Geoscience Canada

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Volume 24, Number 1, March 1997

URI: https://id.erudit.org/iderudit/geocan24_1art03

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

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Cite this article

Dalrymple, R. W. & Hoogendoorn, E. L. (1997). Erosion and Deposition on Migrating Shoreface-attached Ridges, Sable Island, Eastern Canada. *Geoscience Canada*, *24*(1), 25–36.

Article abstract

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Erosion and Deposition on Migrating Shoreface-attached Ridges, Sable Island, Eastern Canada

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SUMMARY

The shoreface-attached ridges present along the south side of Sable Island, Nova Scotia, are the largest and deepest yet described, but become smaller and finer grained to the east because of decreasing energy levels. Strong, alongshore, storm currents cause them to migrate eastward at rates that may reach 50 m·a^{-1}. Their migrating troughs erode underlying sediments, modifying the wave-ravinement surface and creating shoreline-oblique depressions up to 12 m deep. Deposition occurs on their lee side, in the form of gently dipping, graded storm beds up to 1.2 m thick containing both high-angle cross bedding and hummocky cross-stratification. Overall, the ridge deposits coarsen upward and resemble shoreface successions. Obliquely onshore, cross-ridge flow causes upbuilding by the Huthnance process and accounts for the unusually high angle (~ 50°) between the ridges and the shoreface.

RÉSUMÉ

Les crêtes situées dans la zone infratidale du littoral, au sud de l'île *Sable Island* en Nouvelle-Écosse sont les plus grosses et les plus profondes décrites à ce jour, bien que leurs volumes et la granulométrie de leurs constituants diminuent vers l'est, à cause de la diminution des niveaux d'énergie ambiants. De forts courants côtiers engendrés par des tempêtes provoquent leur migration vers l'est à des vitesses pouvant atteindre 50 mètres par année. Leurs cuvettes d'affouillement mobiles érodent les sédiments sous-jacents, modifient les surfaces d'érosion créés par les vagues et creusent des dépressions, obliques par rapport à la ligne du littoral, dont la profondeur atteint 12 m de profondeur par endroits. Les sédiments se déposent sur la face aval sous la forme de couches sédimentaires de tempête, granoclassées et faiblement pentues, mesurant jusqu'à 1,2 m d'épaisseur et montrant des stratifications entrecroisées normales ainsi que des stratifications entrecroisées à surfaces bosselées (HCS dans l'article). Globalement, la granulométrie des sédiments de ces crêtes s'accroit vers le haut, ressemblant en cela aux empilements littoraux. L'existence d'un courant côtier oblique vers le rivage, et en travers des crêtes, provoque l'accumulation de sédiments en vertu du mécanisme de Huthnance et explique le grand angle (~ 50 degrés) que font les crêtes par rapport à la ligne de rivage.

INTRODUCTION

Shoreface-attached ridges are linear- to slightly-curved, shoreline-oblique sand bodies that lie directly seaward of the shoreface and are outlined by seaward deflections of coast-parallel, shoreface isobaths (Duane *et al.*, 1972). Globally, they are characteristic features of transgressive coastlines:

- United States' east coast: Duane *et al.*, 1972; Swift and Field, 1981; McBride and Moslow, 1991
- Sable Island, Nova Scotia: Hoogendoorn and Dalrymple 1986; Hoogendoorn, 1989
- Argentina: Parker *et al.*, 1982
- Brazil: Figueiredo *et al.*, 1982
- the Dutch and German North Sea coasts: Antia, 1993; van de Meene, 1994.

Although the morphology, surficial grain sizes, and bedforms of these ridges have been described in some detail (*e.g.*, Duane *et al.*, 1972; Swift *et al.*, 1979; Stubblefield and Swift, 1981; Swift and Field, 1981; Figueiredo *et al.*, 1982; Parker *et al.*, 1982; Hoogendoorn and Dalrymple, 1986; Antia, 1993; van de Meene, 1994; Snedden *et al.*, 1994), comparatively little is known about their internal structure, stratigraphy, and genesis.

The purpose of this study is to add to our knowledge of the origin and stratigraphic expression of these ridges, based on an examination of shoreface-attached ridges at Sable Island on the outer part of the Nova Scotian Shelf, eastern Canada (Fig. 1). In particular, we describe the local and regional distribution of sediment grain size, the nature of small-scale bedforms, and the large- and small-scale internal structure of the ridges. The relevance of these observations to the origin and nature of ravine-

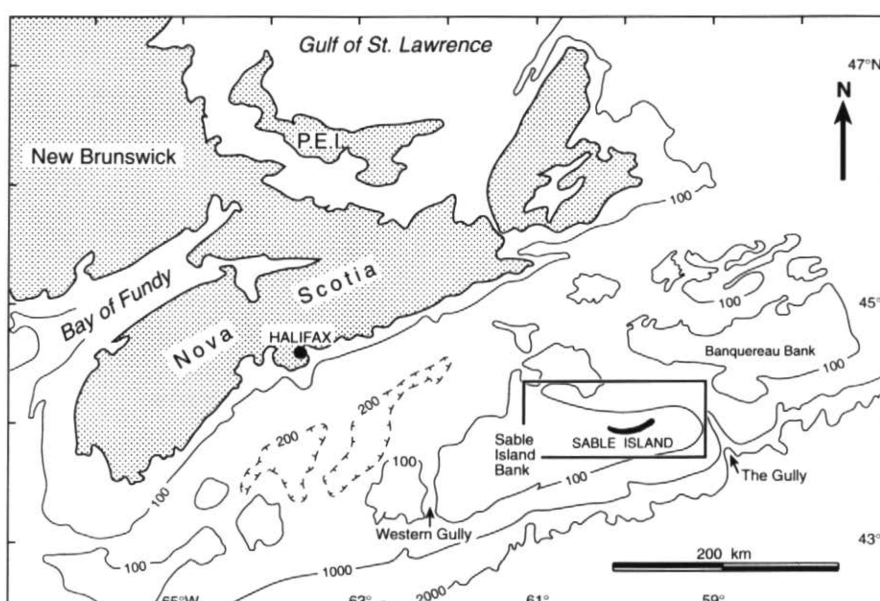

Figure 1 *Location map of Sable Island Bank and the Sable Island study area (rectangle), outer Scotian Shelf, eastern Canada. Bathymetry in metres.*

ment surfaces is also considered. The storm-generated waves and currents at this location are more intense than those in many other areas so the observations will assist in the development of a more comprehensive understanding of shoreface and inner-shelf sedimentation.

LOCATION AND SETTING OF THE STUDY AREA

Sable Island Bank is one of several isolated bathymetric highs along the outer edge of the Scotian Shelf (Fig. 1). The Bank is 225 km long (east-west), up to 115 km wide, and is enclosed by the 100 m isobath. The continental slope lies directly to the southeast. The average depth on the bank is 40-60 m, except in the vicinity of Sable Island, which is an arcuate sand body, 40 km long by 1.6 km wide, located in the northeast corner of the bank (Fig. 1). Sable Island (Fig. 2) is surrounded by a shoreface that reaches to depths of 20 m. Shoreface-attached ridges occur at the foot of this shoreface in two areas. The main ridge field, consisting of 79 ridges, extends for 110 km along the south side of the island and its shallowly submerged extensions (Fig. 2). A smaller field containing six ridges lies to the north of the island. All of the observations presented here are from the main ridge field.

