The Ichnology of Modern and Pleistocene Brackish-Water Deposits at Willapa Bay, Washington: Variability in Estuarine Settings

MURRAY K. GINGRAS, S. GEORGE PEMBERTON, and TOM SAUNDERS
The Ichnology Research Group, 1–26 E.S.B., University of Alberta, Edmonton, Alberta T6G 2E3, Canada

H. EDWARD CLIFTON
CONOCO Inc., 600 North Dairy Ashford, Houston, TX 77252-3197

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Detailed analysis of modern and Pleistocene deposits at Willapa Bay, Washington concentrated on identifying ichnological and sedimentological characteristics of five estuarine subenvironments. These include: (1) intertidal flat deposits, which are typically thoroughly bioturbated by a somewhat diminutive suite of various vertical and horizontal shafts and burrows that are locally cross-cut by robust crustacean dwellings; (2) unburrowed to rarely burrowed tidal creek point-bar deposits, which are sporadically burrowed by minute Gyrolithes, Skolithos, Cylindrichnus, Planolites, Palaeophycus, and rare bivalve equilibrichnia; (3) fluvially- through tidally-influenced main point-bar deposits, which are sporadically bioturbated with vertical traces superimposed upon inclined heterolithic stratification; (4) well to thoroughly bioturbated bay deposits, burrowed by relatively robust forms of Ophiomorpha, Teichichnus, Skolithos and bivalve equilibrichnia; and (5) locally bioturbated channel-bar deposits, typically displaying robust bivalve equilibrichnia, rare Ophiomorpha, and deep-penetrating Skolithos. Traces from both the modern and ancient deposits display a marked reduction in size and diversity in the upper estuary.

Ongoing research at Willapa Bay confirms the validity of the brackish-water model and provides data that potentially improve our understanding of these deposits. Our findings suggest that strong textural controls are overprinted by salinity stresses; commonly vertical deposit-feeding structures, made by infauna that are mining and/or stoking organic-rich laminae, are present; and there is a potential for the presence of large diameter crustacean burrows in brackish deposits. This research emphasizes ichnologic variability due to autocyclic changes and climatic variability, and urges caution when integrating ichnologic and sedimentologic data into a genetic stratigraphic model.

INTRODUCTION

Research Rationale

Ichnology has been employed widely to assist in identifying brackish-water deposits. Several notable core studies underscore the utility of ichnology when applied to ancient estuaries (e.g., MacEachern et al., 1992; Pemberton and Wightman, 1992). However, there is a marked paucity of outcrop and actualistic studies in the recent literature.

This is particularly unfortunate as the recognition of lateral variation and the identification of key subenvironments provide the tools needed for resolving complex geographic problems, predicting compartmentalization of potential reservoirs, and identifying pool-edge indicators in the subsurface. Outcrop-based studies and an understanding of modern estuarine processes may provide some of the solutions to these complex geological puzzles.

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

This paper focuses on the ichnologic characteristics of five subenvironments: (1) intertidal flats; (2) intertidal point bars; (3) fluvially- through tidally-influenced main point-bar deposits; (4) subtidal, laterally-accreted mid-channel tidal bars; and (5) quiescent central bay deposits. Both modern and Pleistocene examples are utilized, lending insight into the taphonomy of traces in IVF. Studies at Willapa Bay were also designed to test whether archetypal ichnofacies could be consistently applied to ancient estuaries and bays. The aim of this research is to establish whether predictable exceptions to the ichnologic brackish-water model are present in modern bays and how they might enhance the interpretation of the rock record.

The Brackish-water Model

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

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

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

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

**Setting**

Willapa Bay, located in the southwest corner of Washington (Fig. 1), is separated from the Pacific Ocean by the North Beach Peninsula, a 27-km-long spit derived from sand transported from the mouth of the Columbia River. Five river systems discharge into Willapa Bay, from the south, east, and north margins, complicating facies distribution within the estuary. The bay is sheltered from oceanic waves by the North Beach Peninsula and Willapa Bar, a set of shoals at the bay mouth. Also, Willapa Bay is a mesotidal estuary with a tidal range of 2 to 3 m. Tremendous water exchange occurs in the bay, and the tidal prism, which exceeds 700,000 m³, comprises about 45% of the bay's total volume (U.S. Army Corps of Engineers, 1975). This volume is by no means constant. The maximum exchange occurs during spring tides, whereas neap tides proffer a much smaller tidal prism. The bay becomes somewhat 'stagnant' with the neap tides, affecting the food-resource, oxygenation, and salinity levels on a monthly and yearly basis (L. Bennet, pers. comm., 1997).

![Figure 1](image-url) - Location map of Willapa Bay, Washington. The right frame details Goose Point and the Palux River, an area of focused modern and ancient ichnological study.

Longer-term climatic patterns, such as El Niño, have a similar effect.

