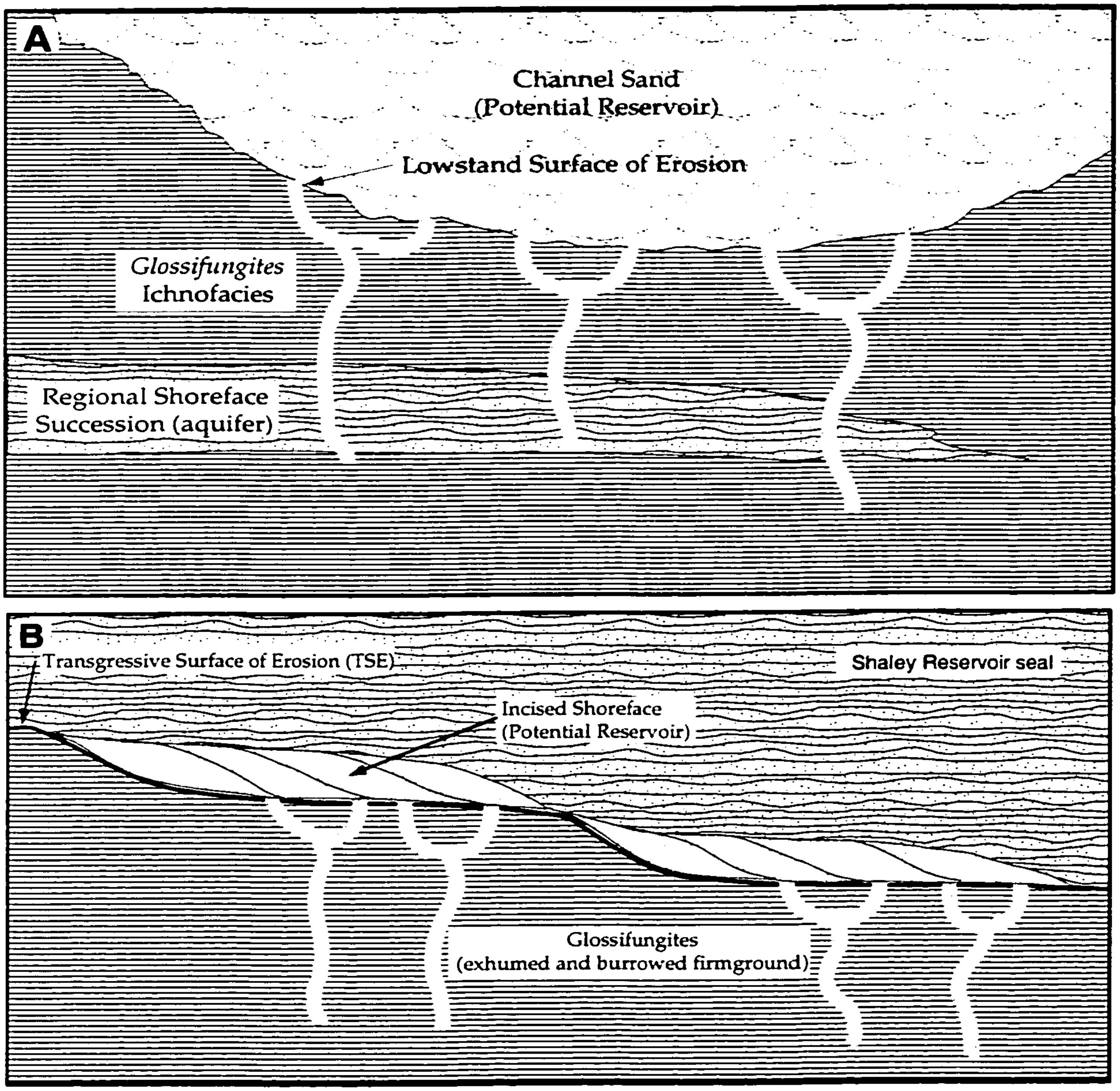

FIGURE 7.6 - Potential stratigraphic configurations of *Glossifungites* surfaces. Not to scale. (A) A *Glossifungites* surface developed below a channel. In this case, the surface intersects a regional aquifer. (B) The burrowed firmground shown in this schematic lies beneath a sharp-based shoreface deposit.

Because the key considerations in applying (1) and (2) are burrow connectivity, and the degree of permeability contrast between the matrix- and burrow-fill, these formulae can be applied to carbonate deposits as well. Dolomitization of burrows in limestone is a commonly observed phenomena (Morrow, 1978: Fig. 7.7) that develops heterogeneity in the limestone matrix (Bromley, 1990). As with clastic sediments, permeability contrasts can span several orders of magnitude. Unlike clastic sediments, burrowed carbonates may be typified by 10's of meters of burrowed and networked sediment. The potential for hydrocarbon development from these horizons is vast (Chow and Longstaffe, 1995) and essentially unrealized. Several stratigraphic configurations are amenable to this type of deposit, although the possibility of diagenetic trapping mechanisms can not be overlooked.

The results of this study indicate that *Glossifungites* surfaces can serve as permeable conduits at the base of a reservoir. Furthermore, *Glossifungites* surfaces may connect

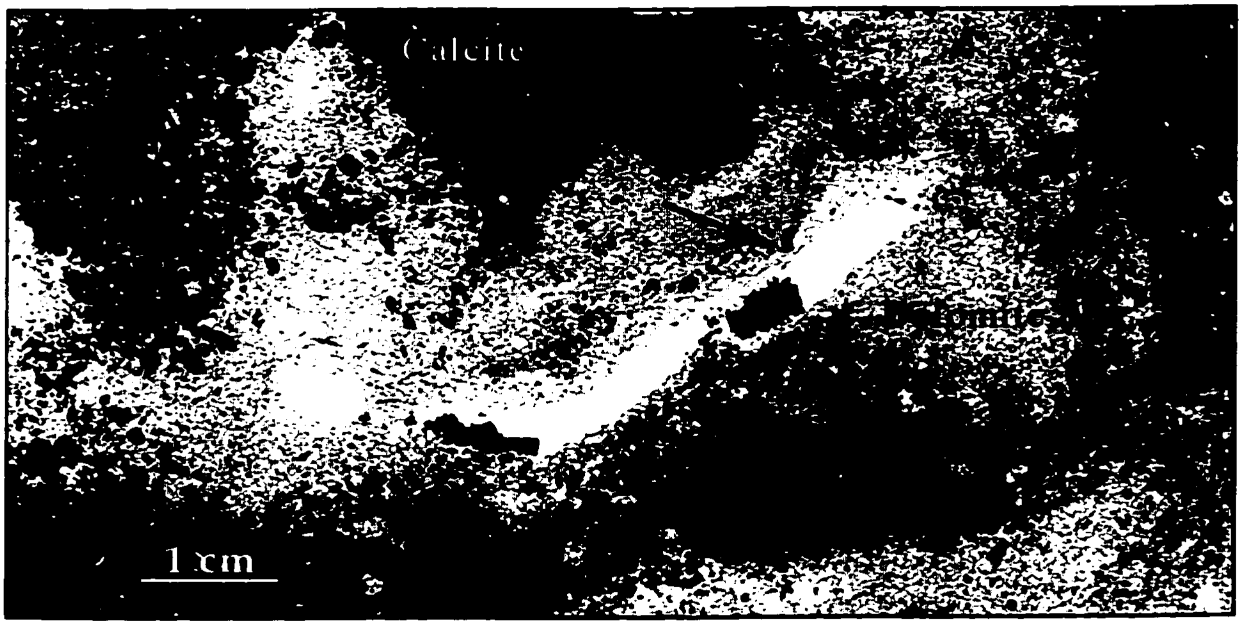

FIGURE 7.7 - Thin section of burrowed limestone where diagenesis has altered the rock mineralogy and texture associated with the matrix surrounding the burrow.

otherwise separate reservoir packages, providing pressure and, or, fluid communication between them. Potentially, these horizons have a role in determining whether a reservoir is charged or bypassed. More importantly, they may influence the effectiveness of secondary recovery techniques, such as water flooding (Fig. 7.8).

Permeable surfaces, characterised by the *Glossifungites* ichnofacies, contribute to reservoir heterogeneity and may pose hydrocarbon production problems. The presence of permeability streaks in a reservoir can lead to early "watering out" and reduce the volume of recoverable oil (Weber, 1986).

The presence of *Glossifungites* burrows also increases the surface area and the potential volume at the base of a reservoir. For instance, the exposed surface area of the

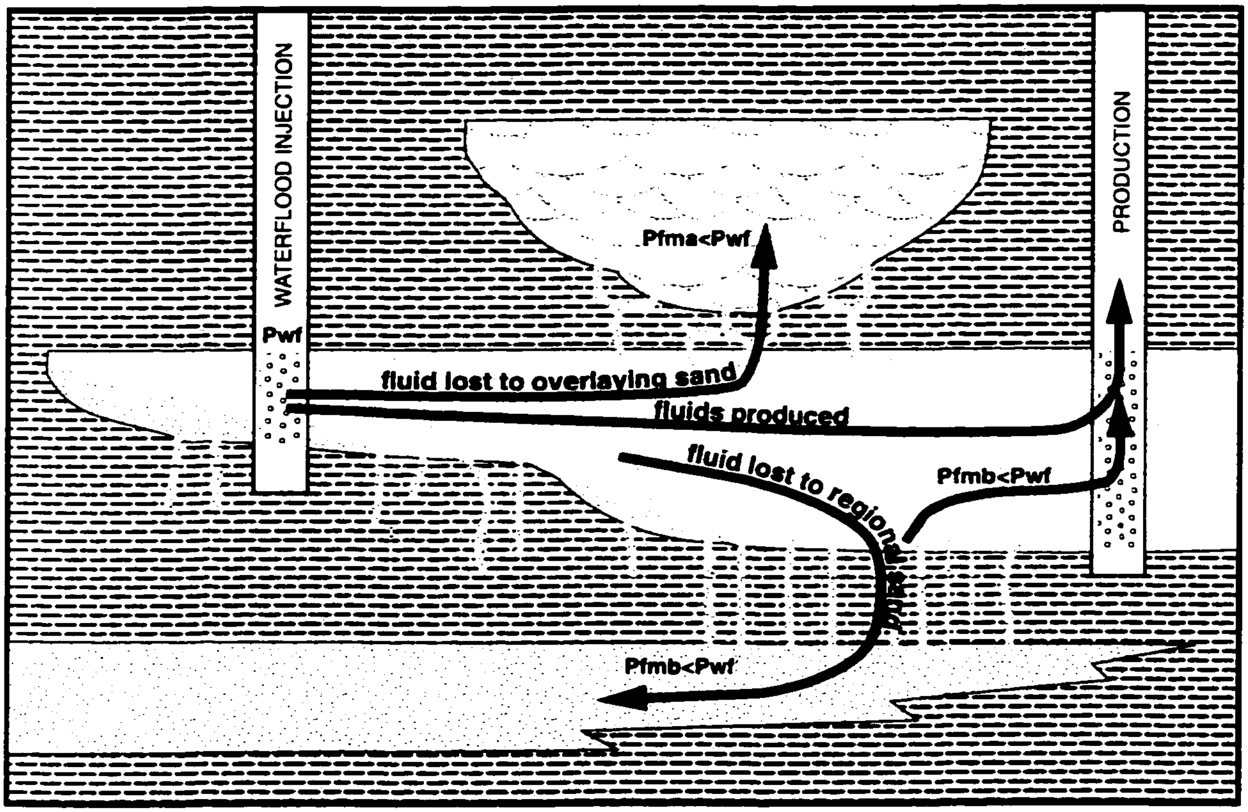

FIGURE 7.8 - Summary schematic of potential stratigraphic associations and their relationship to fluid flow at the reservoir scale. Formation pressure is indicated as Pfm, and relative water-flood pressure denoted by Pwf.

base is doubled by extending 16 burrows/m^2, 2 cm in diameter, 1 m into the substrate. The *volume* is increased by 0.01 to 0.02 m^3/ m^2, where burrow densities approach 32 burrows/m^2. Modern data from Willapa Bay implies burrow densities may approach 120 burrows/m^2, potentially increasing the reservoir volume by 0.05 m^3/ m^2. In extreme cases, *Ophiomorpha*, a robust trace fossil typically attributed to the activities of crustaceans, can occupy up to 43 % of the matrix, by volume (Diller and Martin, 1995). In this example, the volume at the base of a 10000 m^2 reservoir would be increased by 4300 m^3 (1075 m^3 at 20 % ø). These examples illustrate that burrowed horizons not only change flow characteristics within a reservoir, they may have an impact on reserve calculations as well.

CONCLUSIONS

To model fluid flow, a three-dimensional model of burrow networks was conceived and integrated with appropriate flow-modeling software. This paper proposes that a simplified burrow network, consisting of simple branching and varying degrees of connectivity, adequately simulates burrow networks observed at Willapa Bay, Washington. Three variables determine the flow characteristics of a burrowed matrix: the degree of contrast between k_b and k_m; the degree to which burrows are networked; and burrow density. Computer simulations indicated that the dominant influences are permeability contrast and the degree of burrow networking. Empirical and analytical formulae show that the effective permeability can be determined from k_b, k_m, and the degree of connectivity. These formulae can be applied in any geologic medium as a simple, first-run approximation.

Laboratory tests and field-based slug tests appear to confirm the computer model for flow through *Glossifungites* surfaces. Accuracy within an order of magnitude is possible and depends, in part, on the size of the sample considered.

Modern analogs and surfaces in outcrop at Willapa Bay show that these surfaces are areally extensive. Relevant stratigraphic configurations include incised valleys and transgressive shorefaces. Each stratigraphic model proposed in this paper is geologically plausible and is confirmed in the rock record.

