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DEPTH OF ACTIVITY, SEDIMENT FLUX, AND MORPHOLOGICAL CHANGE IN A BARRED NEARSHORE ENVIRONMENT

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Abstract

Sediment flux and associated morphological change in a continuously submerged, nearshore, crescentic bar system is documented for discrete storm events using an array of depth of disturbance rods in conjunction with structural indices recorded in epoxy peels of box cores from the active layer. Steel rods (≈1 or 2 m in length, 0.5 cm in diameter) buried to a depth of 55 cm with a free sliding washer (≈0.6 cm internal diameter) accurately record the spatial variability of: (1) maximum depth of sediment activation; (2) net bed elevation changes; and (3) degradation-aggradation cycles. The depth of activity is related to the magnitude of the incident wave –(70 cm for deepwater waves of 2 m height, 6 sec period versus 23 cm for a height of 1.5 m and period of 5 sec)– and location within the bar system. Maximum values occur on the seaward side of the bar crest where wave breaking, asymmetric oscillatory motion and/or rip current flow would be a maximum during the storm. A secondary maximum is associated with longshore currents in the landward trough. Depths of activity minima occur on the landward slope in response to height loss due to breaking and increase in water depth. In general storms erode the bar profile with scour maxima on the seaward side of the crest and near the toe of the landward slope. Aggradation occurs on the upper landward and upper seaward slopes steepening both slopes and producing a seaward displacement of the bar crest over the crescent area. Structural indices suggest increasing rates of landward transport (through either ripple or lunate megaripple migration and sheet flow) as water depth decreases up the seaward slope. Landward transport across the bar crest and down the landward slope is also indicated. On the upper landward slope and bar crest of the crescent, however, small- to medium-scale seaward-dipping cross-stratification indicates a distinct seaward flux of sediment, which is interpreted as resulting from rip-type flow. This is not found on the shoal areas and this differentiation is instrumental in maintaining the on-offshore sediment balance as well as the crescentic form.

Résumé

Les auteurs donnent des précisions au sujet des apports de matériaux de l'évolution morphologique connexe dans un ensemble de cordons arqués, situé près du littoral et continuellement submergé afin de déterminer des apparitions de tempêtes discrètes au moyen d'un réseau de tiges de perturbation en profondeur combiné à des indices structuraux enregistrés dans des pelures d'époxy situées dans des carottes encastrées tirées de la couche active. Des tiges d'acier (≈1 ou 2 m de longueur et 0,5 cm de diamètre) enfouies à une profondeur de 55 cm et munies d'une rondelle mobile libre (≈0,6 cm de diamètre interne) enregistrent avec précision la variabilité spatiale des phénomènes suivants: (1) profondeur maximale de l'action sédimentaire; (2) les modifications altimétriques nettes du lit et (3) les cycles de démaigrissement-engraissement. La profondeur de l'action sédimentaire est liée à la force de la vague incidente –(70 cm dans le cas des vagues en eau profonde de 2 m de hauteur, une période de 6 s contre 23 cm pour une hauteur de 1,5 m et une période de 5 s)– et un emplacement situé à l'intérieur du réseau de cordons. On constate des valeurs maximales sur la façade maritime de la crête de cordon où le déferlement des vagues, le mouvement oscillatoire asymétrique ou le courant d'arrachement atteignent généralement un sommet au cours d'une tempête. Un maximum secondaire est associé à la dérive littorale dans le creux situé côté terre. Des profondeurs minimales d'action existent sur le versant intérieur par réaction à la perte de hauteur due au déferlement et à l'accroissement de la profondeur d'eau. De manière générale, les tempêtes contribuent à éroder le profil des cordons en pratiquant un affouillement maximal sur le côté maritime de la crête et près de l'encoche de la pente côté terre. L'engraissement se produit dans les parties supérieures des pentes situées tant du côté de la terre que du côté de la mer, ce qui accentue les deux pentes et engendre une migration vers la mer de la crête du cordon pardessus la zone arquée. Certains indices structuraux permettent de penser que les vitesses de transport en direction de la terre (soit par l'arrachement ou une forte migration parabolique des matériaux et un écoulement en nappe) augmentent à mesure que la profondeur de l'eau diminue en remontant le versant marin. Le transport vers la terre en travers de la crête du cordon et vers le pied du versant terrestre est aussi indiqué. Toutefois, sur la partie supérieure du versant terrestre et de la crête du cordon du croissant, des interlaminations de petite à moyenne échelle et à pendage orienté vers la mer indiquent la présence d'un transport de matériaux distincts en direction de la mer, ce qui peut s'expliquer par l'existence d'un écoulement d'arrachement. Le même phénomène est absent des zones de hauts-fonds et cette différenciation sert à maintenir tant l'équilibre des matériaux de va-et-vient que la forme arquée du relief.

INTRODUCTION

In coastal studies at present one of the most important problems being addressed concerns the direction and rate of sediment flux in the nearshore zone and its spatial and temporal variability. It is important, therefore, to develop techniques whereby sediment flux can be determined and related to both the transport mechanisms and morphological changes, particularly during high wave energy events. A number of approaches have been adopted in an effort to measure sediment flux (for a brief review see Dowling, 1977) including: (a) direct sensing of sediment load with various electro-optical, electromechanical, electroacoustical or entrapment devices (e.g., Watts, 1953; Fukushima and Mizoguchi, 1958; Bruun and Purpura, 1964; Sternberg and Creager, 1965; Thornton, 1968; Cook, 1969; Das, 1972; Fairchild, 1972; Swift and McGrath, 1972; Wenzel, 1974; Lee, 1975; Brenninkmeyer, 1976; Kana, 1976; Kilner, 1976; Lesht et al., 1976; Thornton and Morris, 1977); and (b) indirect determinations based upon either dispersion patterns of natural and artificial tracers (e.g., Goldberg and Inman, 1955; McMaster, 1960; Zenkovitch, 1960; Yasso, 1966; Ingle, 1966; Komar and Inman, 1970; Boon, 1970; Boone and Slowey, 1972; Nelson and Coakley, 1974; Judge, 1975; Heathershaw and Carr, 1977), or simple profile differencing procedures based upon bathymetric surveys (e.g., Davis and Fox, 1972; Coakley et al., 1973; Shaw, 1977). However, with the possible exception of the strain gage and almometer techniques (Shideler and McGrath, 1973; Brenninkmeyer, 1976) no method provides both sediment flux and bed elevation determinations; indeed at present no satisfactory technique exists for the determination of Lagrangian patterns of sediment transport and associated morphological changes during high wave conditions.

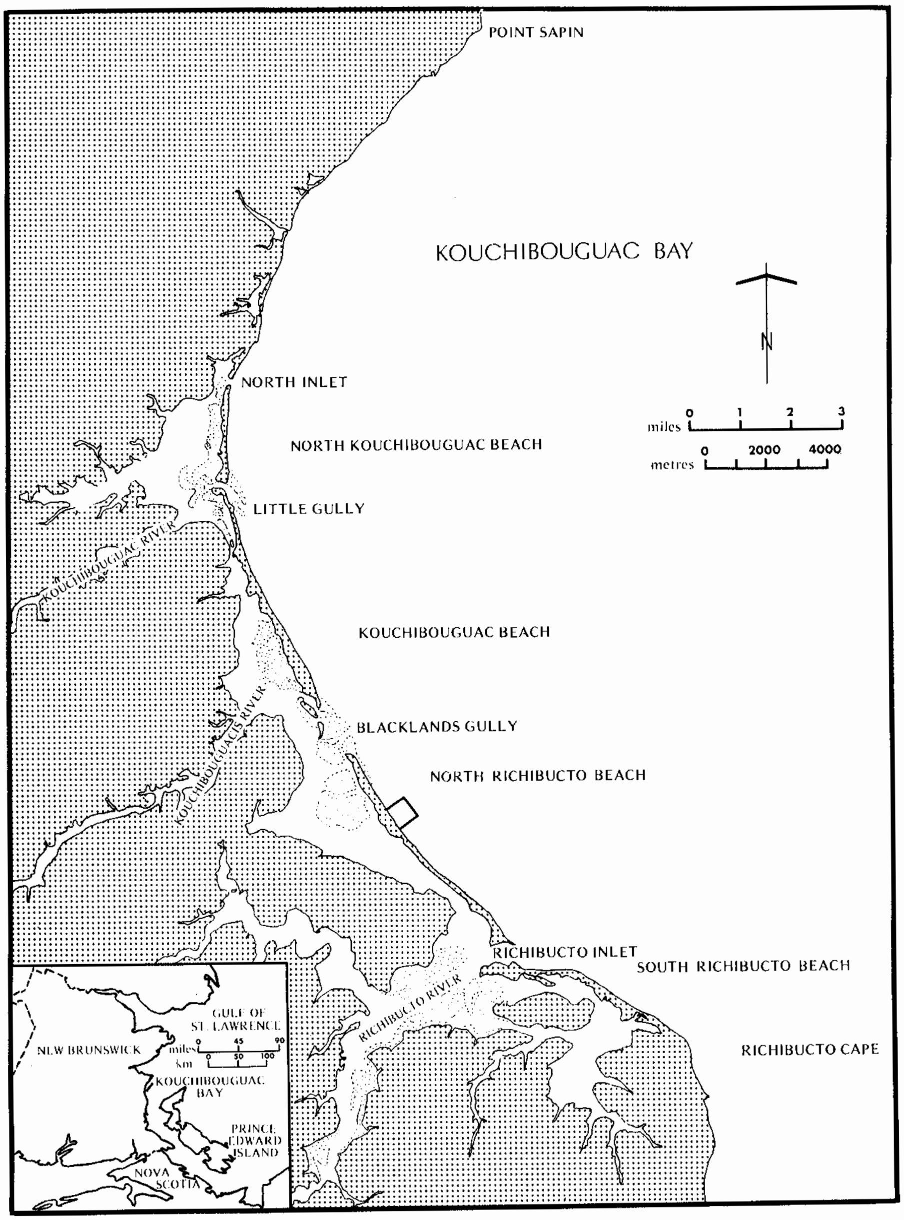


Figure 7.1

Location of the study area. Detailed work was carried out in the area of the nearshore zone shown by the box.

This paper describes a simple technique, the depth of disturbance rod, used to measure sediment flux (degradation-aggradation cycles) and bed elevation changes, which in conjunction with the analysis of sedimentary structures, provides a first approximation to the spatial and temporal patterns of sediment transport and associated morphodynamic behaviour of the nearshore zone. Experiments carried out during two discrete storm events are described from a barred nearshore environment in the southern Gulf of St. Lawrence.

The experimental site was established on an outer, crescentic nearshore bar system in Kouchibouguac Bay, New Brunswick (Fig. 7.1). Although the form of the nearshore bars, their spatial and temporal variability and basic sedimentary character have already been documented (Greenwood and Davidson-Arnott, 1972, 1975, 1979; Davidson-Arnott and Greenwood, 1974, 1976) some questions remain to be answered. Specifically, the relationship between the net alongshore sediment flux and the collective movement of sediments within the bar systems is still unclear. Estimates of the net alongshore sediment transport rate reveal values of approximately $10^5\ m^3\ a^{-1}$* to the south (Greenwood and Davidson-Arnott, 1977). In a single outer bar crescent, however, with a wavelength of 500 m there is approximately $2 \times 10^5\ m^3$ of sediment. Since this outer bar occupies much of the length of the bay, it is evident that the net littoral drift is only a small part of the sediment available in the nearshore zone. Furthermore, collective movement of sediment through bar migration is only in the order of $10^2\ m^3\ a^{-1}$ (Greenwood and Davidson-Arnott, 1979) and bar stability is a strong characteristic of the outer system. Thus while the bar form does change under storm wave activity, it is in the nature of a quasi-equilibrium in an environment of high sediment flux. Under such conditions, therefore, pertinent questions arise:

(1) What proportion of sediment in the bar system becomes mobile?
(2) What is the relationship between the thickness of the active layer and form changes?
(3) What is the spatial pattern of the degradation/aggradation cycles?
(4) What are the directional components of sediment transfer at different points in the bar during the period of sediment reworking and how are they related to the equilibrium form?

