WIND/WAVE AND TIDAL PROCESSES ALONG THE UPPER DEVONIAN CATSKILL SHORELINE IN PENNSYLVANIA, U.S.A.

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ABSTRACT

To better determine the relative contributions of wind/wave versus tidal processes along the westward prograding Catskill shoreline of eastern North America, seven stratigraphic sections comprising the marine–nonmarine transition were measured along a NNE-SSW line across central Pennsylvania over a distance of 279 km. The interval includes the upper Lock Haven Formation and equivalents up to the base of the Sherman Creek Member of the Catskill Formation. Each section, excepting Entriken, yielded a *Diaphanospora reticulata* palynomorph assemblage, implying that six of the sections are isochronous and of middle Frasnian age. Thus, the shoreline lay along the NNE-SSW trend of the outcrop belt. The sections contain approximately similar vertical sequences, starting with thick intervals of olive-grey hackly mud shales with a sparse brachiopod fauna that pass by way of hummocky-stratified, very fine sandstones into intervals up to 25 m thick of fine, often large-scale trough or planar cross-stratified sandstones. This assemblage is interpreted as a shelf sand ridge complex and associated inter-ridge seafloor constructed by wind/wave-driven flows. These are separated from shoreline deposits by a mixed mud shale, bioturbated fine sandstone interval interpreted as shoreface deposits. The shoreface deposits are replaced landward by either progradational sequences of transgressive bioturbated shoreface sands overlain by tidal flat muds, or by fining upwards sequences composed in ascending order of large-scale trough or planar cross-stratified fine to medium grained channel-filling sandstone, inclined heterolithic strata with flaser or lenticular bedding and asymmetrical ripple forms, and red laminated siltstones and mudstones with mudcracks and root traces. This sequence is interpreted as the product of tidal channel migration through muddy tidal flats. These interfinger with large-scale cross-stratified quartzose sandstone bodies interpreted as estuarine sand shoals. The tidal features are interpreted to indicate at least a mesotidal range for the shoreface and inshore environments. Thus, the Catskill shoreline across Pennsylvania was shaped by a mixture of offshore wave/wind and onshore tide-dominated sedimentation.

INTRODUCTION

Recent studies of ancient shoreface and inner shelf deposits have revealed numerous examples of continental shelves that defy classification by process. Whereas for convenience we divide continental shelves by hydraulic regime into tide- or wind/wave-dominated, many shelf deposits imply that both processes operated either simultaneously at different sites or at different times. For example, the Doulbasgaissa Formation (Banks, 1973), the Jura Quartzite (Anderton, 1976), the Cretaceous Moosebar-Gates (Leckie and Walker, 1982), Viking (Leckie, 1986), and Milk River (McCrory and Walker, 1986) Formations of Alberta, the Tocito Sandstone Lentil of New Mexico (Tillman, 1985), and the Late Jurassic Curtis Sandstone of Utah (Kreisa and Moiola, 1986), all show evidence of spatially or temporally mixed tidal and wind/wave processes. Nowhere is this better illustrated than in the Upper Devonian nearshore-marine facies of the Catskill shoreline in Pennsylvania. The result has been the bewildering thicket of interpretations reviewed below.

In this study we have attempted to define the paleogeography and sedimentary environments of a Catskill shoreline as it existed across Pennsylvania during an interval of Frasnian time and relate the occurrence and intensity of tidal and wind/wave processes to it. We hope to show that tidal processes dominated the foreshore and inshore at the same time that wind/wave (especially storm) processes dominated the shoreface and inner shelf. The absence of high wave energy facies in the upper shoreface and foreshore is attributed to the infrequency of the storms relative to a low wave energy background, and to protection by offshore sand ridges. The general trend of the coast was NNE-SSW as predicted by earlier workers and net shelf sediment transport was to the south, apparently by wind-driven geostrophic currents.

PRESENT STATE OF KNOWLEDGE

It has been nearly three-quarters of a century since Joseph Barrell, in three landmark papers (1913, 1914a, 1914b), presented the idea of a great Upper Devonian Catskill delta in the Appalachian geosyncline of Pennsylvania and New York. Prior to his studies, Stevenson (1891) and others held the opinion that the Catskill and lower formations were shore and offshore deposits of the Interior Continental Sea. The present view of Upper Devonian sedimentation in Pennsylvania, well summarized in Woodrow and Sevon (1985), is one of a westward prograding shoreline complex with possibly as many as three identifiable deltaic depocentres (Dennison and Dewitt, 1972; Rahmanian, 1979; Smith and Rose, 1985; Williams and Slingerland, 1986; Warne, 1986), one of which occupied the center of the state during Frasnian time (Figs. 1 and 4). The depocentres were fed by rivers that arose in the Acadian Highlands to the east (present coordinates), and flowed westward across a proximal braid plain (Sevon, 1985; but see Bridge and Nickelsen, 1986 for an alternative view) onto a vast low gradient delta plain. Just across the border in New York state, the delta plain rivers are documented to have flowed in low sinuosity, perennial, laterally-migrating single channels (Bridge and Gordon, 1985). Bankfull discharges calculated at four cross sections thought to be within about 10 km of the shoreline ranged from 40 to 115

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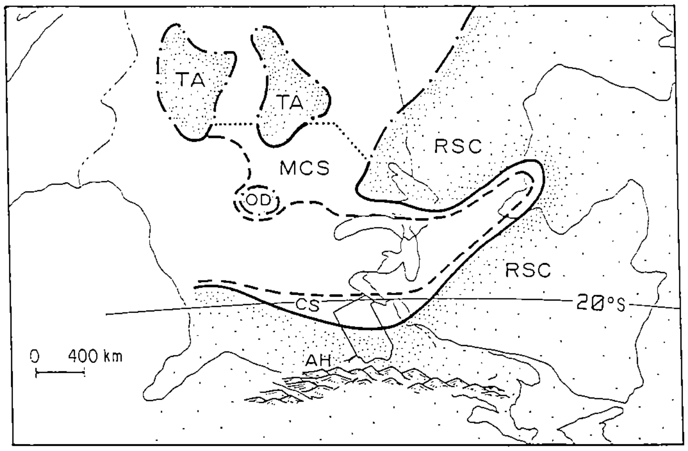


Fig. 1. Paleogeography of eastern North America during the Frasnian Stage (adapted from Heckel and Witzke, 1979). The dark solid line represents the probable limit of the Catskill Sea on the craton; the dark dashed line is the base of the clinoform. Pennsylvania state outline denotes study area. TA = Transcontinental Arch; RSC = Red Sandstone Continent; MCS = Mid-continent Shelf; OD = Ozark Dome; CS = Catskill Shelf; AH = Acadian Highlands.

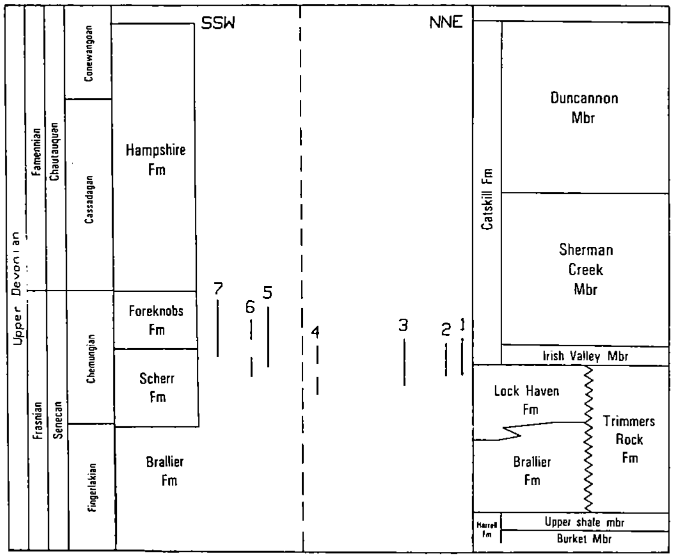


Fig. 3. Stratigraphic correlation chart adapted from Berg *et al.* (1983), giving approximate positions of measured sections along a NNE–SSW transect across middle Pennsylvania. Vertical dashed line denotes approximate boundary between formations. Measured intervals have been located by lithostratigraphic criteria only; see text for details.