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CHAPTER 8: CONCEPTUAL MODELS FOR BURROW-RELATED, SELECTIVE DOLOMITIZATION; EXAMPLES FROM THE TYNDALL LIMESTONE AND THEIR IMPLICATIONS ON THE RESERVOIR QUALITY OF BIOTURBATED CARBONATE ROCKS[1]

INTRODUCTION

The study of trace fossils in carbonate rocks is commonly impeded by the poor preservational character of ichnofossils in these rocks. Paleoecology in carbonate systems is therefore most dependent on the fossil content and textural aspects of the preserved deposits. As discrete structures in calcareous strata, burrows can effect changes in many of the physical parameters manifest in the rock. These include permeability (Chapter 2), porosity, shear strength, fabric, and texture. In carbonates these changes may be profound where dissolution and precipitation occur preferentially within and adjacent to trace fossils. Dolomitization, for instance, can occur as a diagenetic halo several millimetres in thickness around the original burrow. An excellent example of this is the Ordovician-aged Tyndall limestone of the Red River Group in Manitoba.

Many models exist for the large-scale processes required to precipitate dolomite in carbonate strata. These include seepage/reflux, water mixing, burial processes, sabkha dolomite, and the Coorong model (see Morrow, 1990 for a general discussion regarding these disparate models). Equally interesting are the small-scale physico-chemical heterogeneities that must influence the distribution of "patchy" dolomite. Variability on this scale is strongly influenced by the activities of burrowing infauna. Their interaction with the sediment alters the grain size distribution and locally changes the chemical microenvironment in the substrate. Ichnological research over the last three decades indicates that trace fossil distribution is to an extent predictable, and therefore dolomitization associated with burrow fabrics may be better characterized than has been previously accomplished. An understanding of how these burrow-associated

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[1] A version of this chapter has been submitted for review by The Journal of Sedimentary Research as "Conceptual Models for Burrow-Associated Dolomitization: Implications on Reservoir Heterogeneity", by Murray K. Gingras, S. George Pemberton, Carl Mendoza, and Floyd Henk..

heterogeneities may control dolomitization is required to determine the distribution and fluid flow characteristics of similarly dolomitized units in the subsurface. Towards this end, selective dolomitization and its relation to physical and chemical modifications of the substrate are reviewed in this paper. This synthesis is tested using examples of Tyndall Stone and selected core from Red River Group strata. Simple dispersivity experiments are used to assess the relative tortuosity and bulk permeability (k) in blocks of Tyndall stone. Bulk measurements of k are compared to spot measurements acquired from a profile permeameter.

BIOGENIC MODIFICATION OF THE SUBSTRATE

Modification of PhysicalProperties

Burrowing organisms significantly alter the physical character of a substrate. These changes include modification of grain size, redistribution of grain size (vertically and laterally), compaction, and sorting (Bromley, 1996). Infauna mediate changes in the physical parameters by burrowing through and ingesting the substrate. Burrowing is accomplished by one or more means of removing or pushing aside sediment. These include inversion, compression, excavation, or backfill. The physical manifestations of these processes are variable as infauna can either increase or reduce the grain size of, and sort or mix the sediment. Grain size reduction is thought to represent the most significant substrate modification (Chow and Longstaffe, 1995). Reduction of a substrate's grain size permits a larger surface area to interact with dolomitizing fluids and provides a larger number of nucleation sites per given volume. An increase in grain size may contribute to dolomitization in a substrate if the burrow system then provides a conduit through which dolomitizing fluids may interact with the matrix.

Generally, biogenic reworking imparts an indelible signature on carbonate substrates before the onset of diagenetic processes. Depending upon the degree and nature of bioturbation, burrows may be present as discrete elements, or can produce homogeneous fabrics where the degree of bioturbation is high (Keswani and Pemberton, 1995).

Many studies suggest primary fabrics and textural properties strongly influence common dolomitization patterns observed in the rock record (Beales, 1953; Murray and Lucia, 1967; Kendall, 1977; Morrow, 1978). As diagenesis proceeds, the original texture of the rock deteriorates and becomes subordinate to the diagenetic texture; however, at the onset of diagenesis the primary sedimentary character of the deposit must exert an irresistible control on the patterns of remineralization and dissolution. Murray and Lucia (1967) demonstrated the potential of determining dolomite distribution by understanding rock selectivity. Their study of the Turner Valley (Mississippian) Formation in southwest Alberta indicated that dolomitization was related to the development of early diagenetic porosity that created the conduits through which dolomitizing fluids flowed. Murray and Lucia did not explicitly state the potential for burrow fabrics to affect the bulk permeability of a carbonate deposit. However, contrasts between the burrow fill and matrix potentially develop notable anisotropic permeability that can be exploited by dolomitizing fluids (Beales, 1953; Kendall, 1977; Morrow, 1978; Jones *et al.*, 1979; Chow and Longstaffe, 1995).

Research on flow modeling through bioturbated horizons (Chapter 7) indicates that trace fossils can substantially enhance fluid flow through bioturbated media. The results presented in Chapter 7 demonstrate that in highly connected / interpenetrating systems, such as those observed in the Tyndall, the burrow networks dictate the bulk flow characteristics. Significant permeability contrasts are commonly associated with *Glossifungites* surfaces in both clastic and carbonate depositional environments. In contrast, softground burrows are normally characterized by permeability values that are only slightly different than those of the matrix. The susceptibility of carbonate deposits to early diagenetic processes probably enhances permeability shortly after deposition. This diagenetic disposition is partly due to the inclusion of organic material and the presence of a contrasting geochemical microenvironment in discrete burrows. This topic is explored in the following section.

Chemical Modification of the Substrate

An important result of burrowing in substrates is the incorporation of localized, concentrated organic material in the form of mucous or fecal material. Decomposing organic debris creates a geochemical microenvironment that may extend several centimetres into the substrate. Sander and Kalff (1993) showed that the presence of organic material is most important to the production and activity of microorganisms. Organic material is provided from a number of sources, such as fluvial input, plankton blooms, and oceanic upwelling (Tyson, 1995). In well-aerated sediments, however, burrow linings composed of agglutinated, fecal, or primary organic material, contain the most concentrated local sources of organic material. These burrows therefore provide excellent loci for bacterial colonization.

Incorporation of organic matter into the substrate substantially alters the local geochemistry. The most significant chemical byproduct in oxygenated substrates is CO_2, which is a produced during the oxidization of organic material. Increased CO_2 activities can enhance carbonate dissolution in the early diagenetic environment. Burrow-associated CO_2 can generate an anisotropic, heterogeneous network that can be exploited by early diagenetic fluids. Sulfate ions (SO_4^{-2}) may also be present in oxidizing subenvironments. These ions not only inhibit the dissolution and precipitation of dolomite (Reddy, 1977; Baker and Kastner, 1981), they may bond with $Mg^{++}$and thus lower the overall Mg/Ca ratio. Early diagenetic processes under these geochemical conditions tend to favor carbonate dissolution in association with burrow fabrics.

Notably, Mg-siderite and pyrite are common accessory minerals in many dolomites, implying that dolomitization can occur under reducing conditions. In burrow microenvironments characterized by reducing conditions, the geochemical processes and byproducts are much different from those found in oxygenated substrates. Although CO_2 is a common product in this geochemical setting, NH_3 is also abundant (Slaughter and Hill, 1989). Ammonia combines with H_2O [$NH_3 + H_2O \longleftrightarrow NH_4^+ + OH^-$] and effectively raises the pH of interstitial fluids in and around the burrow networks. High pH increases the activity of the bicarbonate ion (HCO_3^-), which favors the direct precipitation of dolomite:

$Ca^{++} + Mg^{++} + 2(CO_3^{=}) \longleftrightarrow CaMg(CO_3)_2$ *or*

$CaCO_{3(solid)} + Mg^{++} + 2(CO_3^{=}) \longleftrightarrow CaMg(CO_3)_{2(solid)}$ (Lippmann, 1973)

but, not necessarily the replacement of calcite by dolomite, the equilibrium constant of which can be distilled to $K_{cd} = {}^{[Mg^{++}]}/_{[Ca^{++}]}$ (Tucker and Wright, 1990). Slaughter and Hill (1989) suggest that organogenic dolomitization can result from the transfer of neutral ion pairs $CaCO_3^0$ and $MgCO_3^0$ to and from a construction site on the crystal surface. For this reason they conclude that dolomitization requires the concentration of $CO_3^{=}$ to be high and exceeding that of HCO_3^-. For these conditions to be met, the pH and carbonate alkalinity must be high, such as in the burrow microenvironment.

In reducing substrates, sulfate ions are consumed by sulfate reducing bacteria and the inhibitory effects of these ions are removed from the system. The combination of elevating pH and reducing sulfate levels may be key to the precipitation of dolomite during early diagenesis. Brown and Farrow (1978), studying dolomite concretions surrounding modern crustacean burrows, proposed that $CO_3^{=}$ ions were produced during sulphate reduction:

$SO_4^{=} + 2C + H_2O \longleftrightarrow CO_3^{=} + CO_2 + H_2S$ *and*

$SO_4^{=} + 2H_2 + H_2O \longleftrightarrow CO_3^{=} + 3H_2O + H_2S$

The authors postulated that because of the ubiquity of Mg in marine environments, the geochemical microenvironment was the most important parameter for cementation of modern burrows. They went on to note that "early diagenetic events may be common in temperate waters and may be associated with organic activity - burrowing and bacteria". Garrison and Lutenauer (1971), working at the Fraser River Delta, noted the occurrence of cemented sand-filled burrows that may have formed under similar conditions.

An interesting example of dolomitization of crustacean burrows was provided by Gunitilaka *et al.* (1987) from Quaternary (clastic) tidal-bar deposits in northern Kuwait. These burrows were associated with two types of dolomite cement. The inner cores of the burrow were typically cemented by microdolomite, described by the authors as a fine-grained, void-filling dolomitic cement. At the burrow margins a spherulitic dolomite, that had sharp boundaries with the microdolomite, was present. Gunitilaka *et al.* (1987) noted that both fabric zones in a given burrow showed variable Mg composition longitudinally, suggesting that the dolomitizing fluid composition and the kinetics of crystal growth were variable. They surmised that organic material mediated the dolomitization and that the burrows had served as a fluid conduit. Potentially the Mg source required for dolomitization was enriched in the burrow wall prior to dolomitization, concentrating dolomite occurrence in the burrowed zones. This concept is explored in detail in the next section (metal enrichment).

Dolomitization of organic-rich continental margin sediments appears to be relatively common. Baker and Burns (1985) described a strong relationship between dolomitization of the substrate and its organic content (typically over 0.5 wt. %). The dolomite cements present in these deposits were depleted in ^{13}C, indicating microbially-mediated cementation within the reducing zone. Although their data was applied to sedimentary accumulations, it can conceptually be applied on a smaller scale to burrow microenvironments.

In summary, consideration of the different geochemical microenvironments characterized by oxidizing and reducing horizons implies that each set of geochemical conditions can facilitate dolomitization in different ways. Oxidizing subenvironments favor the development of a porosity/permeability network, whereas reducing environments are conducive to precipitation of dolomite. Conceivably, as a horizon passes from oxidized to anoxic layers, the permeability created during earliest diagenesis promotes dolomitization in the reducing geochemical subenvironment (Fig. 8.1). In other words, early calcite dissolution creates permeability and porosity networks that are utilized by dolomitizing fluids in later stages of diagenesis.

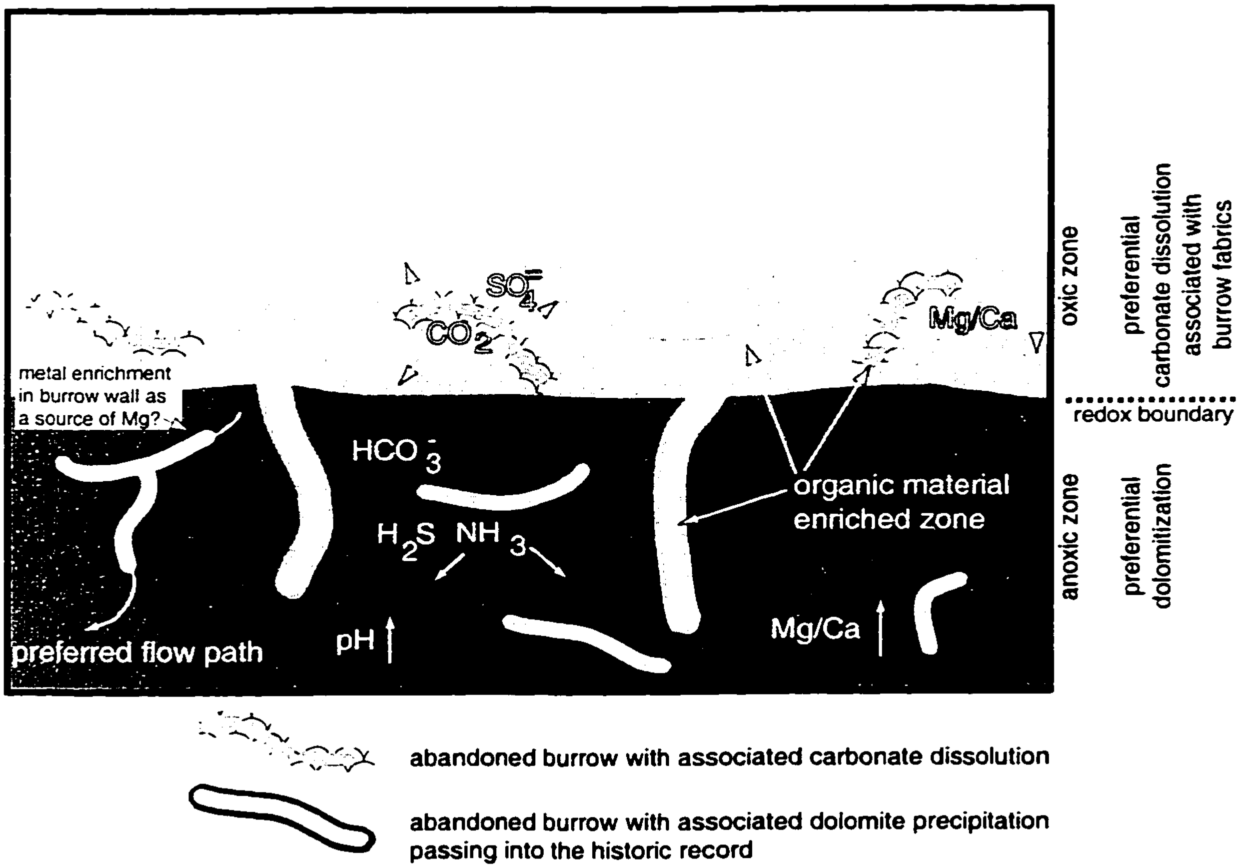

FIGURE 8.1 - A schematic illustrating the geochemical characteristics of the oxic and anoxic zones in a subaqueous (marine) substrate.

