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Secondary sedimentary structures associated with fluidization zones in Permo-Carboniferous redbeds of Prince Edward Island, Canada

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Internal parting surfaces associated with fluidization zones up to 20 m in length, occurring in the alluvial redbeds of Prince Edward Island contain secondary sedimentary structures resembling sole marks. These are described and their origin considered in terms of physical diagenesis.

Rapidly escaping pore water in conjunction with load deformation within fluidized zones during dewatering and compaction of the redbeds are thought to have been the principal processes involved in the formation of these structures.

On rencontre dans les lits rouges alluviaux de l'Ile du Prince-Edouard des plans internes de rupture qui sont associés à des zones de fluidité mesurant jusqu'à 20 m de long et qui font voir sur leur substratum, des empreintes ressemblant à des structures sédimentaires secondaires. Ces structures sont décrites et on envisage une origine due à la diagenèse physique.

L'éjection rapide des eaux interstitielles accompagnée d'une déformation de charge au sein des zones de fluidité pendant la déshydratation et le tassement des lits rouges expliqueraient en grande partie la formation de ces structures.

[Traduit par le journal]

INTRODUCTION

In this paper we describe and briefly discuss the possible origin of a range of unusual secondary sedimentary structures that occur in the redbeds of Prince Edward Island. They comprise dish and pillar structures, intrastratal surfaces and intrastratal surface structures resembling sole marks, all of which are interpreted to reflect physical diagenesis of the redbeds.

Prince Edward Island is situated in the Gulf of St. Lawrence, eastern Canada (Fig. 1) and is underlain by gently inclined redbeds of Permo-Carboniferous age (Pictou Group, Poll 1981). The redbeds were deposited on a broad, sparsely vegetated alluvial plain, which at the time extended eastward along the southeastern flank of the Appalachian orogen. The lithologies include conglomerate, coarse to fine arkosic wacke, siltstone and minor non-marine limestone. Trough crossbedding, ripple foreset laminations and parting lineation are the most common primary sedimentary structures.

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PHYSICAL DIAGENESIS OF THE PRINCE EDWARD ISLAND REDBEDS

As used here physical diagenesis embraces all post depositional, pre-metamorphic processes that cause physical modification of sediments during compaction. Conditions favouring physical diagenesis include high initial porosity, excessive pore-fluid pressures, rapid sediment accumulation, and unstable density gradients. The principal processes involved are fluidization, liquefaction, elutriation, loading and sediment intrusion.

The secondary sedimentary structures described in this paper are attributed to localized fluidization and penecontemporaneous load deformation of the redbeds at the time of compaction. They may be grouped as follows:

Host Structures:

	Host Structures:	Associated features:
Fluidization zones	Fluidization columns (≈ perpendicular to bedding)	dish structures
	Fluidization sheets (≈ parallel to bedding)	intrastratal surfaces and intrastratal surface structures resembling sole marks

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Fluidization Zones

Fluidization zones in the redbeds of Prince Edward Island comprise massive, featureless, homogeneous sediment. Two types can be recognized: 1) consisting of relatively small, (1 cm diameter) more or less vertical, pipe-like structures and 2) sheet-like zones 50 cm or more in thickness, that extend parallel to and across bedding for 20 m or more. Because of the tabular nature of the latter it is proposed here to refer to these structures as fluidization sheets irrespective of size. In contrast, pipe-like fluidization zones may be referred to as fluidization columns.

Fluidization columns of varying diameter have been described from a range of sedimentary environments (see Dietrich 1952, Gabelman 1955, Allen 1961). They can vary from small columnar structures called pillars (Lowe and LoPiccolo 1974) to the large cylindrical structures up to 3 m in diameter described by Hawley and Hart (1934).

The only fluidization columns currently recognized in the redbeds of Prince Edward Island are relatively small (<1 cm diameter) features, approximately perpendicular to bedding, occurring in association with rare dish structures. These columns occur in fine silty sand and have an internal structure that is steeply discordant to bedding (Fig. 2). The sediment within the columns is slightly darker red than the surrounding sediment. This is probably due to the concentration of fines by the filtration of colloidal material from migrating interstitial fluids.

