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Origin of basinal carbonate laminites of the Mesoproterozoic Society Cliffs Formation (Borden Basin, Nunavut), and implications for base-metal mineralization

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Abstract: Laminated, dark-brown-weathering carbonate rocks from the Society Cliffs Formation in the western part of the Milne Inlet Graben, Borden Basin, are host to the Nanisivik Zn-Pb deposit, but their sedimentology, diagenesis, and stratigraphy are not adequately understood. Previous interpretations for the origin of planar, millimetric laminae, lacking sedimentary features of shallow-water or peritidal origin, and of enigmatic, ubiquitous breccia networks, are here negated by field evidence. Laminae are interpreted as particles of water-column carbonate precipitate that accumulated in a deep-water setting, below all important water-column interfaces, and under an anoxic deep-basin water mass. Persistent basin anoxia and a rift setting are important prerequisites for sedex potential, which may be present in this carbonate part of the Bylot Supergroup.

Résumé : Des roches carbonatées laminaires de la Formation de Society Cliffs, dans la partie occidentale du graben de Milne Inlet (bassin de Borden), encaissent le gisement plombo-zincifère Nanisivik; ces roches prennent une couleur brun foncé à l'altération, mais leur sédimentologie, leur diagenèse et leur stratigraphie sont mal connues. Des interprétations antérieures de l'origine des lamines planaires d'épaisseur millimétrique dépourvues de caractéristiques sédimentaires de milieu d'eau peu profonde ou péritidal et des réseaux ubiquistes énigmatiques de brèches sont ici réfutées d'après des observations sur le terrain. Les lamines sont interprétées comme étant formées par des particules de précipitat carbonaté dans la colonne d'eau qui se seraient accumulées en eau profonde, sous toutes les interfaces importantes de la colonne d'eau, et sous une masse d'eau anoxique de bassin profond. Des conditions d'anoxie persistantes dans le bassin et un cadre de rift sont d'importants prérequis pour l'apparition d'un potentiel sedex qui pourrait exister dans ces roches carbonatées du Supergroupe de Bylot.

GEOLOGICAL SETTING

The 300 km long Milne Inlet Graben, one of three grabens in the aulacogenic Borden Basin (ca. 1.2 Ga), spans the Borden Peninsula of northwestern Baffin Island (Fig. 1). The graben is characterized by a system of syndepositional, repeatedly reactivated, northwest-trending dominant faults and variably oriented subsidiary structures, along which basin opening was accommodated; some of these faults were subsequently injected with gabbro of the ca. 723 Ma Franklin dyke system (Heaman et al., 1992; Pehrsson and Buchan, 1999). The general structure and stratigraphy of the basin have been described by Jackson and Iannelli (1981) and Iannelli (1992). Sedimentary and volcanic rocks that fill the graben belong to the Bylot Supergroup (Fig. 2). The middle part of the succession is dominated by carbonate and fine terrigenous rocks of the Arctic Bay (Jackson and Iannelli, 1981; Iannelli, 1992), Society Cliffs (Geldsetzer, 1973; Kah and Knoll, 1996; Kah, 1997; Kah et al., 2001; Turner, 2003a), and Victor Bay (Sherman et al., 2000, 2001) formations. The stratigraphy and sedimentology of the Society Cliffs Formation have been documented for the southeastern part of the Milne Inlet Graben, where the formation records deposition in shallow-water to peritidal environments, but little is known of the formation in the northwestern two-thirds of the basin, an area in which the Society Cliffs Formation is host to numerous base-metal showings and the Nanisivik Zn-Pb orebody (Fig. 1).

This work forms part of a study designed to determine the structural, stratigraphic, and sedimentological controls on the distribution, nature, and origin of the numerous Pb/Zn/Fe (± Cu, Ag, F) showings known from the Milne Inlet Graben (Jackson and Sangster, 1987; Sangster, 1998). The most important of these mineral deposits is the Nanisivik Zn-Pb orebody (mined 1976–2002). Known mineralization in the Milne Inlet Graben is predominantly constrained to distinct lithofacies and stratigraphic levels of the Society Cliffs Formation (e.g. Turner, 2003b).

FIELD OBSERVATIONS

Society Cliffs Formation — sedimentology of basinal laminite

In the southeastern third of the Milne Inlet Graben, pale-grey- and pale-brown-weathering Society Cliffs Formation dolostones represent a peritidal ramp (Kah, 1997). As described in Olson (1984) and Turner (2003a), in the northwestern two-thirds of the Milne Inlet Graben, west of Bellevue