Metal Enrichment in Burrows

Historically, geologists have recognized an association of organic matter with ore minerals (Giordano, 1994). There are a number of reasons for this association including the presence of strong geochemical gradients, the production of organo-metallic compounds, and the biogenic concentration of ore constituents (Giordano, 1994).

Metal-humate and metal-fulvate complexes (among others) are actively transported in chemically aggressive ground waters (Giordano, 1994). Where these waters encounter a geochemical threshold, such as fresh water, sea-water, or lithologic boundaries, precipitation of complexed organometallic compounds may occur. Metals such as Fe, Pb, Cu, Mg, Mn, Ni, Zn, Ag, Au and Hg can be relatively enriched; trace elements, including Cd and Pt are also associated with organometallic complexes.

Trace fossils are commonly enriched in organic material, notably humin and fulvin. In marine environments, microorganisms (including algae and plankton) are generally thought to be the source of humin (Hatcher and Orem, 1986). Humin, through chemical and / or biological oxidation, is the progenitor of fulvic and humic acid. If the oxidation of humin is biologically mediated, then mucous or fecal material in burrow walls becomes an ideal site for organic acid production. These acids subsequently complex with metal ions which have a markedly reduced solubility in water where the pH is approximately neutral (Giordano, 1994). The strong geochemical gradients associated with burrow systems suggest metallic complexes can be enriched in the sediment in and adjacent to the burrow. *It is proposed that cation enrichment in burrows provide a plausible source of Mg as diagenesis commences* (Fig. 8.2). This is supported by earlier research that indicates metals present in organic material facilitate dolomitization (Beales, 1953; Morrow, 1978; Mirsal and Zankl, 1985).

Furthermore, humic substances may act as nucleation sites. Murphy and Zachara (1995) showed that mineral-bound humic substances have an increased adsorptive richness and act as sinks for the removal of contaminants from water, commonly forming

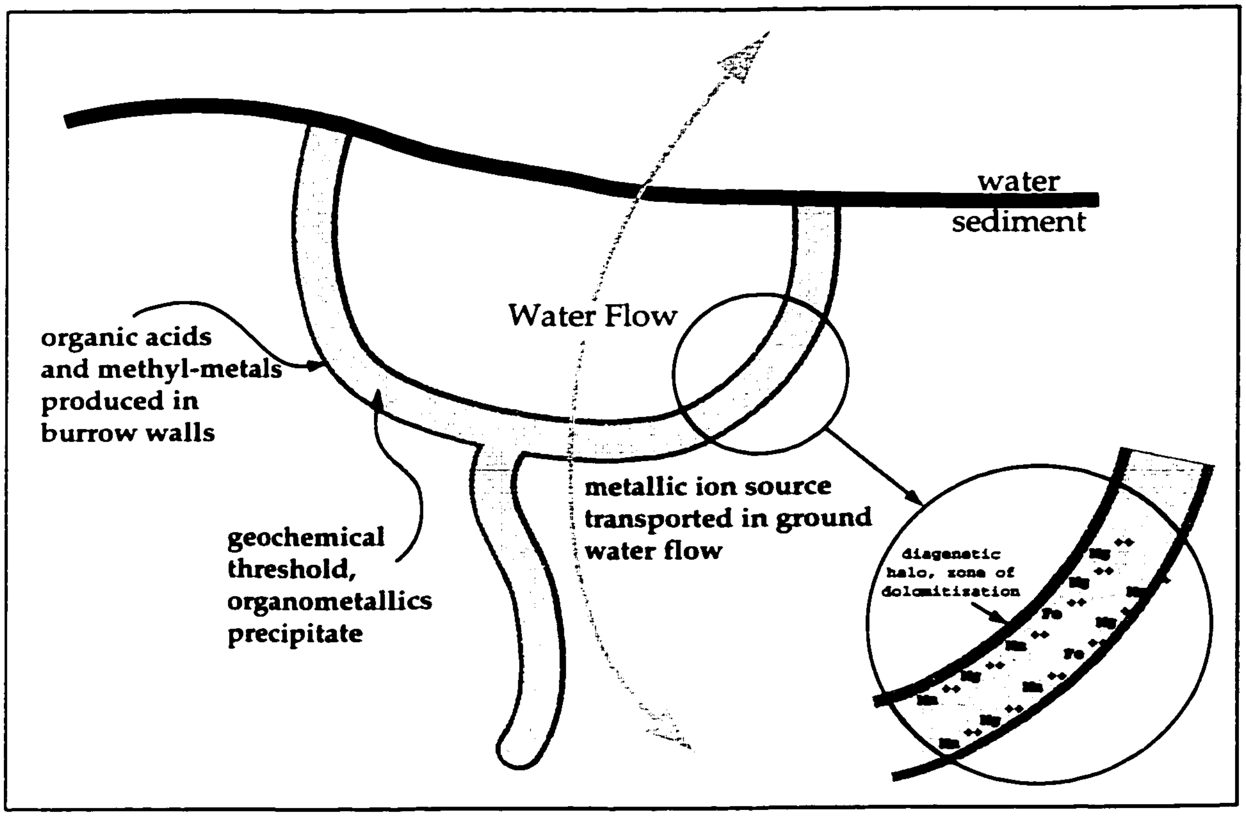

FIGURE 8.2 - Metallic concentration in burrow walls results from steep geochemical gradients that are present in the burrow microenvironment.

Mn-, Fe-, and Mg-rich nodules. These nodules are typically calcareous and even develop dolomitic compositions (Calvert and Price, 1970; Brown and Farrow, 1978).

Another important type of organometallic compound is the methylmetal. Methylmetals are the most frequently found organometals in the natural environment (Thayer, 1995). Microorganisms have the ability to transfer methyl groups to metals during "biomethylation". Methylmetal are typically insoluble and provide an important means of concentration for many metals (Thayer, 1995).

Enrichment of trace metals in burrow walls is well documented. Over (1991) found trace metals were preferentially concentrated in burrow linings (primarily *Ophiomorpha nodosa*). Iron, Mn, Cu, Ni and Zn were concentrated in burrow walls in three ways: adsorption, as oxide or oxyhydroxide coatings onto the high-energy surfaces provided by fine-grain particles (silt and clay); as sulfide or phosphate phases under reducing conditions; or, associated with organic material (as adsorbed coatings or forming organometallic complexes). The relative importance of each type of enrichment mechanism was not addressed. Significantly, metal enrichment occurred before burial, but its imprint persisted into the rock record.

THE TYNDALL LIMESTONE

Geologic and Stratigraphic Setting

Tyndall Stone is a dolomite-mottled limestone that is quarried in Manitoba, Canada. The formal designation of this unit is the Selkirk Member of the Red River Formation, and it is considered to be Ordovician in age (Cowan, 1971, Kendall, 1977). Shallow drilling indicates that the mottled limestone occurs in the lower half of the Selkirk Member (Kendall, 1977). Similarly mottled limestone comprises the subsurface equivalent Yeoman Formation, which lies in southeastern Saskatchewan (Kendall, 1975). Both the Selkirk and Yeoman Formations are overlain by evaporitic dolomicrites that are in turn overlain by evaporites (Kendall, 1975, Kendall, 1977).

Selkirk and Yeoman strata were deposited as an epicontinental carbonate platform in the Williston Basin. Their distinct sedimentologic and ichnologic signature are reminiscent of other Paleozoic epicontinental carbonates, most notably the Devonian Palliser Formation of the Western Canadian Sedimentary Basin (Beales, 1953).

Lithologic Description

The Tyndall Stone is a fossiliferous, cream colored limestone with buff colored dolomitic mottling. The matrix of this unit typically consists of a crinoid-echinoderm-bryozoan-brachiopod wackestone, grading to mudstone locally. Rare sharp-edged patches of crinoid-brachiopod packestone are present. These patches are commonly interlinked in irregular appearing networks. Large fossils are comprised of abundant cephalopods, corals, receptaculites, and stromatoporoids. Little recrystalization appears to have been developed in the matrix and most of the large fossils are comprised of calcite. Many of the fossils are micritized or have micritized rinds. Allochems are not abraded, though disarticulation is common. Larger allochems are typically intact and unabraded.

The most distinctive feature of the Tyndall stone is a ramifying burrowed texture, which consists of branching and interpenetrating *Thalassinoides*-like burrow patterns (Fig. 8.3). A dolomitic halo, 1-2 cm in diameter, encompasses 2-3 mm diameter causative burrows (Fig. 8.3). The dolomite is typically fine-grained, though sucrosic crystals may be adjacent to the causative burrows. Many of the burrows have been internally filled by a late stage calcite cement, which forms an interlocking crystal mosaic. The causative burrows are separated into two categories (Kendall, 1977), open- or calcite-filled, and meniscate back-filled. Staining from the original organic material is locally present at the trace margins. Close inspection of the causative burrows indicates the original trace fossils primarily belong to the ichnogenera *Palaeophycus* and *Chondrites*. Kendall (1977) noted that the degree of dolomitic mottling varies locally, but is typically confined to areas adjacent to burrows and, less commonly, replacement of aragonitic allochems.

Petrographic analysis reveals that 4 different cements are commonly present in the Tyndall stone, including: a micritic cement (C1), or fine-grained microcrystalline cement (Fig. 8.4); a very fine-grained dolomite (C2), characterized by subplanar subhedral crystals that form an idiotopic mosaic texture with calcite allochems dispersed throughout, this cement lends the mottled appearance to the Tyndall Stone (Fig. 8.4); fine- to medium-grained euhedral dolomite (C3), that locally exhibits a sucrosic texture and forms an isopachous to undulatory rind adjacent to, and inside the causative burrow structure (Fig. 8.4); and a calcite mosaic cement (C4), infilling allochems, open burrows, and voids (Fig. 8.4).

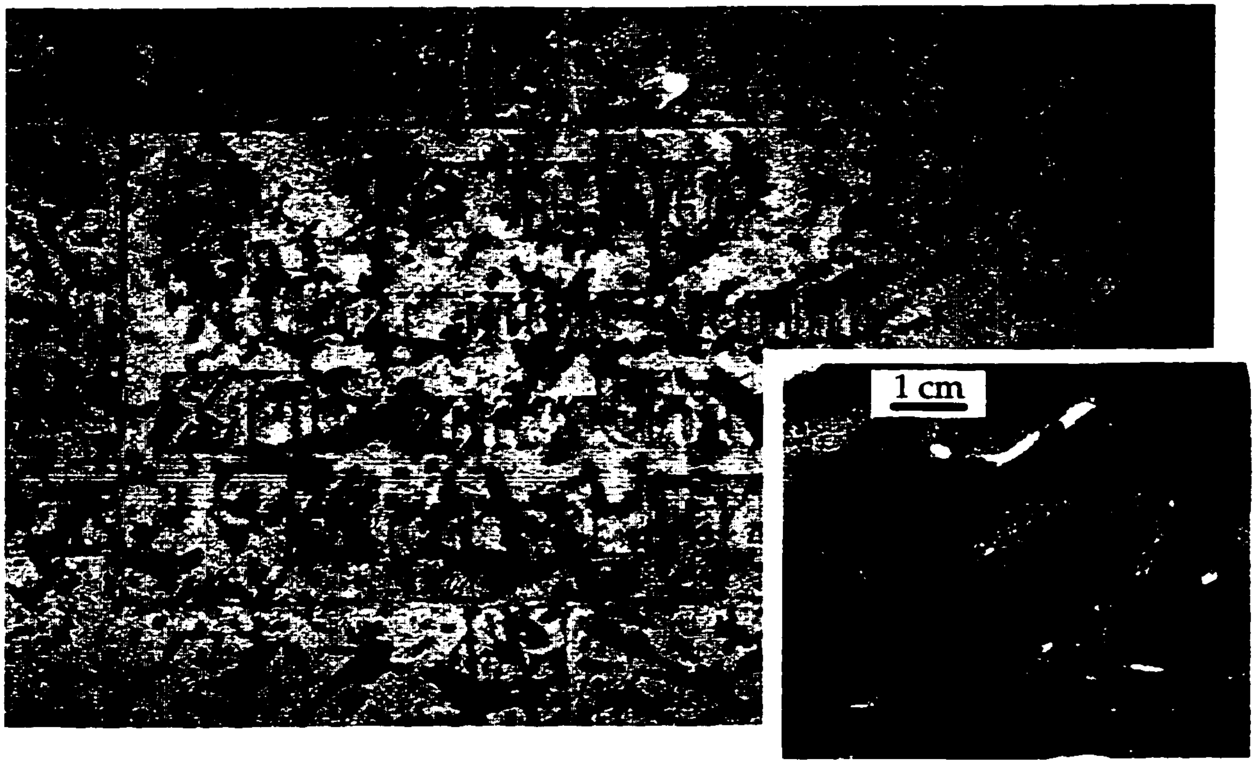

FIGURE 8.3 - A building-stone of Tyndall stone. Here extensive networks of dolomitized burrows are evident as darker mottling. Pervasive branching and interpenetration are apparent. The inset shows a stained (alizarin red) thin section in which the burrow mottling is unstained (lighter gray) and the matrix is stained (darker). Causative burrows are present near the middle of most dolomite patches.