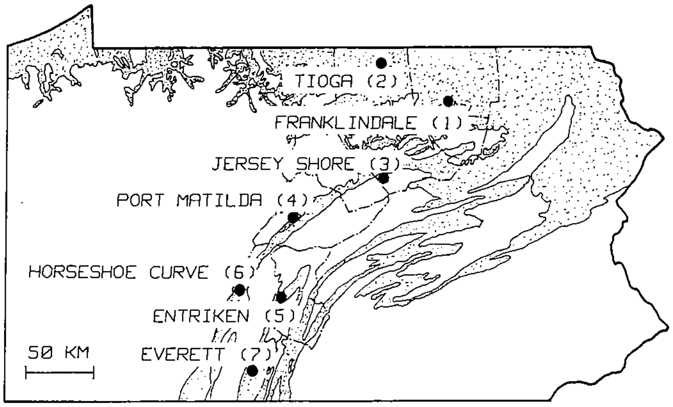


Fig. 2. State of Pennsylvania, USA, showing section locations and outcrop extent of Upper Devonian strata (stippled).

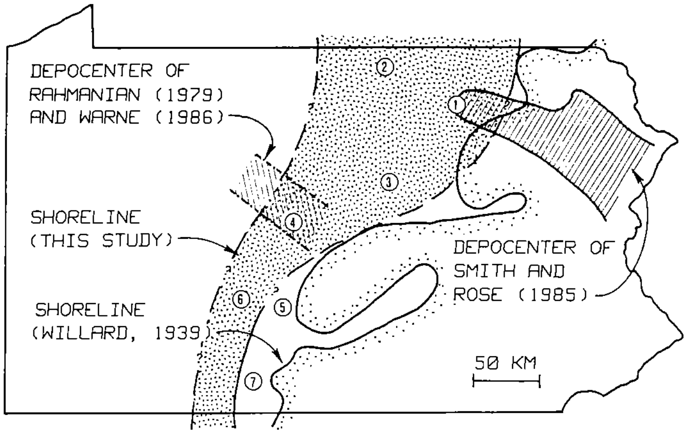


Fig. 4. Location of Catskill Shoreline during *ovalis–bulliferus* time as determined by this study (stippled area) compared to the shoreline of Willard (1939). Also noted are the locations of two depocentres determined by those authors from increased percentage of sandstones.

m^3-sec^{-1}. Although similar small rivers are recognized in eastern Pennsylvania (Sevon, 1985), by the time the delta plain had prograded through central Pennsylvania, the rivers were fewer and larger (Rahmanian, 1979; Williams, 1985). A low paleolatitude (less than 20 degrees) created a tropical climate with alternating wet and dry seasons. Plants were restricted to the fringes of rivers, lakes, and the shoreline (Woodrow, 1985; Banks *et al.*, 1985).

There is much less agreement on the nature and hydraulic regimes of the foreshore, shoreface, and offshore. The shoreline was oriented roughly northeast-southwest, but the precise geometry at any one time is still unclear. The often cited paleoshoreline of Willard (1934, 1939), based on the eastward disappearance of *Cyrtospirifer*, was constructed by assuming that the first appearance of the brachiopod and nonmarine strata are not time-transgressive. This apparently is not true (Woodrow, 1985). Dennison (1985) located four shorelines across Pennsylvania during the Upper Devonian using the shape and lithology of terrigenous clastic wedges. The geometries are generalized however, and their accuracy can't be evaluated.

Numerous interpretations of shoreline environments have been presented, some mutually contradictory, including tide-dominated deltas (Rahmanian, 1979; Williams, 1985; Slingerland, 1985; 1986), tidal flats (Woodrow and Fletcher, 1967; Humphreys and Friedman, 1975; Rahmanian, 1979), estuary or tide-dominated delta distributaries (Bridge and Droser, 1985), barrier bars (Allen and Friend, 1968), and a quiet muddy shoreline (Walker, 1971; Walker and Harms, 1975). Most agree the coastal wave climate was of low energy but estimates of the tidal regime range from microtidal (Woodrow, 1985) to high mesotidal (Slingerland, 1986).

The shoreface (low tide line to fair weather wave base) and inner shelf (shoreface to about 30 m water depth) have not been characterized as such. Walker (1971) concluded that the shoreline generally was muddy in east-central Pennsylvania whereas Friedman and Johnson (1966), Sutton *et al.* (1970), Glaeser (1970), and Krajewski and Williams (1971) refer to coastal margin sands in northeastern Pennsylvania and New York. McGhee and Sutton (1985) suggest a more complex shelf in New York during intervals of the Frasnian Stage, with delta-front sand bars protecting a finer grained delta platform. This interpretation was applied earlier to the Appalachians south of Pennsylvania by McGhee and Sutton (1981). An alternative view (Goldring and Bridges, 1973; Goldring and Langenstrassen, 1979; Woodrow and Isley, 1983) is that these more distal sands are of storm-wave origin. The latter point of view has been well documented and amplified by Craft and Bridge (1987) for hummocky sequences near the base of the Chemung Magnafacies at Waverly, New York. In Pennsylvania, elongate fine sandstone pods of the First Bradford Fm. are interpreted as inner to mid-shelf sandbars of uncertain origin (Murin and Donahue, 1984).

STRATIGRAPHIC SETTING

The rocks described here are exposed in seven sections roughly along paleodepositional strike (Figs. 2 and 4), and span the Upper Devonian marine-nonmarine boundary between the Chemung and Catskill Magnafacies. Figure 3 places the sections in the chrono- and lithostratigraphic framework of Berg and others (1983), based on lithostratigraphic criteria alone. Figure 3 suggests that the south-southwest sections may be younger, but the palynological dating described below does not substantiate this.

PALYNOLOGICAL DATING

Twenty-three silty shales were sampled at the horizons marked in Figures 5-11 and processed for palynomorphs. Sixteen were analyzed by Prof. A. Traverse and seven by one of us (JPL) using standard procedures of the Palynological laboratories of The Pennsylvania State University. The assemblages for each sample were plotted on the range chart recently compiled for the Devonian System of Canada (Richardson and McGregor, 1986) relating palynomorphs to the existing conodont zones. Although many forms are new and still under investigation, all of the sections except Entriken (5) (Fig. 9) yielded a *Diaphanospora reticulata* assemblage from at least one sample, thus placing them in the *ovalis-bulliferus* spore zone, that is, the middle two-thirds of the Frasnian Stage. Samples from the bases of the Port Matilda (4) (Fig. 8) and Everett (7) (Fig. 11) sections and all of the Entriken section yielded slightly older palynomorphs.

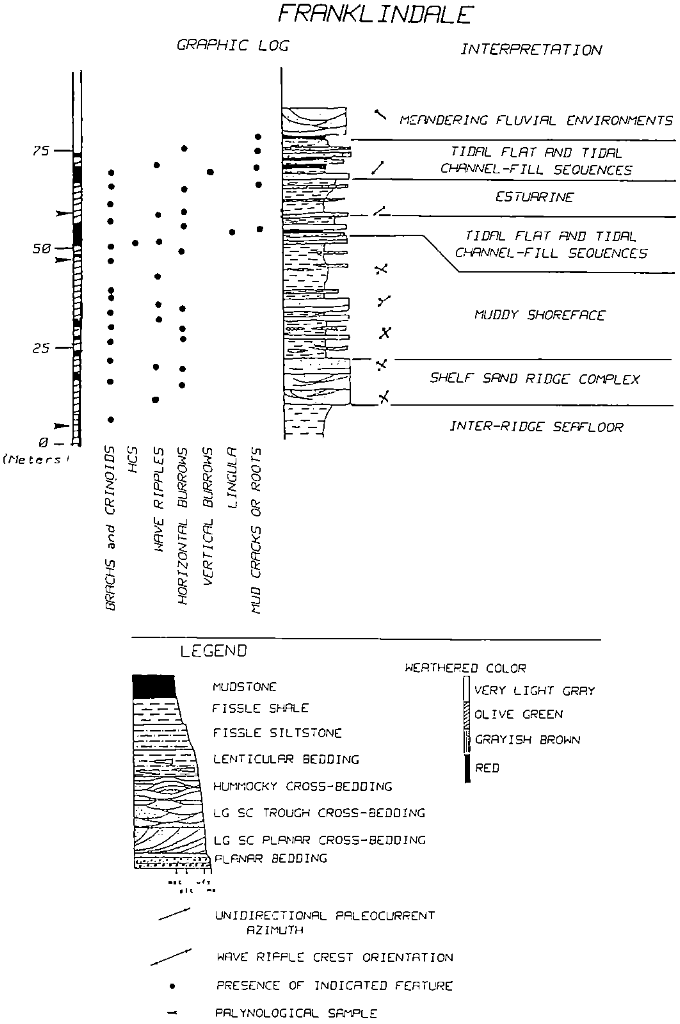


Fig. 5. Graphic log and interpretation of the section at Franklindale (1). Filled circles on the left indicate presence of the features noted below (arranged from left to right indicating increased continental affinities). Brachs = brachiopods; HCS = hummocky cross-stratification.