PROCEDURE

The depth of disturbance rod is a simple adaptation of the vigil network erosion pin (Leopold, 1962; Slaymaker and Chorley, 1964), which has previously been used in intertidal conditions (Clifton, 1969; Dolan et al., 1969; Williams, 1971; Knight, 1972; Dalrymple, 1972, 1973) but has not been tested in a continuously submerged nearshore situation. In this study a round steel rod (0.5 cm diameter, 1 - 2 m long) stamped with an identifier and tagged with a fluorescent streamer to aid recovery, is driven vertically into the sand until 0.45 m is left exposed above the surface; a loose-fitting washer (0.6 cm internal diameter) placed over the rod provides the control for determining bed surface scour or aggradation. Rods were deployed in two radial arrays using SCUBA prior to a storm event and re-examined in the immediate poststorm period. Rod measurements (Fig. 7.2) allowed determination of net surface change, maximum depth of activity relative to the prestorm surface and the total aggradation, if any. The only sequence of events that cannot be deciphered by the rod is an episode of aggradation followed by a smaller degree of degradation; the net result would appear as aggradation.

* a is the SI abbreviation for year.

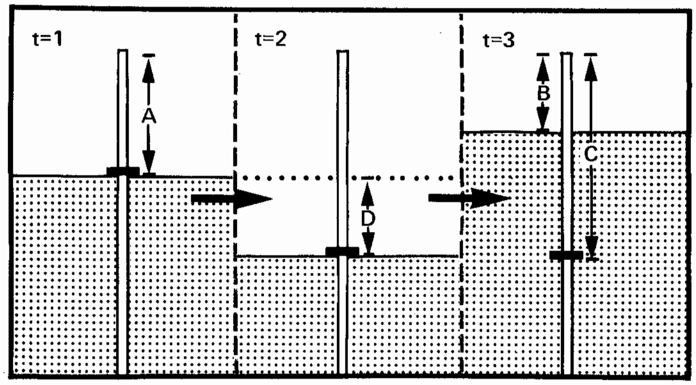
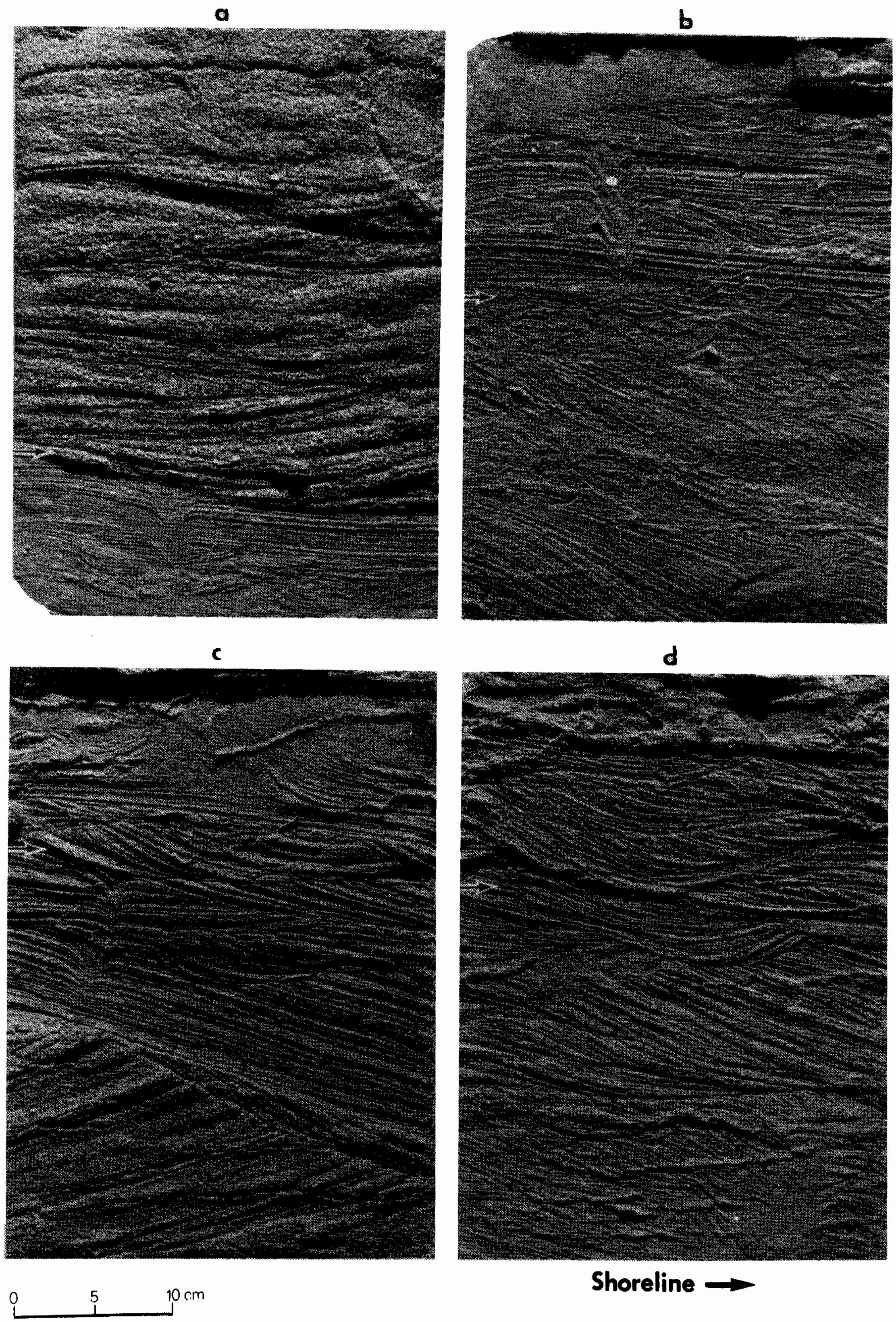


Figure 7.2. *Interpretation of depth of disturbance rod: t = 1,2,3 represent time intervals, stippling the sand bed and A,B,C,D measurements made relative to the top of the rod. The determinations to be made are: (a) net bed elevation change (A-B), this value may be positive or negative indicating aggradation or degradation; (b) maximum scour depth or depth of activity relative to the pre-storm surface (C-A); (c) total aggradation subsequent to maximum degradation (C-B).*

As with other techniques used in sediment flux determinations a calibration is necessary. A second estimate of the poststorm depth of activity and aggradation is indicated in epoxy peels of box cores by strong scour planes, structural or textural changes and truncation of bioturbation phenomena (Fig. 7.3). The good correlation achieved between rod values and core characteristics is illustrated in Figure 7.4a. A further estimate of the depth of activity can be made from the depth of burial of fluorescent tracers in core samples and Figure 7.4b illustrates again the good correlation with rod measurements. The consistency of the three measures of depth of activity indicates that no excessive scour or deposition is associated with flow interference from the rod itself. Direct observation of bedform generation and migration with no irregular surface deformation at the rod locations, at least under moderate energy conditions, provides further support for this conclusion.

The rods are reliable under both wave-induced oscillatory flow and longshore and rip current conditions, although difficulties of underwater measurement are encountered through failure to locate or identify the rod, rod bending, biogenic activity around the rod and difficulties of washer excavation in areas of high aggradation.

Besides providing a check on the accuracy of the depth of disturbance rods, box cores also indicate the assemblages of structures produced by bedforms during active sediment transport. Examination of these structures provides a measure of the type (and therefore relative rate) and direction of bedload movement, which is the dominant mode in the nearshore (Cook and Gorsline, 1972; Komar, 1976, 1977, 1978). For example, in Figure 7.3c the lowest sedimentation unit shows seaward-dipping, high-angle cross-stratification, indicative of the curved foresets of a dune form migrating seaward and obviously associated with a sediment flux in that direction. This unit is truncated above by a set of planar stratification dipping landwards at a lower angle, suggesting a shift through time to sheet flow and a probable reversal in the direction of sediment transport.



(a) core illustrating distinct scour surface, textural and structure change and truncation of a bioturbation feature at the depth of disturbance

(b) core illustrating scour surface and truncation of bioturbation feature at depth of disturbance

(c) core illustrating simple scour surface at depth of disturbance

(d) core illustrating multiple scour surfaces with no clear indication of most recent depth of activity

Figure 7.3. *Epoxy peels of box cores taken at the location of depth of disturbance rods illustrating scour sufaces: the depths of activity indicated by the rods are denoted by arrows.*

Therefore, the rods may be used to determine the amount of sediment flux occurring spatially, but also, using the structural indices, possible sediment transport paths during individual storm events may be reconstructed.

SEDIMENT FLUX AND MORPHOLOGICAL CHANGE: A CASE STUDY

The results of monitoring arrays of 62 depth of disturbance rods deployed over a single crescentic bar form together with analysis of selected pre- and poststorm box cores give a coherent picture of the patterns of sedimentation and morphological change associated with high wave conditions in the barred nearshore of Kouchibouguac Bay.

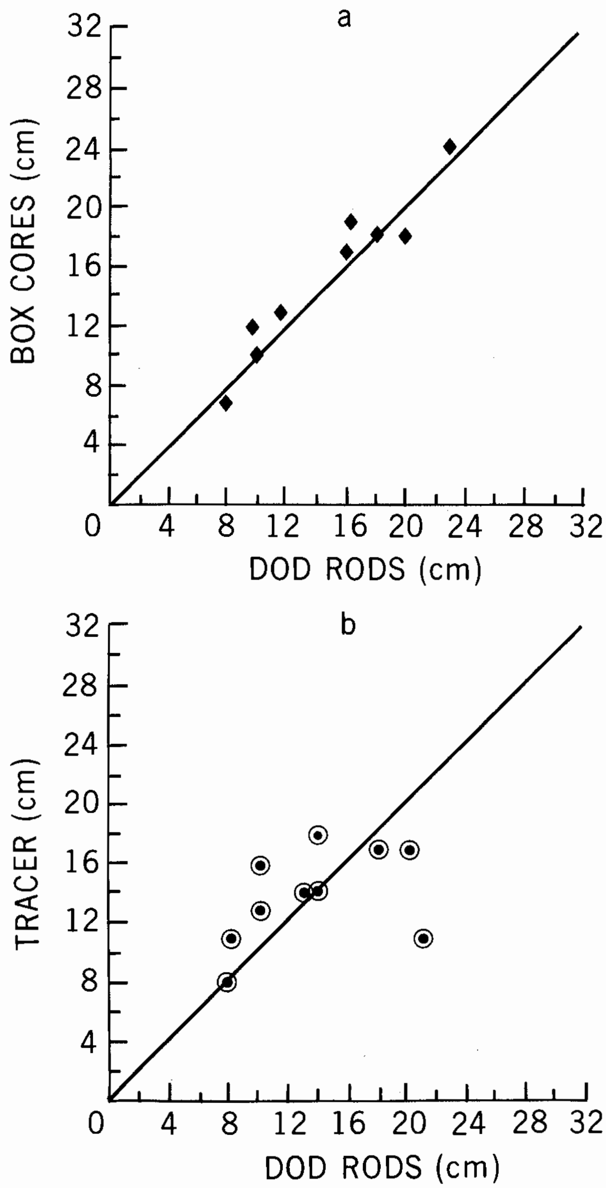


Figure 7.4. *Correlation between depth of activity determined from the depth of disturbance rods and: (a) sedimentary indicators in box cores; in these instances at least 3 of the indicators were present, (b) depth of incorporation of fluorescent tracers; 10 grains per 30 g sample was used as a cutoff concentration.*

Storm Event 1

A relatively shallow meteorological depression travelling southeast across New Brunswick on 1976-6-11 generated winds out of the northeast for 34 hours at North Beach in Kouchibouguac Bay (Fig. 7.5). Wave hindcasting (Hale and Greenwood, 1980) revealed maximum significant deep-water wave heights of 2 m with periods of 6 s (Fig. 7.5) and a return period for this storm of approximately 1.3 years. This is close to the return period of the most probable annual maximum storm, when the annual duration series is considered.