Cementation History and Discussion

The first stage of cementation is represented by micritic calcite cement (C1; Fig. 8.4). Cement 1 represents either a cemented mud, an *in situ* precipitate, or a recrystallized fabric. Its association with micrite envelopes around allochems suggests that this cement developed during early diagenesis in a shallow marine environment, possibly penecontemporaneous with deposition. The deposit subsequently passed into oxygenated historical layers, and the porosity and permeability were enhanced by the byproducts of oxidation (most notably CO_2). This is evidenced by the local replacement of C1, and the partial dissolution of some allochems.

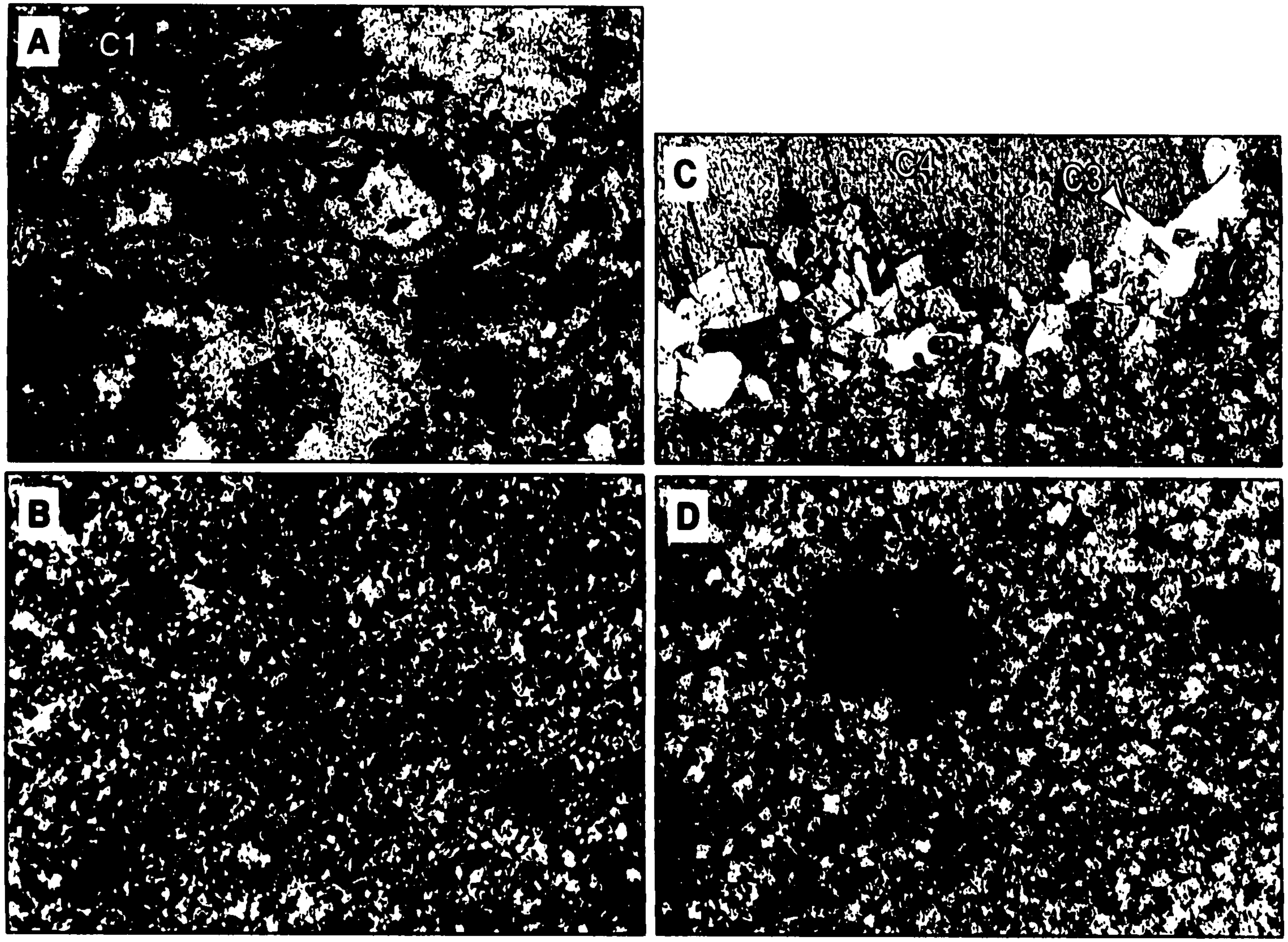

FIGURE 8.4 - A. Cement 1 (C1) a micritic cement, or fine-grained microcrystalline cement. B. Cement 2 is represented by a fine-grained dolomite, comprised of subplanar / subhedral crystals forming a idiotopic mosaic texture. This cement gives the Tyndall stone its mottled appearance. C. Fine- to medium-grained euhedral dolomite (C3), that developes a sucrosic texture and and is present as isopachous to undulatory rind --->

(cont.)adjacent to, and inside the causative burrow structure. Also present is a calcite mosaic cement (C4), that infills dissolved allochems, open burrows, and voids. D. A calcite crinoid ossicle present in a dolomitized zone. This indicates that dolomite patches do not represent burrow fill, but are best explained as diagenetic halos.

The brief interval of dissolution was disrupted by the first phase of dolomitization (C2; Fig. 8.4), that preferentially developed in association with the fluid conduits made available by the higher permeabilities present in the burrow networks. Cement 2 cross cuts C1 and impinges on allochem boundaries locally. The rare preservation of partially micritized allochems within the zone of pervasive dolomitization suggests C2 replaced original calcite and/or aragonite. Cement 2 is gradational with C1 and C3 over 1-2 mm, and is present in the calcite matrix as isolated or clustered subhedral crystals which are interpreted to have formed concurrently with the pervasive zone. This cement represents the primary phase of dolomitization. Furthermore, C2 is interpreted to have developed during early diagenesis, while the deposit passed through the zone of sulfate reduction, for two reasons. Firstly, the boundaries of this secondary cement are relatively sharp, suggesting the deposit passed out of the 'dolomite window' abruptly as might be expected if catalyzing agents in the causative burrows were depleted or if the strata passed quickly through the sulfate reduction zone. Significantly, C2 apparently disrupted the development of C1, which probably represents a very early diagenetic product.

Cement 3 (Fig. 8.4) was deposited on the internal surface of open trace fossils and cavities during later (perhaps burial) diagenesis. Partial dissolution may have preceded the precipitation of C3, as no vestigial fabric or calcite remains in these cemented zones. As the dolomite crystals are euhedral and show no signs of resorption, C3 is considered to be a primary cement that was developed during the broad range of time that encompasses later diagenesis.

The final stage of cementation is represented by C4 (Fig. 8.4), a void-filling calcite mosaic. Cement 4 completely occludes burrows and pores locally, though partially open trace fossils and voids are abundant. A lack of geopetal or meniscate rinds implies that C4 precipitated in a phreatic environment, possibly with a meteoric influence (Tucker and Wright, 1990). This is a primary cement, as evidenced by its sharp boundaries and the euhedral state of C3, which is normally enveloped by C4. It is indicative of a striking change in fluid chemistry that may have been related to uplift and the introduction of recharging meteoric waters.

In summary, the cementation history can be separated into four distinct phases of cementation: an early phase (C1) that probably occurred in a marine environment, contemporaneous with or shortly after deposition; a second phase (C2) which was developed in the sulfur-reducing zone and represents the primary diagenetic stage; deposition of a medium grain to sucrosic primary dolomite, possibly due to burial diagenesis; and, the precipitation of a calcite mosaic indicative of meteoric waters in a phreatic environment. These cements detail a burial history that can be summarized as follows:

1) deposition of the micritic sediment (C1)
2) transition into the redox zone (C2)
3) burial and exposure to subsurface brines (C3)
4) uplift or exhumation and exposure to meteoric recharge flows (C4)

The diagenetic expression of the Tyndall Stone strongly reflects the original sedimentological and ichnological character of the deposit. Evidence such as pronounced dolomitized halos surrounding causative burrows, locally abundant open tubular cavities, and the selectivity of dolomitization, strongly imply that dolomitizing fluids were channeled through networks of *Palaeophycus*- and *Chondrites*-like burrows. The original diameter of the causative burrows ranged between 2 and 4 mm. This is contrary to Kendall's (1977) interpretation that suggested the mottled dolomite pattern was the result of larger diameter arthropod burrows, reburrowed by polychaete worms. Kendall suggested that the passive fill in the arthropod burrows was ultimately dolomitized, lending the Tyndall Stone its patchy appearance. To support his interpretation, Kendall relied on the following evidence: dolomitic halos are too regular to result from a dolomitizing front radiating from a causative burrow; the relative uniformity in size of the burrows / halos; and, causative burrows are not always present or are not necessarily located at the center of the diagenetic halo.

Our observations indicate that certain petrographic details are contrary to Kendall's initial observations. For example, thin section analysis indicates allochems and matrix fragments are present in the dolomitized zones (Fig. 8.4). Also, the halo boundary is not always sharp, but commonly grades over 1-2 mm. In other Paleozoic rocks, the sharp wall of *Thalassinoides* is typically preserved as a sharp lithologic boundary even though modes of preservation vary (Myrow, 1995). Furthermore, *Paleophycus*-like burrows *do* commonly occur near the center of the dolomitic halo. The presence or absence of these burrows may be more closely related to the degree of dolomitization that developed in association with the bioturbate texture. Bromley (1996) noted many criteria that can be used to determine whether a structure is biogenically produced or not. Two of these criteria, including regular, sharply demarcated boundaries and a consistent burrow diameter throughout the network, are not met by the mottled pattern of the Tyndall Stone.

The Tyndall Stone is an excellent example of how burrow structures facilitate dolomitizing processes in at least two ways: by enhancing the bulk fluid flow through the matrix; and, by enriching the substrate in organic and metallic material that can be used to catalyze and construct dolomite. In many ways the dolomitization of the Selkirk Formation is comparable to that of the Devonian age Palliser Formation in the Western Canadian Sedimentary Basin. Beales (1953) noted that dolomitization was sharply-bounded and tended to exploit flow paths 'of least resistance' such as burrows, skeletal debris, fractures, and high permeability laminae and beds. Based on his observations, Beales suggested that organic material in the limestone was responsible for the localized dolomitization, and that the source for Mg may have been stabilized by the organics before dolomitization ensued. Discrete diagenetic alteration associated with burrow fabrics alters the physical character of the Tyndall stone, Palliser, and many similar deposits. The development of such textures imparts important changes in the fluid flow parameters inherent to these rocks, a matter discussed in the next section.

IMPLICATIONS ON RESERVOIR CHARACTERISTICS

Due to the inherent physical heterogeneities derived from burrow-related dolomitization, several fluid flow parameters are expected to change as a result of the aforementioned diagenetic processes. Permeability, porosity, dispersivity and tortuosity are altered locally. Striking permeability contrasts may therefore exist between the matrix and burrow-dolomite, creating a dual-permeability system.

To demonstrate these characteristics, bulk-permeability, and -dispersivity were characterized with a dispersometer, the experimental configuration of which is shown in Figure 8.5. Flow volumes were measured volumetrically at the discharge end of the apparatus. From this data, permeability was calculated using Darcy's Law (modified for gas transport). An oxygen detector tracked the changing concentrations of tracer gas (O_2) which was used to measure the relative dispersivities of burrow-mottled limestone, unburrowed sandstone, and a fractured carbonate rock. Each sample was tested as a 10 cm cube.

Mini perm (spot permeability) measurements were mapped on a block of Tyndall stone. The permeability data sets were compared and assessed using the modified arithmetic mean of the matrix and burrow permeabilities (Chapter 7).