Glacial, glacio-fluvial, and glacio-marine deposits comprise the upper 100-200 m of the Quaternary succession be-

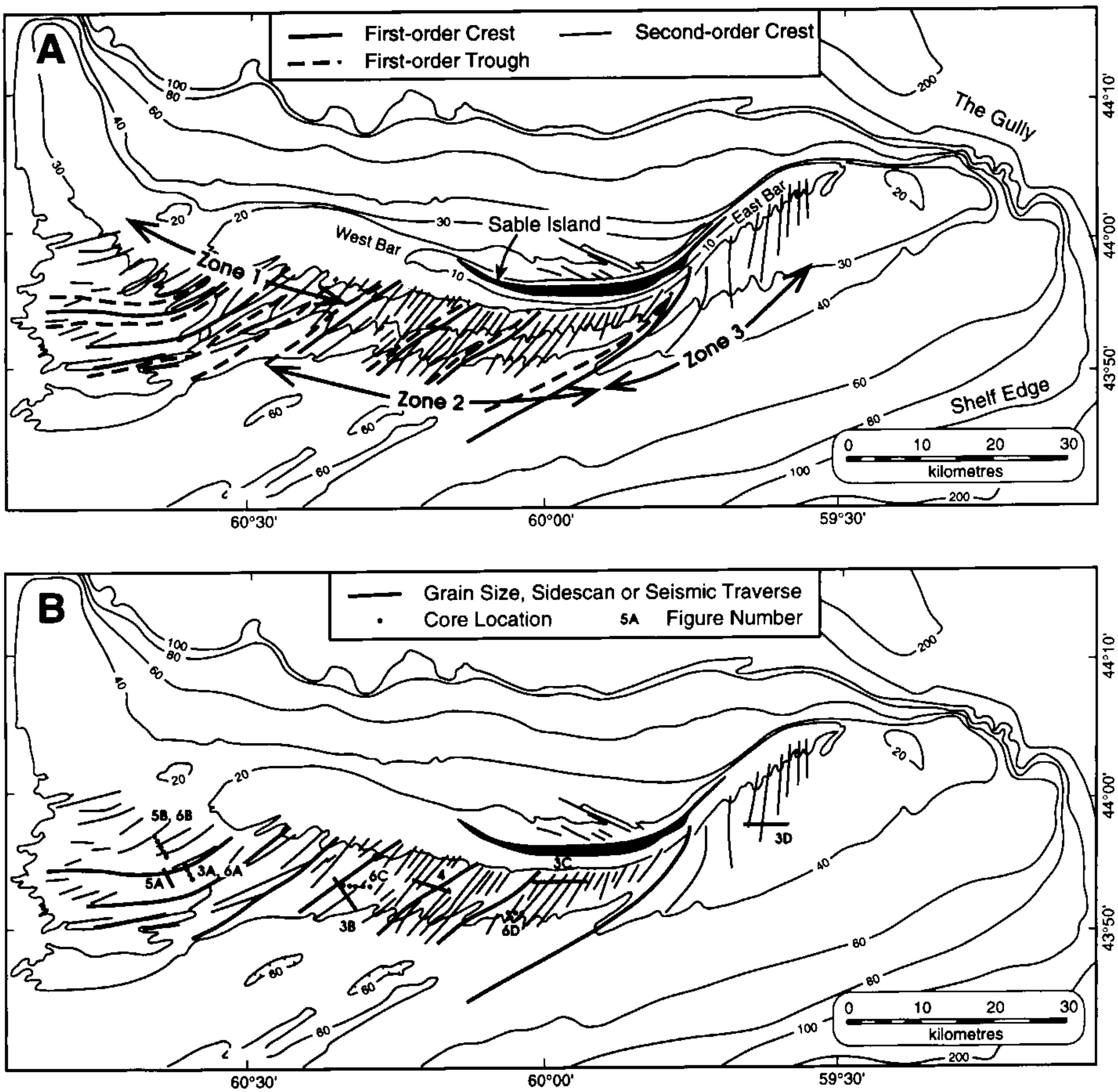

Figure 2 (**A**) *Bathymetry (in metres) of the area surrounding Sable Island, with crestline positions of the shoreface-attached ridges and locations of morphological zones discussed in the text.* (**B**) *Location of grain-size transects, sidescan and seismic profiles, and vibrocores shown in subsequent figures.*

neath Sable Island Bank (King and Fader, 1986; McLaren, 1988; Amos and Miller, 1990). The bank was emergent following the retreat of the Wisconsinan ice sheet. Transgression began approximately 13,000-14,000 years BP, with sea levels rising rapidly from the *ca.* -110 m lowstand position, reaching -25 m at about 8000 years BP. Since then, sea level has risen more slowly (0.4 metres per 100 years; Scott *et al.*, 1989; Amos and Miller, 1990). During the transgression, glacial outwash sands and gravels were reworked by aeolian and marine processes and transported to the northeast (Amos and Nadeau, 1988; Amos and Judge, 1991) to form the Holocene sand body that underlies Sable Island. This sand body grew upward as relative sea level rose (Scott *et al.*, 1984) and reaches 40 m in thickness (Amos and Nadeau, 1988). Cores from present-day, offshore areas reveal the presence of Holocene-age coastal barrier, tidal inlet, lagoon, and aeolian deposits (Scott *et al.*, 1984; McLaren, 1988), indicating that the island has decreased in size. These deposits are erosionally overlain by the shoreface-ridge sands that are the subject of this paper. Shell dates from these ridges range from 5140 years BP to the present, but do not show a systematic, upward-younging trend (Mc-Laren, 1988; Amos and Miller, 1990), because of the recycling of older material. The presence of "modern" ages to considerable depth indicates that the ridges are active features.

The hydrodynamic regime of Sable Island Bank is more energetic than that of the east coast of the United States. Sedimentation is dominated by severe winter storms that follow a northeasterly path, typically passing to the north of Sable Island (Tucker and Barry, 1984). Wind speeds reach 25 $m \cdot s^{-1}$ annually, while the 100-year peak winds are 51.5 $m \cdot s^{-1}$ (Mortsch *et al.*, 1985). The strongest storm winds come from the west and northwest, as do most storm-generated waves. The peak wave heights from these directions are 8-9 m (peak period *ca.* 12 seconds), while the maximum wave heights from the open ocean to the south and southwest are 10-13 m (periods up to 16 seconds). The predicted 100-year maximum wave height is 26 m (Neu, 1982). Using linear wave theory, peak wave-orbital speeds just outside the wave boundary layer for a typical storm can reach 3.8 $m \cdot s^{-1}$ at a depth of 25 m, although most waves produce wave-orbital speeds less than 1 $m \cdot s^{-1}$. Sheltering by Sable Island causes the intensity of wave action to decrease from west to east through the ridge complex.

In situ measurements and numerical models of storm-generated currents indicate that the predominant flow is to the northeast on Sable Island Bank (Hoogendoorn, 1989; Amos and Judge, 1991; Amos *et al.*, 1996), with maximum current speeds of 0.7-1.0 $m \cdot s^{-1}$. Peak near-bottom tidal currents only rarely exceed 30 $cm \cdot s^{-1}$, because of the small tidal range (approximately 1 m), and exhibit relatively open tidal ellipses with weak (0.05-0.08 $m \cdot s^{-1}$) residual flow to the west and northwest (Hoogendoorn, 1989). As a result, sediment transport is dominated by winter-storm currents, supplemented by the accompanying wave action, with net transport to the east and northeast (Hoogendoorn, 1989; Amos and Judge, 1991). As a result, the ridges are actively migrating to the east (Hoogendoorn and Dalrymple, 1986).

DATA COLLECTION AND ANALYSIS

Data for this study were collected on seven research cruises between 1983 and 1985. A total of 1800 km of seismic and sidescan data were obtained. The seismic data that provide the greatest detail of ridge structure were collected using the Nova Scotia Research Foundation (NSRF) Surface-Tow sparker. This system was operated at a firing rate of 2 per second at 300 joules, providing a minimum vertical resolution of 0.4 m (Hoogendoorn, 1989). Sidescan data were collected using a Klein 531-T, 100 kHz system, with a total swath width of either 200 m or 300 m. Morphological information on the ridges was obtained from high-precision bathymetric data collected by the Canadian Hydrographic Service in 1984. Remote bottom cameras and a manned submersible were used to observe the surficial bedforms.

The internal structures were studied using 24 vibrocores that were positioned accurately on seismic profiles obtained at the time of coring, using a combination of Satnav and Loran-C. Positional accuracy is estimated to be ~15 m. Because the sediment thickness in the larger ridges (>10 m) was more than the length of a single core (maximum penetration 3.1 m), several cores were obtained from different heights on their lee face in order to construct a composite stratigraphic succession. Each of the vibrocores was split, logged, photographed, sampled for textural analysis, and peeled. Textural variations over the ridges were sampled by repeated deployment of a Van Veen grab sampler while drifting across the ridges. All grain-size samples were analyzed using a large-diameter settling column.

