WAVE-MODIFIED TURBIDITES: COMBINED-FLOW SHORELINE AND SHELF DEPOSITS, CAMBRIAN, ANTARCTICA

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ABSTRACT: **Sandstone tempestite beds in the Starshot Formation, central Transantarctic Mountains, were deposited in a range of shoreline to shelf environments. Detailed sedimentological analysis indicates that these beds were largely deposited by wave-modified turbidity currents. These currents are types of combined flows in which storm-generated waves overprint flows driven by excess-weight forces. The interpretation of the tempestites of the Starshot Formation as wave-dominated turbidites rests on multiple criteria. First, the beds are generally well graded and contain Bouma-like sequences. Like many turbidites, the soles display abundant well-developed flutes. They also contain thick divisions of climbing-ripple lamination. The lamination, however, is dominated by convex-up and sigmoidal foresets, which are geometries identical to those produced experimentally in current-dominated combined flows in clear water. Finally, paleocurrent data support a turbidity-current component of flow. Asymmetric folds in abundant convolute bedding reflect liquefaction and gravity-driven movement and hence their orientations indicate the downslope direction at the time of deposition. The vergence direction of these folds parallels paleocurrent readings of flute marks, combined-flow ripples, and a number of other current-generated features in the Starshot event beds, indicating that the flows were driven down slope by gravity. The wave component of flow in these beds is indicated by the presence of small- to large-scale hummocky cross-stratification and rare small two-dimensional ripples.**

Wave-modified turbidity currents differ from deep-sea turbidity currents in that they may not be autosuspending and some proportion of the turbulence that maintains these flows comes from storm waves. Such currents are formed in modern shoreline environments by a combination of storm waves and downwelling sediment-laden currents. They may also be formed as a result of oceanic floods, events in which intense sediment-laden fluvial discharge creates a hyperpycnal flow. Event beds in the Starshot Formation may have formed from such a mechanism. Oceanic floods are formed in rivers of small to medium size in areas of high relief, commonly on active margins. The Starshot Formation and the coeval Douglas Conglomerate are clastic units that formed in response to uplift associated with active tectonism. Sedimentological and stratigraphic data suggest that coarse alluvial fans formed directly adjacent to a marine basin. The geomorphic conditions were therefore likely conducive to rapid fluvial discharge events associated with storms. The abundance of current-dominated combined-flow ripples at the tops of many Starshot beds indicates that excess-weight forces were dominant throughout deposition of many of these beds.

INTRODUCTION

Early facies models for storm-influenced shelves suggested that shallow-marine storm-generated sandstone beds (tempestites) were deposited by turbidity currents. This idea lost favor because oceanographic studies indicated that modern storms generally produce nearly shore-parallel geostrophic flows (Swift et al. 1986; Snedden et al. 1988) and because autosuspension seemed unlikely on the gentle slopes that characterize most modern shelves (Pantin 1979; Parker 1982; Swift 1985). Duke (1990) and Duke et al. (1991) took a uniformitarian approach to argue that ancient tempestites were deposited by geostrophic combined flows. They concluded that one could reconcile the fact that aspects of many ancient tempestites were seemingly incongruous with deposition from geostrophic flows (Leckie and Krystinik 1989) if one understood the dynamics of such flows. Since then, detailed studies have demonstrated that geostrophic combined flows were in fact important for producing some ancient sandy tempestites (Martel and Gibling 1994; Beukes 1996; Midtgaard 1996). However, Myrow and Southard (1996) argued that sedimentary rocks may record a wide range of shallow-marine tempestites and that gravity acting on suspended sediment—excess-weight forces—might be important in various combined flows generated by storms even if autosuspension was not achieved. Excess-weight forces specifically refer to the downslope component of the excess weight (per unit volume) of a sediment-rich dispersion relative to clear water. Myrow and Southard (1996) argued that under certain conditions the turbulence added by storm waves could maintain and/or enhance suspended sediment concentrations and thus increase excess-weight forces. Some tempestites were interpreted as the deposits of shelf turbidity currents, or combined flows with strong excess-weight force components, produced by river floods that moved directly into the ocean as hyperpycnal flows (Bartolini et al. 1975; Higgs 1990).

Few studies of ancient deposits have demonstrated conclusively that flows other that geostrophic combined flows have been important agents of deposition. In this study, we present a detailed description and analysis of tempestite beds from the Starshot Formation, a Cambrian unit of the central Transantarctic Mountains, Antarctica (Fig. 1). We interpret these tempestites as the deposits of combined flows dominated by storm-generated waves and excess-weight forces; i.e., they are wave-influenced turbidites. Stratigraphic and sedimentological analyses of this formation presented herein, and those on coeval proximal deposits, constrain the nature of the depositional system that was responsible for the production of wave-modified turbidity currents.

STRATIGRAPHY AND DEPOSITIONAL HISTORY

Neoproterozoic to early Paleozoic sedimentary rocks occur within the Ross Orogen underlying the Transantarctic Mountains (Fig. 1). In the prevailing view (e.g., Goodge 1997), these units collectively represent a transition from a rifted and passive-margin setting to an active-margin setting. The oldest sedimentary rocks of the central Transantarctic Mountains overlie Archean and Early Proterozoic basement (Nimrod Group) and are assigned to the Beardmore Group (Fig. 2). These have generally been considered to be Neoproterozoic to possibly lowermost Cambrian in age (Laird et al. 1971; Borg et al. 1990). The group consists of a lower unit, the Cobham Formation, of metamorphosed siliciclastic and carbonate rocks and a younger and less metamorphosed sandstone-rich Goldie Formation. The overlying Byrd Group is of lowermost Paleozoic age and is generally thought to unconformably overlie the Goldie Formation (Laird et al. 1971; Stump 1995). The carbonate-ramp deposits of the Lower Cambrian Shackleton Limestone (Rees et al. 1989) is the oldest unit, and its age is constrained by trilobite and archeocyathan fauna (Debrenne and Kruse 1986; Palmer and Rowell 1995). A number of siliciclastic units overlie the Shack-

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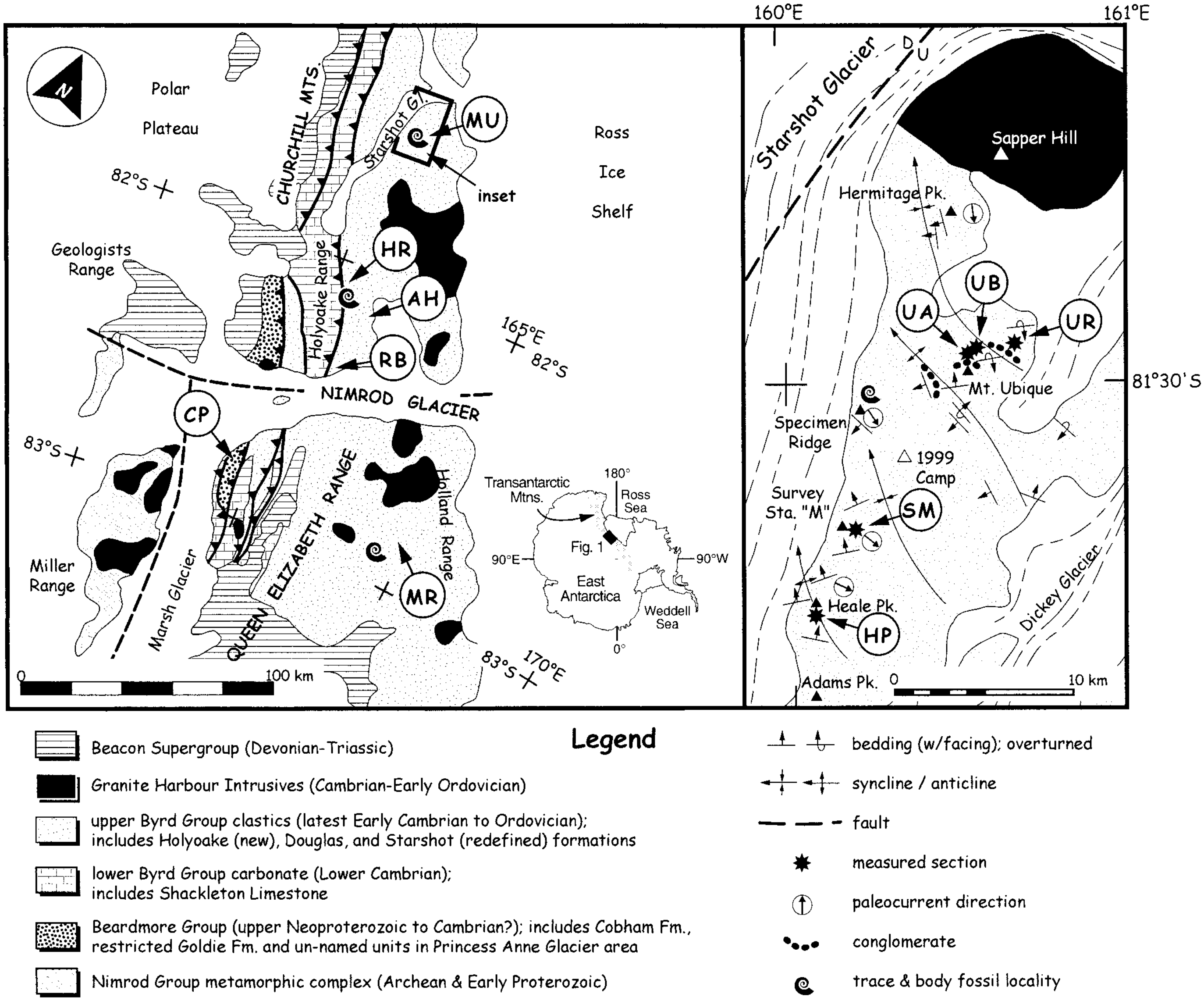

FIG. 1.—Generalized geologic maps of study areas in central Transantarctic Mountains. Left-hand map shows major geologic units in the Nimrod Glacier area. Localities discussed in this paper include: Cotton Plateau (CP), Holyoake Range (HR), Masquerade Ridge (MR), Russell Bluffs (RB), Algie Hills (AH), and Mt. Ubique (MU). Inset map to right shows geology of the area near Mt. Ubique. Measured sections include: Mt. Ubique ''A'' (UA), Mt. Ubique ''B'' (UB), northeast Ubique ridge (UR), Heale Peak (HP), and Survey Station ''M'' (SM), the latter locality from Laird (1963). Note that stratigraphic units of the Beardmore and Byrd groups follows the revisions suggested by Goodge et al. (in press) and Myrow et al. (in press).

leton Limestone, namely the Starshot, Douglas, and Dick formations, but the stratigraphic and age relationships of these units have been difficult to establish, largely because of poor control on depositional ages and lack of exposed formation contacts. With the exception of carbonate deposits of the Lower Cambrian Shackleton Limestone, few fossils had been collected from the Byrd Group and purported ages of its clastic units range from latest Early Cambrian to Devonian. Recent work has resolved many of these problems through a combination of field mapping, sedimentology, paleontology, and detrital zircon geochronology (Goodge et al. 2002; Myrow et al. in press; and this study; Fig. 2).