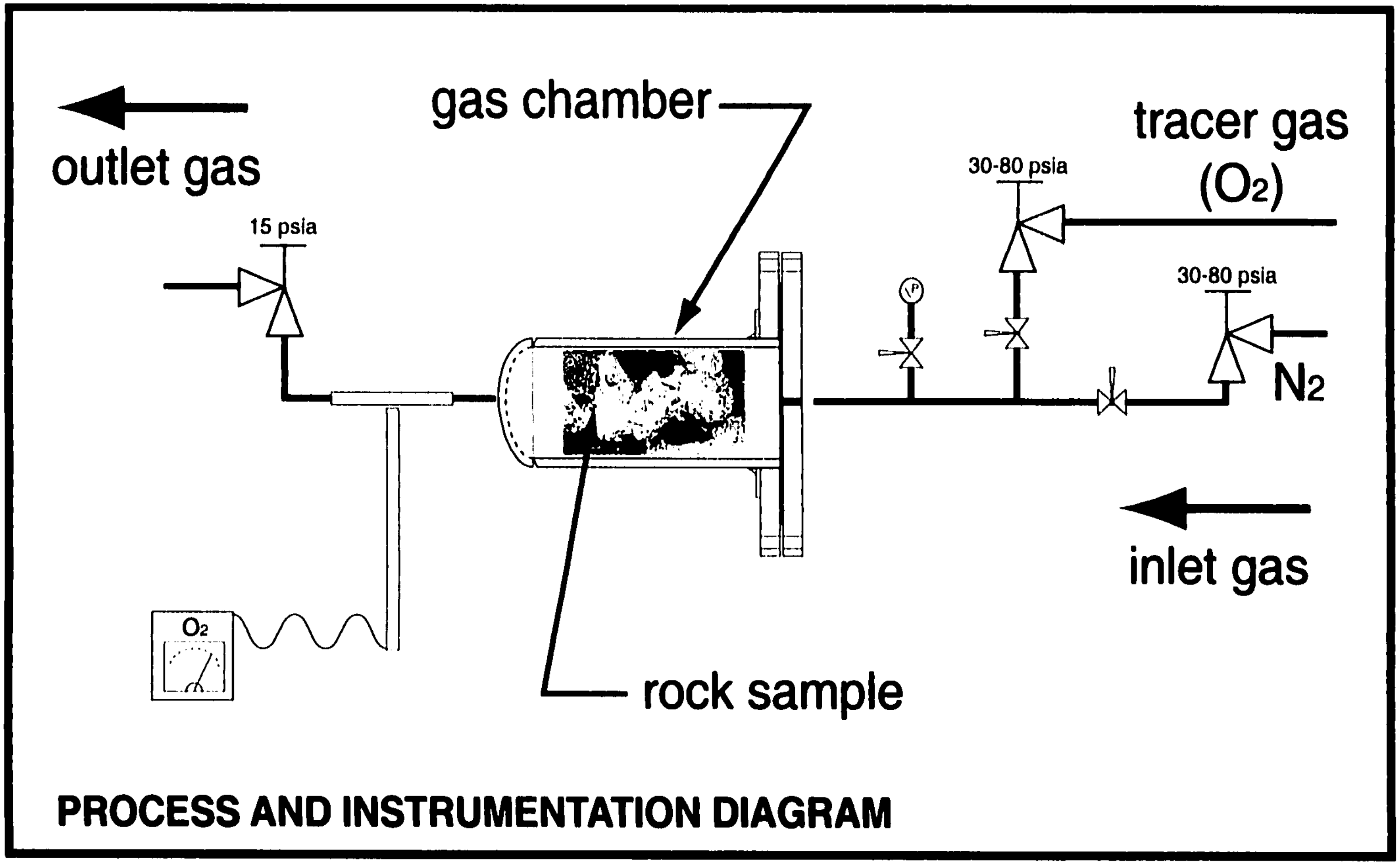

FIGURE 8.5 - Process and instrumentation schematic of the dispersometer (psia = pounds per square inch, actual)

Permeability Results and Discussion

Thirty-four mini perm data points from a block of Tyndall stone are shown in Figure 8.6. The average permeability of the matrix is 1.65 md, whereas average burrow permeability is 19.2 mD. Although the matrix permeability is relatively uniform (the mode is 1.3 mD), the burrow permeability varies widely (Fig. 8.6). These data can be used to estimate k by calculating the (modified) arithmetic mean of the burrow and matrix permeability (this volume, Chapter 7).

Image analysis indicates the undolomitized matrix represents approximately 45% of the sample volume (and burrow-associated dolomite represents 55%). These values in conjunction with average values of k_m and k_b (mini perm data) estimate k to be 11 md. Steady state flow tests through the dispersometer, assessed using Darcy's Law, indicate average bulk measurements are closer to 20 md.

In this example k_{bulk} is enhanced by approximately one order of magnitude over the matrix permeability. Such high permeability contrasts potentially channel flow through the trace fossil networks. This is important, as secondary recovery techniques, such as waterflooding, would preferentially sweep burrow-dolomite in this instance (Figs. 8.7, 8.8). Furthermore, where such recovery methods are attempted, the likelihood of isolating matrix hydrocarbons is higher compared to enhanced recovery attempts in homogeneous media. Tyndall stone, then, is characterized by burrow-mottled dolomites that locally comprise the bulk of the flow conduits in this deposit. Flow paths are tortuous and interaction with the matrix is probably extensive. These properties increase the dispersivity of flow media, which is addressed in the next section.

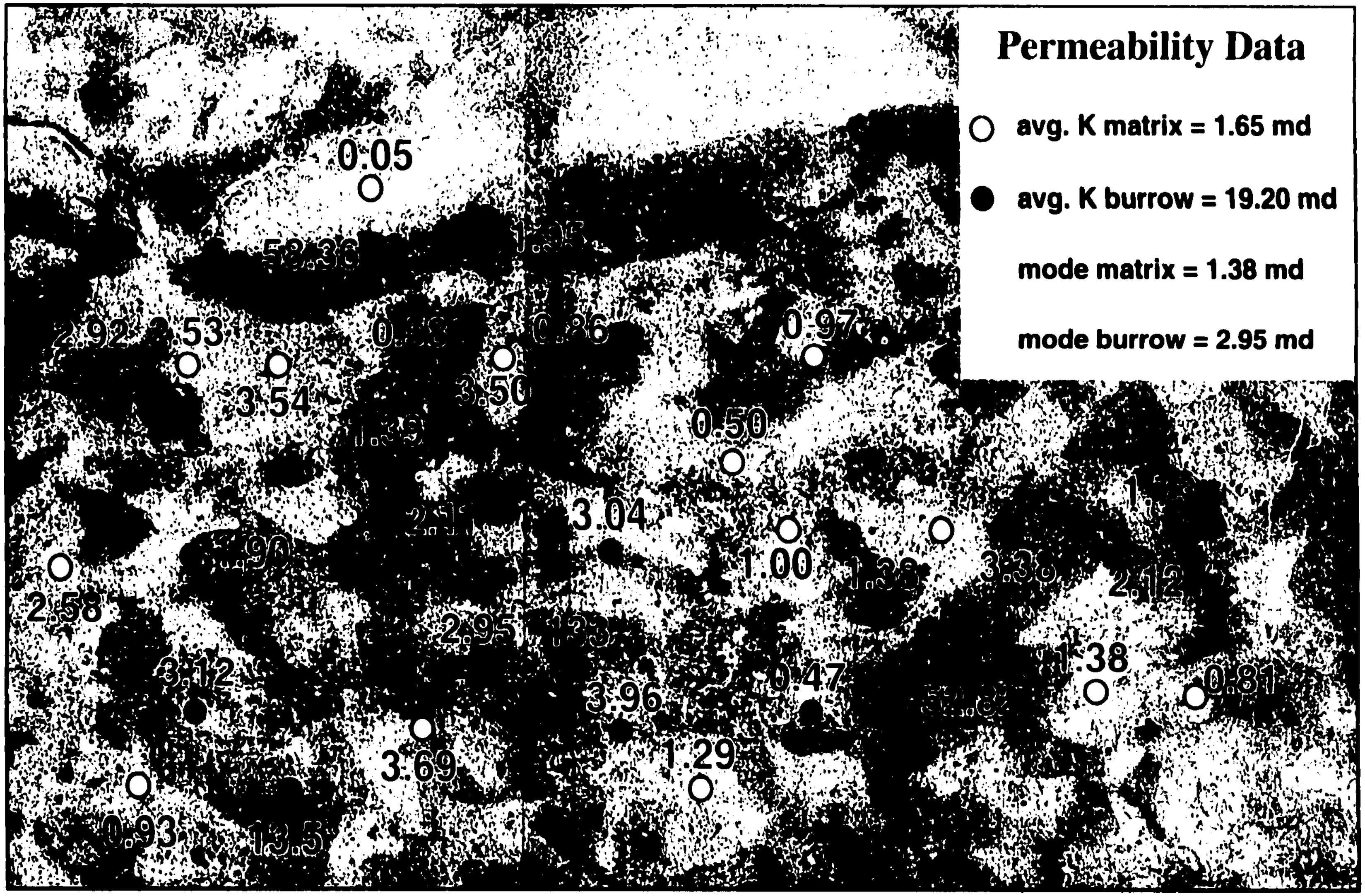

FIGURE 8.6 - Mini perm data from a block of Tyndall stone (quarried in Manitoba).

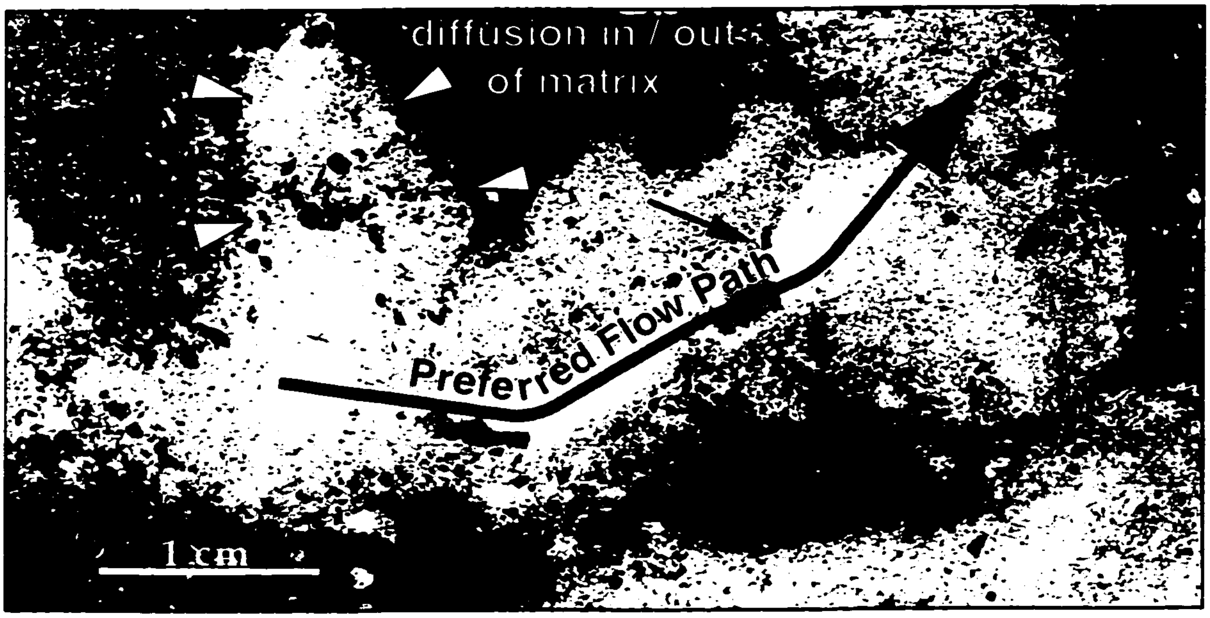

FIGURE 8.7 - Thin section demonstrating the path of least flow resistance in Tyndall stone.

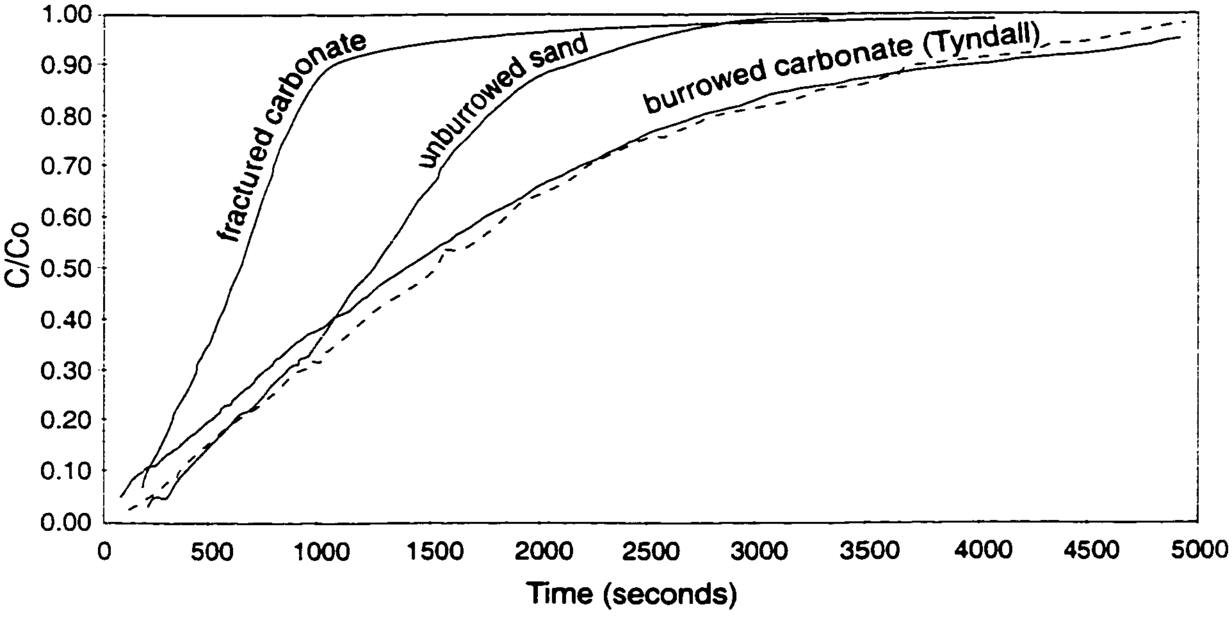

FIGURE 8.8 - Results from the dispersometer flow experiments. The concentration of a tracer gas is plotted against it's arrival time at the outlet of the dispersometer. Gas travelling through burrowed carbonate shows significant smearing and tailing as a result of the tortuous flow paths and matrix/burrow interaction. These results are directly comparable to tracer tests through less tortuous media (fractured limestone and sandstone).