These are generally older dates than those of previous chronostratigraphic work in the area. The dark grey shales at the base of the Franklindale (1) section (Fig. 5) and at Tioga (2) (Fig. 6) are correlated by Woodrow (1981) based on physical criteria, to the Dunkirk Shale (Rickard, 1975), in which case the rocks above would be of Famennian age. (But note that this is not the interpretation of Berg *et al.* (1983) in Fig. 3 for the NNW column). Also, Warne (1986) traced the Minnehaha Springs member of the Scherr Formation to sections near Port Matilda (4) and Jersey Shore (3), placing it approximately 660 m below the marine-nonmarine transition. It is thought to be an isochronous unit at the base of the Cohocton (Chemungian) stage, that is, middle Frasnian, in which case the rocks of the transition studied here should be much younger. Until the situation is clarified, the only point we will make is that, except for Entriken, the sections are, for the most part, isochronous.

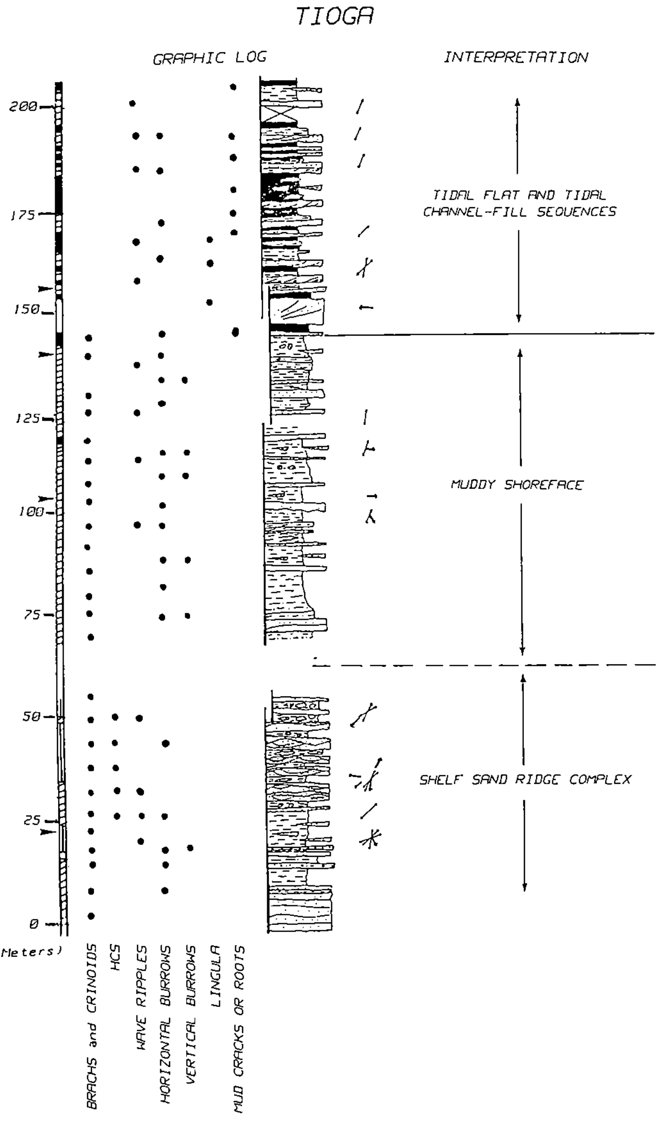


Fig. 6. Graphic log and interpretation of the section at Tioga (2); see Fig. 5 caption for details.

PALEOGEOGRAPHY OF THE SHORELINE

Based upon these palynological dates, the shoreline during *Diaphanospora reticulata* (middle Frasnian) time as indicated by the first occurrence of mudcracked and rooted rocks, probably occupied the cross-hatched area in Figure 4. We can be certain it was west of locations 5 and 7 because the first subaerial facies are older there, but elsewhere the whole marine-nonmarine transition zone falls within this range. This is a disappointing precision; perhaps as new palynomorphs are identified, the dates can be refined.

To provide additional information we measured the orientation of wave ripple crests on the tops of sandstone beds subjacent to (offshore from) the first subaerial facies. The assumption is that these reflect the crestal orientation of water surface waves in the shallow foreshore. These waves in turn will have been refracted to near parallelism with regional bathymetric contours. The results (Fig. 13) lend support to the shoreline geometry of Figure 4. The morphology also is similar to Willard's (1939) and Warne's (1986) shorelines in trend although this may be an artifice of the outcrop distribution.

DESCRIPTION AND INTERPRETATION OF STRATA

Upper Devonian rocks of the study area have been subdivided into 12 monolithic and 4 heterolithic facies and grouped into the genetic sequences presented in Figures 5-11. These are discussed in order from most seaward to most landward.

SHELF SAND RIDGE COMPLEX

This environment is represented in decreasing proportion by: 1) reddish brown-weathering, large scale trough or planar cross-bedded, fine to medium grained sandstone in beds up to 0.5 m thick, recording strong flows (greater than 0.5 m/sec^{-1} for this grain size) either offshore as at Franklindale (1) (Fig. 5) or alongshore as at Tioga (2) (Fig. 6); 2) light grey-weathering massive to planar-bedded, fine grained sandstone; and 3) thin interbeds of wavy and flasered very fine sandstone (Fig. 12A and B). Wave ripples and mud drapes are common on bedding surfaces. Brachiopods and bivalves are scattered throughout and occasionally concentrated in coquinites, the beds are moderately bioturbated, and trace fossils are of the *Cruziana* and *Skolithos* ichnofacies. This facies assemblage occurs in all the sections except Port Matilda (4) and Everett (7).

We interpret this facies assemblage as an offshore sand ridge, perhaps formed by offshore-directed geostrophic or tidal flows (Fig. 13), similar to the Shannon Sandstone and others reported from the Upper Cretaceous of Wyoming (Tillman and Martinsen, 1984). Rahmanian (1979), Ehrets (1981), and Craft and Bridge (1987) have described similar sandy sequences in these or equivalent units to the north, but suggested delta-lobe progradation and abandonment as a possible cause. We prefer the growth, migration, and abandonment of sand ridges on a generally muddy shelf because these sandstones are overlain by landward mud-rich deposits, only one (Entriken) contains channels, and because one (Tioga) possesses shore-parallel flow indicators.

RIDGE-MARGINS

Often occurring gradationally above or below the thick sands interpreted as a shelf sand ridge complex are light olive grey-weathering interbedded silt shale, siltstones, and fine-grained sandstone with the sandstone predominating. The sandstones commonly display a vertical sequence commencing with a sharp sole-marked base overlain by pockets of coquinite and quartz pebbles, hummocky cross-stratified or wave ripple cross-laminated and flasered fine sandstone, and terminate with wave or asymmetrical ripple forms (Fig. 12C). Wave ripple orientations displayed in Figure 13 for the offshore units are predominantly from this