A critical step has been the recognition that much of the Starshot Formation was inadvertently mapped as the much older Goldie Formation (Goodge et al. in press; Myrow et al. in press). Several aspects of Byrd Group stratigraphy have been uncertain until recently. These include the stratigraphic relationship between the coarse-grained deposits of the Douglas Conglomerate and the sandstone-dominated Starshot Formation. Both were recognized to contain clasts of the Shackleton Limestone and thus postdate that unit (Laird et al. 1971), but their relative ages were not constrained. Myrow et al. (in press) provide evidence to demonstrate age equivalence between the proximal (inboard) Douglas Formation and the more distal (outboard) Starshot Formation. Paleocurrent data presented herein from the Starshot Formation indicate sediment transport eastward towards outboard regions, similar to that inferred for the Douglas Conglomerate. The depositional reconstruction of Myrow et al. (in press; Fig. 2) shows the coarse conglomerate deposits of the Douglas as thick alluvial fan wedges, as suggested by a detailed facies analysis of this formation by Rees and Rowell (1991). Conglomerate beds of the Starshot Formation are interpreted as the distal pinchouts of the proximal Douglas fans where they pass outward into sand-dominated shoreline deposits.

The lower contact of these upper Byrd Group units with the underlying Shackleton Limestone was shown to be an unconformity at one locality (Rees et al. 1988; Rowell et al. 1988), although in most cases it is mapped

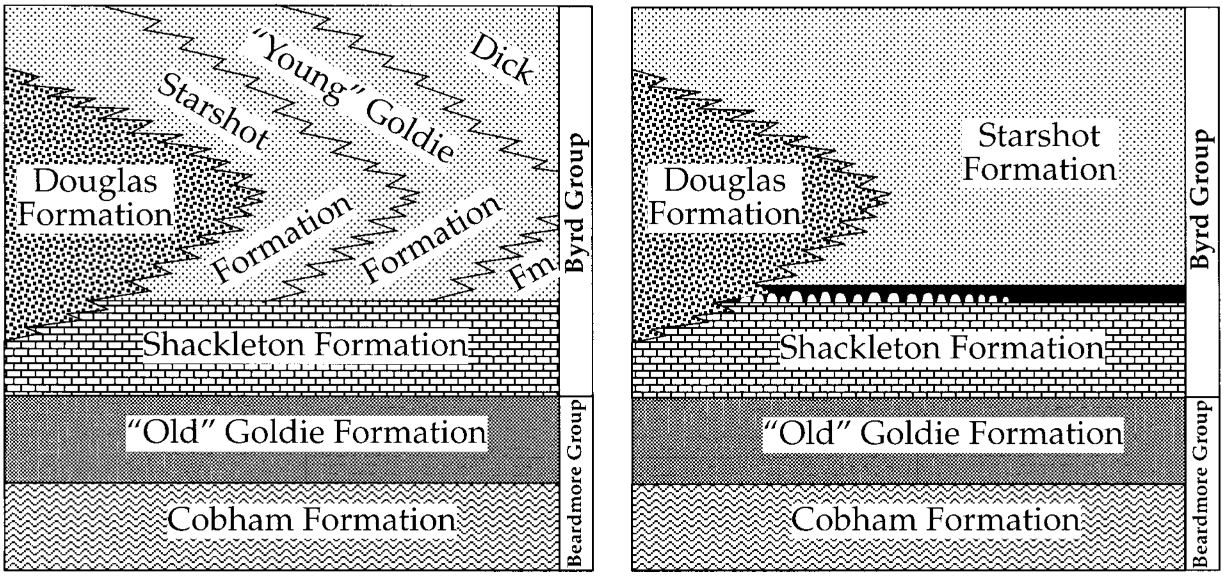

FIG. 2.—Revised age relationships of previously defined units (left) and revised stratigraphy of central Transantarctic Mountains (right).

as a fault. Myrow et al. (in press) discovered a depositional contact between the upper Shackleton Limestone and upper Byrd Group siliciclastic deposit at several localities along the Holyoake Range (Fig. 1). In these sections, large, isolated archeocyathan bioherms (up to ~ 40 m in height) cap the Shackleton Limestone and show evidence of a terminal rapid drowning event. The bioherms and inter-bioherm areas are coated with phosphatic hardground deposits, succeeded by dark organic-rich shale and a mixed shale/nodular limestone facies. These deposits are overlain by siltstone and then mixed sandstone, conglomerate, and shale facies of the Douglas and Starshot formations.

The transition within the Byrd Group from the carbonate platform of the Shackleton Limestone to the Douglas/Starshot formations records an important tectonic event associated with the prolonged Ross Orogeny (Stump 1995; Goodge 1997). Synchronous development of an erosional unconformity and rapid drowning of the Shackleton carbonate ramp indicates uplift and erosion in proximal settings and tectonically induced subsidence in more distal areas (Myrow et al. in press). Trilobite fossils recovered from the lower part of the Douglas Conglomerate date these strata as Lower Cambrian and specifically as upper Botomian (Myrow et al. in press). The stratigraphic revisions (Fig. 2) and history of the Shackleton–upper Byrd Group transition described above (Myrow et al. in press) provide a framework for understanding the depositional setting of the Starshot Formation.

Starshot Formation

This study provides the first detailed sedimentological analysis of the Starshot Formation. Considerable exposure of the formation exists in the Churchill Mountains and also in the Queen Elizabeth Range, where these rocks were inadvertently mapped as Goldie Formation (Goodge et al. 2002). The thickness of the formation is unknown because no complete stratigraphic section has been described, but mapping and measurement of sections indicate that it is probably more than 2000 m thick. Studies postulated a range of possible ancient depositional environments from deep water to shallow-water shelf (Laird 1963; Laird et al. 1971). Rees and Rowell (1991) described fine-grained facies in the Douglas Conglomerate with lithological and sedimentological character similar to that of the Starshot Formation, and these were interpreted as possible lacustrine deposits due to a lack of trace or body fossils. Three facies are described below: conglomerate and sandstone, shale, and thin- to medium-bedded sandstone and shale (Fig. 3). The last makes up the bulk (~ 80%) of the formation. Graded beds in this facies were thought to represent turbidites (Laird et al. 1971). This study focuses first on the general sedimentological framework of this formation and then on the analysis of the event beds. We also explore the implications of such beds for understanding the geologic record of shallow-marine storm events.

CONGLOMERATE AND SANDSTONE FACIES

Proximal deposits of the Starshot Formation consist of medium- to thick-bedded sandstone and cobble conglomerate. Coarse conglomerate beds (Fig. 4A) are generally confined to the southern slope of Mt. Ubique and scattered outcrops a short distance to the southwest and northeast (Fig. 1). These beds are generally 10–50 cm thick. The coarser conglomerate beds consist of clast-supported mixtures of cobbles and pebbles with a poorly sorted sandy matrix. The clasts are generally well rounded and range in size up to boulders approximately 30 cm across. The conglomerate contains a wide variety of siliciclastic and carbonate clasts, the latter of which are readily recognized as common lithofacies of the Shackleton Limestone. Most of the siliciclastic clasts are composed of quartz, although siltstone, sandstone, and silicic volcanic clasts were also noted. Beds contain a wide variety of depositional fabrics from poorly sorted and nongraded to moderately sorted and graded. Most of the conglomerate beds are lenticular over lateral distances of meters to tens of meters.

One anomalously thick (18 m) unit of pebble to cobble conglomerate with minor interbedded sandstone occurs east of Mt. Ubique (Fig. 5). It rests sharply on a thick unit (> 50 m) of black shale with minor very thin, very fine to fine sandstone beds.

Stratigraphic transitions in this section are (in ascending order): (1) 18 m of conglomerate, (2) nearly 10 m of interbedded conglomerate and sandstone, (3) nearly 50 m of parallel and hummocky cross-stratified sandstone, and (4) interbedded sandstone and shale facies (described below). The first three of these units are included in the conglomerate and sandstone facies.

Thick units of very fine- to mixed fine–medium-grained sandstone are found in association with the conglomerate beds (Fig. 4B, 6). The sandstone is greenish-gray on fresh surfaces but commonly weathers light reddish-brown. Medium to very thick beds of sandstone are separated by very thin to thin shale beds (< 20%) or amalgamated into units up to 15 meters thick that are devoid of shale. Sections with thinner sandstone beds, 20–60 cm thick, have more abundant and thicker shale beds, although the shale

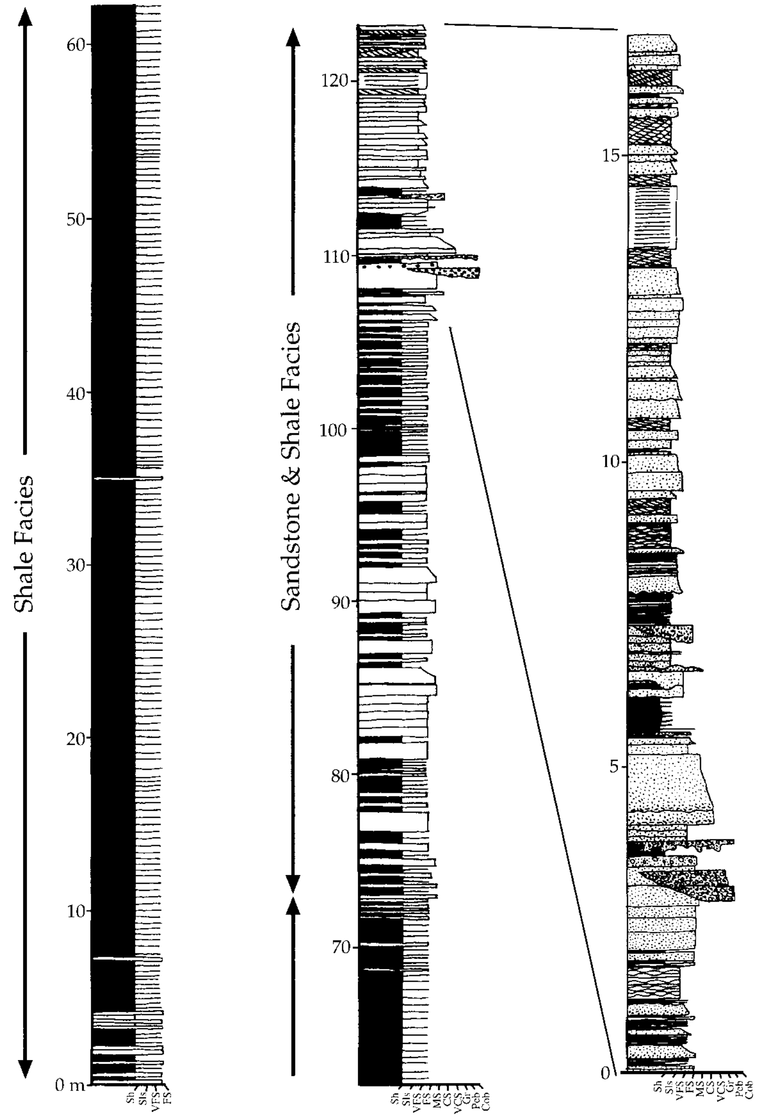

FIG. 3.—Stratigraphic section B from south flank of Mt. Ubique. Lower part of section contains thick interval of shale facies and the rest is dominated by thin to medium-bedded sandstone and shale facies. The enlargement shows a sandstone-rich part of section with lenticular conglomerate beds.