Figures 7.6a and 7.6c illustrate the values obtained for both depth of activity relative to the prestorm surface and the resulting bed elevation change. Scour depths range from a minimum of 6 cm on the landward slope of the bar to a maximum of 70 cm on the bar crest; bed elevation change reaches a maximum of 37 cm on the bar crest and a minimum of zero on the seaward slope. Clearly some areas have aggraded but the total pattern is one of surface lowering and apparent bar erosion. To examine sediment flux in greater detail variability normal to shore would seem an important aspect because wave approach approximates this after extensive refraction into Kouchibouguac Bay.

Figures 7.7a and 7.7b illustrate the changes revealed by the depth of disturbance rods along profiles across two areas of the outer bar system. Line BT illustrates the general one-bar profile of a simple crescent area whereas line CF illustrates a zone close to the shoal area where a distinct two-bar form is generated by a 'tail' extending landward from the southern crescent.

Line BT reveals maxima of depth of activity at two locations: seaward of the initial bar crest position (43 to 70 cm), and in the trough landward of the bar (43 cm). Depth of disturbance is relatively uniform over the landward slope (13 - 14 cm) whereas a general decrease is observed seaward over the seaward slope. Bed elevation change along the same line reveals: (a) maximum degradation on the seaward side of the prestorm bar crest (35 cm), coinciding with the zones of maximum depth of activity; (b) small but relatively constant lowering of the landward slope (1.5 - 4 cm); and (c) net aggradation at only one location, i.e., seaward of the zones of maximum scour and thus well seaward of the prestorm bar crest position. The rod data indicate a general deepening of the trough (up to 21 cm), seaward shift of the bar crest position and slight steepening of the seaward slope.

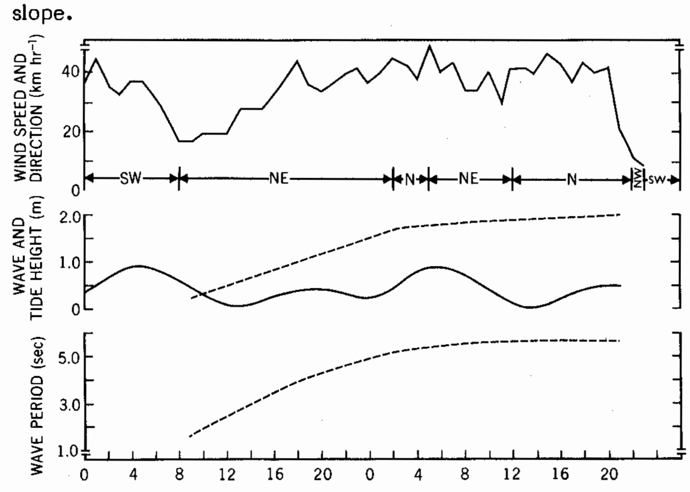


Figure 7.5. *Winds and predicted wave and tidal conditions, North Beach, Kouchibouguac Bay, 1976-6-11 to 1976-6-12.*

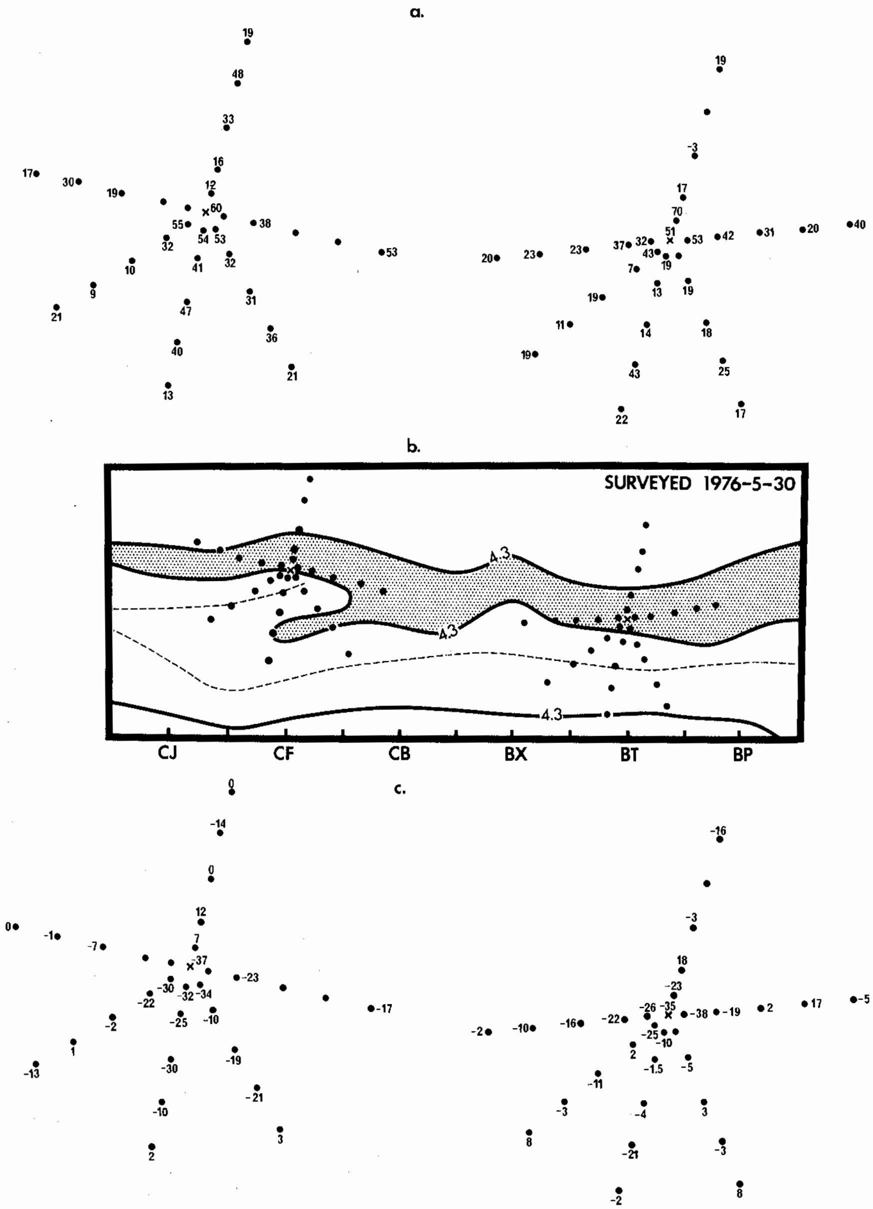


Figure 7.6

Depths of disturbance (a) and net bed elevation changes (c) from two radial grids centred on the bar crest along lines BT and CF (b) for the storm event 1976-6-11. Rods were spaced at 10, 25, 50, 75 and 100 m intervals from the centre along lines running approximately N, E, S, SW, W and NW. Rod locations lacking values reflect loss of rods. The contour line is referenced to a datum 1.1 m above mean water level.

Examination of the structures preserved in the active storm layer (this time relative to the poststorm bed surface) gives a clear indication of the directional component of the sediment flux. On the seaward slope significant sediment motion was initiated in 5.3 m of water. Figure 7.8 illustrates the structural indices developed at this location during the storm. The depth of activity is 14 cm and the plane bedding, dipping gently seaward, was generated by near-symmetrical oscillatory flow at the bed under conditions of wave shoaling. If the large pebble incorporated in the stratification was in motion during the storm then it may be possible to estimate the orbital velocity existing at the time (Komar and Miller, 1973, 1974, 1975a, b). For this pebble (sandstone S.G. = 2.6, average diameter = 5 cm) an orbital velocity of 183 cm s^{-1} is necessary for the initiation of motion with a 6 s wave period. As the pebble was in approximately 5.3 m of water, the necessary wave height would be 2.5 m, close to that hindcast for deep water during this storm. Thus with high velocities near the bed but near symmetric flow, upper flat bed conditions (Southard, 1975) would exist; however, the depth of activity was still relatively small and certainly bed elevation change was low.

On the bar crest, the zone of maximum activity (both depth of scour and bed elevation change) is clearly associated with the development and migration of large asymmetrical dunelike bedforms (lunate megaripples: Clifton et al., 1971; Davidson-Arnott and Greenwood, 1976), which are preserved as distinct sets of trough cross-stratification (Fig. 7.9b). The marked scour plane identified in Figure 7.9b separates the storm-generated megaripple cross-stratification and massive bedding from the small-scale ripple cross-stratification built up under low waves before the storm. A prestorm peel from the same location consists of small- to medium-scale trough cross-stratification and massively bedded medium sand in sequence (Fig. 7.9a).

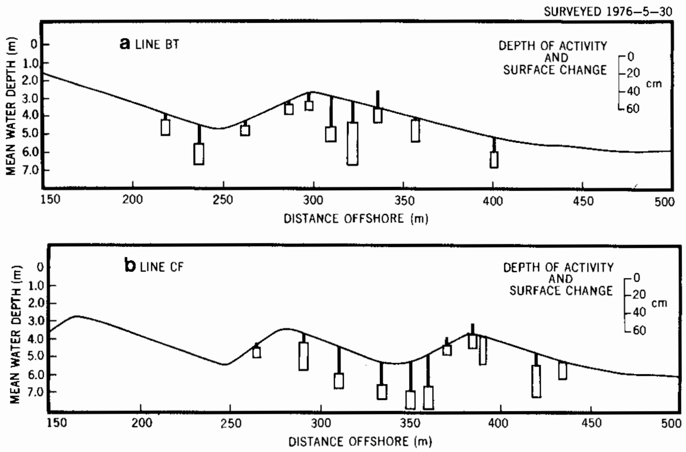


Figure 7.7. *Pre-storm profiles illustrating net bed elevation change (solid bar) and depth of active layer (open bar), relative to the pre-storm surface, along: (a) line BT and (b) line CF (Fig. 7.6). Note the scale difference for the depth of disturbance rod data.*

These structures are indicative of landward and oblique migration of ripples and megaripples. There is no evidence from this peel for seaward migration of bedforms at this point, in contrast to the poststorm peel. The juxtaposition of seaward- and landward-dipping cross-stratification in Figure 7.9b indicates that the direction of sediment movement varied greatly during the storm. However, it is extremely important to note that the major set of cross-stratification illustrates a clear seaward dip, and therefore seaward transfer of sediment at this point during the storm. Overlying this unit is a set of plane bedding dipping gently landward. This sequence is interpreted as representing lunate megaripple migration seaward under 'rip-type' currents generated during intense wave breaking on the seaward side of the bar crest followed by upper flat bed generated either as the storm abates and the rip currents decay, or as the rip migrates and asymmetric oscillatory flow over the bar crest is strong as the high waves continue to shoal. Furthermore, it is evident from the bed elevation change data that the location from which this core was taken changed from a position on top of the bar crest to one on the landward slope. This correlates well with the idea of erosion of the bar crest under rip-type flow and deposition seaward of the breaker line, producing a seaward migration of the highest point of the bar crest (see Figs. 7.6, 7.7).

