Chapter 14

The Sequence Stratigraphic Significance of Trace Fossils: Examples from the Cretaceous Foreland Basin of Alberta, Canada

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ABSTRACT

Trace fossils represent both sedimentologic and paleontologic entities and, as such, represent a unique blending of potential environmental indicators in the rock record. Trace fossils and trace-fossil suites can be employed effectively to aid in the recognition of various types of discontinuities and to assist in their genetic interpretation. Ichnology may be employed to resolve surfaces of sequence stratigraphic significance in two main ways: (1) through the recognition of substrate-controlled ichnofacies, which mark time gaps between the original deposition of a unit (with or without softground burrowing) and later superimposition of a postdepositional trace-fossil assemblage, and (2) through careful analysis of vertical ichnological successions (analogous to facies successions). Integrating the data derived from substrate-controlled ichnofacies with data from vertical ichnological successions provides a powerful tool for the recognition and interpretation of important sequence stratigraphic surfaces.

INTRODUCTION

Stratigraphy, once considered to be a somewhat routine and mundane discipline consisting mainly of the dry cataloging of lithostratigraphic units, has recently undergone a dramatic renaissance. During the last decade, stratigraphers have radically altered how the rock record is perceived and, therefore, interpreted. Once almost exclusively the domain of biostratigraphers and geochronologists, the stratigraphic column has been subjected to new ideas and methods. A synergistic approach has resulted in the development and refinement of new stratigraphic tools such as seismic stratigraphy, allostratigraphy, tephra-stratigraphy, magnetostratigraphy, eco-stratigraphy, event stratigraphy, and, of course, sequence stratigraphy.

The stratigraphic utility of trace fossils can take on many guises, and their significance varies depending on what stratigraphic paradigm one is employing. In the past, trace fossils were considered to be almost useless in stratigraphy because:

1. most have long temporal ranges;
2. they are largely facies dependent;
3. a particular structure may be produced by the work of two or more different organisms living together, or in succession, within the structure;

4. the same individual or species of organism may produce different structures corresponding to different behavior patterns;
5. the same individual may produce different structures corresponding to identical behavior but in different substrates (e.g., in sand, in clay, or at sand-clay interfaces); and
6. identical structures may be produced by the activity of systematically different tracemaking organisms, where behavior is similar (Ekdale et al., 1984).

These factors combine to make the biostratigraphic value of trace fossils negligible. Traditionally, it was thought that there were only three ways in which trace fossils could be utilized in chronostratigraphy: (1) tracing the evolution of behavior, (2) as morphologically defined entities (with no assumptions concerning their genesis), and (3) as substitutes for the tracemaking organisms (Magwood and Pemberton, 1990). In contrast, trace fossils are proving to be one of the most important groups of fossils in delineating stratigraphically important boundaries related to sequence stratigraphy (MacEachern et al., 1991a, b, 1992a, b; Savrda, 1991a, b), allostratigraphy (Pemberton et al., 1992a), and event stratigraphy (Frey and Goldring, 1992; Pemberton et al., 1992b).

Facies analysts have generally found it difficult to reconcile sedimentologic observations with lithostratigraphic frameworks. In recent years, stratigraphers have moved away from lithostratigraphic analysis and have approached the rock record in terms of genetic stratigraphy. Genetic stratigraphy lies at the core of three main stratigraphic paradigms: genetic stratigraphic sequences (Galloway, 1989a, b), allostratigraphy (North American Commission on Stratigraphic Nomenclature, 1983), and sequence stratigraphy (Wilgus et al., 1988; Van Wagoner et al., 1990).

No matter which stratigraphic paradigm is utilized, the recognition of stratigraphic breaks is of paramount importance and is commonly a difficult task, particularly in subsurface analysis. The stress on discontinuities emphasizes processes that are external to the depositional system itself (allocyclic) and which may initiate or terminate deposition of sedimentologically related facies successions (Walker, 1990). Delineation of the origin of the discontinuity is vital in resolving depositional environments and in determining the characteristics of allocyclic controls on depositional systems. Trace fossils and trace-fossil suites can be employed effectively both to aid in the recognition of various types of discontinuities and to assist in their genetic interpretation. This method requires an integrated approach employing diverse stratigraphic, sedimentologic, and paleontologic techniques.

CONCEPTUAL FRAMEWORK OF ICHNOLOGY APPLIED TO SEQUENCE STRATIGRAPHY

Trace fossils (other than borings) are both sedimentologic and paleontologic entities, and therefore represent a unique blending of potential environmental indicators in the stratigraphic record. Like physical sedimentary structures, trace fossils reflect many of the effects of environmental parameters prevailing during deposition and, to an appreciably greater extent than body fossils, are a record of the behavior of active, in-situ organisms. The behavioral record of benthic organisms, as dictated or modified by environmental constraints, is thus the mainstay of ichnology. Biogenic structures appear in many guises (Frey and Pemberton, 1985), but in paleoenvironmental analysis the main concern is with tracks, trail, burrows, and borings. The ultimate objective is to portray the facies implications of these various structures.

Ethological Classification of Trace Fossils

Unique classification schemes have been developed in order to decipher trace fossils, because they represent behavior rather than actual body remains. Historically, trace fossils have been classified in descriptive, preservational taxonomic and behavioral terms. Of these, the behavioral (or ethological) scheme is by far the most important; the behavioral record of benthic organisms is dictated and modified not only by genetic pre-adaptations but also by prevailing environmental parameters.

Ekdale et al. (1984) recognized seven basic categories of behavior: resting traces (cubichnia), locomotion traces (repichnia), dwelling structures (domichnia), grazing traces (pascichnia), feeding burrows (fodinichnia), farming systems (agrichnia), and escape traces (fugichnia). Ekdale (1985) added predation traces (praedichnia), and Frey et al. (1987) emphasized the importance of equilibria (fugichnia) to all other behavioral patterns.

Such fundamental behavioral patterns, although genetically controlled, are not phylogenetically restricted. The basic ethological categories, for the most part, have persisted throughout the Phanerozoic (Hiscott et al., 1984). Individual tracemakers have evolved, but basic benthic behavior essentially has not. For example, deposit feeders are pre-adapted to quiescent environments where deposited foodstuffs are most abundant; therefore, they do not fare well in turbulent-water settings. The opposite is true of suspension feeders. Similarly, locomotion traces can be preserved only under a strict set of environmental conditions. The ability to discern behavioral trends of benthic organisms represented in the rock record greatly facilitates environmental interpretations.

The Ichnofacies Concept

Perhaps the essence of trace-fossil research involves the grouping of characteristic ichnofossils into recurring ichnofacies. This concept, developed by Adolf Seilacher in the 1950s and 1960s, was based originally on the observation that many of the parameters that control the distribution of tracemakers tend to change progressively with increased water depth (Figure 1).

Because of the potential geological value of this bathymetric relationship (Figure 1, Table 1), the Seilachernian ichnofacies concept soon came to be

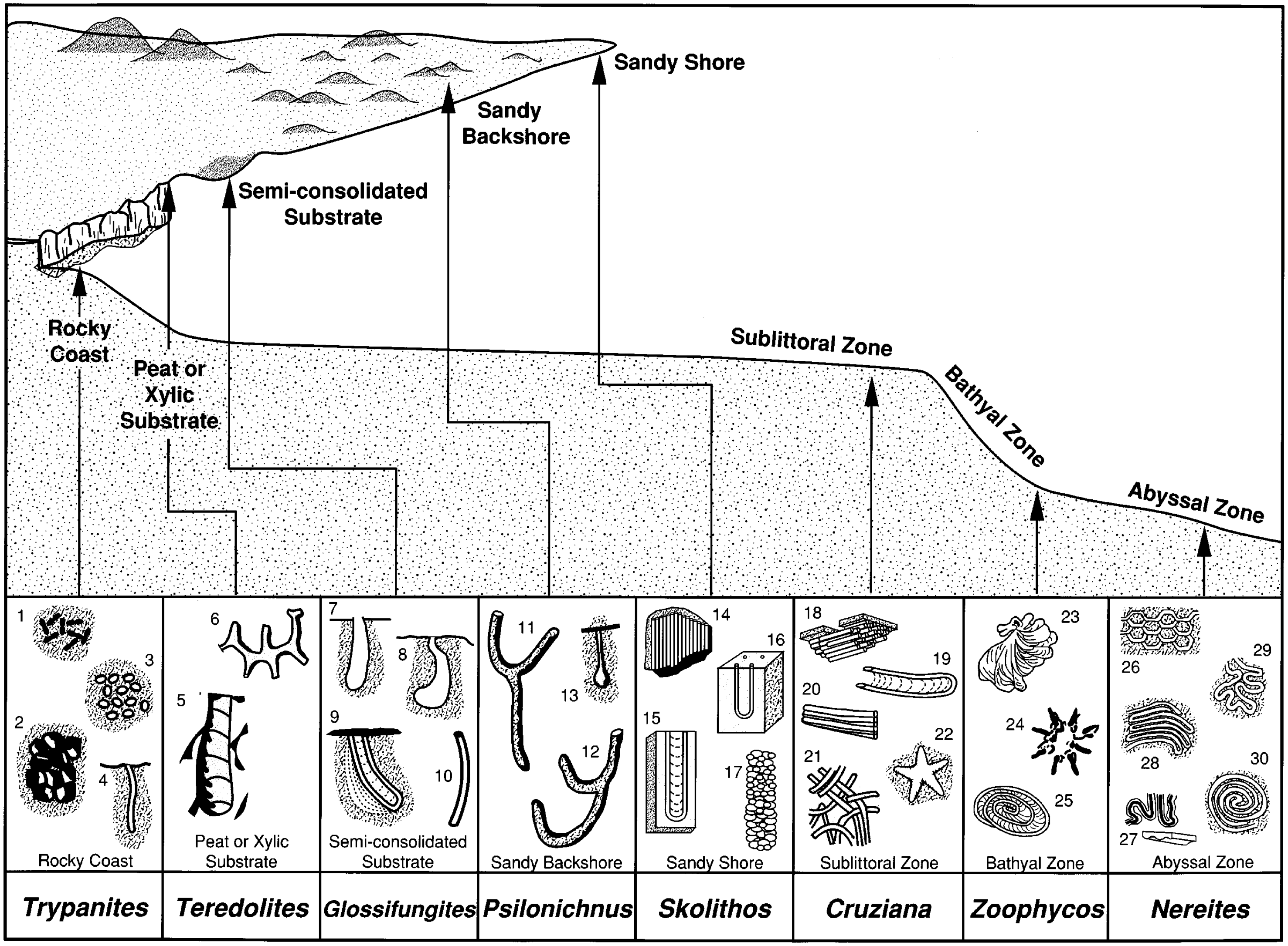


Figure 1. Synoptic diagram illustrating recurring marine ichnofacies, placed in a representative, but not exclusive, suite of environmental gradients. Local physical, chemical, and biological factors ultimately determine which traces occur at which sites. Typical trace fossils include: (1) *Caulostrepsis*, (2) *Entobia*, (3) echinoid borings, unnamed, (4) *Trypanites*, (5) *Teredolites*, (6) *Thalassinoides*, (7, 8) *Gastrochaenolites* or related ichnogenera, (9) *Diplocraterion* (*Glossifungites*), (10) *Skolithos*, (11, 12) *Psilonichnus*, (13) *Macanopsis*, (14) *Skolithos*, (15) *Diplocraterion*, (16) *Arenicolites*, (17) *Ophiomorpha*, (18) *Phycodes*, (19) *Rhizocorallium*, (20) *Teichichnus*, (21) *Planolites*, (22) *Asteriacites*, (23) *Zoophycos*, (24) *Lorenzinia*, (25) *Zoophycos*, (26) *Paleodictyon*, (27) *Taphrhelminthopsis*, (28) *Helminthoida*, (29) *Cosmorhaphe*, and (30) *Spirorhaphe*. Modified from Frey and Pemberton (1985).

Table 1. Recurring archetypical trace-fossil associations and their common (but not exclusive) environmental implications (adapted from Frey and Pemberton, 1984, 1985, 1987, and Frey et al., 1990).

Typical Benthic Environment	Characteristic Trace Fossils
***Scoyenia* ichnofacies (waterside or overbank substrates)**	
Moist to wet, pliable, argillaceous to sandy sediments at low-energy sites: either very shallowly submersed lacustrine or fluviatile deposits periodically becoming emergent, or waterside subaerial deposits periodically becoming submergent. Intermediate between aquatic and nonaquatic, nonmarine environments. Allied sedimentary structures may include desiccation cracks, root mottles, and other waterside features.	Small horizontal, lined, backfilled feeding burrows; curved to tortuous unlined feeding burrows; sinuous crawling traces; vertical, cylindrical to irregular shafts; tracks and trails. Invertebrates mostly deposit feeders or predators; vertebrates are predators, herbivores, or grovelers. Invertebrate diversity very low, yet some traces may be abundant. Vertebrate tracks may be diverse and abundant around water bodies.
***Teredolites* ichnofacies (xylic substrates)**	
Resistant substrates consisting of driftwood pavements, peat deposits, or related xylic substances, many of which appear as lignite or coal in the rock record. May represent omission surfaces developed on matted wood clasts, log jams, or other xylic materials (but not single clasts or trunks), or slow deposition in marshy or swampy areas of peat accumulation. Most common in estuarine, deltaic, or various back-barrier environments.	Sparse to profuse clavate (shipworm) borings. Dense excavations may be deformed but ordinarily do not interpenetrate. Boring walls may be ornamented with the texture of the host substrate (e. g., tree-ring xenoglyphs). Stumpy to elongate, subcylindrical, subparallel excavations predominate in marine or marginal marine settings. Shallower, sparse to profuse nonclavate etchings (isopod borings) typify freshwater ichnofaunas.
***Trypanites* ichnofacies (hard substrates)**	
Consolidated marine littoral and sublittoral omission surfaces (rocky coasts, beachrock, hardgrounds), reefs, or particulate strata formed of organic constituents (bone beds, shell beds, coquinites, but not individual bones, shells, or clasts). Bioerosion is as important as, and also accelerates, physical erosion of the substrate. Intergradational with the *Glossifungites* ichnofacies; in sequential hardground development, the *Trypanites* suite may crosscut a former *Glossifungites* or an even earlier *Cruziana* suite of traces.	Cylindrical to vase-, tear-, or U-shaped to irregular domiciles of endolithos, oriented normal to the respective substrate surface, or shallow anastomosing systems of borings (sponges, bryozoans; excavated mainly by suspension feeders or passive carnivores). Raspings and gnawings of algal grazers and equivalent organisms (chitons, limpets, echinoids mainly). Diversity moderately low, although borings or scrapings of given kinds may be abundant. In particulate lithic substrates, boring walls cut through grains or shells instead of skirting them.
***Glossifungites* ichnofacies (firm substrates)**	
Firm but unlithified marine littoral and sublittoral omission surfaces, especially semi-consolidated carbonate firmgrounds or stable, cohesive, partially dewatered muddy substrates either in protected, moderate-energy settings or in areas of somewhat higher energy where semi-consolidated micritic or siliciclastic substrates offer resistance to erosion. The final sedimentary record typically consists of a mixture of relict and palimpsest features, including cross-cutting ichnofaunas.	Vertical cylindrical, U-, or tear-shaped borings, or sparsely to densely ramified dwelling burrows, or various mixtures of burrows and borings. Protrusive spreiten in some U burrows, developed mostly through growth of animals (fan-shaped *Rhizocorallium* and *Diplocraterion,* formerly *Glossifungites*). Many intertidal species (e.g., crabs) leave the burrows to feed; others are mainly suspension feeders. Diversity is typically low, yet given kinds of structures may be abundant. Unlike *Trypanites* suites, *Glossifungites* excavations tend to avoid obstructions within the substrate.
***Psilonichnus* ichnofacies (shifting substrates I)**	
Supralittoral to upper littoral, moderate to low-energy marine and/or eolian conditions subject to modification by torrential rains or storm surges. Associated with well-sorted, variably laminated to cross-stratified sands, to root- and burrow-mottled, poorly sorted sands or muddy sands. A common coastal setting,	Predominantly vertical small shafts, some with bulbous basal cells, to larger, irregularly J-, Y-, or U-shaped dwelling burrows; local invertebrate and vertebrate crawling and foraging traces or surficial tunnels; algal mats and vertebrate tracks and coprolites may be present. Invertebrates mostly predators

Psilonichnus ichnofacies (shifting substrates I)

typically represented by the beach backshore and dunes but also by washover fans and supratidal flats. Intergradational with the maritime zone.

or scavengers, of low diversity. Vertebrates mostly predators or herbivores; diversity may be appreciable locally. In pre-Cretaceous occurrences, crablike dwelling structures may be absent.

Skolithos ichnofacies (shifting substrates II)

Lower littoral to infralittoral, moderate to relatively high-energy conditions most typical. Associated with slightly muddy to clean, well-sorted, shifting sediments subject to abrupt erosion or deposition. (Higher energy increases physical reworking and obliterates biogenic sedimentary structures, leaving a preserved record of physical stratification.) Generally corresponds to the beach foreshore and shoreface, but numerous other settings of comparable energy levels also may be represented, such as estuarine point bars, tidal deltas, and deep-sea fans.

Vertical, cylindrical, or U-shaped dwelling burrows; protrusive and retrusive spreiten in some U burrows, developed mainly in response to substrate aggradation or degradation (escape or equilibrium structures); forms of *Ophiomorpha* consisting predominantly of vertical or steeply inclined shafts. Animals are chiefly suspension feeders or passive (tubicolous) carnivores. Diversity is low, though given kinds of burrows may be abundant. Vertebrate lebensspuren may occur locally, especially in low-energy intertidal settings.

Cruziana ichnofacies (shifting to stable substrates)

In shelfal settings, typical sequences include infralittoral to shallow circalittoral substrates below minimum but not maximum wave base, to somewhat quieter conditions offshore; moderate to relatively low energy; well-sorted silts and sands to interbedded muddy and clean sands, moderately to intensely bioturbated; negligible to appreciable—though not necessarily rapid—sedimentation. A very common type of depositional environment, including not only shelves and epeiric embayments but also littoral to sublittoral parts of certain estuaries, bays, lagoons, and tidal flats.

Abundant crawling traces, both epi- and intrastratal; inclined U-shaped burrows having mostly protrusive spreiten (feeding swaths; soft-sediment *Rhizocorallium*); forms of *Ophiomorpha* and *Thalassinoides* consisting of irregularly inclined to horizontal components; scattered vertical cylindrical burrows (suspension feeders or passive carnivores). Animals may include mobile carnivores as well as various mixtures of suspension and deposit feeders. Diversity and abundance generally high, although crawling traces of limited diversity may predominate in certain Paleozoic nearshore settings.

Zoophycos ichnofacies (oxygen-poor settings)

Circalittoral to bathyal, quiet-water conditions, or protected intracoastal to epeiric sites (silled basins, restricted lagoons) with muds or muddy sands rich in organic matter but more or less deficient in oxygen. Epeiric or coastal sites reflect somewhat stagnant waters. Offshore sites range from just below maximum wave base to fairly deep water in areas free of turbidity flows or significant bottom currents. Where relict or palimpsest substrates are present, especially if swept by shelf-edge or deeper water contour currents, this ichnofacies may be omitted in the transition from infralittoral to abyssal environments.

Relatively simple to moderately complex, efficiently executed grazing traces and shallow feeding structures; spreiten typically planar to gently inclined, distributed in delicate sheets, ribbons, lobes, or spirals (flattened forms of *Zoophycos* or, in pelitic sediments, *Phycosiphon*). Virtually all animals are deposit feeders. Diversity is very low, though given structures typically are abundant. (The ichnogenus *Zoophycos* may also be abundant in the *Cruziana* and *Nereites* ichnofacies under normal oxygen levels; occurrences of the ichnogenus thus do not necessarily constitute the ichnofacies.)

Nereites ichnofacies (turbidite-type settings)

Bathyal to abyssal, mostly quiet but oxygenated waters, in places interrupted by down-slope or down-canyon bottom currents or turbidity flows (flysch settings). Resident pelagic muds typically are bounded above and below by turbidites, some exhibiting complete Bouma sequences. (In more distal regions, the sedimentary record is mainly one of continuous deposition and bioturbation; few physical or biogenic structures are preserved, unlike the *Nereites* ichnofacies sensu stricto.)

Complex grazing traces and patterned feeding/dwelling structures, reflecting highly organized, efficient behavior; spreiten structures typically nearly planar, although *Zoophycos* forms are spiraled, multilobed, or otherwise very complex. Numerous crawling/grazing traces and sinuous fecal castings *(Helminthoida, Cosmorhaphe),* mostly intrastratal. Animals chiefly deposit feeders or scavengers, although some may have trapped or farmed microbes within essentially permanent, open domiciles *(Paleodictyon, Megagrapton).* Diversity and abundance are generally significant.

regarded almost exclusively (albeit erroneously) as a relative paleobathymeter. Today, these ichnofacies remain valuable in environmental reconstructions, but paleobathymetry is only one aspect of the modern ichnofacies concept (Frey et al., 1990).

Ichnofacies are part of the total aspect of the rock and therefore, like lithofacies, are subject to Walther's Law. For example, isolated bored shells or clasts do not in themselves constitute the *Trypanites* ichnofacies (Table 1). Rather, there should be some semblance of stratification, lateral continuity, and vertical succession. This relation is another strength of ichnology; interpretations of ichnofaunas are improved substantially when the traces are studied in the context of the host rocks and their implications.

Archetypical Ichnofacies

Nine recurring ichnofacies have been recognized, each named for a representative ichnogenus (Table 1): *Scoyenia*, *Teredolites*, *Trypanites*, *Glossifungites*, *Psilonichnus*, *Skolithos*, *Cruziana*, *Zoophycos*, and *Nereites*. These trace-fossil associations reflect adaptations of tracemaking organisms to numerous environmental factors such as substrate consistency, food supply, temperature, hydrodynamic energy, salinity, and oxygen levels (Frey and Pemberton, 1984; Frey et al., 1990). Traces in nonmarine assemblages (other than in the *Scoyenia* settings) are in need of further refinement; the marine softground ichnofacies (*Psilonichnus*, *Skolithos*, *Cruziana*, *Zoophycos*, and *Nereites*) are distributed according to numerous environmental parameters; traces in the firmground (*Glossifungites*), woodground (*Teredolites*), and hardground (*Trypanites*) ichnofacies are distributed on the basis of substrate type and consistency.

Representative occurrences of the various ichnofacies are summarized below; however, each may appear in other settings, as dictated by characteristic sets of recurrent environmental parameters. From the standpoint of ethological requirements of tracemaking organisms, for example, certain intertidal backbarrier environments are not all that different from certain subtidal forebarrier environments, and may contain virtually identical suites of trace fossils.

Contrary to a popular misconception, the *Scoyenia* ichnofacies is only one of many nonmarine ichnofacies and is, itself, quite distinctive (Frey and Pemberton, 1985; Bromley and Asgaard, 1991). Furthermore, prospects for the recognition of additional archetypical nonmarine ichnofacies remain encouraging. For example, Ekdale et al. (1984) and Frey and Pemberton (1987) noted that distinct suites of trace fossils characterize eolian dunes, fluvial overbanks, paleosols, and lake environments.

The *Psilonichnus* ichnofacies is associated with supralittoral/upper littoral, moderate- to low-energy marine and/or eolian conditions typically found in beach to backshore to dune environments (Table 1). The comments by Bromley (1990) and Bromley and Asgaard (1991) notwithstanding, the *Psilonichnus* ichnofacies was founded on fossil examples (Frey and Pemberton, 1987) and is no more theoretical than any other recurrent ichnofacies. The modern ichnocoenoses were emphasized to show the richness that one might reasonably expect to have existed for various ancient ichnofaunas. Furthermore, one of the major tenets of ichnofacies reconstruction is that the name-bearer need not be present in every occurrence of the ichnofacies; thus, just as *Cruziana* are rare in post-Paleozoic occurrences of the *Cruziana* ichnofacies, *Psilonichnus* may well be absent in pre-Mesozoic occurrences of the *Psilonichnus* ichnofacies.

The *Skolithos* ichnofacies is generally associated with high-energy, sandy, shallow marine environments (Table 1). The trace fossils are characterized by: (1) predominantly vertical, cylindrical or U-shaped burrows, (2) few horizontal structures, (3) few structures produced by mobile organisms, (4) low diversity, although individual forms may be abundant, and (5) mostly dwelling burrows constructed by suspension feeders or passive carnivores.

The *Cruziana* ichnofacies is typically associated with marine substrates lying below minimum wave base and above maximum wave base (Table 1). The trace fossils are characterized by a number of features, including: (1) a mixed association of vertical, inclined, and horizontal structures, (2) the presence of traces constructed by mobile organisms, (3) generally high diversity and abundance, and (4) mostly feeding and grazing structures constructed by deposit feeders, except where crawling traces are predominant.

The *Zoophycos* ichnofacies ideally is found in shelfal to bathyal, quiet-water marine muds or muddy sands lying below maximum wave base to fairly deep water, in areas free of turbidity flows and subject to oxygen deficiencies. The trace fossils are characterized by: (1) low diversity, although individual traces may be abundant, (2) grazing and feeding structures produced by deposit feeders, and (3) horizontal to gently inclined spreiten structures. However, the ichnofacies also may occur in restricted intracoastal settings (Table 1), particularly in Paleozoic intervals. The ichnogenus *Zoophycos* is present in deeper-water environments in Mesozoic and Cenozoic deposits than in Paleozoic deposits (Frey and Pemberton, 1984). Hence, the character of the *Zoophycos* ichnofacies may vary from one part of the stratigraphic column to the next.

The *Nereites* ichnofacies typically is associated with bathyal/abyssal, low-energy, oxygenated marine environments subject to periodic turbidity flows. The trace fossils are characterized by: (1) high diversity but low abundance, (2) complex horizontal grazing traces and patterned feeding/dwelling structures, (3) numerous crawling/grazing traces and sinuous fecal castings, and (4) structures produced by deposit feeders, scavengers, or possibly harvesters (Ekdale et al., 1984). As presently understood, the *Nereites* ichnofacies is restricted primarily to flysch or turbidite successions; sediments in the great expanses of sea floor beyond influence of turbidity flows consist chiefly of bioturbate textures rather than discrete traces (Frey and Wheatcroft, 1989). Hence, there is no well-preserved record of these specific ichnocoenoses.