Dispersivity Results and Discussion

Tracer gas concentrations versus time are shown in Figure 8.8. These curves are indicative of the dispersivity inherent to a sample of tested media. Dispersivity is largely scale-dependant, therefore only relative dispersivities are discussed herein. Of the three sample types tested (burrow-mottled limestone, unburrowed sandstone, and a fractured limestone), burrow-mottled limestone shows the greatest 'smearing', or tailing of tracer gas (Fig.8.8). The observed tailing is a consequence of the tortuous pathways experienced by the tracer gas, and extensive interaction with the lower-permeability matrix (Fetter, 1999). Tailing is less pronounced in the unburrowed sand, as it represents a comparatively homogeneous medium. Data from the fractured sample shows that the tracer gas was delivered rapidly through the more direct flow path, although tailing and interaction with the low permeability matrix is evident (Fig. 8.8).

Figure 8.8 demonstrates that flow through burrow-mottled media is notably tortuous. It also shows that this and similar rocks behave as dual permeability systems and merit special consideration where production is delivered from such strata. Conceptually, initial deliverability depends upon burrow-volume, -permeability, and -connectivity. Where the burrows are characterised by higher k than the matrix, early production drains the burrow networks (Fig. 8.9). As a reservoir matures, hydrocarbons would be produced primarily from the matrix. At that time, secondary recovery techniques should be carefully considered.

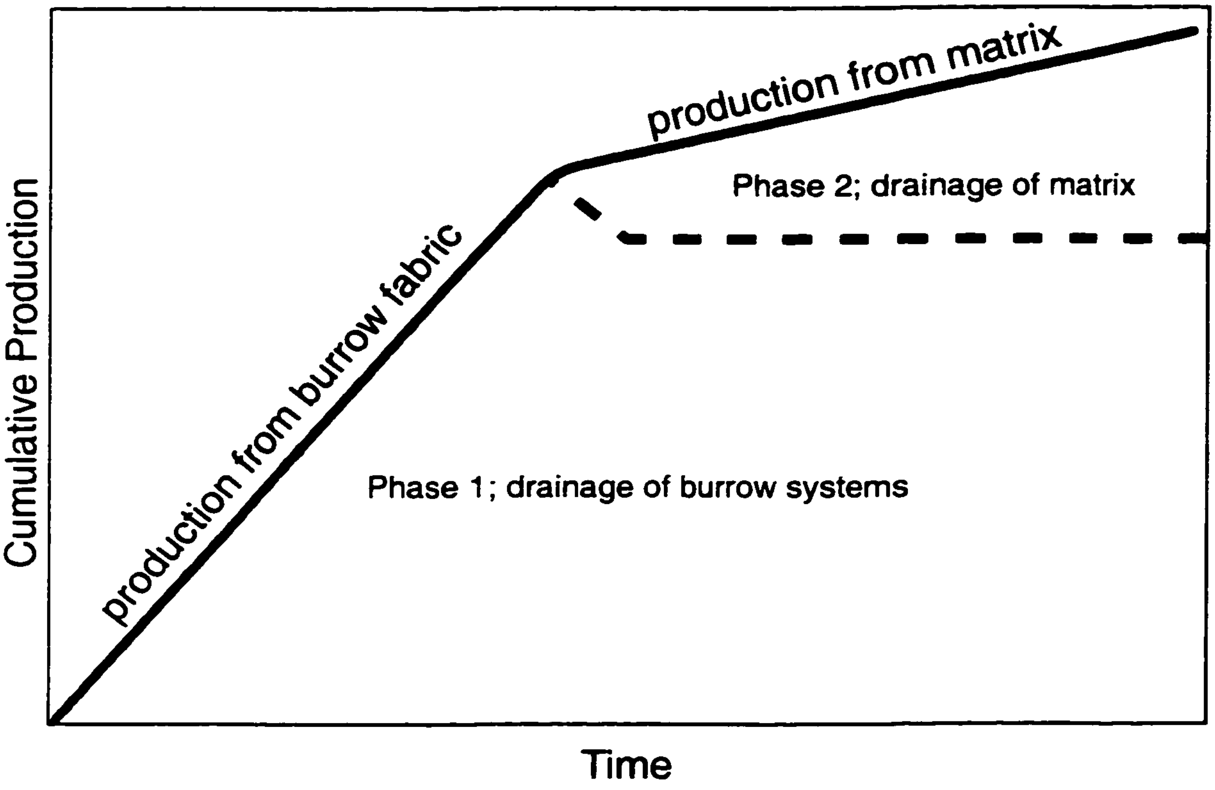

FIGURE 8.9 - Conceptualized production from a strongly heterogeneous reservoir.

CONCLUSIONS

Although the 'dolomite problem' is typically addressed by models that consider larger-scale processes that dictate the supply and transport of Mg, local heterogeneities in the substrate may play a more important role than previously considered. Localized concentrations of organic material in burrows may be related to increased permeability and porosity, support microbial populations whose byproducts mediate dolomitization, and provide a source of organic acids which compound with metal ions and act as chelating agents. Physical alteration of the substrate by burrowing infauna can increase the overall permeability of a carbonate deposit and provide conduits, through which early dolomitizing fluids can flow.

The result of burrow-facilitated dolomitization is evident in the Tyndall Limestone (Selkirk Formation). Dolomitization of the Tyndall Stone is attributed to dolomitizing fluids that developed in and flowed through burrow networks. The higher permeability in the burrows is due to physical modification of the substrate and chemical dissolution of calcite, probably during early diagenesis. Organic material is still present in association with burrows and may have mediated diagenesis.

Burrow-related, selective dolomitization is associated with distinct textural heterogeneity. Approximations of bulk permeability are reasonably accurate where the normalized arithmetic mean of the burrows and matrix is applied. Permeable conduits, however, are chaotically distributed and the flow paths are tortuous, and interaction between the flow paths and the matrix may be extensive. These deposits therefore act as dual permeability systems in the subsurface. Production from such units should consider these inherited qualities which strongly influence primary and secondary recovery. Future research should focus on the characterisation of similar units in the subsurface, production history from selected pools, and geochemical analysis of the dolomitic and calcitic components of the reservoir rock.

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CHAPTER 9: STABLE ISOTOPIC ANALYSIS OF BURROW-ASSOCIATED DOLOMITE IN THE TYNDALL LIMESTONE

INTRODUCTION

This chapter explores the hypothesis that the development of dolomitic halos in burrow-mottled carbonates is due to microbial mediation. If this thesis is tenable, isotopic fractionation of ^{13}C should be evident between the primary calcite cements and the later dolomitic cements. The byproducts of the oxidation and reduction of organic material show strong fractionation trends. Aerobic decomposition of organic detritus produces acids, alcohols, ketones, and ^{13}C-depleted CO_2 (Leadbetter and Foster, 1959; Dimitrakopoulos and Muehlenbachs, 1987). Anaerobic consumers of organic substrate consist primarily of fermenters, which consume organic acids, and reducing bacteria. Both types of anaerobic organic degradation preferentially fractionate ^{13}C into CO_2 (see Dimitrakopoulos and Muehlenbachs, 1987, for a summary). The dominance of aerobic *versus* anaerobic processes depends upon the depth of the redox boundary, rates of sediment accumulation, the type of organic material available, and the rate of organic material degradation. If the organic material is subjected to aerobic conditions for an extended time it will completely oxidize, providing a ^{13}C-depleted CO_2 reservoir. Organic detritus that passes below the redox potential discontinuity (RPD) is decomposed by anaerobic processes and lends enriched ^{13}C to the reservoir.

Whether fermentation or reduction is dominant below the RPD relates to the quantity of organic material available. If organic material is available only in small quantities, reduction of CO_2 to CH_4 is the primary microorganic metabolate (Reitsema, 1980). Where organic material is abundant, fermentation dominates. Fermentation has been implicated by a number of authors to explain the occurrence of high-^{13}C carbonates (Reitsema, 1980 and Dimitrakopoulos and Muehlenbachs, 1987).

The overall paucity of organic detritus in many burrow-mottled carbonates reflects the low sedimentation rates that are associated with carbonate depositional environments. Low sedimentation rates allow more time for organic material to become completely oxidized before passing into the historical record. Locally, organic material is concentrated in burrow walls (this volume, Chapter 8) representing a somewhat depleted food-resource for microorganisms. In such instances, CO_2 reduction is the dominant process and the CO_2 reservoir may be relatively small. This has two implications: 1) the short supply of CO_2 may expire before dolomitization processes can permeate the fabric (this volume, Chapter 8), and: 2) enrichment of ^{13}C may be lower than in carbonate cements derived from CO_2 provided from fermentation. These are equivocal statements that require a great deal more modern observation, as both reduction and fermentation processes may occur concurrently.

Wright (1997) showed that Cambrian dolomites of the Eilean Dubh Formation in Scotland are organogenic in nature. Notably, the isotopic variability in these carbonates is small. Delta ^{13}C values for the dolomites are slightly negative to neutral when compared to the marine carbonates, which range from $0^0/_{00}$ to $4^0/_{00}$(all PDB). Wright speculated that two key factors mitigate the degree of depletion or enrichment of the carbonate reservoir. These are cannibalism of dissociated bicarbonate from marine pore waters, and inheritance of carbon from precursor calcite. A suppressed isotopic variance may indicate that organogenic dolomite precipitated during early diagenesis while marine pore water was still available.

Small variations in isotopic composition of organogenic dolomites have been observed in modern deposits as well. Vasconcelos and McKenzie (1997) noted that depletion of ^{13}C in dolomites precipitating in lagoonal deposits at Lagoa Vermelha, Brazil was less than $3^0/_{00}$ in nodular layers characterized by intense dolomitization. Their data further indicates an apparent unlinking of the delta ^{13}C and ^{18}O values, which are locally altered by seasonal influxes of ground water.

Biogenic mediation may be more easily identified by isotopic data other than ^{13}C depletion or enrichment. Delta ^{13}C values from marine carbonates typically reflect the organic resource available and its ensuing decomposition. The heavy isotope of oxygen (^{18}O), on the other hand, is strongly depleted, as the temperature of the depositional environment is lowered. There is therefore a passive relationship between palaeotemperature and $\partial^{18}O$. Plots of $\partial^{18}O$ *vs.* $\partial^{13}C$ for *unaltered* marine carbonates characteristically indicate more notable variation in $\partial^{18}O$ than in $\partial^{13}C$ (Hudson, 1977). Organogenesis alters this relationship. Dolomites produced from organic byproducts normally plot different $\partial^{18}O$-*verses*-$\partial^{13}C$ –trends than those derived from calcite. However, values measured for $\partial^{18}O$ in replacive dolomite should have a range similar to those observed for marine calcite. In contrast, $\partial^{13}C$ values should be distinctly different in organogenic dolomite when compared to marine calcite. This indicates that burrow-mottled dolomite records evidence of biogenic fractionation, albeit as a subtle isotopic signature. The possibility of resetting by later diagenesis can not be ignored, however. This would homogenize isotopic values between calcite and coexisting dolomite. An examination of the isotopic composition of the Ordovician Tyndall Stone of the Red River Group in Manitoba follows, testing the preceding hypothesis.

Methods

Cored and quarried samples of Tyndall stone were first stained with alizarin red to identify burrow-related dolomite and matrix calcite (Fig. 9.1). Sample points for isotopic analysis were subsequently mapped (Fig. 9.1). In all cases, samples were chosen where the matrix was comprised of calcite, and the diagenetic halo comprised of calcareous dolomite. Sucrosic dolomite (sDx) was commonly present inside causative burrows, this was sampled separately. All samples were taken from discrete burrow-mottles (Fig. 9.1). Isotope samples were extracted on a millimeter scale using either small diameter, high speed saws (Dremel tools), or 1 mm diameter coring bits. Sawed samples had a mass