EXTERNAL CHARACTERISTICS OF RIDGES

Ridge Morphology

The shoreface-attached ridges display considerable variability in size, but it is

Table 1 Morphological characteristics (mean values) of shoreface-attached ridges in the main ridge field, south of Sable Island (after Hoogendoorn, 1989, Tables 4.1-4.3). See text for definition of zones and ridge orders. The first-order ridges in Zone 2 are too poorly defined, because of the presence of the second-order ridges, to accurately determine the slope of their flanks.

Zone/Ridge Order (# of ridges)	Water Depth (m) Inner End	Water Depth (m) Outer End	Length (km)	Height (m)	Spacing (km)	Side Slope	Closing Angle
ZONE 1							
First Order (4)	18	45	22.5	9.7	5.1	0.61°	56°
Second Order (28)	18	45	5.6	4.4	1.65	0.33°	50°
ZONE 2							
First Order (3)	20	40	18.5	~9.0	7.9	?	44°
Second Order (35)	20	40	6.7	4.4	1.35	0.34°	60°
ZONE 3 (9)	15	30	8.0	2.3	2.0	0.13°	39°

possible to recognize two distinct ridge sizes (Fig. 2A, Table 1). Larger, first-order ridges are about 20 km long and 10 m high, with spacings of 5-10 km. The smaller, second-order ridges generally are about 5 km long, with spacings of 1-2 km and heights less than 5 m; they are commonly superimposed on the first-order ridges. Both sizes of the ridge are straight-to-gently curved and strike SW-NE (Fig. 2). The angle between the ridges and the shoreface (the shoreface closing angle) is unusually high, by comparison with other ridge fields, averaging about 50° but reaching 75°. All of the ridges exhibit rounded crests and V-shaped troughs (Figs. 3-5). Most are asymmetric, with the eastern (lee) side being steepest. The opposite asymmetry occurs locally, most commonly near the shoreface attachment point and at the seaward end of some second-order ridges.

The morphological characteristics of the ridges change systematically through the ridge complex. Based on these changes, the complex has been subdivided into three zones (Fig. 2A, Table 1): Zone 1, south of West Bar; Zone 2, south of Sable Island; and Zone 3, south of East Bar. In general, the size of the ridges decreases to the east. Zones 1 and 2 are similar, having superimposed first- and second-order ridges, but the first-order ridges are larger and more nearly symmetrical in Zone 1 than in Zone 2. Zone 3 lacks first-order ridges. Maximum ridge height decreases to the east, from 20 m in Zone 1 to 3.2 m in Zone 3. The slope of the ridge flanks decreases to the east, from values in excess of 0.5° (maximum values every-

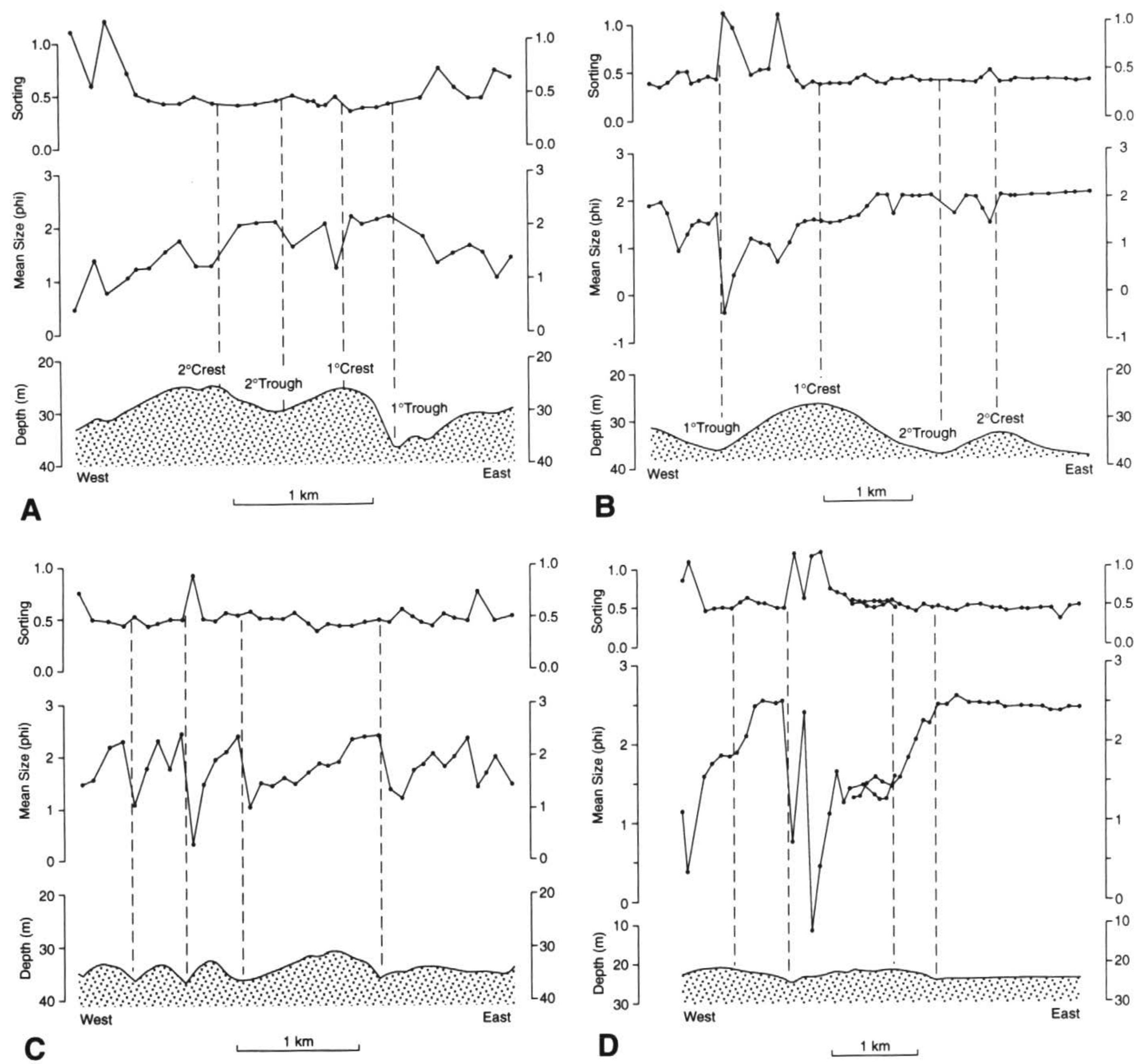

***Figure 3** Variation of mean grain size and sorting over ridges in various parts of the complex: (**A**) Zone 1; (**B**) western end of zone 2; (**C**) central part of Zone 2; and (**D**) Zone 3 (see Fig. 2B for profile locations). 1°=first-order; 2°=second order. All ridges in (**C**) and (**D**) are second-order ridges. Sorting measured in phi-units. Note that the horizontal scale varies between panels.*

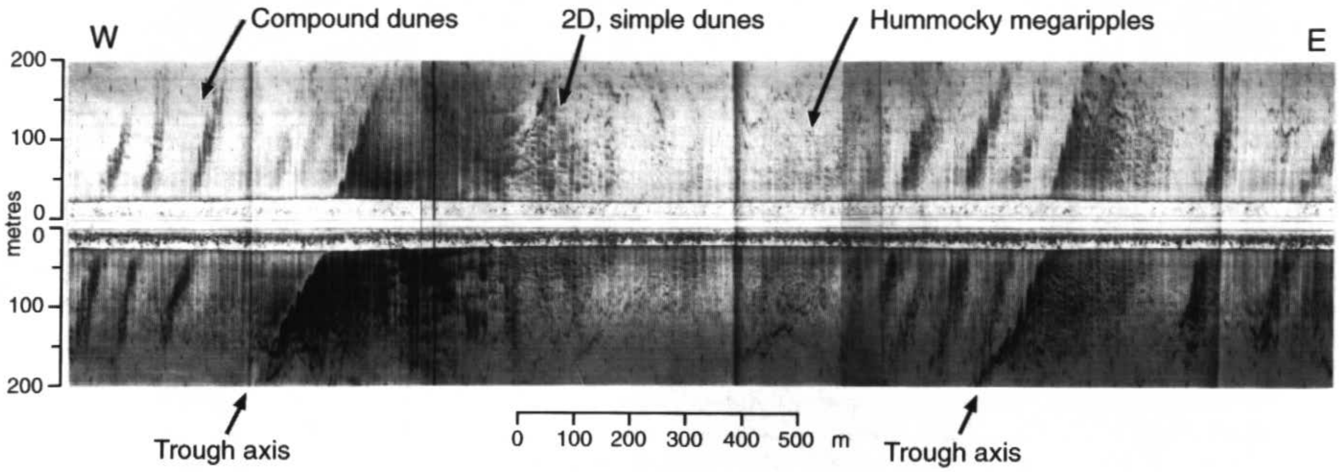

Figure 4 *Sidescan sonar image from the western part of Zone 2 (see Fig. 2B for location) showing the textural variation over the ridges and the superimposed bedforms. The abrupt contact between light-coloured (finer) sediment on the lee faces and the dark-coloured (coarser) sediment on the stoss sides is coincident with the axis of the V-shaped troughs. The compound dunes are migrating toward the east-southeast, whereas the simple, 2D dunes are migrating to the north-northeast. Note the restriction of hummocky megaripples to the finer (lighter) sediment on the ridge crest. Vertically oriented segmentation of the 2-D dunes and offsets of the trough axis are caused by wave-induced movement of the sidescan instrument.*