The remaining three ichnofacies are specialized, substrate-controlled suites and, environmentally, are very general in scope, although typically marine or marginal marine in character. The *Glossifungites* ichnofacies develops in firm but unlithified substrates (i.e., dewatered muds). Such substrates can dewater as a result of burial and are made available to tracemakers if exhumed by later erosion (Pemberton and Frey, 1985). Exhumation can occur in shallow-water environments as a result of coastal erosion processes or from submarine channels cutting through previously deposited sediments. Other substrates may reflect subaerial exposure prior to onset of marine conditions. Such horizons may prove to be critical sequence stratigraphic breaks in the rock record.

The *Trypanites* ichnofacies characterizes fully lithified marine substrates such as hardgrounds, reefs, rocky coasts, beachrock, unconformities, and other kinds of omission surfaces. The ichnofacies may develop even on igneous substrates (Fischer, 1981), and the collective volume of bio-eroded sediments may be substantial (Torunski, 1979).

The *Teredolites* ichnofacies, on the other hand, encompasses a characteristic assemblage of borings in mostly marine- or marginal marine-influenced xylic (woody) substrates. The latter differ from lithic substrates in three main ways (Bromley et al., 1984): (1) they may be flexible instead of rigid, (2) they are composed of organic material instead of mineral matter, and (3) they are readily biodegradable. Woodgrounds may appear in freshwater settings (e.g., logjams in fluvial cutoffs), but wood-boring bivalves (shipworms) do not; freshwater examples of this ichnocoenose consist principally of isopod and allied borings. Furthermore, one should discern whether the woodground borings are autochthonous (Arua, 1989) or allochthonous (Dewey and Keady, 1987); only the former are true members of the *Teredolites* ichnofacies. Such assemblages also may be of considerable importance in defining sequence and parasequence boundaries.

Evaluation of the Ichnofacies Models

Ichnofacies stand today as one of the most elegant but also most widely misunderstood concepts in ichnology, especially where paleobathymetry is concerned (Frey et al., 1990). Marine ichnofacies are not intended to be paleobathymeters; rather, they are archetypical facies models based upon recurring ichnocoenoses (Seilacher, 1967, 1978; Frey and Pemberton, 1984, 1985). If a particular ichnocoenose tends to occur repeatedly within a given bathymetric setting, so much the better, but water depth per se is rarely, if ever, a governing factor. Ichnofacies, therefore, are best viewed in the context of actual deposition.

One of the most fundamental tenets of modern ichnofacies analysis is that all available evidence—physical, chemical, or biological—should be integrated and utilized in interpretations. For bathymetric assessments, those collective observations should be placed in the context of proximality trends, whether emphasized from a sedimentologic viewpoint (Nittrauer et al., 1984; Clifton, 1988) or an ichnological one (Crimes, 1973; Wetzel, 1981; Howard and Frey, 1984). Associations between and configurations of biogenic and physiogenic sedimentary structures are powerful combinations in the reconstruction of environmental gradients (Wightman et al., 1987; Moslow and Pemberton, 1988); they are especially useful where otherwise prevalent trends have been modified by episodic events or other environmental fluctuations (Pemberton and Frey, 1984; Frey, 1990; Frey and Goldring, 1992; Pemberton et al., 1992b).

Numerous authors have noted occurrences of certain ichnofacies in settings outside the zone specified in the original paradigm (Figure 1), and have used these discrepancies as an argument against the validity or usefulness of the overall ichnofacies concept. For instance, if each shoreline involved only a "normal" beach-to-offshore trend, then the classic onshore *Skolithos* ichnofacies would indeed give way to the offshore *Cruziana* ichnofacies, virtually without exception. But in many settings, the nearshore zone includes bays, lagoons, estuaries, deltas and tidal flats, and the offshore zone includes bars, shoals, submarine canyons, or ridges or other features that might disrupt the "normal trend." For similar reasons, the *Skolithos* ichnofacies may appear on proximal parts of deep-sea fans (Crimes, 1977; Crimes et al., 1981), or the *Zoophycos* ichnofacies may appear in silled marine basins or restricted lagoons (Miller, 1991).

In short, the idealized ichnofacies succession works well in "normal" situations (Frey and Pemberton, 1984); yet, one should not be surprised to find nearshore assemblages in offshore sediments, and vice versa, if these accumulated under conditions otherwise like those preferred by the tracemaking organisms (Frey et al., 1990). The basic consideration rests not with such inanimate backdrops as water depth or distance from shore, or some particular tectonic or physiographic settings, but rather with such innate, dynamic controlling factors as substrate consistency, hydraulic energy, rates of deposition, turbidity, salinity, oxygen levels, toxic substances, the quality and quantity of available food, and the ecologic or ichnologic prowess of the tracemakers themselves. Resulting ichnocoenoses are related to bathymetry only where particular combinations of environmental parameters are aligned with bathymetry.

SUBSTRATE-CONTROLLED ICHNOFACIES AND STRATIGRAPHIC DISCONTINUITIES

Three substrate-controlled ichnofacies have been established (Bromley et al., 1984): *Trypanites* (hardground suites), *Teredolites* (woodground suites), and *Glossifungites* (firmground suites). Although all three suites may indicate the presence of a regional stratigraphic discontinuity, only the *Glossifungites* ichnofacies has been recognized to commonly do so in Cretaceous intervals of the Western Canada sedimentary basin (WCSB). The *Glossifungites* ichnofacies (redefined by Frey and Seilacher, 1980) encompasses trace fossils associated with semilithified or firm substrates (e.g., dewatered, cohesive muds), attributable either to subaerial exposure or burial and subsequent exhumation (Figure 2). Less commonly, *Glossifungites* suites may be developed in incipiently cemented sandstone substrates, such as in the Appaloosa Sandstone of the Bearpaw Formation–Horseshoe Canyon Formation transition (Saunders and Pemberton, 1986).

Firmground traces are dominated by vertical to subvertical dwelling structures of suspension-feeding organisms (Figure 3A and 3B). The most common structures correspond to the ichnogenera *Diplocraterion*, *Skolithos*, *Psilonichnus*, *Arenicolites*, and firmground *Gastrochaenolites* (Figure 2). Dwelling structures of deposit-feeding organisms are also constituents of the ichnofacies, and include firmground *Thalassinoides*/*Spongeliomorpha* (Figure 3C and 3D) and *Rhizocorallium*. The presence of vertical shafts within shaly intervals is anomalous, as such structures are not capable of being maintained in soft muddy substrates (Figure 3A and 3B). *Glossifungites* ichnofacies traces are typically robust, commonly penetrating 20–100 cm below the stratigraphic break. Many shafts tend to be 0.5–1.0 cm in diameter, particularly *Diplocraterion habichi* and *Arenicolites*. This scale of burrowing is in sharp contrast to the predominantly horizontal, diminutive trace fossils common to shaly intervals. The firmground traces are generally very sharp walled and unlined, reflecting the stable, cohesive nature of the substrate at the time of colonization and burrow excavation. Linings are typically employed by the tracemaker in an attempt to stabilize dwelling burrows in unconsolidated material. Many structures, particularly in outcrop, show preserved sculptings or scratch marks on the burrow wall, confirming that construction of the dwelling burrow occurred in a firm substrate (Figure 4A). Further evidence of substrate stability, atypical of soft muddy beds, is the passive nature of burrow fill. This demonstrates that the structure remained open after the tracemaker vacated the burrow, thus allowing material from the succeeding depositional event to passively fill the open structure. The postdepositional origin of the *Glossifungites* suite, in relation to the original softground assemblage, is clearly demonstrated by the ubiquitous crosscutting relationships observed in the rock record. The final characteristic of the *Glossifungites* suite is the tendency to demonstrate colonization in large numbers (Figure 4B). In several examples, seven to 15 firmground traces, commonly *Diplocraterion habichi*, have been observed on the bedding plane of a 9 cm (3.5 in.) diameter core. This density corresponds to between 1100 to 2300 shafts per m^2. Similar populations were observed from *Glossifungites* suites on the modern coast of Georgia (Pemberton and Frey, 1985). Dense populations are typical of many opportunistic assemblages (Levinton, 1970; Pemberton and Frey, 1984).

In siliciclastic settings, most firmground assemblages are associated with erosionally exhumed (dewa-

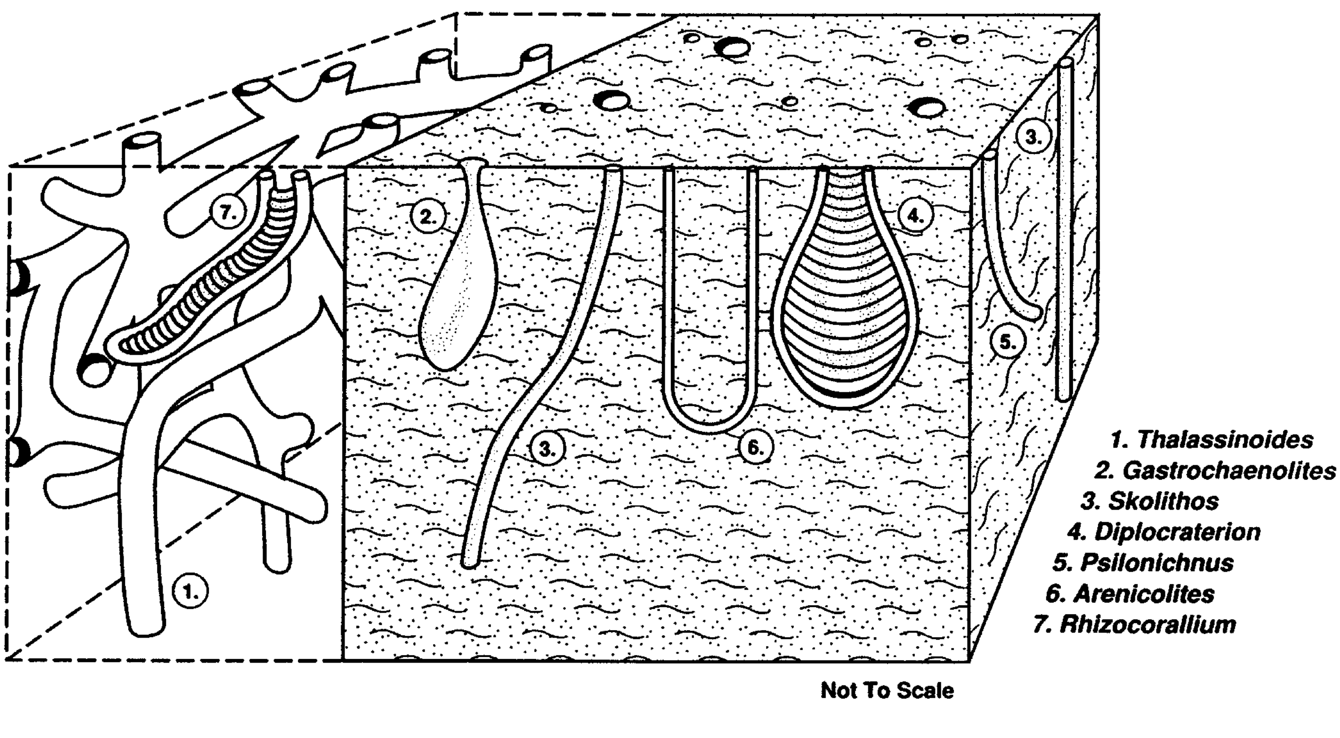


Figure 2. Trace-fossil association characteristic of the *Glossifungites* ichnofacies (modified from Frey and Pemberton, 1984).

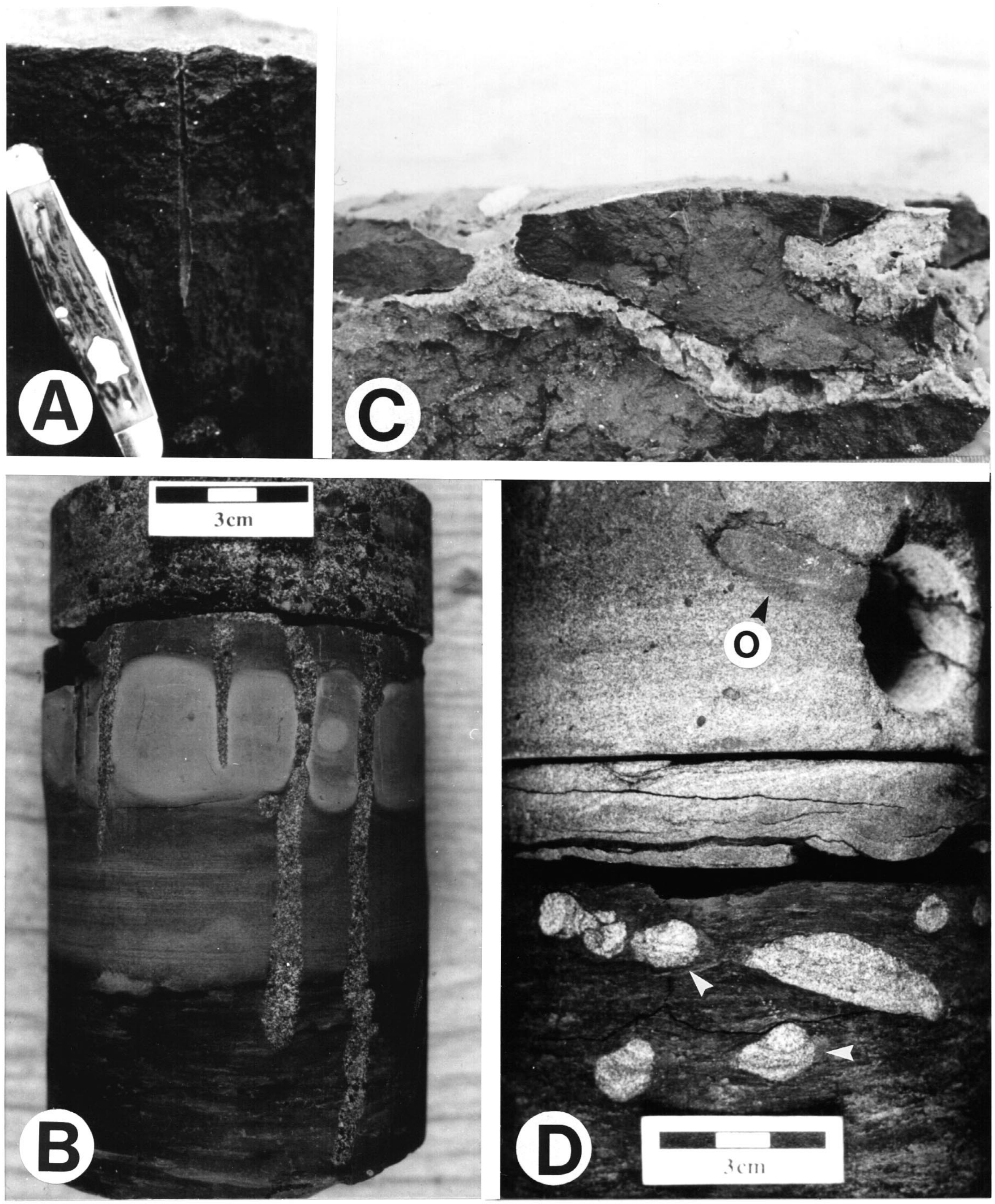


Figure 3. Characteristics of modern and ancient elements of the *Glossifungites* ichnofacies. (A) Relict, transgressively exhumed salt marsh mud penetrated by a sharp-walled vertical shaft attributable to the ichnogenus *Skolithos*. The tracemaker is the polychaete *Nereis succinea*. St. Catherines Island, Georgia. (B) Offshore silty shales, siderite cemented near the top, are crosscut by *Skolithos* shafts of the *Glossifungites* ichnofacies. Note the vertical, sharp-walled, unlined nature of the shafts. Tube diameters reach 0.7 cm. The tubes were passively filled with pebbly sand from the overlying conglomerate bed. Surface corresponds to a high-energy FS. Viking Formation, Gilby A field, 8–17–40–1W5, depth 1721.5 m. (C) A dwelling structure of the tracemaker *Upogebia affinis* (a shrimp) attributable to the ichnogenera *Thalassinoides/Spongeliomorpha*, excavated into transgressively exhumed salt marsh muds. Note the sharp, unlined walls of the structure, consistent with the *Glossifungites* ichnofacies. The structure has been passively filled with beach sand. Petit Chou Island (after Pemberton and Frey, 1985). (D) *Thalassinoides* (arrow) of the *Glossifungites* ichnofacies penetrates lower offshore silty shales from the base of an incised valley system. Note the *Ophiomorpha* (O) in the sandstone, attesting to marine-influenced valley fill. Viking Formation, Willesden Green field, 11–31–40–6W5, depth 2285.8 m.

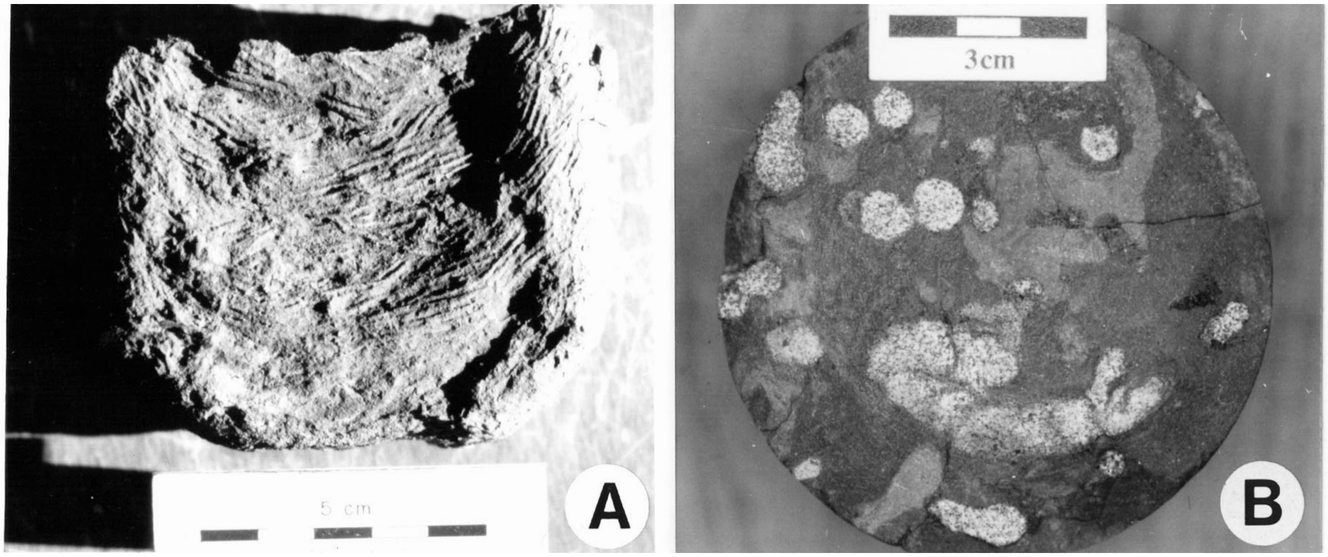


Figure 4. (A) ***Diplocraterion parallelum*** **showing preservation of chelaped scratch marks, indicating the stiff nature of the substrate at the time of burrow excavation. Bearpaw–Horseshoe Canyon formation transition, Drumheller, Alberta (Saunders and Pemberton, 1986). (B) Bedding-plane view of a dense population (12 shafts) of traces of the** ***Glossifungites*** **ichnofacies.** ***Diplocraterion*****,** ***Skolithos*****, and** ***Arenicolites*** **are present. There are 12 shafts visible on a 9 cm diameter core, corresponding to a density of more than 1800 shafts per m^2. Note the sharp walls and robust nature of the traces. Viking Formation, Kaybob field.**

tered and compacted) substrates and, hence, correspond to erosional discontinuities. Although certain insect and animal burrows in the terrestrial realm may be properly regarded as firmground (e.g., Fürsich and Mayr, 1981) or, more rarely, hardground suites, they have a low preservation potential and constitute a relatively minor component in the preserved record of these associations. The overwhelming majority of these assemblages originate in marine or marginal marine settings, particularly in pre-Tertiary intervals. As such, a discontinuity may be generated in either subaerial or submarine settings, but colonization of the surface corresponds to marine conditions. This has important implications regarding the genetic interpretation of the discontinuity in question. Finally, the substrate-controlled ichnocoenose, which crosscuts the preexisting softground suite, reflects conditions postdating both initial deposition of the underlying unit and its subsequent erosional exhumation following burial. The *Glossifungites* suite, therefore, indicates that a temporal break (e.g., depositional hiatus) occurred between the erosional event and sedimentation of the overlying unit; significant depositional cover precludes firmground colonization. These three aspects of the *Glossifungites* suite make it useful both in the recognition of the discontinuity and in its genetic interpretation.

PALEOENVIRONMENTAL SIGNIFICANCE OF ICHNOFOSSILS

The application of ichnology to paleoenvironmental analysis goes far beyond the mere establishment of general or archetypical ichnofacies. For instance, shallow-water, coastal marine environments comprise a multitude of sedimentological regimes which are subject to large fluctuations in many physical and chemical parameters. In order to comprehend the depositional history of such zones represented in the rock record, it is imperative to have some reliable means of differentiating subtle changes in these parameters. Detailed investigations of many coastal marine zones have illustrated the value of using biogenic sedimentary structures in delineating such ecological parameters as oxygenation, salinity, and energy levels. For instance, Dörjes and Hertweck (1975) subdivided the coastal zone into three major environments, based primarily on the position of mean high-water, mean low-water, and wave base. Their faunistic investigations of the distribution of benthic organisms also confirmed the importance of minimum and maximum wave base as distinct boundaries separating animal communities (Figure 5).

Softground ichnofacies tend to be differentiated from one another by variables that typically are depth related. The *Zoophycos* and *Nereites* assemblages are more characteristic of deep-water environments, whereas the *Psilonichnus*, *Skolithos*, and *Cruziana* ichnofacies are represented in nearshore marine environments. For example, in the Cretaceous of the Western Interior of North America, the marine shoreface can be zoned ichnologically (Figure 5). This zonation is based on the food-resources paradigm, which is influenced by relative energy levels. Recent summaries of the ichnology of marine shoreface environments can be found in publications by Frey and Pemberton (1987), Frey and Howard (1990), and MacEachern and Pemberton (1992).

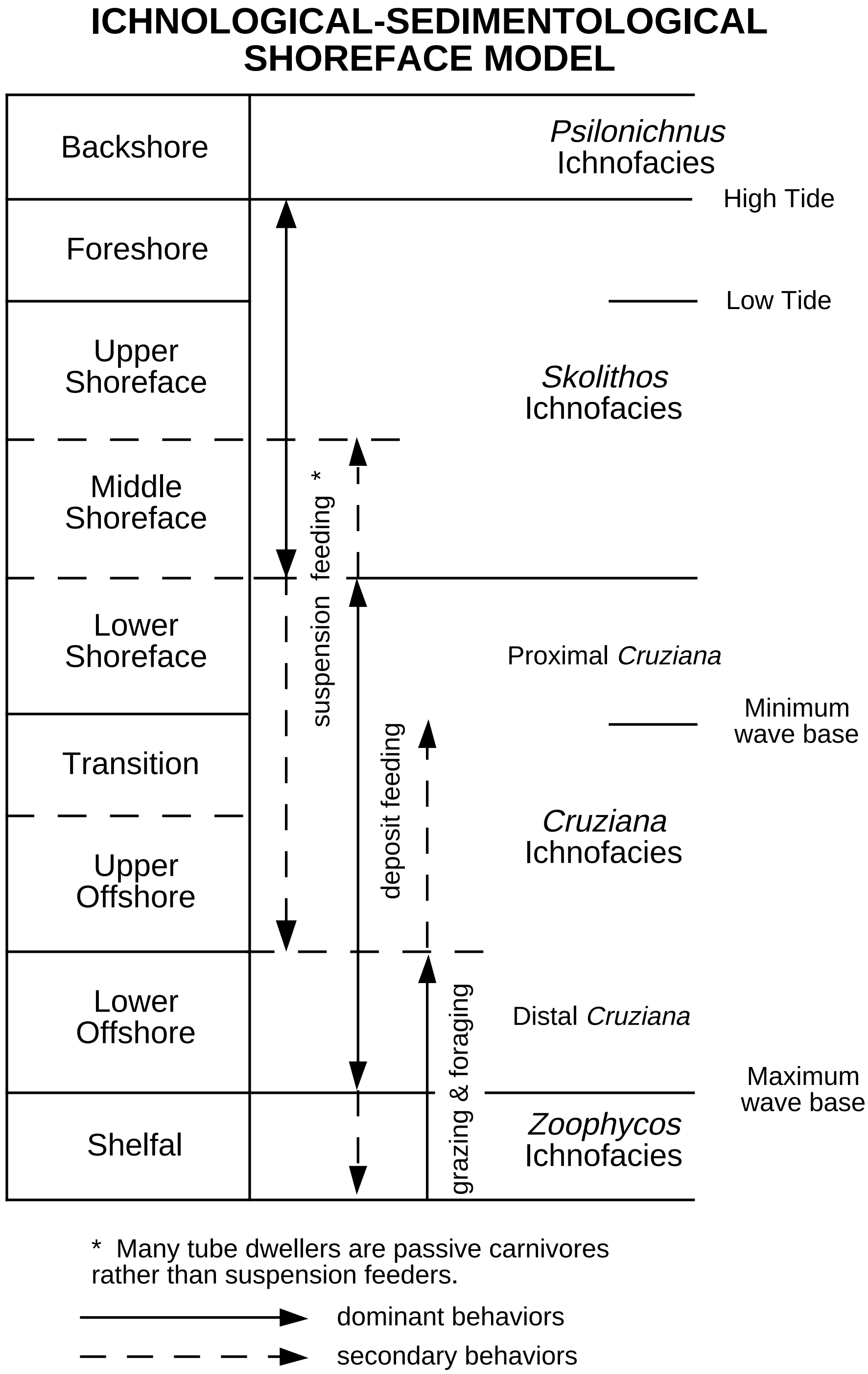


Figure 5. Idealized shoreface model of ichnofacies successions, based on observations of Cretaceous strata of the Western Interior Seaway of North America (modified after Pemberton et al., 1992a).

