BYPASS-ZONE TEMPESTITE FACIES MODEL AND PROXIMALITY TRENDS FOR AN ANCIENT MUDDY SHORELINE AND SHELF[1]

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ABSTRACT: Member 2 of the late Precambrian to Lower Cambrian Chapel Island Formation of southeast Newfoundland was primarily deposited in storm-influenced, nearshore and shelf environments along a fine-grained coastline. Deposition took place within or adjacent to a deltaic system that supplied abundant silts and clays. Thin-bedded graded sandstone beds, hummocky cross-stratified beds, and a variety of very thin conglomerate units contain evidence for deposition by storm currents.

Sedimentological and stratigraphic evidence is used to reconstruct the relative paleobathymetric position of the three major facies in member 2. The Gutter Cast Facies is a shallow-subtidal deposit characterized by very thin sandstone laminae and abundant pot and gutter casts. The Siltstone-Dominated Facies contains more laterally extensive thin-bedded sandstones and fewer erosional features, and was deposited in the inner shelf. The Sandstone-Dominated Facies consists of thin to medium, graded and hummocky cross-stratified sandstone beds deposited in a more distal shelf setting, but above storm wave base.

The facies model and set of proximality trends developed for member 2 deposits may be applicable to other storm-influenced fine-grained shorelines. In this model, the shallow subtidal is a zone of throughput with high-velocity, sediment-laden flows eroding deep narrow scours (gutter casts) and depositing very little sand outside of these scours. As the storm-generated flows move into deeper water they decelerate, resulting in less erosion of the sea floor and depositing thicker and more continuous sand beds (Siltstone-Dominated Facies). Further from shore, bed thickness reaches a maximum (Sandstone-Dominated Facies) and hummocky cross-stratification is abundant. Even more distally, bed thickness decreases again (represented by thinly laminated siltstones of the overlying member 3). Analysis of sedimentary structures and paleocurrent data suggests deposition by storm currents that transported sediment nearly perpendicular to shore.

INTRODUCTION

Facies models for storm deposition have historically involved sandy or coarser-grained foreshore and shoreface zones (e.g., Walker 1984). These models incorporate proximality-distality trends that are useful in paleoenvironmental reconstructions, resolution of sea-level fluctuations, and other aspects of basin analysis (Aigner and Reineck 1982; Aigner 1985). Unfortunately, there are very few examples of well-described storm deposits from modern fine-grained coastal to inner shelf areas. Ancient examples are even more scarce, and therefore no facies models have been developed for these nonsandy, storm-influenced shelves.

In facies models developed for storm-influenced shelves with sandy shorelines, sandstone bed thickness decreases seaward as sediment entrained at the shoreline is swept to sea by "relaxation currents" of variable character. The thin to medium bedded siltstones and sandstones of member 2 of the Chapel Island Formation provide evidence for an alternative model for coastal to inner-shelf storm-dominated sedimentation in which the shallow subtidal zone, dominated by fine-grained sediment, is a zone of sediment bypass in which high-velocity, sediment-laden flows erode shore-normal scours preserved as gutter casts. A few studies have made reference to a nearshore zone of bypass (Leckie et al. 1990; Kidwell 1989), but no facies models have been proposed for storm-influenced fine-grained shorelines. The facies model developed in this study includes a set of proximality-distality trends, including aspects of bed thickness and primary sedimentary structures, that deviate significantly from those associated with storm-influenced shelves with sandy shorelines (Brenchley et al. 1979; Howard and Reineck 1981; Kreisa 1981; Aigner 1982, 1985; Aigner and Reineck 1982; Allen 1984; Howard and Nelson 1982; Walker 1984; Pederson 1985; Handford 1986; Decelles 1987).

The first part of this paper is a detailed description of the volumetrically important lithofacies of member 2, with particular emphasis on various storm-generated structures. Brief descriptions of the shoreline deposits from member 1 and lower member 2 and the outer shelf deposits of member 3 are included to help constrain the paleoenvironmental reconstruction of the facies in member 2 and complete the facies model herein described. The second part of the paper is a description of the facies model, with particular emphasis on tempestite proximality-distality trends.

LOCATION AND GEOLOGIC SETTING

The late Precambrian–Lower Cambrian Chapel Island Formation crops out around Fortune and Placentia bays, southeast Newfoundland; most of the data for this study were gathered from outcrops along the southwest tip of the Burin Peninsula (Fig. 1). These rocks lie within the Avalon Zone, the easternmost terrane within the Appalachian Orogen (Williams and Hatcher 1983). The Chapel Island Formation, a 1000-m-thick unit of sandstones, siltstones and mudstones with subordinate limestones, has been the focus of intense interest because it contains a record of continuous sedimentation across the Precambrian–Cambrian boundary (Bengston and Fletcher 1983; Crimes and Anderson 1985; Narbonne et al. 1987; Landing et al. 1988, 1989).

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[1] Manuscript received 3 August 1990; accepted 17 May 1991.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 62, NO. 1, JANUARY, 1992, P. 99–115

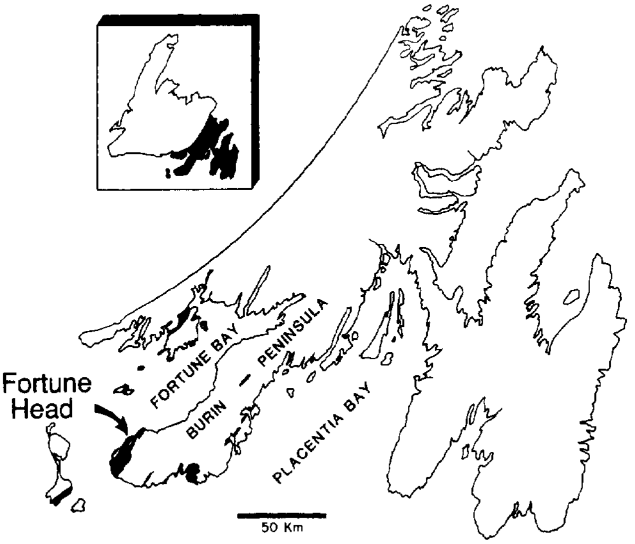


FIG. 1.—Outcrop distribution of the Chapel Island Formation (shown in black) within the Avalon Zone of Newfoundland.

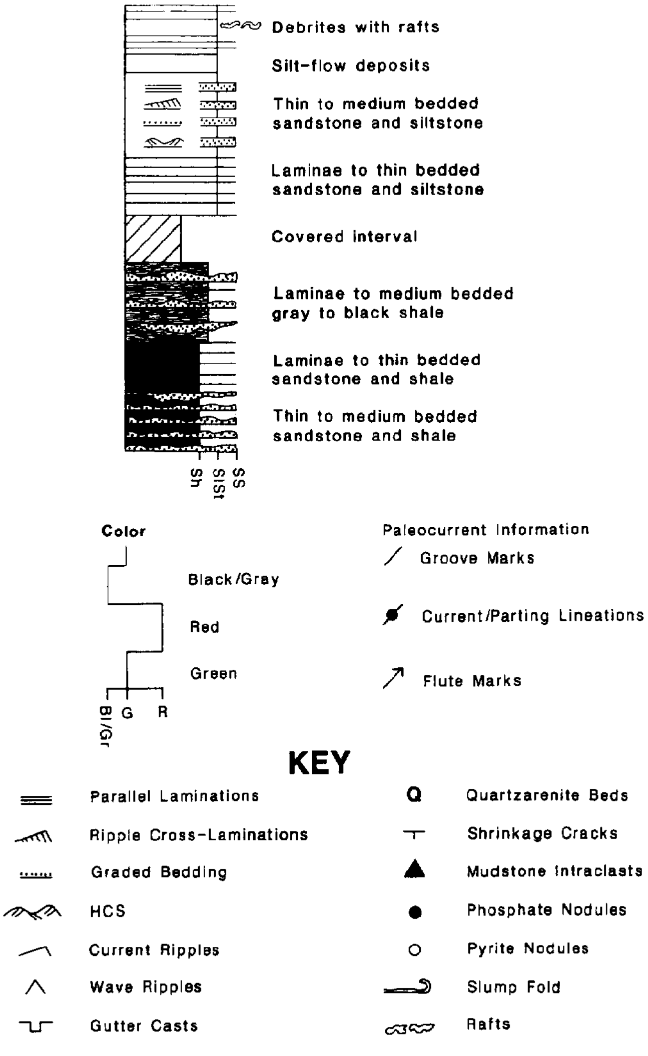
CHAPEL ISLAND FORMATION

The formation is divided into five informal members (Bengston and Fletcher 1983; Narbonne et al. 1987). The sedimentology of the formation was studied by Myrow (1987; also see Myrow et al. 1988). The lowest member contains red and green sandstones and shales deposited in tidal flat and shallow subtidal environments, and darker green/gray siltstones and black shales deposited in semi-restricted shoreline environments. Member 2 consists primarily of green siltstone and thinly laminated to medium-bedded, very fine to medium-grained sandstones deposited in a storm-influenced deltaic setting. The third member is a thinly-laminated siltstone unit with abundant carbonate nodules deposited in a mid to outer-shelf setting, predominantly below storm wave base. Member 4 contains red and green mudstones with minor limestone beds. Member 5 is a coarsening-upward sequence of storm- and wave-dominated sandstones and siltstones.

This paper focuses on the sedimentology of the second member of the Chapel Island Formation. Stratigraphic and sedimentological evidence from member 2 indicates deposition in nearshore and inner-shelf settings (between the shoreline and the storm wave base). Deposition took place in a deltaic setting characterized by high sedimentation rates of silt and clay (Myrow et al. 1988; Myrow and Hiscott, 1991). Three facies make up the bulk of member 2: Gutter Cast Facies, Siltstone-Dominated Facies, and Sandstone-Dominated Facies (Fig. 2). These facies are intimately interbedded within member 2, although they do not make up its full thickness. Other facies not relevant to this paper are described in Myrow (1987).