component is low ($<$ 20%). In these cases, sole markings such as flutes are large and abundant and the beds are commonly graded with lower divisions that range from coarse to medium sandstone (Figs. 4C; 7A–D, G, H). In rare cases the tops of these coarser sandstone divisions are molded into symmetrical ripples either with sharp steep-sided crests (Figs. 7B, 8A) or with lower-relief rounded geometries. Steep-crested ripples show form discordance with complex cross-stratification including numerous curved truncation surfaces. The sandstone beds of this facies are dominated by graded bedding and parallel lamination. Parting lineation occurs on some bedding planes of parallel-laminated sandstone. The sandstone beds also contain, to a lesser degree, large-scale hummocky cross-stratification (HCS). Views along multiple fracture surfaces confirm that the lamination is low angle ($< 15°$) and contains low-angle, curved scour surfaces. Bedform spacings range to $>$ 1 m and bedform heights range up to $\sim$ 30 cm. Well-developed aggrading forms of HCS show thickening of individual laminae onto hummock crests. In many cases, preserved hummocks show subtle to pronounced asymmetries (Figs. 7E, 8B, C) and lamination produced by the preferential migration of hummocky bedforms (Figs. 7E, F, I, 8B). Although the true direction of bedform migration is difficult to measure, it is not perfectly unimodal, inasmuch as oppositely oriented *apparent* migration directions occur in closely spaced beds on relatively planar outcrop surfaces.

Interpretation

The thick sandstone deposits contain clear evidence of deposition under high-energy flows that reached upper-plane-bed conditions (parallel lamination and parting lineation). Large-scale hummocky bedforms develop under storm-generated waves due either to combined flows (waves and currents) or complex oscillatory flow (Arnott and Southard 1990). Thick (up to 15 m) amalgamated fine sandstone units with large-scale HCS and parallel lamination are typical of shoreface and foreshore deposits (e.g., Dott and Bourgeois 1982; Walker 1984). The shalier end member of this facies is considered to be more distal deposits associated with a lower-shoreface transition zone with an inner-shelf setting.

The clast-supported textures and normal grading of the conglomerate beds indicate bedload transport of coarse material. The abundance of cobbles and presence locally of rounded boulders indicates powerful traction transport. The range of depositional fabrics likely reflects variable sedimentation rates, with some flows depositing their load relatively quickly.

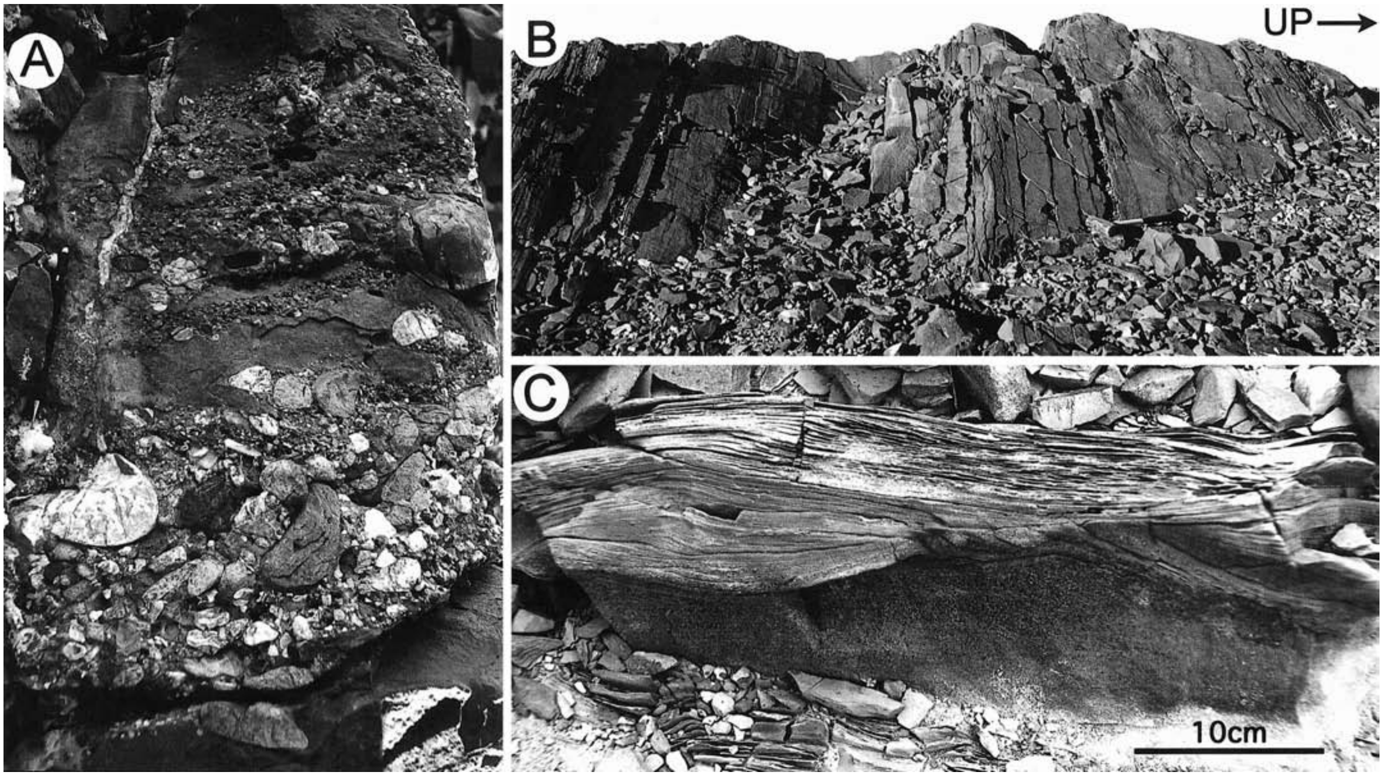

FIG. 4.—Proximal deposits. **A)** Interbedded conglomerate and sandstone facies from Mount Ubique. Pencil is 14 cm long. **B)** Thick-bedded sandstone facies from Starshot Formation at Russell Bluffs. Hammer for scale. **C)** Graded bed with lower coarse sandstone division with 2D wave ripple and upper fine sandstone division with small-scale HCS.

The lenticular geometries of these beds indicate channelized flows. These aspects of the flows, and the fact that these relatively thin conglomerate beds occur in association with thick sandy shoreline deposits, suggest that they likely represent the deposits of high-energy fluvial discharge events. The presence of large flutes and graded bedding in the thick sandstone beds of this facies indicates that they were deposited by powerful decelerating currents possibly also as the result of either direct discharge or shoreline mobilization of sand associated with episodic fluvial-discharge events (floods).

The section east of Mt. Ubique with the thick conglomeratic section (Fig. 5) further supports the interpretations made above. The facies transitions define a well-developed upward-fining and -deepening succession with the thick ($\sim$ 50 m) parallel-laminated and hummocky cross-stratified sandstone unit representing wave-influenced shoreline deposits. The underlying 18-m-thick unit of cobble conglomerate rests directly on a thick shale unit and thus represents a significant base-level fall. Its base is a probable sequence boundary within the formation. The lower conglomerate could represent an incised conglomeratic shoreline deposit, or more likely, given the interbedding with sandy shoreface deposits at the base of the unit above, it is for the most part a fluvial deposit. In either case, the deepening recorded at the top of this section into interbedded sandstone and shale reinforces the interpretation that the sandstone and conglomerate facies is of shoreface origin.

In a general sense, the association of conglomerate beds with shoreline sandstone units reflects a stratigraphic interfingering with a coarse fluvial system. The restricted spatial occurrence of these intercalated deposits indicates that the facies belts interfingered over a relatively narrow zone. The thick coarse-grained conglomeratic deposits of the Douglas Conglomerate, which are the proximal equivalents of the Starshot Formation (Myrow et al. in press), contain a variety of facies that range in paleoenvironment from proximal to distal alluvial fan (Reese and Rowell 1991). Thus, the conglomerate and sandstone facies of the Starshot Formation in this report are the shoreline to nearshore deposits that correspond with the more proximal alluvial deposits of the Douglas Conglomerate. Given this stratigraphic relationship, the proximal facies of the Starshot Formation are interpreted to be fan-delta deposits.

SHALE FACIES

This facies consists of gray to black shale with generally less than 25% sandstone. Siltstone to very fine sandstone occurs as millimeter-thick laminae to beds several centimeters thick (Fig. 8D). In most occurrences of this facies, the sandstone beds are rarely greater than 2 cm thick. The facies is generally interbedded with the thin- to medium-bedded sandstone and shale facies (described below) on the scale of a few meters to tens of meters. Sedimentary structures in the sandstone beds of this facies include climbing-ripple cross-stratification and parallel lamination. An unusually thick interval ($\sim$ 65 m) dominated by this facies occurs on the south slopes of both Mt. Ubique (Fig. 6) and Heale Peak, and probably represents the same stratigraphic unit.

Interpretation

There are few diagnostic sedimentary structures in this facies. The close stratigraphic association with the sandstone and shale facies (described below), the high percentage of shale, and the thinner nature of the sandstone beds indicates that this facies is a more distal equivalent of the sandstone and shale facies. The sandstone beds are interpreted as deposits of storm events. The nature of these events, including the mode of transport and deposition, is explored below.