Fluidization sheets are more common in these redbeds than fluidization columns. They are quite widespread and can range from the relatively thin zones (<1 cm) of homogeneous sediment below dish structures (Fig. 2) to intervals, up to 50 cm thick, of featureless sediment that extend parallel to, and across bedding for 20 m or more (Fig. 3). The featureless appearance of fluidization sheets within plane laminated or cross-bedded strata suggests destruction of the primary sedimentary fabric by fluidization during dewatering and compaction.

The presence of one or more separation surfaces characterize the fluidization sheets: when small (<5 cm diameter) these surfaces are called dish structures (Lowe and LoPiccolo, 1974). For the separation surfaces associated with the larger fluidization sheets, the term "intrastratal surface" is newly introduced here.

Dish structures are relatively uncommon in the redbeds and where encountered, appear restricted to fine-grained sandy siltstone. They are flat or convex downward ovoid structures 1-5 cm in diameter (Fig. 4). In vertical section, individual dish structures are separated by zones of lighter coloured, somewhat coarser grained sediment exhibiting a more open framework (Fig. 2). These probably represent the more or less horizontal fluidization sheets below individual dish structures as defined by Lowe and LoPiccolo (1974).

Horizontal sections through dish and pillar structures reveal a convoluted pattern (Fig. 5) reflecting differential vertical movement between subsiding masses of grain supported sediment and rising columns of fluidized sediment. The importance of internal loading in the formation of dish structures was previously recognized by Lowe (1975) who suggested that discrete masses of grain supported sand within fluidized zones slowly subside to replace the underlying sediment removed by fluidization. These masses, according to Lowe (1975, p. 180), "are typically defined by the presence of dish structures along their lower margins".

Intrastratal Surfaces

The term "intrastratal surface" is introduced here to denote single and multiple, commonly bifurcating fracture-like separation planes that lie at the base of, or within, fluidization sheets (Figs. 6, 7, 8). Where intrastratal surfaces are closely spaced, individual fluidization sheets merge and then strata take on a massive, homogeneous