SHORELINE DEPOSITS OF MEMBER 1 AND LOWER MEMBER 2

The bulk of member 1 and portions of lower member 2 contain very thin to medium bedded, red and green, fine-grained sandstone, siltstone, and mudstone. Flaser- and wavy-bedded sandstone-rich facies (approximately 50–80% sandstone) (Fig. 3A) contain abundant erosional surfaces and lenticular scour-and-fill or channel-fill beds of sandstone or interlaminated shale and sandstone. Sandstone beds have sharp erosional contacts and are commonly amalgamated. Laminated and very thinly bedded shaly facies (15 to 50% sandstone) exhibit wavy and lenticular bedding and contain fewer erosional surfaces and channel sandstones. Sedimentary structures in these facies include abundant current ripples and interference ripples, sandstone-filled desiccation cracks (Fig. 3B) and synaeresis cracks (particularly abundant in the shaly facies), mud-chip conglomerates, and rare raindrop prints.



Legend.—Figure 2

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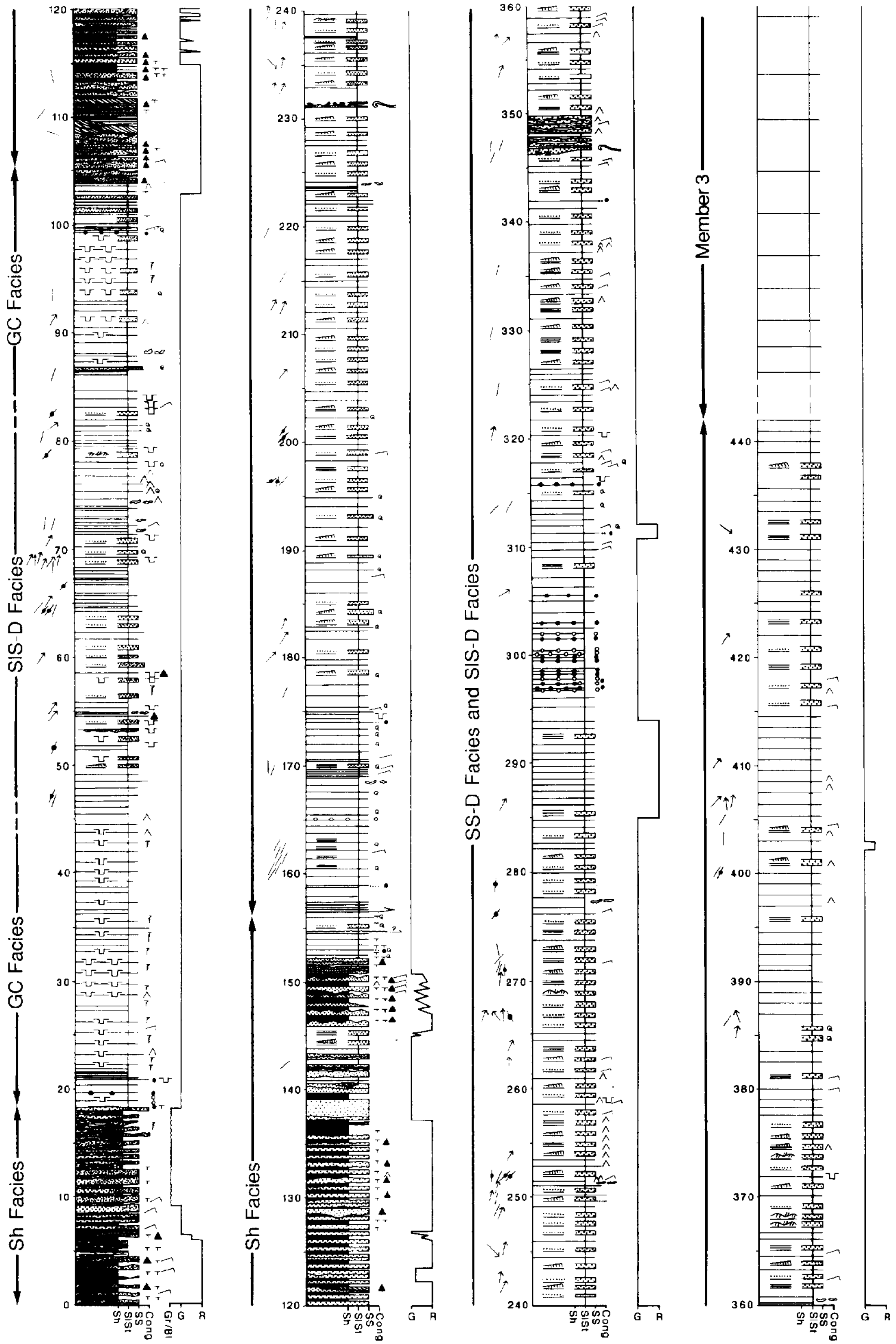
FIG. 2.—Stratigraphic section from member 2 of Fortune Head locality (Fig. 1). The member 1–member 2 contact is at the 18.2 m mark. The top of the section is in the transition zone into member 3.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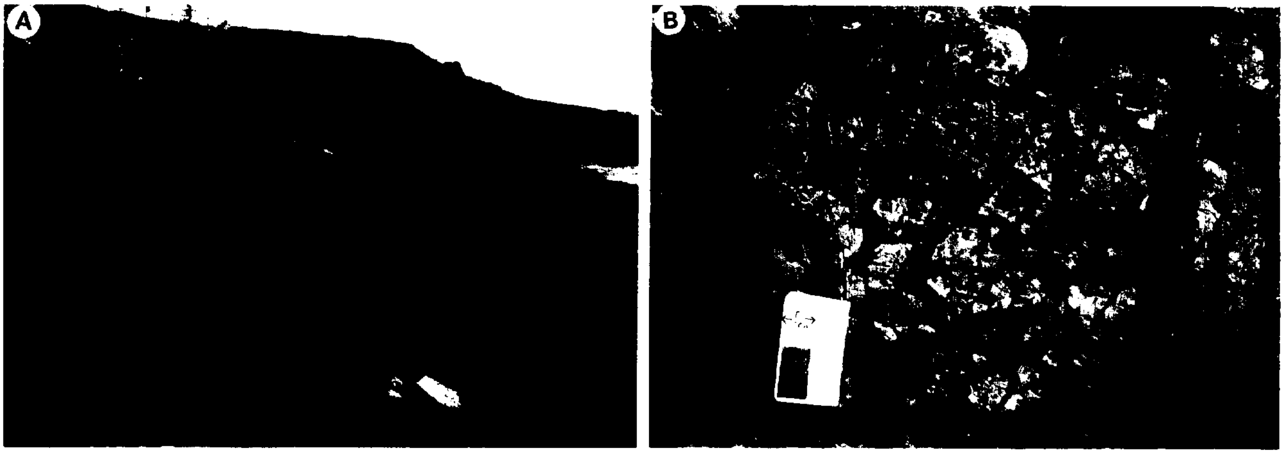

FIG. 3.—Shoreline deposits of member 1 and lower member 2. **A)** Medium bedded sandstone and thin shale from lower member 2 (105–110 m interval, Fig. 2); railing and base of foghorn tower in upper left for scale. **B)** Several generations of different size of polygonal desiccation cracks preserved on a bedding surface (151 m mark, Fig. 2). Notebook is 18.5 cm tall.

Paleocurrent data gathered from current ripples indicate bimodal-bipolar flow conditions, with the stronger mode towards the southwest (Fig. 4).

The full suite of sedimentary structures and overall organization of beds indicate marine conditions, as does the albeit limited suite of trace fossils (*Bergaueria* sp. and *Planolites*). Thinly interlayered beds, ubiquitous mud-chip conglomerates, abundant scour surfaces, desiccation and synaeresis cracks, bimodal-bipolar paleocurrent distribution, and many other features are most consistent with a tidally-influenced peritidal environment. The scale of interbedding, sandstone/shale ratio, and suite of sedimentary structures in the sandy lithofacies would be most typical of lower-tidal-flat to shallow-subtidal settings, whereas the shaly facies, deposited in shallower water conditions, represents middle to upper tidal-flat deposits. Full descriptions of the shoreline facies described above are given in Myrow (1987) and Myrow et al. (1988).

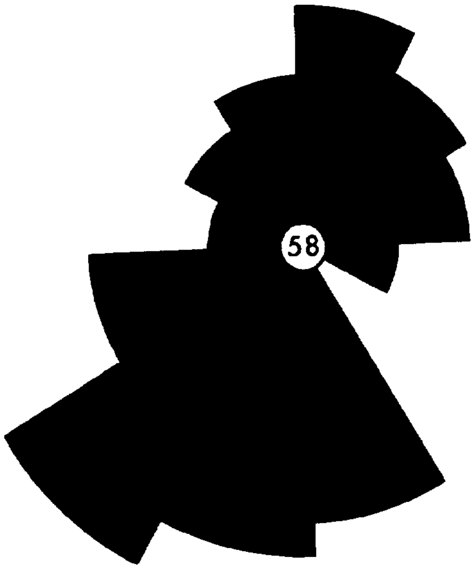

FIG. 4.—Paleocurrent equal area rose diagram of ripple cross-lamination from member 1 (n = 58). Data collected at Grand Bank Point locality (Fig. 1).

GUTTER CAST FACIES

The Gutter Cast Facies of member 2 is composed of thinly laminated to very thinly bedded sandstone and siltstone beds with abundant gutter and pot casts (Fig. 5A, C). The sandstone content, excluding gutter casts, varies roughly from 10–40%, with beds greater than 2 cm thick making up < 2% of the strata. Quartzose sandstone beds (described below) make up approximately 5% of this facies. There is an inverse relationship between the abundance of gutter casts and the thickness of bedding; for instance, an 11 m interval with abundant gutter casts contains no sandstone beds thicker than 2.5 cm.