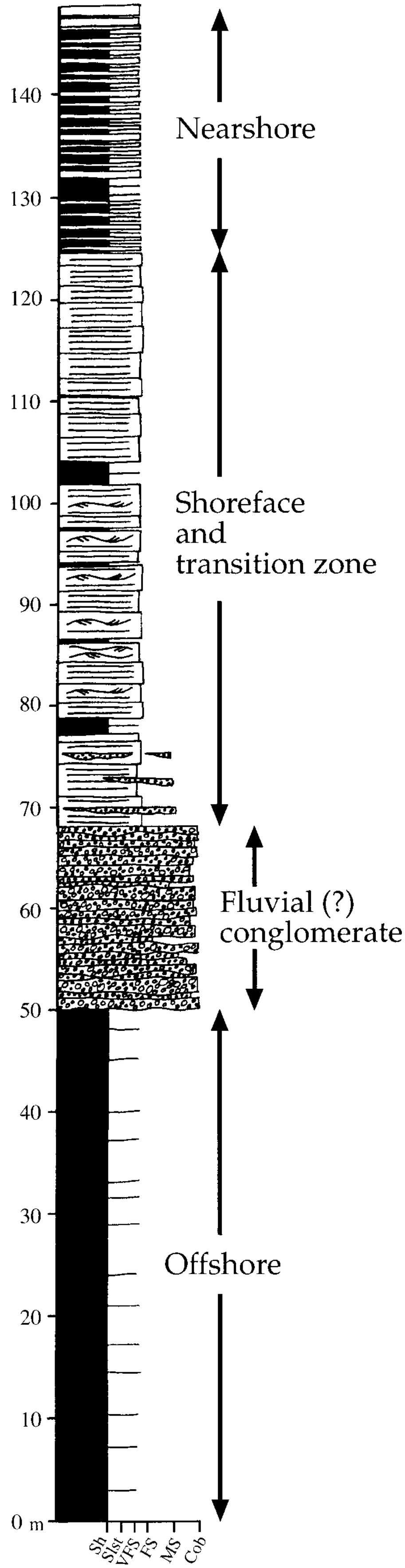

FIG. 5.—Stratigraphic section from northeast Mt. Ubique Ridge.

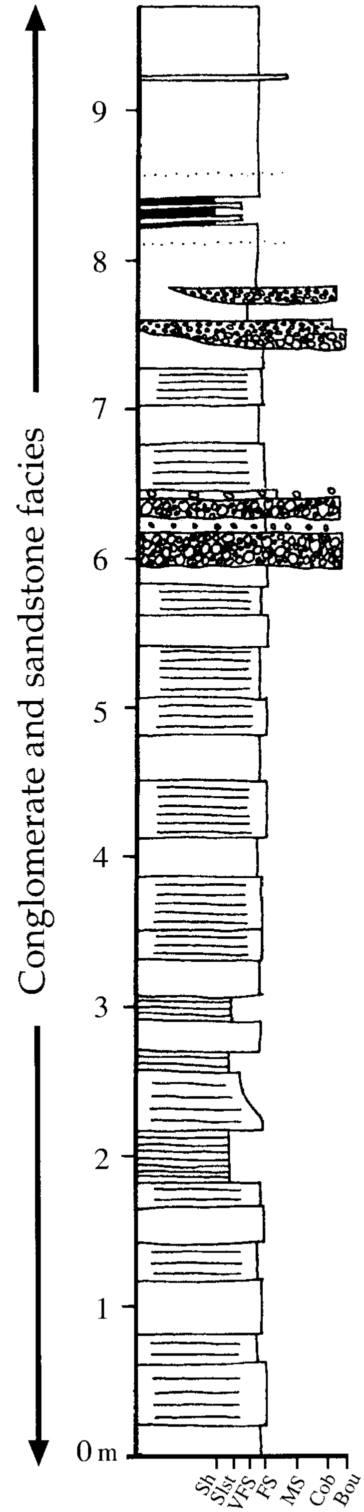

FIG. 6.—Stratigraphic section A from peak of Mt. Ubique. Section is dominated by parallel-laminated sandstone and lenticular cobble conglomerate beds.

THIN- TO MEDIUM-BEDDED SANDSTONE AND SHALE FACIES

This facies consists of very thin to medium beds of sandstone and lesser amounts (20–50%) of silty shale (Fig. 9). Sandstone beds are very fine to coarse grained, although the bulk are fine and very fine sandstone. Most beds are normally graded and contain a variety of sedimentary structures

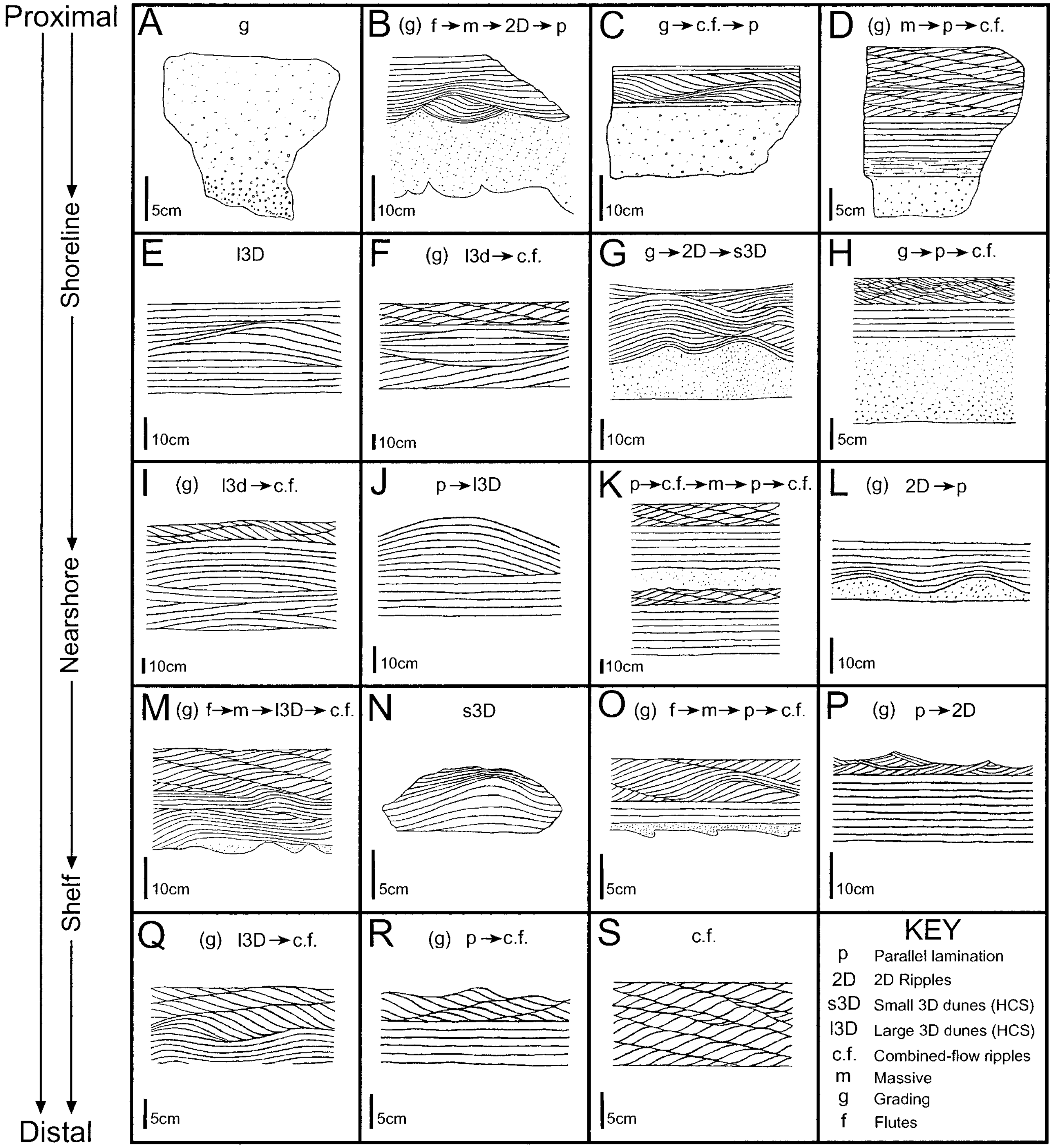

FIG. 7.—Sketches of event beds from several facies in Starshot Formation illustrating the range of internal structures and vertical stratification sequences. Beds A through I are part of the sandstone and conglomerate facies and J though S the sandstone and shale facies.

(Fig. 7J–S). Although in many outcrops the soles of beds are not well exposed, where visible they display abundant flute marks (Figs. 7M, and O, 8E) and sparse groove marks and prod marks. The flutes have geometries (Fig. 10A) identical to those produced experimentally (see Allen 1984) and well documented from turbidite deposits (e.g., Kuenen 1957). The graded beds have massive to graded lower divisions that range from fine to coarse sandstone (Fig. 10B) and are capped in cases by small-scale symmetrical (2D) ripples. Parallel lamination is most common in fine sandstone divisions, although it is crudely developed in some medium sandstone. Small-scale hummocky cross-stratification is common and is also developed mainly in fine sandstone (Figs. 7J, N, F; 10C, D). Sharp-crested 2D wave ripples occur sporadically but are relatively rare for storm-influenced deposits. Climbing-ripple cross-stratification is extremely abundant and occurs almost exclusively in very fine sandstone (Fig. 10B). The angle