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

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

The younger Pleistocene strata have been divided into 5 units (I through V, Fig. 2). Unit I is primarily a muddy accumulation that has been interpreted to indicate deposition in intertidal and uppermost subtidal environments (Clifton et al., 1989). Both intertidal flat and intertidal creek point-bar deposits have been identified in Unit I. Unit II, in contrast, is comprised mostly of sand. Clifton et al. (1989) compared this to the central channel of the modern bay. Unit III is typically muddy and contains abundant organic detritus. Locally cross-cutting Units I and II, Unit III has been interpreted as being primarily alluvial and is indicative of a basinwards shift of facies (Clifton et al., 1989). The most widespread interval in the younger...
Pleistocene deposits is Unit IV. It outcrops almost continuously from Goose Point to Pickernell Creek (Fig. 1), except where it is truncated by Unit V. Unit IV is lithologically variable, consisting of two facies types: unstratified fossiliferous muds and stratified mud and/or sand (Clifton et al., 1989). Locally, unstratified sand and fossiliferous sand are observed, particularly in the vicinity of Johnstone Beach. The ubiquity of the oyster Ostrea lurida in Unit IV reflects that it was deposited subtidally and, based on further sedimentologic and stratigraphic evidence, was probably deposited partly in the trough of a broad bay and partly in tidal channels (Clifton et al., 1989). Unit V is a channelized deposit typically containing gravelly beds and unstratified and stratified mud. Rhythmic sedimentation patterns suggest tidal influence; an absence of burrowing, however, reflects deposition accompanied by extreme salinity stress. Unit V is primarily fluvial (Clifton et al., 1989).

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

Methods

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

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

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

MODERN AND ANCIENT DEPOSITS AT WILLAPA BAY, WASHINGTON

Common Tracemakers at Willapa Bay

A number of organisms leave distinctive traces in the sediments of Willapa Bay. Figure 3 details some of the most common burrowers, many of which display a strong preference for muddy or sandy substrates, although much overlap is evident in substrate selection (Fig. 3). The burrow architectures are varied and many are potentially analogous to common trace fossils. The most common tracemakers include Skolithos- and Gyrolithes-like burrows, which are made by a number of burrowers including Saccoglossus (an entrepeneust), maldanid polychaetes, Heteromastus (a capitellid polychaete), and more rarely Nereis (Fig. 3). Cylindrichmus-like burrows also are constructed by maldanid worms, whereas terebellid polychaetes commonly construct a Rosselia-like structure at the ends of their parchment-lined U-shaped burrows. This latter observation confirms Masakazu’s (1995) speculation that terebellids might construct such structures. Planolites and Palaeophycus structures typically represent the work of the polychaetes Nereis or Neptys (Fig. 3); sections of Saccoglossus or Heteromastus burrows may invoke a similar interpretation. Decapod crustaceans, such as Upogebia pugnans and Callianassa californiensis, commonly construct Thalassinoides- or Ophiomorpha-like burrows (Fig. 3). Diplacatopora and Arenicolites structures are utilized by the spionid worm, Polydora, and the amphipod Corophium.

Figure 3 indicates which burrows are transient, or occupied for a short time, and which are used by the organism for much of its life cycle. More transient burrows are relocated often and, although the trace itself may have lower preservation potential, their producers potentially bioturbate the substrate to a higher degree. The illustration therefore relates taphonomic considerations to the burrowing assemblage.
That contain Macaronichus (Clifton and Thompson, 1978).

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

Biogenic reworking on the intertidal flat is extensive. Radiographs of cores retrieved from both sandy and muddy intertidal flat deposits show that, as the sediment passes into the historic record, primary sedimentary structures are all but obliterated (Fig. 5). In muddier deposits, a vestigial lamination may be preserved (Fig. 6). Below sediment depths of 10 to 20 cm, sandflat deposits are characterized by the absence of physical sedimentary structures. An exception to this is the presence of lamination produced by rapidly aggraded run-off channels (Fig. 7A). Resulting ichnofabrics are typically dominated by crustacean burrows, or appear massive (ichnofabric index, i.e. 6) due to extensive biogenic reworking.

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

Although striking lateral variability exists between the upper, middle, and lower intertidal zones, they are complex and not easily summarized. In both muddy and sandy intertidal flats, the depth and intensity of burrowing is
FIGURE 5—Various mudflat radiographs. (A) Radiograph of modern intertidal sandflat. The sand is ripple laminated to a depth of approximately 13 cm. Lamination is destroyed and replaced by a zone of cryptic bioturbation (Cr) at about the depth of the U-portion of the lugworm burrow (Ar). *Thalassinoides* (Th?) is detailed on the left side of the frame. The lugworm, *Abernicola*, is visible in its burrow. (B) Radiograph of a robust terebellid burrow from a modern mudflat at Willapa Bay. Primary sedimentary structure is absent due to intense reworking. *Rosellina*-like lamination is visible near the top of the photo (Ro), and a *Gyrolithes*-like *Saccoglossus* coil is also present (Sa). Other burrows include *Chondrites* (Ch?), *Palaeophycus* (Pa), and *Planolites* (Pl). (C) Radiograph of an extremely stressed assemblage of mudflat burrowers from Teal Slough, Willapa Bay. Primary sedimentary structure is eroded below 4 cm depth, even though the bioturbation results from only two burrowers, *Nerites* (the visible burrows) and *Heteromastus* (barely visible vertical threads).
highest in the lower intertidal zone, which is consistently dominated by burrowing shrimp, most commonly Callianassa or Upogeobia. Other burrowers include threadworms, Nereis, Nephtys, and various bivalves, notably Mya, Macoma, and Cryptoma. Subtidal organisms, such as Dungeness and sturgeon, venture into this zone during the high tide. Their search for food is documented by locally abundant feeding pits, which give the lower intertidal a pitted appearance. Traces generated by shrimp commonly extend 60 cm into the substrate and constitute the dominant component of the observed ichnoocoenose.

