Maritime Sediments and Atlantic Geology

Vol. 17 April 1981 Number 1

Flute casts and related structures on moulded silt injection surfaces in continental sandstone of the Boss Point Formation: southeastern New Brunswick, Canada

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Flute, load and groove casts occur widely at the sharp interfaces of siltstone diapirs, injection lenses, and pods in fluvial sandstone of the Boss Point Formation of southeastern New Brunswick. These concordant and discordant injection features range from approximately 20 centimetres (pods) to many metres (injection lenses) in diameter. They are confined to "brecciform intervals" that can be traced along strike and dip for a hundred metres or more.

The flute, load and groove casts on the injection surfaces, have evidently not been formed by any primary sedimentary process but are the result of liquefaction, sediment injection and flow moulding during post-depositional compaction of the strata. The term "rheoplasis" is proposed to denote this process, and the general term "rheoplastic structures" or "rheoplasts" refers to the range of sole-marking like structures formed as a result of this process.

The realization that flute casts can form as a result of post-depositional processes is of great significance in the classification of sedimentary structures and the interpretation of depositional environments and attendant sedimentary processes.

Au sud-est du Nouveau-Brunswick, dans les grès fluviatiles de la formation de Boss Point, on peut voir de nombreux exemples de flûtes, empreintes de charge et cannelures aux interfaces distincts de diapirs de siltstone, de lentilles d'injection, de mottes et de loupes. Ces éléments d'injection sont concordants ou discordants et possèdent un diamètre allant de 20 cm (pour les loupes) jusqu'à plusieurs mètres (pour les lentilles d'injection). Ils sont également restreints à des "intervalles bréchiques" que l'on peut suivre sur des centaines de mètres et plus, le long de la direction et du pendage de la stratification.

Les flûtes, cannelures et empreintes de charge que l'on retrouve sur les surfaces d'injection ne résultent évidemment pas d'un processus sédimentaire primaire mais plutôt de la liquéfaction, de l'injection du sédiment et du moulage des coulées durant la compaction après la déposition de la strate. Pour marquer ce procédé, on propose le terme "rhéoplasie" alors que le terme plus global "structures rhéoplastiques" (ou "rhéoplastes") s'applique aux empreintes de toutes sortes qui résultent de ce même procédé et que l'on retrouve sur la surface inférieure d'une strate.

La classification des structures sédimentaires ainsi que l'interprétation des environnements de déposition et des procédés sédimentaires connexes seront grandement influencées par le fait que des flûtes peuvent résulter d'un procédé post-dépositionnel.

[Traduit par le journal]

INTRODUCTION

Flute, load and groove casts occur widely in the lower Pennsylvanian Boss Point Formation of southeastern New Brunswick. The presence of these structures is easily overlooked because they occur primarily on the flanks and upper surfaces of a variety of detached injection structures of siltstone in sandstone rather than on the underside of soles or beds. Their relationship to diapiric structures suggests that they may be the result not of scour (Allen 1968) but of plastic flow-moulding at the interface between two immiscible sediments during lique-

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faction: a process we propose to name "rheoplasis". The term is derived from the Greek word "rhein" to flow, and "plasis", a process of moulding. As proposed here the term rheoplast applies to all structures which, though resembling common sole markings, have not formed by turbidity-current flow but are the result of liquefaction and rheoplasis during compaction. Examples of these structures are illustrated in Figures 9-18.

Flute and load casts, because they are commonly found at the sharply defined contacts between mud or silt below and silt or sand above in rhythmically alternating sand-shale sequences, have often been regarded as characteristic of turbidites. On this basis, turbidity-flow interpretations have over the years been applied to a variety of depositional environments. These include situations where rapid vertical facies-transitions alternate from turbidites to shallow water sequences with almost no sedimentary record of a slope facies in between (Walker 1969), turbidites in deltaic facies (Allen 1960) and turbidite transitions to near-shore coastal plain facies (Raaf, *et al.* 1965, Walker 1966).

Processes similar to turbidity flow are also considered to account for the presence of sole markings (mainly flute casts) at the underside of sandstone units in fluvial fining-upward sand-shale sequences (Friend 1965, Allen and Friend 1968, Stanley 1968), in continental sheet-flood deposits (Cummins

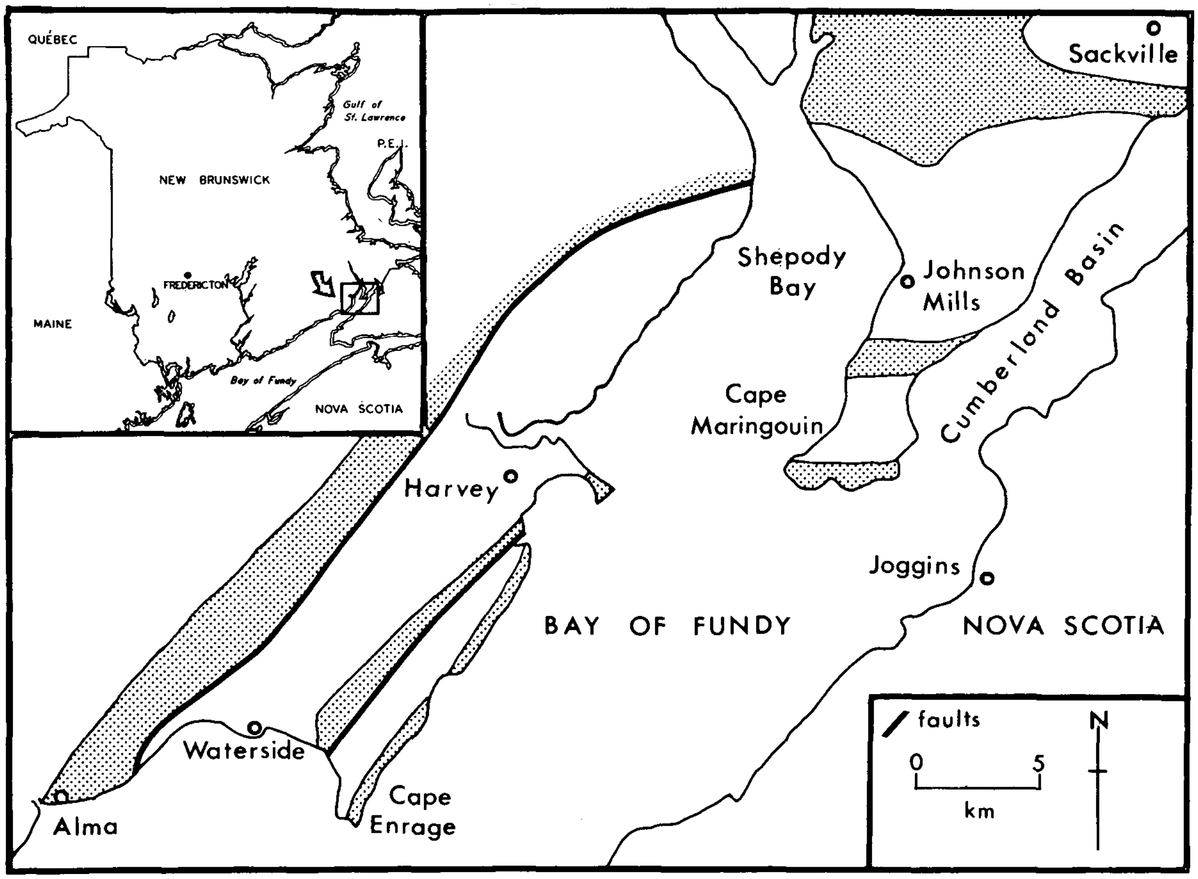


Figure 1 - Location map showing the approximate distribution of Boss Point rocks (stipped ornament) in the Alma—Cape Enrage—Cape Maringouin area of southeastern New Brunswick.