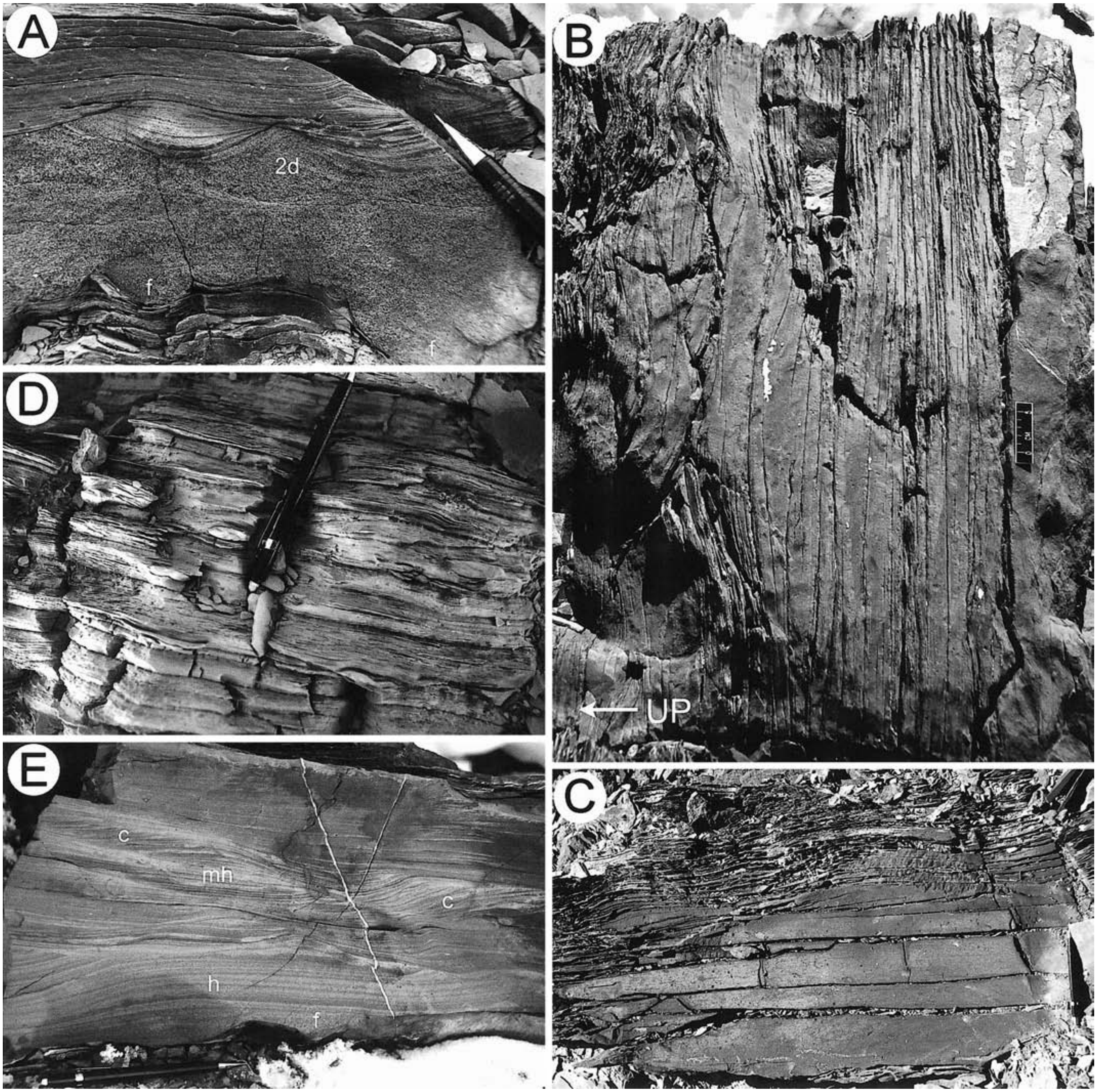

FIG. 8.—**A)** Graded bed (VCS/CS to VFS) from Survey Station M. Note deep flutes (f) along base. Sharp grain-size transition marks the middle of the bed. Two-dimensional wave ripples (2d) cap lower coarse division, and draping and wavy lamination characterize the fine sand above. Pencil tip is 2 cm in length. **B)** Parallel lamination and large-scale asymmetric HCS from Algie Hills, Holyoake Range. Scale is in centimeters. **C)** Graded bed with parallel lamination at the base and asymmetric HCS above. Bed occurs at Masquerade Ridge, Holland Range. Measured migration direction of asymmetric hummocky bedform is 022°. Pencil is 14 cm long. **D)** Shaly facies with very thin beds of fine and very fine sandstone in Starshot Formation at Heale Peak. Pencil is 14 cm long. **E)** Graded bed (MS to VFS) with the following succession of sedimentary structures: flutes (f) at base, asymmetric hummocky cross stratification (h), combined-flow ripple cross-stratification (c) with local micro-hummocky cross-stratification (mh). Bed from Specimen Ridge. Pencil is 14 cm long.

of climb is generally high, and ripple cross-stratified divisions are up to tens of centimeters thick. In intervals with greater mudstone percentages, many beds are composed entirely of very fine sandstone with climbing-ripple lamination (Figs. 7S, 11A). In beds with parallel lamination and either climbing-ripple lamination or small-scale HCS, the parallel lamination is found below (Figs. 7M, O–R; 11B, C).

The climbing-ripple cross-lamination within event beds of the Starshot Formation is not typical of that generated by current ripples. In many cases the ripple cross-stratification is sigmoidal and convex-up (Fig. 11B, D, E), even in cases that exhibit subcritical bedform climb. In other words, the curvature is not due to preservation of the crest-to-brinkpoint of the ripples due to high climb. The middle parts of the forsets are convex-up and there-

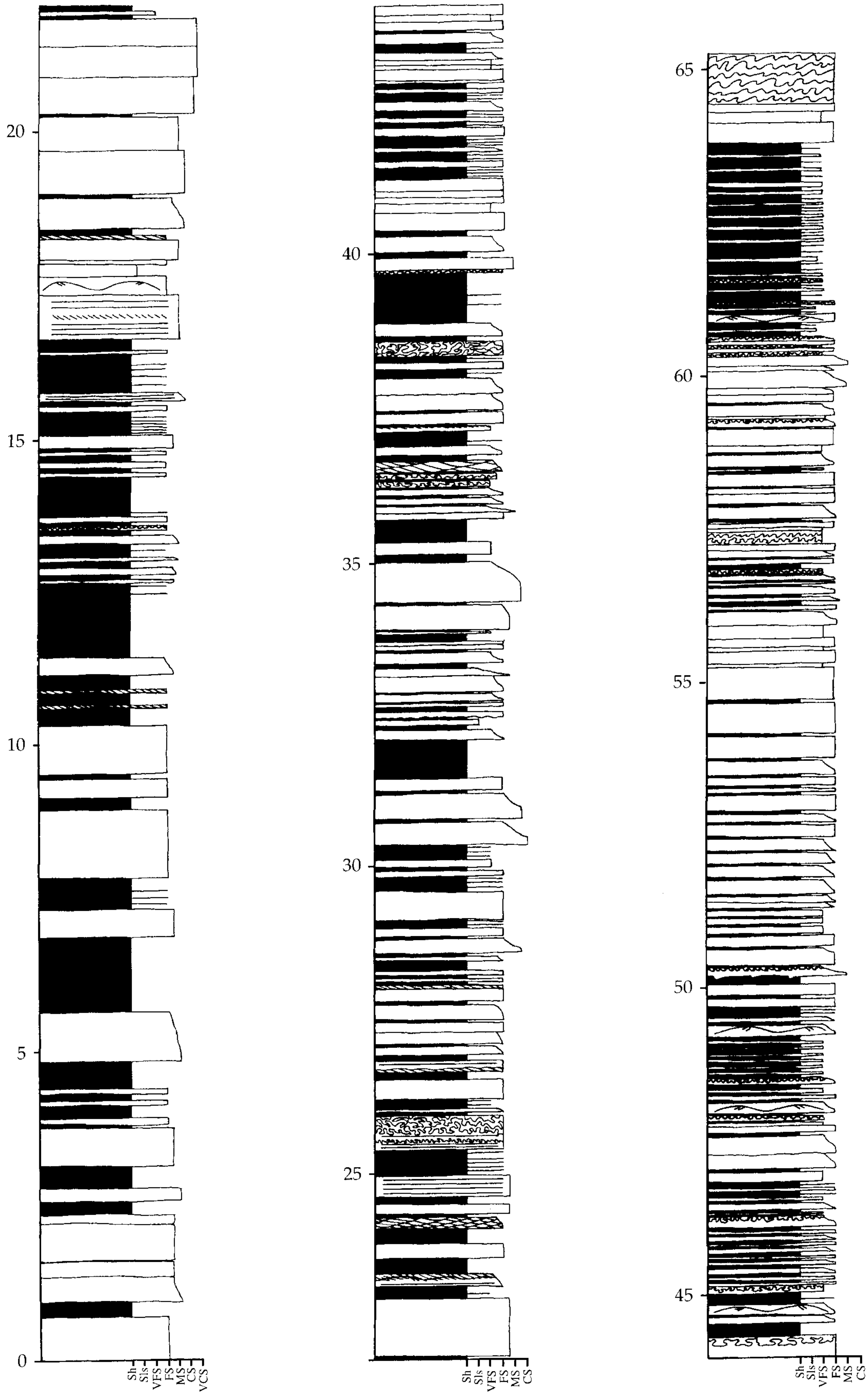

FIG. 9.—Stratigraphic section from Heale Peak dominated by thin- to medium-bedded sandstone and shale facies.

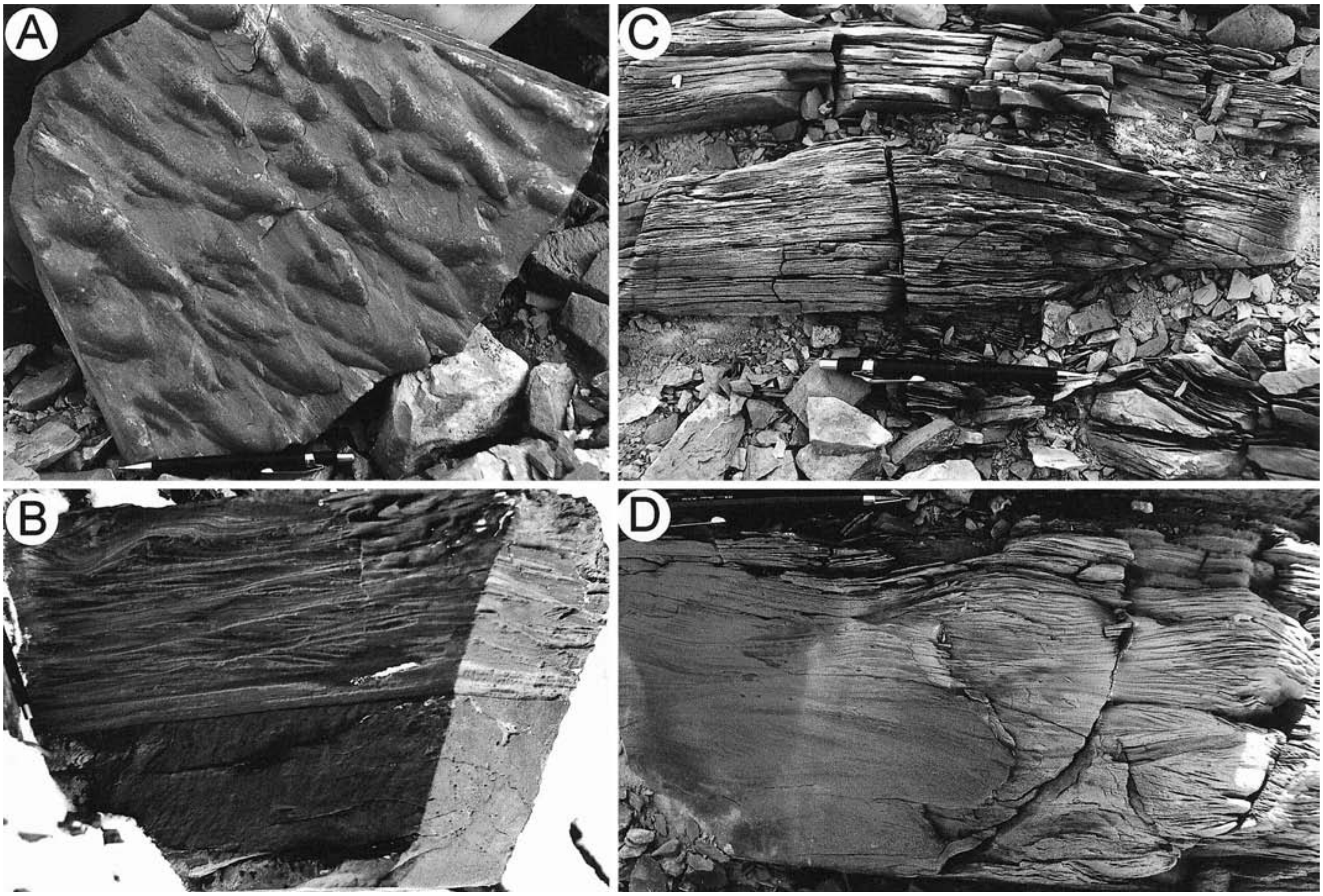

FIG. 10.—**A)** Well-developed flutes at base of graded fine sandstone bed in Starshot Formation at Survey Station M. **B)** Graded bed with massive fine sandstone base and upper division of very fine sandstone with climbing combined-flow ripples. **C)** Small-scale hummocky cross-stratified bed from Starshot Formation at Survey Station M. **D)** Hummocky cross-stratified very fine sandstone with evidence of nearly symmetrical, small-scale, three-dimensional dunes. Bed from Mt. Ubique Section B (Fig. 8). Pencil is 14 cm long; tip is 2 cm long.

fore did not form simply by avalanching of grains as in current ripples. Thus, the cross-lamination does not have planar to concave-up tangential foresets typical of current ripples, nor does it exhibit the complex form-discordant geometries of wave-generated stratification (cf. De Raaf et al. 1977). The presence of abundant graded beds and sole markings precludes misidentification of up-direction in these outcrops.

