

# POT AND GUTTER CASTS FROM THE CHAPEL ISLAND FORMATION, SOUTHEAST NEWFOUNDLAND<sup>1</sup>

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**ABSTRACT:** Member 2 of the Chapel Island Formation of southeast Newfoundland contains a diverse suite of erosional structures known as pot and gutter casts. These are particularly abundant in a lithofacies deposited in a nearshore zone characterized by erosion and sediment bypass during storm emplacement of sands.

The steep-to-overhanging walls of both pot and gutter casts imply rapid filling during the same storm events that created these depressions. Erosion is thought to have taken place under strong offshore-directed unidirectional flow (storm surge or other relaxation flow). As with many sandstone tempestites, the initial stages of the storm events were dominated by strong—and in this case highly erosive—unidirectional flow, and the latter stages by oscillatory flow, as evidenced by wave-diagnostic lamination in the sandy infills.

Pot casts have geometries and soles indicating vortex flow similar to that which forms potholes in bedrock in glaciated regions. Gutter casts that lead into potholes do so at their edge, a requirement for generating rotary currents within the depression. Pot casts are commonly tilted relative to paleohorizontal, and their direction of plunge is either upcurrent or downcurrent.

Variation in geometry of the erosional structures from the Chapel Island Formation, and from erosional structures in general, can be accounted for by the following: substrate type; diagenetic history of substrate; and flow parameters such as pattern of water motion, velocity, and intermittency of flow.

## INTRODUCTION

Erosional structures of a variety of sizes and shapes have been described in the literature using a host of different names. Linear structures have been referred to as priels, furrows, gutter casts, rinnen, erosionrinnen, large groove casts, rills, cut-and-fill, scour-and-fill, and gouge channels; rounded structures have been called pot casts or scour pits. The size and geometry of these depressions are likely a function of many complex variables such as the intensity and nature of the eroding flows, length of time that erosion takes place, and the grain size and diagenetic history (e.g., degree of compaction or lithification) of the underlying substrate. Erosional structures, such as the pot and gutter casts described herein, form in a wide variety of marine environments, presumably from a variety of processes. Possible types of eroding currents include: oscillatory flows (Bloos 1976; Aigner 1985), erratic unidirectional flows, helical horizontal and vertical (vortex) flows (Flood 1983), and combined flows (Bridges 1972; Brenner and Davies 1973; Aigner 1985).

The late Precambrian–Early Cambrian Chapel Island Formation of southeast Newfoundland includes an interesting nearshore facies that contains abundant pot and gutter casts. This facies was deposited in a shallow subtidal zone dominated by erosion and sediment bypass (Myrow 1992). This paper examines pot and gutter casts from this nearshore facies and takes a broader look at erosional sedimentary structures and the processes that control their formation, based on data from the Chapel Island Formation and the literature.

## LOCATION AND GEOLOGIC SETTING

The outcrops examined in this study are exposed along the southwest tip of the Burin Peninsula, Newfoundland

(Fig. 1) which lies within the Avalon Zone, the easternmost terrane within the Appalachian Orogen (Williams 1979; Williams and Hatcher 1983). The features described in this paper are found within the second of five members within the upper Precambrian–Lower Cambrian Chapel Island Formation, a 1000-m-thick nearshore and shelf sequence composed dominantly of sandstone, siltstone, and mudstone. The formation overlies continental and marginal-marine deposits of the Rencontre Formation (Smith and Hiscott 1984) and underlies the shallow-marine tidalites of the Random Formation (Anderson 1981; Hiscott 1982).

## MEMBER 2: SEDIMENTOLOGY

The sedimentology of the Chapel Island Formation was described by Myrow (1987) and summarized in Myrow et al. (1988). The second member of this formation, containing the pot and gutter casts described below, consists of green muddy siltstone and thin-to-medium bedded sandstones deposited in a storm- and wave-influenced deltaic setting (Myrow 1992). The deltaic nature of this shallow-water sequence is demonstrated by distributary-channel and delta-abandonment facies (Myrow 1987; Myrow et al. 1988) and the presence of a wide variety and abundance of gravity-flow deposits (Myrow and Hiscott 1991). A brief description of the facies relationships and a paleoenvironmental reconstruction for the deposits of member 2 are given below.

### *Tempestite Model and Proximity Trends*

Myrow (1992) presents a facies model for storm deposition along muddy coastlines based on the sedimentology of member 2. Three facies are described: 1) a Gutter Cast Facies characterized by muddy siltstone with well-preserved thin laminae to very thin sandstone beds and abundant pot and gutter casts; 2) a Siltstone-Domi-

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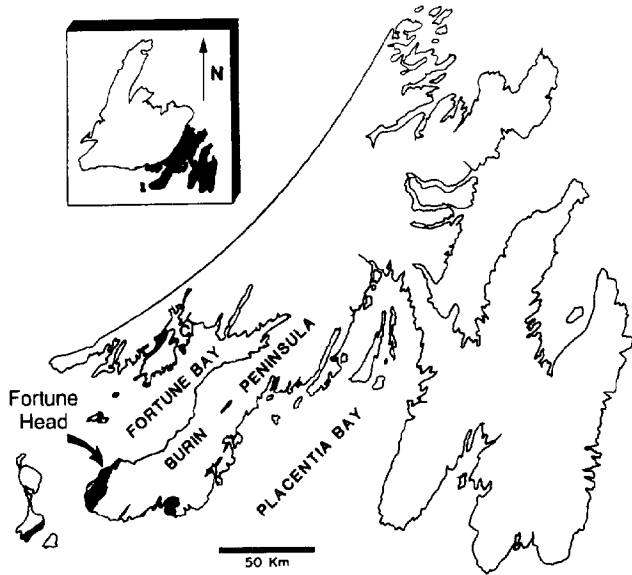


FIG. 1.— Outcrop distribution of Chapel Island Formation (shown in black). Much of the data for this study comes from the Fortune Head Locality.

nated Facies composed of laminated siltstone with 30–50% laminae to medium beds of sandstone and few, if any, erosional structures; and 3) a Sandstone-Dominated Facies of similar lithology and character but with thicker sandstone beds (with hummocky cross-stratification) and a higher sandstone percentage.

The model for storm sedimentation illustrated in Figure 2 (Myrow 1992) shows the inferred spatial reconstruction of these lithofacies and the associated processes. In this model, the Gutter Cast Facies occupies the shallow subtidal zone, an area dominated by sediment bypass or

throughput across which high-velocity, sediment-laden flows erode deep, narrow scours (gutters) into a muddy, cohesive substrate. Very little sand is deposited outside of these scours: most of the sediment bypasses the very shallow subtidal zone and is deposited in deeper water where, due to flow deceleration, erosion of the sea floor ceases and continuous beds of more even thickness are deposited (Siltstone-Dominated Facies). Farther from shore, bed thickness reaches a maximum (Sandstone-Dominated Facies) and hummocky cross-stratification is abundant. More distally, below storm wave base (represented by the thinly-laminated siltstones of member 3 of the formation), bed thickness once again decreases. Abundant paleocurrent data from tempestites in members 2 and 3, including gutter cast orientations, show that, as in most ancient storm-influenced sequences (Leckie and Krystinik 1989), there is generally an orthogonal relationship between the orientation of sole marks and wave ripple crests. The data indicate that sediment-laden storm flows carried sand offshore towards the northeast, nearly perpendicular to the paleoshoreline (Myrow 1992).

This paper examines the erosional structures generated in the deposits of the shallow subtidal bypass zone and compares these structures with similar erosional structures described from the literature. The nature of erosional and depositional currents is investigated within the framework of the tempestite facies model.

GUTTER CASTS

The term “gutter cast” was first used by Whitaker (1973) for downward-bulging sole structures and isolated channels in Llandoveryan rocks in Norway. The gutter casts were interpreted to form by current erosion. Erosional structures of a variety of sizes and shapes have been described in the literature using a host of different names.