Massive siltstone gravity-flow deposits up to a meter thick are abundant (Myrow and Hiscott 1991), making up 10–15% of the facies. These beds are analogous in scale, geometry and grain size to the silt-flow deposits in gullies described by Prior et al. (1986) from the delta front region of the Huanghe (Yellow River) Delta. Ptygmatically folded sandstone dikes are surprisingly abundant and are testimony to the high sedimentation rates. Below is a description of the bed types common in this lithofacies.

Silver-Green Siltstone

The dominant lithology in the Gutter Cast Facies (and member 2 as a whole) is homogeneous silver-green to gray-green muddy siltstone, comprising 60–90% of the strata (Fig. 5A, D). Siltstone beds vary from millimeters to a few centimeters in thickness, and range from undisturbed to strongly bioturbated. The homogeneity of grain size and lack of lamination indicates slow, uniform de-

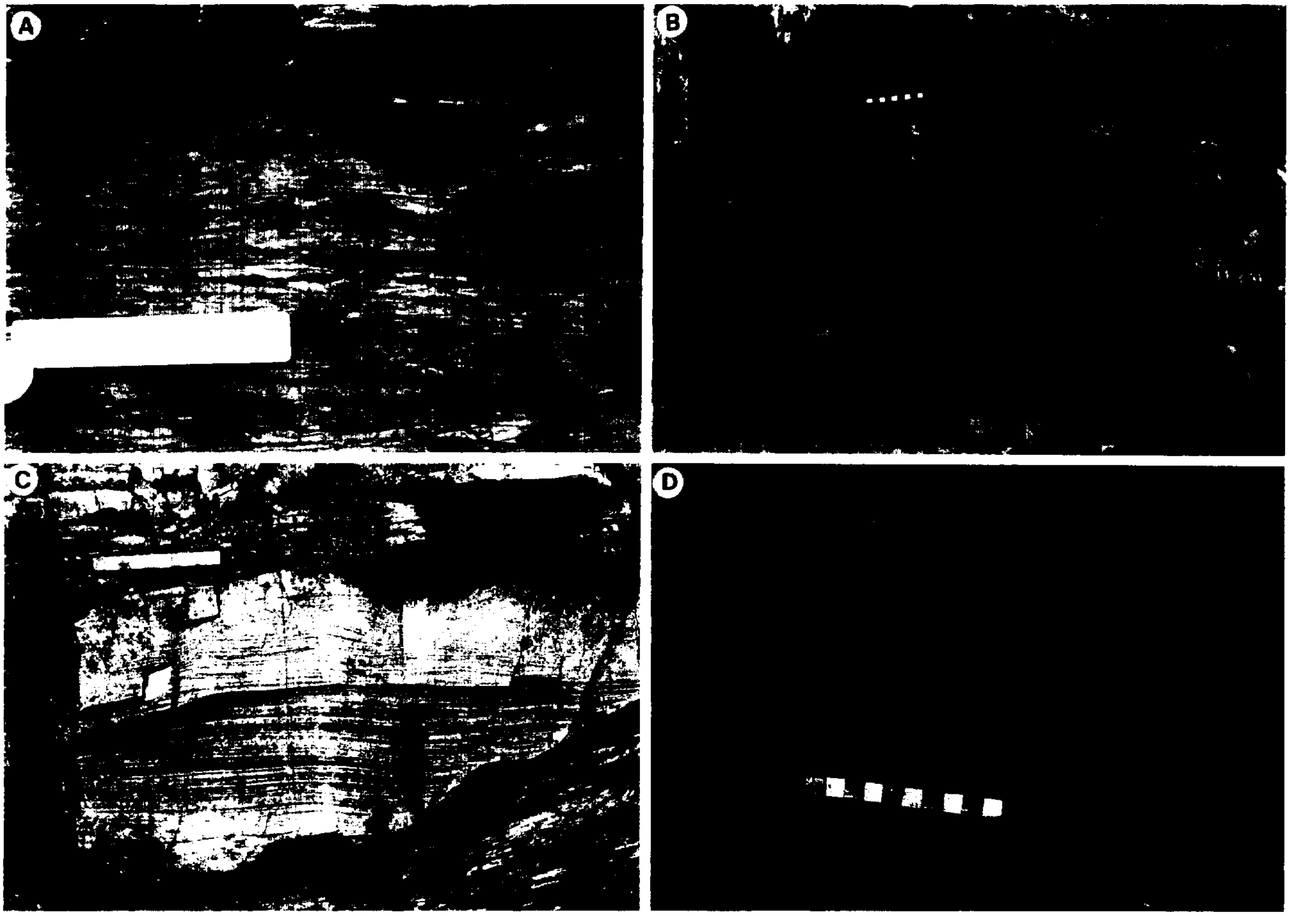

FIG. 5.—Gutter Cast Facies. A) Close-up of bedding showing thin sandstone laminae and gutter casts (arrowed); numerous *Skolithes annularis* traces cut the lamination; scale is 2.5 cm wide. B) Partially-starved wave ripples; note tuning-fork junction; scale is 10 cm long. C) Carbonate-cemented (concretion) gutter cast with horizontal lamination at base and climbing wave-ripple lamination above; scale in cm. D) Close-up of 8 cm-thick graded rhythmite (GR) bed. Note thin pinch-and-swell lower sandstone division, thinly-laminated middle division and upper division of homogeneous siltstone; scale in cm.

position from suspension. Some of the siltstone was also deposited more rapidly during late-stage fall-out associated with sandstone tempestites.

Very Thin Sandstone Laminae and Graded Rhythmites

Very thin laminae of coarse siltstone to fine sandstone, less than 0.5 mm thick, are interlaminated with siltstone with millimeter to several centimeter spacings. These laminae pinch and swell and locally form starved symmetrical ripples (Fig. 5A, B). These thin sandstone laminae are present both in isolation and in groups that make up the upper divisions of graded rhythmite beds (up to 6 cm thick). The graded rhythmite beds show an upward increase in spacing and a decrease in grain size and thickness of sandstone laminae within a siltstone matrix (Figs. 5D; 6). These beds generally contain three divisions: basal, middle, and upper. The basal division (not always present) consists of up to 2 cm of parallel laminated or ripple cross-laminated fine sandstone with a sharp lower surface and a sharp *or* gradational upper surface. Sole marks include grooves, prods, flutes, and trace fossils. A middle division of fine siltstone (> 50% of bed thickness and up to 10 cm thick) contains submillimeter-thick coarse siltstone/very fine sandstone laminae that become thinner, more widely spaced and finer upward. Where ripple form sets are present in the lower division, laminae in the middle division mimic the underlying rippled surface, and then lose their topography upward. Individual laminae are remarkable planar and extensive, with very little variation in thickness. The upper division (3–6 cm thick) of smooth-weathering fine siltstone contains few (if any) very thin and widely spaced laminae (Fig. 6).

The overall size grading and sequence of structures in the graded rhythmites indicate deposition under decelerating flow. The lower divisions indicate deposition from traction under either upper (parallel lamination) or lower (ripple lamination) flow regime conditions. The middle and upper divisions contain no evidence of traction and

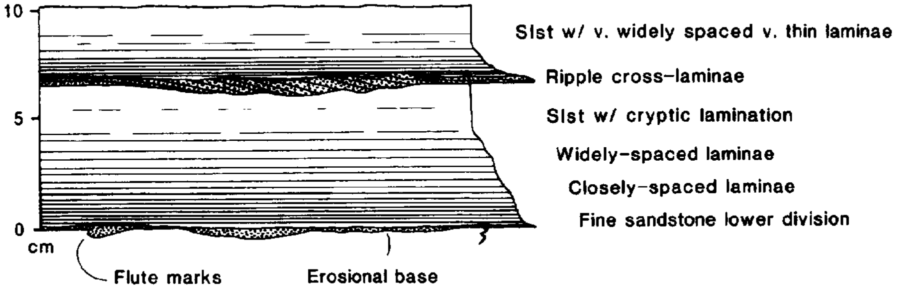

FIG. 6.—Schematic diagram of graded rhythmite beds showing erosional lower surface (± sole marks), lower sandstone division (± traction structures), middle division with upward increase in spacing of fine sand laminae within siltstone, and upper siltstone division. Details provided in text.

therefore were probably deposited from suspension. Several aspects of the very thin sandstone laminae support this interpretation: 1) extreme thinness, 2) lack of visible internal structure, 3) lateral persistence, 4) uniform thickness and 5) nonerosional lower contacts (Fig. 6). Grain size of these laminae is coarser than the coarsest grains in the intervening green siltstone, ruling out *in situ* winnowing as a mechanism of formation.

Graded rhythmites, described from both modern and ancient shallow marine facies, have been attributed to deposition from suspension clouds during the waning stages of a storm (Gadow and Reineck 1969; Reineck and Singh 1972; Dott and Bourgeois 1982). Most examples of graded rhythmites (e.g., Reineck and Singh 1972, fig. 2) are thicker and much less regular than those in this study. If deposition of the Chapel Island Formation examples took place from decelerating combined flows, the planar laminae of uniform thickness are enigmatic because laminae produced under the influence of strong oscillatory currents are very irregular in general (De Raaf et al. 1977).

FIG. 7.—Quartzose bed capped with irregularly-shaped ripples. In the lower part of the bed, low-angle lamination passes upward into ripple cross-lamination; scale in cm.

Carbonate-Cemented Quartzose Beds

A volumetrically minor component of member 2 is thin to medium bedded, white-weathering, carbonate-cemented, quartzose sandstone beds (Fig. 7). These well-sorted, medium- to very coarse-grained beds are normally graded and commonly contain a thin upper division of gray fine-grained sandstone. The thinner beds, less than 3 cm thick, typically pinch and swell and were formed by infilling of shallow erosional scours. Sedimentary structures in these thin beds include parallel lamination, ripple cross-lamination, and symmetrical ripple form sets. Thicker quartzose beds have abundant well-developed symmetrical ripples which show significant variability in size and geometry of adjacent crests.