Large-scale HCS, although abundant in sandy parts of the conglomerate and sandstone facies, is much less common than stratification produced by various small-scale bedforms. In most cases, the HCS is asymmetric. In one example, climbing ripples are developed along the flanks of a large asymmetric hummock (Fig. 12A, B). The migration direction of the climbing ripples is oriented towards the steep side of the asymmetric HCS.

Convolute bedding is remarkably common in this facies. Judging from grain size (very fine sandstone) and abundant relict stratification, almost all of these beds with soft-sediment deformation were originally dominated by climbing-ripple stratification. The susceptibility of fine cohesionless sediment (silt to very fine sand) to liquefaction is well established (Terzaghi and Peck 1948; Keller 1982). These convolute beds contain well-developed folds with consistent asymmetries (Figs. 11A, 12C), such that there is uniformity in vergence direction both within beds and between beds from any particular section. These folds weather in such a way that trend and plunge of fold axes are easily measured, and multiple fold axis orientations were collected from each bed. Fold axes were rotated stereographically around the strike of bedding to reconstruct their original orientations prior to regional folding. The axes of the reconstructed folds are subhorizontal, and the directions of overturning or vergence, perpendicular to the fold axes, are plotted in Figure 13. The consistency of vergence of these soft-sediment folds is considered a result of gravity-driven instability acting on unconsolidated water-saturated sediment. Therefore, the vector mean of a number of such vergence directions is considered to be the down-paleoslope direction for these deposits. Although powerful currents could hypothetically have caused the soft-sediment deformation, this seems unlikely. First, the convoluted sediment in many cases contained numerous mud and sand beds up to 50 cm thick. These would have had considerable time to dewater, and the depth of deformation is considerable for shear induced by flow. Second, there is no experimental or observational evidence to suggest that surface flows create asymmetric soft-sediment folds. Paleocurrent measurements for a variety of sedimentary structures (e.g., flutes and ripples) are also shown in Figure 13. A strong parallelism is evident between soft-sediment fold vergence and other paleocurrent data. This parallelism exists in the data from each of two widely spaced localities, the Mt. Ubique area and Masquerade Ridge (Fig. 1; $\sim$ 120 km apart), despite the data from each area being different by $\sim 90°$ (SE and NE) due to either paleogeographic or structural variations. The northeast to southeast range of paleocurrent data is consistent with the general north–south trend of the east-facing continental margin at this time (Goodge 1997).

The tempestite beds of this facies are separated by gray to black shaly beds of equal or lesser thickness. These beds range in grain size from pure

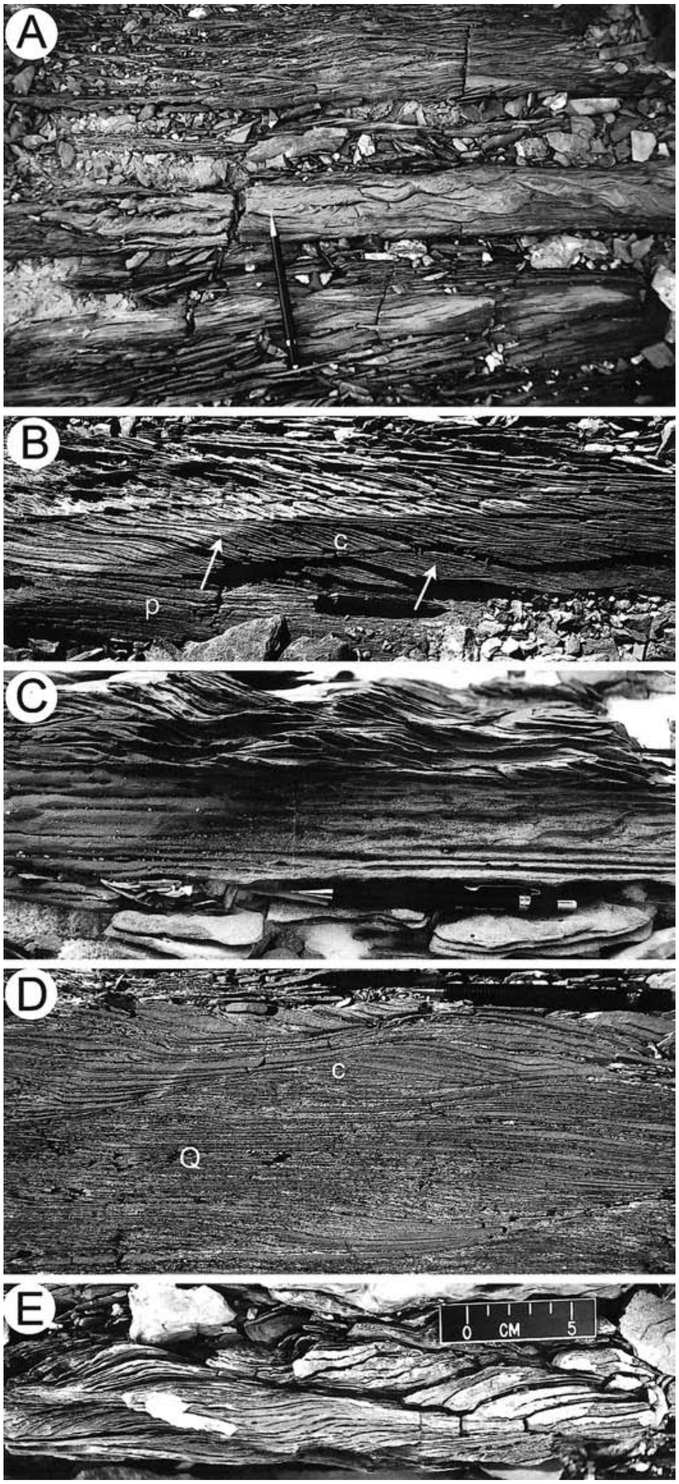

FIG. 11.—**A)** Thick beds of climbing-ripple lamination and a bed (center) with asymmetric convolute lamination. Exposure at Masquerade Ridge, western Holland Range. Pencil is 14 cm long. **B)** Graded bed with lower division of parallel lamination (p) and thick upper division of combined-flow ripple lamination (c). Arrows point to convex-up ripple lamination. Bed from Starshot Formation at Algie Hills, Holyoake Range. Pencil is 14 cm long. **C)** Graded bed with lower division of parallel-laminated fine sandstone and upper division of combined-flow ripple lamination in fine sandstone. Bed from Heale Peak. Pencil is 14 cm long. **D)** Bed of fine to very fine sandstone with quasi-planar lamination (Q) and overlying combined flow ripple lamination (c). From Algie Hills, Holyoake Range. Pencil is 14 cm long. **E)** Convex-up combined-flow ripple lamination in very fine sandstone from exposure of Starshot Formation at Algie Hills, Holyoake Range.

clay to clay-rich siltstone. In some cases, they contain subordinate amounts of laminae to very thin beds (generally < 2 cm) of fine and very fine sandstone.

Interpretation

Most sandstone beds in this facies exhibit normal grading and successions of sedimentary structures that indicate deposition from decelerating flows. Small- to large-scale HCS, 2D wave ripples, and complex ripple cross-stratification reflect the importance of storm-generated waves, indicating that these beds are tempestites. The combination of strong grain-size control on the development of sedimentary structures and overall grading produced a wide range of vertical stratification successions (Myrow and Southard 1991) in these tempestites (Fig. 7). Such vertical successions are important for interpreting their dynamics of deposition. Myrow and Southard (1996) argued that three storm-related processes are responsible for the wide range of characteristics of tempestites in the rock record: wave oscillations, geostrophic currents, and excess-weight forces. Three lines of evidence are strongly suggestive of deposition from flows dominated by excess-weight forces (i.e., turbidity currents), and these are shown in Figure 14. First, many of these beds have Bouma-like sequences (Figs. 7; 10C; 11C, B, N), despite abundant evidence for deposition under the influence of waves. Second, many beds contain thick graded lower divisions and thick upper ripple cross-stratified divisions, the latter with evidence for high angles of bedform climb, both of which are common in turbidites. These features result from high depositional rates that in turbidity currents are associated with rapid deceleration. Finally, these beds contain abundant, well-developed flute marks with no evidence of wave modification (Fig. 10A), which suggests that erosion occurred under powerful unidirectional currents. Importantly, the orientations of flutes and other internal sedimentary structures, including ripple cross-lamination, are all oriented downslope, as deduced from gravity-driven, asymmetric soft-sediment deformation features. This is the case for widely separated outcrops (Mt. Ubique area vs. Masquerade Ridge) from parts of the basin that are recording different downslope directions (Fig. 13). It is also the case for a spectrum of facies from sandy lower-shoreface deposits to more distal muddier shelf deposits. Thus there is no evidence for Coriolis deflection and shore-parallel geostrophic currents. The tempestite beds of this facies therefore record deposition from offshore-directed flows with aspects of both wave oscillations and turbidity currents. A flow of this kind is a combined flow that we herein call a wave-modified turbidity current.