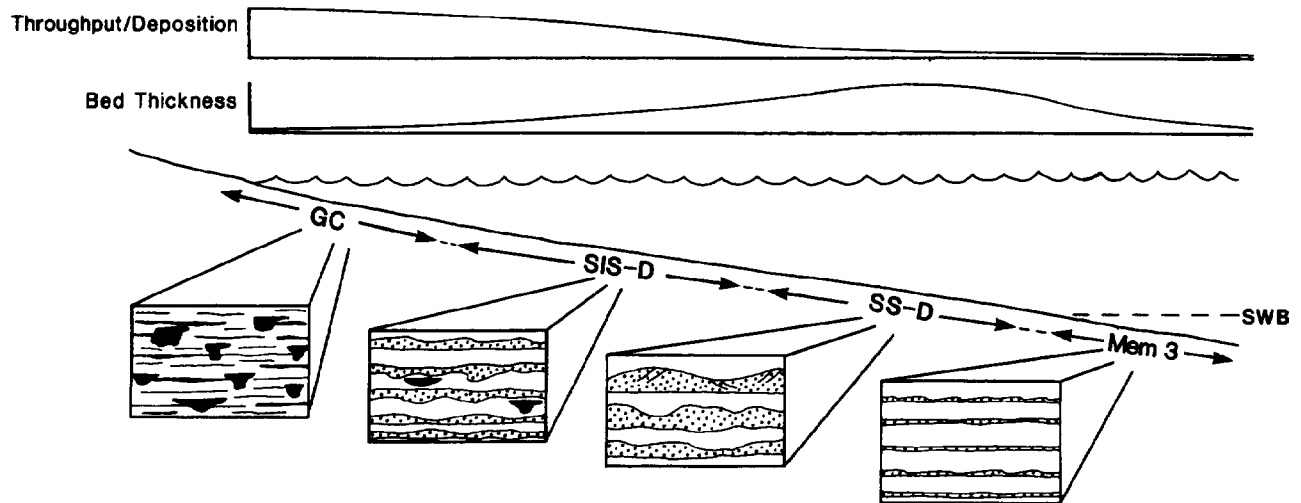


FIG. 2.— Facies model and proximity trends for member 2 of Chapel Island Formation (from Myrow 1992). The model shows a bed-thickness trend that first increases and then decreases away from the shoreline. The proximal setting is one of bypass, where erosion is the dominant process (Gutter Cast—GC—Facies). Passing seaward, gutter casts die out and bed thickness increases (Siltstone-Dominated—SIS-D—Facies). Hummocky cross-stratification is formed in the thicker sandstone beds farther out on the shelf (Sandstone-Dominated—SS-D—Facies). Below storm wave base (SWB) distal tempestites of member 3 (Mem 3) are turbiditic in character.



FIG. 3.—Rounded symmetrical gutter cast at base of quartzarenitic sandstone bed. White ruler is 15 cm long.

(A table summarizing data from over 30 studies is available from the author upon request.) Problems associated with such a multiplicity of names are compounded by significant variability in the characteristics of these erosional structures. Scale is particularly variable, with widths from more than one meter (Williams 1881; Greensmith 1965; Schroder 1965; Nagtegaal 1966; Richter 1967;

Tucker 1969; Wincierz 1973) to a few centimeters (Van Straaten 1951; Dineley 1960; Berry 1961; Allen 1962; Schroder 1965; Daley 1968). The wide range of sizes, shapes, lithologies and internal structures of these erosional features suggests that their origins are polygenetic.

*Chapel Island Gutter Casts*

The following discussion will refer almost exclusively to deep, narrow, erosional features that occur isolated or “connected” by an overlying thin sandstone bed (e.g., Fig. 3). Pot casts are cup-shaped and cylindrical pillars of sandstone that are found in intimate association with the gutter casts.

Gutter casts in member 2 show variability in lithology and in geometry, as seen in cross section (Fig. 4) and plan view (Fig. 5). These are dominantly composed of fine sandstone and less commonly of white-weathering, well-sorted fine to medium quartzose sandstone (Figs. 3, 4D) and granule to pebble conglomerate (Fig. 4C). The latter consists of phosphatic shale clasts, green siltstone intraclasts and large quartz pebbles set in a well-sorted, medium to coarse sandstone. These conglomeratic gutter casts are weakly normally graded, and the long axes of the clasts are dominantly parallel to bedding.

The sandstone gutter casts are most commonly either massive or parallel-laminated. Several beds contain evidence of deposition under oscillatory flow: low-angle and wavy lamination with low-angle truncation surfaces,

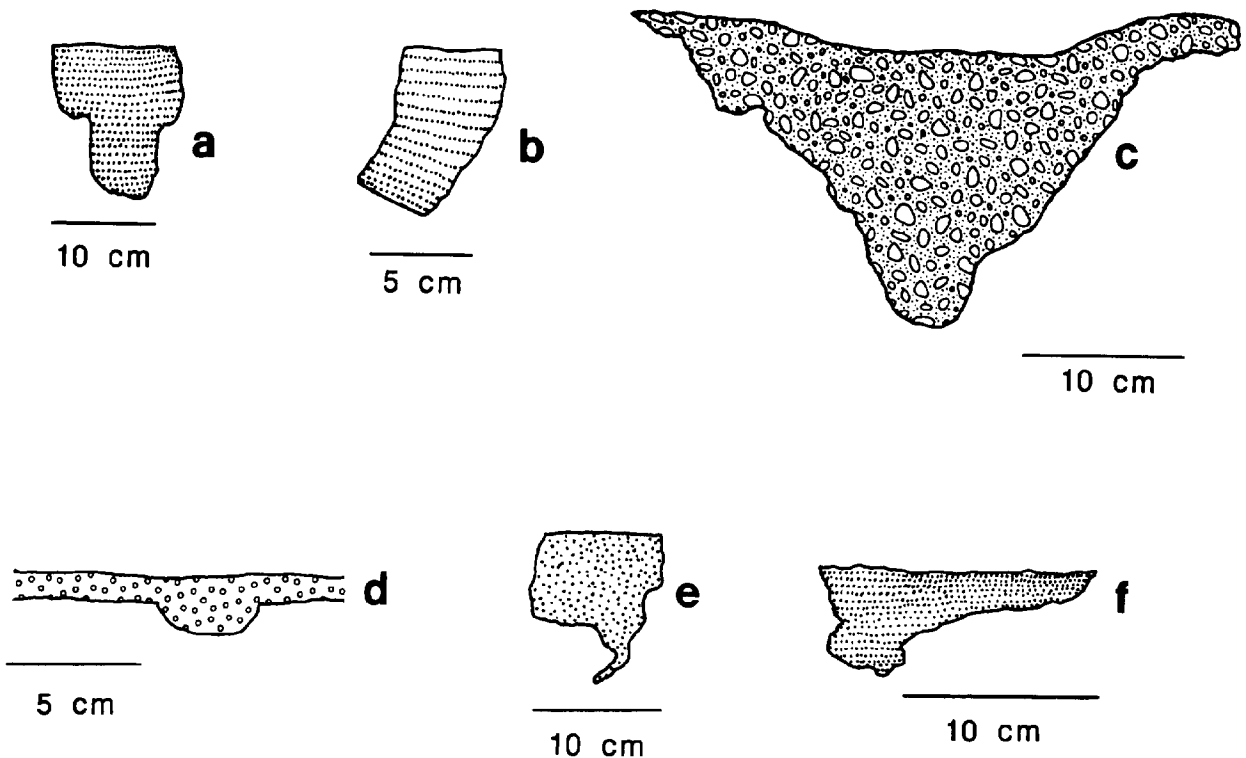


FIG. 4.—Sketches of cross-sectional views of gutter casts. See text for description.