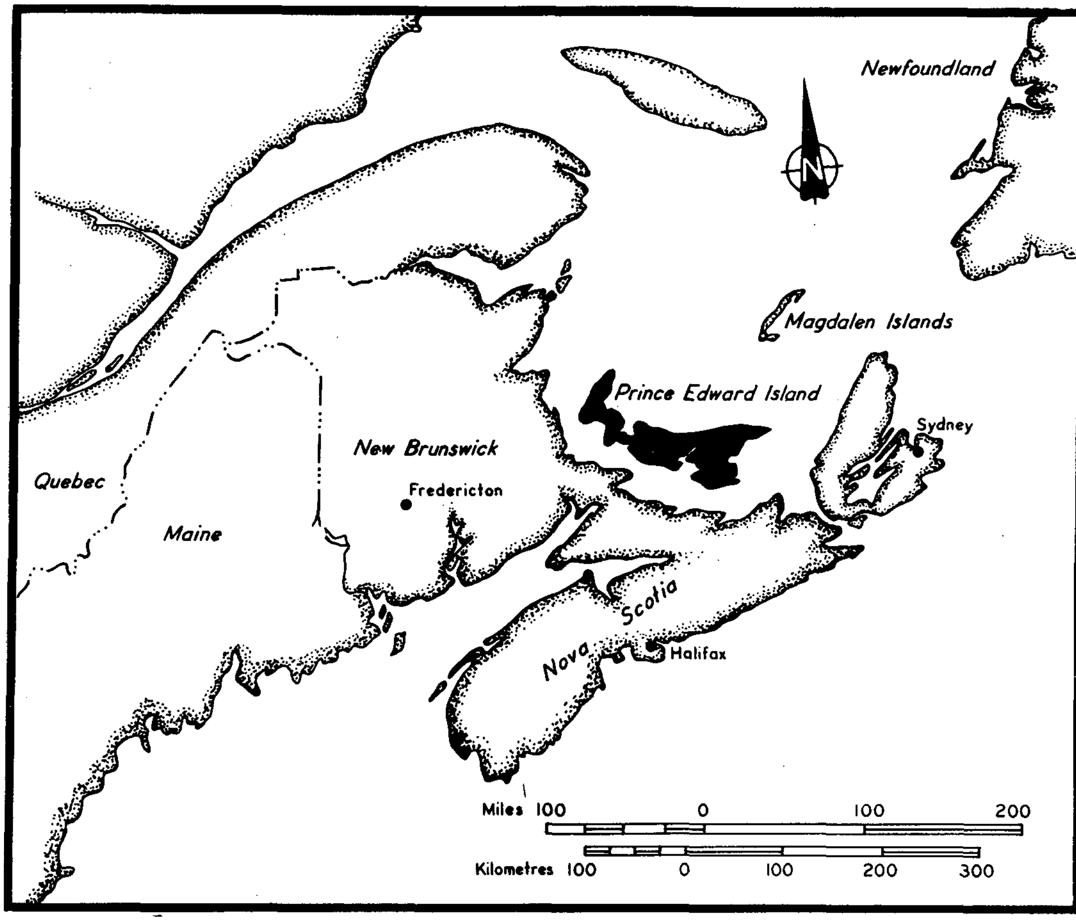


Fig. 1 - Location map. Prince Edward Island.

appearance in which original bedding is no longer discernable.

Intrastratal surfaces and associated fluidization sheets can usually be seen to emanate from mud intrusions (Fig. 9). Isolated lenses, lumps and flakes of red mudstone commonly occur along intrastratal surfaces and a thin surface-film of red mudstone may also be present. Intrastratal surfaces usually have a scalloped appearance and may locally be characterized by a series of shallow adjoining depressions, separated by sharply defined ridges (Fig. 10). Parallel striations, probably representing intrastratal flow markings, are common on these surfaces as well.

The various forms taken by intrastratal surfaces, when seen in section, are schematically shown in Figure 11.

Intrastratal Surface Structures

Intrastratal surface structures resembling sole marks are common on intrastratal surfaces (Figs. 12, 13, 14, 15). They are secondary features that occur at the sandstone-sandstone interfaces of internal parting surfaces.

Intrastratal surface structures are always convex downward with the positive counterparts always on the upper surface. Their close association with fluidization sheets and the discordant nature of many of the intrastratal surfaces, indicate a post-depositional origin.

The flute-like structures found on intrastratal surfaces are extremely varied in shape and dimensions. They range from relatively narrow, elongate features up to 50 cm long, 10 cm wide and 2-3 cm high to more equant structures about 20-30 cm long, 10-15 cm wide and 2-3 cm high. Conical, linguiform, comet and bulbous forms are present. They may have smooth surfaces or be ter-

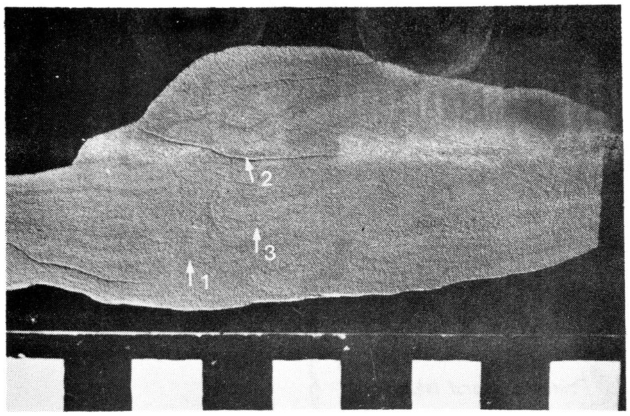
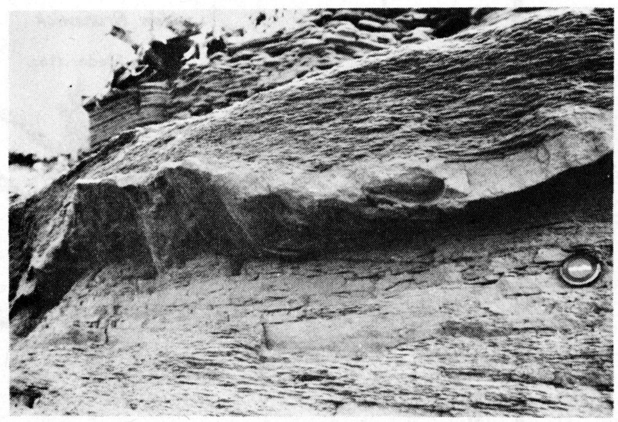