The unusual sigmoidal and convex-up geometries of the ripple cross-stratification in these beds are interpreted to result from deposition under such combined flows. Combined flows involving waves and geostrophic flows are well known from modern settings and have been used to explain stratification and unusual sole marks in the rock record (Martel and Gibling 1994; Beukes 1996; Midtgaard 1996). There are a few descriptions of combined-flow ripples from tidal flats (Reineck and Singh 1980) and ancient tidal deposits (Wunderlich 1970), and a few authors have interpreted ripples associated with storm deposits as being of combined-flow origin (Dott and Bourgeois 1982; Nottvedt and Kreisa 1987; Myrow 1992; Jennette and Pryor 1993). However, the studies of Yokakawa (1995) and Yokakawa et al. (1995) are the only comprehensive experimental studies on combined-flow ripples and the only work of import on these small bedforms since the early study of Harms (1969). The experiments of Harms (1969) were limited, but they led to the suggestion that combined-flow ripples had more rounded crests and foresets at less than the angle of repose. More advanced criteria for recognition of such ripples were established by Yokokawa (1995), who documented the existence of current-dominated and wave-dominated combined-flow ripples in fine sand. The former are stable when the unidirectional component of flow exceeds approximately 19 cm/s. Wave-dominated combined-flow ripples were shown to have geometries similar to those formed in purely oscillatory flow (Boersma 1970; De Raaf

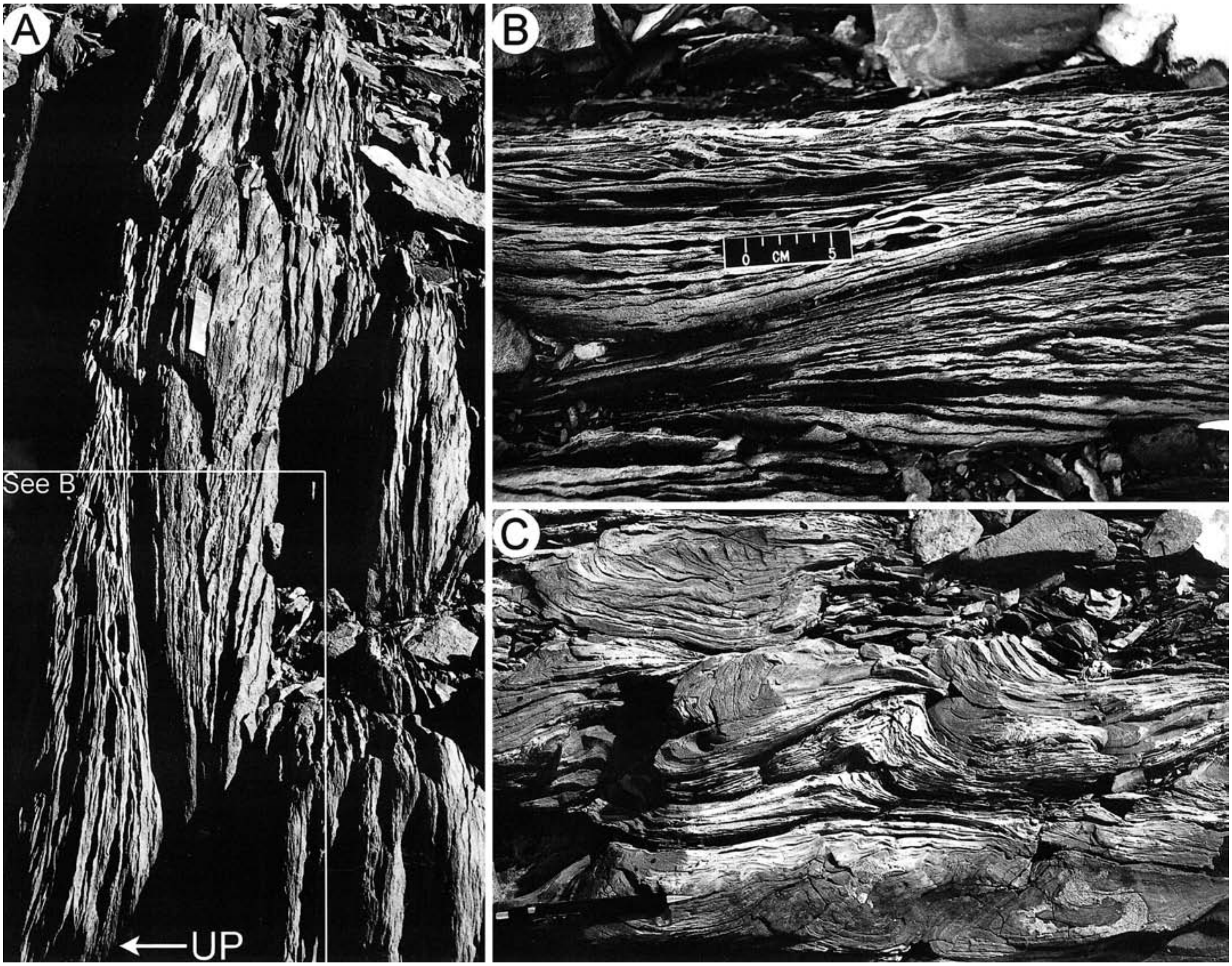

FIG. 12.—**A)** Large-scale HCS with slight asymmetry towards top of photo. Bed from Starshot Formation at Algie Hills, Holyoake Range. Scale in centimeters. **B)** Close-up of Part A showing combined-flow ripple cross-stratification along flank showing migration from swale to crest. Transport direction of ripples in same direction as migration direction of asymmetric HCS. **C)** Asymmetric soft-sediment folds in fine sandstone of the Starshot Formation at Heale Peak. Pencil is 14 cm long.

et al. 1977; Allen 1981; Harms et al. 1982), whereas current-dominated forms have, among other features, highly rounded crests. The current-dominated ripples create convex-upward round, sigmoidal foreset laminae (Yokokawa 1995, figs. 9–12) identical to those described in this study (Fig. 11B, D, E). The rounded crests arise from unusual fluid flow and sediment transport, including small vortices that form in the troughs of these ripples (Yokokawa 1995; Yokokawa et al. 1995, fig. 2).

The combined-flow ripples described herein are interpreted to form from a combination of waves and excess-weight forces (wave-modified turbidity currents), as opposed to waves and geostrophic flow. Although the ripple stratification may be similar, event beds deposited from the two types of combined flow should produce different depositional products. For wave-modified turbidites, paleocurrents would be dominantly offshore instead of along or slightly oblique to shore. Beds would have a greater likelihood for turbidite-like features such as well-developed graded bedding and thick climbing-ripple-laminated divisions, as documented for the beds in this study. The temporal histories of the wave and turbidity-current components of the flows were highly variable, as deduced by the variety of vertical stratification successions in these beds (Fig. 7). These show that both wave-dominated and current-dominated combined flows occurred. Erosion of the underlying sea floor and the initial stages of deposition appear to have been in most cases dominated by powerful turbidity currents. Although the influence of wave oscillations increased somewhat during deposition of some beds, in many cases even the latest phase of deposition was dominated by current-dominated combined flow.

The interbedding of wave-modified turbidites and shale indicates that this facies was deposited at or below the lower-shoreface transition zone associated with fair-weather wave base. This is supported by the transitional nature of this facies with both the deeper-water shaly facies and shoreline deposits of the conglomerate and sandstone facies. Rees and Rowell (1991) described an identical interbedded sandstone and shale facies from strata mapped as the Douglas Conglomerate, and interpreted it as waterlaid deposits of lacustrine origin. The lacustrine interpretation was based primarily on a lack of biogenic structures. Burrows and related ichnofabrics in the Starshot Formation are, in general, strikingly absent for a Cambrian shallow marine succession. We have found a number of isolated occurrences of trace fossils, some with substantial diameters (1.5 cm), within the Starshot Formation. Also, trilobites and hyolithids occur in the basal Douglas Conglomerate as part of a shoaling succession above the Shackleton Formation (Myrow et al. in press). Therefore, parts of the upper Byrd Group certainly

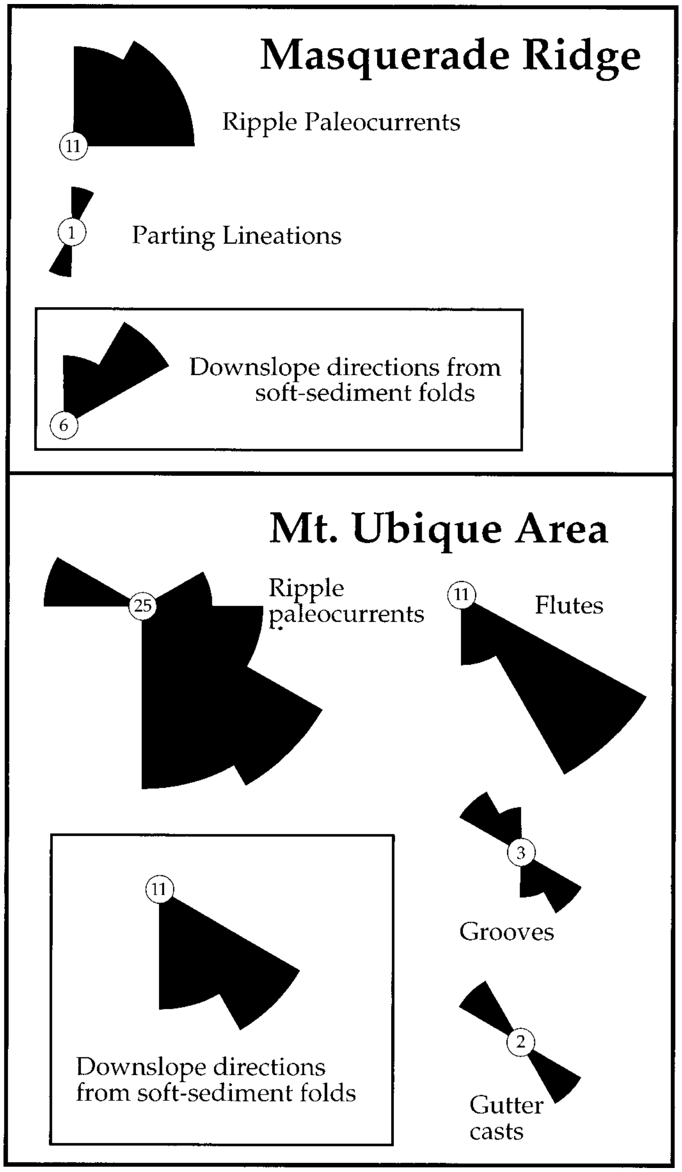

FIG. 13.—Paleocurrent data from Starshot Formation at localities Masquerade Ridge (western flank of Holland Range) and Mt. Ubique (Fig. 1). Downslope directions ascertained from soft-sediment folds are plotted from vergence directions of folds.

record marine deposition. It may ultimately be impossible to prove why infauna were so scarce during the bulk of the deposition of this unit. However, if much of the time the basin was brackish in character, this may have limited the distribution of marine invertebrates and also have affected event-bed deposition by creating favorable conditions for the production of hyperpycnal flows associated with oceanic floods (discussion below). Age-equivalence and large-scale interfingering of the alluvial fan deposits of the Douglas Conglomerate makes such flows likely.