1958), a coastal evaporite sequence, (Raaf 1964), coastal plain beds (Pryor and Barr 1968), a glacial sequence (Banerjee 1966), lacustrine strata (Dineley and Williams 1968), a fluvial coal measures sequence (Sen 1967), and progradational fluvial successions along a rapidly subsiding basin margin (Eisbacher 1978).

The broad range of depositional environments in which sole markings have been found, rather than indicating the wide variety under which turbidity flow conditions can exist, may alternatively suggest that these structures can form as a result of more than one process. This alternative concept; basic to our thesis, that a process entirely different and unrelated to turbidity-current scour may be involved in the formation of at least some flute casts and related structures, acquired clear definition following the discovery of such structures on discordant siltstone-sandstone interfaces in continental fluvial strata of the Boss Point Formation of southeastern New Brunswick. Tentatively attributed at first to the effects of excessive current scour on steep-walled fluvial channels in silty overbank deposits, this hypothesis was abandoned in favour of liquefaction as additional exposures supporting the latter interpretation were discovered.

GEOLOGICAL SETTING

Rheoplastic structures on silt injection surfaces described in this paper, occur in the Carboniferous Boss Point Formation of the Alma—Cape Enrage — Cape Maringouin area on the Bay of Fundy shore of southeastern New Brunswick (Fig. 1).

The Term "Boss Point Formation" applies to a non-marine sequence of grey-buff fluvial conglomerates, sandstone and mud-clast breccias with lenses and interbeds of mainly dark grey siltstone. The sequence extends from Boss Point, the type area in northwestern Nova Scotia, to southwestern New Brunswick (Bell 1912, Norman 1941, Gussow 1953, Poll 1970).

Boss Point strata of the Fundy Bay area have previously been described by Lawson (1962) and Laming and Lawson (1963). Two main interdigitating facies consisting of predominantly coarse sandstone and conglomerate in southeastern New Brunswick and mainly fine sand and siltstone in western Nova Scotia have been recognized. The facies transition is well displayed in coastal exposures of southeastern New Brunswick where dark grey and black siltstone horizons up to 10 metres thick alternate with fine- to medium-grained grey-buff sandstone and minor conglomerate (Belt 1968). Thin coaly partings and coalified plant remains are common throughout the sequence, in particular the finer grained beds. Convolute bedding and pseudonodules, now commonly attributed to liquefaction, (see Potter and Pettijohn 1977, for a review) are widely present within the dark grey siltstone, whereas quicksand slump structures have previously been identified in the conglomerate sandstone of the Boss Point Formation (Laming and Lawson 1963).

DESCRIPTION OF THE SILT INJECTION FEATURES AND RELATED STRUCTURES OF THE BOSS POINT FORMATION

Diapiric structures, in Boss Point strata are contained within brecciform intervals. The term "brecciform interval" refers to a sequence or bed occurring "in the form or shape of a breccia or resembling a brecciform" (Glossary of Geology, Second Edition, 1980). As applied here, brecciform intervals are widely present in the Boss Point and consist of the following related features: (Fig. 2)

1) Detached flakes, pods and lumps of dark grey siltstone in sandstone.
2) Detached sandstone lenses and convolutions, clastic injections and pseudonodules of sandstone in siltstone.
3) Small diapirs and injection lenses of dark grey siltstone in sandstone.
4) Rheoplastic structures, resembling flute, groove and load casts on the moulded siltstone - sandstone interfaces of injection features.

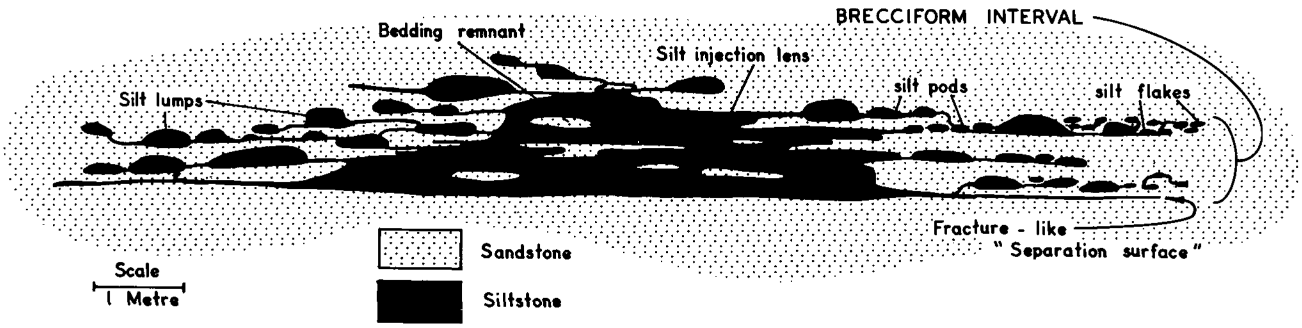


Figure 2 — Diagrammatic interpretation of a brecciform interval showing a combination of common injection features.

Brecciform intervals comprise irregular zones of variable thickness consisting of flakes, pods, lumps, small diapirs and lenses of siltstone in sandstone and of detached sandstone bodies in siltstone. There does not appear to be a major difference in the mode of formation of the injection structures and their main distinguishing features are essentially size, shape and degree of discordance with respect to the enclosing strata. Siltstone flakes pods and lumps are detached bodies of siltstone in sandstone ranging respectively from a few centimetres to approximately one metre in diameter. Siltstone diapirs are injection structures that are clearly discordant to bedding, whereas injection lenses are essentially concordant to bedding. Brecciform intervals can be traced along strike and dip of the strata for up to several hundred metres.

A characteristic feature of brecciform intervals is that they do not form individual bedding units but comprise anastomosing zones that pinch and swell parallel to bedding or may cut across bedding to form two or more subparallel zones. They tend to follow apparent planes of weakness such as bedding surfaces, and may split laterally from a thick unit into a series of thin parallel traces along foreset laminations of crossbedded sandstone. Consequently, brecciform intervals can be extremely varied in appearance and thickness, ranging from a few centimetres as a single row of mudflakes in sandstone, to intervals several metres thick where siltstone flakes, pods, lumps, convolute bedding, pseudonodules, clastic injections, diapirs and injection lenses occur together. A diagrammatic interpretation of

Figure 3 (above)
Medium-grained sandstone and interbedded mud pellet conglomerate showing fracture-like "separation surfaces" (marked by arrows) that interconnect siltstone flakes, pods and small lumps of a brecciform interval, Cape Enrage, N.B. (30 cm ruler for scale).

Figure 4 (left)
Two vertically interconnected silt injection lenses. Note the irregular "rubbly" nature of the siltstone, Cape Maringouin, N.B. Dip of the bedding is towards lower left on photograph (hat and hammer marked by white arrow for scale).