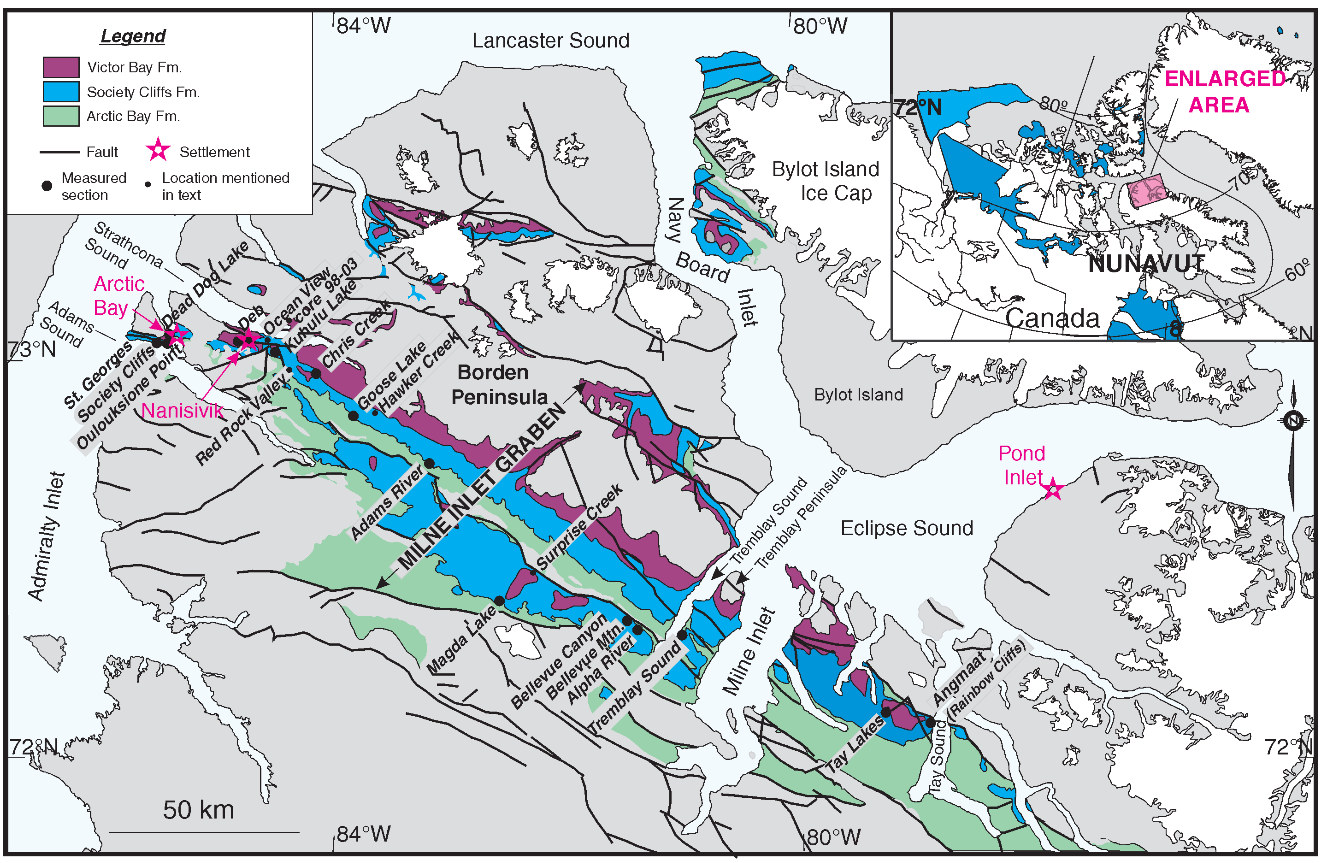

Figure 1. Map of northernmost Baffin Island showing exposure areas of Arctic Bay, Society Cliffs, and Victor Bay formations, major faults in the Borden Basin, and locations mentioned in text.