Fig. 2 (left)
Vertical section through dish and pillar structures 1) pillar structure, 2) dish structure, 3) horizontal fluidization sheet. Prince Edward Island Redbeds. Cavendish Capes, P.E.I. Centimetre bar for scale.

Fig. 3 (right)
Fluidization sheet comprising massive featureless sandstone in thinly laminated (?) sandstone. Prince Edward Island Redbeds, Point Prim, P.E.I. 5 cm lense cap for scale.



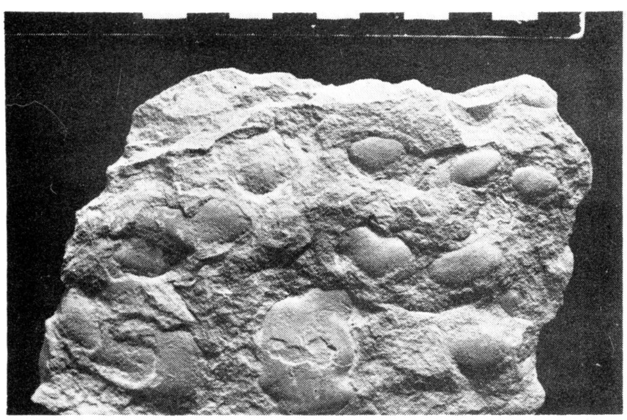
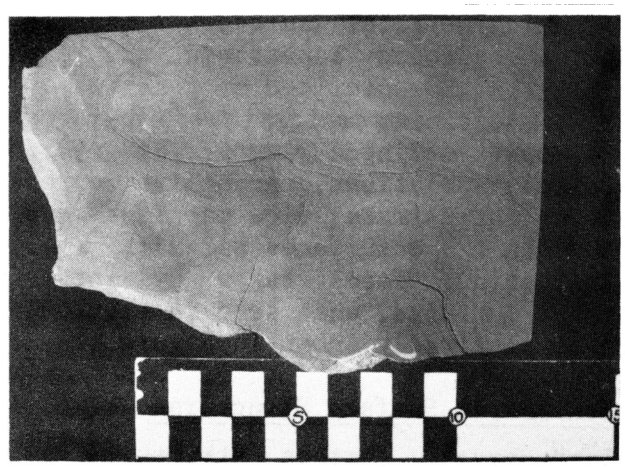


Fig. 4 (left)
Positive (underside) impressions of dish structures. Prince Edward Island Redbeds, Cavendish Capes, P.E.I. Centimetre bar for scale.

Fig. 5 (right)
Horizontal section through dish and pillar structures revealing a convoluted pattern. Prince Edward Island Redbeds, Cavendish Capes, P.E.I. Centimetre bar for scale.