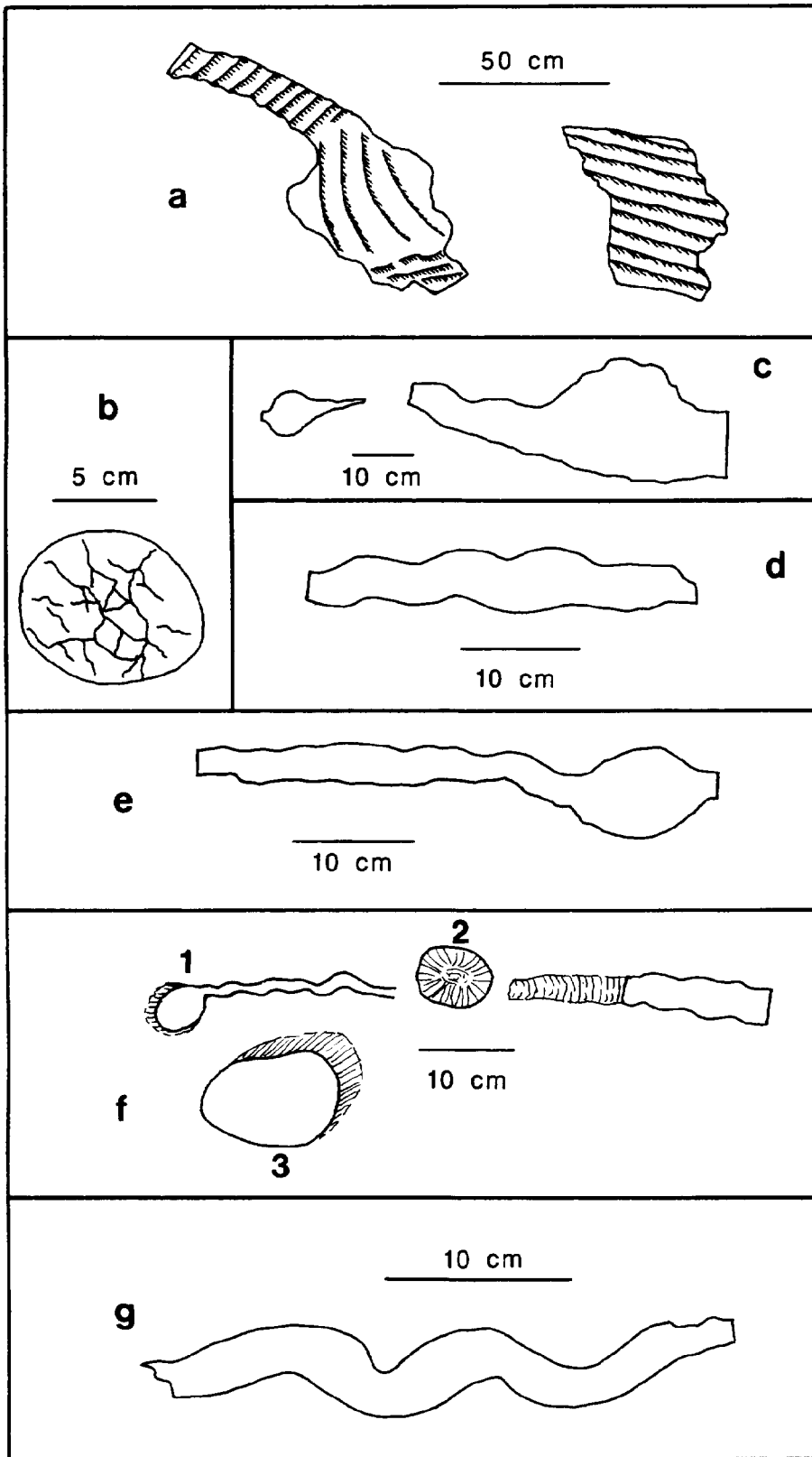


FIG. 5.—Sketches of plan views of gutter and pot casts. See text for description. In F, the trend and plunge of the long axes of pot cast "1" and the mold left by the excavation of pot cast "2" is toward the left (roughly northeast). Pot cast "3" indicates a long-axis trend and plunge towards the right (south to southwest).



FIG. 6.—Hour-glass-shaped gutter cast with locally overhanging wall (on the left). Divisions on stick scale are 10 cm.

symmetrical climbing-ripple lamination, and draping and offshooting laminae (Boersma 1970; De Raaf et al. 1977; Allen 1981; Harms et al. 1982). With rare exception, the gutter casts are not amalgamated. Some gutter casts are carbonate cemented, as are some of the sandstone beds with which they are found. This cementation is an early diagenetic phenomenon (Myrow 1987).

The cross-sectional shapes of these gutter casts range from symmetrical (Fig. 4A, C, D) to strongly asymmetrical (Fig. 4F), and include u-shaped, bilobate, v-shaped (Fig. 4C), semicircular (Figs. 3, 4D), flat-based (Fig. 4B) and wide, shallow forms. Extremely steep to overhanging walls are common (Figs. 4B, E, F; 6). In a very few examples, bending of lamination in the gutter casts and/or the surrounding strata indicates minor deformation by compaction (Figs. 4C, E; 6). The paucity of such evidence of deformation indicates relatively rapid consolidation and dewatering prior to erosion of the gutters and pots.

Cross-sectional views that are parallel or nearly parallel to the long axes of these gutter casts are wide and shallow. The ratio of maximum width to maximum thickness (taken roughly normal to long axes of the gutter casts) for a small sample of isolated gutter casts ( $n = 16$ ) is 1.7, with ratios noted as low as 0.4. Average maximum width is 8.9 cm, and average maximum thickness is 6.1 cm. The thicknesses are generally one or more orders of magnitude thicker than the sandstone beds with which they are intercalated. The cross-sectional geometries and nature of infill of the Chapel Island gutter casts are summarized in Figure 7.

#### *Plan-view Geometry*

The plan-view shapes of the gutter casts vary from narrow (Figs. 5D–G, 8, 9) to wide (Fig. 5A, C), and straight to sinuous (Figs. 5D, F, G; 8, 9) to highly irregular (Fig. 5C). Full three-dimensional exposures of several sinuous gutter casts (Fig. 10) show that in cases their geometry is comparable to modern meandering rivers: cross sections perpendicular to flow are strongly asymmetrical on meander bends, with steep to overhanging outside walls.

Sinuous gutter casts tend to be narrow, with widths less than a few centimeters. From the small number of sinuous gutter casts observed, it appears that narrow ones are more sinuous. In some cases, gutter casts are closely associated with pot casts (described below). Gutter casts originate from and lead into, then out of, pot casts (Figs. 5C, E, F, 9). One interesting example is shown in Figures 5F and 9, in which a slightly sinuous gutter cast leads into the mold of a pot cast, which leads to a thinner, more sinuous gutter cast and finally into a small pot cast.

Numerous examples of bifurcating gutter casts were noted, as well as those that taper and pinch out along strike. All of the bifurcating casts have their “forks” opening toward the northeast, and nearly all of those that show pinchout do so towards the northeast as well. The long axes of 90 gutter casts measured at the Fortune Head locality (Fig. 11B) show a strong northeast-southwest orientation, parallel to flutes and other paleocurrent data from sandstone beds (Myrow et al. 1988; Myrow 1992), indicating erosion of the gutters by the same offshore-directed flows that deposited the sand. With a few notable exceptions (Aigner 1985; Aigner and Futterer 1978), most gutter casts in ancient sequences are oriented perpendicular to the shoreline, as they are in this study (Van Straaten 1951; Berry 1961; Allen 1962; Prentice 1962; Whitaker 1965; Daley 1968; Tucker 1969; Wincierz 1973).

The upper bedding surfaces of some gutter casts are covered with symmetrical oscillation-ripple marks with high spacing-to-height ratios ( $> 10:1$ ). The crests of these ripples are generally perpendicular to the trend of the gutter cast.

#### *Sole Markings*

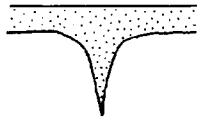
Sole markings are common features along the sides and bases of these gutter casts. The markings include groove marks, poorly-developed prod and flute marks, and post-depositional trace fossils. Groove marks are generally parallel to subparallel to the long axes of the gutter casts and circular to downward-spiraling on pot casts. One sinuous gutter cast was noted in which grooves on the outer surface plunge obliquely downward along the “inner” wall of the gutter at a meander bend (Fig. 10).

Trace fossils on the walls of isolated gutter casts are found to a depth of only 3–4 cm below their flat upper surfaces. Parts of gutter casts that extend below this depth are either smooth or bear only current marks. The burrows on the walls of the gutter casts are considered post-depositional because 1) they are not fluted, and 2) they extend only a limited, yet consistent, depth below the ancient sediment-water interface. This limited depth of 3–4 cm is also consistent with maximum burrowing depths determined from the more tabular sandstone tempestites using the technique outlined by Seilacher (1962) (G. Narbonne and Myrow, unpublished data).

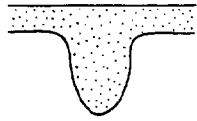
#### *Gutter Cast Erosion and Deposition*

Field observations support the suggestion of Whitaker (1965, 1973) that there is a continuum between isolated

# SHAPE



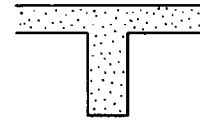
V-SHAPED



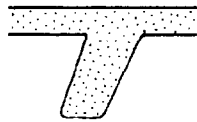
DEEP ROUNDED



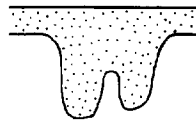
SHALLOW ROUNDED



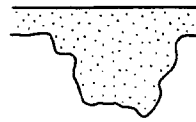
RECTANGULAR



OVERHANGING



BILOBED



IRREGULAR

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# LATERAL CONTINUITY



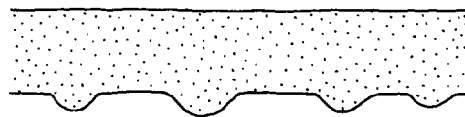
DISCRETE



PARTIALLY CONNECTED



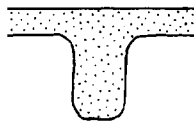
CONNECTED THIN BED  
( $<$ Depth of gutter)



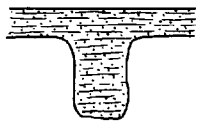
CONNECTED THICK BED  
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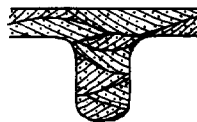
# INFILL



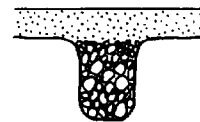
STRUCTURELESS



PLANAR LAMINATED



CROSS-LAMINATED



CONGLOMERATIC

FIG. 7.—Characteristics of gutter casts in cross-section.