The *Zoophycos* and especially the *Nereites* ichnofacies tend to characterize deep-water environments, including outer shelf, slope, and bathyal to abyssal settings (Figure 1). For details on ichnology of deep marine deposits, see the papers by Ekdale et al. (1984), McCann and Pickerill (1988), and Crimes and Crossley (1991).

It is also important to be able to differentiate autocyclic successions (sedimentary event layers), resulting from in loco fluctuations in energy, from allocyclic successions. Only allocyclic successions have sequence stratigraphic significance. Sedimentary event layers represent beds that were deposited during short periods of time and differ in some significant way from the ambient sediment (Wheatcroft, 1990). Event beds include such diverse entities as volcanic ash beds, tephra deposits (i.e., Pedersen and Surlyk, 1983), beds resulting from seismic shocks (i.e., seismites, Seilacher, 1969), as well as episodic sedimentation events such as turbidites (Seilacher, 1962), tempestites or storm deposits (Aigner, 1985), phytodetritus pulses (Rice et al., 1986), and inundites or flood deposits (Leithold, 1989). Trace fossils are known to be significant features of most of these deposits.

For instance, tempestites exhibit a characteristic suite of trace fossils that are related to the population strategies of benthic organisms. The general succession of most tempestites consists of:

1. a fair-weather resident trace-fossil suite;
2. a sharp basal contact, with or without a basal lag;
3. parallel to subparallel laminations (reflecting hummocky or swaly cross-stratification);
4. common escape structures;
5. the dwelling burrows of opportunistic organisms that colonize the unexploited storm unit;
6. gradational burrowed tops, representative of bioturbation resulting from subsequent burrowing by organisms from higher colonization levels; and
7. a fair-weather resident trace-fossil suite indicative of a return to quiescent conditions (Pemberton et al., 1992b).

The use of trace fossils in the interpretation of freshwater deposits is becoming increasingly important. Recent work by Pollard (1988), Maples and Archer (1989), and Bromley and Asgaard (1991), among others, has stressed the abundance and diversity of tracemaking organisms in freshwater environments and emphasized their potential importance in paleoenvironmental reconstructions. Distinct differences in trace-fossil types and abundance have been reported from a wide range of freshwater terrestrial environments in both ancient and recent settings (Ekdale et al., 1984).

Recently, marginal marine environments (including tidal channels, estuaries, bays, shallow lagoons, delta plains, etc.) have been recognized with greater frequency in the rock record. Such environments characteristically display steep salinity gradients which, when combined with corresponding changes in temperature, turbulence, exposure, and oxygen levels, result in a physiologically stressful environment for numerous groups of organisms. The typical trace-fossil suite in such environments reflects these stresses and is characterized by:

1. low diversity;
2. ichnotaxa which represent an impoverished marine assemblage rather than a true mixture of marine and freshwater forms;
3. a dominance of morphologically simple structures constructed by trophic generalists;
4. a mixture of elements which are common to both the *Skolithos* and *Cruziana* ichnofacies;
5. assemblages that are commonly dominated by a single ichnogenus; and
6. diminished size compared to fully marine counterparts (Wightman et al., 1987; Pemberton and Wightman, 1992).

One of ichnology's greatest strengths, the bridging of sedimentology and paleontology, in some respects can be its greatest liability. Sedimentologists tend to use a strict uniformitarian approach to paleoenvironmental interpretation and rely heavily on modern analogs. Paleontologists, on the other hand, must temper their observations in the light of organic evolution. Although trace fossils can be considered as biogenic sedimentary structures and are difficult to classify phylogenetically, they are constructed by biological entities and are thus subject, at least to some degree, to evolutionary trends.

ICHNOLOGICAL APPLICATIONS TO SEQUENCE STRATIGRAPHY

The main applications of ichnology to sequence stratigraphic analysis is twofold. The most obvious use is in the demarcation of erosional discontinuities having a significant temporal break between the eroding event and the successive depositional event. The second use is more subtle and is concerned with the environmental implications of the trace-fossil suites, both softground- and substrate-controlled. When these aspects are integrated with sedimentologic and stratigraphic analyses, the result is a powerful approach to the delineation and genetic interpretation of sequence stratigraphic surfaces, as well as to their associated deposits. The Cretaceous of the WCSB is well suited to demonstrate the effectiveness of ichnology to sequence stratigraphic analysis (Figure 6; Table 2).

SEQUENCE BOUNDARIES

Sequence boundaries are generated during lowstands of relative sea level. In the Cretaceous of the WCSB, sequence boundaries are manifest by subaerial exposure surfaces locally associated with paleosols, erosionally incised valley surfaces, and submarine erosion surfaces related to "forced regressions" (cf. Posamentier and Vail, 1988; Posamentier et al., 1992). Although subaerial exposure and/or erosion during lowstands of sea level generates widespread dewatered, firm or incipiently cemented substrates, such surfaces are unlikely to become colonized by substrate-controlled trace-fossil suites unless they are subsequently exposed to marine or marginal marine conditions. As such, most sequence boundaries are not colonized by substrate-controlled suites, unless capped by a marine flooding surface (i.e., FS/SB).

Incised Valley Surfaces

At the seaward margins of some incised valley complexes, estuarine conditions prevail prior to transgression, permitting the colonization of the sequence boundary and deposition of marginal marine facies in what is legitimately part of the lowstand systems tract. Such incised valley surfaces correspond to distal sequence boundaries (J.C. Van Wagoner, 1993, personal communication). Proximal sequence boundaries within the incised valley are typically overlain by freshwater deposits and are not demarcated by substrate-controlled assemblages.

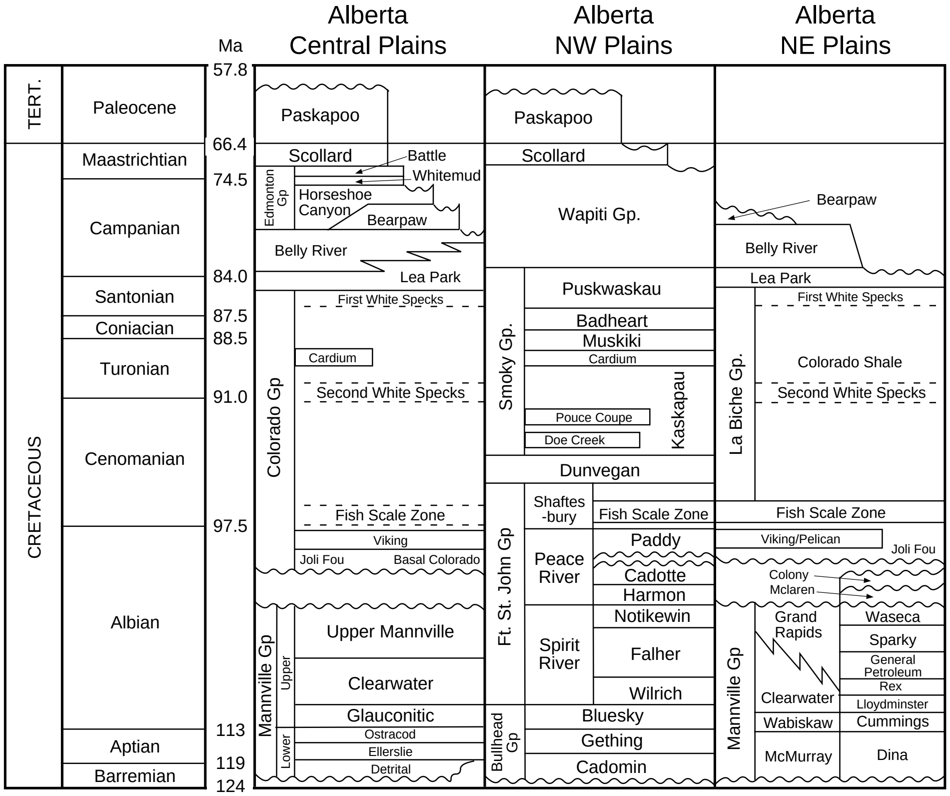


Figure 6. Stratigraphic chart of Cretaceous intervals occurring in the Western Canada sedimentary basin, Alberta, Canada.

In Cretaceous strata of the WCSB, the bulk of the preserved incised valley fill deposits are not associated with lowstand, but rather, subsequent transgressive conditions. Many of the valley systems appear to have dominantly been a zone of sediment bypass during falling sea level. Much of the sediment accumulation overlies either low-energy (nonerosive) flooding surfaces or, more commonly, high-energy (erosive) FS. Erosive FS are generated by tidal scour associated with transgressive invasion of the valley. These incised valley surfaces predominantly correspond to amalgamated FS/SB and are discussed below.

Forced Regression Shoreface Surfaces

The character of sequence boundaries generated during forced regression (cf. Plint, 1988; Posamentier and Vail, 1988) differs from many other sequence boundary expressions in that the surface is cut under submarine conditions. During falling sea level, sediments previously lying below fair-weather wave base are brought into a zone of persistent wave attack. This produces an erosional sequence boundary which passes basinward into a correlative conformity and landward into a subaerial exposure surface. The rapid basinward shift of the shoreline "forces" a shoreface to prograde rapidly over the sequence boundary, with minimal, if any, record of its passage. The diminished accommodation space associated with the base level fall results in the abrupt establishment of shallow-water deposits over deeper-water sediments, typically occupying a wave-cut terrace at the most basinward position of the shoreline.

The forced regression shorefaces differ stratigraphically from the more typical regressive shoreface successions, which are associated with simple progradation. The forced regression shorefaces directly overlie the sequence boundary, are produced by conditions of lowstand, and are sourced from sediment derived from the cutting of the unconformity. As such, these successions are legitimate components of the lowstand systems tract. In contrast, sediment-induced progradational regressions directly overlie either marine flooding or FS/SB and correspond to parasequences, fitting within highstand or transgressive systems tracts depending on the stacking pattern of the parasequence set.

The Albian Viking Formation of the Kaybob field (Figures 7–9), central Alberta, produces hydrocarbons from a sharp-based, coarsening-upward, northwest-southwest–trending sandstone body interpreted as a forced regression shoreface (MacEachern et al., 1992b; Pemberton et al., 1992a). The sequence boundary is incised into thoroughly burrowed silty and sandy shales containing a mixture of grazing and deposit-feeding structures consistent with lower to upper offshore deposition. The sequence boundary is locally demarcated by a *Glossifungites* suite of *Skolithos*, *Thalassinoides,* and rare *Diplocraterion* passively filled with medium- to coarse-grained sand from the overlying forced regression shoreface (Figure 7).

In proximal positions, upper shoreface sandstones, consisting of thin bedsets of trough cross-stratification with rare, intercalated swaly cross-stratified storm beds, directly overlie the sequence boundary. Soft-ground trace fossils consist of *Arenicolites*, *Skolithos*,

Table 2. Ichnologically demarcated sequence stratigraphic surfaces within the Cretaceous of the Western Canada sedimentary basin. The table outlines outcrop and subsurface examples (*continued*)

AGE	LOCATION	FORMATION	PRE-EROSION TRACE SUITE	EROSION SURFACE TRACE SUITE
Lower Albian	WCSB NE British Columbia	Gething/ Bluesky contact (subsurface)	Unburrowed, finely laminated and rooted mudstones and coals (Gething Formation).	*Glossifungites* assemblage consisting of *Skolithos* and *Thalassinoides* with associated pebble lag.
Upper Albian	WCSB Kaybob S. Field	Mannville Gp /Joli Fou Fm (subsurface)	Unburrowed, rooted paleosols (terrestrial) with coals (Mannville Group).	*Glossifungites* assemblage consisting of *Thalassinoides*. Associated pebble lag.
Upper Albian	WCSB Chigwell Field	Viking Fm (subsurface)	Silty shales with *Helminthopsis, Planolites*, *Terebellina, Chondrites* and *Asterosoma*, of the distal *Cruziana* ichnofacies.	*Glossifungites* ichnofacies consisting of *Thalassinoides* with associated pebbles and granules.
Upper Albian	WCSB Joffre Field	Viking Fm (subsurface)	Silty shales and distal storm sands: *Planolites*, *Helminthopsis, Chondrites*, *Terebellina*, rare *Zoophycos*, *Asterosoma* and *Rhizocorallium.*	*Glossifungites* assemblage consisting of *Skolithos*, ?*Arenicolites*/*Diplocraterion* and *Thalassinoides* with associated pebble lag.
Upper Albian	WCSB Gilby A Field	Viking Fm (subsurface)	Intensely burrowed muddy siltstone deposits containing *Helminthopsis*, *Terebellina*, *Planolites* and rare *Chondrites.*	*Glossifungites* assemblage of *Skolithos* and ?*Arenicolites*/*Diplocraterion* associated with sideritised surface and pebble lag.
Cretaceous (U. Albian)	WCSB Kaybob Field	Viking Fm (subsurface)	Thoroughly burrowed sandy shale: *Teichichnus, Helminthopsis, Asterosoma, Terebellina, Zoophycos, Chondrites*, rare *Rosselia* and *Rhizocorallium.*	*Glossifungites* assemblage consisting of *Thalassinoides* and *Skolithos* with associated rip-up clasts and pebbles.
Upper Albian	WCSB Kaybob S. Field	Viking Fm (subsurface)	Pebbly and sandy shales with *Planolites, Asterosoma, Terebellina*, rare *Chondrites, Helminthopsis* and *Zoophycos.*	*Glossifungites* assemblage consisting of robust *Arenicolites* shafts.
Upper Albian	WCSB Crystal Field	Viking Fm (subsurface)	Highly burrowed muddy sandstone with *Terebellina, Chondrites, Planolites*, *Helminthopsis, Asterosoma* and rare *Zoophycos.*	*Glossifungites* assemblage consisting of *Diplocraterion* shafts, *Thalassinoides* and *Gastrochaenolites*.
Upper Albian	WCSB Willesden Green	Viking Fm (subsurface)	Shales and silty shales with *Helminthopsis*, *Terebellina, Planolites*, *Chondrites* and *Zoophycos* (distal *Cruziana* ichnofacies).	*Glossifungites* assemblage consisting of *Rhizocorallium*, *Thalassinoides* and *Skolithos*.
Upper Albian	WCSB Sinclair Field	Peace River Fm Paddy Mbr (subsurface)	Pebbly shale, intensely burrowed, with *Chondrites, Helminthopsis, Terebellina, Asterosoma* and *Planolites.*	*Glossifungites* assemblage consisting of *Diplocraterion,* associated with dispersed pebbles.
Cenomanian	WCSB Jayar Field	Dunvegan Fm (subsurface)	Largely unburrowed and locally rooted mudstones in shallow water (lacustrine?) and deltaplain settings.	*Glossifungites* assemblage consisting of *Thalassinoides* systems.
Turonian	WCSB Pembina Field	Doe Creek Fm (subsurface)	Sandstones with *Ophiomorpha*, *Palaeophycus, Teichichnus*, *Terebellina*, *Planolites*, *Asterosoma* and *Zoophycos*.	*Glossifungites*, ichnofacies consisting of *Thalassinoides*.
Turonian	WCSB Pembina Field	Cardium Fm (subsurface)	Silty shales containing *Planolites*, *Chondrites*, *Helminthopsis*, *Terebellina* and rare *Zoophycos*, (distal *Cruziana* ichnofacies).	*Glossifungites*, ichnofacies consisting of *Thalassinoides*.
Maastrichtian	WCSB Drumheller Alberta	Horseshoe Canyon Fm (outcrop)	Unburrowed and rooted shales and coals formed within a back-barrier setting.	*Teredolites* assemblage consisting of abundant *Diplocraterion parallelum* subtending into a back-barrier coal.

Table 2 *(continued)*. of substrate-controlled ichnofacies and the interpreted sequence stratigraphic significance of the demarcated discontinuity (modified after Pemberton et al., 1992a).

POST-EROSION TRACE SUITE	INTERPRETATION OF SURFACE
Bar margin: highly burrowed muddy sands with *Teichichnus, Helminthopsis, Palaeophycus, Rosselia, Asterosoma, Planolites, Terebellina*. Brackish pro-delta: sands and shales with *Teichichnus, Planolites* and *Palaeophycus.*	Subaerial exposure and progradation of coal-bearing delta plain sediments, followed by high-energy flooding surface (FS/SB). Colonization of erosion surface preceded main transgressive lag deposition. Overlying sediments consist of prograding bar margin or brackish-water pro-delta of the next progradational cycle (Oppelt, 1988).
Silty shale with a distal *Cruziana* assemblage consisting of *Helminthopsis, Zoophycos, Terebellina, Planolites* and *Chondrites.*	Mannville Group surface was subaerially exposed (sequence boundary), subsequently transgressed, producing a high-energy flooding surface (FS/SB) colonised by a firmground suite. The overlying shales reflect offshore to outer shelfal settings (Joli Fou Formation).
Intensely burrowed muddy sandstone with robust *Teichichnus, Asterosoma, Terebellina, Helminthopsis, Chondrites* and *Planolites*, reflecting the *Cruziana* ichnofacies.	Sequence boundary incised into offshore deposits, modified during transgression (FS/SB). FS/SB surface is buried by shoreface which praded during sea level stillstand. Resumed transgression capped shoreface with flooding surface (Raychaudhuri et al., 1992).
Sparsely burrowed, cross-bedded pebbly and coarse-grained sandstone with rip-up clasts. Mud drapes contain *Planolites.*	Subaerially exposure surface cut into offshore deposits during lowstand of relative sea level, modified by a high-energy flooding surface reflecting erosive shoreface retreat (FS/SB). Surface overlain by shoreface sandstones during a relative stillstand of sea level (Downing and Walker, 1988; Pattison, 1991a).
Unburrowed, pebbly, medium-grained sandstones.	High-energy flooding surface reflecting erosive shoreface retreat, amalgamated with subaerial exposure surface (FS/SB) incised into underlying offshore deposits. Relative stillstand of sea level permitted progradation of shoreface over FS/SB (Raddysh, 1988; Pattison, 1991a).
Trough and low angle parallel laminated sandstone: *Arenicolites, Skolithos, Ophiomorpha, Teichichnus, Palaeophycus, Helminthopsis, Chondrites, Rosselia, Planolites, Terebellina* and *Asterosoma.*	Surface corresponds to a sequence boundary (lowstand unconformity) incised into underlying offshore/inner shelf deposits as they are brought into zone of wave attack. Basinward displacement of the shoreline results in forced regression shoreface directly overlying sequence boundary (MacEachern et al., 1992b).
Pebbly and sandy shales with *Teichichnus, Terebellina, Asterosoma, Planolites*, rare *Chondrites* and *Helminthopsis.*	The surfaces are high-energy flooding surfaces generated during incremental transgression of the Colorado sea. The surfaces bound progradational wedges of sediment and constitute high-energy parasequence boundaries (MacEachern et al., 1992a).
Sandstones, interbedded sands and shales, and shales with *Teichichnus, Ophiomorpha, Palaeophycus, Diplocraterion, Rosselia, Skolithos, Asterosoma, Terebellina*, and *Planolites.*	The surface reflects an FS/SB, interpreted as an incised valley, cut into underlying shelf to lower shoreface deposits during sea level lowstand. Sequence boundary is modified by high-energy flooding surface during transgressive fill of the valley (Reinson et al., 1988; Pattison, 1991 a and b; Pemberton et al., 1992c).
Cross-bedded pebbly sandstones and conglomerates; sands and shales contain a brackish suite of *Cylindrichnus, Teichichnus, Planolites, Terebellina, Palaeophycus* and *Asterosoma.*	Surface reflects an FS/SB. Sequence boundary cut as an incised valley, excavated into offshore to outer shelfal deposits. Surface is modified by a high energy flooding surface during ensuing transgression. Valley is filled with estuarine sediments of the transgressive systems tract (Boreen, 1989; Boreen and Walker, 1991).
Pebbly shale, intensely burrowed with *Helminthopsis, Zoophycos* and *Chondrites,* grading into less burrowed sandstone and shale with *Asterosoma, Planolites* and *Chondrites.*	The discontinuities are interpreted to reflect high-energy flooding surfaces, associated with incremental transgression of the Shaftesbury/Colorado sea. The surfaces bound thin progradational wedges of sediment and constitute high-energy parasequence boundaries.
Medium-grained sandstones, intensely burrowed with *Ophiomorpha* (transgressive sheet sand), passing into marine shales with *Zoophycos, Planolites,* and *Chondrites.*	Delta plain facies capped by subaerial exposure surface, reflecting a lowstand of relative sea level. High-energy flooding surface modified this surface (FS/SB). Reworking of underlying facies produced a transgressive sheet sand (Bhattacharya, 1989; Bhattacharya and Walker, 1991).
Medium- to fine-grained sandstone containing *Zoophycos, Chondrites*, and *Planolites*. Passes into silty shales with *Helminthopsis, Planolites, Terebellina, Chondrites* and *Zoophycos*.	The surface overlies lower shoreface deposits, and reflects an FS/SB. Siderite cementation of underlying sandstones corresponds to subaerial exposure. Colonization of surface reflects initial transgression. Continued transgression produces a low-energy flooding surface.
Largely unburrowed conglomerate, overlain by marine shale with dispersed pebbles; shales contain *Helminthopsis, Planolites, Chondrites, Terebellina* and *Zoophycos.*	The surface may be a sequence boundary with overlying conglomeratic forced regression shoreface, or an FS/SB reflecting transgressive modification of SB by erosive shoreface retreat. Overlying conglomeratic shorefaces may reflect stillstand of sea level (Walker and Plint, 1992).
Lower shoreface HCS and SCS sandstone with *Ophiomorpha, Rhizocorallium, Teichichnus, Conichnus, Skolithos* and *Rosselia*.	The erosion surface is interpreted as a high-energy flooding surface separating back barrier deposits from overlying, prograding, storm-dominated shoreface deposits (Saunders and Pemberton, 1986).

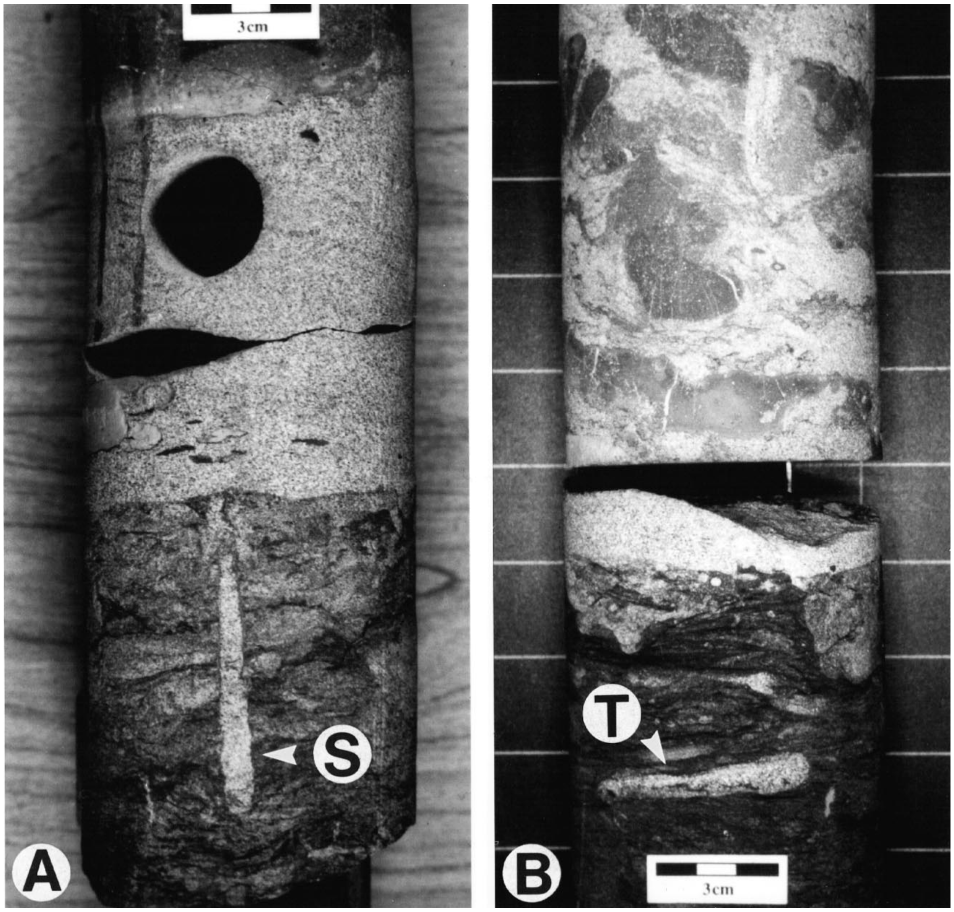


Figure 7. Kaybob forced regression shoreface, Viking Formation. (A) Thoroughly burrowed upper offshore sandy shale of a highstand parasequence is erosionally truncated by lower to middle storm-influenced shoreface sandstones of the Kaybob shoreface. A few rip-up clasts occur above the erosional contact. A sharp-walled, robust *Skolithos* (S) burrow of the *Glossifungites* ichnofacies demarcates the surface. The erosion surface is interpreted as a sequence boundary. Kaybob field, 11–35–61–20W5, depth 1759.1 m. (B) Thoroughly burrowed upper offshore sandy shale of a highstand parasequence is erosionally truncated by thoroughly burrowed lower shoreface shaly sandstone of the Kaybob shoreface. This core lies basinward of the core in (A). The erosion surface correlates to the same sequence boundary in (A), and is demarcated by *Thalassinoides* (T) of the *Glossifungites* ichnofacies. Fox Creek field, 10–15–62–19W5, depth 1672.0 m.

Diplocraterion, *Palaeophycus*, *Cylindrichnus*, rare *Conichnus*, and escape traces. In intermediate positions, lower to middle shoreface sandstones (Figures 8 and 9) immediately overlie the sequence boundary. The sandstones consist of alternating storm beds characterized by swaly cross-stratification and combined flow ripple lamination, and thoroughly burrowed shaly sandstone fair-weather beds. The succession is typical of storm-dominated to storm-influenced settings (MacEachern and Pemberton, 1992; Pemberton et al., 1992b). The trace-fossil suite consists of a mixture of deposit-feeding, suspension-feeding and passive-carnivore structures, with less abundant grazing structures, typical of lower to middle shoreface deposits.