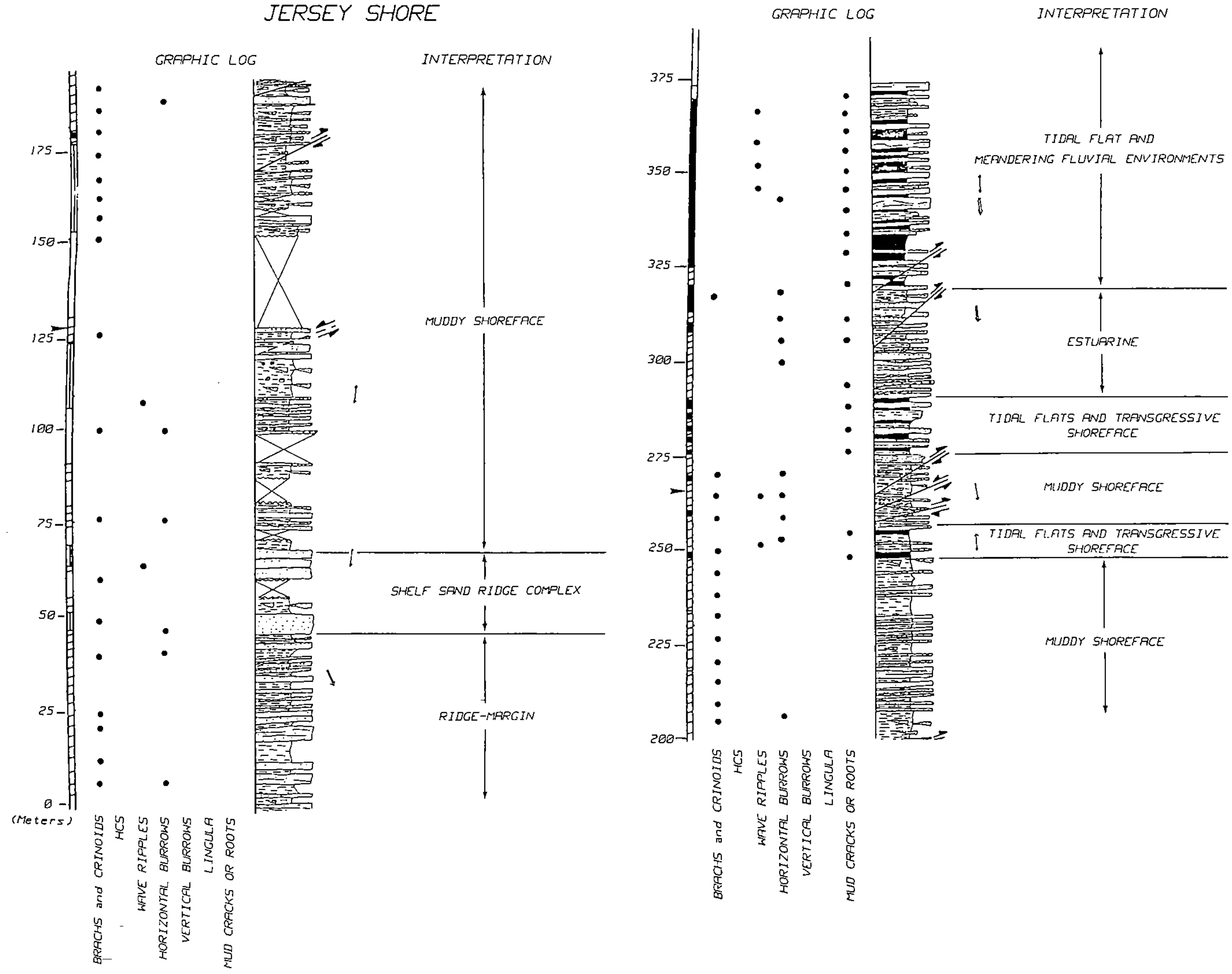


Fig. 7 (a & b). Graphic log and interpretation of the section at Jersey Shore (3); see Fig. 5 caption for details.

facies. More rarely, the sandstones are deformed into ball-and-pillow structures. The sandstone beds pinch and swell or disappear laterally over distances of many metres. Fossils include transported brachiopods, crinoid fragments, gastropods, and traces of *Cruziana* and *Skolithos* ichnofacies. This assemblage occurs in the lower portions of the sections at Jersey Shore (3) (Fig. 7), Port Matilda (4) (Fig. 8), and Horseshoe Curve (6) (Fig. 10).

These facies are interpreted as forming in a ridge-margin environment because of their stratigraphic position and indications of lower flow strengths. They are similar to the hummocky sequences reported by Dott and Bourgeois (1982) and Duke (1985), and described by Craft and Bridge (1987) for the type locality of the "Chemung Group" directly north of the study area. Thus, storm-driven geostrophic flows (Swift, 1985) or dilute, storm-induced, shelf turbidity currents (Walker, 1985) and strong oscillatory flows are hypothesized to have redistributed sand around the ridges.

INTER-RIDGE SEAFLOOR

This environment is characterized by a dark grey to olive grey non-fissile mud shale or greenish grey fissile silty shale associated with rare, thin, very fine sandstone beds. It contains a few slightly disarticulated brachiopods, no corals or sponges, and is considered to be the deepest water assemblage deposited farthest from ridges. It occurs in the lower portions of the sections at Franklindale (1) (Fig. 5), Port Matilda (4) (Fig. 8), and Entriken (6) (Fig. 9).

MUDDY SHOREFACE

Overlying the facies interpreted as ridge and ridge-margin in origin, and below demonstrable tidal flat facies, in most sections is from 30 to 100 m of interbedded grey, or olive grey silty shales and thinly bedded fine grained silty sandstones (Fig. 12D). The sandstones comprise less than 30% of the assemblage, commonly are bioturbated, wave-rippled, and flaser or lenticular bedded, and preserve an

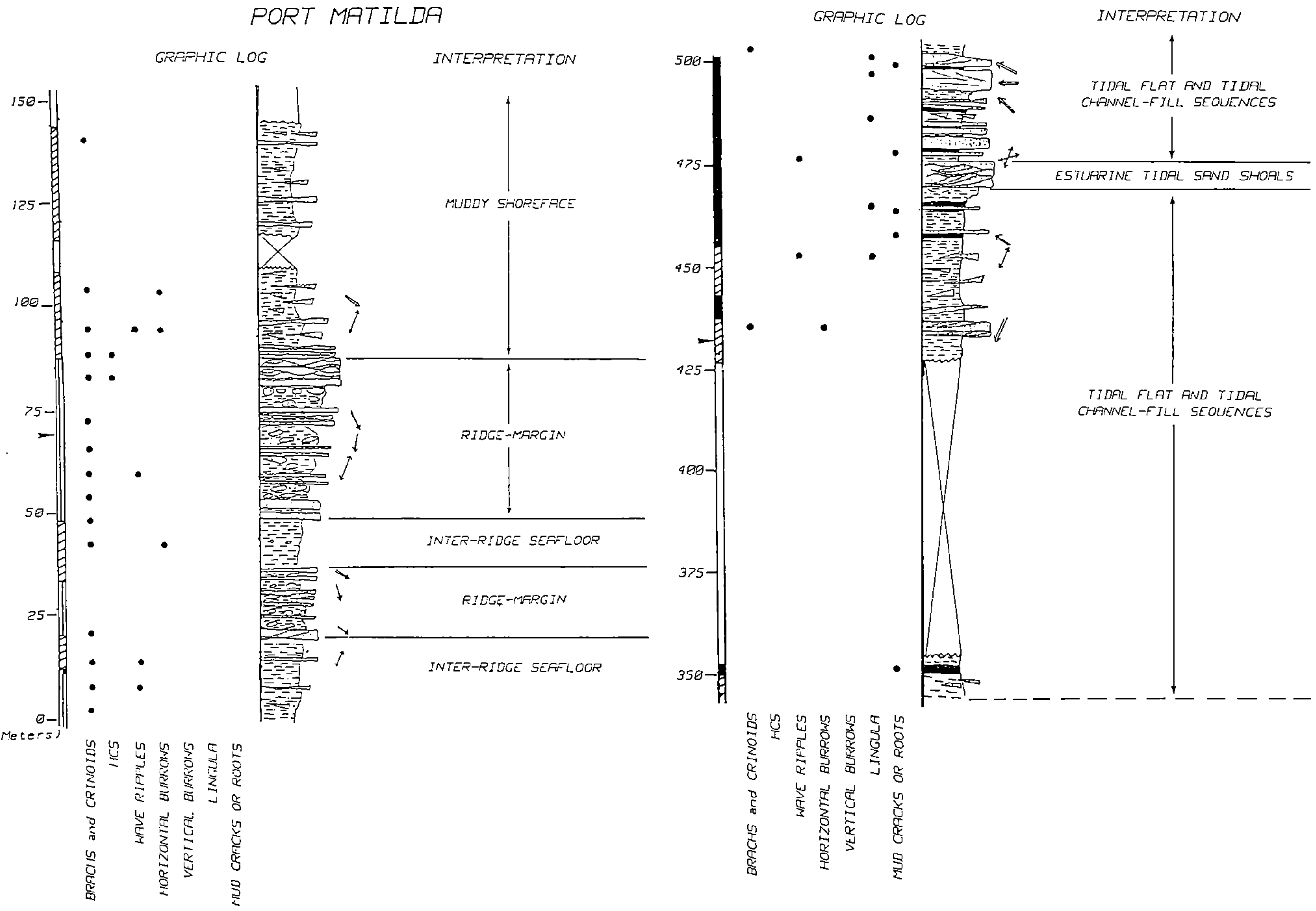


Fig. 8 (a & b). Graphic log and interpretation of the section at Port Matilda (4); see Fig. 5 caption for details.

abundant brachiopod and bivalve fauna, most notably *Cyrtospirifer* sp. and *Grammysia*. Thin coquinite beds often contain fish plates and bones. The dominant ichnofacies is *Cruziana* although a *Skolithos* assemblage increases in proportion towards the top. This environment is present at all the sections except Horseshoe Curve (6); at Tioga (Fig. 6) 20 m of shale, slightly siltier than the inter-ridge lithology, is included within it.