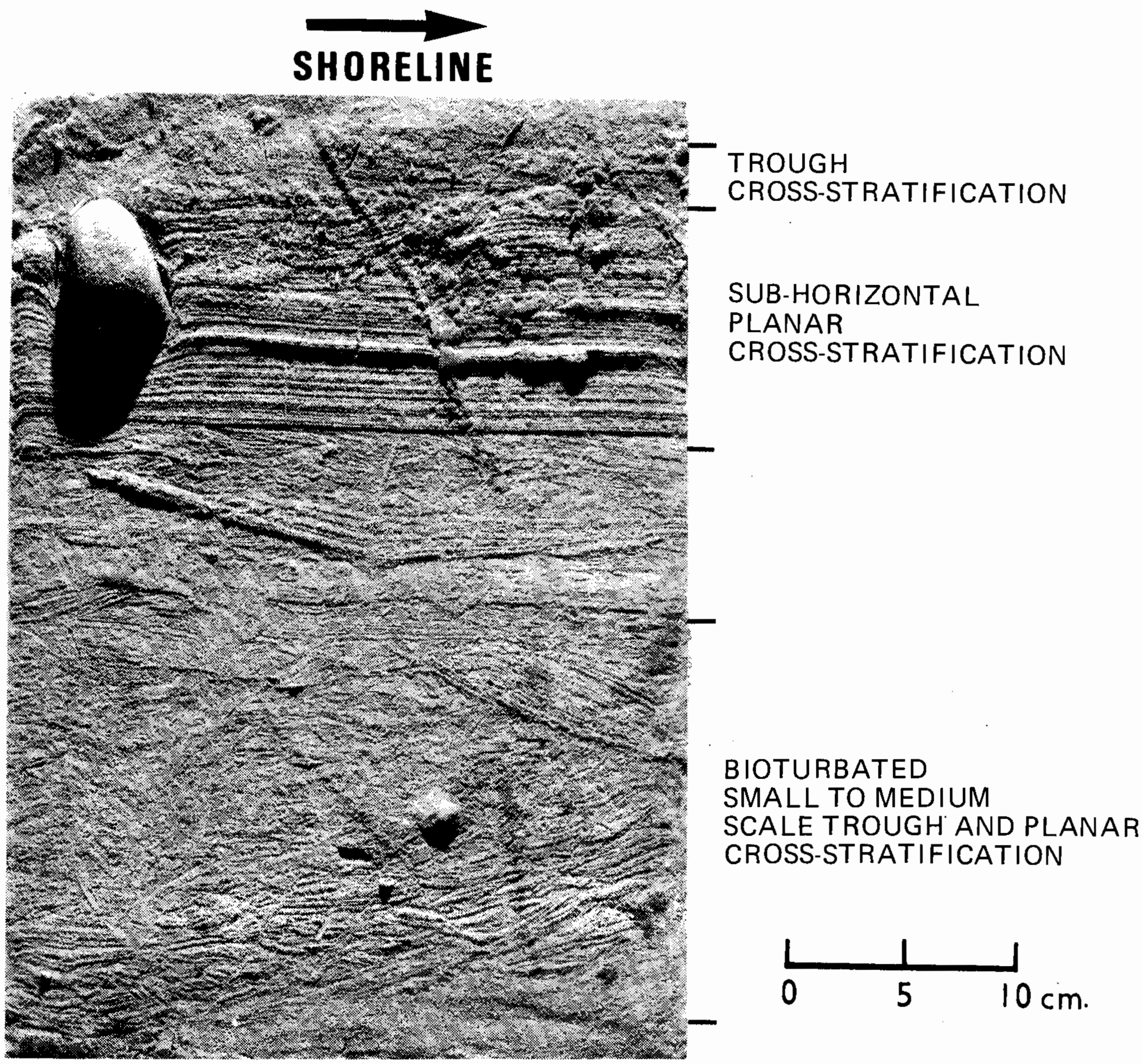


Figure 7.8. *Epoxy peel of box core from the active storm layer on the seaward slope in 5.3 m of water on line BT illustrating the structural indices of sediment transport.*

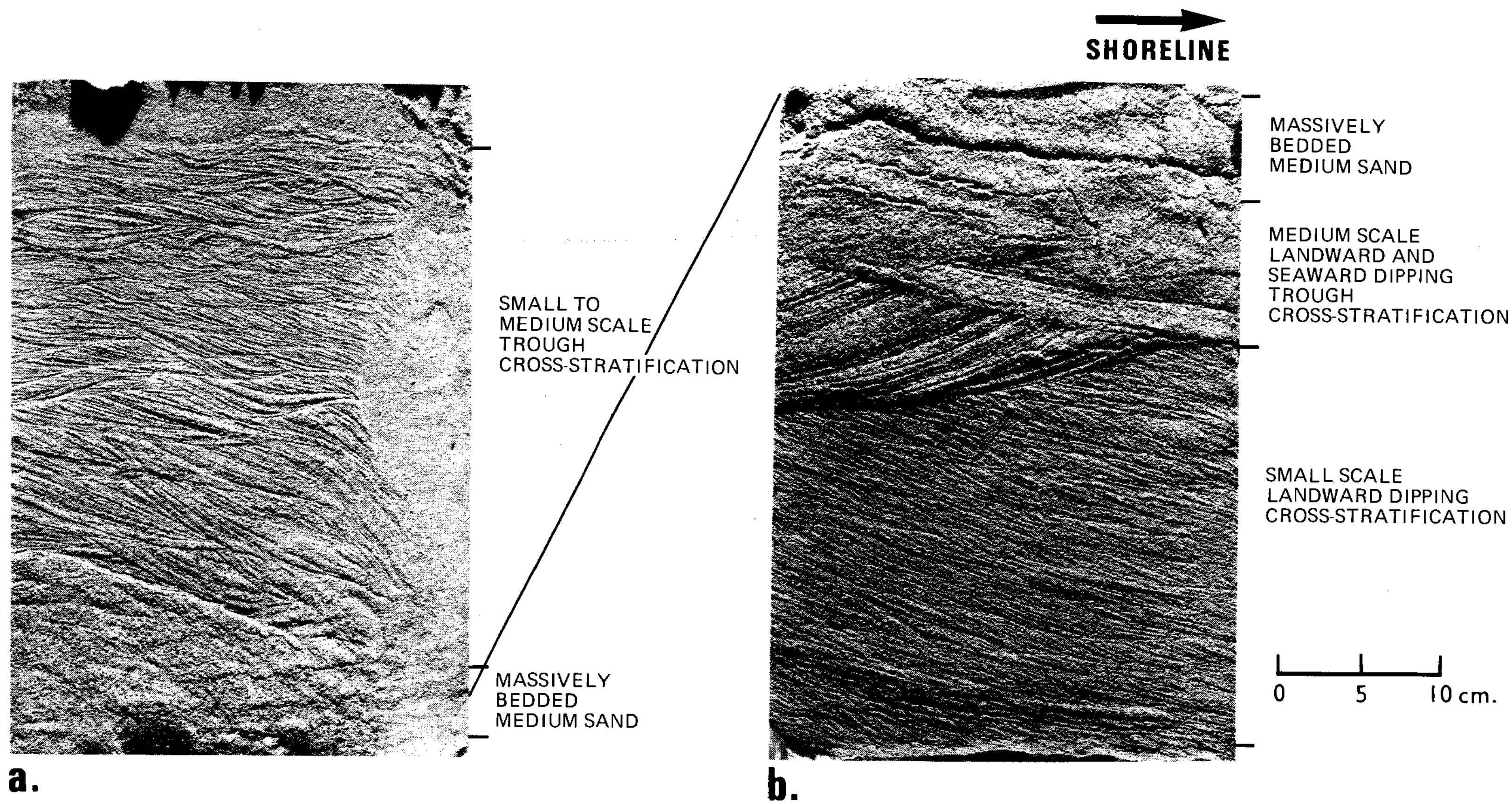


Figure 7.9. *Epoxy peels of prestorm (a) and post-storm (b) box cores from the bar crest in 2.5 m of water on line BT; the solid line marks the equivalent stratigraphic position.*

A pre- and poststorm sequence of cores was also taken from the bar crest north of the previous area at line BW (Fig. 7.10), at the northern limit of the depth of disturbance rods. Similar patterns emerge. The prestorm peel (Fig. 7.10a) consists of small- to medium-scale, trough cross-stratified indicative of ripples and megaripples migrating landward and oblique to shore. The direction and intensity of currents near the bed in this area must have fluctuated throughout the storm because both landward- and seaward-dipping cross-stratified units can be seen in the poststorm peel (Fig. 7.10b). The angle of dip is greatest for the seaward-dipping cross-stratification, suggesting that seaward migration may have been more or less normal to shore whereas landward migration was slightly oblique. The uppermost unit of small-scale trough cross-stratification is typical of ripple generation by low wave conditions following the storm.

On the bar crest it is evident that water and sediment flowed seaward over the crescentic area during the storm either as a very broad flow over 100 m wide, or as two distinct flows separated spatially or temporally. At present it is not possible to state unequivocally which interpretation is correct, but because the structural analogy is most closely correlated with rip currents in a measured inner system (Davidson-Arnott and Greenwood, 1974), then the most likely explanation is that narrow rips shifted spatially and temporally over a wide area of the crescent as the storm wave breaking conditions change.

Figure 7.11 illustrates the peel taken after the storm in the trough landward of the crescent (40 m landward of BT grid centre). Since no peel was taken before the storm and there was no DOD rod in the immediate area, the depth of disturbance can only be surmised from this peel, much of which is structureless. Unlike most other peels from the outer bar system this one contains a wide range of sediment sizes and several large shells. The only structures visible are seaward-dipping trough cross-stratification. These were formed by seaward-migrating dunes or megaripples; thus there must at some time have been a relatively strong seaward-flowing current in this area.

Some 60 m landward of the previous location on the seaward slope of the inner bar, two cores were taken, one before the storm and another following (Fig. 7.12). Both peels consist of cross-stratification indicative of ripple bedforms migrating normal, oblique and parallel to shore. Since the water depth averages just over 4 m the velocities near the bed generated by short-period waves will be low. These may or may not have been sufficient to initiate sediment transport and ripple formation; this will depend on the wave period at the time. Although low wave activity may account for the generation of ripples migrating normal or oblique to shore it could not account for ripple migration parallel to shore. Longer period waves break on the outer bar thus expending much of their energy. Hence the wave-induced velocities near the bed on the seaward slope of the inner bar are relatively low. The longshore current produced by the breaking waves, however, may be sufficient to generate ripple bedforms which migrate parallel, oblique or seaward depending on the direction and intensity of flow at that particular location. Since the peels were taken landward of the trough it seems unlikely that the longshore current would be flowing seaward in this location. The seaward return flow from a rip channel in the inner system 60 m north of the core location (line BV, Fig. 7.6) may, however, have produced sufficient seaward flow to generate migration of ripples in this location.