In more basinal positions, the sequence boundary is abruptly overlain by thoroughly burrowed lower shoreface shaly sandstones, which contain a diverse trace-fossil suite dominated by deposit-feeding structures, with subordinate amounts of suspension-feeding, passive-carnivore, and grazing structures. Further basinward, the sequence boundary passes into a correlative conformity and is difficult to recognize. The succession in this position demonstrates a gradual coarsening-upward profile, which is difficult to differentiate from the highstand parasequences underlying the correlative conformity.

The upper portion of the Kaybob forced regression shoreface has been removed by a low-relief, high-energy (erosional) flooding surface. Any backshore or

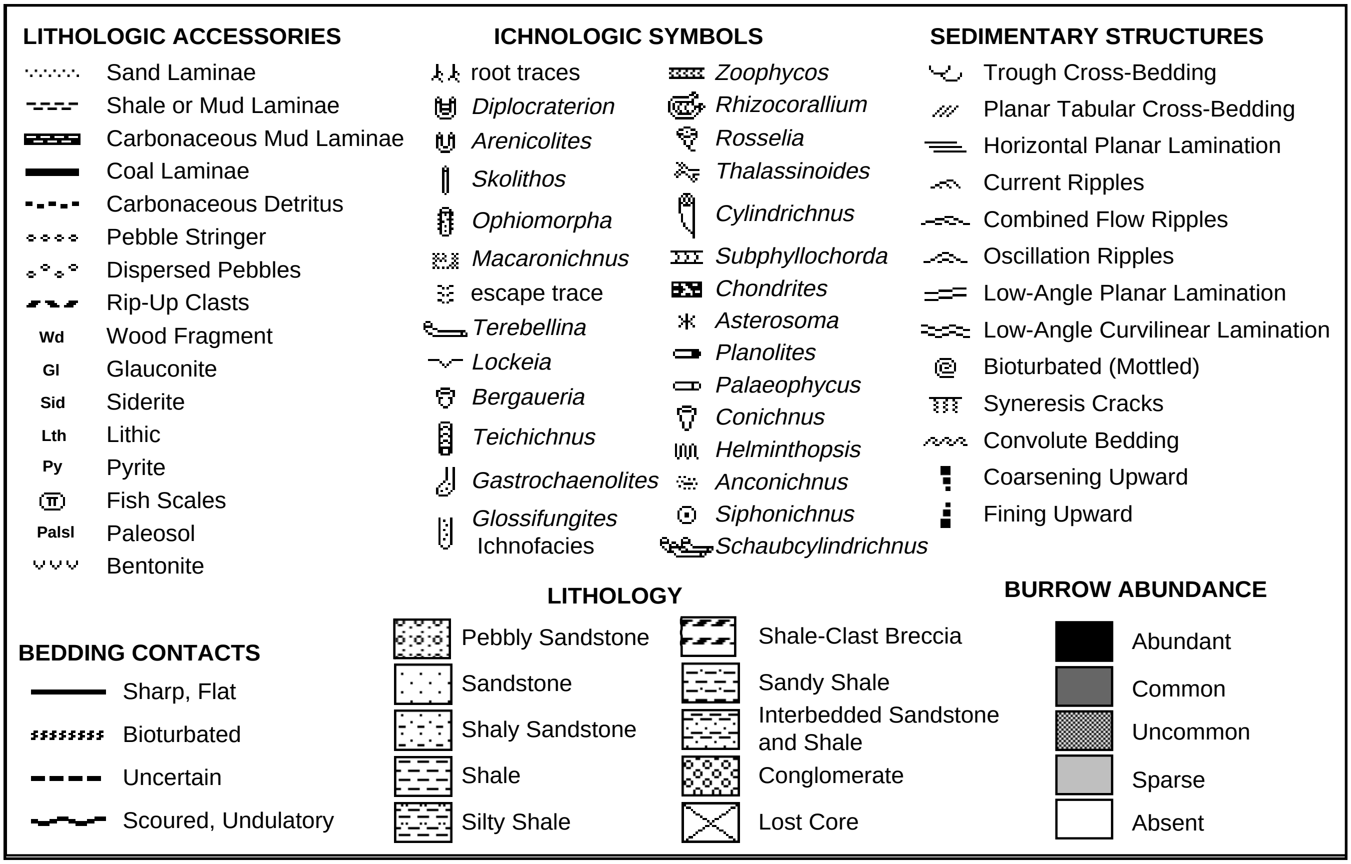


Figure 8. Legend of symbols employed in lithologs.

foreshore deposits that had accumulated have been subsequently removed. The sand body is relatively thin, typically less than 10 m, and shows rapid upward transition from lower to upper shoreface deposits. These features are consistent with the reduced accommodation space associated with a lowering of relative sea level.

A forced regression setting has also been proposed for the Viking Formation at the Joarcam field (Posamentier and Chamberlain, 1991; Posamentier et al., 1992). In the few cored intervals from Joarcam studied by the authors, no substrate-controlled suites were observed to demarcate the sequence boundary. Nonetheless, the sharp, erosionally based character of the shoreface sandstone attests to an abrupt basinward shift of facies, consistent with a relative fall of sea level. The Viking Formation of the Sunnybrook A and B sandstones have also been interpreted as forced regression shorefaces (Pattison, 1991a), as have some conglomeratic shorefaces of the Turonian Cardium Formation (Walker and Plint, 1992).

TRANSGRESSIVE SURFACES

Transgressive surfaces are possibly the most abundantly represented stratigraphic break in Cretaceous strata of the WCSB. This is believed to be due to the additive effects of subsidence in the foreland basin (Stockmal and Beaumont, 1987; Cant and Stockmal, 1989) and conditions of overall (eustatic?) sea level rise during the Cretaceous (Haq et al., 1987).

Transgressive surfaces are manifest by largely nonerosive low-energy marine FS and low-relief, high-energy (erosive) FS. The low-energy FS correspond to the FS or marine FS of others (e.g., Bhattacharya and Walker, 1991; Beynon and Pemberton, 1992). The high-energy FS are analogous to the transgressive surfaces of erosion (TSE) of others (e.g., Bhattacharya and Walker, 1991; MacEachern et al., 1992a) and the ravinement and marine erosion surfaces of Nummedal and Swift (1987).

Low-Energy Marine Flooding Surfaces

Low-energy marine FS are typically abrupt, sharp contacts across which there is evidence of an increase in water depth. Many such surfaces are mantled with dispersed sand, granules, or intraformationally derived rip-up clasts, indicating minor amounts of erosion. The preservation of underlying markers attests to the minimal degree of erosion.

FS are typically characterized by the abrupt juxtaposition of offshore, shelfal, or prodelta shales on shallow marine sandstones (e.g., Figure 10) and are easily picked on geophysical well logs. As such, FS have been utilized by several workers to subdivide stratigraphic intervals in the WCSB, such as the Cenomanian Dun-

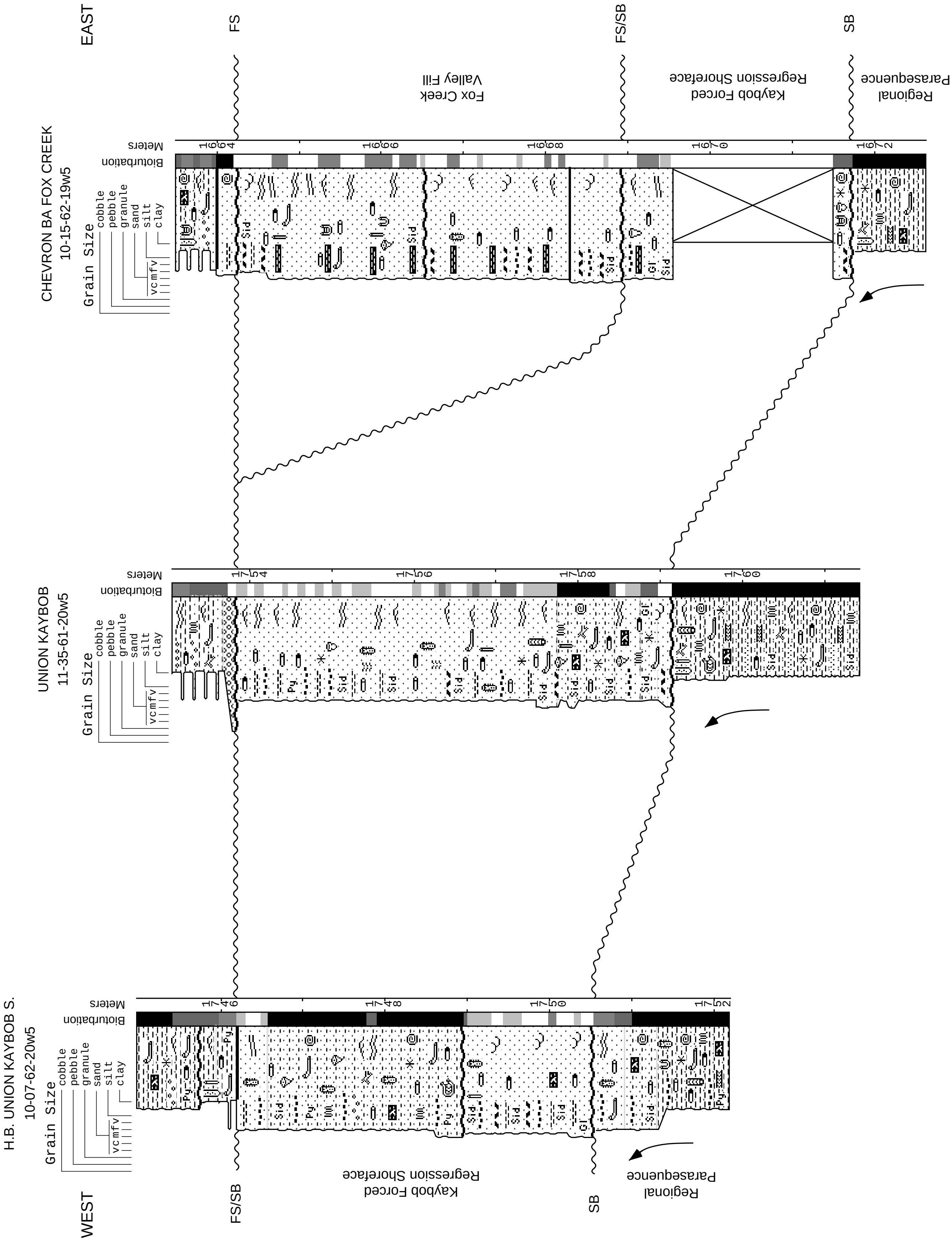

EAST
WEST
CHEVRON BA FOX CREEK
10-15-62-19w5
UNION KAYBOB
11-35-61-20w5
H.B. UNION KAYBOB S.
10-07-62-20w5
Grain Size
cobble
pebble
granule
sand
silt
clay
Bioturbation
Meters
FS
FS/SB
SB
Fox Creek
Valley Fill
Kaybob Forced
Regression Shoreface
Regional
Parasequence
Sid
Py
Gl

Figure 9. Depositional dip-oriented stratigraphic cross section of the Kaybob forced regression shoreface. Landward lies to the left of the cross section. Well 10–07–62–20W5 corresponds to the most proximal cored position of the shoreface. The sequence boundary is relatively cryptic, but appears to correspond to the base of a trough cross-stratified sandstone (upper shoreface) erosionally overlying lower shoreface sandstones of the regional Viking Formation parasequences. The 11–35–61–20W5 well lies in an intermediate position and shows lower to middle shoreface sandstones erosionally overlying upper offshore sandy shales of the regional Viking Formation parasequences. The erosional discontinuity corresponds to the sequence boundary and is demarcated by a *Glossifungites* suite of *Skolithos* and *Thalassinoides*. The 10–15–62–19W5 well lies in a basinal position and demonstrates upper offshore sandy shales of the regional Viking Formation parasequences erosionally truncated by lower shoreface sandstones. The erosional surface is demarcated by a *Glossifungites* assemblage of *Thalassinoides* and corresponds to the sequence boundary. The upper portion of the Kaybob shoreface in this well is erosionally removed by an incised valley succession developed in the Fox Creek field area. The entire depositional complex is capped and locally erosionally truncated by a flooding surface. The Kaybob sand body is interpreted as a forced regression shoreface related to a lowstand of sea level. The legend for lithologs is given in Figure 8.

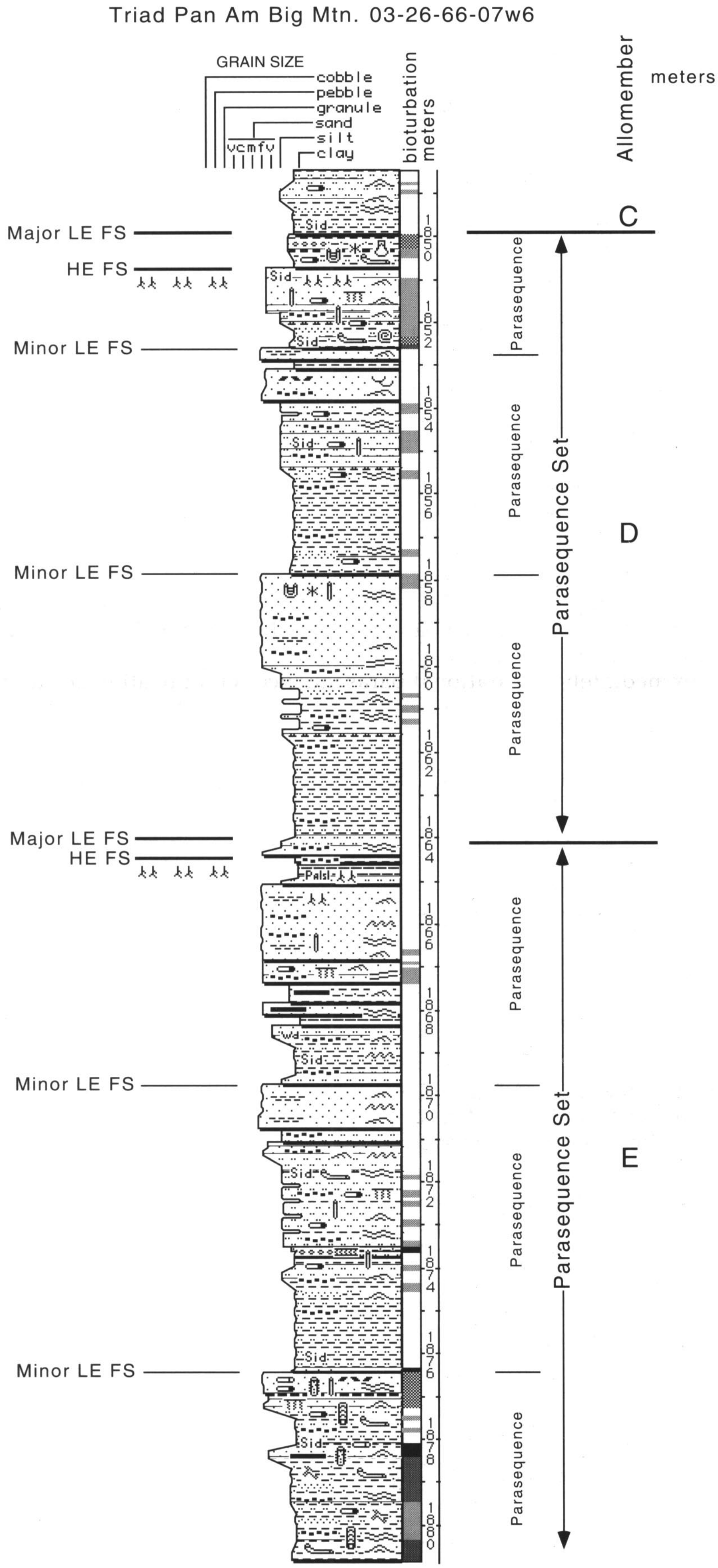


Figure 10. Litholog of stacked parasequences bound by low-energy marine flooding surfaces and high-energy flooding surfaces in the Dunvegan Formation. The succession records delta progradation and can be separated into parasequence sets bounded by major flooding surfaces, locally with associated erosion, recording initial transgression. These major surfaces commonly overlie rooted intervals. The parasequence sets can be further subdivided into individual parasequences bound by minor flooding surfaces. The parasequence sets have been mapped as regionally correlatable allomembers of the Dunvegan Formation (Bhattacharya, 1989; Bhattacharya and Walker, 1991). Legend for the litholog is given in Figure 8; transgressive surface of erosion (TSE).

vegan Formation (Bhattacharya, 1989; Bhattacharya and Walker, 1991) and the Albian Grand Rapids Formation (Beynon, 1991; Beynon and Pemberton, 1992).

Low-energy FS in the Cenomanian Dunvegan Formation have been differentiated into minor, major, and maximum types, depending on their areal correlatability (Bhattacharya, 1990; Bhattacharya and Walker, 1991). The Dunvegan Formation is interpreted to represent a deltaic setting, ranging from river dominated to wave dominated over the history of its accumulation. The minor FS appear to separate individual delta lobes, with a correlatable scale of tens of kilometers and may correspond to autocyclic abandonment of the lobes or to local tectonic events. Minor FS bound individual parasequences and correspond to low-energy parasequence boundaries. Major marine FS separate discrete, regionally extensive parasequence sets, have a correlatability on the scale of hundreds of kilometers, and are interpreted to represent eustatic rises in sea level. The maximum FS are correlatable on a scale of thousands of kilometers and are bound the base and top of the Dunvegan Formation itself, separating major over- and underlying transgressive systems tracts from the Dunvegan progradational wedge (Bhattacharya, 1989; Bhattacharya and Walker, 1991).

The ichnology associated with the Dunvegan Formation marine FS is sparse. The facies immediately overlying the FS is related to prodelta progradation and is characterized by tan-colored, largely unburrowed, highly silty shale, suggesting rapid sediment accumulation. In contrast, burrow intensity is moderate to common where minor associated erosion produces gritty and sandy shales above the FS. In such shales, *Planolites* is the dominant element, with far less common *Terebellina*, *Thalassinoides*, and exceedingly rare *Teichichnus*. The suite consists of deposit-feeding structures of trophic generalists, and may demonstrate stresses imparted on the infauna such as high sedimentation rates, water turbidity, and salinity reductions, particularly in the river-dominated intervals. In general, the minor marine FS bound thickening-upward successions of storm-generated delta front sandstone beds (parasequences) characterized by wavy parallel lamination, combined flow ripple lamination, and convolute bedding. These sandstones possess an impoverished suite of *Ophiomorpha*, *Skolithos*, *Arenicolites,* and *Diplocraterion*, crosscut by *Planolites*, *Terebellina*, *Teichichnus*, *Palaeophycus,* and *Thalassinoides* (cf. tempestites, Pemberton et al., 1992b). Major marine FS cap progradational sets of delta lobes (parasequence sets) and commonly overlie rooted delta plain deposits or incipiently developing paleosols (Figure 10).

In the Grand Rapids Formation, the most common facies consistently overlying marine FS consists of interlaminated mudstones and sandstones. These intensely burrowed units contain a low diversity trace-fossil suite dominated by *Teichichnus*, *Planolites,* and *Skolithos*, with rare *Asterosoma*, *Chondrites*, *Gyrolithes,* and *Rhizocorallium*. Diversity is low, but individual elements, particularly *Teichichnus*, are locally abundant. These facies are interpreted as brackish-water deposits, suggesting that the transgressive events did not inundate the area with fully marine waters (Beynon, 1991; Beynon and Pemberton, 1992). Facies underlying the FS record interdistributary bay, rooted delta plain, and marsh deposits of bay-fill successions, and delta-front sandstones within a salinity-stressed deltaic setting.

In contrast to these deltaic settings, the Viking Formation possesses numerous low-energy FS separating coarsening- and cleaning-upward parasequences of regional extent, which correspond to shoreface progradation within fully marine conditions. These successions are informally referred to as the regional Viking cycles. These grade out of the marine shales of the Joli Fou Formation, which transgressively overlie a sequence boundary developed on the Mannville Group (i.e., FS/SB). Five main coarsening-upward successions (fourth-order parasequences), the lower two of which contain numerous minor cycles (fifth-order parasequences), are interpreted to reflect changes in relative sea level attributed to a combination of eustasy, local, or regional tectonics, and variations in sediment supply (Pattison, 1991a). The fourth-order parasequences are capped by more pronounced FS. The parasequences reflect shoreface progradation from the northwest to southeast, with a NNE-SSW–oriented strike. The parasequences occur as a regionally extensive progradational parasequence set, indicating accumulation within a highstand systems tract, downlapping onto the Joli Fou Formation marine shales of the underlying transgressive systems tract.

Three facies make up a complete coarsening cycle, although the minor cycles rarely comprise a complete cycle. The basal facies (facies 1) consists of silty shale, typically showing intense bioturbation (Figure 11A). Silt is dispersed biogenically throughout the facies, and may be locally present as discontinuous remnants or stringers. Very rare, vfL–vfU sand interbeds (<2 cm thick) may be intercalated and possess low-angle wavy parallel lamination or combined flow ripple lamination.

The observed trace fossils of facies 1 are relatively uniformly distributed and present in most intervals studied, with the exception of the accessory traces. *Helminthopsis*, *Chondrites*, *Planolites,* and *Terebellina* comprise the dominant elements of the suite, occurring in moderate to abundant numbers in greater than 90% of the cored intervals. *Zoophycos* and *Thalassinoides* are present in 80–90% of the intervals in rare to moderate amounts and constitute the secondary elements. *Asterosoma*, *Teichichnus*, *Rhizocorallium*, *Palaeophycus,* and *Rosselia* occur in less than 30% of the examples and, when present, are in very rare to rare amounts.

Grading from the silty shale facies is the sandy shale facies (facies 2; Figure 11B). Sand is typically vfL–fU in size and is present both as biogenically dispersed grains and as remnant wavy parallel laminated or combined flow ripple laminated beds. Burrowing is generally uniform and intense, although a few parasequences in the Cyn-Pem field area (cycle 3 of Pattison, 1991a) show reduced degrees of burrowing.

The trace fossil suite of facies 2 is more diverse than that of the silty shale underlying it and is dominated

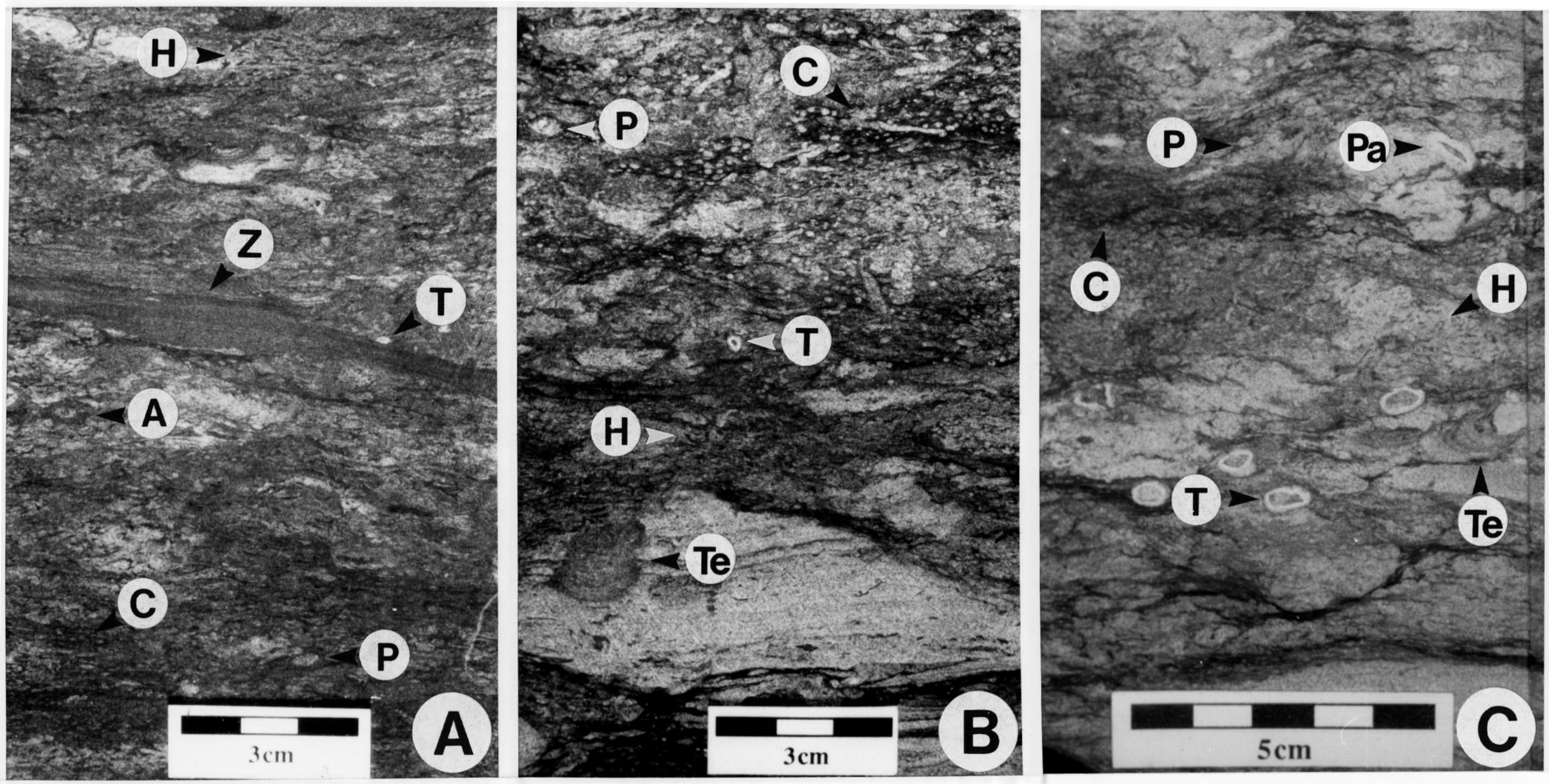


Figure 11. Depositional facies comprising parasequences of the regional Viking Formation. (A) Thoroughly burrowed silty shale with *Zoophycos* (Z), *Helminthopsis* (H), *Chondrites* (C), *Planolites* (P), *Terebellina* (T), and *Asterosoma* (A). Facies is interpreted to reflect lower offshore deposition. Sundance field, 10–34–54–20W5, depth 2579.0 m. (B) Thoroughly burrowed sandy shale facies with remnant distal storm bed near the base. Trace fossils include *Chondrites* (C), *Planolites* (P), *Terebellina* (T), *Helminthopsis* (H), and *Teichichnus* (Te). Facies is interpreted to reflect upper offshore deposition. Sundance field, 07–36–54–20W5, depth 2484.4 m. (C) Thoroughly burrowed shaly sandstone facies with *Terebellina* (T), *Teichichnus* (Te), *Palaeophycus* (Pa), *Planolites*, (P), small *Chondrites* (C), and *Helminthopsis* (H). Facies is interpreted to reflect distal lower shoreface deposition. Crystal field, 13–05–46–3W5, depth 1754.0 m.

by *Helminthopsis*, *Chondrites*, *Planolites*, *Terebellina*, *Teichichnus*, and *Asterosoma*, occurring in moderate to abundant amounts in all intervals studied. Secondary elements are present in 40–80% of studied intervals and are rare to moderate in numbers. This component of the suite comprises *Zoophycos*, *Palaeophycus*, *Thalassinoides*, *Skolithos*, and *Diplocraterion*. Accessory elements remain rare in number, occur in less than 30% of the intervals, and are represented by *Rosselia*, *Arenicolites*, *Cylindrichnus*, *Rhizocorallium*, *Ophiomorpha*, *Siphonichnus*, *Lockeia*, and fugichnia (escape traces).