The interpretation of this assemblage as a muddy shoreface deposit rests primarily on its stratigraphic position and a suggestion of an increase in vertical burrows. The shoreface was muddy because the shelf ridges filtered out the high energy waves that produced hummocky cross-strata on their margins. In addition, as will be discussed below, the estuaries seemed to have trapped sand, and what sand did leak out moved offshore.

Sandy Shoreface

At Everett (7) (Fig. 11) and Horseshoe Curve (6) (Fig. 10) the muddy shoreface is replaced by from 30 to 40 m of greenish grey, moderately to strongly bioturbated, quartzose, fine grained sandstones with subordinate interbeds of olive silt shales. The sandstones possess sharp and planar bases and are either planar and thinly bedded or trough cross-stratified (medium scale) where not destroyed by burrowing, contain a sparse brachiopod fauna, and often preserve asymmetrical ripples on their upper surfaces. Most importantly, they contain numerous vertical burrows of the *Skolithos* ichnofacies.

The interpretation of this assemblage as a sandy shoreface is based on its stratigraphic position below mud-cracked tidal flat deposits, the greater quartz content and vertical burrows in the sandstones, and the indications of unidirectional flows.

Foreshore and Beach Environments

No foreshore and beach deposits can be identified with certainty in any of the sections, a conclusion also reached by Walker (1971) and Walker and Harms (1975) in their study of an older Catskill shoreline 100 km to the east. We attribute this to a variety of causes working in combination. As suggested above, although sand was available, it appears to have been trapped in estuaries and shunted directly to the shelf in riverine or tidal plumes. Secondly, the shoreline wave climate may have been low because of the presence of offshore ridges. Rine and Ginsburg (1985) documented a

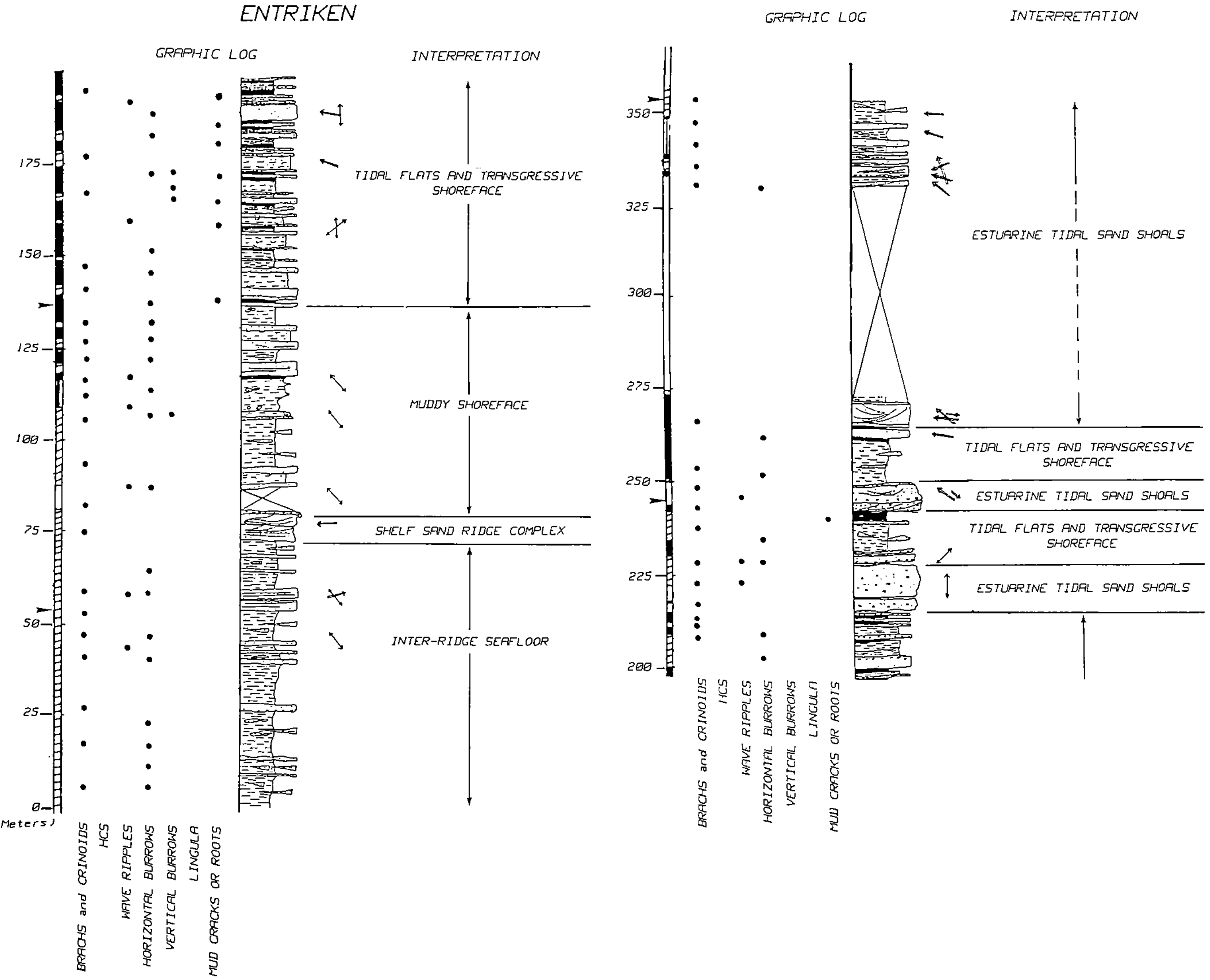


Fig. 9. Graphic log and interpretation of the section at Entriken (5); see Fig. 5 caption for details.

modern muddy shoreface in Suriname containing 5 m high mud banks occupying the position of shoreface-connected ridges on a sandy coast. Even in this sand deficient system, sandy beaches are maintained by the intermediate to low wave climate of the region, suggesting either the Catskill wave climate or available sand at the shore must have been even lower than the present Suriname shore. Without the sand or energy to winnow muds, we may not be able to identify facies from this environment even if they exist. Thirdly, foreshore and beach facies could have been removed by the lateral migration of backshore tidal channels during progradation or by ravinement during transgression of the more energetic ridge environments. The evidence for both processes is given below.

TIDAL FLATS AND TRANSGRESSIVE SHOREFACE

At Jersey Shore (3) (Fig. 7), Entriken (6) (Fig. 9), and Everett (7) (Fig. 11), deposits of the shoreface are overlain by progradational sequences of transgressive shoreface sands and tidal flat muds; these are the Irish Valley motifs of Walker (1971) *sensu stricto* and the silty-muddy motifs of Rahmanian (1979) (Fig. 12E). A complete sequence comprises in ascending order: a basal bioturbated quartzose sandstone with an erosive base; a green fissile silty shale; a green to reddish mudstone with subordinate thin cross-laminated sandstone beds; red laminated siltstones; and red massive mudstones. The basal sandstones often contain marine fauna and traces of the sandy shoreface deposits. The green to reddish mudstones contain *Lingula* and their sandstones are often capped by asymmetrical small-scale ripple forms. The red laminated siltstones and massive mudstones contain mudcracks, root traces, and in stratigraphically higher units, calcareous concretions (caliche).