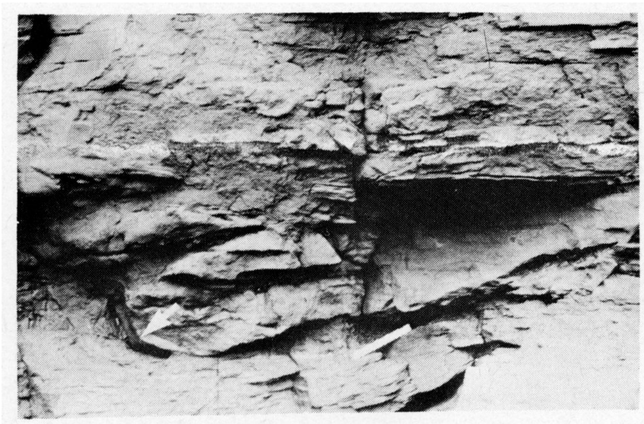
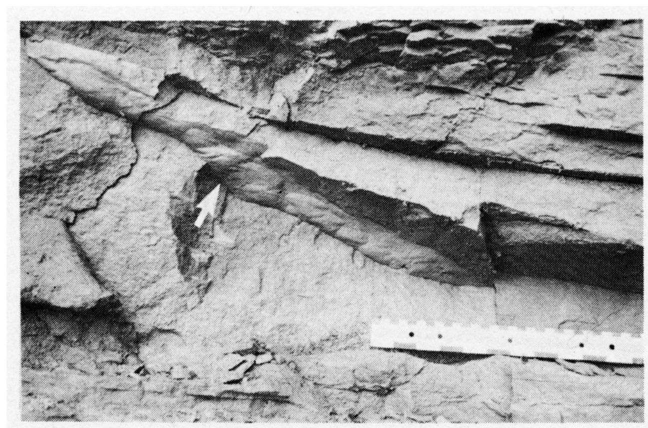


Fig. 6 (left)
Section view of single discordant intrastratal surface in horizontally bedded strata. Prince Edward Island Redbeds, Guernsey Cove, P.E.I. 30 cm ruler for scale.

Fig. 7 (right)
Detailed section view of single intrastratal surface with intrastratal surface structures (see arrow) within massive featureless fluidized sandstone (fluidization sheet). Prince Edward Island Redbeds, Cape Turner, P.E.I. 30 cm ruler for scale.



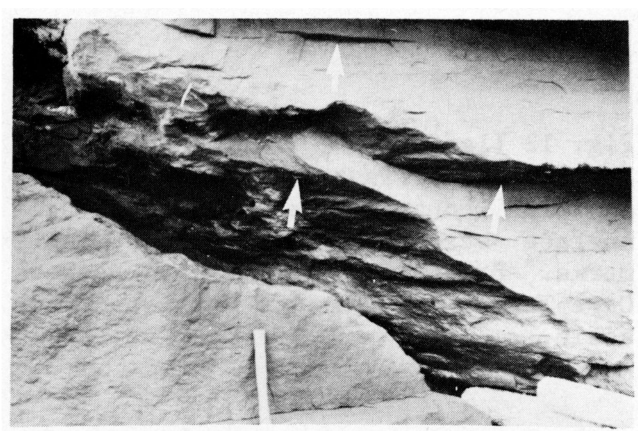


Fig. 8 (left)
Section view of multiple, bifurcating, discordant and concordant intrastratal surfaces (see arrows) in horizontally bedded strata. Prince Edward Island Redbeds, Rock Barra, P.E.I. 34 cm hammer for scale.

Fig. 9 (right)
Section view of intrastratal surfaces (see arrows) extending from mud intrusions. Prince Edward Island Redbeds, White Sands, P.E.I. 30 cm ruler for scale.

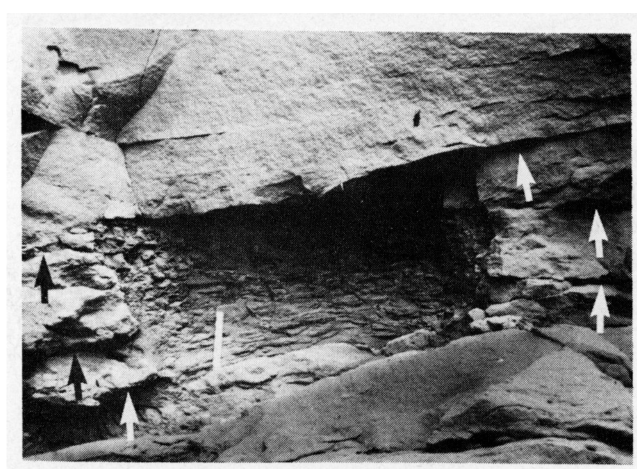
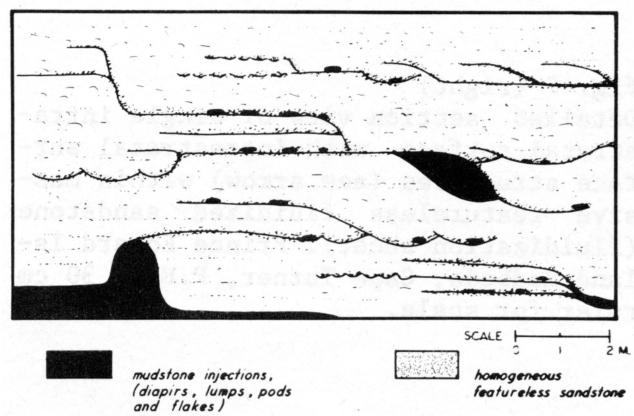