Grading upward from the sandy shale facies is the shaly sandstone facies (facies 3; Figure 11C). The sand remains vfL–fU, though typically lower fine; mud is generally dispersed throughout the facies and present as partings and discontinuous stringers. Discrete sandstone beds are rare, but show wavy parallel lamination where present. The general absence of discrete sandstone beds is a reflection of the high degree of bioturbation and the penetrative action of more robust infauna than in the previously described facies.

The dominant trace fossil elements of facies 3 are *Planolites*, *Terebellina*, *Chondrites*, *Helminthopsis*, *Asterosoma*, *Palaeophycus*, *Skolithos*, *Teichichnus*, *Rosselia*, and *Diplocraterion*, though individual ichnogenera are less abundant (moderate to common in number) and occur with less consistency (70–100%) than in the underlying facies. Secondary elements include *Ophiomorpha*, *Arenicolites*, *Zoophycos*, and *Cylindrichnus* and occur in rare to moderate abundances within 40–60% of the studied intervals. Accessory elements occur in <40% of the examples, are rare in number, and include *Thalassinoides*, *Rhizocorallium*, *Schaubcylindrichnus*, *Lockeia*, *Siphonichnus*, and fugichnia.

The cycles reflect both coarsening upward of facies and an increase in diversity of ichnogenera under fully marine conditions. Each major cycle is interpreted as lower offshore to lower shoreface progradation (Figure 5). The silty shale facies reflects a dominance of grazing and deposit-feeding structures of the distal *Cruziana* ichnofacies and is interpreted as lower offshore deposition. Rare, thin sand beds reflect the distal deposits of exceptionally strong storms. The sandy shale facies shows a more diverse suite of trace fossils and a dominance of deposit-feeding over grazing behavior. The introduction of suspension-feeding and passive-carnivore structures is also distinctive. This facies is interpreted as upper offshore deposition at and above storm-wave base. Thin sand beds record preservation of storm beds whose thicknesses exceeded the infauna's ability to completely obliterate it. The shaly sandstone facies shows an increase in diversity of behavior, but less of a dominance by individual forms. Deposit-feeding structures dominate, with diminishing influence of grazing behavior and enhanced influence of suspension feeding, reflecting a proximal *Cruziana* suite. This facies is interpreted as distal lower shoreface deposition.

The marine FS bounding the fourth-order parasequences are commonly marked by the return to lower offshore or shelfal shale deposition and are typically abrupt (Figure 12). The low-energy FS is unlikely to be disturbed by the diminutive tracemakers which characterize the lower offshore settings. FS bounding fifth-order parasequences tend to show much biogenic modification, particularly where lower shoreface deposits are overlain by upper offshore sandy shales. Such contacts locally appear gradational, owing to the biogenic homogenization of the surface by the more robust tracemakers. Elsewhere, the upward transition from shallow- to deeper-water deposits may occur over intervals of several decimeters or more. Such transitions must reflect gradual relative sea level rise, possibly due to enhanced sedimentation rates contemporaneous with transgression.

The stacked fourth- and fifth-order parasequences comprise a progradational parasequence set, reflecting a highstand systems tract, downlapping onto the Joli Fou marine shales of the underlying transgressive systems tract (Figure 13). The trace-fossil suites show abundant burrowing, characterized by a high diversity of forms, a lack of dominance by a few forms, presence of significant numbers of specialized feeding/grazing structures, and uniform distribution of individual elements, supportive of an equilibrium (K-selected), unstressed community (cf. Pianka, 1970) within fully marine environments. Sedimentation is interpreted to have been relatively slow and generally continuous.

High-Energy Flooding Surfaces

High-energy FS are manifest as low-relief erosional surfaces cut by wave and current processes associated with erosional shoreface retreat during transgression. Nummedal and Swift (1987) identified two subcategories of transgressive erosion surfaces: the higher-energy ravinement surfaces (cf. Stamp, 1921) and the lower-energy (distal) offshore marine erosion surfaces. Basinward, high-energy FS pass into low-energy, nonerosional FS.

These high-energy FS afford an elegant means of generating substrate-controlled trace-fossil suites, because the surfaces are erosionally exhumed within a marine or marginal marine environment. This favors colonization by firmground-dwelling organisms after the surface is cut and prior to deposition of significant thicknesses of overlying sediment.

Many of these surfaces are of limited spatial extent and may be discontinuous, limiting their effectiveness in regional correlations. In addition, high-energy FS commonly produce pronounced stratigraphic breaks in the rock record, which may be easily mistaken for sequence boundaries (Nummedal and Swift, 1987) or amalgamated FS/SB unless carefully placed into stratigraphic context.

The upper portion of the Albian Viking Formation in the subsurface of central Alberta contains numerous high-energy FS, recording a complex history of transgression which culminated in maximum flooding of the North American Interior Seaway and deposition of the widespread unnamed Colorado shales and equivalents. Detailed stratigraphic correlations across the south-central portion of Alberta by Pattison (1991a) have demonstrated the complexity of this transgres-

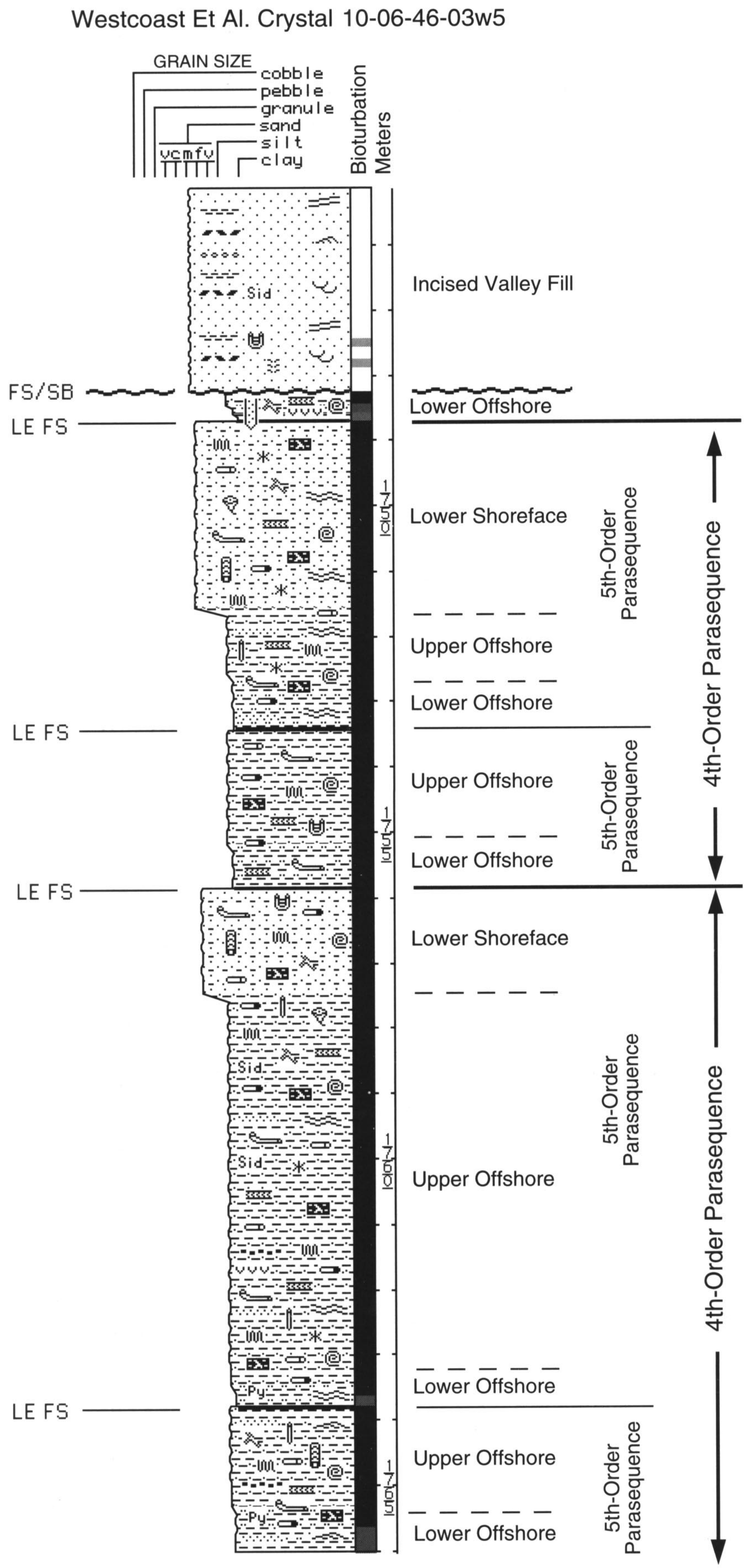


Figure 12. Litholog of stacked fourth- and fifth-order parasequences bounded by low-energy flooding surfaces, erosionally truncated at the top by an amalgamated FS/SB, demarcating the base of an incised valley system in the Viking Formation, Crystal field. These stacked parasequences can be grouped into a parasequence set constituting a highstand systems tract. Incision of the valley reflects lowstand erosion, but eventual fill of the valley did not occur until the ensuing transgression and constitutes the transgressive systems tract. Legend for the litholog is given in Figure 8. Modified after Pemberton et al. (1992c).

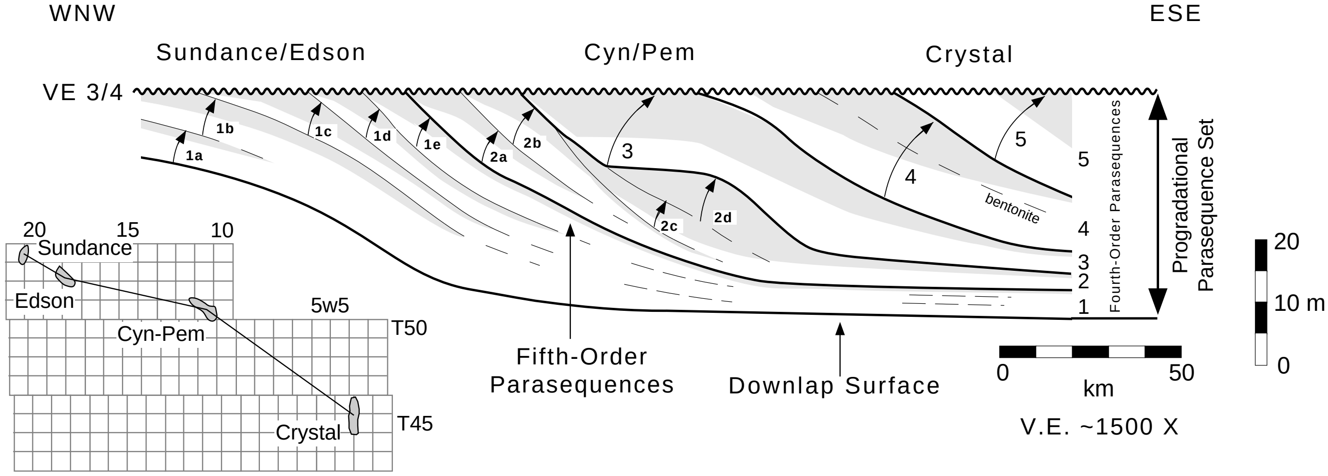


Figure 13. Regional parasequences of the Viking Formation. The schematic cross section shows the character of a number of coarsening-upward successions in the basal portion of the Viking Formation. The main successions (1–5) correspond to fourth-order parasequences consisting of shelfal/lower offshore shales to lower shoreface sandstones. The lower two fourth-order parasequences consist of a number of fifth-order parasequences. All parasequences are generally bounded by low-energy flooding surfaces. The overall stacking pattern corresponds to a progradational parasequence set, reflecting a highstand systems tract. The succession is truncated by a high-energy flooding surface (VE3/4). The map to the lower left indicates the approximate line of section. Figure modified after Pattison (1991a).

sion, where minor falls in relative sea level, stillstand periods, and enhanced rates of relative sea level rise have produced at least seven discrete discontinuities of sequence stratigraphic significance.

The recognition of discrete high-energy FS is difficult on the basis of sedimentology alone, particularly when dealing with the upper Viking Formation, where there exist abundant sharp-based pebble stringers and thin trough cross-stratified coarse-grained sandstones within interbedded sandstones, siltstones, and shales. Many of these coarse stringers could reflect veneers on transgressive surfaces, but, due to their abundance, picking which ones have stratigraphic significance is highly problematic. However, virtually every high-energy FS incising or cutting across shaly sediments shows a *Glossifungites* suite. Several intervals contain up to seven such ichnologically demarcated FS within 6 m of section. Many firmgrounds also appear to have been developed on siderite-cemented intervals within the shales. Whether the siderite is a function of the transgressive erosion, a chemical response related to deep penetration by the tracemakers of the *Glossifungites* suite, or that preexisting siderite-cemented bands formed resistant layers which the high-energy FS could not incise, is uncertain, although in the latter case soft-bodied fauna would find it difficult to penetrate such a layer.

Glossifungites assemblages are manifest by the ichnogenera *Diplocraterion* (dominantly *D. habichi*), *Skolithos*, *Arenicolites*, and firmground *Thalassinoides* (Figure 14). In many cases, the nature of the contact is cryptic, due to biogenic reworking by deeply penetrating structures. The presence of the firmground suite and dispersed pebbles is employed to interpret the existence of these hidden bed junctions (i.e., concealed bed junction; cf. Simpson, 1957). The *Glossifungites* assemblages record suspension-feeding behavior associated with the period of higher energy during active marine erosion. Colonization of the exhumed surface postdates erosive shoreface retreat, but presumably occurs prior to significant deepening. Although these higher-energy suites clearly crosscut the lower-energy softground suites, most authors have routinely regarded them as part of the softground assemblage, obscuring the true, original depositional conditions of the facies.

These high-energy FS are commonly overlain by conglomeratic lags, or by erosionally based, highly burrowed pebbly and sandy shales and shaly sandstones. The transgressive lags locally contain shale interbeds containing an impoverished suite of *Planolites*, *Terebellina*, and rare *Skolithos* (Figure 15A), demonstrating marine conditions of deposition (refer to facies A, MacEachern et al., 1992a). These lags are interpreted as the proximal facies of the transgressive erosion (ravinement) process, and correspond to the erosional remnants of a backstepping shoreface during erosional shoreface retreat. The pebbly and sandy shales may grade out of the lags or sharply overlie the high-energy FS themselves. They typically contain an abundant softground suite of *Terebellina*, *Planolites*, *Chondrites*, *Asterosoma*, *Teichichnus*, *Cylindrichnus*, *Rosselia*, *Siphonichnus*, *Helminthopsis*, *Zoophycos*, rare *Diplocraterion*, and *Palaeophycus* (refer to facies B, MacEachern et al., 1992a; Figure 15B). This facies is interpreted as the distal deposits of the continuing ravinement process; the presence of coarse-grained sand and dispersed pebbles records ongoing transgressive erosion in shallower-water settings, with the coarser material being reworked seaward by storm-

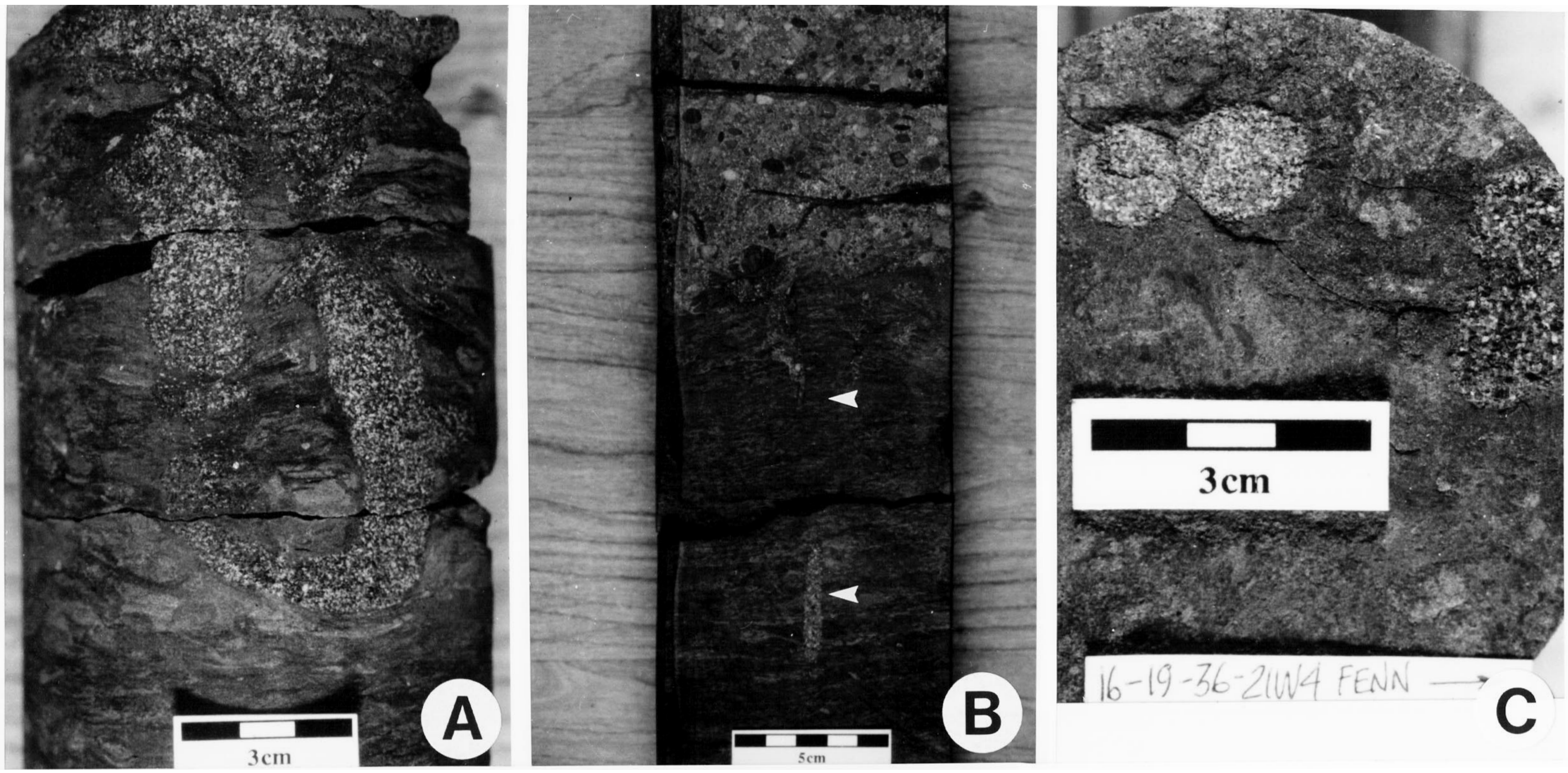


Figure 14. High-energy flooding surfaces demarcated by the *Glossifungites* ichnofacies. (A) Thoroughly burrowed shaly sandstone is crosscut by a robust, medium- to coarse-grained sand-filled *Arenicolites* of the *Glossifungites* ichnofacies, subtending from a high-energy flooding surface. Viking Formation, Kaybob South field, 7–19–62–19W5, depth 1652.0 m. (B) Silty and sandy shales of regional Viking parasequences erosionally truncated by a high-energy flooding surface (VE3 of Boreen and Walker, 1991). *Glossifungites* suite consists of *Skolithos* (arrows) piping conglomeratic sandstone from the overlying transgressive lag. Viking Formation, Willesden Green field, 14–20–40–6W5, depth 2250.0 m. Scale in centimeters. (C) Bedding-plane view of sandy shales crosscut by firmground *Diplocraterion habichi*. Note the robust, sharp-walled character. Viking Formation, Fenn field, 16–19–36–21W4, depth 1302.2 m. Photograph courtesy of I. Raychaudhuri.

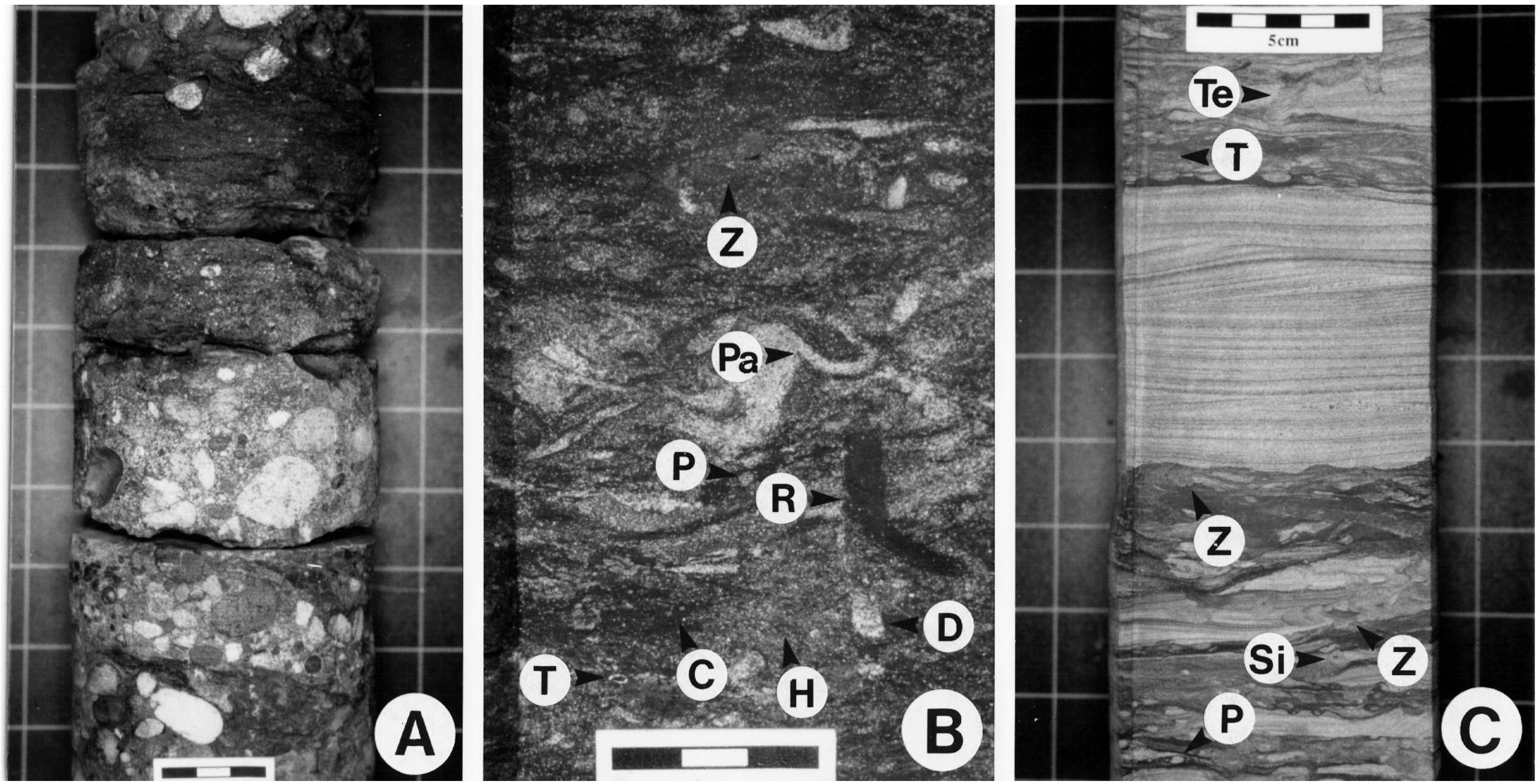


Figure 15. Facies of the transgressive systems tract, Viking Formation. (A) Moderately to poorly sorted polymictic conglomerate facies. Conglomerate with sandy matrix at base passing into muddy matrix upwards. Facies is interpreted as a transgressive lag. Joffre field, 2–21–38–26W4, depth 1582.6 m. (B) Pebbly and sandy shale facies. Thoroughly burrowed sandy shale with dispersed pebbles, containing *Planolites* (P), *Helminthopsis* (H), *Zoophycos* (Z), *Terebellina* (T), *Chondrites* (C), *Rosselia* (R), *Diplocraterion* (D), and *Palaeophycus* (Pa). Facies is interpreted to reflect the distal facies of ongoing erosive shoreface retreat. Kaybob South field, 7–19–62–19W5, depth 1652.8 m. (C) Interbedded fine sandstone and shale facies (sandy subfacies). Storm-bed sandstone consisting of wavy parallel lamination passing into combined flow ripple lamination is interstratified with thoroughly burrowed sandy shale. Sandy shale contains ?*Siphonichnus* (Si), *Zoophycos* (Z), *Teichichnus* (Te), *Planolites* (P), and *Terebellina* (T). Facies corresponds to stillstand progradational cycles, commonly attenuated by a high-energy flooding surface. Joarcam field, 10–4–48–20W4, depth 974.3 m.

initiated or storm-enhanced currents. The associated softground suite supports sediment accumulation in upper to lower offshore settings associated with continuing deepening.