Storm effects in the area of line CF differ in several ways from those in the previous area considered, but the major distinction is in the increase in both depth of activity and bed elevation change (Figs. 7.6, 7.7b). This reflects the larger area of the bar form in shallower water which is thus subject to more intense wave and current activity. The zone of maximum depth of activity occurs again on the seaward side of the bar crest (both the outer and inner bar tail), reflecting the zone of wave breaking during the height of the storm. Excessive scour on the seaward margin of the seaward trough is also evident. Net bed lowering is again the general rule, although here aggradation on the landward side of the bar crest occurs, in contrast to line BT. In 5.3 m of water, at the seaward limit of the grid, depth of activity is considerable although there is zero bed elevation change as a result of the storm. As in the area discussed previously, the upper seaward slope steepens in association with aggradation seaward of the bar crest (Figs. 7.6, 7.7b). Sediment flux in this area can again be related to the bedforms active during the storm and preserved at depth; the inferred magnitude and direction of sediment transport correlates well with observed morphological changes.

At the seaward limit of the grid in 5.5 m of water the prestorm sediments were almost fully bioturbated (Fig. 7.13a), illustrating a lack of wave or current activity. In contrast, the poststorm peel (Fig. 7.13b) illustrates truncation of this deposit and the formation of interbedded sets of subhorizontal plane bedding together with small-scale ripple cross-stratification typical of the seaward slope. This indicates sediment transport under the nearly symmetrical oscillatory currents during wave shoaling (Davidson-Arnott and Greenwood, 1976). While considerable depth of activity occurred during the storm (19 cm below prestorm surface) bed elevation change was zero. This suggests a surface in dynamic equilibrium with these particular storm wave conditions and may well reflect directly the nearly symmetrical sediment flux indicated by the structures at this location. If this is the case, a point equivalent to that of oscillating equilibrium for single particles (Johnson and Eagleson, 1966) can be defined. Figure 7.4 illustrates structures generated in the active layer on the upper seaward slope of the bar (28 cm depth of activity relative to the poststorm surface). They form composite bedsets of plane-to-ripple bedding typical of wave shoaling with nearly symmetrical oscillatory flow (Davidson-Arnott and Greenwood, 1976), overlain by a distinct small- to medium-scale set of trough cross-stratification with dips oriented landward. The composite bedsets, characteristic of wave shoaling on both seaward and landward slopes, were probably developed during storm wave buildup and the landward-dipping cross-stratification is associated with peak conditions close to or at wave breaking, when strongly asymmetrical oscillatory flow covered parts of the seaward slope as well as the bar crest. Since the small-scale ripple cross-stratification is interbedded between sets of plane bedding the flow regime likely shifted during the period of active entrainment. Either wave energy fluctuated or water level shifted. The wind, tide and predicted wave characteristics for this storm, have already been shown in Figure 7.5 and energy dissipation in the nearshore clearly peaked during the falling cycle of a spring tide with a pure tidal fluctuation in water level of 85 cm, while predicted wave heights (at least in deep water) did not vary. It is interesting to note that aggradation of the bed occurred here and was about 12 cm, which would include this upper unit. Since the area immediately seaward experienced no net surface change but extensive scour (33 cm), while the area landward also experienced net aggradation, a net landward transport from the seaward side to the landward side of the bar crest can be inferred.

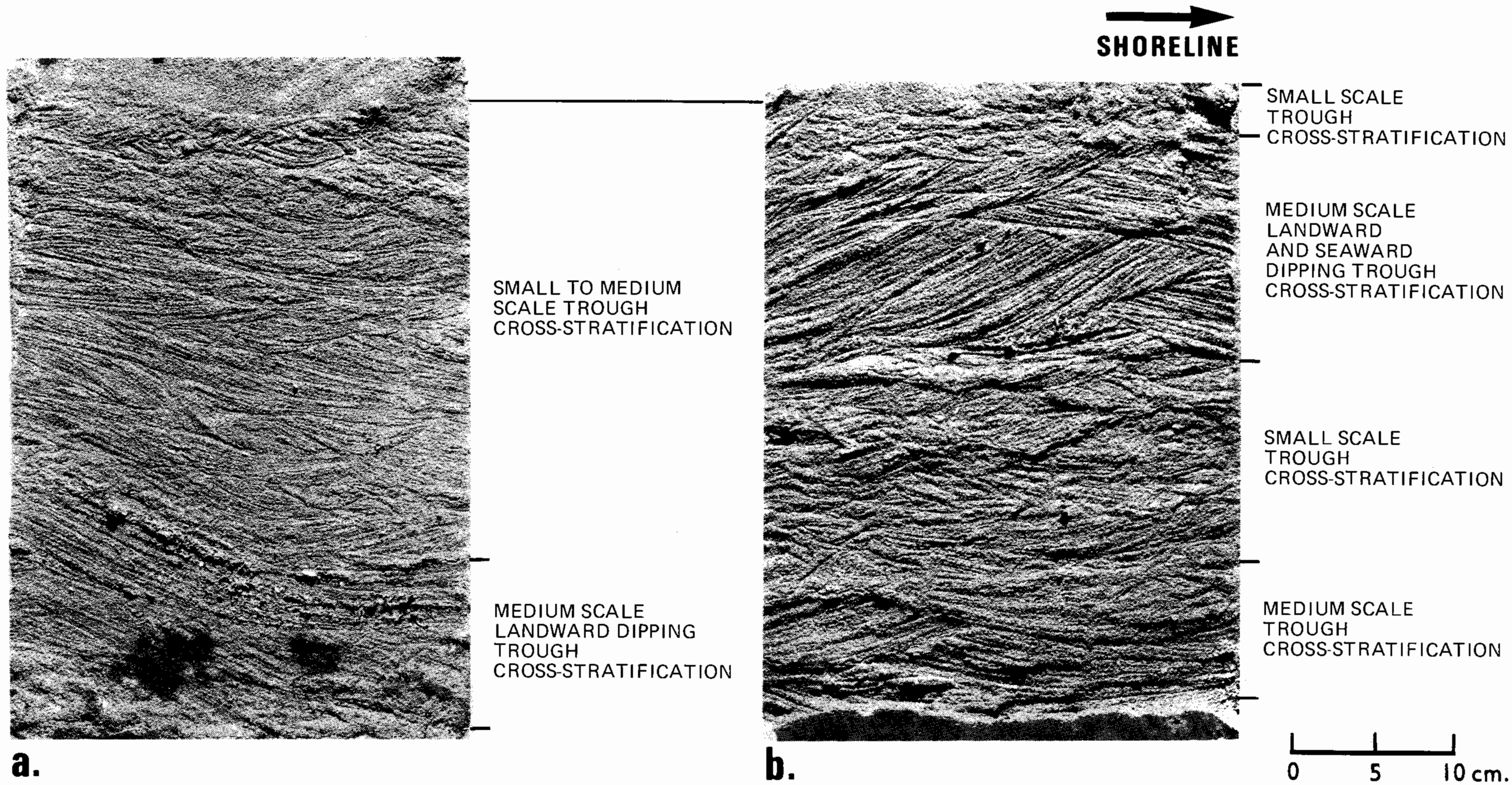


Figure 7.10. *Epoxy peels of box cores from the bar crest line BW: (a) prestorm deposits; (b) post-storm deposits.*

Figure 7.11 *Epoxy peel of box core from the trough in 4 m of water on line BT.*

Twenty-five metres shoreward of the previous location on the landward slope of the bar (see grid centre, line CF on Fig. 7.6) a prestorm peel illustrates features typical of the landward slope facies (Fig. 7.15a). Landward-dipping planar stratification up to 20° dip is the major set on this morphological slope of 2 to 3°. It is underlain and superimposed by landward-dipping trough cross-stratification and a small unit of plane bedding. During the storm, 37 cm of material was scoured away and the depth of disturbance reached 23 cm relative to the poststorm bed. Thus relative to the prestorm bed, the depth of activity was 60 cm, or almost twice the depth visible in the prestorm peel. For this reason one would not expect the prestorm structures in the poststorm peel (Fig. 15b). In the latter there is a distinct break, not only in the sequence of sedimentary structures, but also in the sediment size at a depth correlating closely with the rod measurement. The structures below this break are typical of the landward slope facies where the wave-generated oscillatory currents produce flat bed and ripple bedforms. In contrast, the overlying cosets of seaward-dipping cross-stratification indicate seaward-migrating megaripple bedforms. These must have been generated by seaward return of the longshore current similar to that of a rip current in the inner bar system. That such structures formed on the landward slope of the bar suggests that the speed of this current was considerable and that significant quantities of sediment were being transported obliquely upslope. The massively bedded units near the top of the peel may reflect extremely rapid sedimentation as a result of the interaction between the seaward-flowing current and waves.

The rod data combined with the structural indices illustrate distinct but complex patterns of sediment flux over one crescentic bar during this storm. As the storm represents the most probable annual maximum event in intensity (measured by wave height and cumulative energy) it is probably the controlling event in nearshore equilibrium. This is supported by the depth at which significant sediment movement initiates morphological change: on line CF in 5.5 m of water, for example, the rod indicates considerable depth of activity but zero bed elevation change. On line BT again significant depth of activity occurs but bed elevation change is restricted to 18 cm, this time in 4.5 m of water.