where <1°) in Zone 1, to values of 0.1-0.15° in Zone 3 (Table 1). These changes are accompanied by a gradual eastward decrease of the maximum water depth in which the ridges occur (Table 1).

Grain-Size Trends

The Sable Island ridge complex is part of a storm-generated, sediment-transport path that occupies all of Sable Island Bank (Dalrymple *et al.*, 1988; Amos and Judge, 1991). The average mean grain size in phi units fines eastward from 1.56 (0.34 mm; n = 30) in Zone 1, to 1.62 (0.33 mm; n = 45) at the Zone 1-2 border, and to 1.84 (0.28 mm) in the eastern part of Zone 2 and throughout Zone 3 (n = 131). Sorting averages approximately 0.5 phi units (well-to-moderately well sorted) in all zones.

Considerable textural variability exists over individual ridges (Fig. 3) because of the local addition of coarse material from underlying sedimentary units. In general, the coarsest sediments, which are rich in shell debris, occur low on the erosional stoss side of each ridge. From here, there is a progressive eastward decrease in mean grain size over the crest and down the depositional lee side, with the fining between the ridge crest and the foot of the lee face ranging from negligible to 0.75 phi units (Fig. 3). Such a pattern is present on both first- and second-order ridges. As a result, there is an abrupt and pronounced difference in sediment size on either side of each trough axis. This is shown on sidescan sonograms by the sharp contact between light-colored (fine-grained and absorptive) material on the lee face and dark (coarse and reflective) material on the stoss side (Fig. 4).

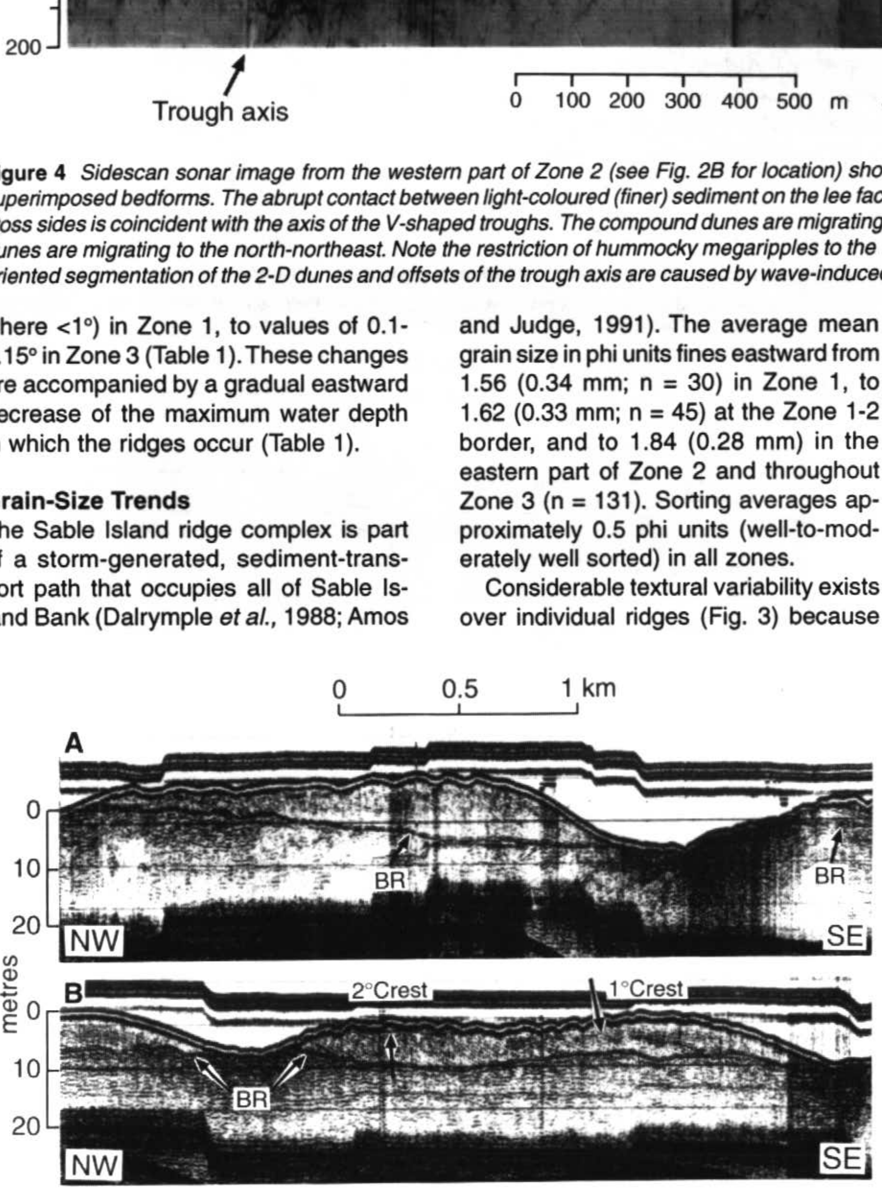

Figure 5 *Two NSRF sparker profiles from Zone 1 (see Fig. 2B for location) showing the internal structure of the ridges. An interpreted version of* (**B**) *is shown in Fig. 6B. In* (**A**), *the Basal Reflector (BR) dips gently to the east beneath the ridge and then rises abruptly by 5 m on the stoss side of the next ridge, because of progressive downward erosion by the trough as it migrates to the east. In* (**B**), *the Basal Reflector (BR) is more irregular and displays less upward stepping on the east side of the trough. Both sections clearly show eastward-dipping master bedding planes within the ridges. Both angular and tangential contacts with the Basal Reflector are evident. An internal discordance (analogous to a reactivation surface) is visible in* (**B**) *(at long arrow); it is believed to have formed as a smaller ridge migrated over the crest of the larger ridge. The small, second-order ridge in* (**B**) *is producing a horizontal erosion surface (at short arrow just beneath the bubble pulse; see also Fig. 6B).*

Surficial Bedforms

The sidescan sonograms show that subaqueous dunes and hummocky megaripples (Swift *et al.*, 1983) occur throughout Zones 1 and 2 (Fig. 4). Such bedforms were not observed in Zone 3, perhaps because of the lack of acoustic contrast in this area.

The dunes are typically straight-crested (*i.e.*, 2-D) and range from medium to very large (wavelengths 5-300 m; heights up to 2 m). Simple and compound varieties are present (Fig. 4). These dunes occur on either the stoss or lee side of the first- and second-order ridges, although they are most commonly seen on the coarser-grained stoss sides (Fig. 4). The larger dunes are weakly-to-strongly asymmetric, with migration generally toward the east. Their crestlines are sub-parallel to the crest of the underlying ridge, or are skewed in an anticlockwise direction relative to the ridge crest (Fig. 4). The orientation of smaller dunes is more variable, with eastward and northeastward (*i.e.*, onshore) migration directions predominating.

Hummocky megaripples occur near ridge crests (Fig. 4). These features are circular to elliptical with slightly coarser (more reflective) material in the swale. They cast no acoustic shadow (*i.e.*, have low slopes) and have heights of less than 1 m and spacings of 2-15 m. Hummocky megaripples and small dunes commonly occur adjacent to each other, with dunes on the ridge stoss side passing into hummocky megaripples on the ridge crest and upper part of the lee flank. The remainder of the lee face typically appears featureless or displays a diffuse mottling because of the finer grain size and minimal acoustic contrast.