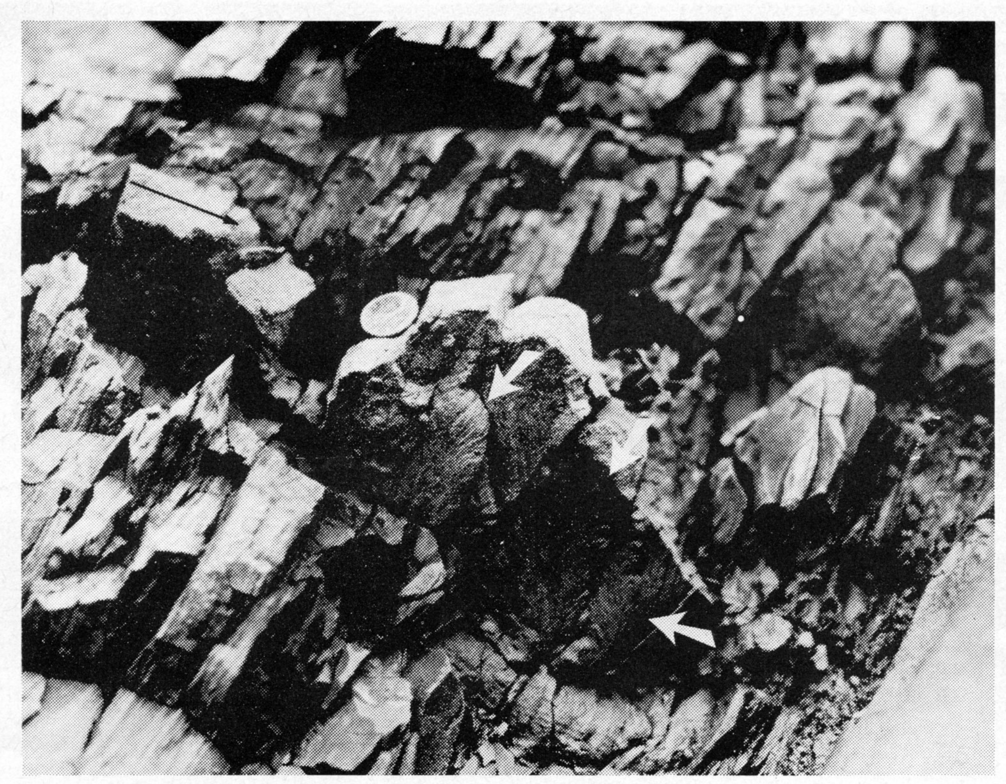


Figure 5 (above)
Small clastic dike of sandstone (its strike marked by extended arrow) in siltstone showing delicate theoplastic structures resembling frondescent load casts and helical striation patterns (marked by white arrows) on its contact surface. Dip of the siltstone is toward lower left on photograph. Orientation of the clastic dike is approximately perpendicular to that of the siltstone, Cape Maringouin, N.B. (23 mm coin for scale).

Figure 6 (left)
Injection lens of dark grey siltstone in sandstone terminating gradually into single fracture-like "separation surface" (marked by arrow) parallel to bedding. Dip of the bedding is toward lower left on photograph. Cape Maringouin, N.B. (injection lens is approximately 50 cm thick).

the features that make up a brecciform interval is shown in Figure 2.

Brecciform intervals can be distinguished from intraformational fluvial breccias by their non uniform and discordant nature; the size of the clasts, which in the case of brecciform intervals can contain bodies up to one metre or more in diameter; the presence of diapirs and injection lenses; and the "moulded" siltstone-sandstone interfaces, suggesting that the siltstone bodies behaved in a plastic manner at the time of their formation rather than as clastic fragments.

Siltstone flakes, pods and *lumps* are discrete bodies of siltstone in sandstone. They occur in a variety of shapes and vary in size from barely visible flakes to lumps with a diameter of approximately one metre. The intermediate sizes include siltstone pods ranging between approximately 10 and 30 centimetres in diameter. Flakes pods and lumps may occur as a few isolated detached bodies of siltstones in sandstone or may be concentrated in great profusion in thick brecciform intervals. Although varied in shape, commonly recurring forms are elongated, angular and almond shapes for the intermediate size ranges whereas the larger siltstone bodies commonly have concave or domed upper surfaces.

A characteristic aspect of these injection features is that although the siltstone occurs as discrete bodies in a sandy matrix, they are invariably inter-connected by one, several or even a maze of fracture-like surfaces that permeate the brecciform interval parallel and across bedding (Fig. 3). Close examination of weathered surfaces commonly reveals small, thin flakes of siltstone and/or thin films of siltstone on their separation planes.

Diapirs and injection lenses in the Boss Point Formation are discrete bodies of dark grey siltstone in grey buff sandstone. The main difference between the two is that injection lenses are essentially parallel to bedding whereas diapirs have a distinctly discordant relationship with respect to enclosing strata. Both concordant and discordant relationships may, however, be present within the same structure. A common form of such local discordance is a series of two or more vertically stacked injection lenses interconnected by diapiric penetration of siltstone through intervening beds (Fig. 4).

Siltstone diapirs and injection lenses within the study area range up to several metres in diameter for the discordant structures and up to several tens of metres or more along strike where injection is essentially concordant to bedding. They commonly contain remnants of detached sandstone beds showing wavy, contorted, or even convoluted forms. Small clastic dikes showing rheoplastic structures on their walls occur within these siltstone bodies as well (Fig. 5). Local extensions or "tongues" of siltstone in surrounding sandstone and involutions of sandstone in siltstone characterize the upper contacts of injection lenses and diapirs.

Injection lenses commonly have gently concave upper surfaces and thin laterally into one or more fracture-like "separation surfaces" that may extend parallel to bedding (Fig. 6), be inclined (Fig. 7) or extend perpendicular to bedding (Fig. 8). These fracture-like "separation surfaces" appear identical to those which, on a smaller scale connect the siltstone flakes, pods and lumps and presumably have a common origin. They can be traced along strike of the brecciform interval for distances that may extend up to a hundred metres or more.

Rheoplastic structures. During the course of the present investigation a wide variety of rheoplastic structures have been found on the cavity walls of eroded silt injection features in sandstone of the Boss Point Formation. In fact, most sedimentary structures commonly found on the bedding soles of flysch and greywackes have now also been documented from moulded silt injection surfaces during the course of the present study. As used here, rheoplasts form an heterogeneous group of structures that are morphologically identical to many of the sole markings as described for instance by Dzulynski and Sanders (1962, Pettijohn and Potter (1964), Dzulynski and Walton (1965) and others. They include structures resembling common flute, groove and load casts, terraced flute casts, polygonal markings, crescentric scour marks, frondescent markings and skip marks. Twisted, corkscrew or helical forms are widely present. These rheoplastic structures range from a few to approximately twenty centimetres in length. The relatively large scale flute-like rheoplasts tend to be confined to the moulded surfaces of silt injection lenses and diapirs, whereas the smaller and less distinct forms more commonly occur on the surfaces of the smaller sized pods and lumps.

The following descriptions and photographs represent some of the structures and features present in the Boss Point Formation attributed here to liquefaction, intrastratal flow and sediment injection.

A nest of small flute-like rheoplasts with conical and linguiform shapes on the wall of an injection cavity from which the silt has been eroded is shown in Figure 9. The same structures are displayed in greater detail in Figure 10. The wall of the silt injection cavity on which the oriented rheoplasts occur is approximately 40° discordant to bedding (dip 80° SE). Top of strata face east (right on Fig. 9) and restoration for tilt would result in the original orientation of the rheoplasts to be inclined upward on the lower injection surface. Their position and orientation is difficult to perceive as resulting from current scour but is quite compatible with the concept of silt diapirism and rheoplasis as a post-depositional process.