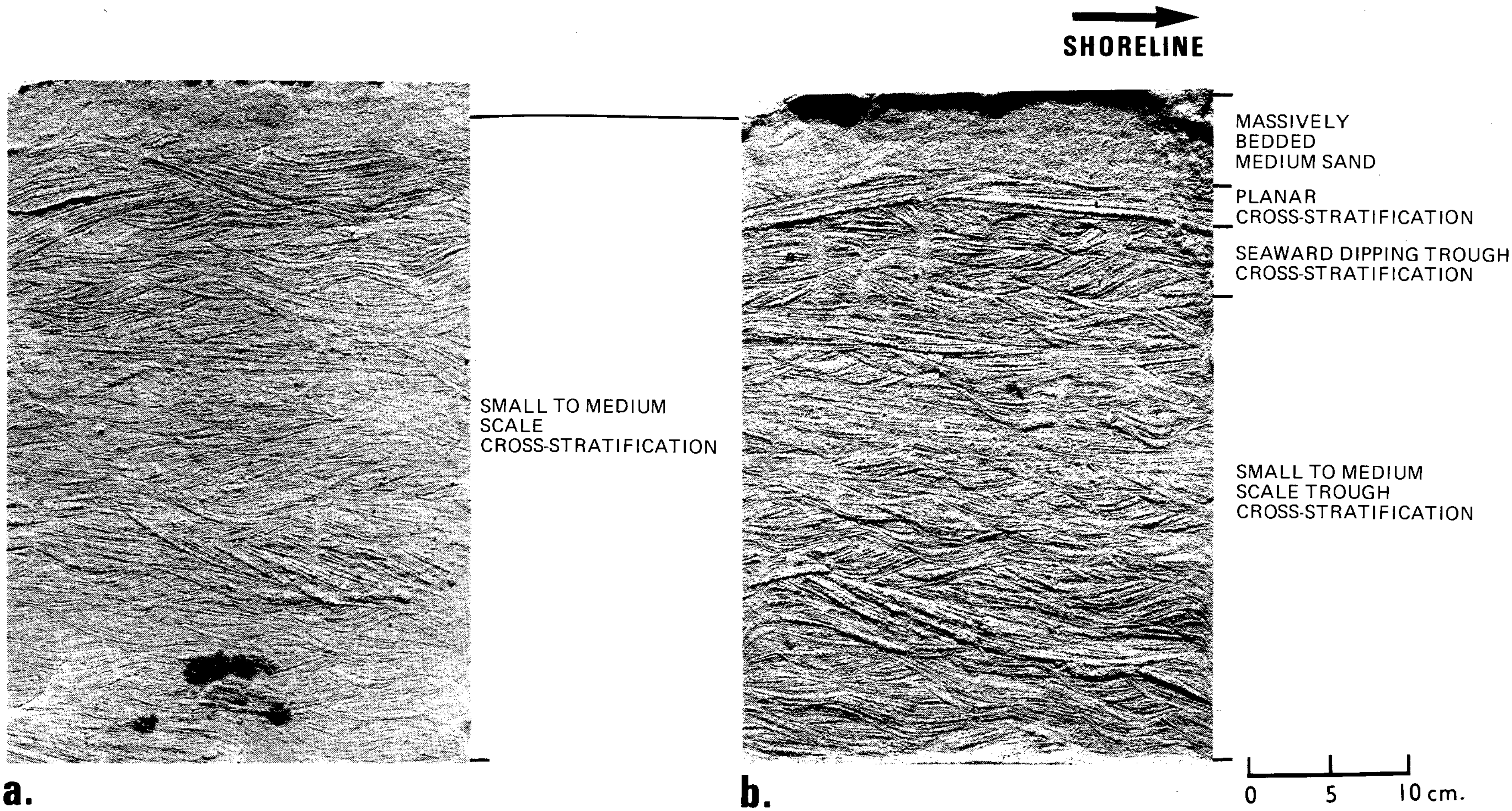


Figure 7.12. *Epoxy peels of box cores from the seaward slope of the inner bar line BT: (a) prestorm; (b) poststorm.*

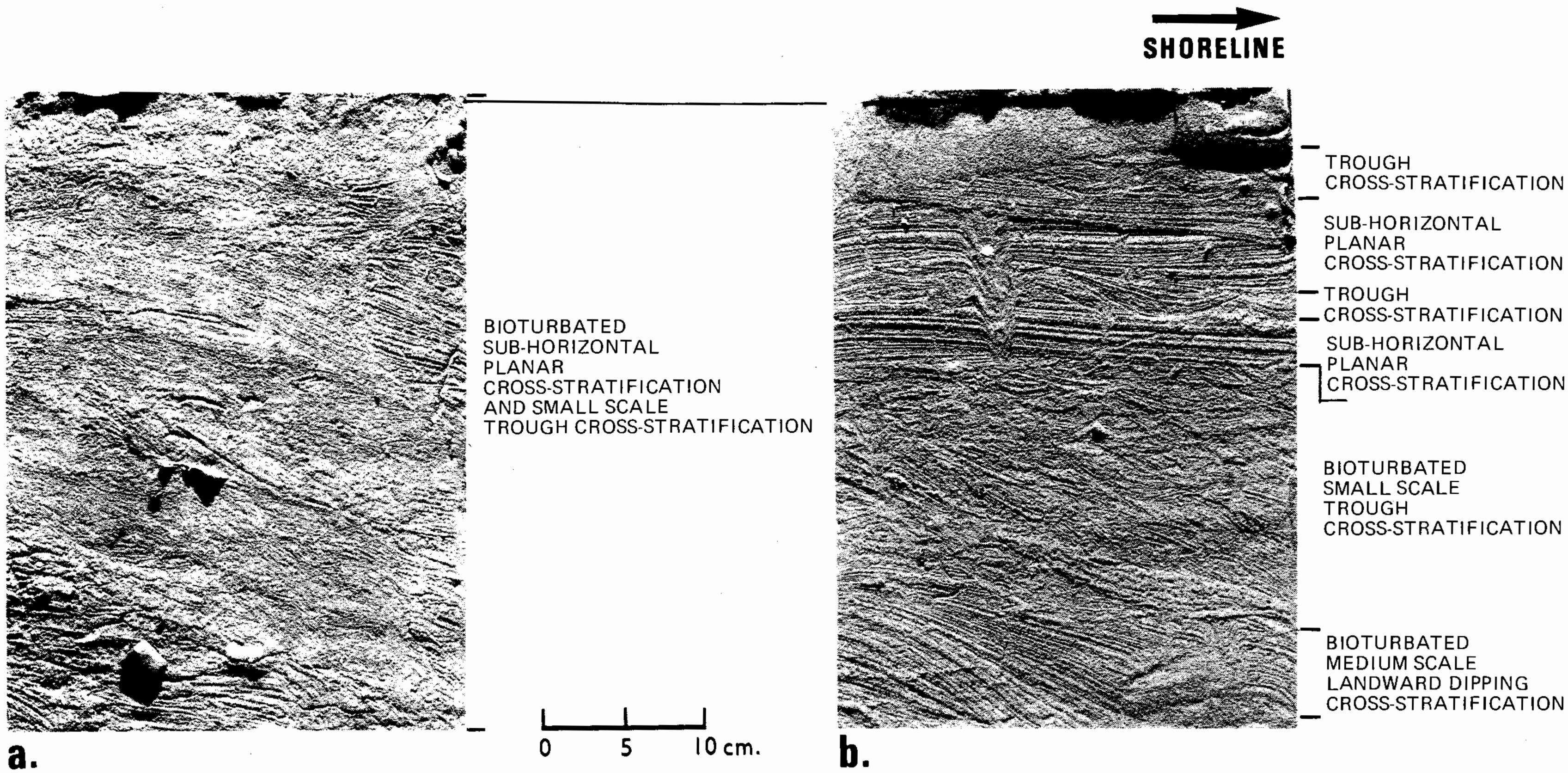


Figure 7.13. *Epoxy peels of prestorm (a) and poststorm (b) box cores from the seaward slope in 5.3 m water depth on line CF.*

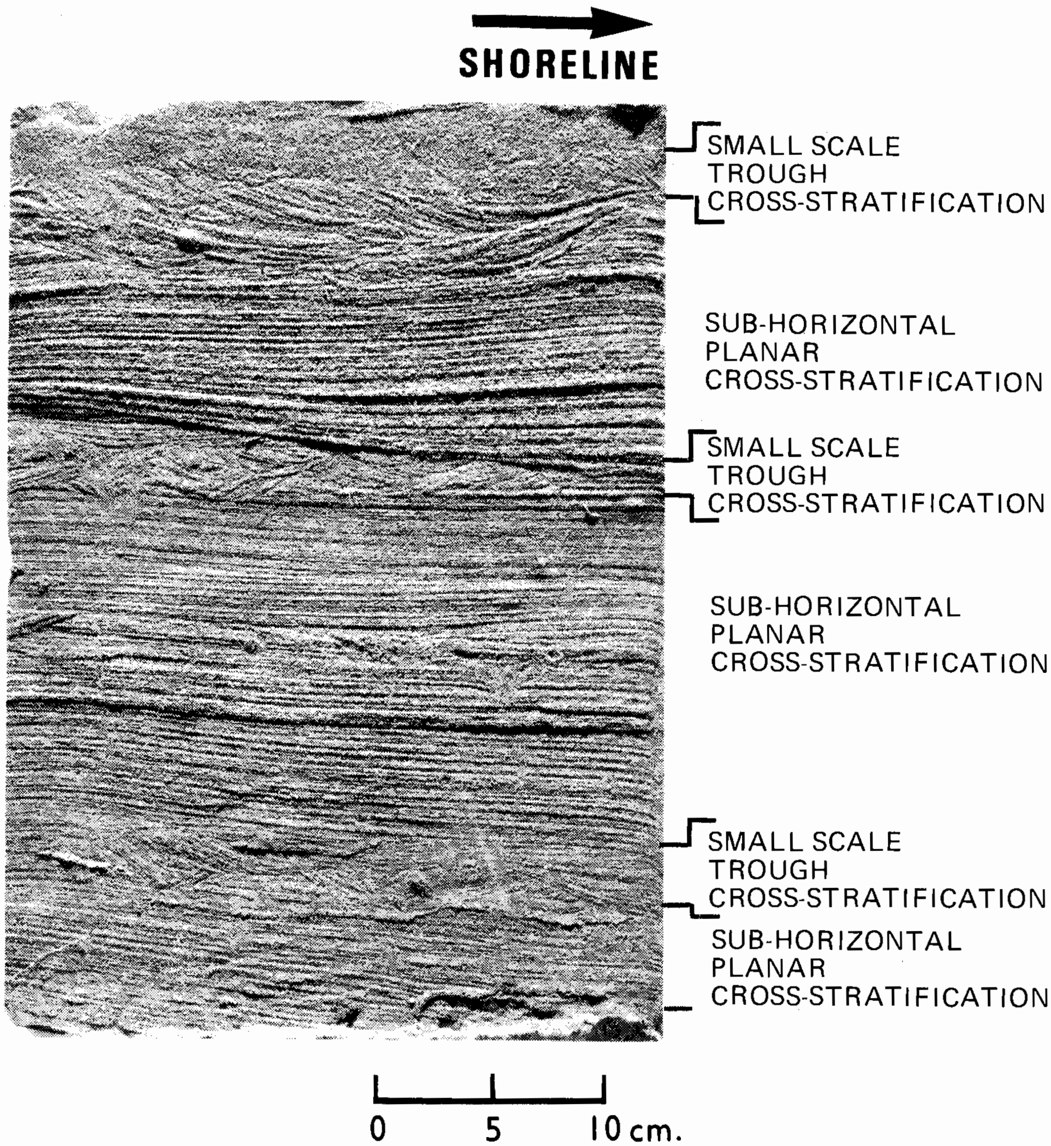


Figure 7.14 *Epoxy peel of post-storm box core from the bar crest line CF in 2.5 m water depth.*

Thus as one moves seaward bed elevation change approaches zero, even though sediment reactivation is considerable. It is also important to note that the point of zero bed elevation change is very close to the marked break-in-slope at the seaward foot of the bar. This clearly suggests that the seaward slope represents a dynamic equilibrium controlled by wave oscillatory currents and secondary rip currents with the seaward foot of the bar marking a point of initiation of the equilibrium slope probably associated with some threshold value of wave asymmetry which produces landward transport. General bar stability will thus be a result of a sediment balance maintained by a seaward flux of sediment in the rip-type currents. This equilibrium is further emphasized when the percentage of the total bar sediment in motion during the storm is computed and compared with the percentage change in bar form. On profile BT approximately 25 per cent of the bar form is mobilized, whereas for line CF it is 32 per cent. Thus large volumes of sediment were set in motion while the bar form remained relatively stable (per cent sediment loss: line BT = 4; line CF = 7).

Storm Event 2

On 1976-8-14 a stationary front situated south of Northumberland Strait generated winds out of the north and northeast in Kouchibouguac Bay, which persisted for almost two days during which maximum hourly wind speeds reached 38 km h^{-1} at North Beach (Fig. 7.4). Hindcast wave conditions gave deep water values of 152 cm for significant height and 5 s for period. Such a storm would have a return period of approximately one month (Hale, 1978) and thus represents a very frequent event in the nearshore time series.