We agree with previous interpretations that these record minor shore-normal fluctuations of the coastline, probably caused by variations in the balance between subsidence and sediment input. The increase in number from north to south is attributed to an accumulation rate for the Upper Devonian in the southern sections nearly double that to the north (Sevon, 1985, Fig. 1).

TIDAL FLATS AND CHANNELS

At Franklindale (1) (Fig. 5), Tioga (2) (Fig. 6), Port Matilda (4) (Fig. 8), and Horseshoe Curve (6) (Fig. 10), shoreface deposits are unconformably overlain by fining upwards sequences interpreted as the product of channels migrating laterally through muddy tidal flats (Fig. 12F, G, and H). A complete sequence contains from the base upwards, pale olive or pink, large-scale trough or planar cross-stratified fine to medium grained channel-filling sandstones; inclined heterolithic strata of red very fine-grained sandstone, siltstone, and mudstone arranged in thin interbeds with flaser or lenticular bedding and asymmetrical ripples forms; and red laminated siltstones and mudstones with mudcracks and root traces. The channel sands often contain a hash of brachiopod, bivalve, gastropod, and crinoid fragments and the heterolithic strata may contain *Lingula*, whereas the upper units are devoid of body fossils.

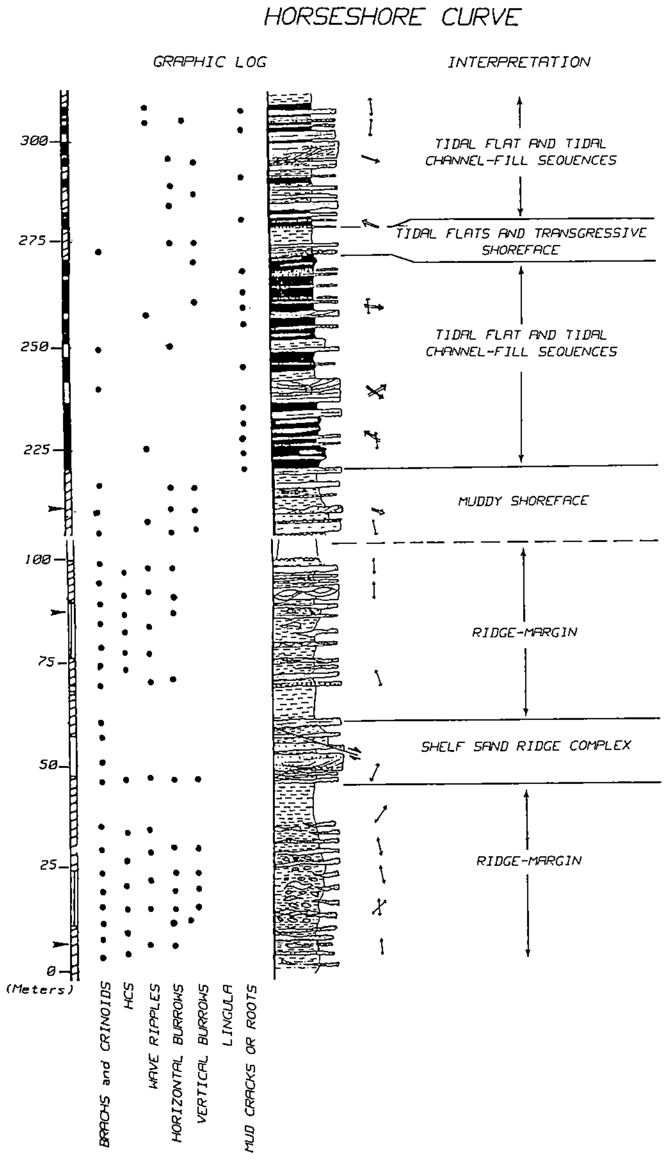


Fig. 10. Graphic log and interpretation of the section at Horseshoe Curve (6); see Fig. 5 caption for details.

The interpretation is based on comparison with tidal flat sequences summarized by Weimer *et al.* (1982). We especially note the similarity of the inclined heterolithic facies with those described by Smith (1985) from the estuary mouths of modern tidally-influenced rivers, where alternating sand and mud is deposited on point bars, probably in response to temporary tidal storage of water.

ESTUARINE TIDAL SAND SHOALS

At Port Matilda (4) (Fig. 8), Entriken (5) (Fig. 9), and Everett (7) (Fig. 11), buff white, medium to coarse grained sandstone bodies up to 10 m thick in this interval are interpreted as estuarine tidal sand shoals. They consist of thick sets of massive or large-scale trough and to a lesser extent, planar cross-strata and solitary sets showing multi-directional and, at Entriken (5) opposing flow directions (Fig. 12I and J). The sets often are draped with shale and contain fragments of marine body fossils and quartz pebbles along bedding planes. Bases of the bodies are planar and can be either erosional or gradational; tops are always gradational. At Franklindale (1) (Fig. 5) and Jersey Shore (3) (Fig. 7), sandstone-dominated heterolithic interbeds also have been interpreted as estuarine in origin, possibly as shoal margins.

We interpret these as estuarine shoals and associated deposits because of their gradational contacts with tidal flat and channel deposits, their relatively lower density of burrows possibly due to decreased salinities, and their multi-directional large-scale bedforms, possibly due to amplified tides. They are similar to estuarine deposits described by Clifton (1982) from Willapa Bay, Washington, USA.

MEANDERING FLUVIAL ENVIRONMENTS

Overlying the above environments at all the sections, but measured only at Franklindale, are environments of a low gradient meandering fluvial system. For further description see the references reviewed above.

DISCUSSION

The facies and the interpretations presented above suggest to us that the fluid and sediment dynamics of the Catskill Sea in Pennsylvania during middle Frasnian time were driven by a combination of wind and tidal forcing. A field of sand ridges with associated inter-ridge environments was maintained offshore, possibly on the inner shelf, by wind/wave-driven currents. How the sands came to be concentrated offshore on a generally muddy coast is problematical, not only here but in other shelf sands, such as the Tocito Sandstone Lentil of New Mexico (Tillman, 1985) and the Woodbine-Eagle Ford sandstones of Texas (Phillips and Swift, (1985). Transport of sands from the shoreface by coastal downwelling during the storm events that produced