The middle intertidal zone is distinguished by medium- to large-sized burrowing bivalves, including Macoma balthica and Tresus nuttalli. Burrowing worms such as Nereis, Nephtys, Scrogielos, Heteromastus, lugworms (particularly in sand-dominated flats), and terebellid polychaetes are typically present, generating an array of trace forms. Grazing fauna, such as the barrel snail (Rictatus punctocaelatus), are more common, and burrowing shrimp are absent to common (up to 110 individuals / M²) and unevenly distributed in this zone.

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

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

As with the modern, Pleistocene intertidal flats are reworked extensively and their bedding is massive to crudely defined by continuous horizons of silt- and sand-filled burrows (Fig. 6). Primary sedimentary structures are rarely preserved, but may include planar bedding, graded laminae, ripple and starved ripple lamination. Organic detritus is locally abundant, including wood fragments and transported rhizomes. Burrows are typically small (1 to 4 mm in diameter) and biogenic disruption is pervasive. Discrete burrows are locally discernible and are commonly limited to the ichnofacies Skolithos, Arenicolites, Gyrolithes, Cylindricalus, Planolites, and Palaeophycus. In outcrop, Skolithos, Gyrolithes, Planolites, and Palaeophycus are evenly distributed; Arenicolites and Cylindricalus are sporadically distributed, generally in closely spaced packages of 2 or more trace fossils along bedding surfaces. Crustacean burrows are present sporadically, attaining notable abundance (> 80/m²). These traces are comprised of relatively large (> 1 cm in diameter) Thalassinoides. Crab burrows also are abundant locally, typically infilled with a crudely laminated, passive infill. Where present, the crustacean burrows overprint the background bioturbate texture and typically represent the deepest tier of mudflat burrows.

Ancient sandflat deposits are most common in the older Pleistocene strata at Willapa Bay. Two examples include the Pleistocene exposure adjacent to the Bruce Port historical marker on Highway 101 and the outcroppings near Pickermill Creek (Fig. 1). At these locations, massive to crudely bedded sand is intercalated with rare mm-scale mud beds. The deposit is intensely cross cut by sift- and sand-filled run-off channels (Fig. 7). Bioturbation consists primarily of medium- to large-sized bivalve traces (equilibrichnia and Siphonichnus), medium-sized Ophiomorpha and Thalassinoides, passively-infilled crab domiciles, and diminutive Planolites and Skolithos. As a whole, smaller trace fossils are absent, probably due to extensive reworking of the deposit by larger burrowers and preservational bias in coarser-grained clastic deposits.

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

**Interpretation of Tidal Flat Deposits**

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

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

Modern and Pleistocene deposits are remarkably similar in many respects. Both are strongly bioturbated and exhibit a paucity of physical sedimentary structures. Planolites, Palaeophycus, Arenicolites, and Skolithos in ancient deposits form ichnofabrics similar to fabrics from the modern (Figs. 5B, C, and 6). Certain trace fossils, such as Ophiomorpha, Thalassinoides, and Cylindrichnus, are morphologically similar to burrows made by the modern trace makers, Upogebia, Callianassa, and maldanid polychaetes. No example of Rosselia has yet been documented.

FIGURE 8—Relationships of intertidal point bars to intertidal flats and the radiographic fabric of intertidal point-bar deposits. (A) Intertidal flats, cutbanks, and point bars near the Bone River at Willapa Bay. Intertidal flat bedding (i.f.) and point-bar bedding (p.b.) are visible in the cutbank. Progradation of the intertidal flat over the point bar allows reworking of the upper portion of the point-bar deposit. (B) X-ray image of modern intertidal point bar, from about the middle of the point bar. The degree of reworking may be high, but vestigial limestone is more apparent than in intertidal flat deposits. The burrows are almost exclusively comprised of small Planolites, Palaeophycus (Pa), Skolithos (Sk), and Gyrolithes (Gy?). No large burrows are present.

FIGURE 7—Various sandflat perspectives. (A) Pleistocene sandflat deposit intercalated with laminated, lens-shaped, silty runoff channels. Large bivalve traces are present, and locally, the animal's siphonate passage is visible. Adjustments to sediment influx are visible below the bivalves indicated by the dashed black rectangle. A magnification of this zone is inset lower left. The bivalves appear to have ascended in pulses, likely in relation to variations in sediment-accumulation rates. The persistence of silty substrate increases upwards, possibly due to progradation of the intertidal flat. (B) Radiograph of ripple cross-laminated sand with abundant Paraonis spirals (black arrows). The spirals are connected to the surface with thin vertical shafts, which are visible near the top of the image. Paraonis and other threadworms disrupt sands and are capable of generating a form of diffuse, cryptic bioturbation. (C) Ophiomorpha eroding out of an intertidal cutbank. These burrows are the result of sand shrimp (Callianassa calliometriosa) colonizing the sand flat. Their capacity for overturning the substrate is evidenced by the undulatory appearance of the sandflat. Sand ejected from the burrow is reworked into small hummocks and ripples during the high tide. A subaqueous dune is visible in the background. Shrimp burrows are visible on these migrating dune forms as well. The black arrows indicate pelletized burrow apertures (Ophiomorpha) weathering out of the substrate (Op).
from the Pleistocene deposits. Stratigraphic thickness in the Pleistocene is variable, but generally 1-to-2.5-m-thick packages are preserved. The thickness of modern deposits ranges from a few centimeters, above wave-ravined Pleistocene firmground, to more than 2.6 m.