Commonly grading out of the pebbly shales are interstratified sandstones, siltstones, and shales, which possess moderate to low degrees of burrowing and preserve remnant low-angle parallel laminae, combined flow ripple laminae, and less common oscillation ripple and current ripple laminae. The softground suite consists of *Planolites*, *Teichichnus*, *Asterosoma*, *Chondrites*, *Terebellina*, *Cylindrichnus*, *Rhizocorallium*, *Siphonichnus*, *Thalassinoides*, *Helminthopsis*, *Zoophycos*, *Anconichnus horizontalis*, rare *Diplocraterion*, *Skolithos*, *Arenicolites*, *Lockeia*, and *Palaeophycus* (refer to facies C, MacEachern et al., 1992a; Figure 15C). This facies is interpreted as upper offshore to distal lower shoreface deposits in a moderately to highly storm-dominated setting, records shallower-water conditions than the underlying pebbly shales, and is attributable to progradation during a relative stillstand of sea level.

The stacking of *Glossifungites*-demarcated, erosionally based pebbly and sandy shales, with interlaminated sandstones, siltstones and shales, supports the interpretation of transgressive erosion followed by short-lived periods of progradation. As such, these successions reflect parasequences with high-energy parasequence boundaries, and appear to be arranged in a retrogradational parasequence set. Many of these parasequences are probably the distal equivalents of more substantial shorefaces developed in landward positions.

The regional significance of these ichnologically demarcated transgressive surfaces requires careful mapping and correlation. High-energy FS appear localized or amalgamated (co-planar) in several localities, making delineation difficult. The character of the overlying transgressive deposits also tends to vary considerably, even across short distances, complicating the process of determining surface equivalence. In addition, some *Glossifungites*-ichnofacies–demarcated surfaces may be autocyclically generated as well. Regardless, the presence of a substrate-controlled ichnofacies overlain by transgressive deposits provides a more distinctive and reliable means of identifying a surface of *more likely* sequence stratigraphic significance than merely choosing the base of any one of a number of pebble stringers or gritty shales. Ichnologically demarcated high-energy FS occur in the Viking Formation over much of central Alberta, as well as in the roughly equivalent Paddy Member (Peace River Formation) of the Sinclair field in north-central Alberta.

High-Energy Parasequences: Stillstand Shorefaces

Several Viking Formation oil and gas fields in central Alberta produce hydrocarbons from northwest-southeast–trending shoreface successions. Many of these shoreface deposits are areally restricted parasequences bounded above and below by high-energy FS (high-energy parasequence boundaries). These successions show a strong genetic affinity with other transgressive intervals and may progressively pass basinward into the high-energy parasequences and low-energy parasequences discussed above, and landward into FS/SB with abundant evidence of subaerial exposure preserved.

Figure 16 schematically illustrates the development of these areally restricted parasequences and their relationship to forced regression shorefaces. The lower parasequence boundary corresponds to a FS/SB, generated by erosive shoreface retreat across a subaerial exposure surface. The high-energy FS removes all evidence of subaerial exposure in the Viking examples studied. A decrease in the rate of sea level rise or an increase in sedimentation rate permits the progradation of a shoreface over the FS/SB, seaward of the backstepping shoreface. The progradational shoreface constitutes the parasequence, marking a basinward shift of facies during a period of relative stillstand of sea level (i.e., a stillstand shoreface). An increase in the rate of transgression (resumed transgression) produces a low-energy FS below fair-weather wave base and a high-energy FS at and above fair-weather wave base. The high-energy FS truncates the upper portion of the stillstand shoreface and cuts a new FS/SB landward of the previous one. It is clear that what initially appears to be a single FS/SB is actually a composite surface generated by multiple, discrete periods of transgressive modification of the sequence boundary. Since each successive stillstand shoreface lies progressively landward of the previous one, these high-energy parasequences stack as a retrogradational parasequence set, and thus constitute elements of the transgressive systems tract.

The Viking interval of the Chigwell field is interpreted to reflect this depositional scenario (Figure 17). The principal sand body overlies highly burrowed silty shales and sandy shales equivalent to those of the regional Viking cycles (Figure 11; Raychaudhuri et al., 1992). The high-energy FS is rarely preserved as a discrete surface—intense burrowing has largely obliterated it. Instead, dispersed pebbles and *Glossifungites* assemblages consisting of *Thalassinoides* highlight the presence of the stratigraphic break. In a basinward direction, evidence of a break is largely lacking, and the discontinuity may have graded into a low-energy FS overlying a correlative conformity which has been biogenically homogenized.

The facies overlying the FS/SB are similar to those of the regional Viking cycles, both sedimentologically and ichnologically, although its distribution is restricted to a transgressively cut notch (cf. Figure 16). A fully marine, diverse assemblage of *Ophiomorpha*, *Skolithos*, *Arenicolites*, *Diplocraterion*, *Conichnus*, *Bergaueria*, *Helminthopsis*, *Chondrites*, *Terebellina*, *Schaubcylindrichnus*, *Planolites*, *Asterosoma*, *Cylindrichnus*, *Rosselia*, *Rhizocorallium*, *Teichichnus*, *Thalassinoides*, *Palaeophycus*, *Subphyllochorda*, *Siphonichnus*, and fugichnia, is recognized from the intensely burrowed shaly sandstone facies (Raychaudhuri, 1989; Raychaudhuri et al., 1992). Interbedded with this facies is a trough cross-bedded to structureless, medium-grained sandstone facies with *Ophiomorpha*, *Skolithos*, *Siphonichnus*, *Asterosoma*, *Palaeo-*

phycus, and *Planolites*. These two facies are interpreted to reflect weakly storm-influenced, low-energy lower shoreface and middle to upper shoreface deposits, respectively. The lower shoreface trace-fossil assemblage is diverse, intensely and uniformly burrowed, consistent with fully marine equilibrium (K-selected) communities in unstressed environments (Pianka, 1970). The predominance of deposit-feeding structures, with associated grazing and suspension-feeding structures, supports a lower shoreface setting (Figure 5; MacEachern and Pemberton, 1992). The cross-bedded facies possesses a reduced diversity, a reduced abundance of burrowing, and a greater dominance of vertical structures, reflecting the shallower water, higher energy, and greater dynamic conditions of deposition in the middle to upper shoreface setting. Basinward, thoroughly burrowed upper offshore sandy shales containing a *Cruziana* suite similar to facies 2 of the regional Viking highstand parasequences constitute the initial deposition on the FS/SB (Figure 17). These grade upward into lower and middle shoreface sandstones. The sand body overlying the FS/SB is interpreted to reflect progradation of a shoreface during a short-lived stillstand of relative sea level which punctuated an overall transgression (Raychaudhuri et al., 1992). The top of the main sand body has been truncated by erosion associated with resumed transgression, and is capped by a transgressive lag; features are consistent with other high-energy FS (cf. MacEachern et al., 1992a). A similar stratigraphic scenario has been proposed for other Viking Formation fields, such as Joffre and Gilby (Downing and Walker, 1988; Raddysh, 1988).

The Turonian Cardium Formation in central Alberta also contains a series of stillstand shorefaces (parasequences) overlying FS/SB surfaces and capped by marine FS (cf. Walker and Eyles, 1991; Walker and Plint, 1992). In the Pembina field, silty shales lying below the FS/SB contain a diverse trace-fossil assemblage, including *Planolites*, *Chondrites*, *Helminthopsis*, *Terebellina*, *Asterosoma*, and rare *Zoophycos*. This suite reflects a distal *Cruziana* ichnofacies, suggesting offshore to shelfal accumulation (Figure 5). This facies was subaerially exposed, probably with associated erosional exhumation, during a fall in sea level. The surface was subsequently transgressed, and a high-energy marine FS substantially modified the sequence boundary, removing the evidence of subaerial exposure. This FS/SB surface is demarcated by a *Glossifungites* assemblage locally consisting of robust *Thalassinoides* (Figure 18), and more rarely *Skolithos*, subtending into the underlying silty shales. The *Thalassinoides* systems are passively filled with pebbles and sand piped from the overlying structureless conglomerates (Vossler and Pemberton, 1988). The conglomerate body sharply overlies the FS/SB and corresponds to a gravelly shoreface which prograded basinward during a relative stillstand of sea level. The conglomerate largely appears structureless and shows no burrowing except within thin mud interbeds. The gravelly shoreface passes upward into a low-energy? FS overlain by shelfal shales that contain *Helminthopsis*, *Planolites*, *Chondrites*, *Terebellina*, and *Zoophycos*. As in the Viking Formation at Chigwell, these successions correspond to parasequences. The FS/SB, as is characteristic of these stratigraphic scenarios, shows a steplike morphology which is steeper along the landward margin and flattens out in a basinward direction. Where the overlying FS (related to resumed transgression) becomes erosional, it truncates the top of the conglomerate body, and landward cuts down to become co-planar with the FS/SB.

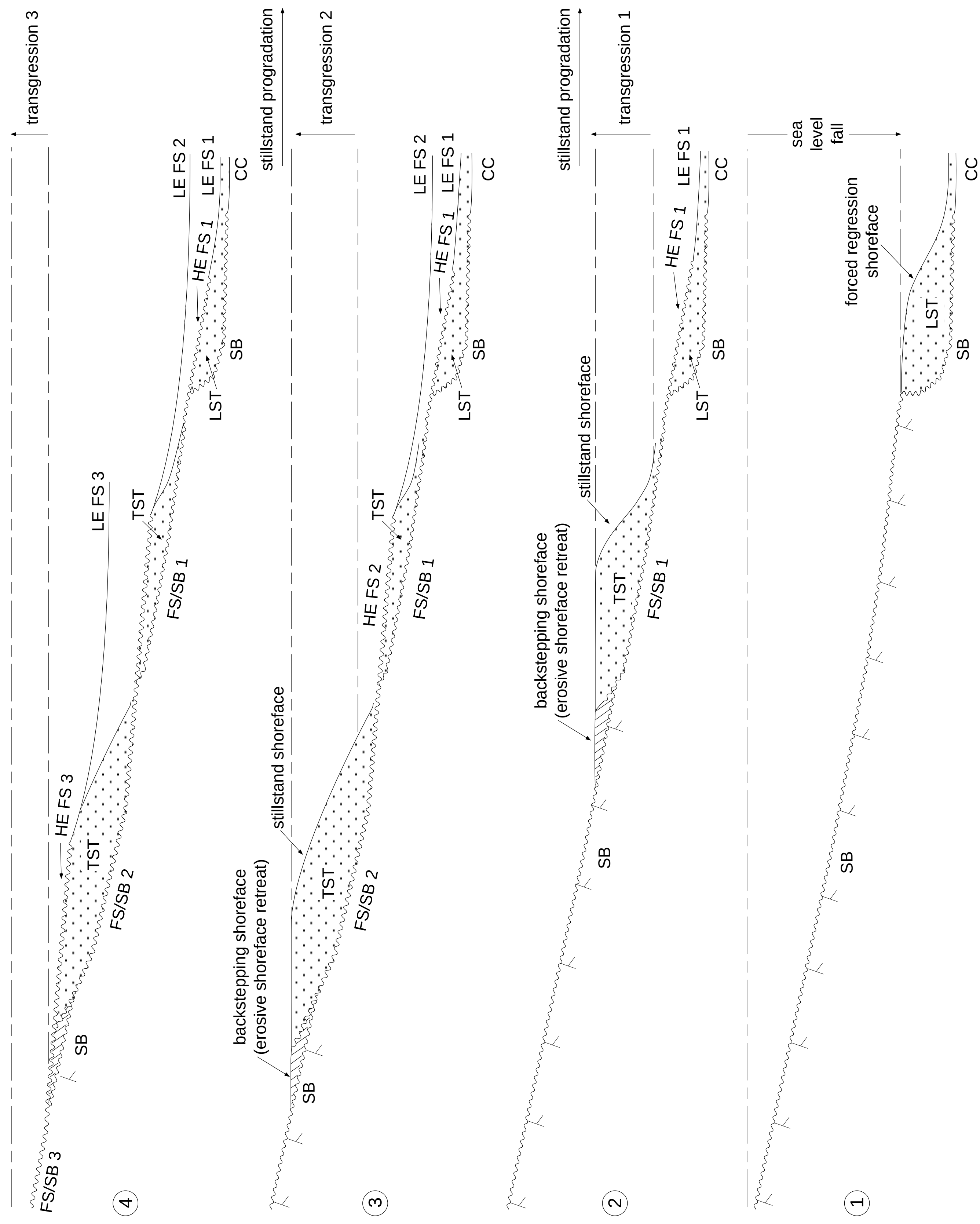
Colonization of the FS/SB surface by the omission-suite tracemakers corresponds to a hiatus in deposition after the initial transgressive modification of the sequence boundary and progradation of the shoreface conglomerates during a stillstand in relative sea level. The stillstand shoreface was ultimately drowned and locally removed during resumed transgression, marked by the capping marine shelfal shales.

Differentiation from Forced Regression Successions

It is imperative to differentiate between lowstand-generated forced regression shorefaces and high-energy parasequences produced during periods of incremental transgression; the two successions reflect markedly different sequence stratigraphic settings. The forced regression shoreface is an element of the lowstand systems tract and lies directly on the sequence boundary. In contrast, the high-energy parasequences are elements of the transgressive systems tract and are separated from the sequence boundary by a marine FS.

Insofar as the ichnology of the sediment is concerned, there is little difference between the two stratigraphic settings. The parasequences and the forced regression shorefaces are shorefaces and are therefore subject to the same physical conditions. Animal behaviors, and hence their biogenic structures, are not significantly affected by either depositional scenario; trace-fossil distributions in both settings largely obey existing models (Figures 1 and 5). Further, both the sequence boundary and the FS/SB are erosionally developed under marine conditions and favor colonization by tracemakers of the substrate-controlled ichnofacies. In the Viking Formation, both shoreface successions are typically truncated by high-energy FS during initial or resumed transgression, respectively. In many cases, therefore, it may be difficult to discriminate between the deposits of these fundamentally different stratigraphic scenarios, except on the basis of regional stratigraphic context. Forced regression shorefaces, for example, occupy the most basinward position of a particular sea level lowstand, with the high-energy parasequences stacking progressively landward along the depositional profile (Figure 16).

There are, however, a few subtle differences in the character of the two successions that may be employed to separate them. In positions lying basinward of the erosional expressions of both the sequence boundary and the FS/SB (i.e., the correlative conformity and the low-energy FS, respectively), the successions are virtually identical. Both intervals are



transgression 3
LE FS 2
LE FS 1
CC
HE FS 1
SB
LST
TST
LE FS 3
FS/SB 1
HE FS 3
TST
FS/SB 2
SB
FS/SB 3
4
stillstand progradation
transgression 2
LE FS 2
LE FS 1
CC
HE FS 1
SB
LST
TST
HE FS 2
FS/SB 1
stillstand shoreface
TST
FS/SB 2
backstepping shoreface
(erosive shoreface retreat)
SB
3
stillstand progradation
transgression 1
LE FS 1
CC
HE FS 1
SB
LST
stillstand shoreface
TST
FS/SB 1
backstepping shoreface
(erosive shoreface retreat)
SB
2
sea
level
fall
CC
forced regression
shoreface
LST
SB
SB
1

Figure 16. Schematic model of forced regression and stillstand shoreface development in the Viking Formation. (1) Relative fall of sea level shifts the shoreline basinward, creating a widespread subaerial exposure surface. At the position of the new shoreline, a wave-cut notch is generated to a depth corresponding to the fair-weather wave base (FWWB). Below this depth, a nonerosional correlative conformity (CC) is developed. Both of these surfaces, as well as the subaerial exposure surface, are manifestations of the same sequence boundary (SB). The new shoreface rapidly progrades over the SB, and is termed a forced regression shoreface (Plint, 1988; Posamentier and Vail, 1988). This shoreface is an element of the lowstand systems tract (LST). (2) Ensuing transgression (transgression 1) generates a low-energy flooding surface (LE FS) below fair-weather wave base and a high-energy flooding surface (HE FS) at and above it. The HE FS is generated by erosive shoreface retreat. Continued transgression truncates the upper portions of the forced regression shoreface and cuts an amalgamated flooding surface and SB (FS/SB). The backstepping shoreface sits on the SB. No evidence of subaerial exposure is preserved at the FS/SB. During a decrease in the rate of sea level rise, or increase in sediment supply (i.e., relative stillstand of sea level) a shoreface progrades over the FS/SB. Note that since the FS/SB is cut during rising sea level, initial deposition on the surface may correspond to facies lying basinward of FWWB (i.e., offshore or shelfal), in contrast to the forced regression shoreface. (3) Resumed transgression (transgression 2) generates a LE FS below and a HE FS at and above the initial FWWB. In this example, the HE FS removes the backstepping shoreface. Erosive shoreface retreat creates a new FS/SB landward of the first stillstand shoreface. The remnant of this shoreface constitutes a parasequence. During a pause in transgression, a new stillstand shoreface is produced seaward of the backstepping shoreface, and progrades over the FS/SB. (4) Resumed transgression (transgression 3) generates a LE FS below and a HE FS at and above initial FWWB. In this example, a remnant of the backstepping shoreface, and hence the SB, is preserved. Evidence of subaerial exposure is removed landward of this remnant as a new FS/SB is cut. The stillstand shoreface constitutes a parasequence. The progressive landward-stepping stillstand shorefaces produce a retrogradational parasequence set, reflecting the transgressive systems tract (TST). Note that the only localities where the initial SB is preserved are immediately below the forced regression shoreface, which was cut under marine conditions, and as small remnants veneered by backstepping shorefaces. Erosive shoreface retreat has removed virtually all evidence of subaerial exposure. Note also that the FS/SB is actually a composite surface made up of segments of FS/SB (i.e., FS/SB 1–FS/SB 3) which are genetically related to their respective transgressive events (transgression 1–3). Each FS/SB therefore correlates to its equivalent HE FS and LE FS, not to the previous FS/SB.

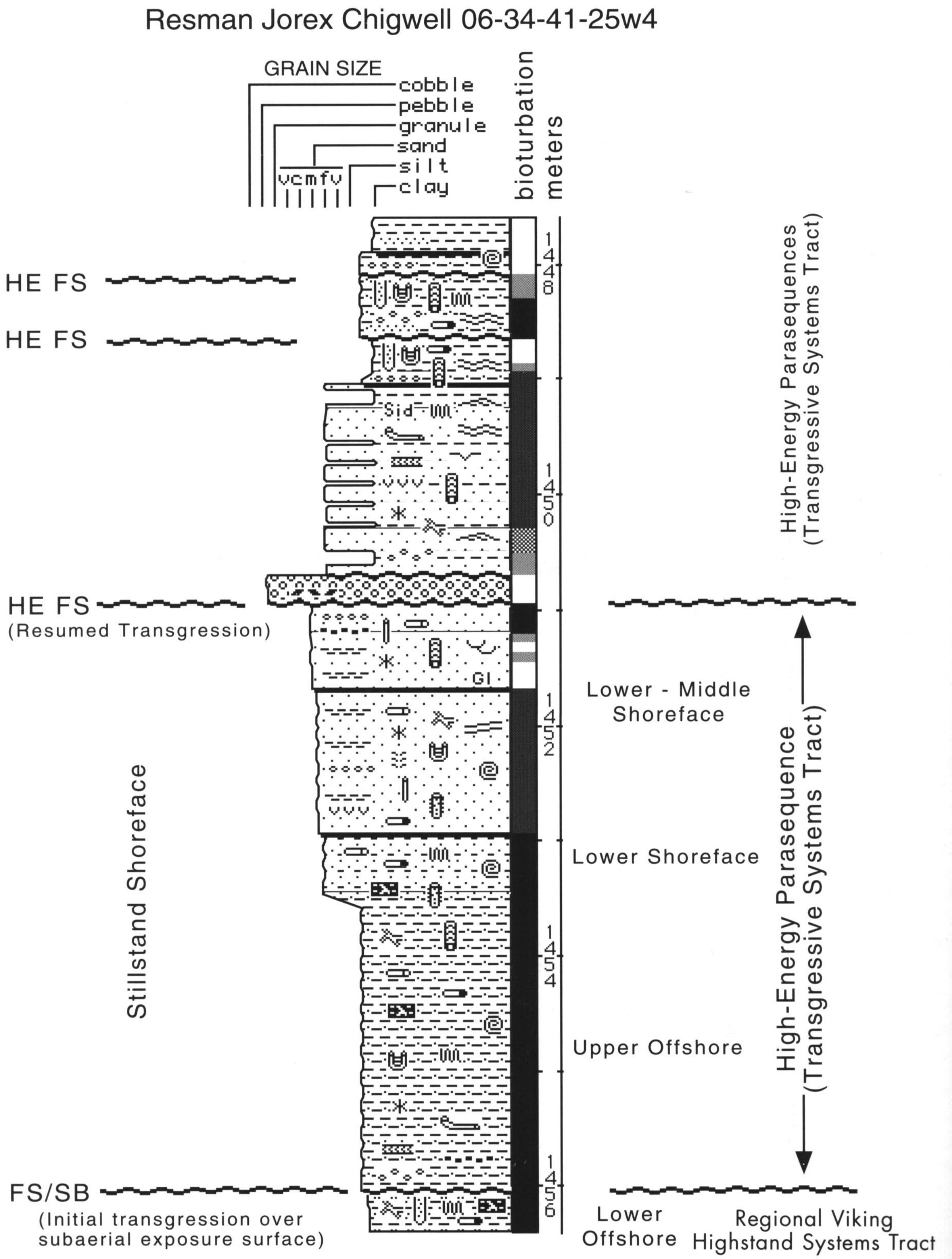


Figure 17. Litholog of a stillstand shoreface deposited on a high-energy FS/SB incised into lower offshore silty shales of an underlying parasequence. A *Glossifungites* suite of *Thalassinoides* with associated chert pebbles demarcates the FS/SB. The overlying shoreface, manifest by upper offshore sandy shales passing into shaly sandstones of the lower shoreface, reflects progradation during a relative stillstand of sea level. Resumed transgression generated a high-energy flooding surface which truncates the succession. The succession reflects a parasequence bound by high-energy flooding surfaces. The overlying facies correspond to those of Figure 15, reflecting later transgressive/stillstand cycles. Litholog is from the Viking Formation of the Chigwell field, based on the interpretation of Raychaudhuri et al. (1992). Legend for litholog is given in Figure 8.

Figure 18. ***Glossifungites*-demarcated base of a conglomeratic shoreface. Distal, lower offshore shales are truncated by conglomerates of a gravelly shoreface. The erosional discontinuity is marked by a *Glossifungites* suite of pebble-filled *Thalassinoides* (arrow). The surface is interpreted either as a sequence boundary overlain by a forced regression shoreface or a high-energy FS/SB overlain by a stillstand shoreface (cf. Walker and Plint, 1992). Cardium Formation, Pembina field, 12–9–51–10W5, depth 1596.2 m.**

characterized by gradual coarsening-upward successions overlying a generally cryptic surface. Some differences do occur in basinal positions, however, where the surfaces are erosional.

Since the erosional sequence boundary extends seaward only to a depth of fair-weather wave base, forced regression deposits directly overlying the surface should reflect conditions no deeper than lower shoreface (cf. Figure 9). Continued sea level fall produces even shallower-water facies overlying the sequence boundary. The FS/SB is also erosionally generated at initial fair-weather wave base but, in contrast, is followed by increasing accommodation space. Thus, stillstand deposits immediately overlying the FS/SB may reflect deeper-water conditions than fair-weather wave base (i.e., offshore or shelfal shales; cf. Figure 17).

In proximal positions, forced regression shorefaces tend to pass from lower to upper shoreface deposits over relatively short intervals, due to the reduced accommodation space. Further, since the shoreface is rapidly displaced basinward during falling sea level, lower, upper, and even foreshore deposits may lie directly on the sequence boundary. It is this sharp-based character of the shoreface that is commonly employed to interpret an interval as a lowstand shoreface (e.g., Posamentier and Chamberlain, 1991; Posamentier et al., 1992). In contrast, parasequences are associated with enhanced accommodation and, therefore, typically show more gradual coarsening-upward successions. Even in proximal positions, initial deposition on the FS/SB will probably be no shallower than lower shoreface, because the parasequence must prograde basinward to fill the accommodation space.

The difficulties in discriminating between the two successions are further compounded by the necessity of detecting the erosional character of the stratigraphic break. Many of these surfaces are cryptic due to bioturbation, and may easily be missed when logging core, particularly when the facies over- and underlying the surface are not fundamentally different. In the Viking Formation, for example, the discontinuity locally lies between upper offshore sandy shales of the regional highstand parasequences and lower shoreface sandstones of these anomalous successions. Intense burrowing in both facies obscures or destroys the contact, and the succession initially appears to be one of conformable progradation from offshore to lower shoreface environments. Locally, the presence of biogenically disturbed and displaced chert and lithic pebbles constitutes the only evidence of the erosion surface's existence. Elsewhere, a substrate-controlled trace-fossil suite demarcates it. Only the full integration of sedimentology, ichnology, and stratigraphy permits the reliable recognition and genetic interpretation of the sequence stratigraphic surface.

This difficulty in discriminating between lowstand and stillstand shorefaces is readily apparent in the Viking Formation of central Alberta. The main sandstones of the Joffre, Gilby, and Chigwell fields were initially interpreted as lowstand shorefaces (Downing and Walker, 1988; Raddysh, 1988; Raychaudhuri, 1989), but have been subsequently re-interpreted as high-energy parasequences produced during a relative stillstand of sea level which punctuated an overall transgression (Pattison, 1991a; Raychaudhuri et al., 1992). The re-interpretations arose principally as a result of placing these sand bodies into regional stratigraphic context.