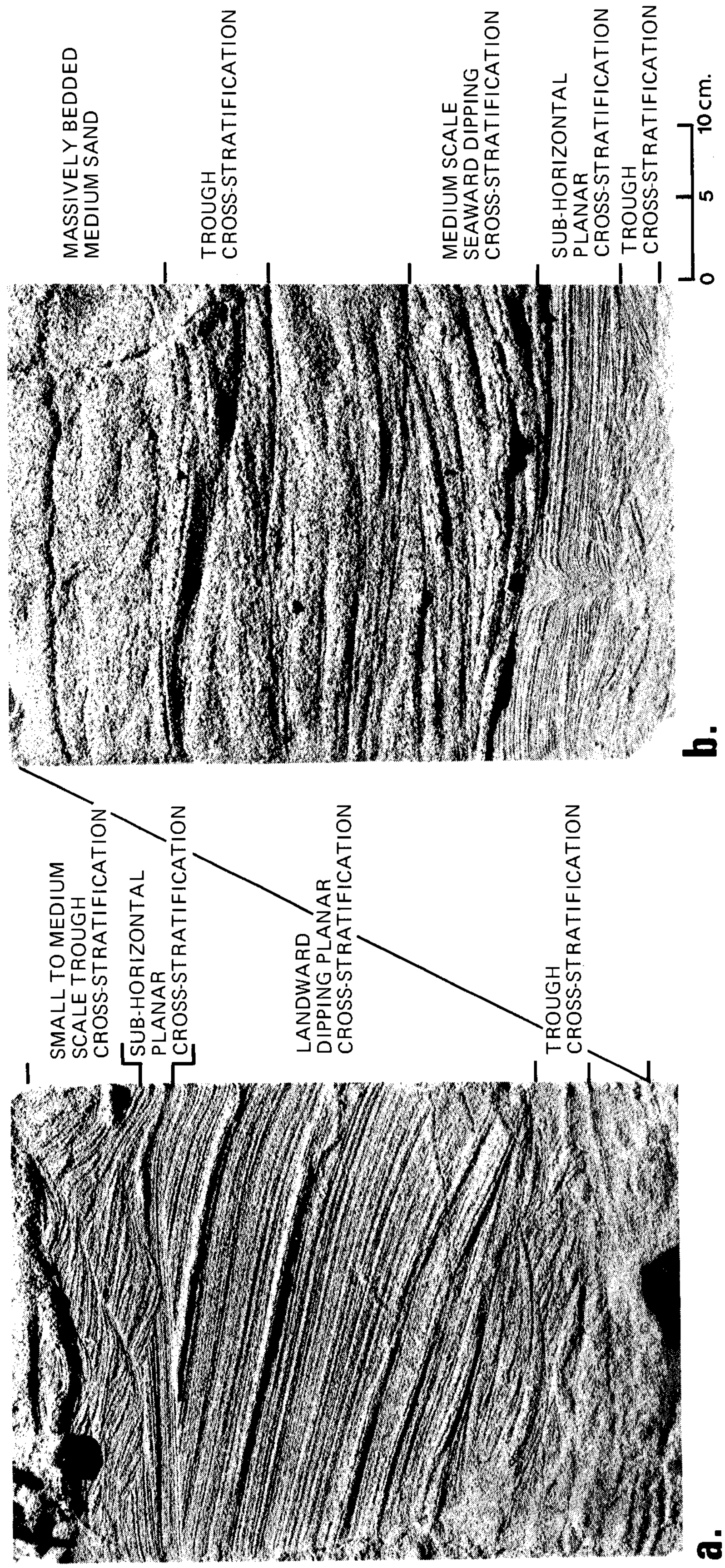


Figure 7.15. *Epoxy peels of prestorm (a) and poststorm (b) box cores from the landward slope line CF in 4.5 m of water.*

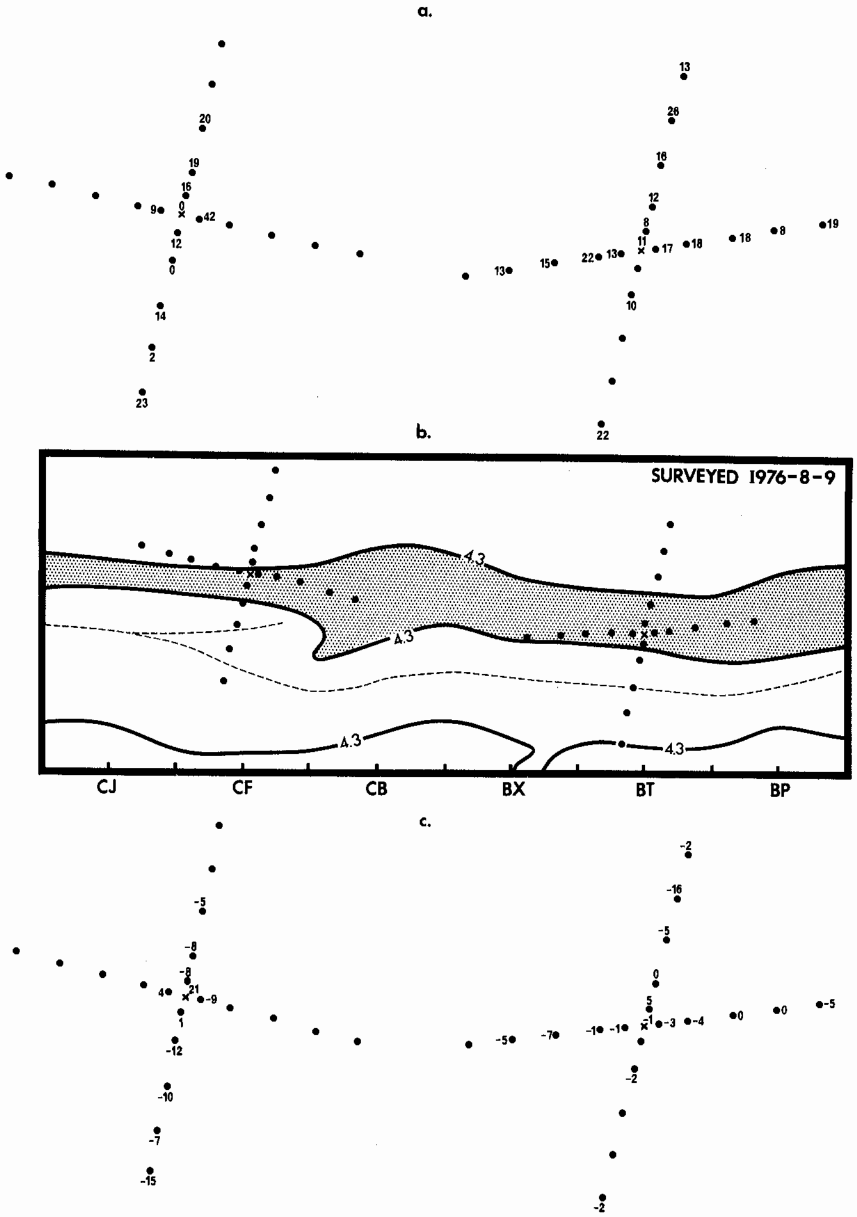


Figure 7.16.

Depths of disturbance (a) and net bed elevation change (c) from two radial grids centred on the bar crest along lines BT and CF (b) for the storm event 1976-8-14. Rods were spaced at 10, 25, 50, 75 and 100 m intervals from the centre along lines running approximately N, E, S and W. Rod locations lacking values reflect loss of rods. The contour line is referenced to a datum 1.1 m above mean water level.

Figures 7.16c and 7.16a illustrate the rod readings for bed elevation change and depth of activity, respectively, and show, as might be expected, the relatively smaller changes generated by this smaller storm. Shore normal changes are again illustrated with reference to prestorm profiles along lines BT and CF (Fig. 7.17a, b). While the degree of change was small (maximum depth of active layer = 33 cm; maximum bed elevation change = +21 cm) the type of change was similar to that of the first storm for similar locations within the bar system. The trough, bar crest and upper seaward slope again exhibit greatest depths of activity while net aggradation is experienced only in areas just seaward of the prestorm crest; all other locations experienced net degradation. The landward slopes in these areas again experienced uniform depth of activity and lowering.

An examination of structures preserved in the crescent area (line BT) reveals the difference between sediment flux under this storm and the previous storm event. Figure 7.18a-c illustrates the structures found on the seaward side of the bar crest (a), the bar crest itself (b), and the landward slope (c). The depth of activity relative to the poststorm surface was 12 cm, 24 cm and 7 cm, respectively. The sequence of structures preserved is subhorizontal plane bedding on the seaward side of the bar crest, small- to medium-scale sets of trough cross-stratification dipping landward on the top of the bar crest, and massively bedded sand on the landward slope. All of this suggests landward migration (if any) of sediments over this crescent area during the storm and in fact a buildup and increase in height of the bar crest itself. However, the structures preserved from previous storms show that this had once been a zone of seaward-migrating megaripples, as evidenced by the sets of medium-scale seaward-dipping cross-stratification shown in Figure 7.18a-c. This suggests that this magnitude of storm did not generate a significant seaward flow of water over the bar crest since wave breaking was not intense enough to

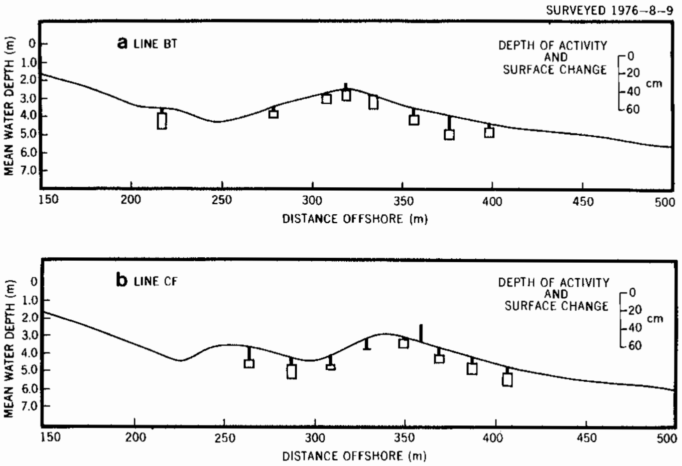


Figure 7.17. *Prestorm profiles illustrating net bed elevation change (solid bar) and depth of activity (open bar), relative to the pre-storm surface along: (a) line BT and (b) line CF. Note the scale difference for the depth of disturbance rod data.*

cause rip currents in this outer bar system. This further suggests a bar response characterized primarily by sediment flux landward and alongshore in the trough. It is interesting that a series of cores taken across the bar crest and landward slope at a shoal area, line BZ (Fig. 7.19b), illustrate structures indicating landward sediment movement across the crest and avalanching down the landward slope. The peel from the crest (Fig. 7.19a) illustrates landward-dipping trough cross-stratification overlain by landward-dipping tabular cross-stratification, trough cross-stratification and finally, small-scale landward-dipping cross-stratification. With the exception of the uppermost unit all others are indicative of high wave energy conditions. The fact that tabular units of steeply dipping cross-stratification are present suggests very strongly that asymmetrical currents were generated in this area, even that a surf zone may have developed and that the bores produced these units. The trough cross-stratification and small-scale landward-dipping cross-stratification associated with megaripple and ripple bedforms, which overlie the tabular units, reflect decreasing wave energy conditions or increasing water depth. The cores from the landward slope at the shoal (Fig. 19b, c) are dominated by avalanche bedding (up to 17° dip) which at the toe of the bar overlies fine sands and silts of the trough and in turn is overlain by massive very fine sands. The bar foresets meet abruptly with the trough sediments; no distinct toesets are present. This is similar to the observations made by Davidson-Arnott and Greenwood (1974) at the base of a migrating slip face on the inner bar system. They concluded that the longshore currents in the trough during high energy conditions, when the bar is actively migrating shoreward, prevent deposition of material from suspension, thus accounting for the lack of distinct toesets. The same situation likely existed on the outer bar during the storm event. The massively stratified unit above the planar cross-stratified unit may reflect settling out of suspension after the peak of the storm whenever wave energy conditions subsided. Although no depth of disturbance rods were present in this area, the incorporation of tracer in the box cores and the soft, unstable nature of the landward slope indicate that the structures represent this small storm event. Undoubtedly the shallow water depth over the shoal would be conducive to greater activity than over the crescent area.