EXCESS-WEIGHT FORCES AND STORM DEPOSITIONAL MODELS

The wave-modified turbidites described in this report have important implications for storm depositional models. The early idea of shelf turbidites for the production of tempestites (Hamblin and Walker 1979; Wright and Walker 1981; Leckie and Walker 1982; Walker 1984) was dismissed shortly thereafter (e.g., Swift 1985) because it did not appear that autosuspension was possible on modern shelves (Pantin 1979; Parker 1982). In addition, oceanographic observations of storms indicated that they formed geostrophic flows and that these flows had far too low suspended sediment concentrations (SSCs; 50–150 mg/l; Swift 1985, table 3). However, threshold sediment concentration for autosuspension is about 1 g/l (Middleton 1966; Lowe 1982), and a number of studies of modern shorelines indicate that very high SSCs (up to 4 g/l) are produced on shorefaces and inner shelves and lead to powerful seaward-directed sediment-laden flows (Lavelle et al. 1978; Wright et al. 1986; Madsen et al. 1993; Héquette and Hill 1993; Wright et al. 1994). Such high concentrations can extend far above the bed; Wright et al. (1994) documented a SSC of $\sim$ 1.4 g/l at 120 cm above the bed at 13 m water depth. However, as Wright et al. (1991, p. 48) point out, ''as long as wave agitation sustains the high suspended sediment concentration, it should not be necessary for such flows to be autosuspending in order to survive a significant offshore excursion''. Storm-induced oscillatory flow provides the boundary layer shear stress and eddy viscosity to reduce deposition from suspension, which in turn maintains elevated density and driving force. This has been demonstrated in the Modern for the cross-shelf movement of fluid mud layers (Traykovski et al. 2000; Wright et al. 2001). Experimental studies have attempted to model wave-modified turbidity currents but have generally been constructed with geologically unrealistic conditions (Thomas and Simpson 1985; Linden and Simpson 1986; Phillips et al. 1986; Simpson 1987; Noh and Fernando 1992). It is clear, however, that turbulence added by waves must be strong enough to enhance bottom-boundary-layer turbidity but not so high as to cause excessive diffusion of the gravity-driven dispersion into the overlying water column. Such a balance is modeled with the Richardson Number, Ri, which relates inertial forces to mixing forces (Fischer et al. 1979; Noh and Fernando 1992): $\mathrm{Ri} = B_m h^*(\cos\theta)/s^2$, where B_m is the maximum buoyancy of the cloud, h^* is the maximum thickness of the buoyant cloud, θ is the angle of the sloping bed, and s is the root mean square (rms) of the background turbulent velocity fluctuations. Flows in which $\mathrm{Ri} \approx 1/4$ or more will be strongly driven by excess-weight forces. Although such conditions are more difficult to reach on the low slopes that characterize modern shelves, once a wave-modified turbidity current is produced such slopes retard its turbulent diffusion and loss of driving force. As Myrow and Southard (1996) suggested, excess-weight forces must be considered in the interpretation of ancient storm-generated sandstone beds. This study documents a case in which such forces are shown to have played a significant role in storm deposition.

Although the combination of storm currents and waves alone may lead to high SSCs and excess-weight forces, these effects may also be produced by catastrophic introduction of sediment dispersions during floods events (Normark and Piper 1991). Fluvial floods with high sediment concentrations can form hyperpycnal flows in the marine environment if the density of the incoming flow is sufficiently high. These particular types of hyperpycnal flows, termed oceanic floods (Wheatcroft 2000), could potentially be pre-ignited with regard to autosuspension, although as stated earlier this is unnecessary for significant cross-shelf transport because storm waves can provide the extra turbulence needed to maintain sediment suspension. Oceanic floods are very common globally in small river basins, which are generally associated with mountainous regions and active continental margins (Mulder and Syvitski 1995; Wheatcroft et al. 1997). In such settings, where sediment storage in small coastal plains is limited and floods produce high sediment flux, the introduction of water and sediment greatly exceeds the sediment dispersal systems of the nearshore oceanic setting (Wheatcroft 2000). Mulder and Syvitski (1995) studied 150 modern rivers and concluded that although 9 of them probably produced hyperpycnal flows on a yearly basis, 100 of them could produce such flows at recurrence intervals of $<$ 1000 years. This indicates that hyperpycnal flow is a potentially geologically important process for understanding storm facies.

Laboratory experiments by Parsons et al. (2001) suggest that hyperpycnal flows can be generated when sediment concentrations of river input is

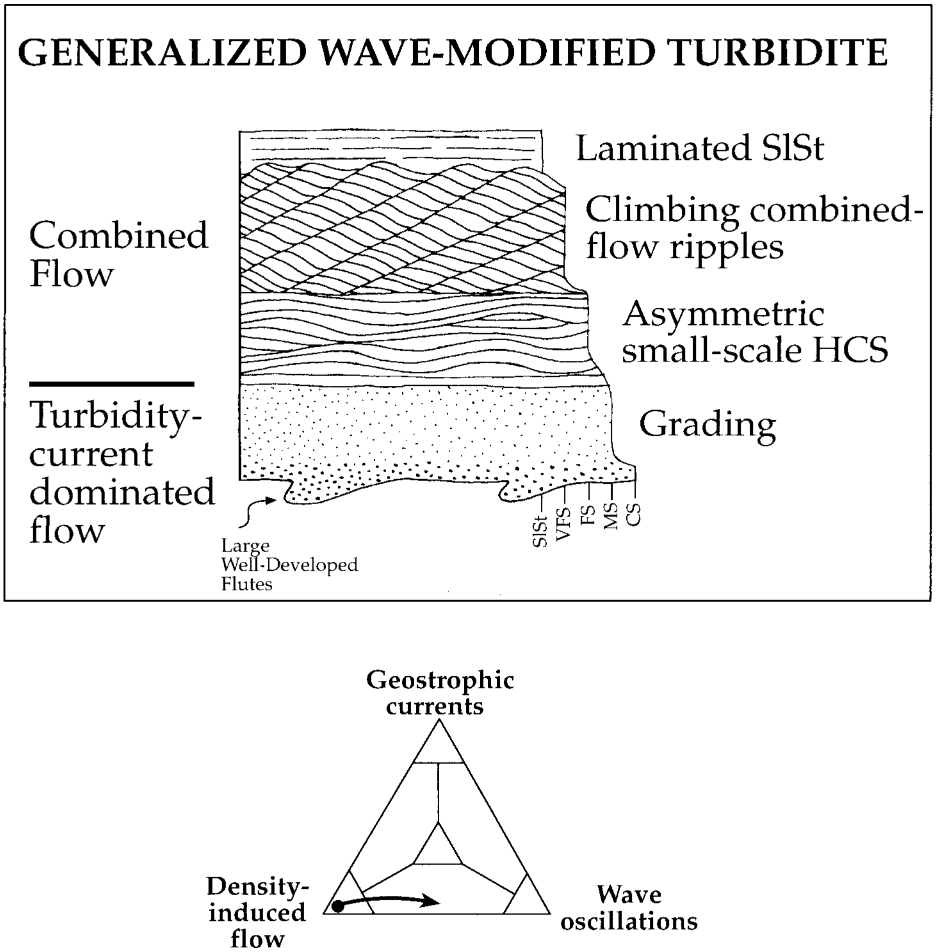

FIG. 14.—Generalized wave-modified turbidite bed. Temporal history of generalized bed is shown in triangular diagram of storm-related effects (see also Myrow and Southard 1996).

40 times less than the density contrasts would suggest. This is the result of convective flow from surface plumes as a result of particle settling and heat diffusion. Results of both oceanographic studies (Nittrouer 1999; Ogston and Sternberg 1999; Cacchione et al. 1999; Wright et al. 1999; Zhang et al. 1999) and modeling experiments (Moorehead and Syvitski 1999) of the northern California coast indicate that gravity-driven underflows associated with ocean floods have high SSCs (up to 2.5 g/l) even at mid-shelf depths (50–70 m). These flows were dominated by silt and clay, however, not the fine to very fine sand that dominates ancient tempestites. Convective circulation acts on surface plumes, which are dominated by fine grain sizes, but one might speculate that it could also lead to enhanced transport in a contemporaneous underflow with a prominent sand component.

The grading, thicknesses, and large well-developed flutes of the more proximal (i.e., lower shoreface to innermost shelf) sandstone beds of the Starshot Formation suggest powerful flows that underwent rapid deceleration. These flows had considerable momentum as they moved across the shoreface, and it is possible that they were deposited from oceanic floods. The production of oceanic floods would be enhanced by (1) sharp relief of the hinterland adjacent to shoreline, (2) high equilibrium slopes of shoreline and inner shelf, and (3) climatic and geomorphic susceptibility to riverine floods with high sediment concentrations (Mulder and Syvitski 1995). Although the climate of this part of Antarctica during the Cambrian is not known, abundant geologic evidence indicates an active tectonic setting, probably at a continental margin where strong physical orographic effects prevailed, and fossils in immediately underlying carbonate rocks indicate a relatively warm-water, low-latitude position (Palmer and Rowell 1995). The Starshot Formation and contemporaneous Douglas Conglomerate record extreme local relief and development of thick alluvial fans directly adjacent to the marine environment. Flashy discharge with high sediment loads is a common feature of alluvial fans, and would have been enhanced by a lack of land plants at this time.

Although previous workers have suggested that storm-event beds were deposited in large part by turbidity currents in association with storm waves (e.g., Hamblin and Walker 1979), such a claim has been difficult to prove. Characteristics of the sandstone beds from this study that have allowed such a determination include: (1) Bouma-like sequences, (2) an independently derived downslope orientation from associated beds, (3) well-developed, unmodified (by waves) flute marks, (4) abundant combined-flow ripple cross-stratification, and (5) parallelism of the orientations of 2–4 above. Wave-modified turbidites may be a more important part of the rock record than previously recognized. Although such beds may be highly variable (Fig. 7), the generalized wave-modified turbidite shown in Figure 14 illustrates some diagnostic evidence for their recognition. In general, wave-modified turbidites tend to have much more pronounced grading than tempestites, the latter of which are generally well sorted very fine to fine sand(stone). The initial stages of deposition are dominated by excess-weight forces and hence the prominence of flute marks and basal graded divisions. The influence of waves is first recorded in fine sand divisions that contain asymmetric HCS. The deceleration of the excess-weight component of a wave-modified turbidity current is likely much more rapid than that of storm-generated currents, which leads to rapid deposition relative to bedform migration rates and thus prominent combined-flow climbing-ripple divisions. The results of this study highlight the importance of excess-weight forces for interpreting ancient tempestites and further illustrates the wide range of flow conditions under which tempestites are deposited.

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