Fig. 10 (left)
Surface view of intrastratal surface showing sharply defined ridges between adjoining shallow depressions. Note the striations resembling flow markings. Prince Edward Island Redbeds, Point Prim, P.E.I. 30 cm ruler for scale.

Fig. 11 (right)
Diagrammatic representation showing straight, curved, bifurcating and rejoining intrastratal surfaces as they may appear in outcrop section.



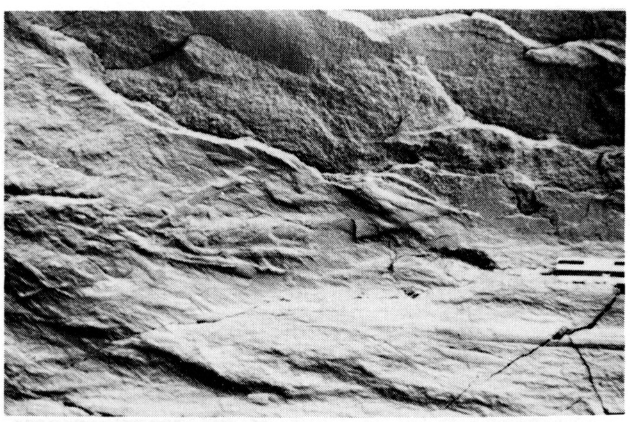


Fig. 12 (left)
Discordant intrastratal surface with positive counterparts of intrastratal surface structures resembling sole marks. Prince Edward Island Redbeds Cape Turner, P.E.I. 2.5 inch ruler for scale.

Fig. 13 (right)
Intrastratal surface with negative counterparts of intrastratal surface structures resembling grooves. Prince Edward Island Redbeds, Point Prim, P.E.I. 30 cm ruler for scale.

raced. Symmetrical as well as curvilinear shapes have been observed.

In general flute-like intrastratal surface structures tend to be less pronounced than flutes occurring on bedding soles (c.f. Pettijohn and Potter 1964) or the flute-like rheoplastic structures on silt injection surfaces described by Poll and Patel (1981). Helical forms and patterns are also present (Fig. 16). It is not uncommon to find closely spaced parallel striations resembling flow markings on intrastratal surfaces and the associated intrastratal surface structures. These striation patterns can be quite varied in their orientations and may be oblique or even transverse to the intrastratal surface structures (Figs. 10, 16).

INTERPRETATION

Fluidization columns and sheets and associated secondary sedimentary structures in the redbeds of Prince Edward Island are thought to have formed during rapid expulsion of pore water along locally fluidized zones or pathways. Periodically accelerated dewatering, causing localized fluidization of the sediment, may have been a spontaneous phenomenon, or be the result of induced shear produced by earthquake motion. During periods of rapid interstitial flow, variations in permeability may have forced fluids to be deflected laterally along well-defined pathways. Impeded dewatering caused a local rise in pore-fluid pressure and the sediment was forced to dilate to accommodate the increased volume of interstitial fluid entering from subadjacent more compactable sediment.

The degree of intrastratal dilation of the sediments along fluidized zones depended, to a large extent, on the lithostatic pressure exerted by the overlying sediment. It may have been accomplished either by lifting the overlying sedimentary column or by forceful compaction of the roof strata (Lowe 1975).