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

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

In the modern, intertidal deposits clearly pass into the historic record. This is particularly true in muddy substrates in which meander rates are relatively slow (Fig. 8). Conversely, in somewhat sandy flats, robust intertidal communities are truncated by rapid intertidal creek migration, biasing the intertidal record towards the deepest-tier traces. The rapid meandering of tidal creeks in sandy substrates is, however, countered by high rates of biogenic reworking. Sandy intertidal flat deposits reflect this balance, preserving completely bioturbated horizons intercalated with run-off channels that appear to have rapidly aggraded and, thus, were spared biogenic eradication (Fig. 7A).

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

Point-bar Deposits

Modern Tidal Creek Point-bar Deposits

Modern intertidal flats are commonly truncated by complex networks of meandering intertidal creeks, particular-

![Figure 9](image-url) - Schematic detail of an intertidal point-bar assemblage (substrate is muddy sand to sandy mud) at Willapa Bay. The burrowers shown represent the dominant trace makers present in an intertidal point-bar at the bay. The lower, more stressed portion of the point bar has the highest preservation potential (below the dashed line). A legend for the biogenic structures is present in Figure 3.

ly in substrates with notable silt or mud content. Associated with these channels are numerous point-bar deposits (Fig. 8A). Depending on the texture of the intertidal flat sediment, these point bars may have a high preservation potential. Dominantly muddy flats inhibit the rate of channel meandering, limiting the distribution of point bars, whereas sandy substrates are rapidly reworked by the sand-flat biota. Intermediate substrates therefore proffer the greater likelihood of passing intertidal point-bar deposits into the geologic record.

Modern intertidal point bars at Willapa Bay typically are burrowed by an extremely low-diversity assemblage of diminutive infauna (Fig. 8B). Threadworms, such as the capitellid polychaete *Heteromastus*, are among the most common burrowers. *Heteromastus* burrows consist of vertical shafts 10 to 30 cm deep, with numerous horizontal to subhorizontal branches. The terminus of the burrows generally ends in a *Gyrotholithes*-like coil, the axis of which is oriented randomly. Other trace makers include *Nereis*, the small amphipod *Corophium*, and juvenile bivalves. The resulting trace suite is a low-diversity assemblage composed of diminutive vertical and horizontal burrows. This assemblage grades into the intertidal flat assemblage over 2 m on smaller point bars (fourth-order channels) and up to 8 m on larger point bars (first- or second-order channels). Figure 9 illustrates the gradational relationship between the intertidal point-bar and tidal flat ichnofaces.

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

Pleistocene Tidal Creek Point-bar Deposits

Ancient intertidal point-bar deposits are present locally in Unit I. Like their modern counterparts, they are com-
to those described herein from the modern tidal creek point bars, except that the overall degree of bioturbation is higher in the Pleistocene strata (Fig. 10). Pebbles and wood debris overlie the sharp lower contact of these deposits; disarticulated bivalve shells are present locally, but not with the ubiquity of analogous modern environments.

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

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

The main channel point-bar depositional environment is common at Willapa Bay. Due to their association with fluvial tributaries, they exhibit notable ichnological, chemical (most notably salinity), and textural variability. As the major supply of coarser clastic detritus comes into the bay through its inlet, sandy deposits tend to be situated near the lower reaches of the estuary. The upper reaches, on the other hand, are typically characterized by silt and mud. In the upper estuary, salinity fluctuations and low background salinities contribute to extreme salinity stress (Fig. 11). Figure 11 outlines the different burrowing taxa (diversity) and quantifies diminution of trace forms, as the point bars are traversed in an up-estuary direction. In the lower reaches of the Palis River (stations 1 and 2), 12 burrowing taxa are commonly observed. Typical burrow diameters range between 3 to 15 mm. At station 4, only 7 taxa are noted, with average burrow diameters falling between 1 and 3 mm. Station 5 is characterized by 5 common burrowers, all of which produce burrows less than 2 mm in diameter.

Muddy point bars typically exhibit low-diversity assemblages that are comprised primarily of diminutive traces. Trace makers include Heteromastus, Corophium, Nereis, juvenile Mya, and Hemigrapsus. The resulting ichnocoenosis is strongly tiered and consists of shallow Arenicolites, moderate-depth (~1–10 cm) siphonate passages, and deep-penetrating (up to 28 cm) Skolithos and Gyrolithes (Fig. 12). Radiographs of modern deposits indicate that the deepest-tier burrows overprint shallow burrows and are preferentially passed into the historic record (Fig. 13).