Bottom-camera and submersible observations indicate that current and wave ripples, together with biogenic disturbance of the seabed, are widespread in areas of medium-to-fine sand during fair weather. These features gradually cause the obliteration of the storm-generated dunes and hummocky megaripples. Large wave ripples are present in the coarser sediment on the stoss side of some ridges. They are also believed to form during storms but are not reworked by fair-weather processes.

INTERNAL CHARACTERISTICS OF RIDGES

Large-scale Internal Structure

Seismic profiles (Figs. 5, 6) show that the modern ridge deposits rest erosionally on older sediments. This erosion surface is marked by a high-amplitude, laterally continuous reflector (Fig. 5) that we term the Basal Reflector. At the scale of an individual ridge this surface commonly shows significant relief because of incision by the ridge troughs (Figs. 5-7). The relief on this surface is less than, but generally mimics, that of the modern surface, ranging from 0 m to 12 m, with average values of about 3-3.5 m (the larger values occur beneath the largest first-order ridges in Zone 1). Typically, modern troughs occupy an asymmetric, elongate depression in the top of the pre-ridge material (Fig. 7). The axis of each depression is coincident with the axis of a trough, but the highs between depressions are offset to the west of the overlying ridge crest (Figs. 5A, 7). Thus, the eastern side of each depression is steeper than the western side. The pre-ridge sediments are buried beneath modern ridge deposits on the entire western side of each depression, whereas the pre-ridge sediments crop out on the erosional, eastern side. This erosional area forms the stoss side of the next ridge to the east. This geometry indicates that the ridge troughs have been eroding progressively downward into the pre-ridge sediments while migrating to the east. As a result of this geometry, the modern ridge deposits generally consist of disconnected parallel bodies, oriented at an angle to the shoreline (Fig. 7). The thickness of ridge sediments is somewhat less than the height of the ridge (Figs. 5-7), with the greatest thicknesses (13 m) occurring in Zone 1 and the thinnest deposits (1-2 m) in Zone 3.

The troughs of some smaller ridges, especially in the eastern part of the ridge complex, do not scour into the underlying sediments (Figs. 5B, 6C, D). In such cases, the top of pre-ridge sediments does not display pronounced depressions; instead, it is gently undulating with a relief of less than 3 m. Similarly, the troughs of second-order ridges superimposed on larger ridges commonly do not erode down to the Basal Reflector (Fig. 6A, B) and modern ridge sediments are continuous between adjacent crests. The eastward migration of such troughs produces a nearly horizontal erosion surface (a second-order Basal Reflector; Figs. 5B, 6A, B) that underlies the deposits of the smaller ridge. The superimposed ridges appear to migrate faster than the larger, underlying ridge; consequently, an erosional discontinuity is formed within the first-order ridge (Fig. 5B) when the trough of a smaller ridge migrates down the first-order lee face.

The modern ridge sediments are characterized by the presence of laterally continuous, eastward-dipping, low-amplitude reflectors that resemble large-scale, low-angle, cross-stratification (Figs. 5-7). These "master bedding planes" are concordant with the present-day lee face of the ridges and thus have dips ranging from less than 0.1° to about 0.5° (average dip *ca.* 0.3°). In general, lower dips occur in areas with finer grain sizes (compare Figs. 6A and 6D). Their contact with the Basal Reflector is generally angular, but tangential contacts also occur. These inclined reflectors have a vertical spacing ranging from 0.4 m (the lower limit of resolution of the NSRF sparker system) to 1.0 m and are laterally continuous for 200 m to 3000 m downdip (averaging 500 m). Their along-strike continuity could not be determined because of the lack of crest-parallel survey lines. Master-bedding planes are prominent in the larger ridges in Zones 1 and 2, but could not be detected seismically in the smaller ridges in Zones 2 and 3.

Vertical Grain-Size Trends and Sedimentary Structures

In cores, the Basal Reflector is commonly marked by an abrupt change in grain size (coarser or finer below; Fig. 6A, B, C) and a downward increase in packing density. This surface is almost everywhere mantled by a gravel lag 0.05-0.5 m thick. In some cases, oxidation and/or incipient cementation of the underlying sediment has occurred. The combination of these characteristics accounts for the strength of the seismic reflection from this surface.

The sediments within the ridges consist of medium-to-fine sand. *Within* individual cores from the crest and lee side of ridges, grain sizes generally coarsen upward slightly or show no vertical change (Fig. 6); only a few fine upward (*e.g.*, Fig. 6C, Core 2-2). Cores from ridge stoss sides show more variable grain-size trends. A comparison of cores taken at different elevations on the lee side of ridges shows an overall coarsening from the trough to the crest of all but one ridge. This is consistent with the surficial-sediment data (Fig. 3).

The most abundant small-scale sedimentary structures within the ridges (Figs. 6, 8) are high-angle cross-bedding formed by dunes, and low-angle-to-horizontal lamination that we interpret to represent hummocky cross-stratification (HCS). Following Swift *et al.* (1983) and Amos *et al.* (1996), we propose that this HCS was generated by hummocky megaripples like those observed on the surface (Fig. 4). The cross-bedding occurs in grain sizes coarser than 2.6 phi (0.16 mm), whereas the low-angle lamination (HCS) occurs in sediments finer than 1.5 phi (0.35 mm). Because of this grain-size difference, cross-bedding is particularly abundant in the surficial layers on the coarser-grained stoss side of the ridges, whereas HCS is more abundant in cores from the finer-grained, lee