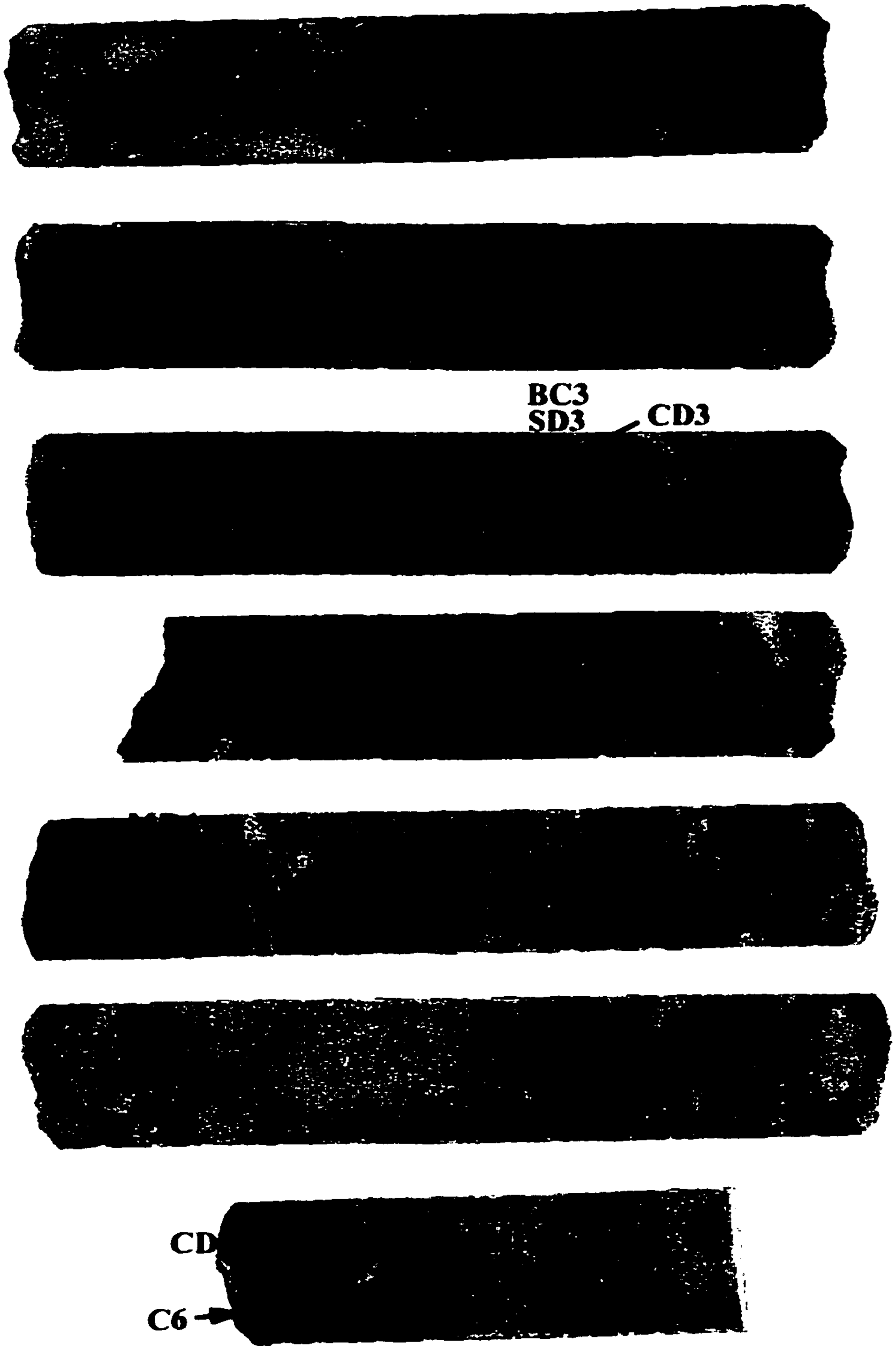

FIGURE 9.1 - Slabbed Tyndall Stone with sample locations indicated. Shown are locations for matrix calcite (Cx), burrow calcite (BCx), matrix dolomite (MDx), and sucrosic-burrow dolomite (SDx).

between 20 and 50 mg, whereas cored samples had a mass of approximately 1 mg. The samples were subsequently prepared for analysis using the McArthy's method (McArthy, 1953). This involves dissolving the sample in hydrochloic acid, and collecting and concentrating the CO_2 produced in the reaction. Carbon dioxide samples were ultimately analyzed on the mass spectrometer and the relative enrichment values of ^{18}O and ^{13}C were assessed.

RESULTS

As outlined in Chapter 8, four different cements are commonly observed in the Tyndall stone. These are resummarized, as they provide the petrographic framework utilized in this study. The cements include, a micritic cement (C1), or fine-grained microcrystalline cement (Fig. 8.4). C2 consists of a very fine-grained dolomite, characterized by subplanar subhedral crystals that form an idiotopic mosaic texture with calcite allochems dispersed throughout, this cement lends the mottled appearance to the Tyndall Stone (Fig. 8.4). C3 is comprised of fine- to medium-grained euhedral dolomite (C3), that locally exhibits a sucrosic texture and forms an isopachous to undulatory rind adjacent to, and inside the causative burrow structure (Fig. 8.4). Finally, a calcite mosaic cement (C4), infills allochems, open burrows, and voids (Fig. 8.4).

Two data sets (Figs. 9.2 and 9.3) indicate striking similarities and differences between the two samples (core and outcrop) of Tyndall Stone analyzed. In data set 1, the calcite cements (C1 and C4) plot a wide-ranging linear trend (Figure 9.2), possibly indicative of an extrinsic control expressed in the ^{13}C and ^{18}O values. Although they plot along a linear trend, C1 is typically depleted and C4 relatively enriched in ^{13}C and ^{18}O. Isotopic ratios measured from C1 range from $\partial^{13}C$ of -0.90 and $\partial^{18}O$ of -8.20 to $\partial^{13}C$ of 0.75 and $\partial^{18}O$ of -7.80. In contrast, isotope values for C4 are constrained within a $\partial^{13}C$ range of -0.10 and $0.20^{0}/_{oo}$, and $\partial^{18}O$ values of -7.30 and -6.90. Dolomite cements (C2 and C3) commonly exhibit $\partial^{13}C$ values of -0.60 to $-0.70^{0}/_{oo}$ (Figure 9.2). Delta ^{18}O is somewhat

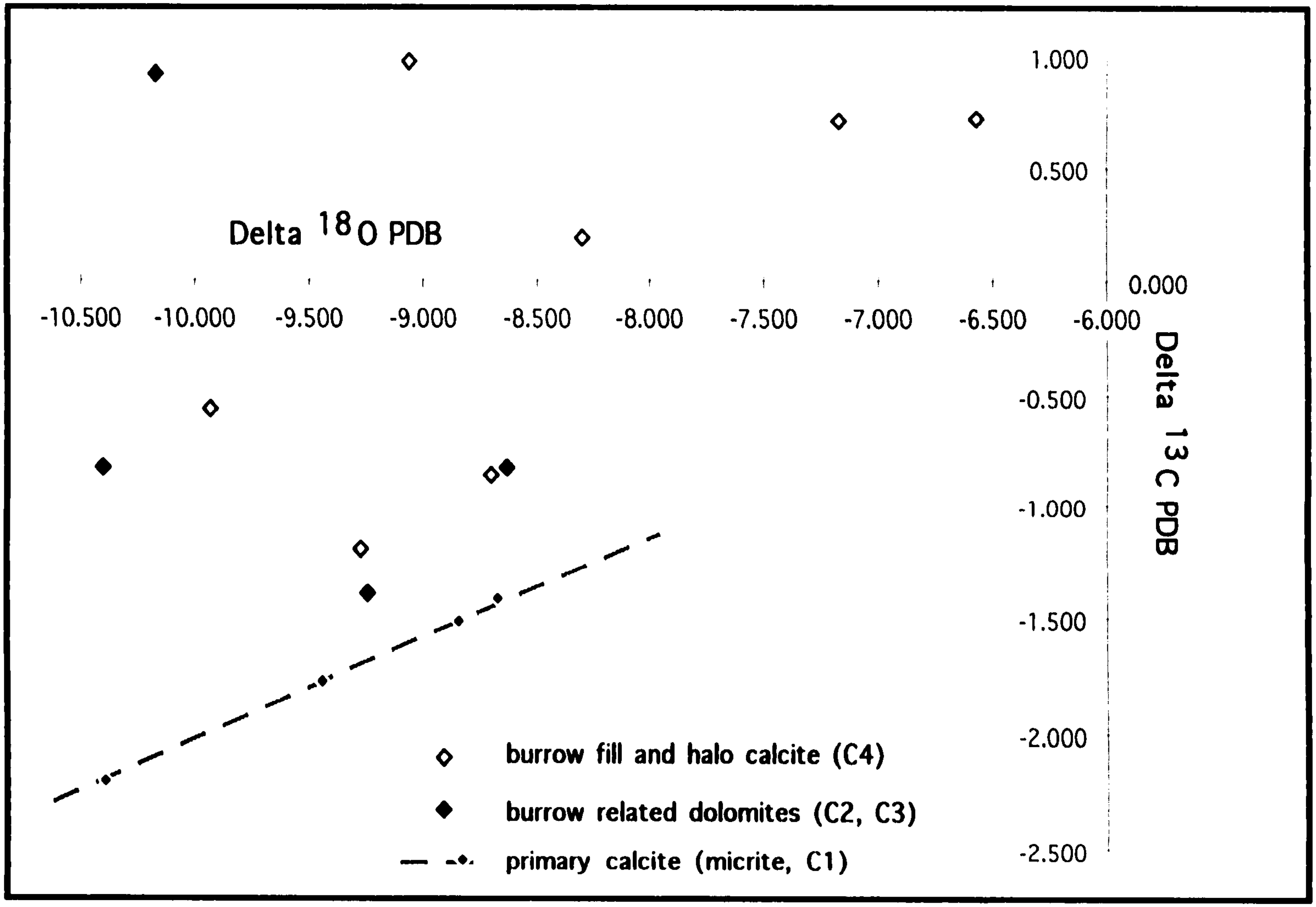

FIGURE 9.2 - Analytical isotopic data from data set #1 (subsurface core).

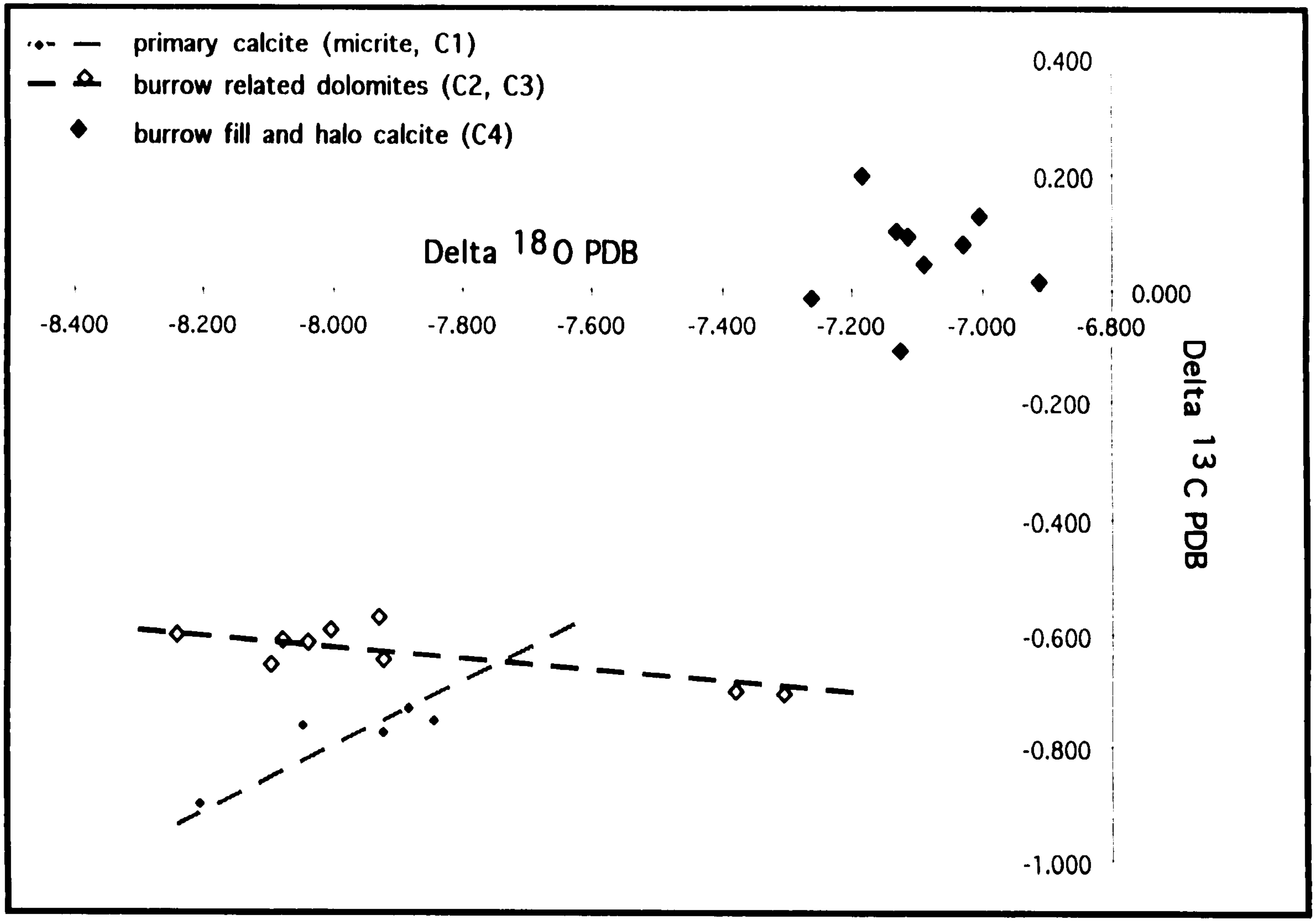

FIGURE 9.3 - Analytical isotopic data from data set #2 (outcrop).

more variable (between -8.20 and $-7.20^0/_{00}$) and may not be linked to the observed C isotope values.

Data set two (Fig. 9.3), presents a very similar linear trend for C1. Notably, the slope and range of values are similar to those indicated for C1 (Fig. 9.2). Cement 4, on the other hand, is not on trend with the C1 data. Furthermore, the isotopic range of C4 is much broader than shown in data set one ($\partial^{13}C = -1.50^0/_{00}$ to $1.00^0/_{00}$; $\partial^{18}O = -8.50^0/_{00}$ to $-10.50^0/_{00}$). Notably C4 is relatively enriched in ^{13}C, as with data set one.

The dolomite cements (C2 and C3), like data set 1, show enrichment in ^{13}C and have wider-ranging $\partial^{18}O$ values compared to $\partial^{13}C$ (Fig. 9.3). Unlike data set one, these cements show greater variability in isotope values. Interestingly, the large field formed by the C2 and C3 data strongly overlaps with analytical data from C4.

Overall, the most striking similarities between the two data sets are: 1) the micrite (C1) trends, which are virtually indistinguishable; 2) cements 2, 3 and 4 are typically enriched in ^{13}C compared to C1, and; 3) dolomitic cements show less variability in $\partial^{13}C$ than in $\partial^{18}O$. Notable dissimilarities include: stronger enrichment of $\partial^{13}C$ in data set 2 compared to data set 1; overlapping of the C2/3 field with C4, and; a broader range of values for the dolomitic cements.