Figures 11, 12 and 13 show examples of rheoplastic structures resembling common flute and load casts, skip marks and transverse scour casts on injection surfaces that are sub-parallel to bedding (Figures 11 and 12) and discordant to bedding (Figure 13). The siltstone has been removed by weathering and the structures are left as positive surface markings on the sandstone. Local directions of intrastratal flow can be interpreted from the orientation of the rheoplasts, which may show linear, semi-circular and/or radial flow patterns within the confines of the individual injection mould (see also Fig. 16).

A segment of an injection lens that is in part concordant and in part discordant to bedding is displayed in Figure 14. Bedding dips 80° to the southeast (left on photograph). Small to medium size oriented and non-oriented rheoplasts occur as moulded structures at the siltstone-sandstone interface. Forms that can be recognized include twisted, subconical welts with a superimposed, lin-

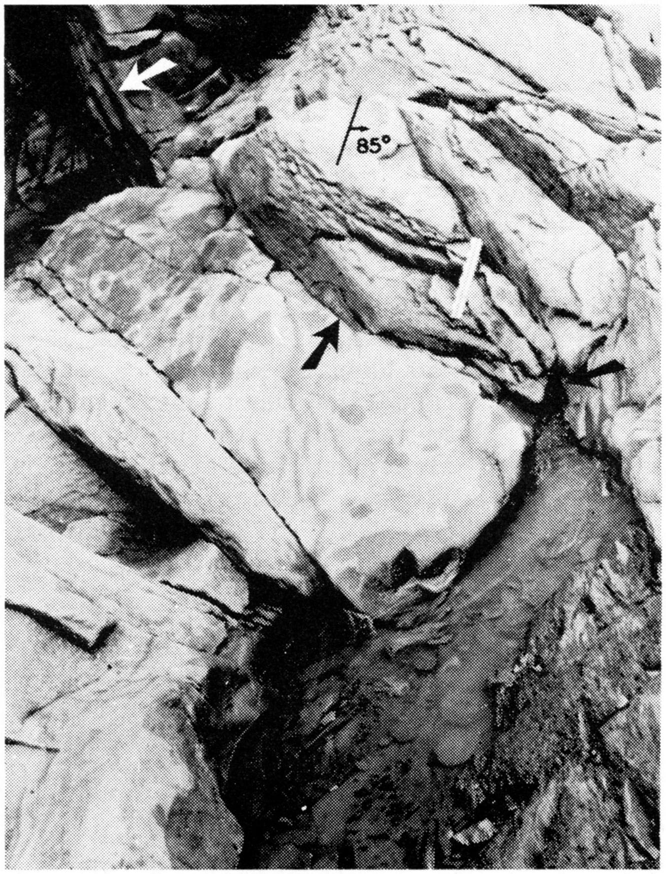
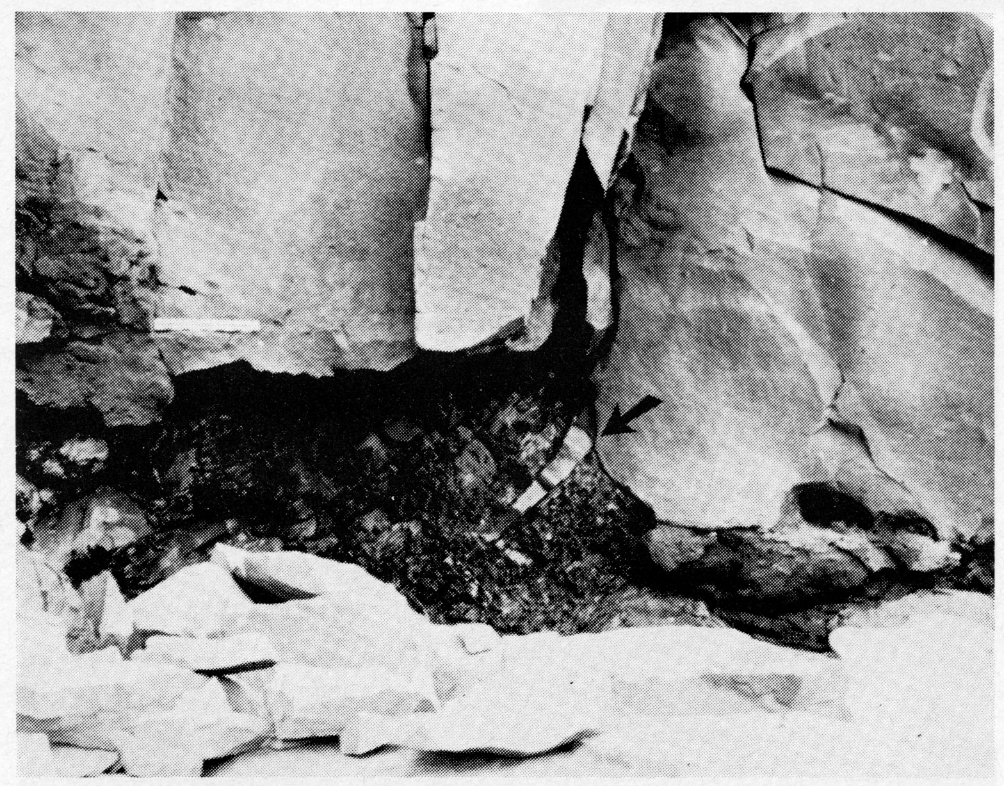


Figure 7 (left)
Bed-transgressive injection lens of dark grey siltstone in sandstone, terminating sharply into several fracture-like "separation surfaces" (marked by arrows) which extend diagonally across bedding into an adjoining injection lens (upper left corner of photograph marked by white arrow). The latter is the same injection lens as the one shown in Fig. 9. Bedding attitude as indicated by symbol. Cape Enrage, N.B. (30 cm ruler for scale).

Figure 8 (below)
Injection lens of dark grey siltstone in sandstone terminating abruptly into two fracture-like "separation surfaces" of which one extends parallel, and the other perpendicular to bedding. Note clastic injection (marked by arrow) of sandstone angled downwards parallel to the cleavage at the terminal end of the silt injection lens. Alma, N.B. (30 cm ruler for scale.