Physical sedimentary structures include planar lamination, graded bedding, and starved ripple lamination (Fig. 13). Bedding is primarily defined by mud and silt laminae, although fine-grained sand laminae are present locally. The deposit is rich in organic detritus, with TOC measurements falling between 6 and 9%; wood clasts are abundant throughout the point-bar deposit. In situ, articulated bivalve shells and imbricated, disarticulated valves along bedding planes are rarely present. The lower contact is erosional and, commonly, a woody, shelly lag has accumulated in the channel adjacent to the point bar.

Sand to muddy sand deposits exhibit a more diverse assemblage of trace makers (Fig. 13). Callianassa colonize the point bar from the middle intertidal zone down to its...
Pleistocene Fluvially- and Tidally-Influenced Main Channel Point-bar Deposits

Pleistocene subtidal point-bar deposits contain variable trace assemblages that appear to be, at least in part, texturally controlled. Dominantly muddy or silty accumulations are characterized by low-diversity suites of small trace fossils. Most commonly, deformed Gymrilithes, Skolithos, Planolites, Palaeophycus, and Arenicolites comprise the trace fossil assemblage. Rare Ophiomorpha and Thalassinoides are present locally. Large, passively-infilled burrows, interpreted to represent the dwelling structures of robust crustaceans (such as crabs) and are therefore comparable to Psilonichnus, are rare to locally moderate, and are typically observed along the lower portions of the point-bar deposit. Overall, the degree of bioturbation is low, and traces are sporadically distributed. Physical sedimentary structures include planar lamination, graded bedding, starved current-ripple lamination, and local current scours. Organic detritus is abundant, particularly woody debris. Bivalve casts are present locally and some bedding-plane exposures show excellently preserved Lockeia (Fig. 15A).

Sandy subtidal point bars, such as those present in older Pleistocene outcrops near the Bone River (Fig. 15B), contain a more diverse array of lebensspuren. The suite is similar to the assemblage in muddy subtidal point bars, with the addition of more abundant Cylindrichnus and Monocraterion. These traces tend to occur in clusters of 3 to 5 shafts. Also, Ophiomorpha and Thalassinoides are most commonly observed in the sandier units. Passively-infilled, unlined burrows (attributed to a Hemigrapsus-like trace maker) are locally common. Physical sedimentary structures include abundant flaser, wavy, and lenticular bedding. Bedding is defined by abrupt changes in grain size (silt to fine- or medium-grained sand), indicative of seasonal changes in sediment supply (Clifton et al., 1989). Organic detritus is comparatively less abundant, although unbored wood clasts are observed locally. The lower contact of these deposits is erosional and is typically demarcated by intraformational rip-up clasts, pebbly lags, and concentrations of woody or shelly debris.

In summary, the Pleistocene deposits at Willapa Bay are comparable to the modern deposits. Sedimentological and ichnological similarities are particularly clear when deposits of like texture are compared.

Interpretation of Point-bar Deposits

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

Trace fossils in muddy point-bar deposits are sporadically distributed and degrees of bioturbation vary between unburrowed to locally moderate. With the exception of rare Ophiomorpha and Psilonichnus, the trace fossils are diminutive, ranging between 1 and 3 mm in diameter and...
include Gyrolithes- (relatively abundant), Planolites- (abundant), Palaeophycus-, Cylindrichnus-, Teichichnus-, Monocraterion-, Skolithos-, and fugichnia-like traces in rare to moderate abundance. These traces are similar to those observed in other brackish-water deposits (Howard and Frey, 1973, 1975; Pemberton and Wightman, 1992). Several parameters may have played a role in limiting the size and diversity of burrowing infauna. They include lower levels of salinity or fluctuating salinity, oxygenation stress, turbidity stresses, rapid rates of sedimentation, and thermal stresses. Salinity is strongly correlated to diminution of infauna and overall reductions in diversity (Fig. 11). Salinity fluctuation and overall low salinity appear to place limitations on the size of burrowing fauna in this environment. Contrasting burrow assemblages in sandy versus muddy substrates are due to two factors; different substrates are exploited in strikingly different manners, and sand and mud present dissimilar taphonomic barriers. This relationship is similar to Dorjes and Howard's (1975) observation in the Ogeechee Estuary on the Georgia Coast. They found that 6 estuarine biofacies exhibited similar distributions as five mapped sedimentary facies. This is partly attributable to passive links between salinity and texture. The authors noted "physical energy and the salinity probably (our italics) play major roles in determining similarities between the physical and biogenic records." Extracting ancient relative salinity stress from the rock record is therefore a daunting, but resolvable challenge. Furthermore, a strong behavioral dependence on substrate texture implies that ichnologic changes within similar lithofacies provide more information than comparing trace assemblages between lithofacies.

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

Taphonomic considerations also are reflected in the preserved trace fossil assemblage. Most of the observable traces are filled with silt or fine-grained sand, and tend to descend from the coarser-grained laminar components of the point-bar deposits. They are typically deformed due to syn- and post-depositional compaction of the sediment. Deep-penetrating burrows (> 25 cm) descend into somewhat compacted mud, and are less likely to undergo severe post-depositional deformation. These traces overprint the more subtle and deformed shallow traces, lending an even more impoverished appearance to the trace assemblage. This bias is exaggerated because shallowly tiered traces are more vulnerable to erosion and may be removed by scouring currents. The deep burrows have the greatest probability of being passed into the historical record (in this case, the Skolithos- and Gyrolithes-like burrows of Heteromastus, and the Thalassinoides-like burrows of Neotrypea).