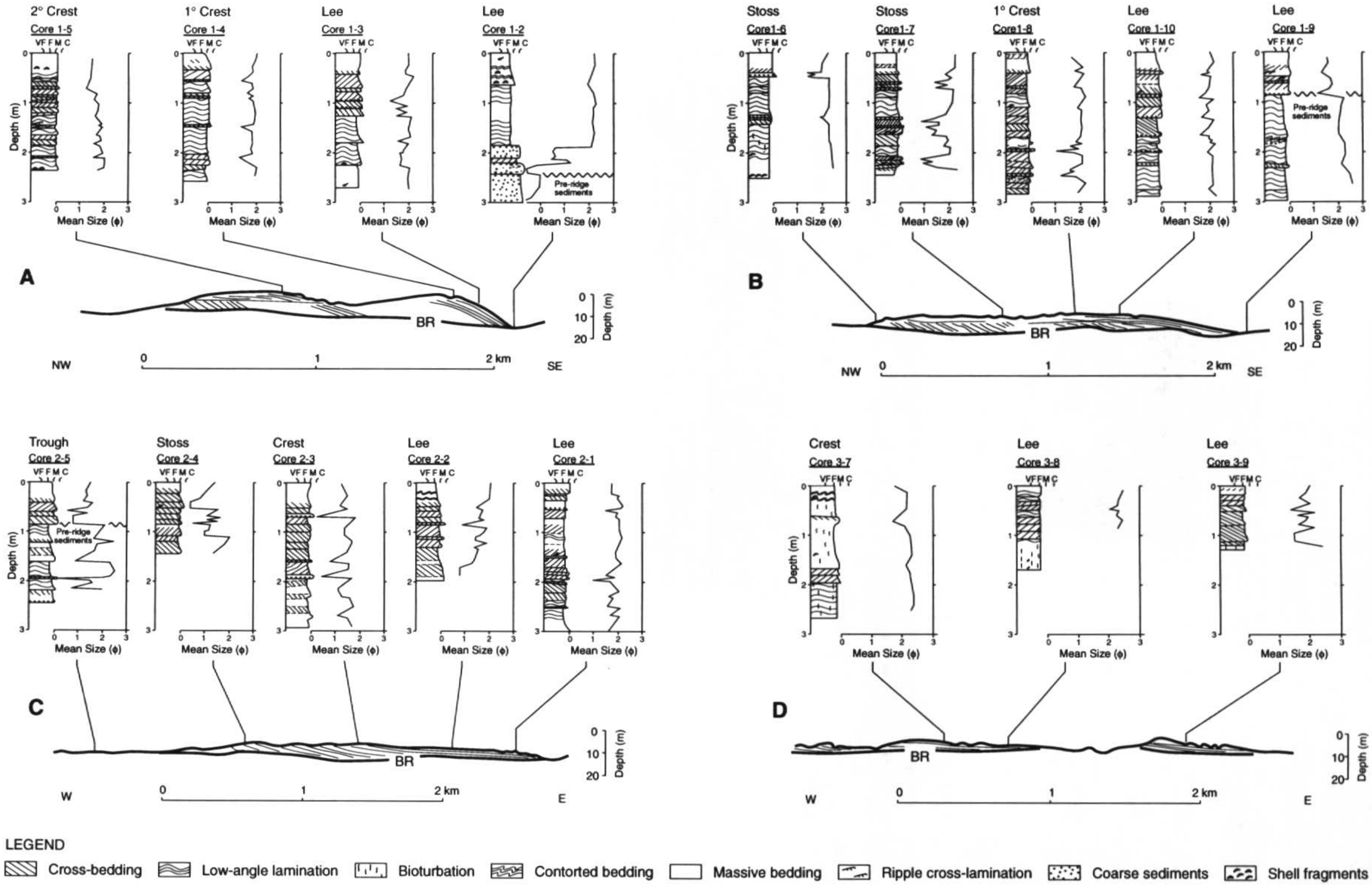

Figure 6 *Core transects and interpreted seismic sections of four ridges (see Fig. 2B for locations): A and B- zone 1; C and D- zone 2. The top of each core is the modern sediment surface. Note the abrupt grain-size change where modern ridge deposits overlie pre-modern (Pleistocene and/or earlier Holocene) sediments and the local presence of a lag at the contact [=Basal Reflector (BR)]. See text for discussion of grain-size trends within and between cores from individual ridges. The base of individual storm beds is commonly marked by a thin, coarse layer. Within each package, mean grain size fines upward (see especially B- Core 1-10) or is uniform (e.g., A- Core 1-4). Note the restriction of burrowing to the finer sands in the eastern part of zone 2 (D). VF- very fine sand; F- fine sand; M- medium sand; C- coarse sand to gravel. Dip direction of cross stratification is not significant as the cores were not oriented. See Hoogendoorn (1989) for additional examples.*

side (Fig. 6). Both structures are present throughout Zones 1 and 2 (Zone 3 was not cored), but HCS makes up a greater proportion of the sediments in Zone 1, whereas cross-bedding predominates in Zone 2, perhaps due to differences in wave intensity and/or the focussing of storm-generated currents. Wave- and/or current-ripple cross-lamination (Fig. 8C) is also present in some cores. Bioturbation was observed only in Zone 2 (Fig. 6D). Contorted and massive bedding occur locally. Most occurrences are believed to be caused by disturbance during coring, but some massive bedding may be the result of rapid deposition or cryptic bioturbation.

The cores show that the ridge sediments consist of erosionally based depositional units that average 46 cm thick (range 8-123 cm). Each of these units

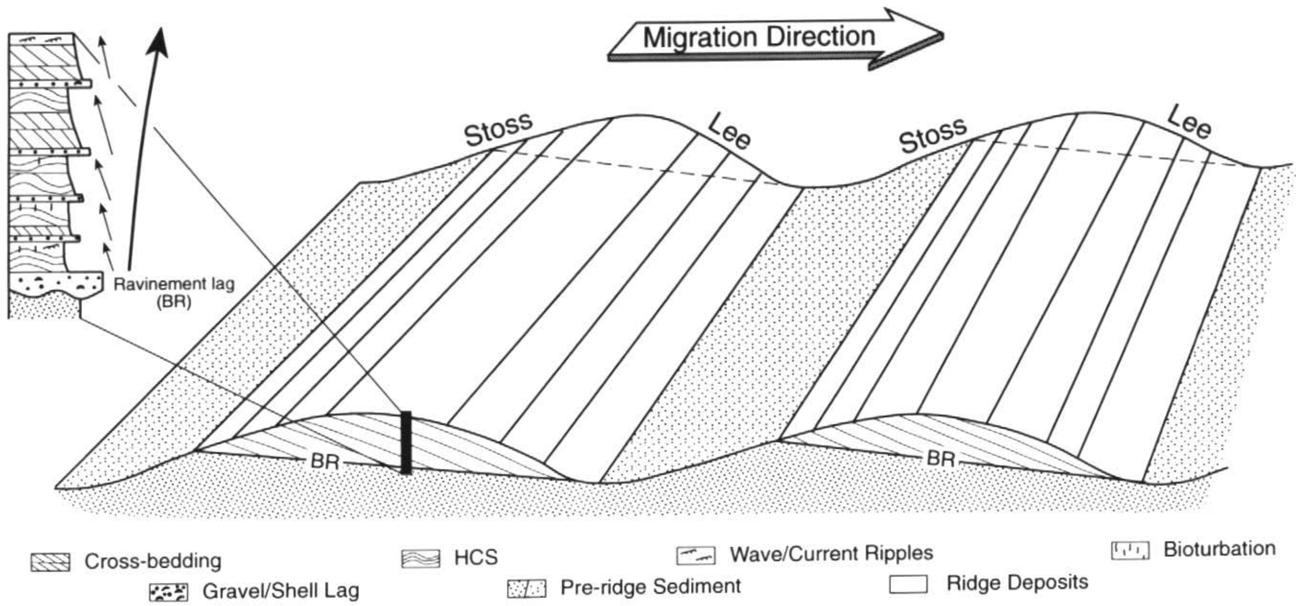

Figure 7 *Schematic model of the migratory shoreface-attached ridges at Sable Island showing the geometry of the ravinement surface [= Basal Reflector (BR)], eastward-dipping master bedding planes, and the vertical succession of deposits. Ridge relief is greatly exaggerated (trough spacing ca. 2-5 km; relief ca. 5-8 m). The vertical profile at left consists of graded event beds but shows an overall, upward-coarsening trend, with an upward increase in the abundance of cross-bedding relative to HCS. The erosion surface beneath the ridges is sculpted into elongate depressions that coincide with the troughs. The migration direction is oblique to the ridge crests.*

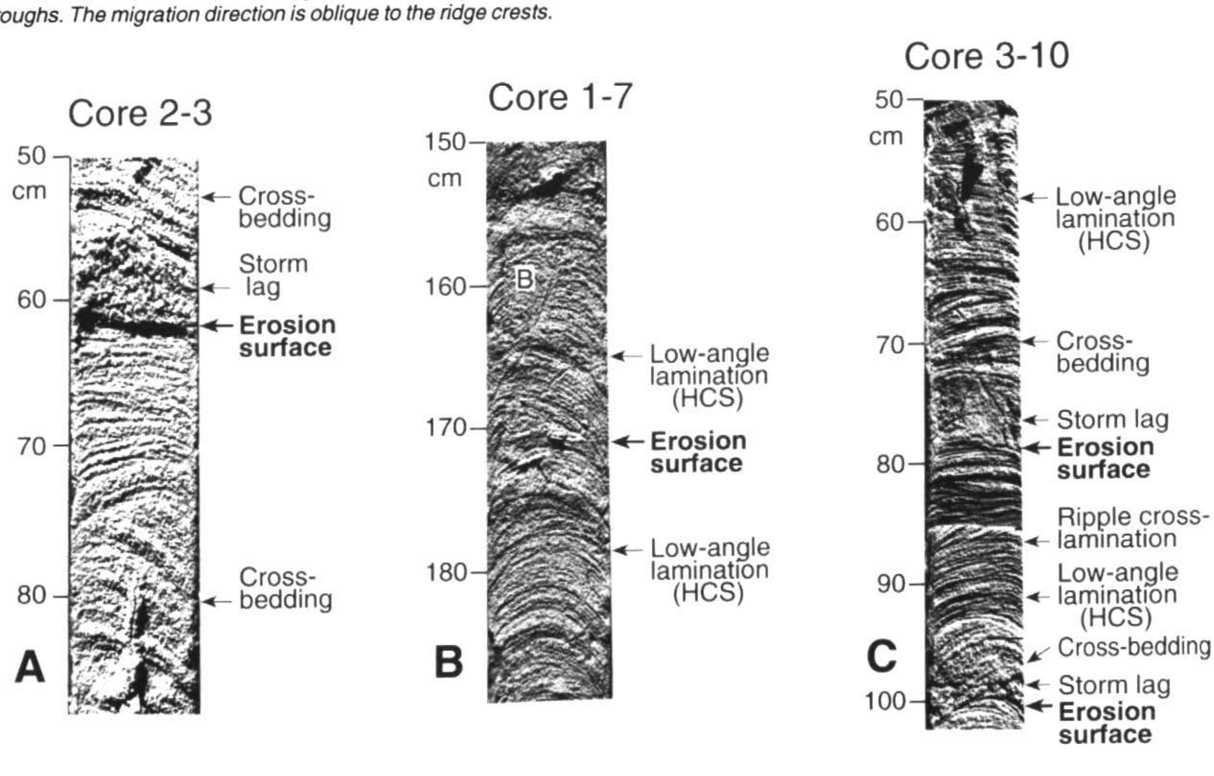

Figure 8 *Core photographs showing:* (**A**) *high-angle cross-bedding formed by subaqueous dunes;* (**B**) *low-angle lamination (HCS) formed by hummocky megaripples; and* (**C**) *event beds containing both high-angle cross-bedding and HCS. Heavy arrows denote erosion surfaces at the base of individual storm-event beds. B=burrow. Scale units in centimetres.*