The sorting and grain size of these beds is unique in member 2 and indicates transport from local settings that are not represented in outcrops of the lower Chapel Island Formation. Most of these beds record reworking by waves during and after emplacement.

SILTSTONE-DOMINATED FACIES

The Siltstone-Dominated Facies, volumetrically the most important within member 2, contains a wide range of bed types, including a large variety of gravity-flow deposits, mostly debris flows, slumps and slides (Myrow and Hiscott 1991). Sandstone content of this lithofacies ranges from 5–40% (average 15–20%). A few thin zones have abnormally high sandstone content (70–85%), mainly in the form of rippled, wavy, and lenticular, very thin and thin sandstone beds. For comparison with the Sandstone-Dominated Facies described below, the percentages of various bed types have been calculated for a 40-m interval of this lithofacies. In this interval 2.0% of the strata are quartzose sandstone beds (described above), and significantly only 2.8% are beds thicker than 3 cm. Two gravity-flow deposits make up 2.5% of this interval.

Average sandstone bed thickness is greater than in the Gutter Cast Facies yet thinner than in the Sandstone-Dominated Facies. Bedding is relatively even and continuous, mainly because of nonerosional upper bed contacts and a paucity of gutter casts. Bed types common to this lithofacies are described below.

TABLE 1.—*Storm-generated sedimentary features from member 2*

Storm-Generated Sedimentary Features	Member 2
Interbedded coarse (storm) and fine (fair-weather) beds	✓
Sharp/scoured base—gradational top	✓
Pot and gutter casts	✓
Flat-pebble conglomerate	✓
Lags	✓
Thickening and thinning and lenticular beds	✓
Reworked but autochthonous fauna	N.A.
Infiltration textures	N.A.
Escape burrows	✓
Graded rhythmites	✓
Wave-generated undulatory lamination	✓
Vertical sequence: planar lamination to wave-generated lamination	✓

* N.A. = Not applicable.

Thin Laminae to Medium Beds of Sandstone

Brown weathering, very fine to fine-grained sandstone beds ranging from 1 mm to approximately 20 cm in thickness make up a considerable portion of this lithofacies. These contain a wide variety of internal sedimentary structures and a plethora of trace fossils and both current- and tool-generated sole marks. There is some correlation, detailed below, between bed thickness and such characteristics as bed geometry and internal stratification. Paleocurrent data from these sandstone beds, given in Figure 8, include orientations of parting and current lineations, grooves, flutes, ripple cross-laminae, and wave-ripple crests.

Sandstone laminae 1 to 10 mm thick typically pinch and swell and are highly discontinuous. Internal sedimentary structures include normal grading, parallel lamination, and small-scale incipient or fully-developed ripple cross-lamination. Sharp-crested, symmetrical ripples with large spacing-to-height ratios (10–15:1) are common on upper bedding surfaces. These ripples have very small crest heights (less than 5 mm) and are locally starved.

Very thin to medium sandstone beds, 1–30 cm thick, are generally continuous and more even in thickness than the thinner sandstone laminae. Over large stratigraphic intervals these beds constitute 20–40% of the section, but make up as much as 80% or more of the section over thin stratigraphic intervals (less than 1.5 m). Amalgamation of beds is uncommon, occurring exclusively in thicker beds. The sandstone beds are sharp-based, but the upper contacts are either sharp and showing evidence of reworking and erosion (Fig. 9C, E, F) or gradational (Fig. 9D) and lacking evidence of reworking. Lower contacts range from planar (Fig. 9E) to highly irregular, and soles are covered with a wide variety of trace fossils and sole markings including flutes, grooves, prods, and current crescents.

Internal stratification styles include 1) nongraded, apparently structureless; 2) graded; 3) erosional-stoss and depositional-stoss climbing-ripple types (Fig. 9B); 4) ripple lamination with concave-up scour surfaces, bidirectional bundled lenses, unidirectional cross-laminae opposed between adjacent crests and offshooting laminae (Fig. 9C); and 5) planar or undulatory parallel laminae (Fig. 9E).

Bed tops display a wide variety of trace fossils and sedimentary structures, including small two-dimensional vortex ripples (Harms et al. 1982), large asymmetrical ripples with sinuous to linguoid crests, interference ripples, and polygonal ripples. Ripple form sets have either symmetrical profiles and form-discordant lamination or asymmetrical profiles and form-concordant lamination (Fig. 9B). Both ripple types exhibit considerable variation in size, shape and internal structure of adjacent crests along ripple trains (Fig. 9B, C, E, F). Two types of combined-flow ripples are common: highly three-dimensional types with rounded crests, and straight and bifurcating types with sharp crests (Fig. 9A). (Combined-flow ripples are generally asymmetrical, but in comparison to current ripples they have a more regular plan geometry and lee faces that slope less than the static angle of repose (Harms et al. 1982).)

The interbedding of the thinner sandstone laminae (described above) with siltstone is similar to facies that De Raaf et al. (1977; see their "Lithotype M2") and Soegaard and Eriksson (1985) attribute to wave reworking during the late stages of deposition during storms. Most of the sedimentary structures described above are considered to be diagnostic of wave-generated features as discussed by Boersma (1970), De Raaf et al. (1977), Allen (1981), Harms et al. (1982) and others. Undulatory laminae, which are common in the thicker beds, are also considered to be formed under intense oscillatory flow (Allen 1981, p. 372; Harms et al. 1982) or combined flow (Arnott and Southard 1990).

Waning flow produced normal grading and vertical stratification sequences (Myrow and Southard 1991) such as parallel laminae to combined-flow or wave-generated laminae (Fig. 9E) that are diagnostic of storm deposits, or "tempestites" (De Raaf et al. 1977; Kreisa 1981; Aigner 1982; Brenchley 1985; and others; also see Table 1). (Gutter casts in the Gutter Cast Facies also contain similar sequences; see Fig. 5C.)

In each of the widely-spaced localities studied, the paleocurrent data from flute marks show a strong unimodal orientation toward the northeast, which coincides with the consistent northeast-southwest orientation of current/parting lineations and grooves (Fig. 8). The long axes of gutter casts are similarly aligned (Fig. 10; Myrow unpublished data). The orientations of wave-ripple crests are uniformly perpendicular to these paleocurrent data. It is well known that as storm waves approach shore they become refracted parallel to the isobaths (Davis 1977), so that the degree of irregularity of a shoreline would be reflected in the degree of scatter of wave-ripple data between localities. The consistency of the member 2 data (Fig. 8) from outcrops as far apart as 100 km indicates that the northwest-southeast orientation is a reasonable approximation of the shoreline orientation during this time. The orthogonal or near-orthogonal relationship between the wave-ripple data and the various other paleocurrent data is similar to many ancient wave-influenced (mainly wave-dominant) shorelines (see review by Leckie

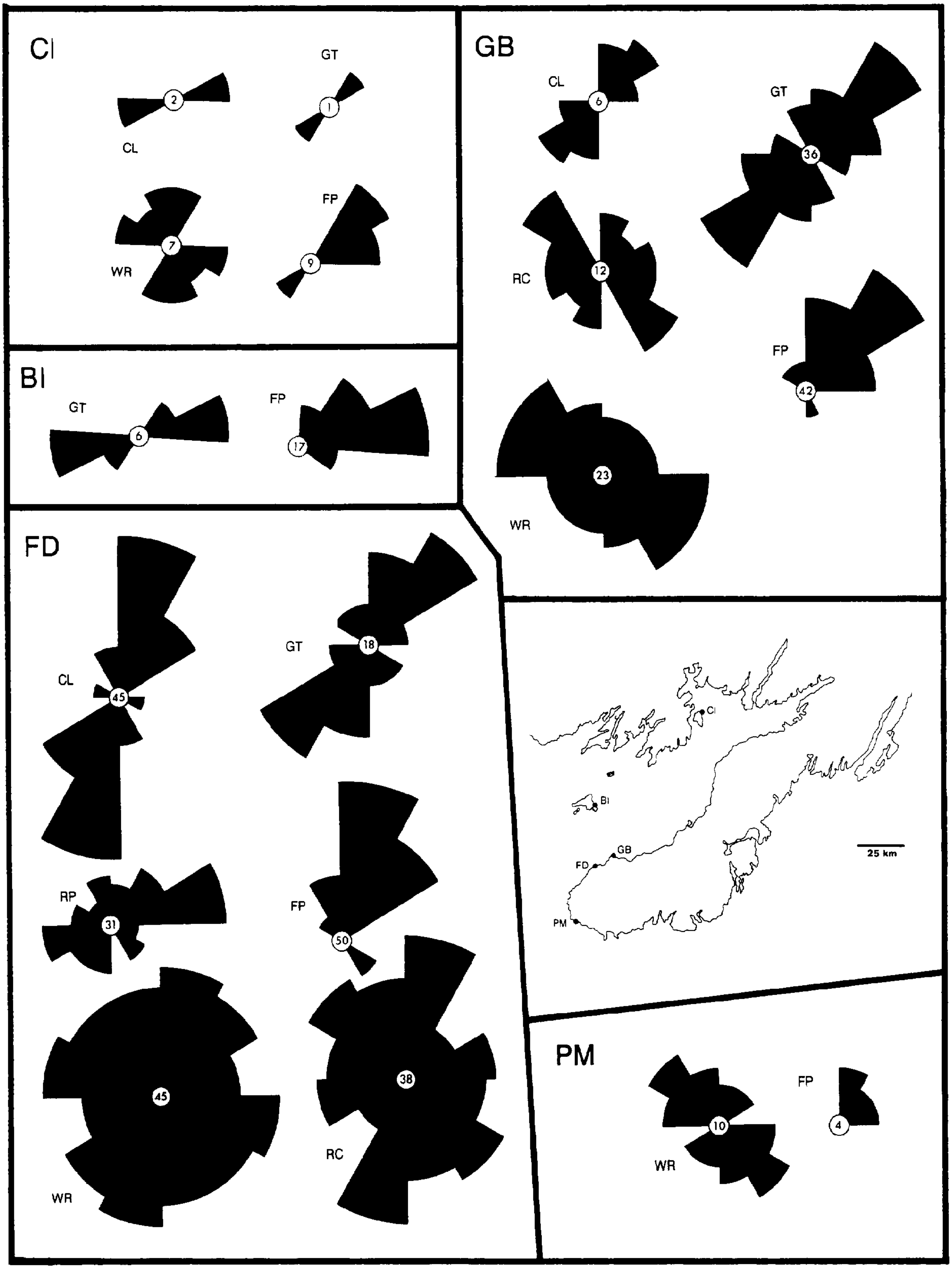

FIG. 8.—Paleocurrent information for member 2 from localities throughout field area. CL = orientations of current lineations, GT = groove trends, FP = flute paleocurrents, RP = ripple paleocurrents, WR = wave-ripple-crest trends, RC = ripple-crest trends (ripple type unknown). Localities as follows: CI = Chapel Island; GB = Grand Bank Point; PM = Point May; FD = Fortune Dump (Head); BI = Brunette Island.