Interpretation and Petrogenesis

Cement 1 represents the first stage of cementation, and is interpreted to represent an early marine cement (Chapter 8, this volume). Isotopic values from data sets 1 and 2 (Figs. 9.2 and 9.3) support this interpretation, plotting unperturbed trends which are consistent with published values for other Ordovician limestones (Hudson, 1997; Railsback *et al*, 1990; Tobin and Walker, 1997). The 'linking' of $\partial^{13}C$ and $\partial^{18}O$ may indicate a response to slight changes in the temperature of the overlying water column at the time of deposition.

Local replacement and dissolution of C1 suggests porosity and permeability were enhanced adjacent to burrow fabrics. This is attributed to the presence of high CO_2 concentrations associated with the oxidation of organic material present in the matrix and concentrated in the burrows. Dissolution of C1 was disrupted by, or contemporaneous with, the first phase of dolomitization (C2), which is concentrated near the fluid conduits made available by the higher permeabilities present in the burrow networks.

Cement 2 occurs adjacent to trace fossils, and as small packages of clustered subhedral crystals. Allochems adjacent to C2 are partially replaced where in contact with this cement. Locally, more robust allochems , such as crinoid ossicles, are preserved within C2 (Fig. 8.4D). This cement was precipitated during the primary phase of dolomitization and may have occurred during early diagenesis while the deposit passed through the zone of sulfate reduction (this volume, Chapter 8).

The relative enrichment of $\partial^{13}C$ in C2 suggests that this cement was biogenically mediated by the byproducts of fermentation (Reitsema, 1980 and Dimitrakopoulos and Muehlenbachs, 1987). The apparent unlinking of $\partial^{13}C$ and $\partial^{18}O$ further supports this observation (Fig. 9.2). Also, this might be expected if the source of carbon during early dolomitization came from interstitial porewater or circulating fluid in the substrate (Wright, 1997).

Cement 3, a sucrosic dolomite (Fig. 8.4C), was deposited on the internal surface of open trace fossils and cavities during later (perhaps burial) diagenesis. It is unlikely that the burrows remained open throughout burial, so open tubular cavities at the burrow cores were probably excavated by aggressive subsurface waters before C3 was deposited. No vestigial fabric or calcite (C1) can be observed in C3. Continued excavation of open cavities did not follow the precipitation of C3, as the dolomite crystals are euhedral and show no signs of solution resorption. Cement 3 is considered to be a primary cement precipitated during later diagenesis.

The isotopic data for C3 is typically indistinguishable from C2, though data set 2 indicates some depletion of both heavy isotopes (^{13}C and ^{18}O). To resolve this data with the textural observations, C3 must be derived from dissolved C2 or, alternatively, recrystallized from C2. Data set two and the textural relationships (infilling of vuggy porosity) strongly support the first interpretation. The large isotopic field defined by the dolomite (C3) probably resulted from a mixture of subsurface fluids and dissolved C2 that supplied the stock for the construction of C3. The discrete trend shown in data set one may indicate that this particular block of Tyndall Stone was characterized by lower permeabilities and therefore not subjected to the isotopically-variable subsurface fluids alluded to earlier.

The final stage of cementation is represented by cement 4 (Figure 8.4), a void-filling calcite mosaic. Cement 4 occludes burrows and pores locally, though partially open trace fossils and voids are common. This cement is interpreted to have precipitated in a phreatic environment, (Chapter 8; Tucker and Wright, 1990; Blanchon, 1994). Cement 4 is a primary cement, as evidenced by its sharp boundaries and the euhedral state of C3, which is typically enveloped by C4. It is indicative of a striking change in fluid chemistry that may have been related to uplift and the introduction of recharging meteoric waters. The isotopic data, however, does not indicate meteoric waters were involved in the precipitation of C4 (Figures 9.2 and 9.3). Delta ^{18}O values, which are notably suppressed in meteoric waters, are not significantly lower than the marine values measured in C1. It is more likely that the isotopes were inherited from dissolved cements (C2 and C3) during dedolomitization of the Tyndall Stone. The values therefore represent a combination of subsurface brines and dissolved matrix. Values from data set two (Fig. 9.3) best support this interpretation; plotted fields for C2/3 and C4 strongly overlap each other and suggest the isotopes present in C4 were, in fact, derived from C2/3.

In summary, the isotopic signatures observed in Tyndall Stone support several observations regarding its paragenesis. The range of ∂^{13}C and ∂^{18}O values observed with C1 is consistent with previously published values for Ordovician limestones. An apparent linking of these isotopes strongly suggests that this cement precipitated very early in diagenesis and was derived from sea-water. Cement 2, which represents the primary phase of dolomitization is potentially microbially mediated, as evidenced by relative enrichment of ∂^{13}C. This enrichment was probably due to fermentation processes occurring within the burrow microenvironment. The products of fermentation potentially catalyzed dolomitization (this volume, Chapter 8). Isotopic values for C3 apparently result from mixing of ground water and C2. Carbon and oxygen isotopes in C4 were derived from C2, C3, and circulating groundwater.

Although the overall enrichment or depletion of carbon and oxygen are comparatively low, trends are discernible in graphical format (Figs. 9.2, 9.3). Furthermore, each cement exhibits a unique trend. This data therefore suggests that burial has not completely overprinted the isotopic signature.

CONCLUSIONS

Two samples of Tyndall Stone were examined and sampled to assess the stable isotopic signature of matrix, burrow-associated dolomite, and burial dolomite observed in this deposit. Each of the cements was shown to have a unique isotopic signature. Cement 1 exhibits strongly linked ∂^{13}C and ∂^{18}O values, supporting the interpretation of this cement as an early cementing agent, probably derived from seawater. Enrichment of ∂^{13}C in C2 suggests it was microbially mediated. Textural data also supports this interpretation. Cement 3 and C4 were derived from circulating ground water and the previously deposited cements, C1 and C2.

Stable isotopic analysis of the Tyndall Stone not only helped resolve the paragenetic history of the deposit, but also showed that ancient carbonate values are not necessarily reset. Although isotopic fractionation may be subtle, ancient (Wright, 1997) and modern deposits (Vasconcelos and McKenzie, 1997) commonly show that the range of isotopic variance is low, even when excellent evidence of biogenic mediation is present (Wright, 1997; Vasconcelos and McKenzie, 1997). Future work should concentrate on a more complete database of isotopic values from the Selkirk Formation, utilizing the extensive database of core that is available.

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CHAPTER 10: SUMMARY AND CONCLUSIONS

This thesis has attempted to approach ichnological research from a unique perspective. Rather than focusing on the more traditional endeavors, such as trace fossil description and taxonomy, it focused on biological/sedimentological relationships and their dependence on larger-scale marginal marine processes. The modern and Pleistocene deposits at Willapa Bay were used as a database, drawing on the success of previous researchers (Clifton and Phillips, 1980; Clifton, 1982) in the tradition of Howard and Frey (1973). This thesis also recognized that bioturbation induces physical changes in sedimentary deposits. These changes alter bulk mechanical properties, such as permeability, and have a profound influence on diagenesis.

Three major concepts were presented. Chapters 2 and 3 (and to a lesser degree, 5 and 6) examined and enhanced the brackish water model and the understanding of tidal biological/sedimentological interaction. Chapters 4, 5, and 6 assessed the temporal and ecological significance of *Glossifungites* surfaces. Finally, Chapters 7, 8, and 9 characterized fluid flow and diagenesis in bioturbated media.

ICHNOLOGY IN ESTUARINE SETTINGS

Chapter 2 provided a detailed analysis of modern and Pleistocene deposits at Willapa Bay and introduced a unique suite of physico-chemical parameters that characterize each depositional environment within the estuary. These parameters strongly influence the physical- and biogenic-sedimentary character, lending a distinctive appearance to each of the deposit types. Interpretations rooted in the modern at Willapa Bay, provided a clearer picture of the physical- and biological-processes active in the ancient bay. Analogous ancient estuary deposits in the subsurface can be better-resolved by comparing them to the modern and Pleistocene accumulations at the bay.

The five depositional environments considered in Chapter 2 can be discerned from each other on the basis of ichnologic and sedimentologic data. Intertidal flat deposits are typically strongly bioturbated and contain a suite of diminutive horizontal and vertical traces. Intertidal pointbar deposits are sporadically bioturbated by a very low diversity suite of small trace makers. The ichnologic signature of bay deposits is variable, and strongly indicative of certain bay parameters at the time of deposition. Finally, sandy, laterally accreted channel bars contain a healthy, robust *Skolithos* ichnofacies. Burrows in these deposits are typically deep-penetrating due to taphonomic considerations. The lateral variability of all five depositional environments is to some extent predictable: this is particularly true of intertidal flat and pointbar deposits.

Although the brackish water model applies to deposits at Willapa Bay, these deposits are not archetypal. A brackish-water ichnofacies is not confirmed in Chapter 2, however the original tenets of Pemberton et al. (1982) are generally applicable to the deposits studied at the bay.

Chapter 3 illustrated the dangers of applying uniformitarian principles in dynamic sedimentary environments. Pleistocene deposits at the bay, though similar in many respects to the modern deposits, contain certain trace fossils that have no clear modern analog. Biologic factors, such as subtle sensitivity to physico-chemical stress and larval recruitment can overstate changes attributed to bay chemistry. Anthropogenic change is also difficult to assess. *Psilonichnus* described in this chapter are extremely interesting in that their fill is tidally influenced, a factor not commonly addressed in the literature.

GLOSSIFUNGITES ASSEMBLAGES AT WILLAPA BAY

Chapter 4 introduced a useful field method for assessing substrate firmness profiles in the field. This was used to generate the data used in Chapters 4 and 5 to appraise the temporal and ecological significance of *Glossifungites*-demarcated discontinuities.

Among the key findings (Chapter 5) was that sandy deposits compact and dewater more rapidly than muddy deposits. The temporal significance of sandy *Glossifungites* surfaces is therefore uncertain, whereas muddy examples are thought to require centuries to millennia to achieve significant firmness values. At Willapa Bay, it was demonstrated that a base level change of approximately 2 to 3 m is required to generate an extensive firmground. This helps quantify the amount of erosion asociated with *Glossifungites* surfaces observed in the rock record.

The sequence stratigraphic utility of *Glossifungites* surfaces has overshadowed their potential as paleoenvironmental indicators. For this reason, this thesis proposed that geologists further consider the ichnological data present in these assemblages. Chapter 6 demonstrated that the nature of the trace fossils observed is in part due to the absolute substrate firmness, the texture of the substrate, and its location in the intertidal or subtidal zones. Although the database utilized is restricted to Willapa Bay, it is thought that this data will enhance subsurface interpretations. The potential of more modern work in this area is vast.

FLUID FLOW AND DIAGENESIS

Both primary and diagenetic processes can alter or preserve higher porosity and permeability in and adjacent to trace fossils. This is contrary to the commonly held belief that bioturbation in clastic rocks reduces overall permeability (Weber, 1982), and is the result of trace fossils locally introducing heterogeneities to the rock matrix that improve the overall flow characteristics of that rock. *Glossifungites* surfaces provide a striking example of bioturbated substrates that alter the flow characteristics of a reservoir.

Chapter 7 illustrated that modeling fluid flow in bioturbated media is possible. To do this, a three-dimensional model of burrow networks was conceived and integrated with flow-modeling software. A simplified burrow network, consisting of rudimentary branching and varying degrees of connectivity, simulated burrow networks observed in

Glossifungites surfaces at Willapa Bay, Washington. Chapter 7 introduces empirical and analytical formulae that calculate the effective permeability from k_b, k_m, and the degree of connectivity. Chapter 8 suggests these formulae can be applied in any geologic medium as a first-run approximation. Laboratory and field-based slug tests confirm the computer model and the proposed formulae utilized to assess the permeability of *Glossifungites* surfaces. Several stratigraphic configurations are provided, demonstrating the potential utility of these concepts.

The remainder of the thesis (Chapters 8 and 9) focused on the development of heterogeneous fabrics in calcareous deposits. A unique dolomitization model was proposed and supported using petrographic and isotopic data. These sections are highly conceptual, and present unique data that indicates further study is required. Chapter 8 also presented tracer gas data that illustrated the tortuous and dual porosity/ permeability nature of the Tyndall Stone, a burrow-mottled dolomitic limestone. This section underscored the problems inherent in producing hydrocarbons from similar deposits.

APPLICABILITY

This thesis presented new data pertaining to the identification and delineation of brackish-water deposits. It should find wide applicability in the subsurface of the Western Canada Sedimentary Basin, where estuarine deposits have played an important role in Canada's oil industry. It enhances the traditional tripartite estuarine models and lends insight into the pitfalls of resolving paleogeographic configuration.

By addressing issues relating to the *Glossifungites* ichnofacies, Chapters 5 and 6 introduced a new tool to address the stratigraphic and ecological significance of these surfaces. The premises derived herein are applicable to the rock record and enhance our overall understanding of *Glossifungites*-demarcated discontinuities. It is hoped that more modern studies of a similar nature will improve our overall understanding of the sequence stratigraphic significance of these surfaces.

Fluid flow studies through *Glossifungites* surfaces contributed simple formulae which should find wide applicability as first run estimates of the bulk permeability of bioturbated media. This technology is conceptually transferable to carbonate strata, where it may find wider application. Dispersivity experiments demonstrated the dual permeability/porosity nature of such media, and the challenges they might present a reservoir geologist. Diagenetic models, though decidedly academic, forced a shift in focus from large scale (regional), to small scale (burrow) processes. Although this concept may find limited application, it represents a philosophical change in approach to unravel the diagenetic history of a deposit.

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