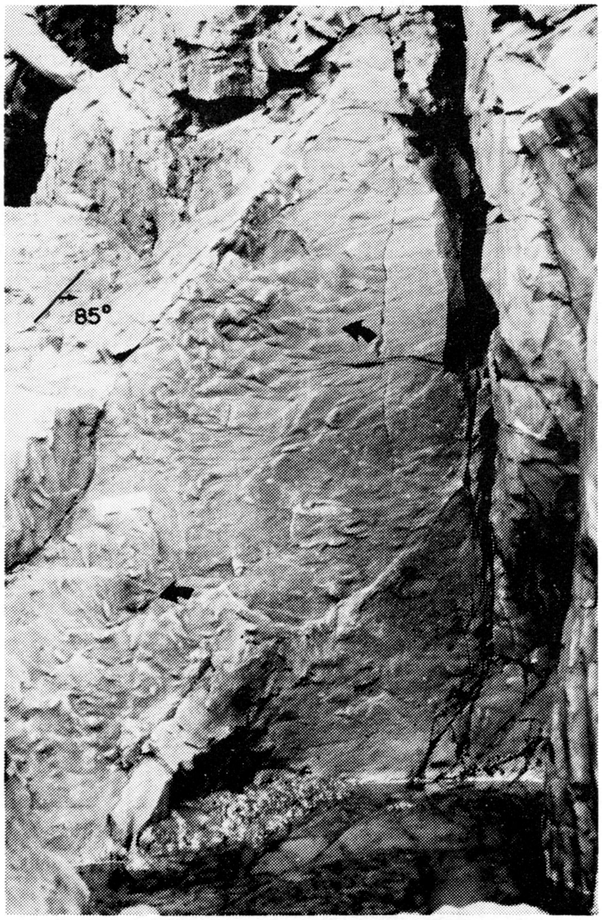
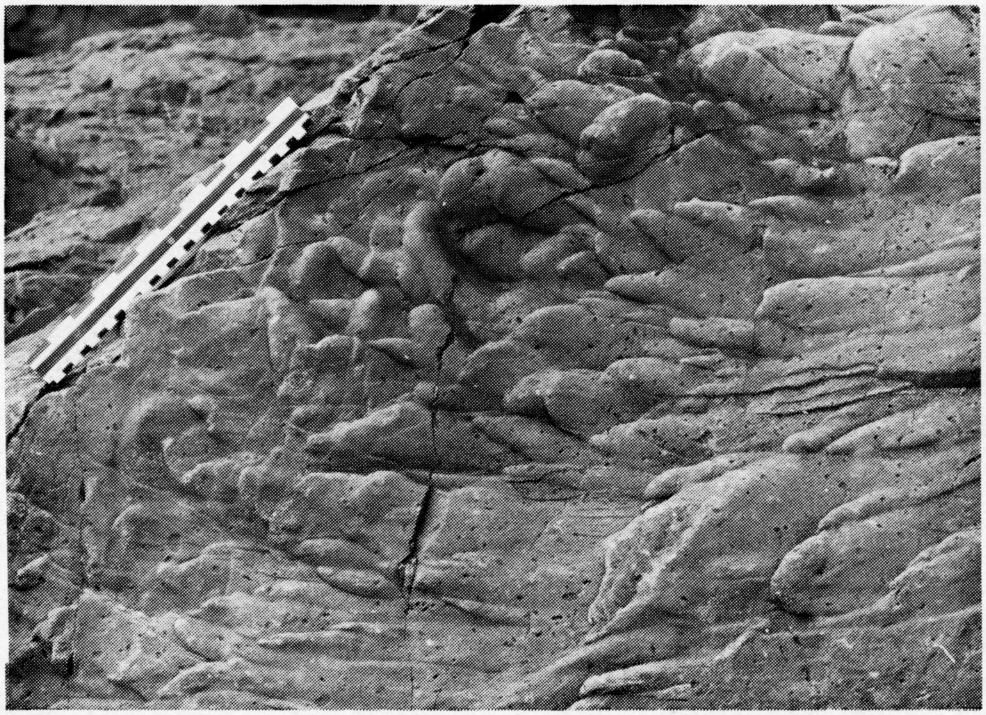


Figure 9 (left)
Cavity wall of a silt injection lens discordant to bedding showing a range of small flute-like rheoplastic structures. Note variation in the apparent "current" directions (see arrows). Bedding attitude as indicated by symbol. Cape Enrage, N.B. (19 cm book for scale).

Figure 10 (below)
Detail photograph of small flute-like rheoplastic structures on the cavity wall of the silt injection lens shown in Fig. 9. (30 cm ruler for scale).



guiform, satellite rheoplast resembling a single flute cast (Fig. 15).

Figure 16 shows a silt-lump cavity wall with oriented and non-oriented rheoplasts. The bedding is steeply inclined to the southeast (see bedding symbol). Restoration for tilt shows the wall of the silt-injection cavity to be the original concave roof of the structure. Concavity to a greater or lesser degree in the direction of superposition is not uncommon in these injection features and, together with rheoplasts on their concave surfaces, may be used as contributory evidence in determining the facing directions of stratigraphic sequences in which these structures occur. The combination of concavity and rheoplasis in Boss Point strata of southeastern New Brunswick, also demonstrates, incidently, that intrastratal flow and injection took place prior to tilting of the sequence. This is potentially an important observation, because it means that these processes are not likely to be related to tectonism but reflect stability readjustments and compaction during diagenesis.

The twisted, bulbous, and linguiform rheoplasts on the roof of the cavity show a crudely radial pattern suggesting that the silt flowed along its domed roof during liquefaction and injection. Lateral flow of silt along a fracture-like "separation surface" evidently extended for some distance parallel to bedding away from the silt injection lump as shown by the oriented flute-like rheoplasts (towards left on photograph, Fig. 16).

Less commonly present are rheoplastic structures resembling groove casts. Figure 17 shows such a structure on the vertical wall of an injection cavity perpendicular to bedding in conglomeratic sandstone. Bedding dips 40° to the south (right on photograph).

A combination of several types of rheoplastic structures on step-like injection surfaces that alternate between being parallel and steeply inclined to bedding is shown in Figure 18. Dip of the bedding is vertical. Top of the strata face to the southeast (right on photograph). The siltstone has been removed by weathering. Structures that can be recognized as positive markings on the original moulded, sand-silt interface include small flute casts, transverse ridges and a load cast. Transverse ridges occur quite commonly on the flanks and roofs of these type of injection structures and represent the casts of small clastic dikes.

DISCUSSION AND INTERPRETATION

Diapirism of clastic sediments can occur when rapid subsidence and sediment-loading prevent adequate dewatering of the sediments to keep pace with rapidly increasing lithostatic pressure from overlying strata (Boswell 1961, Carver 1968, Morgan *et al.* 1968, Paine 1968, Bruce 1973, Stel 1976). The chief characteristics of diapiric sediments, in addition to their fine grain size, are plasticity due to high pore-fluid pressures and low density relative to their surrounding sediments (Freeman 1968, Anketell *et al.* 1970, Hedberg 1974).

Structures resembling sole markings that occur on the moulded surfaces of the injection features are interpreted to have formed by rheoplasis, a post-depositional process of flow-moulding at the interface of liquefied silt and sand. If, as visualized here, moulding of the silt-sand interface took place under compaction of the sediments without intrastratal flow, simple unoriented rheoplastic structures (common load casts) would have formed. If, on the other hand, liquefaction and moulding was accompanied by intrastratal flow and/or diapirism of silt, oriented rheoplastic structures resembling conventional flute and groove casts would have formed at the sand-silt interface. The pointed, bulbous, elongated, twisted and flared shapes so common to oriented rheoplasts resembling flute casts are considered here, therefore, not to be erosional features, but to be stable rheodynamic forms offering least resistence to point loading under any one of the following three alternative conditions:

1) Point loading of liquefied flowing sand on a more or less stationary substrate of silt,
2) point loading of more or less stationary sand pockets on a mobile and flowing substrate of silt, or
3) point loading under conditions whereby both lithologies have flowed past one another at the sand-silt interface.

In keeping with this interpretation it may be assumed that the pointed ends of flute-like rheoplasts will be oriented "upcurrent" into the local or relative direction of liquefied intrastratal flow. As such, their orientation could be used in an analysis of post-depositional flow and stability readjustments during diagenesis, but they would have no significance in paleocurrent studies.

The twisted, corded appearance of some of the rheoplasts (Figures 14 and 15) appears to be primarily a surface rather than an internal feature. Close examination of these twisted forms usually reveals delicately infolded and tucked-in shale wisps, locally trailing thin ingression lines and plumes of silty material.