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

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

Sandy, Laterally Accreted Mid-Channel Tidal Bars

Modern Tidal Bars

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

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

Pleistocene Tidal Bars

Pleistocene mid-channel tidal bar deposits exhibit many of the same sedimentological characteristics noted in the modern deposits. An excellent example is present at the South Bend Section (Fig. 16), where the overall degree of bioturbation is low (i.e. 1 to 2). Nevertheless, sporadically distributed Ophiomorpha, Thalassinoides, Teichichnus, Palaeophycus, and Siphonichnus are present throughout the section (Fig. 16B). These are of intermediate size, typ-
rare. Rare heavy minerals, usually augite or magnetite, are present along the toesets of the cinoforms. Cinoformed packages have an erosional base and exhibit a gradual thinning upward trend; they range in thickness from 3 to 4.5 m.

Interpretation of Sandy Channel Bars

Of the Pleistocene deposits present at Willapa Bay, sandy channel bars lend themselves best to an archetypal (i.e., Seilacherian) ichnofacies classification. The presence of Ophiomorpha, deep-penetrating Skolithos, Thalassino- ides, Teichichnus, and abundant threadworm tubes (Fig. 16C) are indicative of the Skolithos Ichnofacies. The Skolithos ichnofacies is associated with rapidly shifting substrates in moderate to high-energy hydraulic regimes. This interpretation is supported by the physical sedimentary structures, which include current ripples, trough cross bedding, planar-tabular cross bedding, and upper-flow-regime planar bedding. These structures typically are superimposed on, and are indicative of current directions perpendicular to, the laterally accreted cinoforms.

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

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

Subtidal, Quiescent Bay Deposits

Modern and Pleistocene Subtidal Bay Deposits

The present configuration of Willapa Bay is dominated by large tidal channels. Quiescent deposits, sheltered from tidal currents and wave energy, are rare in the modern bay. An exception is the area just southeast of Grass Island (Fig. 1). Here, the moderately sorted sandy substrate is completely bioturbated and colonized by dense popula-
FIGURE 16—The Southbend section, interpreted to represent a succession of migrating tidal mid-channel bars. (A) Outcrop of migrating, sandy clinoforms at the Southbend outcrop. (B) Robust Ophiomorpha nodosa (Op) descending from a clinoform surface. (C) Vertical threadworm burrows, possibly representing the central axes of Paraonis spirals (arrow). (D) A horn-shaped polychaete tube (arrow) similar to the ichnofossil Terebellina (nomen nudem).
tions of large Callianassa (> 250 burrow openings/m²). Robust polychaetes (Nereis, Glyceria, Nephtys) and bivalves are also commonly observed, although their population densities were not assessed. A number of smaller threadworms are ubiquitously distributed throughout the substrate. The most conspicuous traces include Ophiomorpha- and Thalassinoides-like burrows, which overprint a mottled fabric comprised of horizontal and subvertical deposit-feeding structures.

Pleistocene deposits are similar in many respects. Large Ophiomorpha and Thalassinoides are common, crosscutting a suite of smaller deposit-feeding trace fossils, such as Planolites and Teichichnus (Fig. 17). Locally, Psilonichnus-like burrows, interpreted to represent the domiciles of burrowing crabs, are the dominant crustacean burrows (Fig. 17). Siphonichnus and bivalve adjustment traces are sporadically distributed and locally absent. The degree of bioturbation is typically moderate to high, and primary sedimentary structures are commonly obliterated. Where the physical sedimentary structures are preserved, they consist of horizontal lamination, wavy lamination, and low-amplitude ripple forms. These ancient accumulations are generally muddy, although sandy deposits are present in Units 2 and 4. Wood and shell debris is dispersed sporadically. Articulated bivalves may be present; most abundant are the shells of the native oyster, Ostrea lurida, which form lenticular beds locally. These in situ oyster beds are most abundant in strata that, uncharacteristically, are rarely bioturbated.

**Interpretation of Subtidal Bay Deposits**

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

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

Somewhat perplexing is the presence of thin oyster beds in laminated, unburrowed, fine-grained sediment. The oyster, Ostrea lurida, is only moderately tolerant of turbid conditions and, compared to certain burrowing polychaetes, is not particularly hardy. Laminated and unburrowed silt and mud reflects mainly turbid conditions. The presence of a turbid water column is contradictory when juxtaposed with in situ oyster beds. Ostrea lurida and other oysters are primarily filter feeders and are overwhelmed by exceptionally turbid water. The absence of trace fossils indicates extreme physico-chemical conditions were present when these strata were deposited. Ultimately, the question becomes, if oysters are present, why are the traces of their stawlart invertebrate associates not evident? All of the evidence implies that the deposition of

**FIGURE 17**—Radiograph of Pleistocene quiescent bay deposit. Note the large burrows cross cutting the small-burrow-mottled background fabric. Larger burrows include those of shrimp (Ophiomorpha, Op) and crabs (Psilonichnus, Ps). Gyrothoes (Gy), Planolites (Pl), and Palaeophycus (Pa) are also shown.
laminated silt and mud was intermittent, allowing lenticular oyster beds to develop in channels and protected bays. Perhaps this is indicative of shifts of the bay's turbidity maxima. Such a shift would likely have to endure several seasons to permit colonial oyster growth. Burrowing might have been inhibited by the development of oyster beds, which precluded the development of an infaunal community below their densely packed shells. This relationship is certainly reflected in the modern bay, where infauna is notably sparse below well-developed mounds of *Crassostrea*.