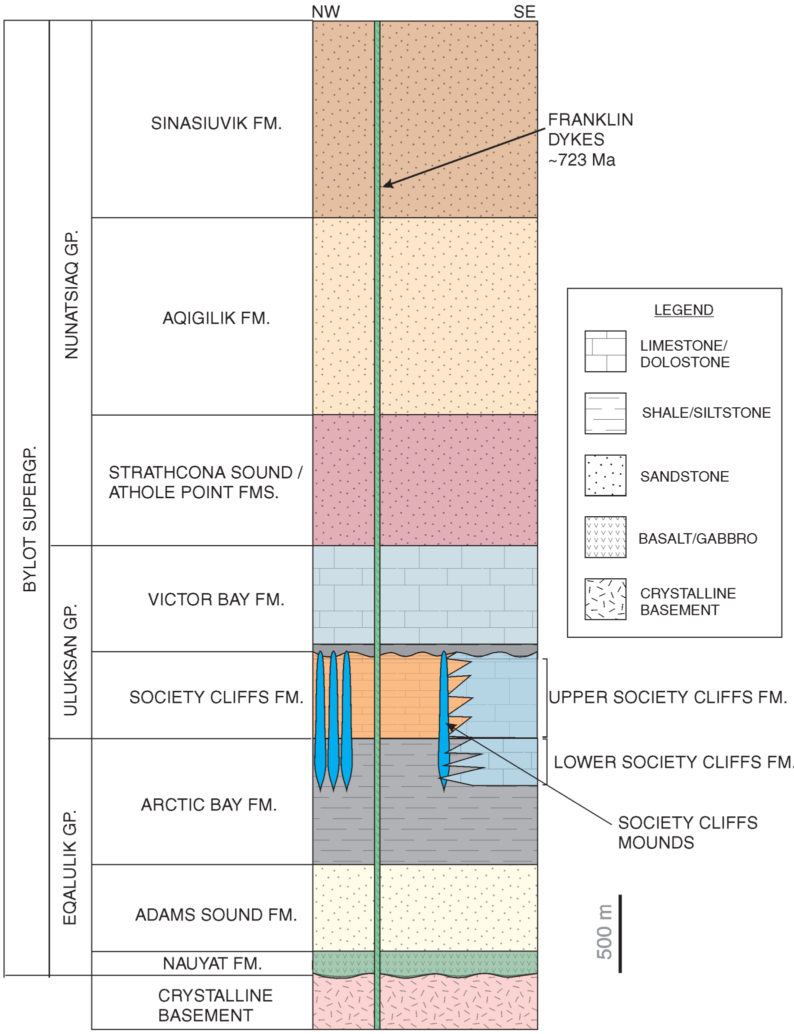

Figure 2.

Schematic stratigraphy of the Bylot Supergroup, northern Baffin Island. Lateral thickness variation and relative thickness of subunits are not accurately depicted.

Mountain on the southern limb of the Milne Inlet Graben synformal sag, the predominant lithofacies is evenly laminated, dark-brown-weathering dolostone that has a strongly bituminous, fetid odour when freshly broken; this is the host rock for the Nanisivik orebody. Dark brown and white millimetric laminae (Fig. 3A) are defined by variation in organic content in a background of carbonate, and are emphasized by weak to strong stylolitization of the dark laminae. The easternmost limit of this lithofacies is on western Tremblay Peninsula, where it interfingers with dolostone facies of the upper Society Cliffs outer ramp. In the extreme northwest, near Nanisivik, massive mounds of homogeneous dolostone (*see* Turner, 2004a, b) are laterally equivalent to the laminite interval.

Laminite is locally interbedded with:

1. terrigenous dolowacke, consisting of subangular quartz and feldspar particles (locally to granule size) and dolostone intraclasts (Fig. 3B), in debrite and turbidite wedges near faults (*see* Turner, 2003a, b);
2. massive pale brown dolostone, in 1 cm to 50 cm beds (Fig. 3C, D, E);
3. pale brown to grey beds of millimetric, tabular to equant dolostone intraclasts, with clast long axes subparallel to bedding (Fig. 3F);
4. dolowackestone to floatstone, consisting of angular to subrounded, millimetric white dolostone clasts (Fig. 3G), in locations adjacent to the flanks of deep-water mounds (*see* Turner, 2004b).

It is uncommon for any given exposure to lack completely any of these interbed types (Table 1). Locally, the lower part of the dolostone unit consists of homogeneous, dark-brown-weathering, bituminous-smelling dolostone (e.g. Adams River section).

Areas of the Borden Peninsula where Society Cliffs dolostone consists of the laminite lithofacies exhibit pronounced reflectivity in Landsat images using bands that select for iron oxide; the formation is highly reflective over the southern limb of the Milne Inlet Graben west of Bellevue Mountain, but non-reflective east and north of the Alpha River and west of Red Rock valley (where most Society Cliffs exposures belong to an unusual mound lithofacies; *see* Turner, 2004b). This attests to a high iron content in the laminated dolostone, which is presumably also at least partly