The Cardium Formation poses an even greater problem, since the principal clastic material is conglomerate rather than sand. These gravelly shorefaces lack a diverse suite of trace fossils and possess few useful physical structures necessary to subdivide the interval into facies. Without this critical data, there is very little to base an interpretation of the shoreface's genesis on, despite the well-preserved character of the

Table 3. Six condensed sections selected from epeiric settings are summarized. Data were collected as follows: Cambrian–Ordovician (Baltic Shield) - Lindström (1963) and Jenkyns (1986); Jet Rock Shales (Toarcian; United Kingdom) - Morris (1979, 1980); Shaftesbury Formation (Albian; Alberta, Canada) - Leckie et al. (1990); Mowry Shale (late Albian; Wyoming, U.S.A.) - Byers and Larson (1979) and Jenkyns (1980); Awgu Shale (Turonian; Benue Trough, Nigeria) - Petters (1978) and Jenkyns (1980); Eocene–Oligocene boundary (Alabama, U.S.A.) - Loutit et al. (1988). Modified after Pemberton et al. (1992a).

Legend
● feature present
○ feature not present
? presence or absence not addressed

	Cambro-Ordovician, Baltic Shield	Jet Rock Shales	Shaftesbury Fm	Mowry Shale	Awgu Shale	Eocene-Oligocene Boundary, Alabama
1. Slow sedimentation rates	●	●	●	●	●	●
2. Reduced oxygen values	●	●	●	●	●	●
3. High organic matter content (TOC)	●	●	●	●	●	●
4. High concentration of platinum elements (iridium)	?	?	○	?	?	?
5. Presence of authigenic minerals (e.g., glauconite, phosphate, siderite)	●	●	○	?	●	●
6. High gamma-ray counts	?	?	●	●	?	●
7. Abundant and diverse plankton	●	○	○	●	●	●
8. Abundant and diverse microfauna	●	○	○	●	●	●
9. Abundant open-ocean planktonic foraminifera	?	○	○	?	●	●
10. Low concentrations of benthic foraminifera	●	●	●	●	●	●
11. Abruptly overlies nonmarine or shallow marine sediments	●	○	●	●	○	●
12. Section overlain by downlap surface	?	?	○	●	○	●
13. Associated with burrowed, bored, or slightly lithified tops	●	?	○	●	?	?
14. Generally unburrowed or sparsely burrowed interval	●	●	●	●	●	?

underlying stratigraphic break; both stratigraphic scenarios are regarded as probable (Walker and Plint, 1992). Purely from a stratigraphic point of view, the most basinward shoreface on each sequence boundary probably reflects the forced regression shoreface, while each shoreface landward of it corresponds to later high-energy parasequences of the transgressive systems tract.

CONDENSED SECTIONS

Condensed sections are deposited over a long span of time, but remain thin due to slow rates of hemipelagic or pelagic sedimentation. Such intervals are most extensive during periods of maximum transgression (Loutit et al., 1988), when the basin is starved of terrigenous material (Van Wagoner et al., 1990). Several condensed sections have been described from the rock record (e.g., Jenkyns, 1980; Legget, 1980; Leckie et al., 1990), and Loutit et al. (1988) summarized most of their common characteristics (Table 3). Leckie et al. (1990) studied a condensed section in the Shaftesbury Formation of the Peace River area, Alberta, which overlies a high-energy FS. Numerous differences exist between those condensed sections summarized by Loutit et al. (1988) and the Shaftesbury example (Table 3), which Leckie et al. (1990) attributed to the shallower-water setting of the latter. This type of shallow-water condensed section may be more typical of basins such as the epicontinental Cretaceous Interior Seaway.

Leckie et al. (1990) did not recognize trace fossils in the Shaftesbury Formation condensed section, mainly due to the poor preservation of the shales in outcrop. In subsurface cores of the Shaftesbury Formation, south of the Peace River arch area, the same high-energy FS and overlying transgressive succession described by Leckie et al. (1990) can be recognized, but the ichnology is more readily observed due to the unweathered character of the rock. The transgressive erosion surface is commonly overlain by a 25–50 cm thick pebble lag, locally grading into an intensely burrowed pebbly or sandy shale. A fully marine suite of *Planolites*, *Terebellina*, *Thalassinoides*, *Teichichnus*, *Helminthopsis*, *Chondrites*, *Asterosoma,* and *Diplocraterion* is present within the transgressive deposits. These pass abruptly into laminated shales with rare, thin, silt stringers. The shale is virtually unburrowed, though it contains a sporadic and impoverished distribution of rare *Planolites*, *Teichichnus*, and very rare *Chondrites*, *Zoophycos,* and *Lockeia*. This may correspond to the shallow-water condensed section of Leckie et al.

(1990). There does not appear to be a significant difference, however, between the abundance, diversity, and distribution of ichnogenera in intervals corresponding to high radioactivity on the gamma-ray well-log signature (i.e., the condensed section) and intervals lying above it. It is unclear whether the impoverished nature of the suite corresponds to reduced oxygenation or is purely a taphonomic phenomenon (cf. facies E, MacEachern et al., 1992a).

The ichnological signatures of condensed sections per se have yet to be documented adequately. In general, the units tend to be unburrowed, which is commonly attributed to low oxygen content and overall stressful conditions for benthic organisms. Six selected condensed sections from epeiric settings show a general adherence to conditions of higher total organic carbon (TOC), reduced oxygen values, low concentrations of benthic foraminifera, and minimal or absent burrowing (Table 3). The interrelationships of low oxygen, preservation of organic carbon, and biologically lethal sea floor conditions have been discussed by numerous authors (e.g., Byers and Larson, 1979; Jenkyns, 1980; Legget, 1980; Savrda and Bottjer, 1987). Savrda and Bottjer (1987) noted that ichnofaunas are generally more indicative of both magnitudes of and rates of change in oxygen levels than are macrobenthic body-fossil suites. Bromley and Ekdale (1984) found that with decreasing oxygenation at the sea floor, *Planolites*, *Thalassinoides*, and *Zoophycos* progressively disappear before *Chondrites* does, suggesting that the *Chondrites* tracemaker may have been capable of surviving conditions of anoxia. Savrda and Bottjer (1987) also found that burrow sizes decrease with increasing depth and decreasing oxygen levels. In their study of the Monterey Formation (Miocene) of California and the Niobrara Formation (Cretaceous) of Colorado, Savrda and Bottjer (1987) proposed oxygen-related ichnocoenoses to distinguish units of more or less uniform bottom-water oxygenation. One possible means of recognizing condensed sections characterized by dysaerobic or anaerobic conditions may be by the presence of a suspiciously unburrowed or slightly burrowed dark carbonaceous shale lying between more intensely burrowed marine deposits. Bhattacharya (1989), in his work on the Dunvegan Formation, differentiated shallow-water shales from those attributed to maximum flooding by the transition from weakly burrowed shales to well-laminated, unburrowed shales. The laminated shales may represent condensed sections separating transgressive systems tract deposits from highstand systems tract deposits.

AMALGAMATED SEQUENCE BOUNDARIES AND FLOODING SURFACES (FS/SB)

Amalgamated sequence boundaries and high-energy FS (FS/SB) are commonly colonized by substrate-controlled tracemakers. The lowstand erosion event typically produces widespread firmground, hardground, and woodground surfaces. The ensuing transgressive event tends to remove much of the lowstand deposits by erosive shoreface retreat and exposes the discontinuity to marine or marginal marine conditions, permitting organisms to colonize the re-exhumed substrate. The sequence boundary component may correspond to subaerially exposed areas, such as delta plains, fluvial flood plains, interfluves, or incised valleys.

Transgressive Erosion Across Subaerially Exposed Surfaces

The Dunvegan Formation in the subsurface of the Jayar field, central Alberta, contains a high-energy FS cut into rooted and subaerially exposed delta plain deposits (Bhattacharya and Walker, 1991). The erosional discontinuity is demarcated by a *Glossifungites* suite of *Thalassinoides*, passively filled with coarse-grained sands infiltrated from an overlying transgressive sand sheet (Figure 19A). The FS/SB constitutes the boundary between Allomembers C and B of the Dunvegan Alloformation (Bhattacharya, 1989; Bhattacharya and Walker, 1991). Oppelt (1988) noted a similar type of FS/SB at the ?Aptian–Albian Gething–Bluesky contact in northeastern British Columbia (Table 2). An excellent example of this also occurs at the lower Albian Mannville Group–Joli Fou Formation contact in the Kaybob field of central Alberta, where rooted, incipient paleosols are crosscut by robust firmground *Thalassinoides*, passively filled with muddy sand and large siderite-cemented clasts (Figure 19B). The overlying silty shales record deposition in proximal shelf to lower offshore conditions, with *Planolites*, *Helminthopsis*, *Terebellina*, rare *Chondrites*, and very rare *Zoophycos*.

Areas marginal to incised valley systems correspond to interfluves which are subaerially exposed during lowstand excavation of the valley and late lowstand valley infill. In the Viking Formation, these interfluves are generated on original fully marine regional Viking offshore to lower shoreface deposits. When the valley becomes filled and is transgressively overrun, a high-energy FS is commonly generated on the interfluve, which removes any evidence of exposure. Differentiating this from pure transgressive erosion is impossible, until placed into regional context. In other localities, the FS/SB may not even appear to reflect deepening, such as where the interfluve is cut into lower offshore or shelfal deposits of a regional Viking parasequence and is overlain by lower or upper offshore shales. In such settings, recognition of the nature of the surface may hinge on the delineation of the associated incised valley fill deposits.

Incised Valley Fill Deposits

Five Viking Formation fields, namely Crystal, Willesden Green, Sundance, Edson, and Cyn-Pem, contain facies associations interpreted to reflect estuarine incised valley deposition. The observed facies types and their distributions indicate that they accumulated in a barrier estuary or wave-dominated embayed estuary setting, in the sense of Roy et al. (1980) and Dalrymple et al. (1992) (Figure 20).

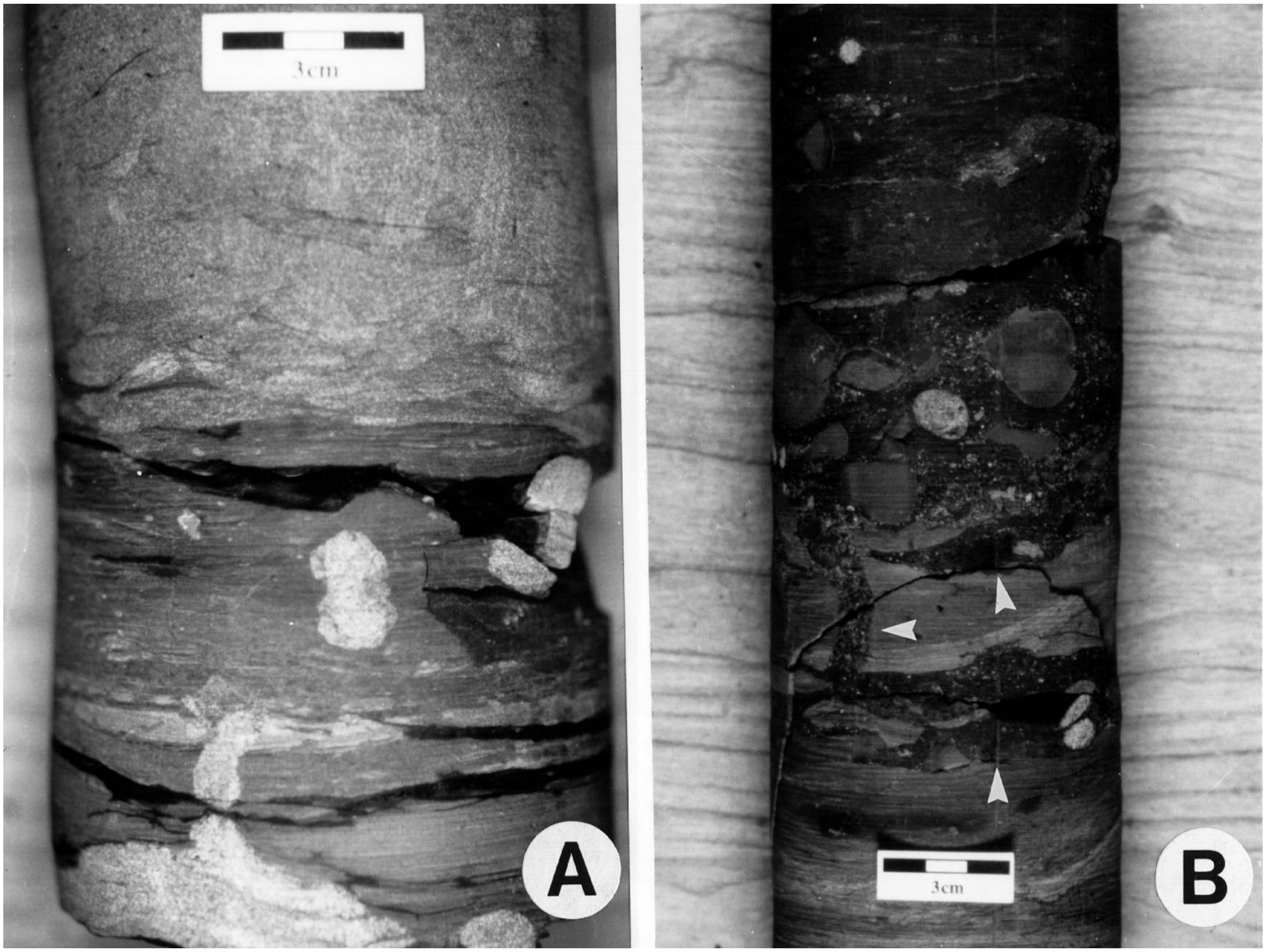


Figure 19. Amalgamated flooding surfaces and sequence boundaries (FS/SB) marked by the *Glossifungites* ichnofacies. (A) Rooted and subaerially exposed delta plain deposits truncated by high-energy flooding surface, overlain by a transgressive sand sheet. The discontinuity, corresponding to the contact between Allomembers C and B of Bhattacharya and Walker (1991), is marked by a robust *Thalassinoides* system of the *Glossifungites* ichnofacies. Dunvegan Formation, Jayar field, 6–11–62–3W6, depth 2523.6 m. (B) Rooted paleosol truncated by transgressive lag consisting of chert and lithic pebbles and intraformational rip-up clasts. The FS/SB surface is demarcated by a robust *Thalassinoides* network (arrows) corresponding to the *Glossifungites* ichnofacies. Mannville Group–Joli Fou Formation contact, Kaybob South field, 11–03–60–19W5, depth 1894.2 m.

The valley fill deposits demonstrate a tripartite zonation of facies and facies associations, defining three major depositional zones within the estuary. The bay head delta complex is sand dominated and formed at the head of the estuary, where much of the sediment is fluvially derived, though commonly wave reworked. The central basin complex grades seaward out of the bay head delta complex and into the estuary mouth complex, and is a zone of interference between marine and fluvial processes. The central basin corresponds to the lowest energy zone of the estuary. The estuary mouth complex occurs seaward of the central basin and is sand dominated. Marine processes (waves and tides) are responsible for transport and deposition of the sediment. A fourth depositional complex reflects channel deposition, largely corresponding to periods of re-incision and fill.

Ichnology of Viking Formation Incised Valley Surfaces

In most of the incised valley systems of the Viking Formation, the valley base and walls are demarcated by a *Glossifungites* assemblage, indicating that the valley probably did not fill until the ensuing transgression. Either the valley served as a zone of sediment bypass and possessed no fluvial deposits, or any lowstand deposits were subsequently eroded and reworked during the transgression, producing a high-energy FS/SB. The high-energy FS most likely reflects tidal scour ravinement associated with rapid rise of

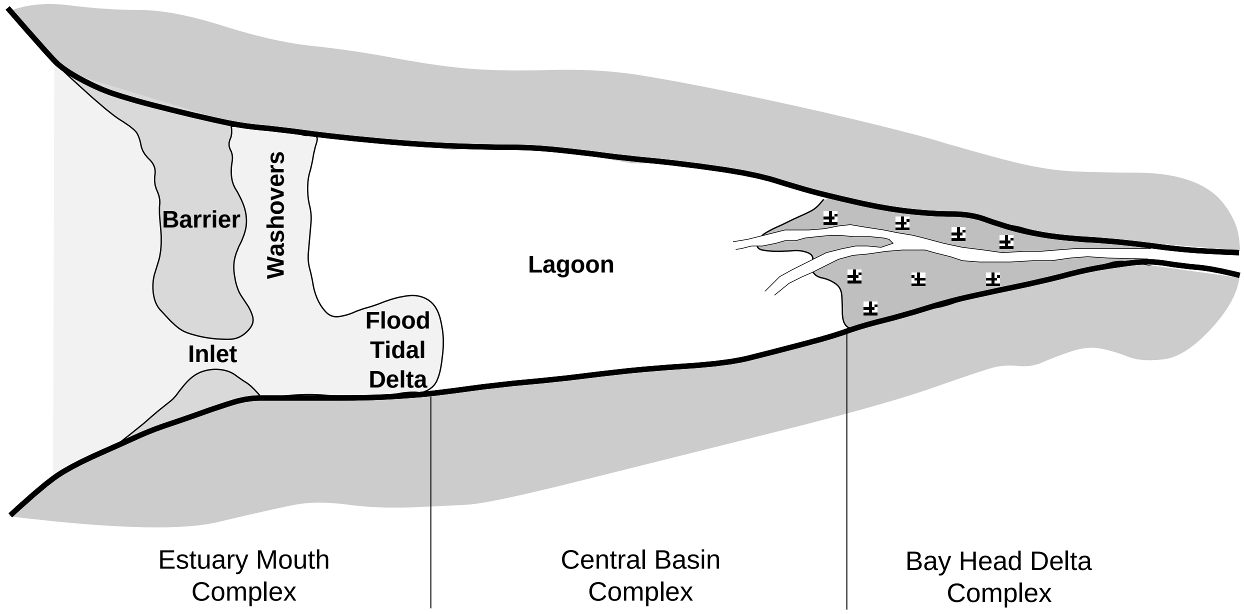


Figure 20. Conceptual model for wave-dominated, embayed estuarine depositional systems. The model best explains the distribution of observed facies and facies associations in the Viking Formation incised valley fills. The system demonstrates a tripartite zonation of facies, corresponding to three main depositional complexes: the bay head delta, the central basin, and the estuary mouth. The model is based on observations of embayed estuary systems along the New South Wales coast of Australia, by Roy et al. (1980). Figure is modified after Dalrymple et al. (1992).

sea level. As such, the base of the valley serves both as a sequence boundary and as the base of the transgressive systems tract.

The FS/SB are excavated into the coarsening-upward, regional Viking silty shales, sandy shales, and shaly sandstones of the underlying highstand parasequence set. These intervals contain fully marine, high-diversity and abundant distal to proximal *Cruziana* softground suites (Figures 5 and 11), in marked contrast to that of the valley-fill successions. In the Crystal field, the FS/SB is marked by the *Glossifungites* ichnofacies, manifest by numerous sharp-walled, unlined *Diplocraterion* shafts (Figure 21A), firmground *Thalassinoides*, *Diplocraterion habichi*, and firmground *Gastrochaenolites*. In the Willesden Green field, the valley base is locally marked by a *Glossifungites* assemblage consisting of spectacular *Rhizocorallium saxicava* (Figure 21B), *Thalassinoides*, *Arenicolites*, *Skolithos*, and *Diplocraterion habichi*. The valley surface in the Sundance and Edson fields is only rarely demarcated by firmground *Thalassinoides*, while the valley at the Cyn-Pem field is marked by abundant firmground *Arenicolites* and *Skolithos*.

Ichnology of Incised Valley Fills

The bay head delta complex (Figure 22A) is generally characterized by weakly and sporadically burrowed, wavy- and parallel-laminated sandstones reflecting delta-front storm beds, horizontal-laminated to current-rippled delta-slope sediment-gravity flows, and trough cross-beds reflecting distal portions of distributary channels. All shallow-water facies of the bay head delta have been removed by subsequent transgressive erosion. The overall trace fossil diversity is high, with 16 ichnogenera noted (Figure 23), though the burrow distribution is sporadic and numbers of individual forms are low. Any one cored interval may possess as few as three or four ichnogenera. The stresses imposed on the organisms and their resulting behavior are due largely to the episodic nature of deposition and the variable sedimentation rates, rather than to fluctuating salinity, although brackish-water conditions may have exerted an influence.

The central basin complex (Figure 22B, C) consists of two interbedded facies. The most distinctive facies comprises delicately interstratified, moderately intensely burrowed sandy mudstones, weakly burrowed sand- and silt-poor dark mudstones, and thin (millimeter- to centimeter-scale) sandstone stringers. Syneresis cracks are present throughout and are locally common. Burrowing is variable on a small scale, but relatively uniform throughout the facies interval. The facies is interpreted as fair-weather deposition of sands and muds within the lagoon or bay environment of the central basin. Most biogenic structures associated with this facies indicate deposit-feeding to grazing behavior, consistent with sediment deposition predominantly from suspension. The other main facies consists of storm-generated wavy parallel laminated to combined flow ripple and oscillation-ripple–laminated sandstone beds. Thin conglomerate beds and dispersed pebbles are locally common. The trace-fossil suite demonstrates opportunistic coloniza-

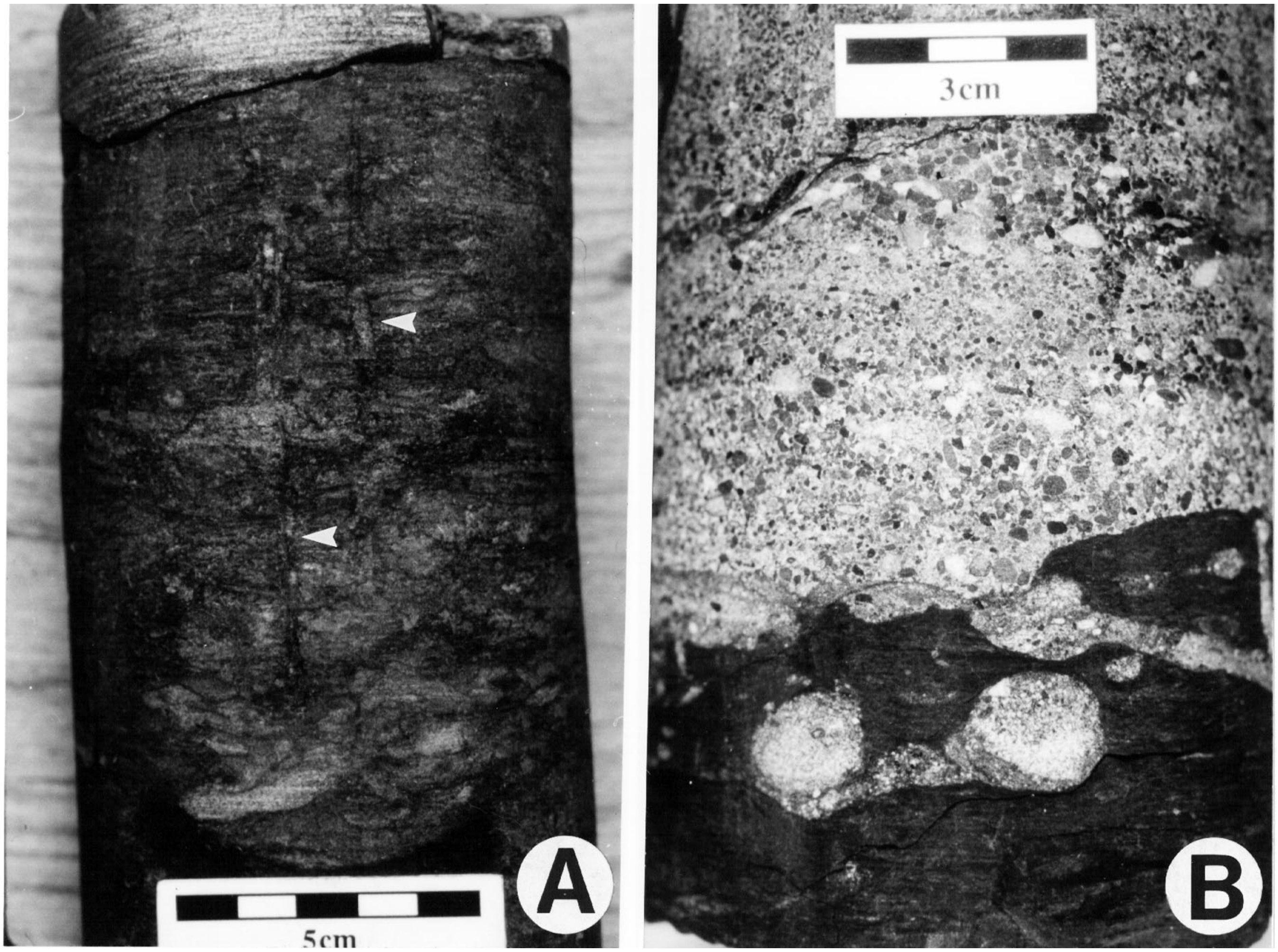


Figure 21. High-energy FS/SB associated with incised valleys. (A) Upper offshore sandy shales of a regional Viking parasequence are erosionally truncated by interbedded sandstones and shales of the central basin complex. The contact is demarcated by muddy sand-filled *Diplocraterion* (arrows) of the *Glossifungites* ichnofacies. Viking Formation, Crystal field, 08–26–45–4W5, depth 1832.1 m. (B) Lower offshore silty shales are erosionally truncated by pebbly sandstones and conglomerates of a channel-fill complex. The contact is marked by robust *Rhizocorallium saxicava* of the *Glossifungites* assemblage. Viking Formation, Willesden Green field, 10–35–40–7W5, depth 2327.0 m.

tion of the tempestite, subsequently replaced by the fair-weather suite. The trace-fossil assemblage for the central basin complex reflects a high diversity (19 ichnogenera; Figure 23), with intense and reasonably uniform burrowing. Close inspection, however, demonstrates that the ichnological suite of the central basin complex is quite complicated and records highly variable depositional conditions. Salinity fluctuations, episodic deposition, and variable substrate consistency appear to be the dominant stresses imparted on the tracemaking organisms.