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

**DISCUSSION**

**Variability in Estuary Deposits**

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

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

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

**Assessment of the Brackish Water Model**

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

Generally, the brackish-water model applies equally well in the modern and Pleistocene deposits at Willapa Bay. Diminutive examples of typical brackish-water forms are present in low-diversity assemblages in every depositional environment, except sandy, laterally accreted channel bars. The notable exception to the aforementioned parameters is the potential presence of robust crustacean traces overprinting typical brackish-water assemblages (Fig. 11). These assemblages, which are common to some
<table>
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<th>Physical Structures</th>
<th>Lithology/Accessories</th>
<th>Contacts/Thickness</th>
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<tr>
<td>Modern Muddy Intertidal Flat</td>
<td>Upogebia, terebellid, Saccoglossus, mal- daniad, various bivalves, Heteromastus, Nereis, Corophium, Nephtys</td>
<td>Moderate to Complete (4, 5, 6)</td>
<td>Typically Vestigial Horizontal Bedding</td>
<td>Organic detritus, oxide stain, shell debris, 50–60% &lt; 4 Φ sand fine to very fine</td>
<td>Gradational/burrowed with intertidal point-bar; undetermined thickness</td>
</tr>
<tr>
<td>Modern Sandy Intertidal Flat</td>
<td>Callianassa, Arenicola, Saccoglossus (r), maldanid (r), Ma- coma, Heteromastus, Nereis, Corophium, Nephtys</td>
<td>Low or Complete (1 or 5, 6)</td>
<td>Ripple Lamination, Low-angle Lamination, Thin Bedded, Scour-and-fill Run-off Channels</td>
<td>Rare organic detritus, approx. 80% 1 to 3 Φ</td>
<td>Abrupt to gradational with intertidal point-bar; undetermined thickness</td>
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<tr>
<td>Pleistocene Muddy Intertidal Flat</td>
<td>Skolithos, Arenicolites, Gyrolithes, Cylindrichnus, Planolites, Palaeo- physicus, Thalassinoides, Pisolithus (r)</td>
<td>Moderate to Complete (4, 5, 6)</td>
<td>Typically Vestigial Horizontal Bedding</td>
<td>Abundant organic detritus, fine sand lamination, approx. 60 to 80% &lt; 4 Φ</td>
<td>Gradational/burrowed with intertidal point-bar; 1 to 3 m thickness</td>
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<tr>
<td>Pleistocene Sandy Intertidal Flat</td>
<td>Skolithos, Arenicolites, Planolites, Palaeophycus, equilibrichnia, Thalassinoides, Ophiomorpha (r)</td>
<td>Low or Complete (1 or 5, 6)</td>
<td>Locally Massive-appearing, Ripple Lamination, Low Angle Lamination, Thin Bedded, Scour-and-fill Runoff Channels</td>
<td>Abundant organic detritus, fine sand lamination, fine to medium sand (visual est.)</td>
<td>Gradational/burrowed with intertidal point-bar; 2 to 3 m thickness</td>
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<tr>
<td>Modern Intertidal Point-bar</td>
<td>Various juvenile bivalves, Heteromastus, Nereis, Corophium, Nephtys</td>
<td>Absent to Moderate (1, 3)</td>
<td>Ripple Lamination, Low Angle Lamination, Inclined Bedding, Soft Sediment Deformation</td>
<td>Terrestrial organic detritus, TOC 5 to 8%, thin sand lamination, approx. 50% finer than 4 Φ</td>
<td>Soured lower contact demarcated by shells and wood; 1 to 3 m thick</td>
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<tr>
<td>Pleistocene Intertidal Point-bar</td>
<td>Planolites, Palaeo- physicus, Skolithos, Arenicolites, Gyrolithes</td>
<td>Absent to Moderate (1, 3)</td>
<td>Ripple Lamination, Low Angle Lamination, Inclined Bedding, Soft Sediment Deformation, Mud Couplets, Rhythmic Bedding</td>
<td>Terrestrial organic detritus, TOC 1 to 6%, variable grain size, see text</td>
<td>Soured lower contact demarcated by shells and wood; several m thick</td>
</tr>
<tr>
<td>Modern Main Channel Point-bar (Sandy)</td>
<td>Various juvenile bivalves, Heteromastus, Upogebia, terebellid, Callianassa, maldanid, Nereis, Corophium, Nephtys</td>
<td>Low to Moderate (2, 3)</td>
<td>Ripple Lamination, Wavy to Flaser Bedding, Inclined Heterolithic Stratification (HHS), Trough Cross Stratification (Rash), Climbing Ripples</td>
<td>Terrestrial organic detritus, TOC 5 to 11%, thin sand lamination, variable grain size, see text</td>
<td>Soured lower contact demarcated by shells and wood; several meters thick</td>
</tr>
<tr>
<td>Modern Main Channel Point-bar (Muddy)</td>
<td>Various juvenile bivalves, Heteromastus, terebellid, maldanid, Nereis, Corophium, Nephtys</td>
<td>Low to Moderate (2, 3)</td>
<td>Ripple Lamination, Low Angle Lamination, Inclined Bedding (10 degrees), Current Indicators Normal to Inclined Bedding</td>
<td>Terrestrial organic detritus, TOC 5 to 11%, thin sand lamination, variable grain size, see text</td>
<td>Soured lower contact demarcated by shells and wood; several meters thick</td>
</tr>
<tr>
<td>Modern Sandy Laterally-accreted Mid-channel Tidal Bar</td>
<td>Clinoecdium, various interstitial threadworms Tre- sus nutalli (?), Callianassa, Cerebratula Nereis, Nephtys</td>
<td>Absent to Moderate (1, 3)</td>
<td>Starved Ripple Lamination, Pin Stripe Lamination, Inclined Stratification</td>
<td>Terrestrial organic detritus, TOC 5 to 11%, thin sand lamination, variable grain size, see text</td>
<td>Soured lower contact demarcated by shells and wood; several meters thick</td>
</tr>
<tr>
<td>Pleistocene Sandy Laterally-accreted Mid-channel Tidal Bar</td>
<td>Ophiomorpha, Thalassinoides, Tich- ichnus (Skolithos ichnofacies)</td>
<td>Absent to Rare (1, 2)</td>
<td>Ripple Lamination, Scour-and-fill, Inclined Bedding, Local Flaser to Wavy Bedding Rhythmic Bedding, Trough Cross Stratification</td>
<td>Organic detritus, oxide stain, rare mm-scale shelly debris, concentrations of heavy minerals</td>
<td>Sharp lower contact demarcated by shells and wood; meter-scale thickness</td>
</tr>
</tbody>
</table>
TABLE 1—Continued.