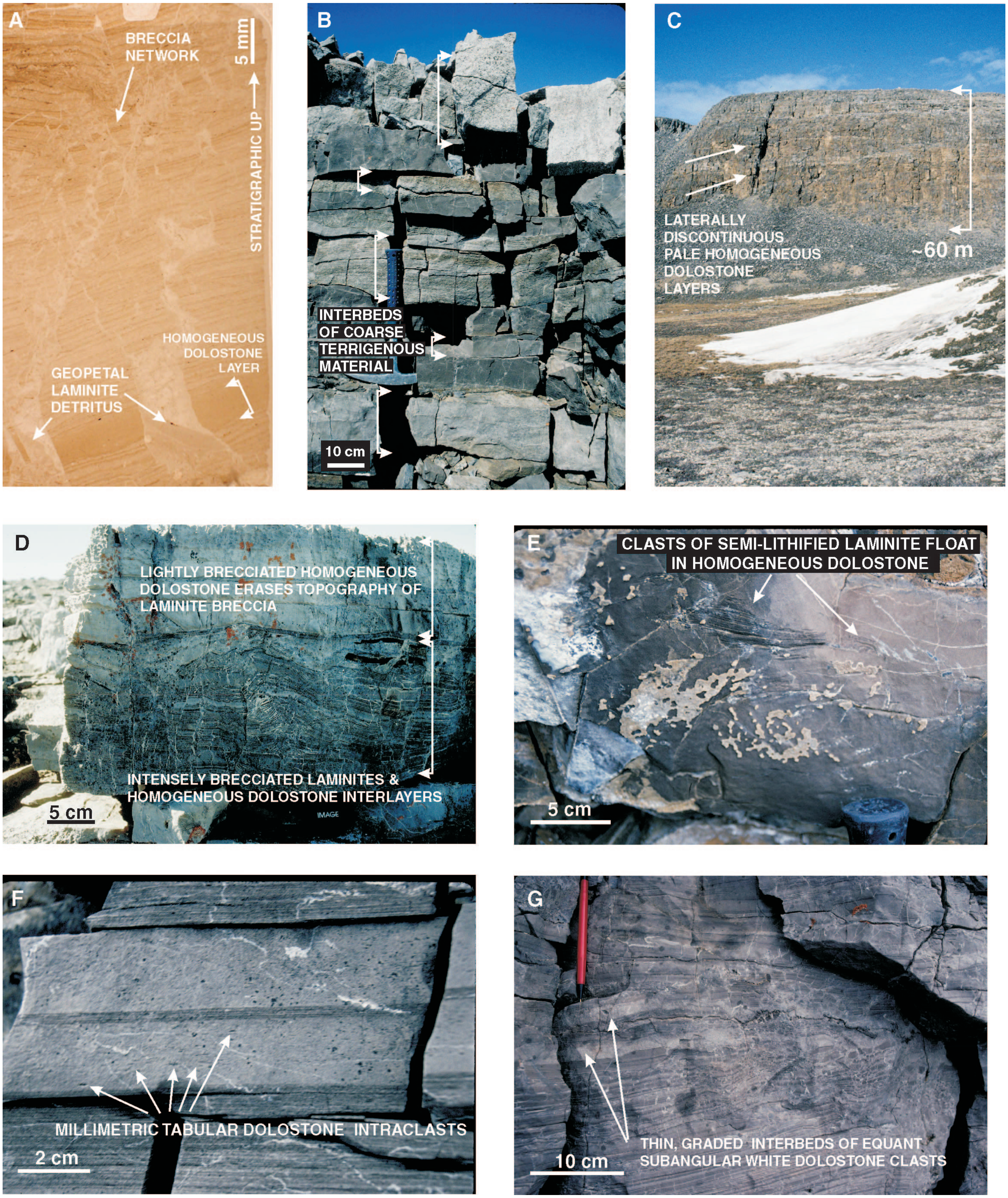

Figure 3. *Society Cliffs Formation carbonate laminite and associated interlayer types. (**A**) Thin section of brecciated laminite (plane light) showing alternating pale and dark (organic-rich) layers, faint pressure solution of dark layers, and geopetal fill of breccia interstices (Adams River section). (**B**) Terrigenous dolowacke interbeds (Adams River section). (**C**) Laterally discontinuous massive dolostone interbeds (Ocean View, Nanisivik). (**D**) Brecciated laminite overlain by homogeneous dolostone (Ocean View, Nanisivik). (**E**) Laminite clast suspended in homogeneous dolostone (Goose Lake section). (**F**) Intraclast wackestone interbed (Goose Lake section). (**G**) Unbrecciated interbeds of equant, subangular, millimetric, white dolostone clasts accommodated movement of breccia clasts while unlithified (Ocean View, Nanisivik).*

responsible for its deep brown weathering colour. In thin section, pyrite is not a conspicuous constituent of the rock, and so the iron may be in the form of ferroan carbonate.

The laminite lithofacies is almost invariably associated with a bituminous odour, except where it has been altered by mineralizing fluid or by proximity to a gabbro dyke (near dykes, laminite is grey rather than brown). Although some lithofacies in the eastern ramp area have similar brown colouring, they generally lack the associated bituminous odour.

Stable isotope data (Fig. 4) for laminite and associated facies from outcrops in the Nanisivik area show an average $\delta^{13}C$ value that is depleted by approximately 2‰ relative to values for correlative shallow-water upper Society Cliffs dolostones in the Milne Inlet area (Kah et al., 1999). Samples analyzed for this study were collected 0 to 5 km from the Nanisivik mine; the data show no relation to proximity to the orebody, and agree with previous data from Nanisivik (Ghazban et al., 1990).

Evidence for the former presence of evaporite minerals is lacking: breccia masses are rarely bedding-parallel, and moulds of gypsum or halite are not evident. Rare halite casts, however, are present in the underlying Arctic Bay shale.

There are no primary physical or biological sedimentary structures of shallow-water origin. Structures are limited to even, planar lamination and a set of synsedimentary and shallow-subsurface deformation structures; laminae are rarely uniformly planar or completely unaffected by at least one type of deformation, if not several (Table 1).

Decimetre- to metre-scale intrastratal folds (Fig. 5A, B), rarely truncated and overlain by undeformed laminae, are locally common. Incipient brecciation is present along the axial planes of some folds (Fig. 5B), and links up with irregular to pipe-like breccia masses at high angles to layering. Brittle deformation by centimetre- to metre-scale microfaults is locally present, with rare healing of the offset by overlying interlayers (Fig. 5C).

Breccia in laminite

Three types of breccia are present in the laminite facies: crackle breccia, mosaic breccia, and rubble breccia (Fig.6; Olson, 1984). They are distinct from superficially similar breccia associated with sulphide mineralization, in that they can be demonstrated in many cases to have formed comparatively early. With the exception of breccia in the bituminous, unlaminated, homogeneous brown dolostone that is locally present at the base of the laminite succession (Turner, 2003a), breccia not associated with mineralization is developed only in the laminite lithofacies and associated thinly interbedded material. Some degree of brecciation is almost always present in the laminite facies, even in the easternmost exposures, where laminite interfingers with ramp dolostones in the Tremblay Sound section. Early breccia is found throughout the entire thickness of the laminite succession.