The estuary mouth complex (Figure 22D, E), like the bay head delta, is preserved as an erosional remnant, consistent with the model of Roy et al. (1980). The dominant facies association reflects the landward side of the estuary mouth adjacent to the central basin, and shows a genetic affinity with sandy central basin facies associations. Fair-weather conditions are manifest by moderately to abundantly burrowed, ripple-laminated sandstones with minor intercalated mud beds. As in virtually all the other valley fill facies associations, tempestites are common. Washover deposits record the breaching of the barrier by storms acting on the seaward side of the estuary mouth. Like the central basin complex, the trace-fossil suite shows a high diversity of forms (19 ichnogenera; Figure 23), but the distribution of individual elements reflects the presence of various environmental stresses. The higher-energy nature of fair-weather deposition is reflected by the general decrease in importance of grazing and deposit-feeding behaviors. Episodic deposition appears to be the main environmental stress indicated by the trace-fossil suite, mainly in the form of opportunistic colonization of the tempestites by simple vertical-dwelling and suspension-feeding structures.

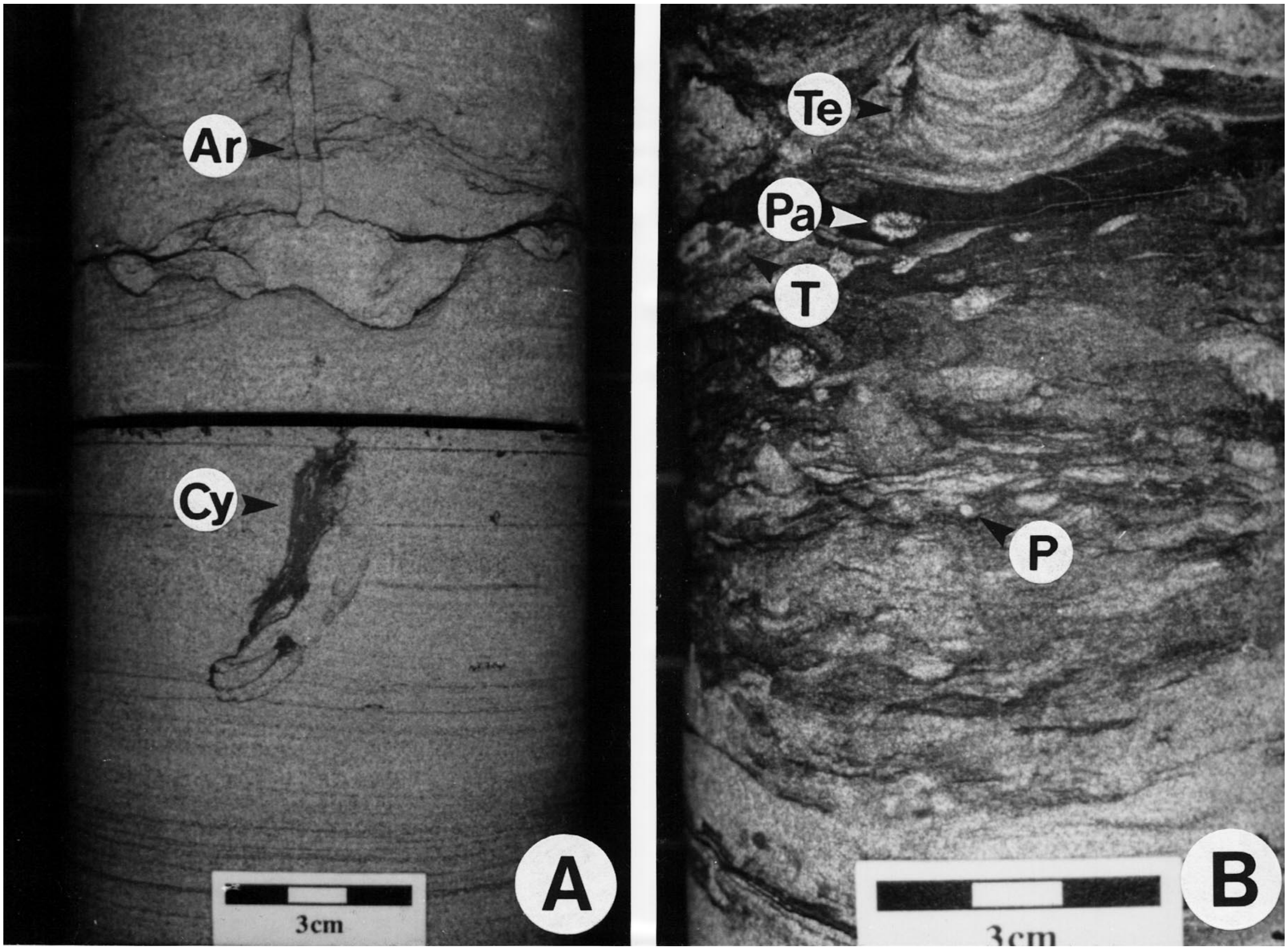
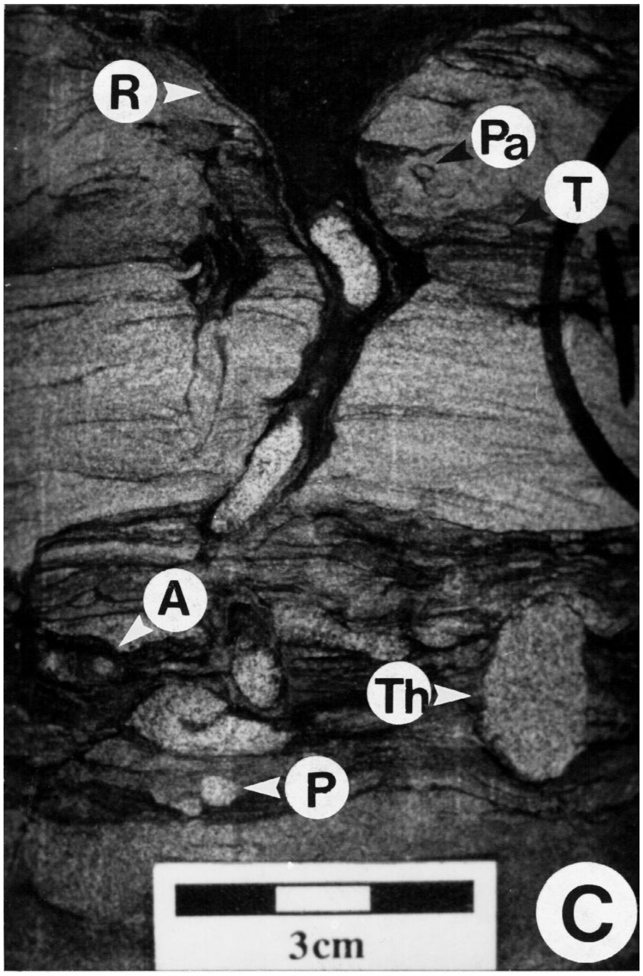


Figure 22. Facies of incised valley systems in the Viking Formation. (A) Wavy parallel-laminated fine sandstone passing into burrowed sandstone, reflecting storm-bed deposition on the delta front of the bay head delta complex. *Cylindrichnus* (Cy) and *Arenicolites* (Ar) correspond to opportunistic colonization of the storm bed. The mottled top of the bed reflects the replacement of this suite by the resident fair-weather community. Crystal field, 16–24–45–04W5, depth, 1807.1 m. (B) Highly burrowed sandy shales of the central basin complex. Remnant storm beds are present, but largely destroyed by infaunal burrowing. *Teichichnus* (Te), *Palaeophycus* (Pa), *Terebellina* (T), and *Planolites* (P) dominate. Crystal field, 08–31–46–03W5, depth 1673.1 m.

The facies association from the seaward side of the estuary mouth (Figure 22E) is erosionally bound and interpreted as the basal portion of the estuary mouth barrier bar itself. It rests on an amalgamated FS/SB surface and is overlain by a high-energy FS. The facies association shows fully marine conditions, consistent with a position on the seaward side of the estuary. Although there may be some transgressive reworking of the top of the succession due to erosive shoreface retreat, the coarsening-upward interval of sandy shales and shaly sandstones is interpreted to reflect the upper offshore to distal lower shoreface component of the erosionally removed estuary mouth barrier complex (Figure 20). The trace-fossil suite shows a uniform distribution of individual forms, a high degree of burrowing, a reasonable diversity of elements (15 ichnogenera), a lack of overwhelming dominance by a few forms, and the presence of moderate numbers of specialized grazing and feeding/dwelling structures: features that contrast markedly with the ichnology of facies associations deposited in the valley. The assemblage associated with the remnant barrier complex is consistent with a fully marine, largely unstressed, equilibrium (K-selected) community and shows a closer genetic affinity with facies associations of the regional Viking highstand parasequences (Figure 11) than to the incised valley fill assemblages.

Channel-fill facies associations (Figure 22F) predominantly reflect relatively small, migrating megaripples. The amalgamation of the trough cross-beds into thick intervals supports a high aggradation rate. Interstratified low-angle planar laminated sandstones with associated current ripple lamination are interpreted as sheet-flow transport of sand capped by waning flow deposits, possibly reflecting higher flow velocities during flood stage discharge in the channel or proximity to



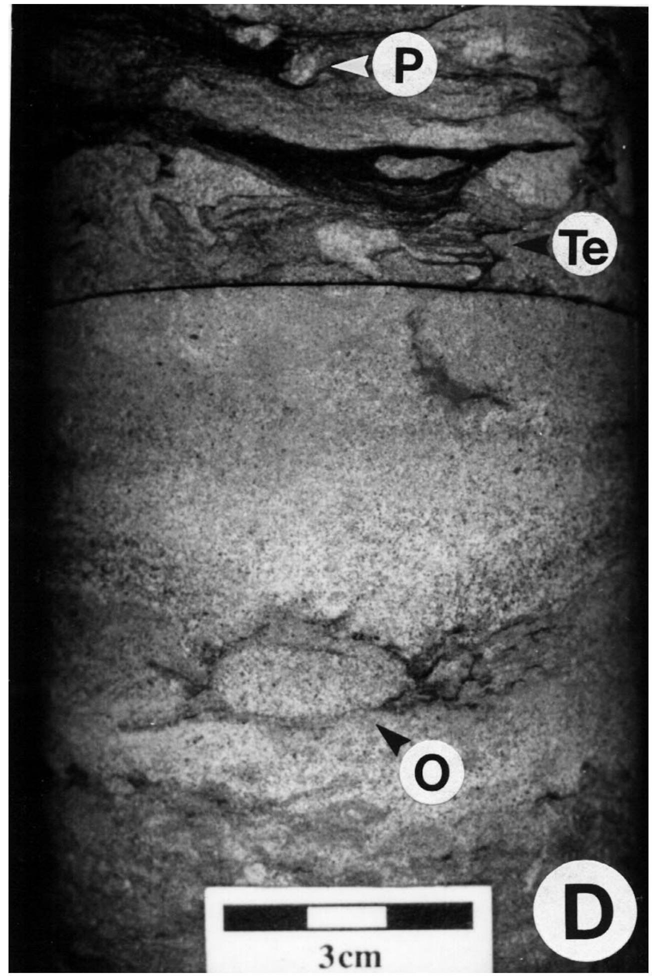


Figure 22. (C) Interbedded sandstones and sandy shales of the central basin complex. Note the combined flow-ripple–laminated sandstone, penetrated by *Rosselia* (R), *Planolites* (P), *Thalassinoides* (Th), *Asterosoma* (A), *Palaeophycus* (Pa), and *Terebellina* (T) are also present. Willesden Green field, 06–36–40–07W5, depth 2322.7 m. (D) Burrowed shaly sandstone of the estuary mouth complex. This interval lies on the landward side of the barrier system and is manifest by storm-generated wavy parallel-laminated sandstones burrowed with *Ophiomorpha* (O), *Teichichnus* (Te), and *Planolites* (P). Willesden Green field, 06–36–40–07W5, depth 2325.9 m.

the channel margins. The trace-fossil suite (Figure 23) demonstrates that most channel complexes accumulated in marine or marginal marine conditions, although the degree of salinity stress is difficult to determine. The main stresses imposed on the trace-fossil suite appear to be related to migration of megaripples and to high-energy sheet-flow conditions followed by rapid deposition.

Facies associations within the incised valley fills sensu stricto show a remarkably high trace-fossil diversity (Figure 23), particularly when compared to other estuarine settings (e.g., Wightman et al., 1987; Ranger and Pemberton, 1992). On close inspection, however, the degree of burrowing, its uniformity, and the distribution of individual elements are highly variable. Overall, *Teichichnus*, *Terebellina*, and *Planolites* dominate in the shaly substrates, while *Ophiomorpha*, *Skolithos*, and *Arenicolites* are dominant in the sandy substrates. Both groups are ubiquitous in the valley fill facies associations and correspond to simple structures produced by trophic generalists. Such r-selected (opportunistic) behaviors are characteristic of stressed environmental settings (Pianka, 1970), particularly those subject to salinity fluctuations. The regular alternation between these two groups of trace fossils reflects the episodic nature of tempestite deposition and the variability in substrate consistency, and constitutes the mixed *Skolithos-Cruziana* ichnofacies (Pemberton and Frey, 1984; Pemberton et al., 1992b).

Many of the secondary and accessory elements of the trace-fossil assemblage are not opportunistic and record more specialized and elaborate feeding behaviors which are uncommon in stressful environmental settings. Their sporadic distribution and variable abundances in the facies associations are interpreted to reflect fluctuations in salinity within the estuary, which may have repeatedly ranged from brackish to fully marine. *Helminthopsis*, *Chondrites*, *Asterosoma*, *Conichnus*, *Rhizocorallium*, and *Macaronichnus* probably only occurred in the valley-fill deposits when condi-

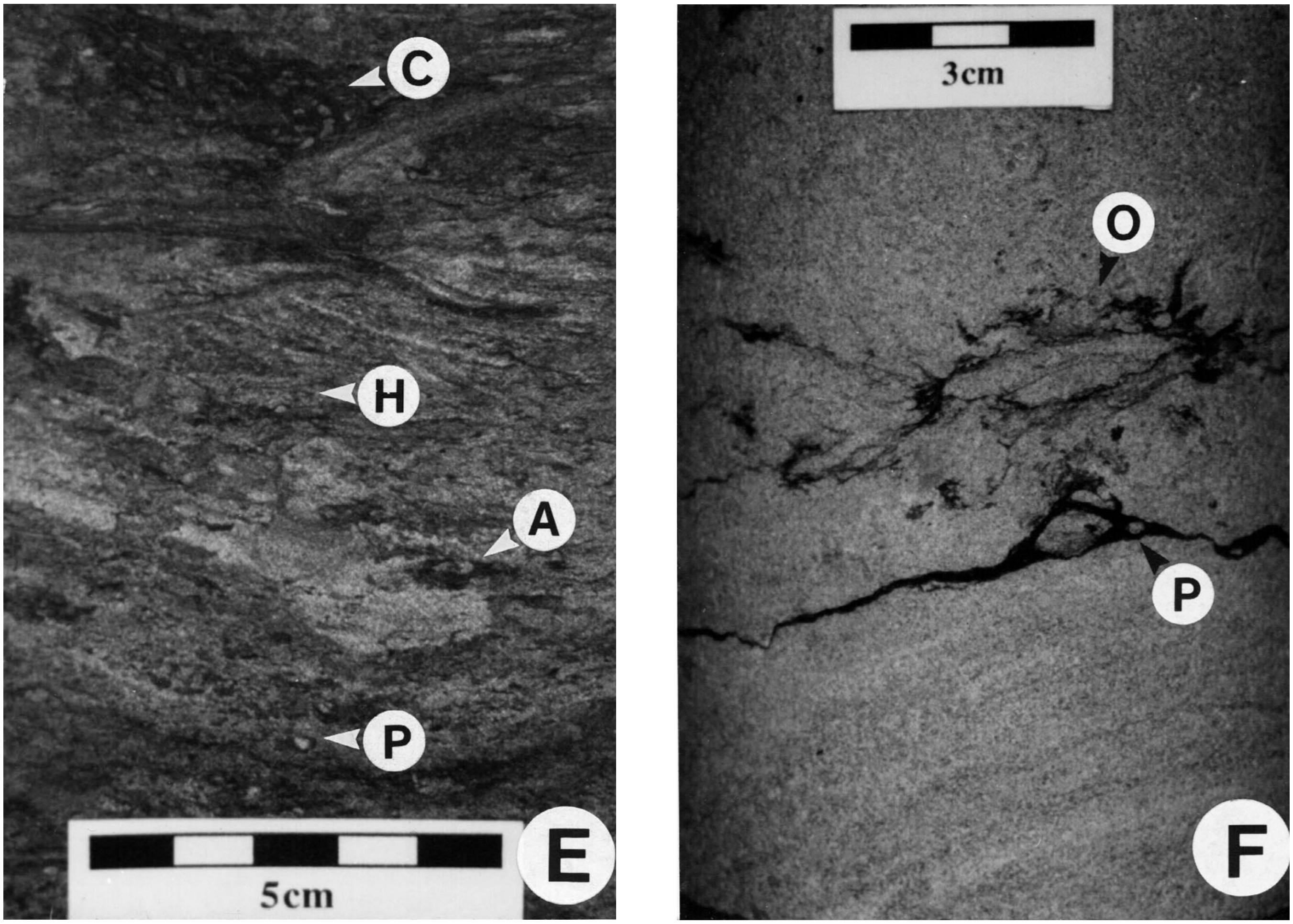


Figure 22. (E) Highly burrowed sandy shale reflecting upper offshore deposits of the barrier system on the seaward side of the estuary mouth complex. The sandy shales contain *Chondrites* (C), *Helminthopsis* (H), *Asterosoma* (A), and *Planolites* (P). Sundance field, 01–06–55–20W5, depth 2676.5 m. (F) Moderately well sorted medium-grained, trough cross-stratified sandstones reflecting the channel-fill complex. The presence of *Ophiomorpha* (O) and *Planolites* (P) attests to a marine influence in the channel fill. Edson field, 12–34–52–19W5, depth 2586.5 m.

tions approached fully marine. Their absence is most pronounced in the bay head delta complex, which probably experienced the lowest overall salinities. *Lockeia*, *Rosselia*, *Diplocraterion*, *Cylindrichnus*, and *Siphonichnus* seem to possess greater tolerance for the observed stresses in the environment and, consequently, are more commonly present in valley fill deposits. In addition, *Asterosoma*, *Rosselia*, and *Cylindrichnus* are typically smaller than their fully marine counterparts, a feature also regarded as characteristic of brackish-water conditions (Remane and Schlieper, 1971).

The bay head delta complex possesses one of the weakest degrees of burrowing, most sporadic distribution of burrowing and, almost exclusively, structures generated by trophic generalists. This supports high aggradation rates, episodic deposition, and reduced salinity as the main controls on the trace-fossil suite. The central basin complex demonstrates a dominance of simple structures by opportunistic organisms, with generally high degrees of burrowing. The sporadic distribution of traces reflecting specialized or elaborate feeding behaviors demonstrates that this zone of the basin probably experienced the greatest salinity fluctuations, ranging from brackish to nearly fully marine. Episodic storm-bed deposition is well represented by alternations between opportunistic assemblages of vertical-dwelling structures and fair-weather deposit-feeding or grazing structures. Vertical structures dominate where storm beds comprise the bulk of the facies association. The landward side of the estuary mouth complex shows high degrees of burrowing, characterized by stresses similar to those of the central basin. The estuary mouth appears less affected by salinity fluctuations than the central basin, although this is difficult to determine with any certainty. The channel fill complex shows a dominance by *Skolithos*, *Cylindrichnus*, and *Ophiomorpha*. Migrating megaripples pose a severe difficulty to infaunal organisms, since progressive avalanching of sand down the slip face of the bed form

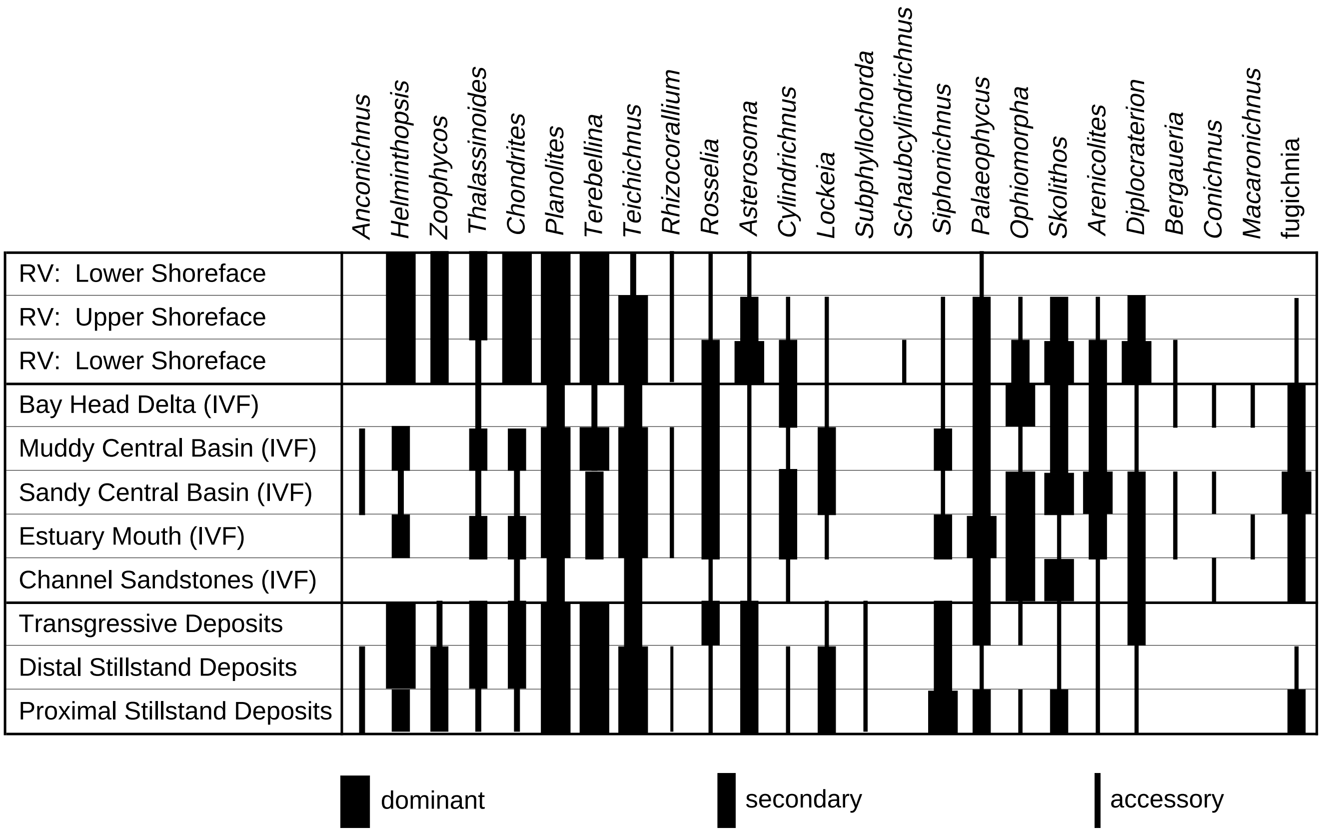


Figure 23. Trace-fossil distributions in Viking Formation depositional complexes. The chart is separated into three main zones; those associated with facies in the regional Viking parasequences (see Figure 11), those related to the various depositional complexes within estuarine incised valley fills (see Figure 22), and those associated with facies of the high-energy flooding-surface bounded parasequences (see Figure 15).

tends to bury the entrance to the dwelling structures, and the noncohesive shifting nature of the substrate precludes effective deposit-feeding or grazing behavior. Only elongate shafts and deeply penetrating, branching networks of dwelling structures are suited to these dynamic settings. The remainder of the suite corresponds to the muddy interlaminae, recording pauses in the migration of the bed forms. These assemblages contrast markedly with those of the regional highstand parasequences and those of the seaward side of the estuary mouth (Figure 23), which are characterized by fully marine equilibrium (K-selected) suites. The fully marine suites are typically uniformly burrowed, with intense degrees of burrowing and uniform distribution of individual elements.

CONCLUSIONS

The main applications of ichnology to sequence stratigraphic analysis are twofold. The most obvious use is in the demarcation of erosional discontinuities having a significant temporal break between the eroding event and the successive depositional event. To date, substrate-controlled ichnofacies have been underutilized as a means of recognizing and mapping stratigraphically important surfaces in outcrop and subsurface. Locally, many surfaces are obvious on the basis of sedimentology alone; however, the character of such surfaces can change markedly with geography, making correlation difficult. The *Glossifungites* ichnofacies is proving to be exceedingly important in the recognition and genetic interpretation of erosional discontinuities in marine-influenced siliciclastic intervals, corresponding to sequence boundaries, high-energy FS, and FS/SB surfaces. Many of the examples cited in this paper deal with their applications to the Cretaceous of the WCSB, but clearly the ichnological applications transcend geography and, to a lesser degree, age.

In many cases, the interpretation as to the genesis of the sequence stratigraphic surface has come principally from the ichnofossil assemblage associated with the underlying deposits, the discontinuity itself, and the overlying units. In other cases, stratigraphically significant surfaces have required re-interpretation as to their genesis; however, the recognition of the surface as a major break in the rock record has not changed. Ultimately, this remains the essential element in any genetic stratigraphic analysis. The continued integration of substrate-controlled ichnofacies with detailed stratigraphic and sedimentologic analysis will undoubtedly enhance and refine developing sequence stratigraphic paradigms.

The second use is more subtle and is concerned with the environmental implications of the trace-fossil suites in general. Many of the genetic interpretations of stratigraphic surfaces hinge on the paleoenvironmental interpretation of facies over- and underlying the discontinuity. Ichnology is ideally suited to impart valuable data about the depositional environment not readily obtainable from lithofacies analysis. Ichnofossils, when used in conjunction with sedimentary structures, are unequalled in the delineation and interpretation of facies and facies associations. When this twofold ichnological procedure is integrated with other sedimentologic and stratigraphic analyses, the result is a powerful new approach to the recognition and genetic interpretation of sequence stratigraphic surfaces and their associated systems tracts.

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