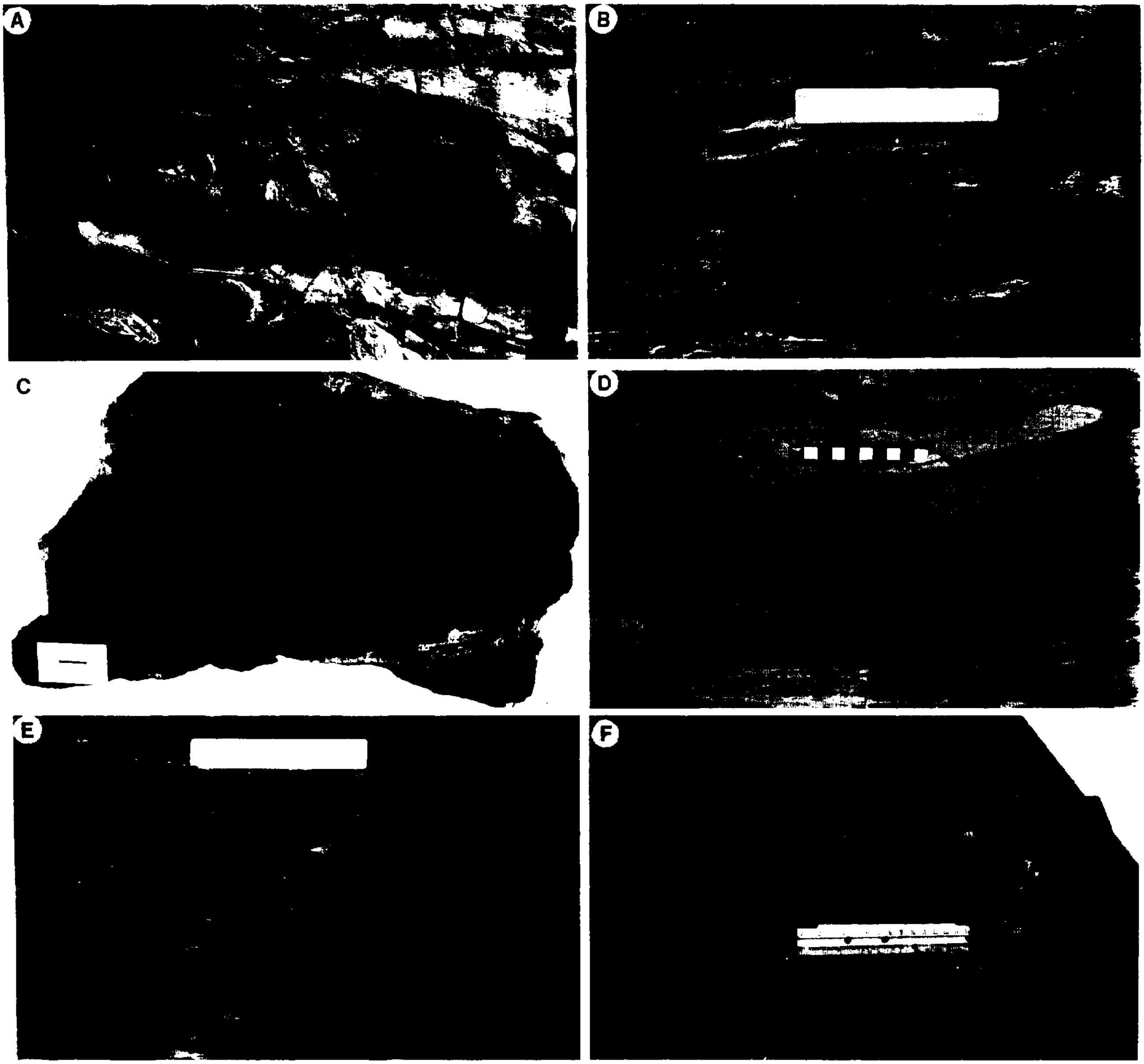

FIG. 9.—A) Combined-flow ripples with sinuous, slightly asymmetrical crest; eroded stoss laminae indicate flow from upper right to lower left; scale is 15 cm long. B) Sandstone bed with low-relief ripples in center of photo showing variation in internal structure between crests and external geometry (symmetrical and asymmetrical); scale is 15 cm long. C) Symmetrical form-discordant ripples in concretion with bundled upbuilding, scooped lower bounding surfaces, bidirectional bundled lenses and draping lamination, all characteristic features of wave-formed ripples; scale is 1 cm long. D) Sharp based bed with flute marks (arrow); top of bed is gradational into the siltstone above; scale is 10 cm long. E) Reworked upper surface of a parallel laminated bed displays symmetrical sharp-crested ripples; note parallel lamination within the ripple crest on the right side of photo; scale is 15 cm long. F) fine sandstone bed with variation in size and shape of adjacent symmetrical crests along a ripple train; scale is 15 cm long.

and Krystinik 1989) and suggests offshore-directed transport (towards northeast) of sediment during storms.

Thin Pebble Conglomerate Beds

Very coarse sand to pebble-sized quartzose conglomerate are found 1) as isolated thin laminae (minimum of 1–2 grains thick) to very thin beds within siltstone, 2) at the base of very thin graded sandstone beds, 3) along the foresets of finer-grained ripple cross-laminated beds (Fig. 11), 4) along gently undulating parting (amalgamation) surfaces within beds, 5) on the top surfaces of sandstone beds, and 6) within small, lenticular, concave-up beds. A few examples were noted in which isolated pebbles were floating within wave-ripple-laminated sandstone beds.

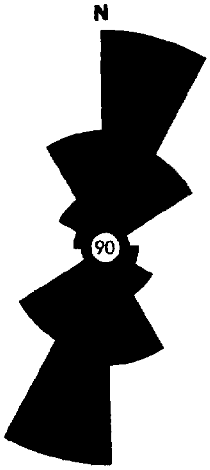

FIG. 10.—Rose diagram of trends of long axes of gutter casts (n = 90) taken from the Fortune Head locality.

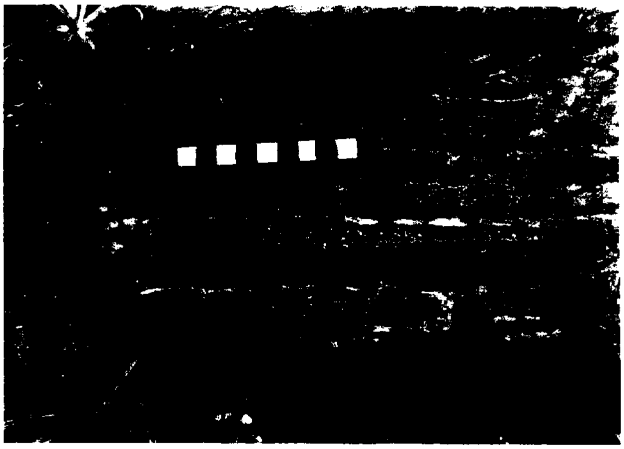

FIG. 11.—Lenticular granule-bearing coarse/very coarse sandstone with concentration of granules along low-angle cross-laminae; scale in cm.

Thicker coarse-grained ripples (e.g., Leckie 1988) were not noted.

In marine sequences, thin conglomerate beds are commonly interpreted as lag or condensation deposits. The extensive (albeit discontinuous) nature of many of the Chapel Island beds may be analogous to thin pebble layers described from a number of ancient storm-influenced deposits (Anderton 1976; Brenner and Davies 1973; Levell 1980).

Flat Pebble Conglomerate Beds

Thin, lenticular beds of flat pebble conglomerate are found widely spaced within the lower part of member 2. These consist of grain-supported beds of blue-tinted black phosphatic shale clasts and gray to green siltstone intraclasts set in a matrix of clean, coarse/very coarse sandstone. The phosphatic shale clasts are well rounded and are dominantly disc-shaped. These clasts represent reworked, lithified fragments of transported shale and sandy shale. The siltstone intraclasts were mostly semilithified at the time of deposition, showing some evidence of plastic deformation (e.g., indentation by other more competent black shale clasts). Some cut and polished slabs show incipient clast formation by the partial disarticulation of the underlying substrate. The beds in this study are similar to most other ancient examples, being less well sorted than modern examples and having horizontal and low-angle (< 30 degrees) imbrication (e.g., Roehl 1967; Kazmierczak and Goldring 1978). A few beds have mounded upper surfaces, with near-vertical imbrication in the upper parts of the bed.

The phosphatic shale clasts, which resemble those found along many modern beaches adjacent to shale outcrops, were probably derived from local sources along the shoreline and carried seaward during storms. Mounded bed tops and local vertical imbrication likely resulted from reworking of small, conglomeratic, low-relief accumulations by waves (Sanderson and Donovan 1974).