<table>
<thead>
<tr>
<th>depositional environment</th>
<th>common infauna/trace fossils</th>
<th>degree of bioturbation (ichnofabric indices)</th>
<th>physical structures</th>
<th>lithology/accessories</th>
<th>contacts/thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>modern quiescent bay deposit</td>
<td>Callianassa, various interstitial thread-worms Crassostrea, Nereis, Nephtys, Glyceria crabs</td>
<td>moderate to thorough (3, 6) locally absent (1)</td>
<td>ripple lamination (vestigial ?) planar lamination (vestigial ?)</td>
<td>organic detritus, woody debris, shelly debris, unconsolidated (texture varies)</td>
<td>contacts not observed; sharp to burrowed; lower contact several meters thick variable</td>
</tr>
<tr>
<td>Pleistocene quiescent bay deposit</td>
<td>Ophiomorpha, Thallasinoides, Teichichnus Ostrea lurida, Psilonichus, Planolites, Palaeophycus</td>
<td>moderate to thorough (3, 6)</td>
<td>ripple lamination (vestigial ?) planar lamination (vestigial ?)</td>
<td>organic detritus, oxide stain, rare woody and shelly debris (texture varies, typically 60% &lt; 4φ)</td>
<td></td>
</tr>
</tbody>
</table>

Bay deposits, illustrate that in certain brackish-water sub-environments crustacean burrows may be relatively large. In these situations, it is appropriate to consider the size and diversity of the primarily worm-burrowed background assemblage as being indicative of salinity stress. Why is the worm-burrowed suite apparently more sensitive to fluctuating and lower levels of salinity? This relates primarily to the evolutionary means by which the animal responds to reduced or fluctuating salinity. Salinity stress is coped with through physiologic, anatomical, morphological, and ecological innovation or through behavioral adaptation (Spaargaren, 1979, 1995). These strategies provide different adaptive landscapes for animals living in brackish-water environments.

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

Most likely, diminution of trace fossils as observed at Willapa Bay is a result of population dynamics as opposed to true morphologic adaptation. Powell and Stanton (1996), working at Copano Bay, Texas, separated the size-frequency distribution of bay populations into small- and large-size classes. They noted that under resource-stressed conditions the two size groups responded quite differently. Typically the large size class reached some fraction of their species optimal size (true diminution). Smaller-size organisms typically attained full growth for the species (Powell and Stanton, 1996) and their biomass was essentially unchanged. Conceivably, this relationship is similar to the salinity-stressed assemblages illustrated in Figure 11. The consistently smaller (worm) burrow diameters are species-specific. At station 1 and 2, robust turbinellids make the largest annelid burrows; the largest common worm burrows at station 3 are excavated by Saccoglossus; and Heteromastus perforates the muddy substrate at Stations 4 and 5 (Fig. 11). Interestingly, Heteromastus is also present at stations 1 through 3 and is identical in every respect (including size) to those observed at Stations 4 and 5 (Fig. 11). These data suggest that, although the burrowing population is comprised of increasingly smaller organisms, the individual species are not enduring size reduction.

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

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

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

**SUMMARY**

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

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

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

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

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

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**REFERENCES**


MACÆCHERN, J.A., and PEMBERTON, S.G., 1984, Ichnological aspects of incised-valley-fill systems from the Viking Formation of the Western Canada sedimentary basin, Alberta, Canada: in DALRYMP-


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