Results from laboratory investigations by Lowe (1975) supported by our own tank observations on sediment behaviour under bouyant pressures (unpublished data), indicates that lifting of sediments above a relatively impervious layer can occur where the local hydrostatic pressure is in excess of the lithostatic pressure. In our tank experiments a layer of water formed within the sedimentary column beneath a relatively impervious layer and raised the overlying sediment by about 2.5 cm (Fig. 17). Eventually the impervious layer ruptured and the water forced its way explosively upward fluidizing the overlying sediments along several fluidization columns at which time the elevated layer of sediment collapsed onto the original surface.

A similar sequence of events operating at varying scales could acount for both the dish and the pillar structures as well as the much larger fluidization sheets containing intrastratal surfaces. Local variations in permeability could force rising pore fluids to migrate laterally along more or less horizontal, curved and/or discordant fluidized zones. Fluidization of the sediment would occur at the instant that the pore-fluid pressure exceeded compactional forces, and the sediment dilated to facilitate the passage of pore fluids. Intrastratal surfaces associated with these fluidization zones could represent the pathways along which rapid water-escape took place below relatively impervious layers. Flow velocities along the intrastratal surfaces were evidently sufficiently rapid to form flow markings, and to entrain sediment now seen trapped as a thin skin of red mud on the intrastratal surfaces.

The origin of intrastratal surface structures is not clear. The pointed or bulbous elongated, convex downward shapes of these structures does, however, suggest that the combined and simultaneous effects of loading and hydrodynamic shaping were important in their development. In general, load structures are most readily observed at the interface between strata with contrasting lithologies. They can also occur, however, within sedimentary

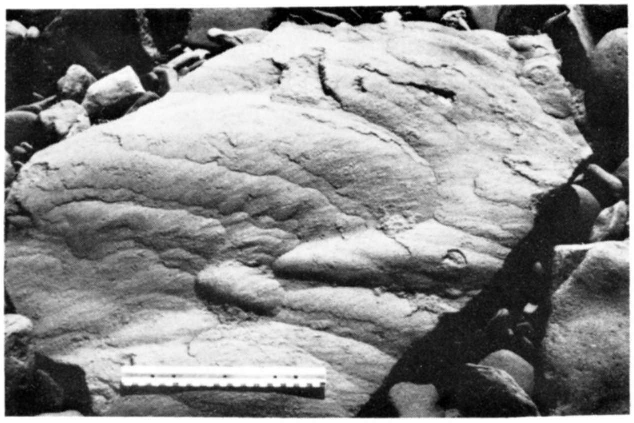


Fig. 14 (left)
Intrastratal surface showing positive counterpart of a flute-like intrastratal surface structure and well developed sets of parallel striations resembling flow markings. Prince Edward Island Redbeds, Cape Turner, P.E.I. 30 cm ruler for scale.

Fig. 15 (right)
Intrastratal surface comprising pits and elongated scours resembling negative counterparts of flute casts. Prince Edward Island Redbeds, Point Prim, P.E.I. 30 cm ruler for scale.

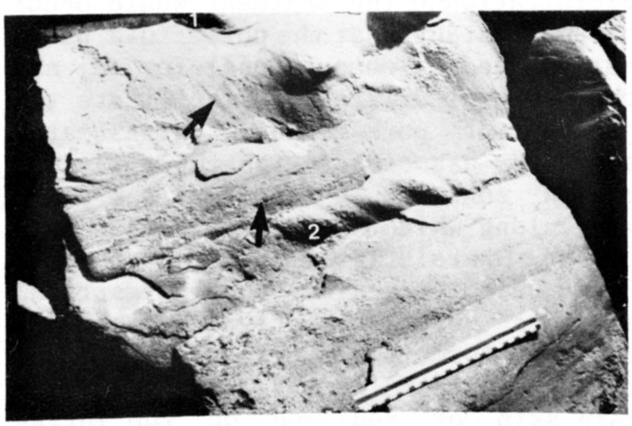
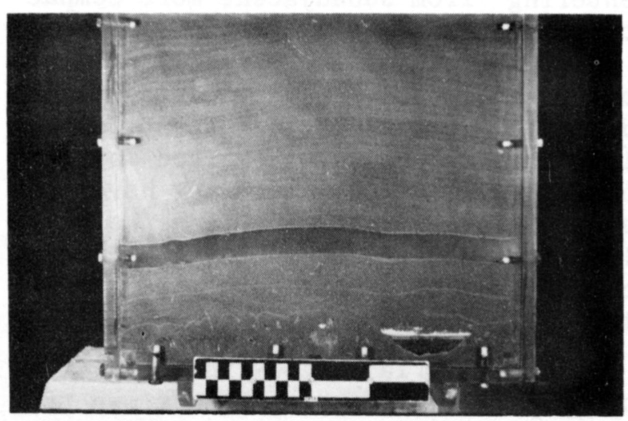