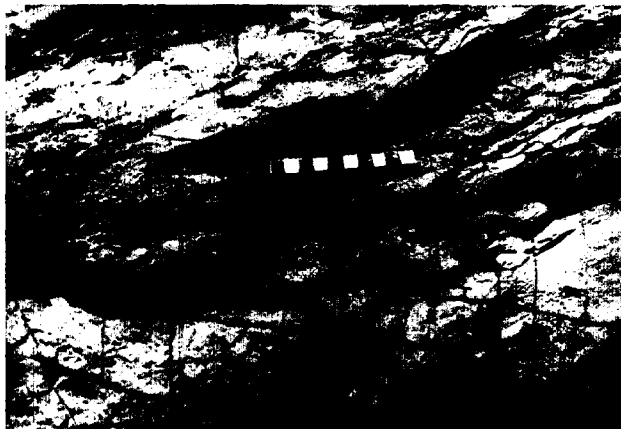


FIG. 8.—Plan view of sinuous gutter cast. Scale is 10 cm long.

or “separated” gutter casts and those connected by an overlying bed that may be a small fraction of the thickness of the gutter cast to several times its thickness (Fig. 7). Whitaker suggests that separated gutter casts are formed when there is insufficient sediment to form a complete bed, whereas those connected by a thin bed and those that bulge downward from a thick bed form under conditions of higher sediment supply. Most of the Chapel Island gutter casts are isolated or are connected by very thin and often discontinuous sandstone laminae. In the Gutter Cast Facies of this study, gutters and potholes formed during the early erosive stages of storms were subsequently filled when velocities dropped and the deposition of fine sand began. However, the bulk of available sand had already bypassed the shallow subtidal zone by that time (Fig. 2).

There are two main phases in the development of gutter casts: erosion, followed by deposition. The time lag between erosion and deposition is difficult to ascertain and may vary from bed to bed. Goldring and Aigner (1982) present criteria for recognizing time breaks between erosion and deposition. These criteria include: 1) fine-grained and banded (heterolithic interlaminae) fills, 2) a history of colonization and/or trapping of organisms, and 3) evidence of predepositional bioturbation. Close examination did not reveal any fine-grained laminae in gutter casts, and there is no sign of predepositional borings or burrows.

In some gutter casts in this study, steep side walls are obviously due to differential compaction (Fig. 4B), but many clearly represent an original erosional geometry (Fig. 4F). Goldring and Aigner (1982) consider sandstone gutter casts with steep to overhanging margins as early-filled structures. Overhanging walls must have also been very common in the Chapel Island potholes (discussion below), because most of the pot casts are tilted and/or widen downward. Even in quite cohesive sediments, such steep walls would not be expected to endure the combined influence of waves, tides and currents for a prolonged period of time. The evidence therefore supports rapid accumulation of sediment in freshly eroded scours, in

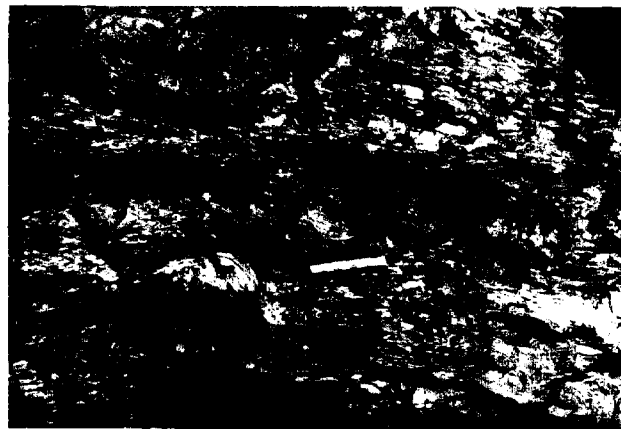


FIG. 9.—Bedding-plane view of pot and gutter casts with northeast to the left. The large pot cast to the left of the scale has its central axis plunging roughly south. Above the scale (right to left), a slightly sinuous gutter cast leads to an exhumed pothole, which in turn leads to a thinner and more sinuous gutter cast, and finally a small pot cast. The central axis of the small pot cast plunges toward the northeast, and the shape of the exhumed pothole indicates a similar tilt. Scale is 10 cm long. (See Fig. 5F and text for details.)

many cases forming massive and parallel-laminated sandy infill. The ripples found on the tops of several gutter casts are considered wave ripples on the basis of their symmetrical profile and their extremely large spacing-to-height ratios. These ripples and the complex wave-ripple lamination in the upper portions of some gutter casts indicate that oscillatory currents influenced at least the late stages of deposition of these gutter casts. The thickness of the gutter casts (generally 10–100 times thicker than the associated sandstone beds) and the evidence for rapid infilling of the gutters is compatible with deposition under thick sediment-laden flows that deposited sediment almost exclusively in the gutters during bypass to deeper shelf environments.

In at least one example (Fig. 5A), the erosional structure was not completely filled during the depositional stage, so that the lip and the shape of the scour affected later overriding flow. The pattern of ripple-crest orientations in Figure 5A shows crests transverse to the gutter in its narrow portion and nearly parallel to the gutter in the irregular widened portion. The pattern indicates that wall effects, governed by the overall geometry of the scour, altered the flow to produce the different crestline orientations.

#### POT CASTS

Pot casts are structures formed from the infilling of potholes, or rounded nonlinear erosional depressions. The pot casts from member 2 of the Chapel Island Formation also have a wide variety of shapes and sizes (Fig. 12). Most are either conglomeratic (Fig. 12A, B, D, F) or composed entirely of fine sandstone without a basal lag. The pot casts commonly weather out as partially free-standing structures. They range in shape from discs to rounded loaflike forms to tall pillars, and in size from



FIG. 10.—Three-dimensional view of steep-walled, U-shaped gutter cast. Note partially spiraling (?) groove marks on the side. White ruler is 15 cm long.

remarkably small (1 cm in diameter) to large (nearly 20 cm in diameter; Fig. 12G, H). Numerous examples were noted in which pot casts widened downward, and several had snail-like or corkscrew shapes (Figs. 12G, H; 13A, B), similar to potholes found in bedrock along modern rivers. The bottoms of pot casts are commonly deepest around the outside, with a central erosional high: the form resembles the base of a wine bottle (Fig. 12A, C–H). Synaeresis cracks were noted at the top of one pot cast (Fig. 5B). The central axes of the pot casts are commonly tilted from the paleovertical ( $< 30^\circ$ ) (Fig. 13A, B); measurements of the direction of plunge of the axes of the potholes are given in Figure 11A.

#### *Pothole Erosion*

The process of fluvial pothole erosion was described by Alexander (1932) in a remarkable study combining laboratory experiments and field study of potholes in bedrock from glaciated regions. He concluded that potholes were formed by the grinding action of tools (sand to boulder size) carried by stationary eddies, replacing the long-held belief that they were formed by vertically plunging water (see review by Higgins 1957). Alexander's laboratory equipment included a cylindrical container with a sliding false bottom and a maneuverable jet at the top. Using sediment and dyes he was able to recreate and observe flows he considered similar to those in natural potholes.

Alexander (1932) demonstrated that flow within potholes takes the form of a jet that enters at one side of the pothole and spirals downward along the outer wall to form a vortex, with flow returning upward through the center of the vortex. In rotary flows, a pressure gradient is established due to centripetal forces: high pressure on the outside and low pressure in the center of the vortex. At the base of the cylinder, the fluid responds to this force