Breccia clasts are angular. Textures are generally framework-supported. Cracks and breccia masses rarely begin or end at any distinct bedding surface; instead, breccia cracks form a network of vertical or inclined crack planes and anastomosing networks linked along slightly dilated laminae.

Table 1. Sedimentary features of basinal laminite, and paleogeographic features that might have influenced its development and distribution. Inferred local, subtle slopes probably lasted for only part of the laminite succession in any given location, based on the sporadic nature of the indicative features. Note that some degree of brecciation or crack development is invariably present wherever the laminite facies is developed.

	SEDIMENTARY FEATURES						INFERRED PALEOGEOGRAPHY		
							Regional Paleoslope	Local Slope	
LOCATION	Intrastratal Folding	Microfaults	Coarse Terrigenous Material	Angular White Mound Clasts	Rubble Breccia	Crackle Breccia		Mound Margin	Reactivated Fault
Nanisivik-Ocean View	X	X		X	X	X		X	X?
Kuhulu Lake				X	X	X		X	X?
Chris Creek					X	X		X	
Goose Lake			X		X	X			X
Adams River			X		X	X			X
Surprise Creek	X				X	X			X
Magda Lake	X	X			X	X		X	
Tremblay Sound					X	X	X		

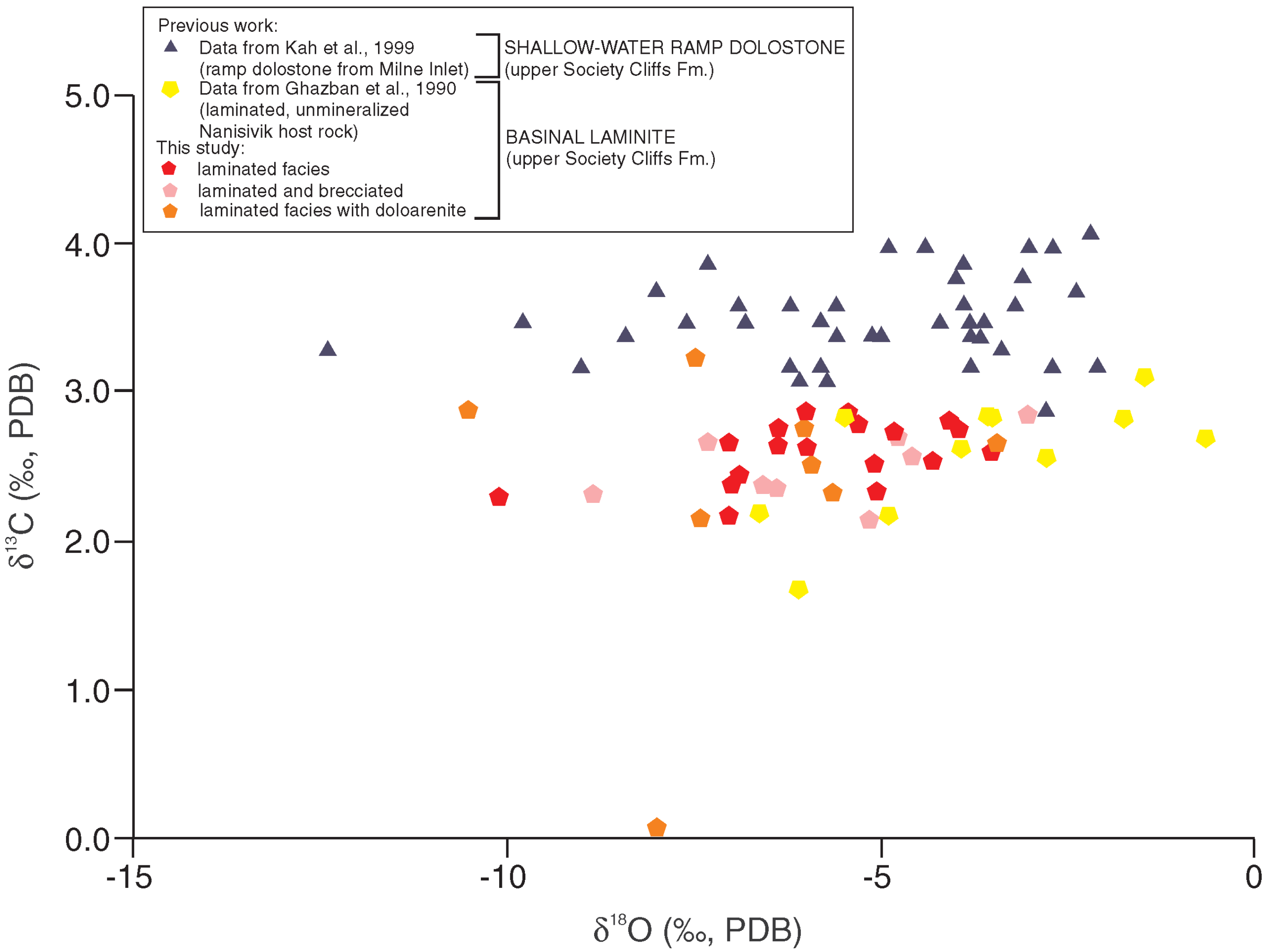

Figure 4. *Comparison of isotope data from basinal laminite in this study (orange, pink, and red symbols) and in Ghazban et al. (1990; yellow symbols), with data from coeval platformal dolostone in Kah et al. (1999; blue symbols).*