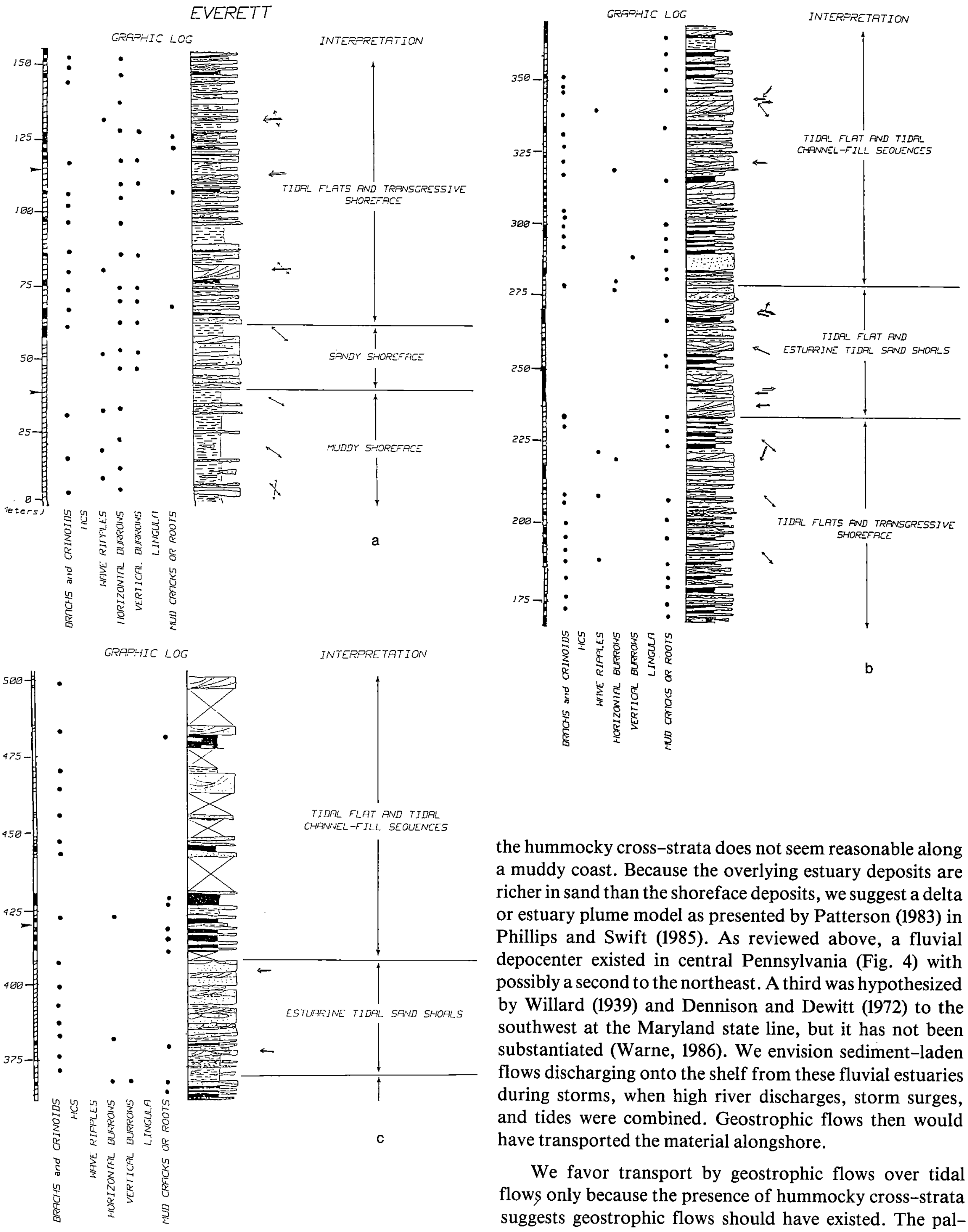


Fig. 11 (a, b, and c). Graphic log and interpretation of the section at Everett (7); see Fig. 5 caption for details.

the hummocky cross-strata does not seem reasonable along a muddy coast. Because the overlying estuary deposits are richer in sand than the shoreface deposits, we suggest a delta or estuary plume model as presented by Patterson (1983) in Phillips and Swift (1985). As reviewed above, a fluvial depocenter existed in central Pennsylvania (Fig. 4) with possibly a second to the northeast. A third was hypothesized by Willard (1939) and Dennison and Dewitt (1972) to the southwest at the Maryland state line, but it has not been substantiated (Warne, 1986). We envision sediment-laden flows discharging onto the shelf from these fluvial estuaries during storms, when high river discharges, storm surges, and tides were combined. Geostrophic flows then would have transported the material alongshore.

We favor transport by geostrophic flows over tidal flows only because the presence of hummocky cross-strata suggests geostrophic flows should have existed. The paleocurrent data (Fig. 12) are equivocal. Both geostrophic and tidal flows could be expected to transport sand offshore as

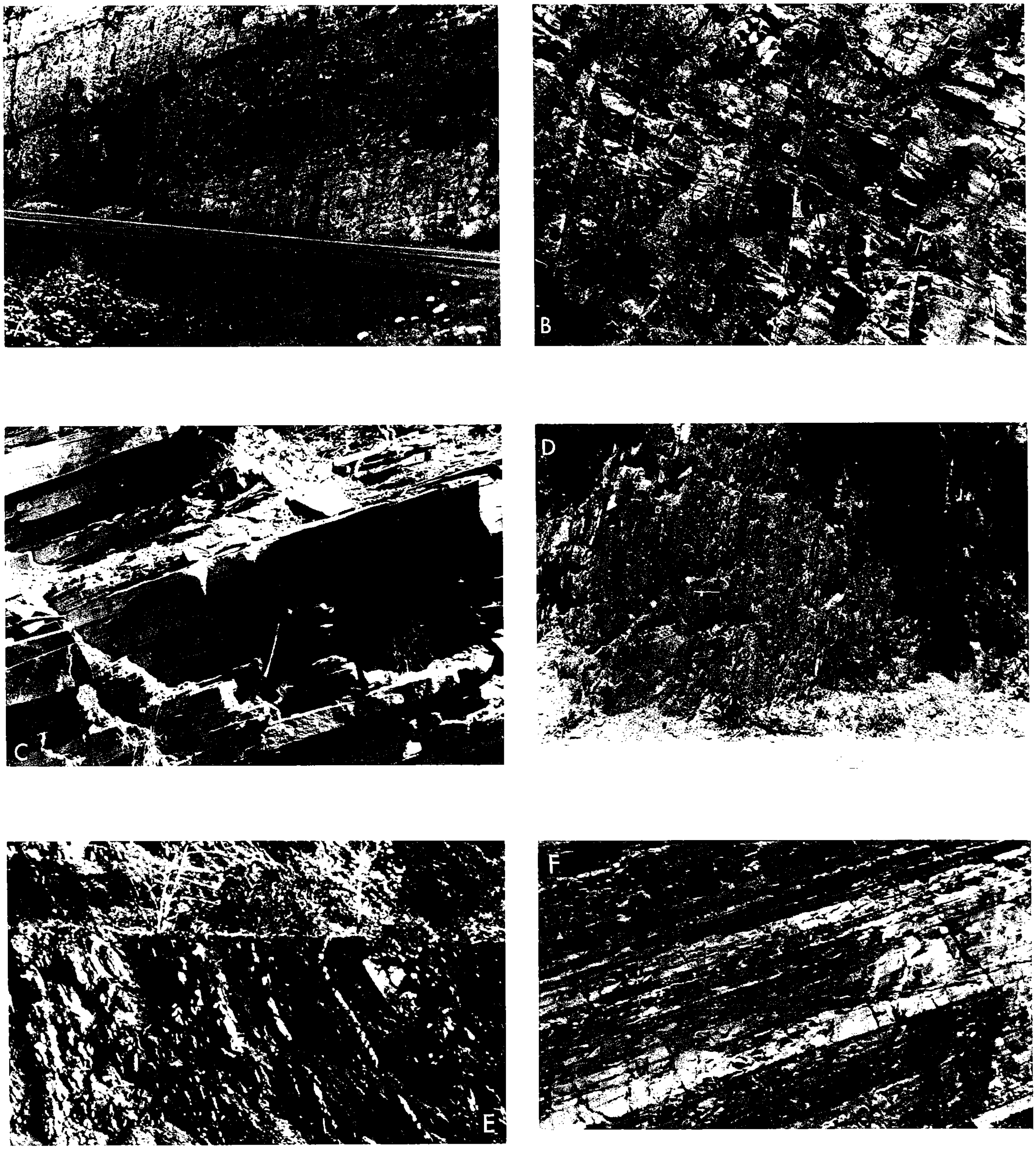
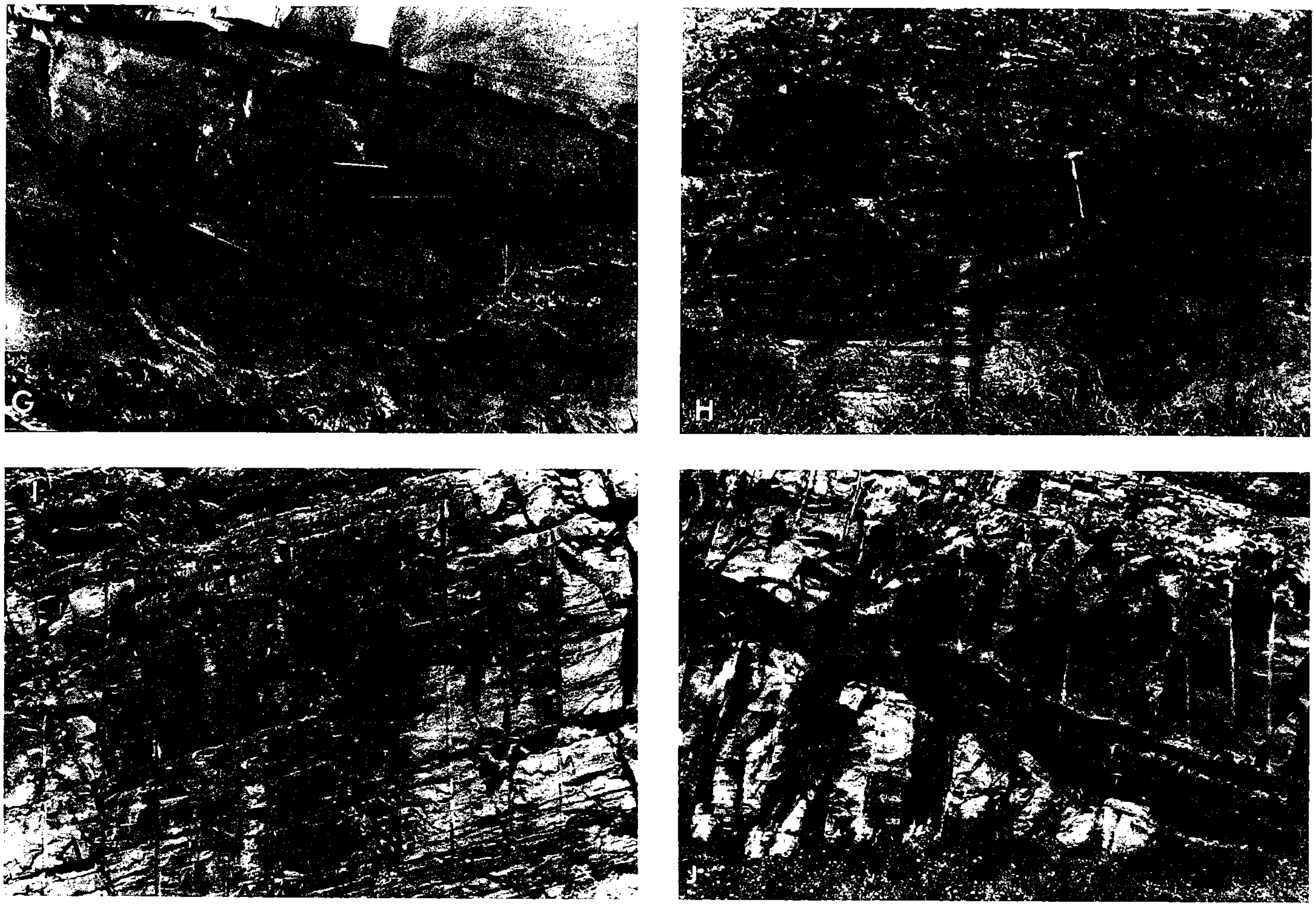