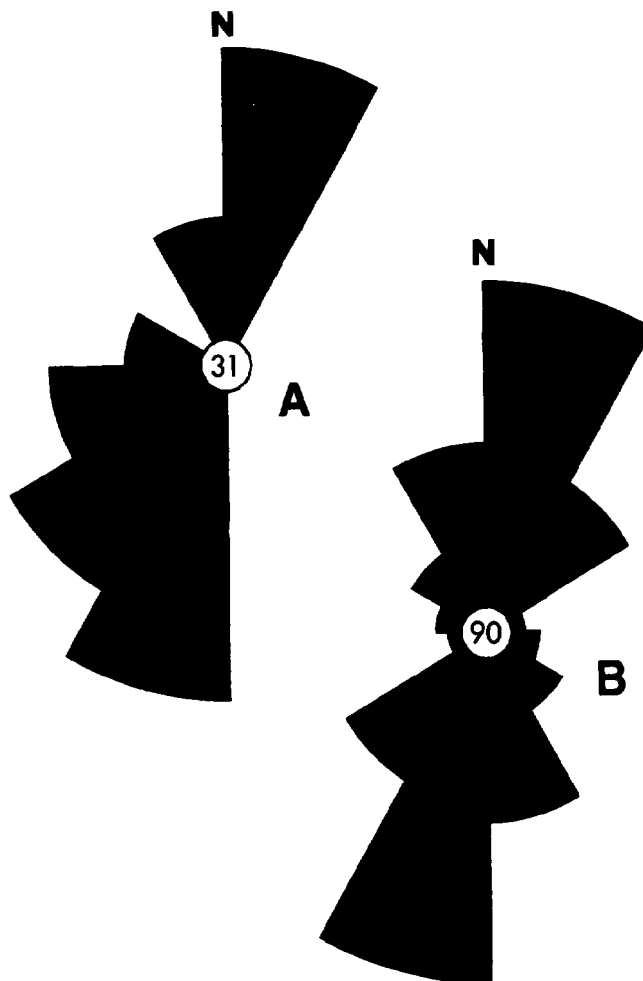
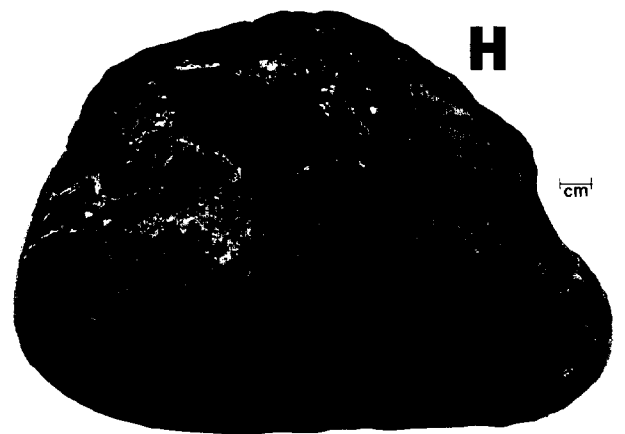
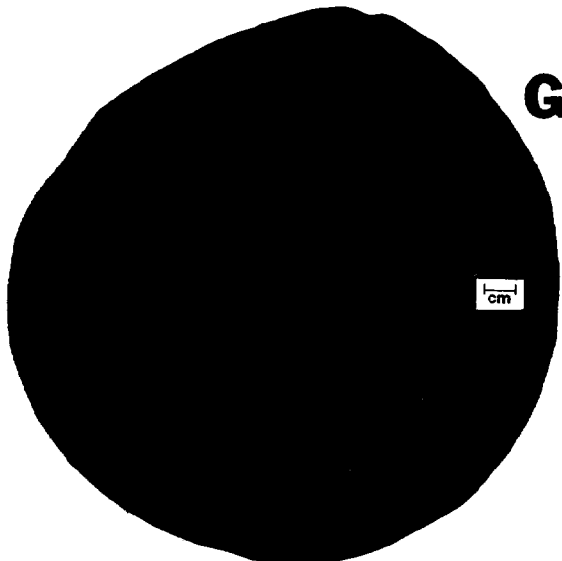
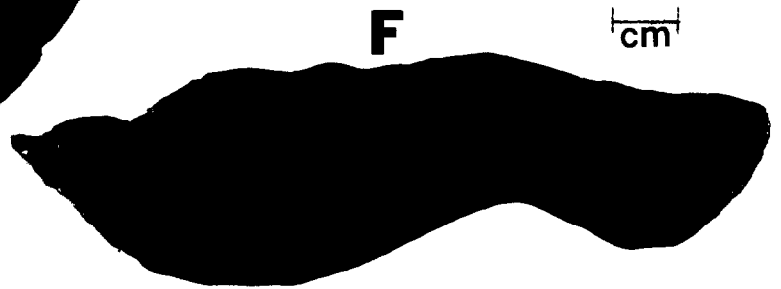
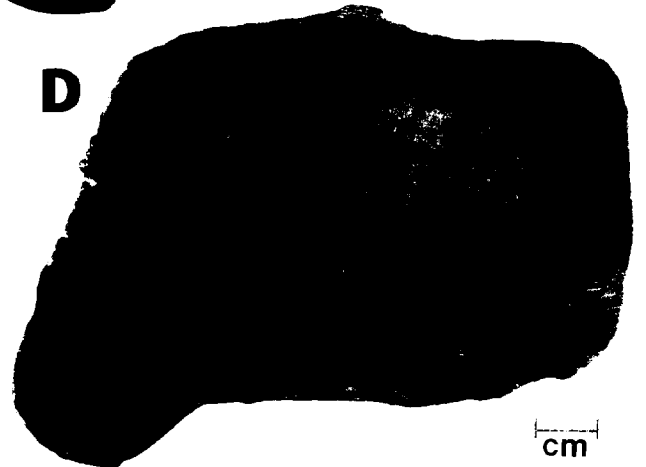
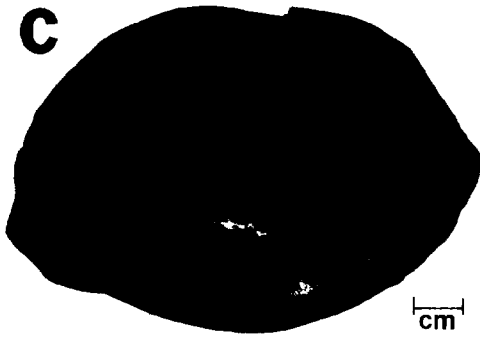
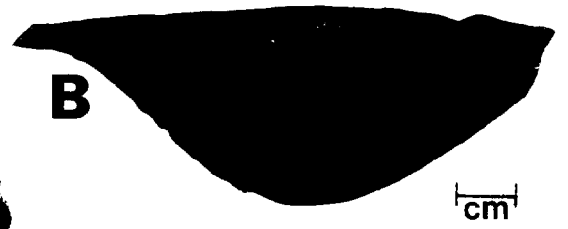
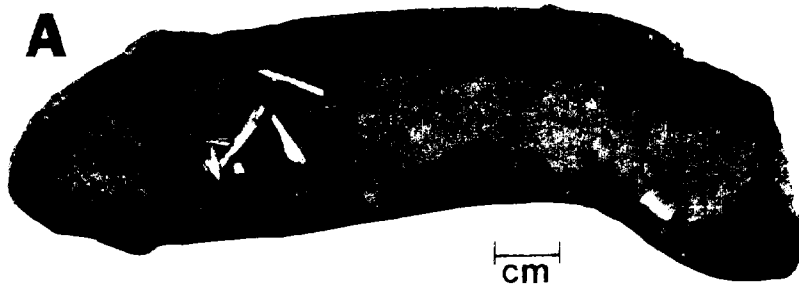


FIG. 11.—Rose diagrams. A) Azimuths of plunge of the central axis of pot casts ( $n = 31$ ). B) Trend of long axes of gutter casts ( $n = 90$ ).

and inertial forces within the rotating flow, and it moves into the rising core of fluid.

A simplified two-dimensional diagram (Fig. 14), illustrates the three-dimensional motion of the water. This diagram shows that the axis of the vortex is not vertical and centrally located, but itself forms a spiral. "The working end of this axis is obliquely directed and off center at the bottom of the tube, and this off-center position moves about the axis of the pothole as it is deepened. The spiral vortex acts as a sort of spiral tool and under favorable and constant conditions drills into the rock in 'corkscrew' fashion, thus giving rise to spiral fluting" (Alexander 1932, p. 322). One aspect of flow in laboratory conditions (Fig. 14) that would differ in a subaqueous system, such as that found in shelf environments, is the presence of a free surface. However, the lack of a free surface in marine settings would have little effect on the general pattern of flow within potholes.

Both the geometry and pattern of grooves of many pot casts in this study indicate a flow pattern similar to that described by Alexander. A major difference in process is



that the Chapel Island potholes were eroded into a cohesive substrate of clayey silt—instead of bedrock—that could potentially have been eroded by currents without the aid of a tool. Large clasts, that could have acted as tools, are rare in these pot casts. However, the presence of delicate groove marks on the sides of these pot casts indicates that sand-sized sediment may have aided in the erosion of the potholes as an abrasive agent. One might expect that the flow would drop into the depression sediment that could act as an abrasive as described by Flood (1983) for large-scale erosional furrows.