CONCLUSIONS

The depth of disturbance rod is clearly successful in determining the depth of the active sediment layer during a storm event at a point permanently submerged in the nearshore zone, the temporal sequence of degradation-aggradation at that point, and the net bed elevation change resulting from the gross sediment flux induced by storm waves. The rod is more accurate, simpler and quicker than other methods presently employed to study depth of activity (compare King, 1951; Kolp, 1958; Kumar and Sanders, 1976; Vvedenskaya, 1977). Although continuous monitoring of absolute values of sediment flux is not possible with this technique, its simplicity permits deployment of considerable numbers of rods for the detection of spatial variability of net flux through time. Furthermore the directions and relative rates of sediment transport can be interpreted from the structural indices preserved in the active layer and recorded in box cores. Even where direct measurement devices have been deployed either in numbers (Brenninkmeyer, 1974) or as a mobile system (Kana, 1976; Coakley, 1978) they were restricted to measuring only part of the total sediment load and generally give no indication of the direction of transport.

The study of sediment flux over two discrete storm events affecting a nearshore crescentic bar system in the southern Gulf of St. Lawrence produced the following conclusions:

1. As might be expected, depths of activity are greater under more severe storms. Maximum depths of scour during the two storms were 70 cm for predicted deep-water significant wave heights of 2 m and periods of 6 s, and 23 cm for wave heights of 1.5 m and periods of 5 s.

2. In both storms maximum depths of activity were on the seaward side of the bar crest, where wave breaking would be most intense and where asymmetrical oscillatory flows or rip current flows at the bed would be at a maximum under all wave conditions. In contrast minima occurred on the upper part of the landward slope. A secondary maximum of depth of activity was associated with the trough where longshore currents caused considerable scour, although in these depths of water (4 to 5 m) they would be active for only a relatively short time during the most intense phase of wave breaking on the bar. This short time period, however, is clearly compensated for by the higher rates of sediment flux associated with unidirectional as opposed to oscillatory flow (whether symmetrical or asymmetrical).

3. In general net bed elevation changes were negative, revealing erosion of the bar form during storms. Maxima of bed surface change were located on the seaward side of the bar crest (35 cm of erosion) and in the trough close to the foot of the landward slope (37 cm of erosion) for Storm 1. Net aggradation was found either on the upper landward slopes (12 cm) or upper seaward slope (21 cm), although the latter was found following the lower wave activity of the second storm.

4. An examination of the structural indices preserved in the poststorm active layer allows an interpretation of water and sediment transport conditions during the storm. On the seaward slope of the bar sediment was being transported in a minimum depth of 4.8 m for both storms. Landward of this, in approximately 4.5 m of water, the structures indicate a transition from small-scale ripples and flat bed of the seaward slope subfacies to flat bed and megaripples of the bar crest subfacies. This reflects increasing asymmetry and speed of oscillatory flow and greater rates of sediment transport towards the crest. On the bar crest the inferred direction of bedform migration

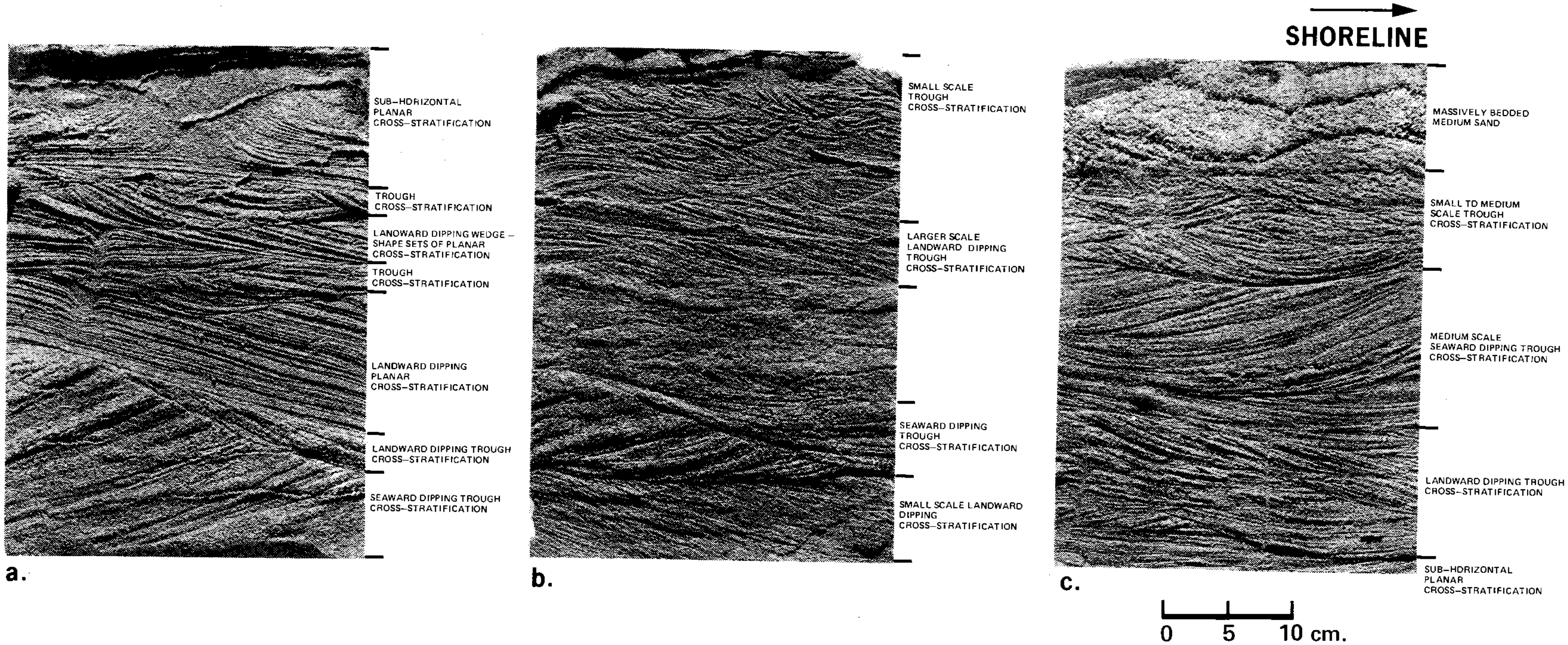


Figure 7.18. *Epoxy peels of box cores from the active storm layer line BT: (a) seaward side of bar crest; (b) top of bar crest; (c) landward slope of bar.*

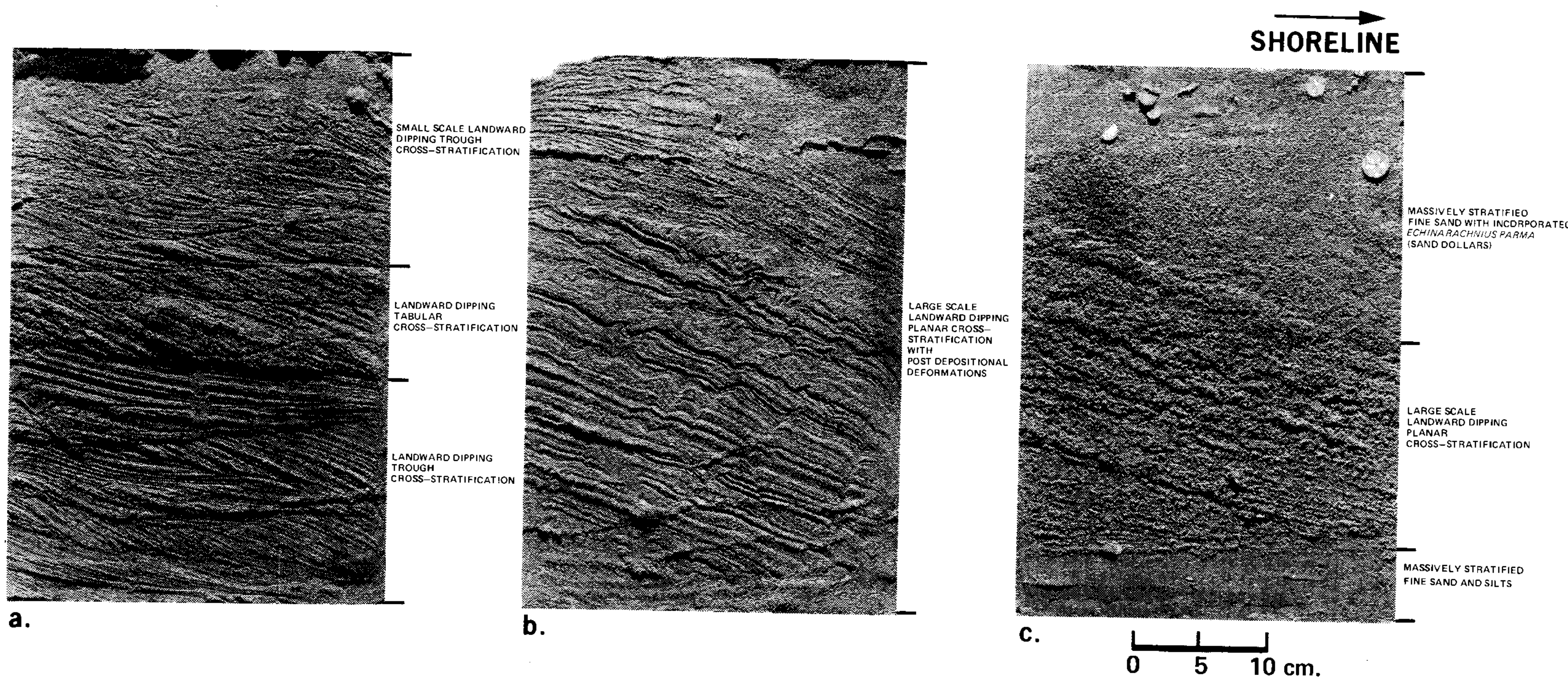


Figure 7.19. *Epoxy peels of poststorm box cores from the bar crest (a), mid-landward slope (b) and toe of the landward slope (c) on line BZ.*

varied considerably from place to place and even at a single location. With the exception of the shoal areas, where bedform migration was consistently shoreward, all other areas of the crescentic form showed evidence of megaripple migration in several directions during the storm. A distinct seaward component could be identified, however, suggesting that a seaward return flow of sediment was dominant at times but that either it was dispersed between the shoal areas, or the position of the return flow varied with time. The evidence of seaward-migrating megaripples on the landward slopes indicates that at some time during the storm the speed of the return flow must have been considerable. It seems highly unlikely that such currents could have existed simultaneously throughout the length of the crescent. The lack of a well defined channel to confine the return flow further suggests that it may shift in position. This could account for the juxtaposition of landward- and seaward-migrating bedforms on the bar cresent.

5. The sediment flux patterns derived from the depth of disturbance rods and structural indices support the conceptual model of bar stability based on rip cell circulation proposed by Greenwood and Davidson-Arnott (1979). The idea is supported that the bars are indeed equilibrium forms in a very dynamic sedimentological environment and respond to storm magnitudes close to that of the most probable annual maximum.

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