These small scale features closely resemble the flame structures described by Kelling and Walton (1957), Friend (1965) and others; hydroplastic intrusions of Lowe (1975); shale intrusions of McBride (1962) and Cook and Johnson (1970); the sharp recumbent anticlines at the base of flow casts of Prentice (1956); flow casts of Shrock (1948); and load-waves of Sullwold (1959). These various forms are generally ascribed to loading and simultaneous injection of hydroplastic silt in sand (Shrock 1948), resulting from reverse density stratification of the sediments (Anketell *et al.* 1970). Allen (1960, p. 197) observed irregular wafers of shale in the Mam Tor Sandstone of Derbyshire, England and thought them the result of compaction from an almost soupy state. Kuenen and Menard (1952) attributed similar but experimentally produced structures to current drag on the watery clay film at the top of the underlying silty bed and local settling and squeezing by the rapid accumulation of overburden on the highly mobile foundation.

The above interpretations differ little from the present one, namely that these small-scale structures represent local injections and ingress of watery silt in sand during compaction and dewatering across the silt-sand interface at the time of liquefaction of the sediments.

Sub-parallel, locally discontinuous striations visible on the twisted and knotted rheoplasts of Figures 14 and 15 display a corkscrew or helical pattern. Similar striations also occur on flute casts where they are interpreted to have been left by the scouring

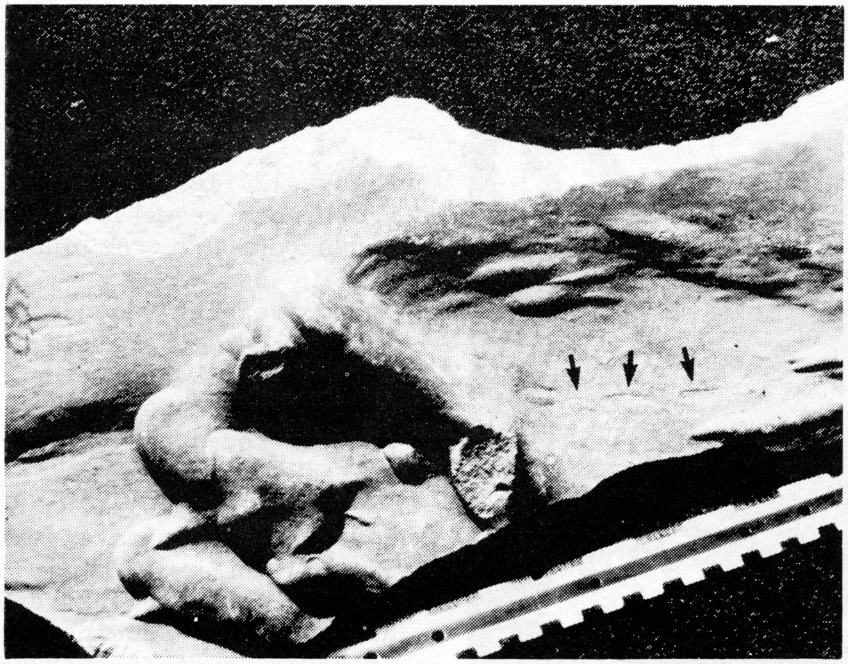


Figure 11 — Irregularly shaped and elongated rheoplasts resembling load and flute casts. Note the slightly curved pattern in the apparent flow direction to the right of load-cast-like rheoplast, and the three isolated oval-shaped markings resembling skip marks (marked by arrows). Cape Maringouin, N.B. (30 cm ruler for scale).

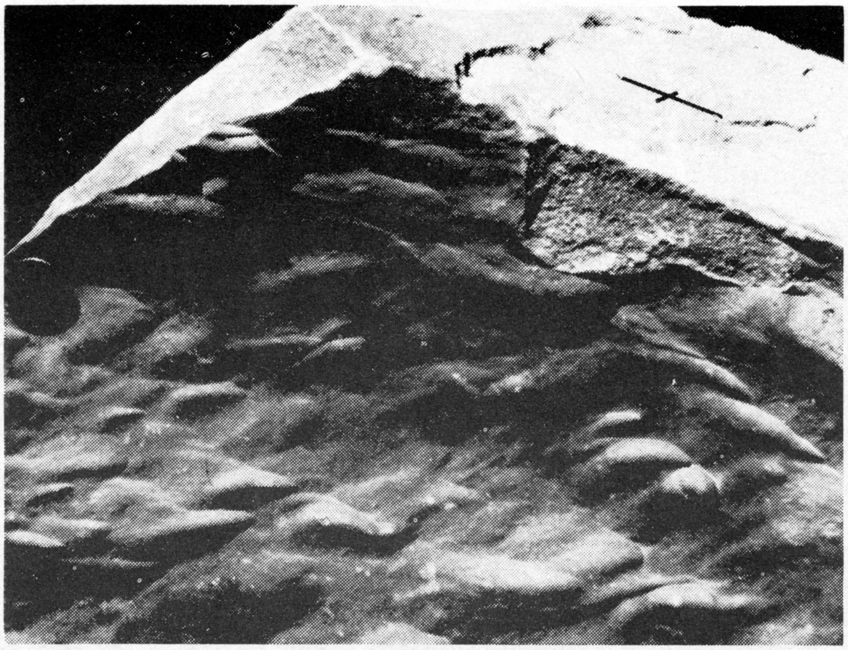
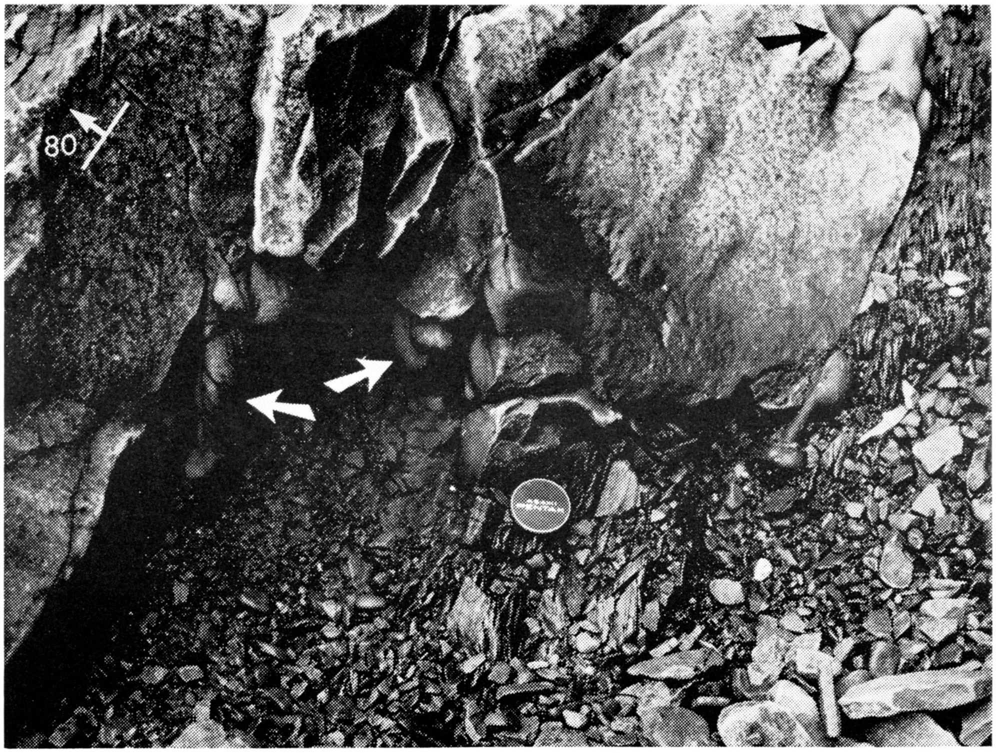


Figure 12 — Elongated rheoplasts resembling asymmetrical flute cast merging into diagonal structures (compare for instance with Fig. 35 in Dzulynski and Walton 1965) on silt injection surface discordant to bedding. Bedding attitude as indicated by symbol. Cape Maringouin, N.B. (23 mm coin for scale).