More important to the application of a simple laboratory vortex model to natural flows is the position of the driving jet. Using his experimental apparatus, Alexander (1932) illustrated that strong rotary motion is induced only when a jet is off-center at the top and that the speed of rotation, and therefore the energy (which varies with the square of velocity), is low when the inclination of the jet is very low (nearly parallel to the surface) or very high (plunging). In natural subaqueous flows, such as storm-generated currents, the dominant flow would be parallel to the bed surface. Some component of downward-directed flow might also be added by flow separation over the lip of the pothole, but this would occur over the entire opening, particularly at the center, instead of to one side as needed for rotary motion. Downward-directed flow might occur in a pothole if a linear scour entered at the edge of the pothole at a level below the pothole lip. The downward component of flow in this situation would be small, and therefore the limitation on depth of erosion would be the degree to which new fluid is introduced to the rotating vortex to drive a sufficient volume of upward-directed fluid, at sufficient velocities, to remove the sediment being eroded at the base. The fact that the Chapel Island potholes formed in fine silts and clays (albeit compacted) would have favored easy transport of sediment out of the depressions.

#### NATURE OF THE ERODING CURRENT

Erosional structures similar to those described in this paper are described from ancient deposits with paleoenvironments that range from tidal flat to submarine fan (Whitaker 1973). Most pot and gutter casts are described from shallow-marine rocks and are considered to be storm-generated features (Bridges 1972; Brenner and Davies 1973; Aigner and Futterer 1978; Kreisa 1981; Hiscott 1982; Leithold and Bourgeois 1984; Aigner 1985). Five fundamentally important and recurring geometries of gutter casts from the Chapel Island Formation are shown in Figure 15; these will be referred to in the following discussions.

The occurrence of a spiraling or ropelike pattern of grooves on the soles of gutter casts has led to the suggestion that they are formed by helical flow at the base of unidirectional currents moving parallel to the long axes of the gutters (Williams 1881; Schroder 1965; Bridges 1972; Whitaker 1973). Other authors (Kuenen 1957; Wood and Smith 1957; Prentice 1962; Aigner and Futterer 1978) describe parallel or near-parallel orientations of sole markings (grooves, prods, flutes) that also argue for unidirectional flow as the agent of erosion. On the other hand, Allen's (1962) "elongate flute marks" have unoriented prod marks, and gutter casts described by Bloos (1976) and Aigner (1985) have bidirectional prod marks, indicating erosion by multidirectional and bidirectional currents. The longitudinal grooves of the Chapel Island gutter casts—and the one example with suggestions of a spiral pattern—imply erosion by unidirectional flow.

Another indication of unidirectional flow is the observation that some gutter casts in this study originate from potholes (Fig. 15C), and that in these cases the gutters are always on the northeast (downstream) side of the potholes. Aigner and Futterer (1978) noted gutter casts in the field that had pot casts at one end and gradually died out at the other. They suggested that these potholes and gutters are produced by currents interacting with obstacles forming horseshoe hollows that were later developed into channels in a downstream direction. They simulated these conditions in the laboratory and created what they considered to be pot-like and channel-like scours.

Whereas some gutter casts in the Chapel Island Formation may have formed from obstacle scour, the following evidence suggests this was not typical: 1) there are relatively few examples in which gutter casts are directly associated with potholes; 2) many gutters are very extensive and of remarkably uniform width for several meters; and 3) some gutter casts are wider than any of the observed potholes.

In the experiments performed by Aigner and Futterer (1978), potholes became deeper on their upstream end and shallower on their downstream end, where they eventually graded directly into a gutter. The resulting plunge of the hole (central axis plunging upstream) corroborated their field observations in which pot casts were similarly plunging with respect to the inferred (unidirectional) paleocurrents. If, as the work of Aigner and Futterer indicates, the plunges of pot casts have paleocurrent significance, then the bimodal-bipolar data on pothole plunge for member 2 (Fig. 11A) would suggest the influence of bidirectional currents such as tides (the larger mode to the southwest would suggest stronger flow to the northeast, as the experimental data suggest "upcurrent" tilting). This means either: 1) flow was bidirectional; 2) both unidirectional and bidirectional currents were operating at

FIG. 12.—Pot Casts. **A)** Slabbed cross-section with characteristic shape indicating erosion at the edge of the pothole. Note abundant shale chips and large angular ripup clast with early-diagenetic calcite crystals. **B)** Cross-section of rounded form with large shale clasts. **C)** Basal view of pot cast showing rounded protuberance indicating the last position of the working end of the eroding vortex. **D)** Cross-section illustrating erosion at the edge of the pothole and significant overhang in the surrounding mud (left side). Note abundant shale chips at base, on edges, and on top. **E)** Cross-section of dark, fine-grained sandstone pot cast. **F)** Cross-section with characteristic shape and shale chip conglomerate fill. **G)** Top view of large sandstone pot cast which widens downward to the left. **H)** Side view of G showing downward widening and spiraling.

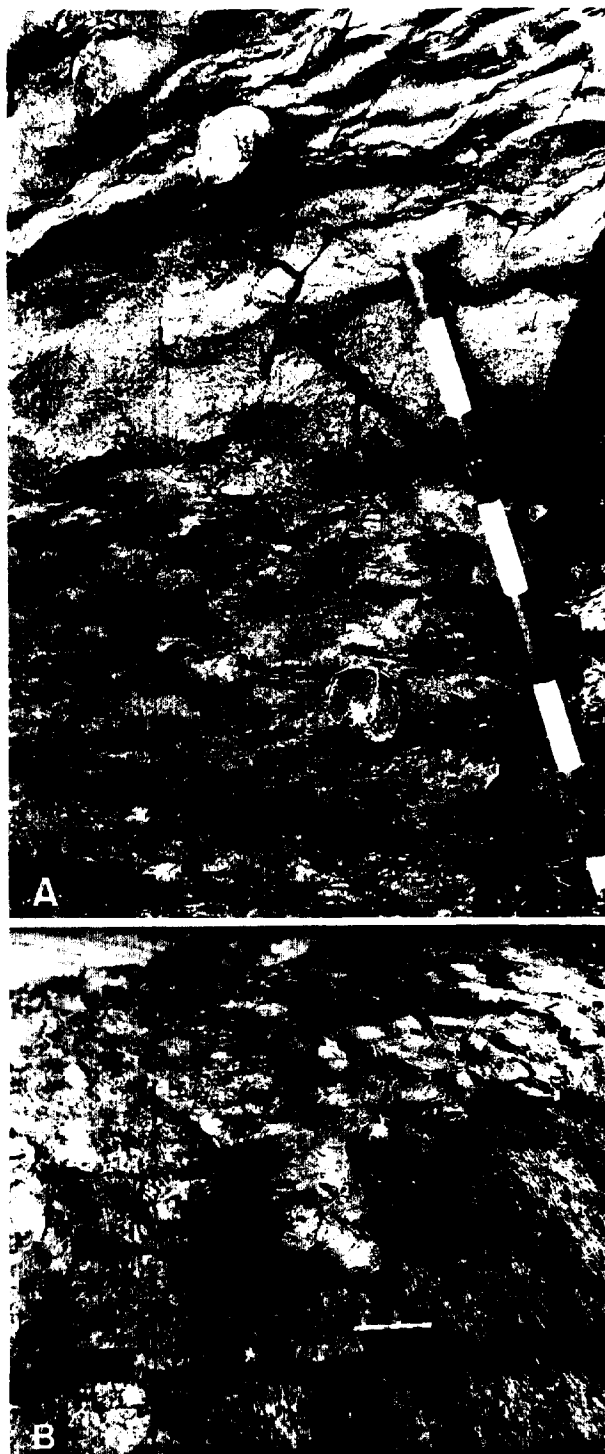


FIG. 13.—A) Bedding-plane view of two pot casts. Pot cast at top of photo widens and spirals downward. B) Oblique view of prominently weathering pot cast with well developed downward-spiraling shape. Scale in foreground is 10 cm long.

different times; or 3) the polarity of the plunge of a pothole can vary under unidirectional flow (i.e., central axes of adjacent potholes tilt upstream or downstream). The third possibility is preferred based on the lack of supporting evidence for bidirectional flow, such as bidirectional prod marks, and the fact that: 1) the pinchouts and bifurcations of gutter casts (Fig. 15D) are preferentially oriented toward the northeast; 2) those gutter casts that originate from pot casts in all cases extend towards the northeast; 3) the geometries of some gutter casts are similar to that of modern river channels (Fig. 15A); 4) pot casts have geometries that are similar to potholes in bedrock that are formed by vortices that are convincingly modelled in the laboratory under unidirectional flow; and 5) gutter casts are aligned parallel to flutes and other paleocurrent indicators from associated sandstone beds showing strong northeast-directed unidirectional flow (Myrow 1992).

It is possible, however, that these strong unidirectional storm flows may have at times interacted with other marine currents such as tides. Kleinspehn (1992) suggests that large, saucer-shaped scour pits in estuarine sandstones may have formed from interaction of storm-surge flows with flood tidal currents, creating strong vortices along vertical shear surfaces separating these oppositely oriented flows. She suggests that the characteristics of these scour pits, many of which are remarkably circular and deep ( $\leq 50$  cm), imply a very delicately balanced system in which the opposed flows moved at almost the same velocity. Otherwise, scour asymmetry and linear channel geometries would result from vortex migration in the direction of the stronger flow.