begins with a layer of coarser material 0.5-2 cm thick (Figs. 6, 8). The sediments above this lag generally fine upward (*e.g.,* Fig. 6A, Cores 1-3; Fig. 6B, Cores 1-10); less than one-third of all depositional units show no vertical grain-size trend and none coarsen upward. Many depositional units contain only one sedimentary structure (*i.e.,* cross-bedding or HCS; Figs. 6, 8A, B), but many of the thicker units (>20-30 cm thick) contain both structures, typically with HCS overlying cross-bedding (Fig. 8C). Ripple cross lamination and/or massive bedding (= bioturbation?) caps some units (Fig. 8C). Correlation of cores with the accompanying seismic line suggests that the contacts between depositional units correspond to the eastward-dipping master bedding planes.

DISCUSSION

Storm-bed Deposition and the Origin of HCS

Each of the depositional units is interpreted as the result of an individual storm. Each one rests on an erosional surface that is mantled by a coarse lag (Fig. 8). The overlying sediments fine upward and may be capped by wave ripples and/or bioturbation. However, the thickness of some packages (> 1 m) and the presence of cross-bedding and HCS within the same unit are not typical characteristics of storm-event beds and warrant discussion.

In the absence of lateral advection of sediment, the thickness of an event bed is limited by the amount of material that can be held in suspension above any area of the bed. Given the range of suspended-sediment concentrations and boundary-layer thicknesses measured during storms, bed thicknesses of more than a few centimetres are not possible. Thus, thicker event beds require lateral transport of sediment and preferential deposition in localized areas as a result of spatial flow deceleration. The lee face of the ridges provides the ideal location for this to occur. In this situation, the thickness of the bed depends as much on the duration of the storm as on its intensity. Amos *et al.* (1996) documented the deposition of a storm bed *ca.* 0.3 m thick (slightly less than the average bed thickness) on one of the Sable Island ridges during an average, monthly winter storm in which significant sediment movement lasted less than 24 hours. Given that this storm was not particularly long lasting or intense, it is reasonable to infer that beds exceeding 1 m in thickness can be generated by the less frequent, but more intense, storms that take longer to traverse the area. If only one event bed 0.3 m thick is deposited on a ridge lee face (average slope 0.3°) each year, a simple trigonometric calculation indicates that the ridge would migrate eastward approximately 50 m·a^{-1}. At this rate, they would move a distance equal to their spacing (1.5-8 km) in only 30-160 years!

The presence of cross-bedding and HCS within single event beds (Figs. 6, 8) and the close spatial association of asymmetric dunes and hummocky megaripples on the modern surface (Fig. 4) call into question the common assumptions that these features form under different conditions and that there is a simple continuum between purely unidirectional cross-bedding and purely oscillatory HCS (Cheel and Leckie, 1993). Clearly, the two bedform and structure types can co-exist under the energetic combined-flow conditions that prevail at Sable Island during storms, with sediment grain size determining which one forms.

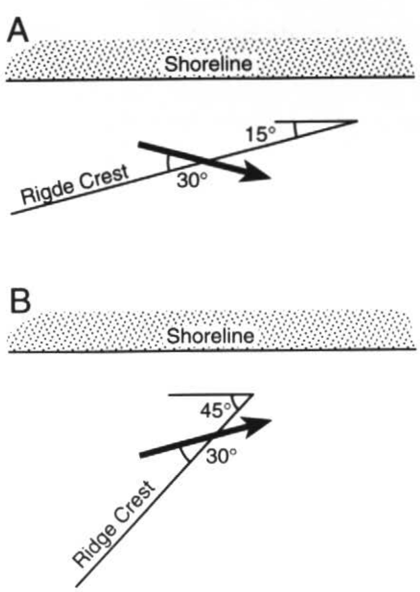

Figure 9 *Sketches showing how the requirement of ridge-oblique flow, as specified by the Huthnance (1982) model, and different near-bed current directions (heavy arrows) control ridge orientation relative to the shoreline. The ridge-shoreline angle was determined by assuming that the near-bed current is oriented 15° from coast parallel and that the ridge crest is skewed 30° relative to the current (the skew that maximizes ridge growth; Huthnance, 1982).* (**A**) *Obliquely offshore (downwelling) flow* (e.g., *US Atlantic coast) generates ridges that close with the coast at a small angle (15°).* (**B**) *Obliquely onshore (upwelling) flow* (e.g., *south side of Sable Island) generates ridges at a high angle (45°) to the coastline.*

Ridge Behavior and Origin

In many ways the shoreface-attached ridges at Sable Island behave like subaqueous dunes. Most significantly, they migrate in the direction of the long-term, net, storm-generated current, eroding on their western, stoss side and depositing on their eastern, lee face (Fig. 7). The distribution of surface sediment sizes (Fig. 3) is consistent with this: the coarser sizes (a lag of sorts) occurring on the erosional side, while finer sizes are found on the eastern side where flow expansion occurs (Swift and Field, 1981). The stepped geometry of the Basal Reflector beneath many of the ridges (Figs. 5A, 7) is identical to that predicted for negatively climbing bedforms (*i.e.,* those occurring in areas with net erosion; Rubin, 1987, fig. 9). Furthermore, the development of "reactivation surfaces" when second-order ridges migrate over the crest of first-order ridges (Fig. 5B) mimics the behavior of small dunes on a larger, compound dune (Dalrymple and Rhodes, 1995). The ridges are also asymmetric in the direction of ridge migration (steepest face to the east; Fig. 7), although exceptions occur in areas where resistant older sediment crops out on the stoss side. Because of this, ridge asymmetry is not an infallible indicator of their migration direction.

Many lines of evidence indicate that the direction of net sediment transport in the ridge field is essentially parallel to the coastline and/or obliquely onshore (*i.e.,* in an overall easterly direction). This evidence includes current-meter data (Hoogendoorn, 1989; Amos *et al.,* 1996), numerical modelling of representative storms (Amos and Judge, 1991), theoretical considerations of storm interaction with the nearshore water column (most storms pass north of Sable Island, thereby causing *set-down* on the south side of the island and *onshore*-directed bottom flows; Hoogendoorn and Dalrymple, 1986), and the orientation of superimposed dunes (Fig. 4). Thus, the ridges are most likely migrating parallel to the coast, in a direction that is oblique to their crestline. In this they are analogous to oblique dunes (Dalrymple and Rhodes, 1995).

Similarity of behavior does not indicate that shoreface-attached ridges and dunes have the same origin. Indeed, the large size of the ridges relative to the water depth precludes them from being related genetically to dunes (Dalrymple and Rhodes, 1995). Three models have been proposed for the origin of shoreface-attached ridges: 1) oblique flow over an initial irregularity that causes flow veering and deceleration over the crest, leading to upward growth of irregularities with a preferred spacing (Huthnance, 1982); 2) interaction of infragravity waves (periods of 80-120 seconds) with the sea bed (Boczar-Karakiewicz and Bona, 1986; Boczar-Karakiewicz *et al.*, 1987); and 3) tidal-inlet migration coupled with coastal transgression, producing a ridge along the ebb-tidal-delta retreat path (McBride and Moslow, 1991).