Figure 13 (left)
Rheoplasts resembling transverse scour casts (compare for instance with Fig. 91A in Dzulynski and Walton 1965) on two converging silt injection surfaces both of which are discordant to bedding. Bedding attitude as indicated by symbol. Cape Maringouin, N.B. (23 mm coin for scale).

Figure 14 (below)
"Twisted" rheoplasts (marked by white arrows) on a silt injection surface that is in part concordant and in part discordant to bedding. Note the smooth "moulded" surface (marked by arrow) in the upper right corner of photograph. Bedding attitude as indicated by symbol. Cape Enrage, N.B. (5 cm camera lens-cap for scale).



action of local helical flow (Bridges 1972) or vortices (Rücklin 1938). They have been used to trace the path of scouring currents (Rücklin 1938 and others) and, as such, were cited as proof that the markings are the result of current erosion (Kuenen 1957). Present work shows that similar grooves on rheoplasts occur on injection surfaces where siltstone is in sharp contact with relatively poorly sorted, coarse or very coarse sandstone. Consequently, the striations on rheoplasts are not interpreted as the result of current action, but as markings left by differential intrastratal flow and loading of a coarse sand on a viscous substrate of hydroplastic silt during rheoplasis.

The exact nature and origin of the fracture-like "separation suffaces" that interconnect the various silt injection features within brecciform intervals is still unclear. The common occurrence of small siltstone flakes and thin surface films of siltstone in addition to the rare presence of flute casts along their extent (Fig. 16) suggest that liquified silt may once have flowed along them. They may represent the original pathways of flowing silt at the time of liquefaction and injection. Alternatively they may be the remains of siltstone horizons that have flowed laterally following their collapse in response to liquefaction and loading under shear or they may conceivably be the result of both.

That flowing mud could have played some role in the formation of flute casts is not an entirely new concept. Some degree of post depositional flow is presumably necessary to account for the presence of transitional forms between the load casts and load-casted current structures described by Kelling and Walton (1957), Kuenen (1957) and Birkenmajer (1958). Flame structures are small-scale injection features of silt in sand (Kelling and Walton 1957) and load casts (flow casts of Shrock 1948) can be directly attributed to flow moulding of water saturated sand in hydroplastic mud or organic sediment beneath (Shrock 1948, p. 156). Birkenmajer (1958) and Prentice (1960) recognized a component of horizontal as well as vertical flow in the formation of flute casts. Prentice used the term "flow cast" for a sole mark resulting from a combination of load casting and current oriented flow and cited the bulbous "nose" of many flute casts as evidence that an element of undercutting by flow is evident in these structures which therefore are neither pure load casts nor pure flute casts. The combined effects of flow and loading were not viewed as strictly post-depositional processes, however, as is suggested here, but instead were interpreted as either the syndepositional interaction of currents and slope effects, or the effects of current-drag on the overlying sediments (Prentice 1960, Stanley 1965), or alternatively to represent flowage of a mobile hydroplastic sand in a downslope direction (Birkenmajer 1958).

Over the past several decades a voluminous literature has grown up on the origin of turbidites in which the interpretation of flute casts and related sole structures play an important role. This point has been previously emphasized by Allen (1968) who cautioned that flute casts are also widely formed in sediments which can be explained otherwise than by the action of turbidity currents. Allen went on to point out that, unfortunately, the effort put into recording the distribution and characteristics of flute casts far exceeds the effort in improving our understanding of how the original structures have formed and what they mean in terms of sedimentary conditions (Allen 1968, p. 4).

Allen's remarks made more than a decade ago still apply to a large extent today. Until the present study there appears to have been no serious challenge or alternative interpretation offered for the formation of flute casts and related structures beyond the presumed hydraulic action of turbidity currents; whether these structures are found in marine flysch, deltaic strata, glacial or fluvio-lacustrine beds. A notable exception is perhaps the discovery by Friedman and Sanders (1974) of "setulfs" (flutes spelled backwards) which occur as positive relief bedforms that resemble counterparts of flutes and grooves sculptured in mud of a modern tidal flat at Abu Dhabi. They did not offer an explanation for the origin of these structures but pointed out that setulfs (like the rheoplasts on moulded silt injection surfaces) introduce complications into the conventional environmental interpretation of sediments based on sole markings.

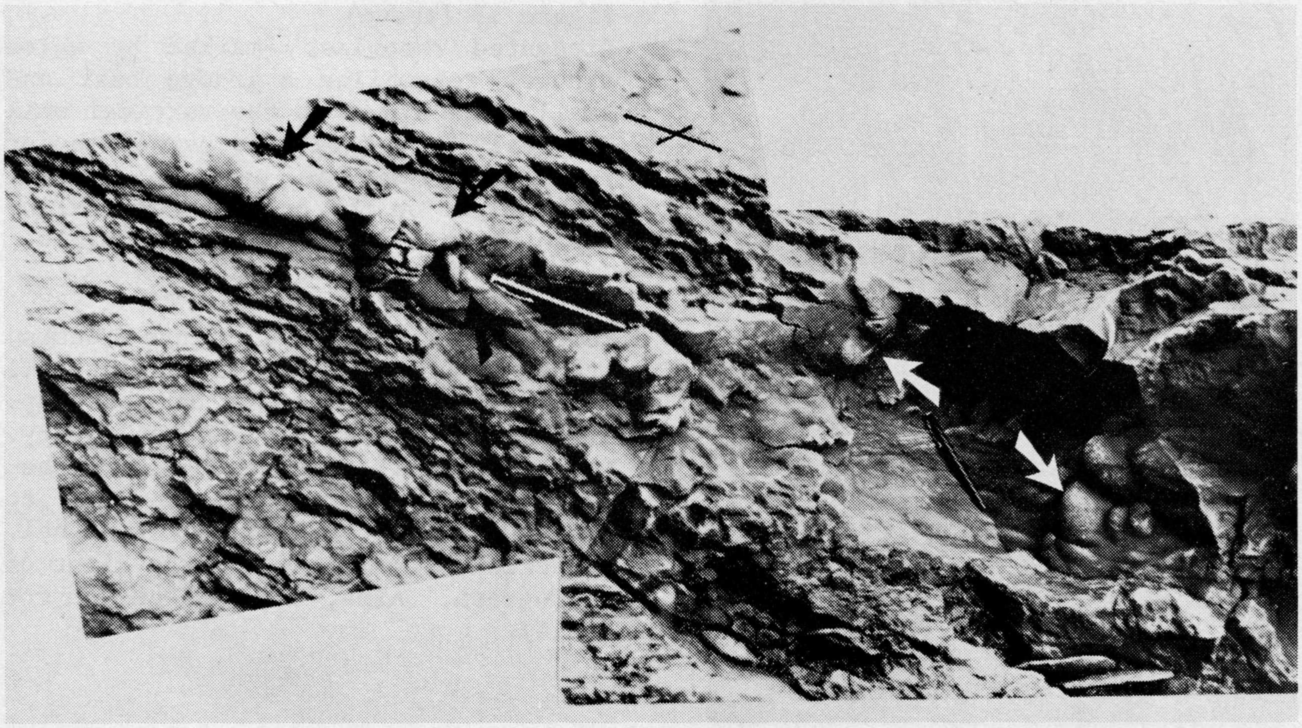
Although it is not suggested that rheoplasis should be favoured instead of turbidity-current scour in the formation of all flute casts and related directional structures, results from the present studies indicate that no longer can one single mechanism of scour in their formation be accepted either. Where the surface on which sole-mark-like structures occur is discordant to bedding such as on walls of clastic dikes (Dott 1966, and this report), on layer-plane surfaces within clastic dikes (Peterson 1968), or on diapiric silt-injection surfaces (this paper), some form of post-depositional flow-moulding or rheoplasis must presumably have taken place to account for their presence. The question arises then whether or not rheoplastic structures are restricted to discordant surfaces only, or whether they can also occur on the underside of bedding planes. The answer is probably in the affirmative as, during the present study, rheoplastic structures have been found on surfaces that are parallel as well as discordant to bedding. The possibility must be considered, therefore, that rheoplasis could take place at any sedimentary interface across which the physical properties of the sediments, in terms of cohesion, density and viscosity, could lead to instability and differential behaviour under shear. As there seems to be no reason to exclude these conditions, and hence the process of rheoplasis, from normal bedding soles, in particular those with inverse density gradients that are prone to liquefaction (i.e. loosely packed fluid saturated sediments), it may be assumed that rheoplasts and conventional sole markings can occur side by side, on either the same, alternate or different bedding soles. Taking into consideration how similar both groups of structures are in their general appearance, the ability to determine whether turbidity-current scour or rheoplasis has been operative in their formation will be a major challenge for the immediate future.