SANDSTONE-DOMINATED FACIES

The Sandstone-Dominated Facies is characterized by a higher percentage of thin and medium (i.e., greater than 3 cm in thickness) sandstone beds and a lower percentage of interbedded siltstone. Hummocky cross-stratified beds are more abundant, and both quartzose sandstones and flat-pebble conglomerate beds are virtually absent. Over one 40-m interval of this lithofacies, sandstone beds > 3 cm thick make up 19.7% of the strata. In particularly sandy intervals, thin to medium sandstone beds alone make up as much as 57.8% of the section. Visual estimates of the *total* sandstone content of this lithofacies—including thinner sandstone beds—is 40–60%, reaching 75% or more over thin stratigraphic intervals. Wave-ripple lamination is particularly abundant, as are form sets of wave ripples and combined-flow ripples. Sandstone beds have strongly erosional lower and upper surfaces and therefore show significant irregularities in thickness and some complete pinch-outs. Slide deposits are present but uncommon in this lithofacies. The hummocky cross-stratified beds of this lithofacies are described below.

HUMMOCKY-CROSS-STRATIFIED BEDS

The thickest sandstone beds within member 2 are commonly hummocky cross-stratified. These fine and very fine sandstone beds range from 12–18 cm in thickness and are both hummocky cross-stratified and hummocky in overall geometry, with meter-scale hummock spacings (Fig. 12A, B). Approximately half of these beds are discontinuous across the outcrop exposure (meters to tens of meters). These beds commonly contain amalgamation surfaces, usually with the hummocky-cross-stratified sandstone truncating an underlying unit of structureless or parallel-laminated sandstone. In several cases, well-developed hummocks are thickest above the deepest level of erosion into the underlying sandstone, as seen in Figure 13. The beds in this figure display 1) complete erosion of the underlying bed under the main part of the hummock,

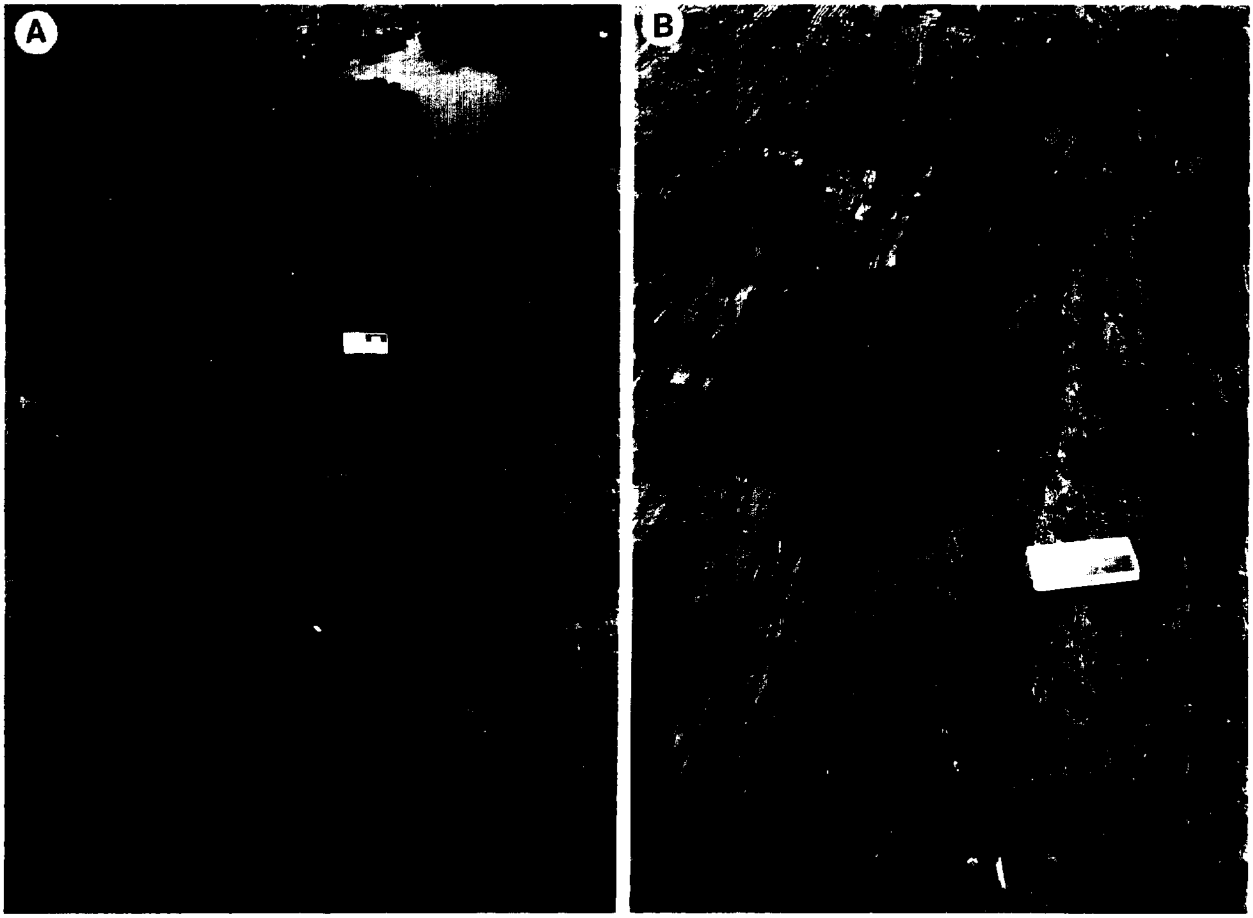

FIG. 12.—**A)** Isolated lenticular hummocky sandstone lens with convex-up lamination; complete erosional truncation of an underlying sandstone bed is seen directly underneath the hummock; stratigraphic top to left; notebook is 18.5 cm long. **B)** Hummocky cross-stratified bed; erosional lower surface defines a surface of amalgamation (arrows) with underlying sandstone bed (detailed sketch of this bed is given in Fig. 13 at bottom); symmetrical ripples on the upper surface near the top of the photo; stratigraphic top to left; notebook is 18.5 cm long.

2) lenticularity of the hummocky-cross-stratified layers, and 3) large symmetrical ripples on the upper surface.

The position of the hummocks above erosional depressions is similar to the stratification described by Surlyk and Noe-Nygaard (1986) from Jurassic sandstones in Denmark. This position may involve feedback between the depositing flow and erosional depressions formed earlier under higher velocities.

The discontinuous nature of most of these hummocky cross-stratified beds is a reflection of original depositional geometry and not of later erosion of their upper surfaces. The spacing of the hummocks in many of these beds is on the order of 3 to 4 m, and thicknesses of these beds average 15 cm (see Fig. 13). Typical heights—swale to hummock—for hummocky cross-stratification with spacings between 1–5 m are 20–40 cm (c.f., Duke 1985; Walker 1984); examples with smaller spacings have correspondingly smaller heights (see Craft and Bridge 1987). It is apparent that, given their spacings, the swale-to-crest heights for the beds in member 2 are smaller than expected for hummocky cross-stratification. This anomaly is considered a result of deposition associated with low sediment supply of cohesionless (sandy) sediment, yet under conditions (long wave periods and large orbital diameters) that would have been capable of generating large, continuous hummocky bedforms. Discontinuous, apparently starved hummocky features like those described in this study are not well documented, although Dott and Bourgeois (1982; p. 678) describe micro-hummocky lenses of sandstone that are similar in morphology and internal structure, if not in scale, to those in the Chapel Island Formation.

There is no consensus on the hydrodynamic conditions under which this stratification forms. The origin is almost surely polygenetic (Brenchley 1985; Leckie 1988) forming under simple or complex oscillatory flow (Harms et al. 1975; Dott and Bourgeois 1982; Harms et al. 1982; Duke 1985; Southard et. al. 1990) and a variety of combined flows (Swift et al. 1983; Greenwood and Sherman 1986; Nottvedt and Kreisa 1987; Arnott and Southard 1990; Duke 1990).

One bed, illustrated in Figure 14, differs from the ex-

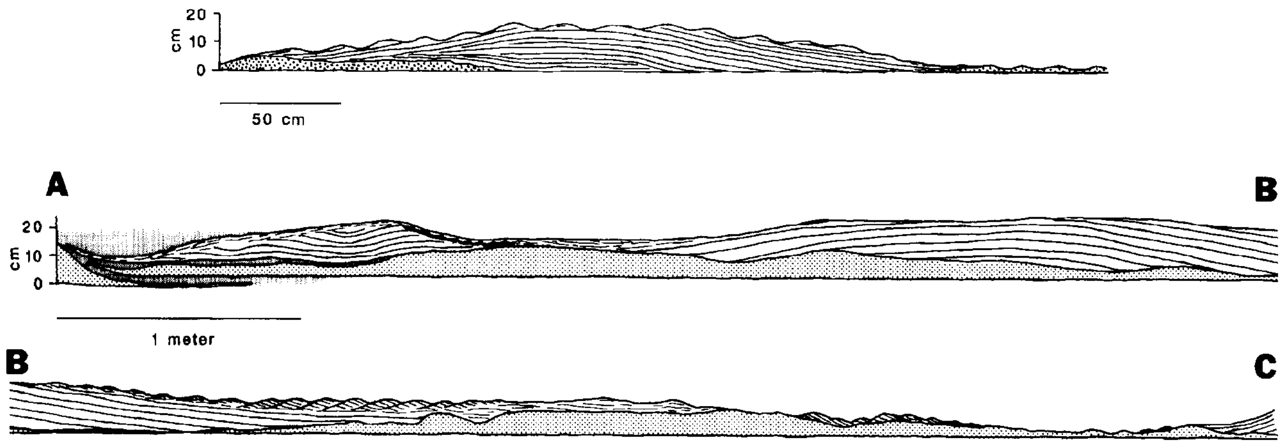

FIG. 13.—Two sketches of hummocky cross-stratified beds at Fortune Head locality. In top sketch, note amalgamation surface and the development of the hummock over the erosional low. Lower sketch A-B-C also shows an amalgamation surface, development of hummock over erosional depression and small 2d oscillation ripples on upper surface (ripples migrated but crests are symmetrical).

amples of hummocky cross-stratification described above. The bed ranges in thickness from 0.4–17 cm and has a hummocky and swaly geometry with small, straight-crested, symmetrical ripples on the swales. It contains very-low-angle laminae that dip consistently at 8° towards the northeast (restored downdip migration direction of foresets is toward 059°). There are no internal truncation surfaces, and the laminae are remarkably uniform and quite planar. The swales show truncation of the underlying laminae on the eastern downdip sides and conformability on the western or updip sides. Such a geometry has a parallel in simple current-ripple migration (Harms et al. 1982). The overall bed geometry and internal structure suggest that this bed formed from migration of a low-relief hummocky bedform under conditions of little or no net aggradation. The experimental work by Arnott and Southard (1990) indicate that unidirectional migration of low-relief hummocky bedforms occurs under oscillatory-dominant combined flow with a small to moderate unidirectional-flow component (> few cm per second). The beds described by Nottvedt and Kreisa (1987) are similar (hummocky geometry and anisotropic dips) except that their stratification is less regular and contains convex-up surfaces which imply deposition in a stoss-preserved climbing bedform under higher depositional rates.