Cracks and interstices between breccia clasts are generally thinly lined with isopachous, fine- to medium-crystalline white dolomite; in some cases, remaining porosity has been preserved, whereas in others, it has been occluded with additional crystalline dolomite. In thin section, breccia-filling dolomite is comparatively clear, unlike the brownish, inclusion-rich laminite dolomite (Fig. 3A). Locally, geopetal accumulations of fine laminite particles postdate the earliest isopachous dolomite phase (Fig. 3A). It is common for several crosscutting generations of dolomite-filled cracks to be present, all with identical, but demonstrably crosscutting fills. Meteoric precipitates and fabrics are absent.

Crackle breccia (Fig. 6A) consists of irregular veinlets generally <1 mm wide. Offset across cracks is generally on the order of a few millimetres or less. Individual cracks commonly branch upward irregularly into anastomosing crack sets, and also commonly follow and dilate lamina planes. Mosaic breccia is a fitted fabric of brecciated, in situ clasts, commonly with many cracks that follow lamina surfaces.

Rubble breccia (Fig. 6B, C) forms irregularly shaped to vertically elongate masses that resemble solution-collapse breccias associated with Mississippi Valley-type deposits; vertical fabrics predominate, and layer-parallel breccia masses are rare. Breccia-mass margins are diffuse, grading laterally to mosaic breccia, then crackle breccia; or abrupt, passing to unbrecciated laminite across a sharp, planar surface, generally at a high angle to layering (Fig. 6B, C). Laminae in unbrecciated material adjacent to rubble-breccia masses are locally bent upwards (Fig. 6D). Non-laminite interlayer material locally accommodated breccia formation before becoming lithified (Fig. 6E); contrasting interlayers are also commonly involved in brecciation (Fig. 6F). Although breccia is reported to be most common on the western Borden Peninsula (e.g. Geldsetzer, 1973; Olsen, 1984), it is locally present across the entire Borden Peninsula.

There is evidence for breccia formation during different stages of host-rock lithification. Comparatively early brecciation is indicated by (1) terrigenous particles from local