Fig. 12 A) Plane-bedded fine sandstones of a shelf sand ridge complex at Tioga (2) (20 m in Fig. 6); B) planar-bedded and large-scale planar cross-bedded sandstones of a shelf sand ridge complex at Entriken (5) (75 m in Fig. 9a); C) hummocky sequences of a shelf ridge margin at Horseshoe Curve (6) (25 m in Fig. 10); D) olive grey silty shales interpreted as a muddy shoreface deposit at Horseshoe Curve (6) (230 m in Fig. 7b); E) typical Irish Valley motif of Walker (1971) and Rahmanian (1979) starting at the base with a transgressive sandstone and fining upwards into red tidal flat mudstones (Entriken (5) at 140 m in Fig. 9a); F) tidal flat and channel sequences at Port Matilda (4) (480 m in Fig. 8b); G) tidal channel sandstone at Tioga (178 m in Fig. 6); H) tidal channel inclined heterolithic strata at Tioga (2) (200 m in Fig. 6); I) large-scale trough cross-stratified sandstone body interpreted as an estuarine tidal sand shoal at Port Matilda (475 m in Fig. 8b); J) solitary cross-strata set in a pebbly medium sandstone at Entriken with ripple forms of opposing azimuth at its top. This is interpreted as an estuarine tidal sand shoal (245 m in Fig. 9b).



well as alongshore to produce the observed sole mark orientations. Large-scale cross-strata orientations in the sand ridge complexes were difficult to measure in quasi-two-dimensional outcrops and therefore are not presented in Figure 13. The only believable data are from Franklindale (1) (Fig. 5), where sand waves migrated almost due northwest, that is, offshore. Shale drapes at many sites suggest periods of relaxation, but again, could support either type of flow. More diagnostic tidal features such as bundles, were not observed in these environments.

Regardless of the mechanism of forcing, it seems certain (Fig. 13) that the net alongshore circulation was to the southwest, corroborating Willard's (1939) almost prescient proposal for a clockwise circulation of waters in the epeiric ocean of eastern North America. Residual tidal circulation was calculated by Slingerland (1986) for various ocean tides propagating into the Catskill Sea and various sea bathymetries. Southerly drift along the Pennsylvania coast was predicted for selected cases (e.g., Fig. 3B of that paper), but no conclusions should be drawn until a more accurate multilayer model including wind stresses is used.

Landward of the shelf ridges, along the shoreface and in the estuaries, diurnal tides were the principal formative process. This is evidenced by the extensive tidal flat facies and estuarine shoals with multi-directional large-scale sand waves (Fig. 12). Some investigators (e.g., Walker, 1971; Walker and Harms, 1975; Woodrow and Isley, 1983; Woodrow, 1985) have minimized the effect of tides as a significant process because of an absence of channels and winnowed sand bodies, and because of a belief that epicontinental seas would be friction-dominated. As defended above, we interpret many of the motifs in the Irish Valley Member of the Catskill Formation as the result of lateral tidal channel migration (for example, at Port Matilda (4)), rather than shore-normal transgressive-regressive cycles. And, as Thompson documented (Weimer *et al.*, 1982), tidal flats at the head of the Gulf of California, along a macro-tidal coast, contain remarkably few channels, presumably because sand is scarce. Finally, Slingerland (1986) solved the equations describing tidal wave propagation in the Catskill Sea to demonstrate that the oceanic tidal wave may be amplified along the Catskill shoreline, depending upon the width of the entrance from the open ocean, the mean thalweg water depth, and the width and concavity of the Catskill margin.

The range of the tides at the shoreline is still difficult to estimate. We believe, as Rahmanian (1979) did, that the absence of deposits traditionally described as deltaic, such as distributary mouth bars, levees, and so on, a fact first noted by Walker (1971), is because the river mouths were

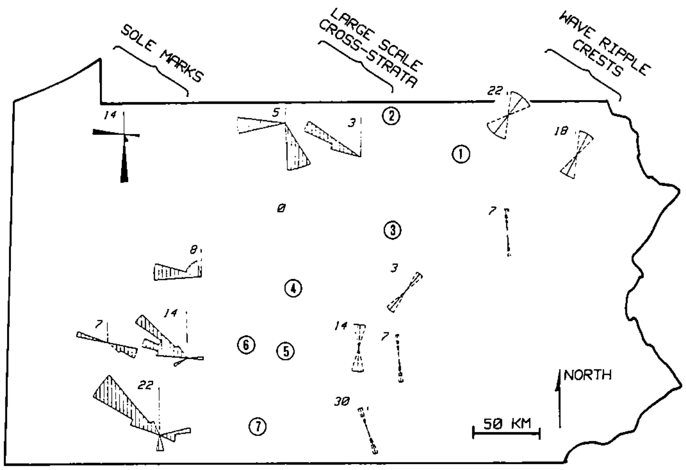


Fig. 13. Paleocurrent data. Orientation roses of wave ripple crests are translated east of the outcrop locations; roses of the cross-strata are translated west. Orientation rose for sole marks is a composite from the bases of hummocky beds at all the sections. Wave ripple crests are from the tops of marine sandstone beds; large-scale cross-strata (both trough and planar) are from transition sandstones (Irish Valley Member and equivalents). See text for interpretation.

tide-dominated. The estuarine sand shoals, as for example at Port Matilda, very near a depocentre, are the equivalents of the river-mouth tidal ridges described by Meckel (1975) at the mouth of the Colorado River, Gulf of California, or by Coleman (1976) at the mouth of the Ord River, Australia. If this is the case, then compared to present coasts (Hayes, 1975) the tidal range must have been at least high mesotidal, although this minimum magnitude depends to some extent upon the wave climate and river discharge.

In summary, seven stratigraphic sections along 250 km of the Catskill shoreline across Pennsylvania record the westward migration of a mixed wind/wave and tidal coast during *Diaphanospora reticulata* (middle Frasnian) time. The coast was oriented roughly along a north by northeast trend as indicated by the near synchronism of the sections and the orientation of offshore wave ripples. It experienced a combination of wind/wave-driven circulation offshore and tidal circulation nearshore and inshore, as recorded in vertical sequences of trough cross-bedded shelf sand ridges with adjacent hummocky-stratified sandstones and associated marine shales and superjacent thick accumulations of tidal flat and channel sequences.

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