MIDDLE TO OUTER SHELF DEPOSITS OF MEMBER 3

Member 3 consists of gray-green siltstone with fine laminae to very thin graded sandstone beds and abundant carbonate concretions. Bedding soles are not exposed, but upper bedding surfaces display current ripples, parting and current lineation, and a limited range of trace fossils (*Diplocraterion, Teichichnus,* and *Helminthopsis*). Ripples are dominantly straight or sinuous crested with asymmetrical profiles, very high spacing-to-height ratios (e.g., 30), and unidirectionally-oriented cross-laminae. Parallel laminated medium grained sandstone laminae, from 1 mm (several grains thick) to > 1 cm, are of uniform thickness and exhibit current and parting lineation. Very thin and thin, fine grained sandstone beds are either ripple cross-laminated or contain parallel laminae that are overlain by ripple cross-laminae. The sandstone beds of member 3 lack oscillatory and combined-flow ripples and corresponding styles of cross-lamination which are so abundant in member 2.

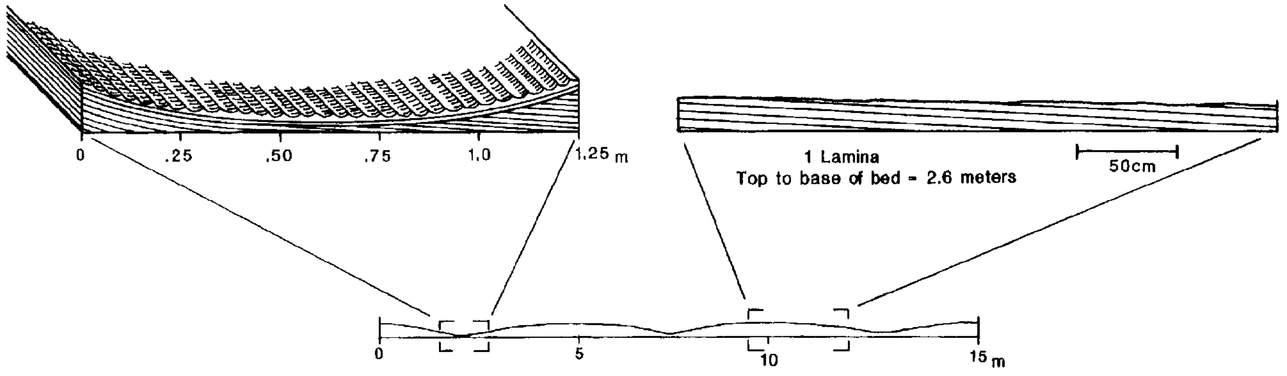

FIG. 14.—Sketch of low-angle cross-stratified bed at Fortune Head locality. Enlargement on left shows features in the swale. Enlargement on right shows the extensive planar lamination.

The suite of sedimentary structures indicates deposition from waning unidirectional flows below storm wave base. Parting and current lineation (Fig. 15), representing flow direction during upper-plane-bed conditions, are strongly oriented northeast-southwest, consistent with the wide variety of paleocurrent data described above for member 2. The deposits of member 3 are similar to other sub-wave-base, storm-generated sandstones (Hamblin and Walker 1979; Brenchley et al. 1979; Walker 1984; Brenchley 1985) and are therefore considered to be distal tempestites. Full description and interpretation of member 3 deposits is given in Myrow (1987).

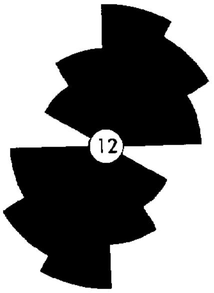

FIG. 15.—Rose diagram of orientation of current and parting lineation from member 3 (n = 12) from the Dantzic Cove locality (Fig. 1).

LITHOFACIES DISTRIBUTION AND PALEOBATHYMETRIC RECONSTRUCTION

Evidence for storm sedimentation has been presented in the descriptions of member 3 and the three facies in member 2. A comparison of the features in member 2 with accepted storm-generated features from ancient tempestites is given Table 1. The similarity is striking and clearly suggests that storms were the most significant agent of deposition. A facies model for storm deposition of members 2 and 3 will follow a discussion of lithofacies distribution and their inferred paleobathymetric relationships.

Member 2 was deposited during a long-term relative sea-level rise upon which were superimposed a number of small-scale relative sea level changes (Myrow 1987; Myrow et al. 1988). The shoreline deposits of member 1 and the lower part of member 2 are not found higher in the member, and the upper part of member 2 grades into the deeper sub-wave-base shelf deposits of member 3. The Gutter Cast Facies is confined to the lower part of member 2, where it occurs in two stratigraphic intervals (Fig. 2) which, in both cases, have gradational contacts with the Siltstone-Dominated Facies and somewhat abrupt contacts with shoreline facies containing polygonal desiccation cracks (Fig. 3B). The Siltstone-Dominated Facies constitutes the bulk of member 2 and is gradational, and interstratified, with the Sandstone-Dominated Facies, which is found primarily in the middle and upper parts of the member. Importantly, neither the Siltstone-Dominated Facies or Sandstone-Dominated Facies is in contact with shoreline facies; only the Gutter Cast Facies is found in contact with shoreline facies (Fig. 2).

The lowest 85–90 m of member 2 (Fig. 2) shows a symmetrical pattern of lithofacies in which heterolithic desiccation-cracked tidal flat deposits are overlain by (in order): Gutter Cast Facies, Siltstone-Dominated Facies, Gutter Cast Facies, and then more shoreline deposits with desiccation cracks. The arrangement of lithofacies suggests that the Gutter Cast Facies was deposited in the shallow subtidal zone and the Siltstone-Dominated Facies in a somewhat deeper subtidal area. Any alternative view, by which the paleobathymetric positions of the Gutter Cast and Siltstone-Dominated Facies were reversed, would not only make little sense in terms of the stratigraphic transitions, but would also require offshore-directed flows to move away from the shoreline at lower velocities depositing sediment and then accelerate, without changing direction, to erode the consolidated muds of the sea floor to form gutters.

Flat pebble and pebbly conglomerate beds (in the Siltstone-Dominated Facies) and quartzose sandstones (in the Gutter Cast Facies) are confined stratigraphically to the lower part of member 2, an overall transgressive sequence, suggesting that the sediment was derived from shoreline deposits and transported a short way into the subtidal zone during storms. The quartzose sand may have been derived from small pocket beaches or sand patches that migrated on the sea floor in the nearshore zone. The flat pebbles were likely derived from wave-washed accumulations at the base of eroding shale outcrops. The abundance of gravity-flow deposits in the Gutter Cast and Siltstone-Dominated Facies in the lower part of member 2 is also evidence for deposition in the proximal areas of a deltaic system where accumulation rates are highest and instability features are most abundant. Gravity-flow deposits are rare in upper member 2 and absent in member 3, the most distal deposits in this transgressive sequence.

The relationship of the Sandstone-Dominated Facies to the other two facies is more difficult to establish. This facies is not stratigraphically related in a systematic manner to shoreline deposits, as are the other two facies; however, it was deposited above storm wave base, as evidenced by abundant wave-ripple lamination and hummocky cross-stratified beds. Interestingly, many examples of the Sandstone-Dominated Facies are found directly above gravity-flow deposits. Myrow and Hiscott (1991) describe debrite and slide deposits that are mantled by hummocky cross-stratified sandstone which was deposited shortly after mass movement. In these cases, sediment failure was presumably due to cyclic wave loading associated with storms, possibly as a result of a lowering in relative sea level which changed wave intensity across the inner shelf. Those packages of the Sandstone-Dominated Facies associated with gravity-flow deposits likely result, therefore, from increased sand supply during base-level lowering. The abundance of hummocky cross-stratification and amalgamated bedding would reflect increased storm activity associated with these periods of lowered relative sea level.