SUMMARY AND CONCLUSIONS

Evidence for post-depositional liquefaction, intrastratal flow and diapirism in Boss Point strata is contained within brecciform intervals comprising concentrations of detached siltstone flakes, pods and lumps, in addition to

Figure 15 (left)
Detailed photograph of "twisted" rheoplasts shown in Fig. 14. (23 mm coin for scale).

Figure 16 (below)
Rheoplasts resembling flute and load casts (marked by white arrows) on the roof of a silt injection cavity; noteworthy is the semi-radial pattern of rheoplast orientation and the well-developed twisted rheoplastic forms along the "separation surface" extending parallel to bedding to the left of the silt lump cavity (marked by arrows). Cape Enrage, N.B. (14 cm pens for scale)



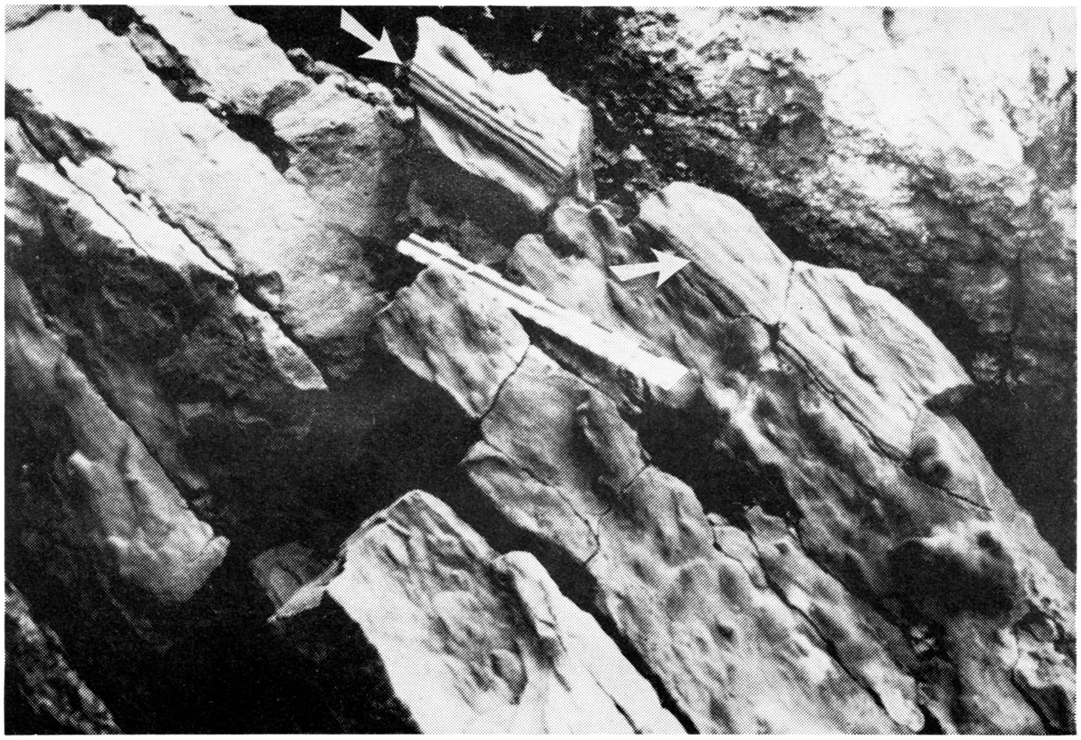


Figure 17 (above)
Elongated rheoplast (marked by white arrows) resembling a groove cast and small flute casts on the vertical wall of a silt injection lens perpendicular to bedding. Dip of bedding towards lower right on photograph. Cape Maringouin, N.B. (30 cm ruler for scale).

Figure 18 (left)
Rheoplasts resembling flute casts, transverse ridges and a load cast (all marked by white arrows) on the step-like flank of a silt injection cavity. The cavity wall alternates between being steeply inclined and parallel to bedding. Dip of bedding is vertical. Direction of younging towards right on photograph. Alma, N.B. (5 cm bar for scale).

diapirs of siltstone in sandstone and injection lenses. Sedimentary structures resembling flute, load and groove casts commonly occur on the concordant and discordant surfaces of these silt injection features. The term rheoplast has been introduced here to denote these structures which, though closely resembling common sole markings, have not formed by turbidity flow or analogous processes of scour and sediment infilling but as a result of rheoplasis at the sedimentary interface. Oriented rheoplasts, resembling flute and groove casts are interpreted as rheodynamic structures that have formed by the action of sediment-loading during liquefaction and differential intrastratal flow. On the other hand, non-oriented conventional rheoplasts (load casts) have formed as a result of loading without intrastratal flow.

Helical striation patterns on some rheoplasts reflect the motion of intrastratal flow around load-pocket obstructions. They are the result of furrowing by coarse sand particles on the soft hydroplastic silt during rheoplasis at the silt-sand interface.

Although rheoplasis on discordant surfaces of the Boss Point Formation has been emphasized, it is erroneous to assume that this process could not also occur on bedding soles in any sedimentary sequence with inverse density gradients and anomalously high pore-fluid pressures. This means that considering their general similarity in appearance, it will be difficult to differentiate between flute and groove casts formed by turbidity flow and similar rheoplasts formed by sediment interflow. In the absence of critical data useful in their differentiation, it is strongly recommended that in order to avoid errors in sedimentary interpretations, the process of rheoplasis as well as turbidity flow be carefully considered wherever flute casts and associated sole markings are encountered.

ACKNOWLEDGEMENTS

We wish to thank J. Lajoie, D.J.W. Piper, D.J.C. Laming and A. Landva for critically reviewing the original manuscript and D.J.C. Laming, E.R.W. Neale, E.K. Walton and B.J. Bluck for reviewing the revised version. Their constructive criticisms helped greatly to improve the original versions. The authors, however, are solely responsible for the opinions expressed herein. We are grateful to Ms. S. Townsend for typing the final copy and to W. Morris and R. McCulloch for assistance in the preparation of the illustrations. M. Mills of the Classics Department, University of New Brunswick, suggested the term "rheoplasis". Financial support was provided by a National Research Council of Canada operating grant (No. A9033) to H.W. van de Poll.

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