Vortex flow along vertical shear surfaces is an attractive model for generating deep potholes, because a significant height of the water column would be in rotation, solving the problem of momentum transfer inherent in sustaining secondary circulation patterns at the base of a unidirectional flow (discussed above). However the need for perfectly balanced flow is problematic. Kleinspehn (1992) also entertains a simpler model involving interaction of storm-surge currents with bottom topography to generate vortices similarly along vertical shear boundaries. This kind of interaction is invoked by Cacchione et al. (1984) to explain large scour pits (up to hundreds of meters in diameter) off the coast of California. It seems likely that the geometry of a depression, once initiated, would control, in part, the nature of circulation within the depression and the position of the overlying vortex as well, such that the vortex could not migrate away from the depression.

Several aspects of the Chapel Island pot and gutter casts are inconsistent with erosion by stationary (pot casts) or migrating (gutter casts) vertically oriented vortices along shear surfaces. First, with regards to the gutter casts in this study, the cross-sectional geometries of sinuous forms (asymmetrical with steep to overhanging walls at meander bends; Fig. 15A) and horizontal or partly-spiraling groove marks (in one example) clearly indicate horizontal and in some cases helical flow similar to that found in rivers (see Bridges 1972; Whitaker 1973), rather than vortices with vertical axes.

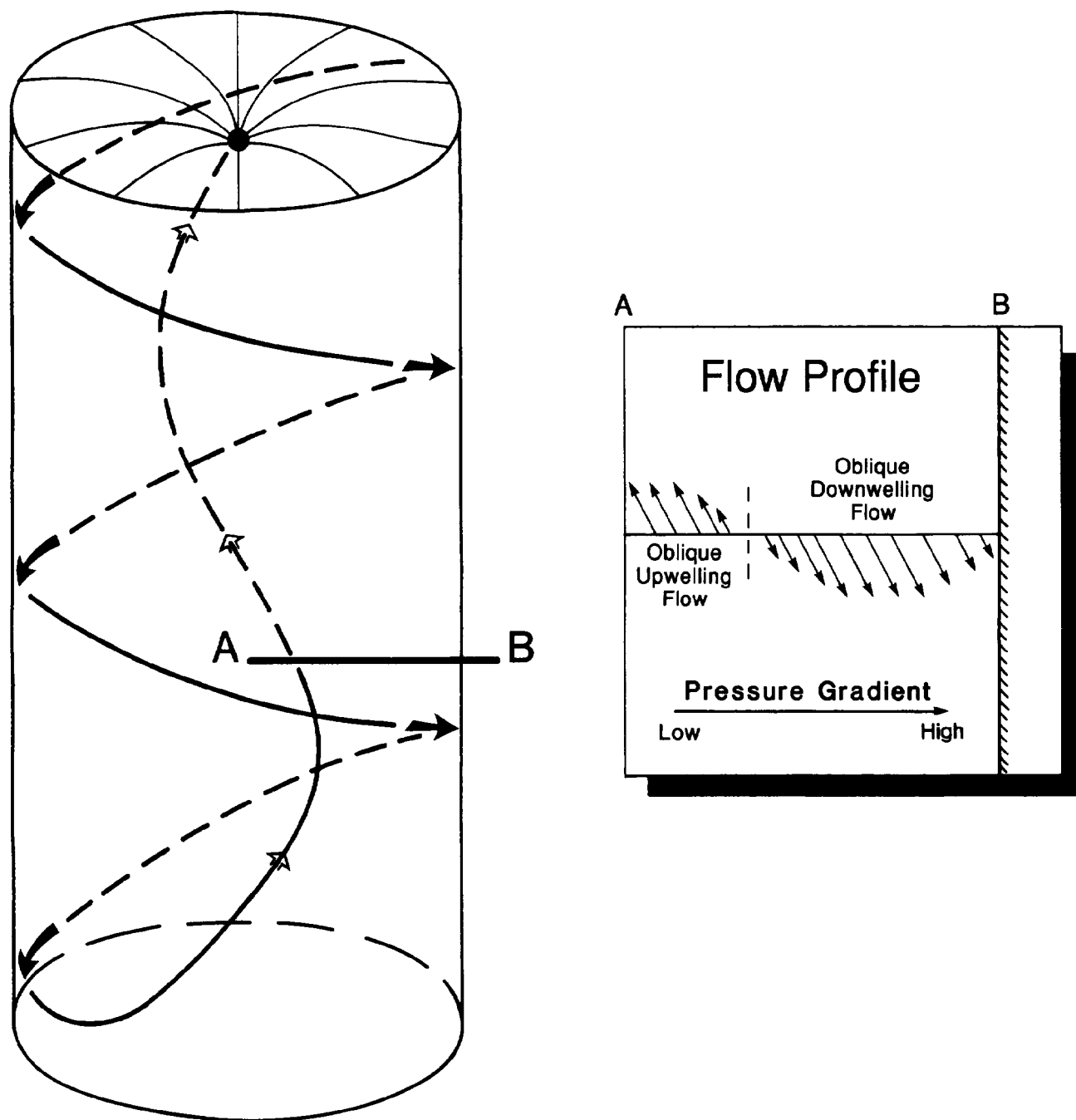


FIG. 14.—Pattern of flow in pothole (left side of diagram modified from Alexander 1932). Path of single fluid element shown on left. Flow profile on right reflects obliquely-directed downwelling and upwelling flow. Velocity profile would go to zero at wall and at interface between downwelling and upwelling flows. The pressure gradient within the flow is shown on the bottom.

The analysis of pot cast features given earlier indicates erosion by vertically oriented vortices. However, the association of sinuous gutter casts with pot casts (Fig. 15C) would support erosion of gutters by horizontal vortices and potholes by vertical vortices, *both* under (near) horizontal unidirectional flow. Pot casts and gutter casts in this study are essentially large erosional sole marks which, in the context of the facies model for the gutter cast facies

in the lower Chapel Island Formation (Fig. 2; Myrow 1992), are commonly left as isolated sand-filled structures because of considerable nearshore sediment bypass during storm flows. The parallelism of a wide range of sole markings including flute marks (Myrow 1992), with the long axes of gutter casts and the plunges of the vertical axes of pot casts (Fig. 11), strongly support this interpretation.