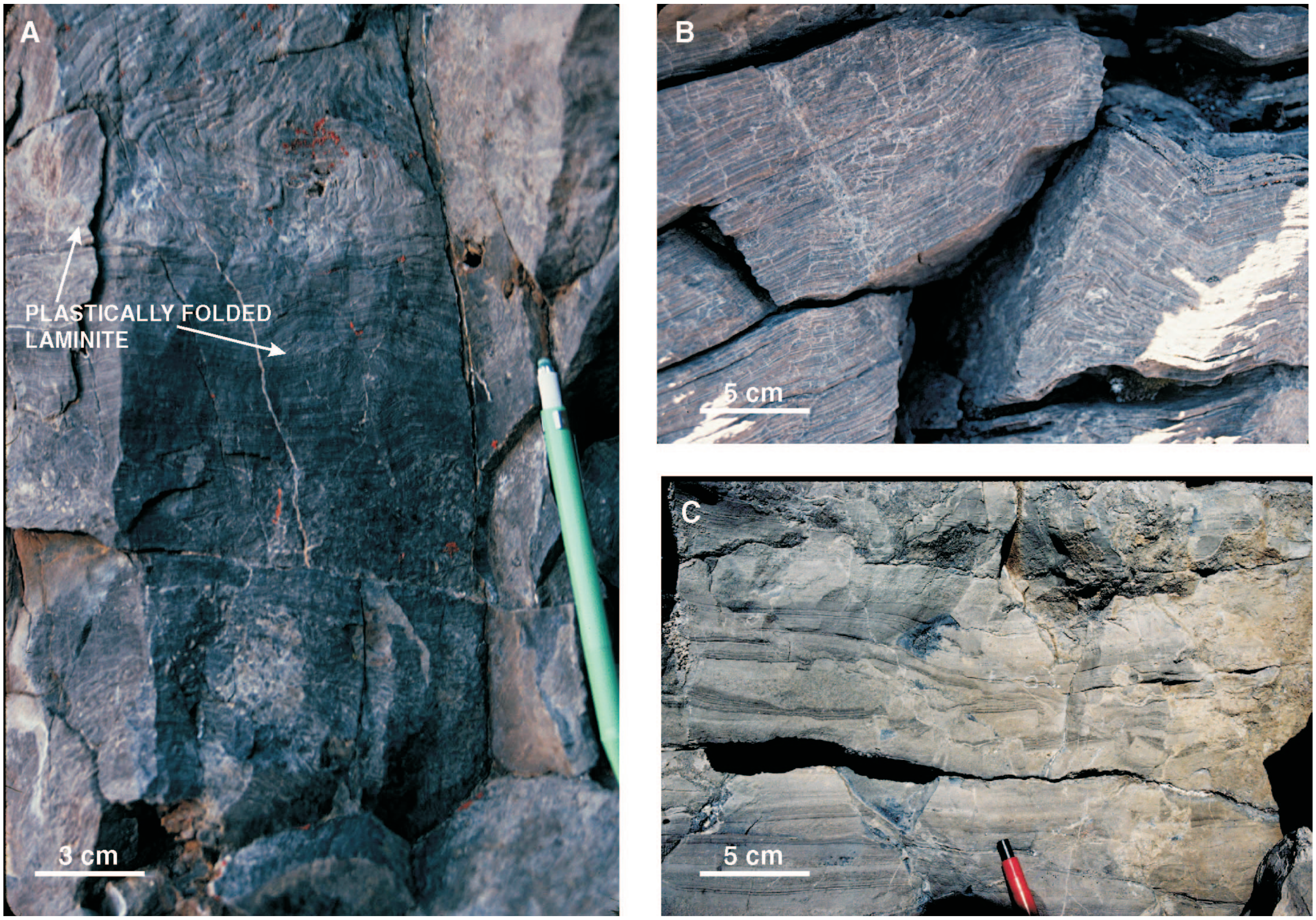

Figure 5. *Syndepositional plastic to brittle deformation of laminite. (**A**) Creep folds (Magda Lake section). (**B**) Incipient brecciation within fold (Surprise Creek). (**C**) Healed synsedimentary microfaults (Ocean View, Nanisivik).*

debrite layers, that infiltrate the uppermost interstices of underlying breccia networks (i.e. laminite lithofacies was lithified and brecciated while non-laminite lithofacies was still unlithified; Turner, 2003a); (2) breccias in noses of decimetre- to metre-scale creep folds in laminite (i.e. brecciation developed in structural weaknesses in incompletely lithified laminite; Fig. 5B); and (3) breccia masses that are enclosed in a matrix of non-laminite material (i.e. unlithified material from a contrasting interlayer moved fluidly between deforming lithified laminite breccia clasts; Fig. 6E). Brecciation at a somewhat later time is indicated by breccia that affects both laminite and interlayered lithofacies (i.e. both were lithified before brecciation; Fig. 6F).

INTERPRETATION

Society Cliffs Formation laminite

The dolostone laminite lithofacies on Borden Peninsula is temporally correlative with the upper Society Cliffs Formation in the southeastern part of the Milne Inlet Graben (Turner, 2004a). Laminated, bituminous, ferroan-carbonate laminite in the northwestern part of the upper Society Cliffs basin represents a monotonous background state against which local influxes of allochthonous material contrast.

In outcrop and thin section, laminae do not resemble any known form of benthic microbialite. No intraclast rudstone or primary sedimentary features such as grading, cross-lamination, desiccation cracks, or microbial features are present; this precludes deposition in storm-affected shallow-water or peritidal environments or on a carbonate slope. There is no variation in lamination style, thickness, or composition across the breadth of the western area, precluding deposition of platform-derived material on a basin floor. Instead, laminae appear to have been deposited uniformly on a substrate that was approximately flat, and at sufficient depth to be below both storm wave base and the photic zone. Laminae are interpreted to represent deposition of carbonate and planktonic organic matter from the water column; if lamination had remained undeformed, individual laminae would likely be traceable across the breadth of the basinal area. Accumulation of dark and light laminae alternated with monotonous periodicity, suggestive of seasonality, on a basin floor that was below all important physical limits in the water column. Evidence of