However, many examples of the Sandstone-Dominated Facies are gradational with the Siltstone-Dominated

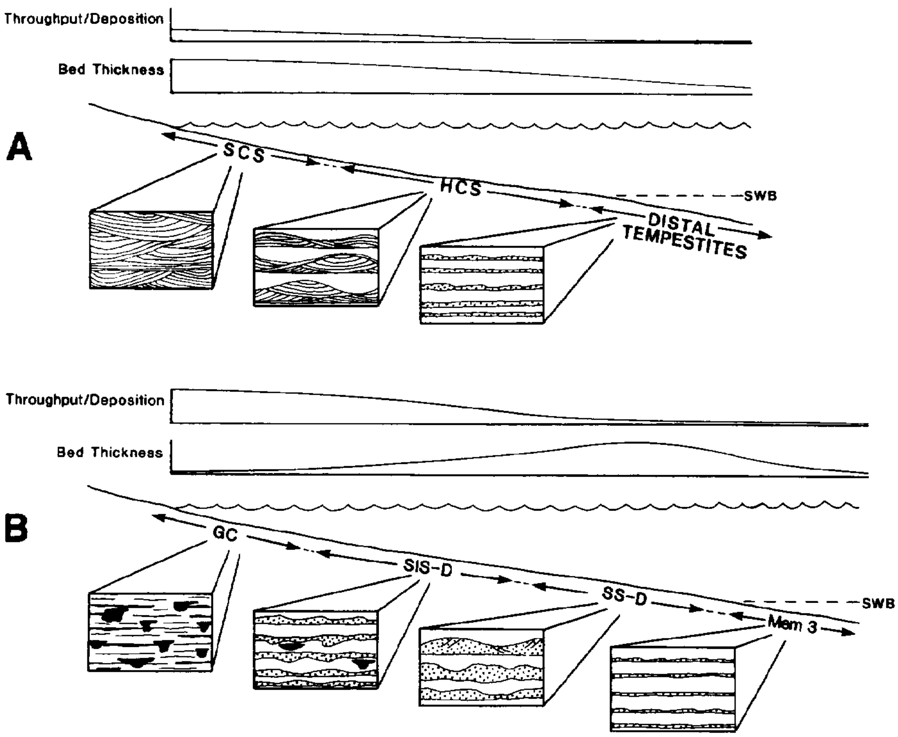

FIG. 16.—Comparison of standard tempestite model versus proposed model for member 2. The spatial distribution of facies in each model is illustrated with onshore-offshore profiles and associated qualitative changes in bed thickness and degree of sediment bypass (throughput/deposition ratio) are plotted above each profile. Proximality trends in the standard model A) include constantly decreasing bed thickness away from the shoreline with a shift from SCS sandstones to HCS sandstones to distal turbiditelike beds. The model for member 2 B) shows a bed-thickness trend that first increases then decreases away from the shoreline. The proximal setting is one of bypass with erosion the dominant process during storms (many gutter casts). Passing seaward, gutter casts die out and bed thickness increases. Rare HCS is formed in the thicker sandstone beds farther out on the shelf. Below storm wave base (SWB) distal tempestites are turbiditelike in character (member 3). The shelf gradient for both models is shown to be the same simply for convenience.

Facies and are not associated with gravity-flow deposits. It is particularly important to note that most of the thick hummocky cross-stratified beds associated with this facies are found in the top 30–40 m of member 2 at the transition into member 3, the thinly laminated siltstones deposited below storm wave base (Myrow 1987; Myrow et al. 1988). This stratigraphic position suggests that the Sandstone-Dominated Facies was in this case deposited in deeper shelf areas than the Siltstone-Dominated Facies, but above storm wave base. The absence of thin conglomerate beds and quartzose sandstones supports this interpretation.

FACIES MODEL AND PROXIMALITY TRENDS

The shoreline to offshore model for member 2 of the Chapel Island Formation (Fig. 16B) differs substantially from models for storm-dominated shelves with sandy coastlines described in the literature, which feature thick, often amalgamated, sandstone beds (swaley cross-stratification) nearshore and progressively thinner sandstone beds (hummocky cross-stratification and distal tempestites) offshore (Brenchley et al. 1979; Aigner 1982, 1985; Allen 1984; Walker 1984; Brenchley 1985; Pederson 1985; Handford 1986) (Fig. 16A). Instead, the shallow subtidal for member 2 was dominated by fine-grained sediments and was a zone of throughput with high-velocity, sediment-laden flows eroding deep narrow scours (gutter casts). Gutter casts are strongly aligned northeast-southwest (Fig. 10), perpendicular to shore, as they are in most ancient deposits (Myrow, unpublished data). Very little sand was deposited outside these scours: most of the sediment bypassed the very shallow subtidal zone and was deposited in deeper water. As storm-generated flows moved into deeper water they started to decelerate, resulting in less significant erosion of the sea floor and increased deposition, to form more continuous and regular beds (Siltstone-Dominated Facies). At some distance from shore, bed thickness reached a maximum (Sandstone-Dominated Facies), and even farther seaward bed thickness decreased again. The most distal tempestites, deposited below storm wave base, are represented by member 3.

Current-generating driving forces associated with storm systems (due to superelevation of the sea surface at the shoreline) decrease in intensity seaward (see reviews of storm deposition by Walker 1984; Brenchley 1985; Morton 1988), and as a result all modern and ancient storm deposits thin distally in mid to outer shelf areas (Howard and Reineck 1981; Kreisa 1981; Aigner 1982, 1985; Howard and Nelson 1982; Walker 1984; Pederson 1985;

Handford 1986; Decelles 1987). In a storm depositional system characterized by shoreline bypass, such as proposed for member 2 of the Chapel Island Formation, tempestite bed thickness would first increase then decrease distally across the shelf, as illustrated in Figure 16B.

Implicit in this model is the idea that variation in bed thickness within any stratigraphic section reflects both distance from shoreline and variation in intensity of the depositing storms. Differences in storm intensity are reflected in the variance in bed thickness *within* a facies. For instance, a few medium sandstone beds punctuate the thin-bedded Siltstone-Dominated Facies and very thin and thin beds of sandstone are found within the Sandstone-Dominated Facies. The distinctive mean bed thicknesses of the various facies, however, indicate that deposition was controlled by an overall onshore-offshore gradient in the effects of storms. Extreme events merely superimposed "noise" on this signature.

Studies of the storm-dominated muddy inner shelf of the Beaufort Sea (Hill and Nadeau 1989) and of a storm bed deposited by Cyclone Winifred between the Great Barrier Reef and the Australian shoreline (Gagan et al. 1988) both show patterns of bed thickness and grain size similar to those of the model in Figure 16B. These authors consider the distributions of thickness and grain size to be solely a function of *in situ* resuspension of ambient sediment. In the case of the Beaufort Sea, resuspension and sand abundance is at a maximum 11–17 km from shore, and fines are transported shoreward, creating the grain size and bed thickness pattern. In the Australian example, the variation in thickness and other textural parameters of the storm deposit simply reflects the distribution of sediment prior to the storm. Neither of these models is appropriate for the Chapel Island Formation deposits, however, because 1) a wide range of paleocurrent features, including gutter-cast orientation, suggest strong offshore-directed transport; and 2) the sediment in the storm beds is coarser than the coarsest fraction in the intervening siltstone beds, ruling out resuspension and settling as a mechanism for deposition of the sandstone beds.

Brief reference has been made in a few studies of ancient deposits to shallow-water zones of sediment bypassing. Kidwell (1989) describes shell deposits associated with a shallow-water zone of sediment bypass from Miocene deposits from Maryland. Leckie et al. (1990) describe a transgressive sequence of organic-rich Cretaceous-age shales in which the lowest marine facies indicate detrital sediment bypass and starvation. The stratigraphic position of their facies directly above a transgressive conglomeratic lag (resting on an erosional marine flooding surface) indicates deposition in a paleobathymetric position similar to that of the Gutter Cast Facies of the Chapel Island Formation.

Sand Source in the Deltaic Setting

The model for tempestite sedimentation described above (Fig. 16B) is compatible with the deltaic model of sedimentation inferred for member 2 (Myrow et al. 1988; Myrow and Hiscott 1991). Sandstone beds with the characteristics of turbidites have been described from a number of ancient deltaic deposits (McBride et al. 1975; Walker 1969; Horowitz 1966), and storm-generated sand beds with Bouma sequences have been described from the Yukon River Delta in Norton Sound, Alaska, a shallow embayment of the Bering Sea (Nelson 1982; Howard and Nelson 1982).

One fundamental question concerning deposition of tempestites in member 2 is the source of the sand. Uncertainty results from lack of lateral facies control: the ancient paleoshore for upper member 2 and all of member 3 are southwest of the available outcrops, either entirely removed by later erosion or under the present Atlantic Ocean (Fig. 1). As emphasized earlier, sand-filled gutter casts in the nearshore zone and paleocurrent data from all facies suggest that the sand was transported seaward from the adjacent coast. There is no evidence for lateral sand input from adjacent parts of the shelf. Three alternatives are outlined below for sources of sand.

Alternative 1.—The shoreline deposits in the upper part of member 1 and lower member 2 contain no evidence for beaches but instead represent heterogeneous (mixed) tidal flats that presumably flanked the delta (Myrow 1987; Myrow et al. 1988). The tidal flat sediments in the lower portion of member 2 consist of thin- to medium-bedded sandstone, siltstone, and shale. The sandier facies in these deposits contain abundant scours and erosional surfaces which indicate frequent erosion. These are the most likely source for the storm sands of members 2 and 3.

Alternative 2.—There may have been one or more nearby narrow delta distributary channels cutting through the intertidal flats. During storms, wave action may have carried distributary mouth sands offshore to fill gutter casts cut into nearshore muds and to supply sand to the shelf. One 13-m-thick shoaling channel sequence is found in a package of tidal-flat deposits in lower member 2 (see Myrow et al. 1988; Stop 2E), lending some credence to this hypothesis.

Alternative 3.—River flood underflows may have discharged directly into the shallow marine environment at high velocities to form a nearshore zone of erosion and throughput. Periodic high rainfall in a nonvegetated landscape, in association with powerful storm wave activity, would explain the overall style of bedding and the stratification styles of storm beds.

The question of sand source may never be adequately resolved. Nevertheless, the model of Figure 16B is clearly established from vertically continuous outcrop data and represents a significant, albeit partly incomplete (i.e., sand source), alternative model for coastal to inner-shelf, storm-dominated sedimentation.

ACKNOWLEDGMENTS

This paper is based on part of a Ph.D. thesis completed under the supervision of R. Hiscott, who provided much help and guidance. The research was supported by an operating grant to R. Hiscott from the Natural Sciences and Engineering Research Council of Canada. The author would like to thank D. Leckie, L. Krystinik, and J. Southard for constructive comments on earlier versions of this manuscript. Thanks to P. Brenchley, G. Plint and D. Cant for reviewing this paper and suggesting many improvements.

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