Fig. 16 (left)
Intrastratal surface showing positive counterparts of helical intrastratal surface structures (marker 1 and 2 see arrows) and parallel and transverse striations resembling flow markings. Prince Edward Island Redbeds, Howe Point, P.E.I. 30 cm ruler for scale.

Fig. 17 (right)
Side view of a plexiglass sedimentation tank. Tank experiment on dewatering and fluidization. Complete lifting of a sedimentary column took place above an impervious layer when hydrostatic pressure exceeded lithostatic pressure. Picture was taken just before water burst explosively through the impervious layer and resedimentation of the overlying sediments took place. Department of Geology, University of New Brunswick. Centimetre bar for scale.



sequences in which density contrasts are not caused by lithological variations but by internal inhomogeneities in void ratios. Internal density contrasts within an apparently uniform sediment may be of primary origin or could result from porosity changes during fluidization (Anketell *et al.* 1970). Load deformation within partially fluidized sedimentary units may thus have been important in the formation of intrastratal surface structures. Dish structures have been interpreted to form in a similar manner although on a considerable smaller scale (cf. Lowe 1975, p. 180).

The elongated shapes and orientation of intrastratal surface structures could reflect the rate and direction of interstitial flow within fluidization channels. Rapid interstitial flow would have tended to modify load structures into more or less elongate shapes. Oriented intrastratal surface structures are regarded therefore, not as erosional features but as stable hydrodynamic forms, shaped intrastratally within fluidized zones. They are internal rather than surface structures and it is this differing relationship with their enclosing strata and not their morphological features that distinguish them from those of primary sedimentary origin. The occurrence of helical forms and flow patterns as internal structures within fluidization zones deserves careful attention, because of the prominent role helical patterns have played in interpreting the vortex flow of scouring currents in primary sedimentary processes (e.g. Rücklin, 1938; Bridges, 1972).

Internal surfaces containing sedimentary structures are rarely described in the geological literature. Those known to us include flow structures resembling flute and groove casts occurring on internal layer plane surfaces within vertical sandstone dikes (Peterson, 1968), the groove molds on "intra-bed" surfaces in flysch sandstone described by Hubert *et al.* (1966) and the ridges and furrows on top of sandstone (donor) beds, interpreted by Burne (1970) to reflect intrastratal erosion by escaping water.

In conclusion we wish to emphasize that structures resembling sole marks are not necessarily the exclusive domain of primary sedimentary processes but can, in some instances, be interpreted as secondary sedimentary structures formed as a result of physical diagenesis.

SUMMARY

Fluidization zones comprising sheets and columns of homogeneous, structureless, fine to medium grained sandstone are locally present in the redbeds of Prince Edward Island. They range from relatively small, columnar structures occurring in association with dish structures, to much larger fluidization sheets that extend parallel to, and across bedding for 20 m or more. The latter contain laterally extensive fracture-like separation planes called intrastratal surfaces when large, or dish structures when small (5 cm). Intrastratal surfaces are commonly ornamented with intrastratal surface structures, which resemble sole marks. Rapid intrastratal flow of water along fluidized pathways, in conjunction with load deformation and hydrodynamic shaping are believed to have been the principal processes responsible for the formation of these structures.

ACKNOWLEDGEMENTS

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