The ebb-tidal-delta retreat model would not appear to be applicable at Sable Island, because of the absence of tidal inlets. Inlets may have existed in the past, as indicated by the presence of lagoonal deposits beneath the modern ridges, so the possibility exists that the ridges are long-lived features (perhaps 2000-3000 years) that continued to exist and migrate long after the ebb-tidal deltas that initiated them were gone. However, there are too many ridges for each one to represent a separate inlet–ebb-tidal-delta pair, given the microtidal conditions that prevail. Thus, this model of ridge genesis is not accepted in the present situation.

The infragravity-wave model (Boczar-Karakiewicz and Bona, 1986; Boczar-Karakiewicz *et al.*, 1987) can explain the general orientation of the ridges (their crests are approximately parallel to the crests of infragravity waves arriving from the open ocean; Fig. 1), but the counterclockwise curvature of the ridge crests in shallow water (Fig. 2A) is the opposite of what would be expected in response to wave refraction in shallow water. More significantly, the infragravity-wave model would predict a northwesterly direction of ridge migration, the opposite of what is observed. Therefore, this model for the origin of the ridges is also discounted.

Although the Huthnance (1982) model was originally developed for tidal ridges, reversing flow is not a necessary condition and the model has been applied to shoreface-attached ridges by other workers (Figueiredo *et al.*, 1982; van de Meene, 1994). The flow-oblique orientation of the Sable Island ridges offers circumstantial evidence in favor of the Huthnance process, and their spacing is in broad agreement with the predictions of the Huthnance model for the observed water depth. The Huthnance model is also able to explain the larger-than-normal shoreface closing angles that these ridges exhibit (30-75° compared with typical values of 20-30°; Swift and Field, 1981) (Fig. 9). Therefore, we conclude that the Sable Island ridges owe their existence to the Huthnance process, although the nature of the irregularities from which they grew is not known.

Stratigraphic Expression

The Sable Island shoreface-attached ridges overlie an erosional ravinement surface that separates them from Holocene back-barrier deposits. In wave-dominated settings, such ravinement surfaces are generally regarded as forming entirely on the shoreface, but in this instance erosion continues on the stoss side of the ridges (Figs. 5, 7) in an area extending a considerable distance offshore from the shoreface. Where the ridges are climbing negatively, this surface has been sculpted into a series of shoreline-oblique ridges and depressions that locally exceed 10 m in relief. If such depressions were oriented at a high angle to the shoreline, as they are at Sable Island, they would be geometrically similar to incised valleys or tidal-inlet scours. Depressions that are more nearly shore parallel (*e.g.*, the east coast of the United States) would superficially resemble shoreface notches created during stillstands in an overall transgression (*cf.*, Walker and Plint, 1992), but would be of limited along-strike continuity. The extent to which such features are preserved on ancient ravinement surfaces (*e.g.*, Walker and Eyles, 1991) remains to be explored.

The fining trend present down each lee face (Fig. 3), coupled with ridge migration, is expected to generate an overall upward-coarsening succession within each ridge (Fig. 7), that is itself composed of stacked, upward-fining event beds. Because of the grain-size control on the nature of the structures discussed above, it is possible that the relative abundance of cross-bedding increases upward. These predictions are generally supported by the changes observed between cores collected at different elevations on lee faces (Fig. 6). Although these ridges lie in the area seaward of the shoreface, their internal structures, including the limited degree of bioturbation, have closer similarity to the deposits of the middle and upper shoreface than they do to what is commonly regarded as typifying the shoreface–inner-shelf transition (Short, 1984; Walker and Plint, 1992, Fig. 14). This implies that the morphological and sedimentological definitions of the shoreface are not consistent.

The preservation potential of shoreface-attached ridges remains to be determined. However, R. Boyd (1997, pers. comm.) has documented the presence of ridge deposits in two places around Sable Island, both of which lie seaward of the modern ridges (one area is in 50-60 m of water, due south of Sable Island, whereas the other is at a depth of 25-30 m, directly north of the island; Fig. 2A). In both locations, two to three "sets" of inclined ridge strata are stacked vertically, indicating that these deposits represent more than the stranding of single ridges on the shelf.

SUMMARY AND CONCLUSIONS

1) Seventy nine, shoreface-attached ridges occur in a field 110 km long on the south side of Sable Island and its underwater extensions, in water depths of 15-45 m. Smaller ridges (lengths 5-8 km; heights 2-4 m) are superimposed on larger ridges (lengths ~20 km; heights ~10 m) throughout most of the field. Average ridge size, depth of occurrence, and grain size decrease to the east, because of a decrease in storm energy associated with sheltering by Sable Island. These shoreface-attached ridges are the largest and deepest described to date, because storm conditions are more intense than in other studied areas.

2) The ridges are migrating alongshore to the east, in response to storm-generated currents, with migration rates perhaps as high as 50 $m \cdot a^{-1}$. They behave like dunes, eroding sediment from their stoss side and depositing storm-event beds on their lee face. Because of this, grain sizes become finer eastward over each ridge and the ridges are typically, but not everywhere, asymmetric in the direction of migration. Their internal architecture resembles large-scale cross-stratification, but with dips of <0.5°. The ridges are oblique to their direction of migration.

3) Migration of the ridges produces a weakly developed, upward-coarsening succession that consists of stacked, upward-fining event beds. The succession rests on a gravel and shell lag that mantles the underlying ravinement surface. HCS predominates in the lower part of the succession; cross-bedding with an alongshore or obliquely onshore orien-

tation is more abundant in the upper part. Event beds reach 1.2 m in thickness (0.46 m average), because of sediment transport onto the ridge lee face throughout a storm. Bioturbation at the top of beds is uncommon, but becomes more abundant toward the east end of the ridge field because of the finer grain sizes, lower energy levels, and less intense erosion. The ridge deposits have broad similarities to those of the middle and upper shoreface, despite the fact that the ridges lie seaward of the shoreface. Thus, the morphological and sedimentological definitions of the shoreface may not be consistent.

4) Subaqueous dunes occur in close proximity to hummocky megaripples on each ridge. High-angle cross-bedding and HCS are present in subequal amounts within the ridges, commonly occurring together in a single event bed. In the energetic combined-flow conditions that affect the Sable Island ridges, grain size appears to exert a strong control on which structure forms.

5) Many of the ridges exhibit negative climb (*i.e.*, net erosion) so that pre-ridge sediments crop out on the lower part of each stoss side. As a result of this downcutting by the troughs, the underlying ravinement surface displays a series of shoreline-oblique depressions with a relief of up to 12 m. These depressions may mimic either incised valleys or incised shorefaces, depending on the angle between the ridges and the shoreline. In these negatively climbing ridges, the ridge deposits are thinner than the ridge relief and are not continuous between ridge crests. Positive climb, relative to the original sea floor, appears to have occurred in two places around Sable Island, leading to the stacking of ridge strata.

6) The Huthnance (1982) process is believed to be responsible for ridge growth. Oblique flow across the ridges, coupled with the obliquely onshore, near-bed flow (that results from storm set-down along the south side of Sable Island) explains the unusually large shoreline closing angles (average 50°) that these ridges display. The absence of modern tidal inlets and ebb-tidal deltas and the large number and close spacing of the ridges argue against their formation from ebb-tidal-delta retreat paths.

7) A spectrum of ridge types exists with respect to the rate of ridge migration: Peahala Ridge, New Jersey (Snedden *et al.*, 1994) is stationary, whereas the Sable Island ridges migrate consistently (and rapidly?). The sedimentary structures are the same in both cases, but the architecture of the ridge deposits and the geometry of the ravinement surface may be quite different.

ACKNOWLEDGMENTS

We thank the following individuals and organizations for their assistance: the Canadian Department of Energy, Mines and Resources and the Natural Sciences and Engineering Research Council of Canada for financial support; Dr. Carl Amos (Bedford Institute of Oceanography) for sharing ship time and discussing the results; the captains and crews of the various research vessels for their co-operation in sometimes less than optimal conditions; Ela Rusak (Queen's University) for her capable production of the figures; and Kathy Bergman and Don Swift for their reviews of the manuscript. The statements made in this paper reflect the views of the authors and are not to be construed as representing the views of Shell Canada Limited.

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Accepted as revised 14 April 1997