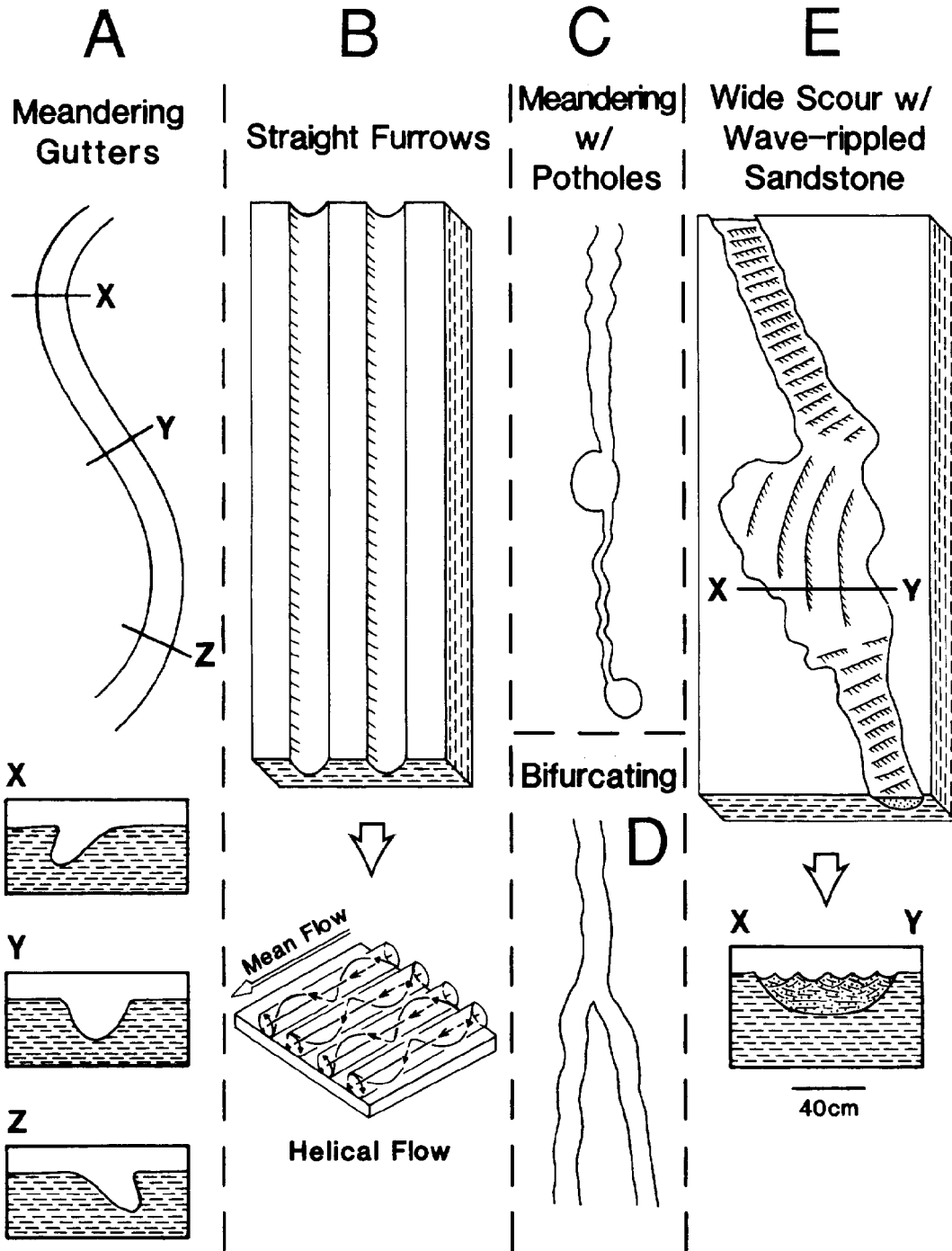


FIG. 15.—Geometries of gutter casts from the Chapel Island Formation. **A)** Plan and cross-sectional geometries of meandering gutter casts. **B)** Straight gutters with inferred helical flow pattern (modified from Flood 1980). **C)** Meandering gutter casts and associated potholes. **D)** Bifurcating gutter cast. **E)** Gutter casts with wave-rippled surface; cross-section shown below.

A final point in support of erosion at the base of unidirectional horizontal flows is that in several well exposed bedding-plane exposures sinuous gutter casts lead into pot casts consistently at their edge (Fig. 5F; also see Allen 1984, figs. 7–11; Aigner and Futterer 1978, fig. 3). The experimental work of Alexander (1932) showed that in

(near) horizontal flow, strong angular momentum transfer into a deepening pothole is possible only if flow enters at the edge of a pothole at a slight angle from horizontal. Therefore, linking of erosion of gutters and potholes under horizontal flow would *require* that gutters enter potholes at their edge. However, if erosion of gutters and

potholes took place under vertical vortices formed along vertical free-shear surfaces which involve much or all of the water column, then one might expect gutters either to lead consistently to the centers of potholes or to have a random distribution. A series of laboratory experiments on fine-grained cohesive sediments are sorely needed to test the conclusions of this study and to constrain better the conditions under which these large scale erosional structures form.

#### *Pot and Gutter Casts and Models of Storm Deposition*

The nature of the eroding flows that form pot and gutter casts has implications beyond a general understanding of how these structures form. These erosional features are a poorly understood component of storm sedimentation models which strive to explain, among other things, the orientation and paleobathymetric position of these features at the time of erosion. These parameters are determined, in part, by a combination of paleocurrent data, facies relationships, and associations with other sedimentary structures within shelf and shoreline successions.

It has been argued that most ancient storm deposits contain evidence for sediment transport nearly perpendicular to shore for long distances (Leckie and Krystinik 1989), presumably by shelf turbidity currents. Such a conclusion is supported by data on the geometry and orientation of pot casts and gutter casts from member 2 of the Chapel Island Formation (this study and Myrow 1992). Oceanographers, however, emphasize that modern storms generate geostrophic flows (Swift et al. 1986; Snedden et al. 1988) which are nearly shore-parallel and whose orientation is due to an interplay of forces, including Coriolis forces. Only a few examples of ancient deposits have been reported in which paleocurrents from storm-generated sandstones are oriented parallel to shore (e.g., Nøttvedt and Kreisa 1987; Winn 1991).

Duke (1990) and Duke et al. (1991) have tried to resolve the apparent conflict between modern studies and data from ancient sequences. They suggest that ancient deposits were formed—similar to modern cases—under combined flows in which the time-averaged flow is a geostrophic current oriented at a low angle to shore. They believe that the paleocurrent indicators reflect the direction of maximum instantaneous shear stress in the thin boundary layer created by the oscillatory-flow component of the combined flow. The net addition of the offshore component of force of the geostrophic current to the storm waves during their seaward stroke results in an asymmetry of shear stress yielding offshore sediment transport and unimodal sole marks.

It is beyond the scope of this paper to evaluate fully these models of storm sedimentation (for reviews see Walker 1984; Brenchley 1985; Duke 1990). However, the data from this study raise important questions concerning these models. First, the suggestion that sole markings and other erosional features such as gutter casts were made by unidirectional flow is inconsistent with the model proposed by Duke (1990) which requires erosion under com-

bined flows, particularly from the more powerful effects of the oscillatory component of flow. The analysis of pothole flow above has demonstrated that the geometry of potholes from this and other studies (e.g., Aigner and Futterer 1978) is explainable by erosion under unidirectional flow. No study has yet demonstrated that any pothole or gutter-cast geometries can form under combined flows. (The same may also be said for current-formed erosional structures such as flutes, which are also found in ancient storm deposits.) A combined-flow origin for pot casts with the geometries described above (or flute casts) would necessitate formation under short-term reversing flows with considerably unequal maximum bed shear stresses to allow erosion only in one direction of flow. This is a considerable constraint, given that current-eroded structures that would form during each offshore-directed stroke would have a hydrodynamically smooth shape (i.e., flutes or potholes) that would be in equilibrium with this component of flow. Such structures would likely be deformed or eliminated with landward-directed flow on alternate wave oscillations under significantly lower shear stresses than those needed to produce the pothole or flute. This argument must be tested, however, by laboratory experiments on the effects of combined flows on the erosion of muddy substrates.

#### DISCUSSION

The variation in shape and scale of the erosional structures in this study is quite remarkable. This variation might be accounted for by any number of factors, such as substrate type, diagenetic history of substrate, and flow parameters such as pattern of water motion, velocity, and intermittency of flow. These factors are ultimately controlled by the paleoenvironmental setting and depositional history (e.g., pattern of relative sea-level changes).

The range of geometries of gutter casts from the Chapel Island Formation (Fig. 15) differs from those found in erosional structures formed in sandy noncohesive substrates, in which linear structures tend to form dendritic patterns (e.g., Baldwin and Johnson 1977; Hiscott 1982; Plint et al. 1988) and circular depressions generally have sides which are at the angle of repose (e.g., Kleinspehn 1992).

The most regular gutter cast geometries in this study are the meandering forms (Fig. 15A) and those with straight and parallel sides (Fig. 15B), the latter of which are rare in this study but are the norm in some deposits. As argued earlier, the similarity of form between the meandering types and modern river channels argues for erosion by horizontal helical flows. A similar interpretation, however, is also suggested for straight furrows (Fig. 15B), which are analogous to the modern, large-scale, shallow-marine structures analyzed by Flood (1983) using sidescan sonar. It is possible that the narrow, sinuous gutters in this study formed from slow helical flows and that wider, straight to highly irregular gutters formed from faster flows that would have tended to cut through meander bends.

Irregularity in shape (Fig. 15C), including bifurcation

(Fig. 15D) and pinchout, might reflect local differences in such things as the cohesiveness of substrate, which would either enhance or inhibit erosion. The coupling of gutter and pot casts in plan view (Fig. 15C) is an interesting and enigmatic phenomenon. There is little evidence to suggest that this occurs as a result of current erosion around obstacles, although such an explanation is certainly plausible, as demonstrated by the work of Aigner and Futterer (1978). An early formed depression, such as an obstacle scour, might allow a vertically oriented vortex to form and be maintained solely within an enlarging pothole at the base of a unidirectional flow—instead of involving the entire water column—as suggested for the pot casts in this study.

The conclusions of this study with regard to the genesis of pot casts and gutter casts will likely pertain to other examples in the rock record. The author has seen pot casts and gutter casts from a wide range of deposits, many with characteristics similar to those in this study. However, the variability in scale, geometry, and depositional setting of erosional structures already described in the literature requires a multiplicity of origins. A reasonable approach to further study would be to look at multiple examples of erosional features from different paleoenvironments to find out if the erosional and depositional processes are consistent within paleoenvironments, and also whether correlations exist between these processes and the geometry, scale and orientation of these structures. Additionally, experimental work on cohesive muddy substrates under a wide variety of flow types would be important for developing a better understanding of the conditions under which these erosional structures form and would, in part, be a test of certain aspects of models for storm sedimentation.

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