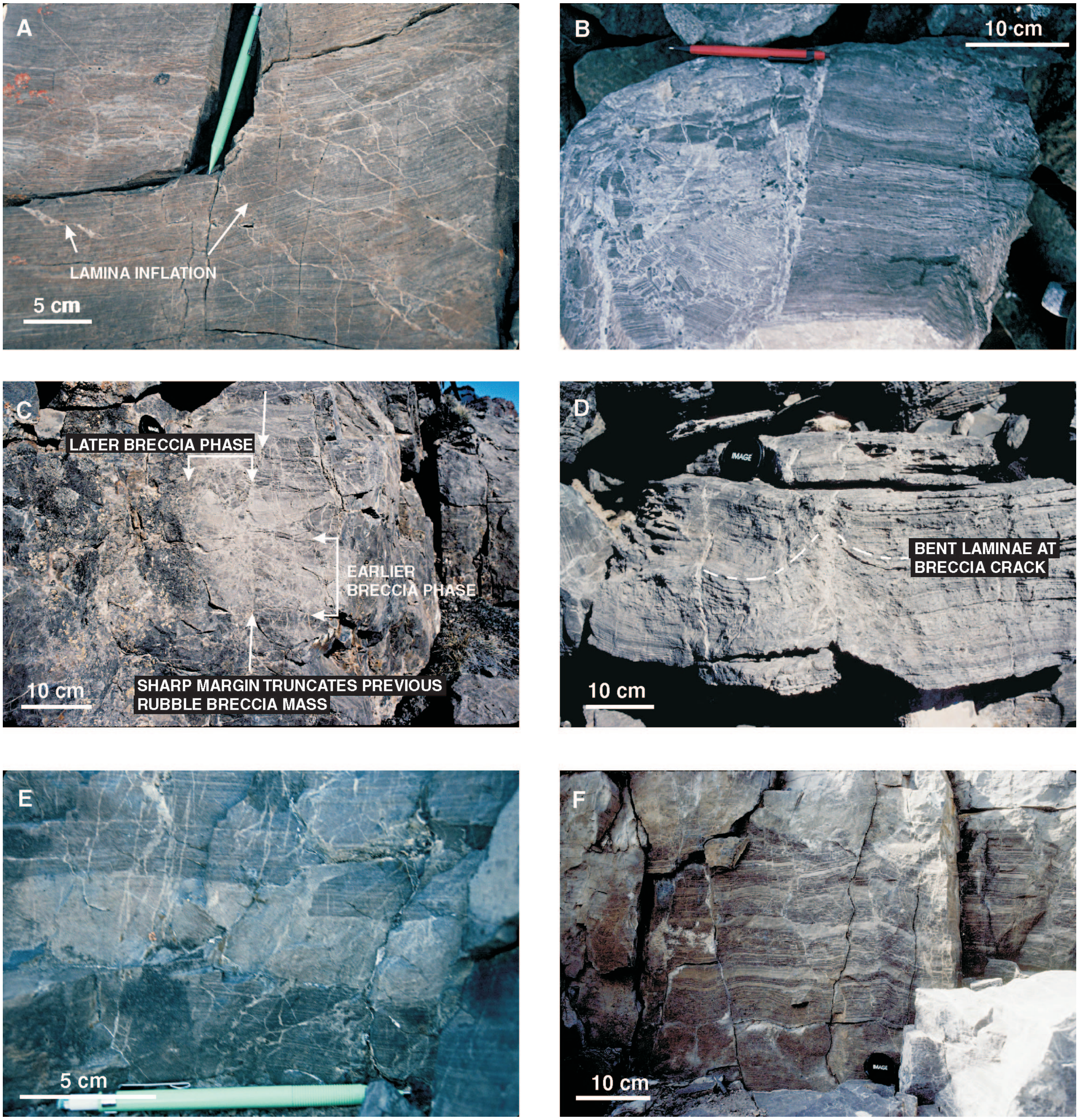

Figure 6. *Laminite breccias. (**A**) Typical crackle breccia with cracks both lamina-parallel and at high angles to lamination (Surprise Creek). (**B**) Sharp contact between rubble-breccia mass and undeformed host laminite (Chris Creek). (**C**) Two crosscutting generations of identical breccia (Twin Lakes Creek, Nanisivik). (**D**) Bent laminae in unbrecciated host laminite beside breccia crack; other cracks are not associated with bent laminae (Mine Hill, Nanisivik). (**E**) Early breccia phase accommodated by fluid movement of unlithified homogeneous dolostone interlayer; later phase affects both laminite and interlayer (Magda Lake section). (**F**) Crackle breccia affecting both laminite and contrasting interlayers (Ocean View, Nanisivik).*

the stratigraphic cyclicity that characterizes shallow-water correlatives to the southeast is completely absent. The lack of sulphate evaporite minerals in this deep-water setting contrasts with evaporite mineral formation demonstrated to have occurred in shallow-water areas during deposition of the Society Cliffs Formation (Jackson and Cumming, 1981; Jackson and Iannelli, 1981; Iannelli, 1992; Kah et al., 2001).

Laminae were deposited incrementally, as carbonate and organic particles that formed in and settled out of the water column, rather than as benthic precipitates or allochthonous, transported material. Laminite lithification was comparatively early, likely taking place close to the sediment-water interface, as indicated by (1) brecciation of lithified laminite rock, followed by infiltration of contrasting surficial sediment into upper breccia interstices (*see* Turner, 2003a); (2) brecciation of laminite, and resulting movement of breccia clasts accommodated by displacement of adjacent unlithified sediment (e.g. massive dolostone or terrigenous dolowacke); (3) synsedimentary faulting of laminite rock, with resulting topography healed by overlying layers; and (4) bending and/or breaking of laminae in creep folds.

The pronounced iron-oxide signal in Landsat images indicates that iron oxide is a weathering product of the basinal laminite; basinal dolostones lack significant volumes of pyrite or other iron minerals, and so the iron may simply be weathering from ferroan-dolomite laminite. It is well established that calcite and dolomite contain significant iron only when they form or are altered under reducing conditions. Given that the ferroan-dolomite laminite interfingers with iron-poor dolostone deposited in demonstrably shallower water, it is possible that the laminite's iron content reflects its primary composition, rather than diagenetic modification that picked out only one lithofacies from among many in the area of interfingering units.

Such an interpretation would require that the deep-water basin be occupied by anoxic, reducing, iron-rich water (Fig. 7) that had either low sulphide content or low enough Eh that iron was taken up by carbonate minerals rather than precipitating as pyrite. A water mass that was anoxic at depth would not only promote formation of iron-rich carbonates, it would also foster the accumulation of unrespired organic matter, here represented by the dark laminae. Anoxia and significant amounts of unrespired organic matter might also explain the 2‰ depletion in $\delta^{13}C$ of basinal laminite as compared to coeval shallow-water carbonates. The original mineralogy of laminae in this possibly reducing, low-sulphate, high-iron, low-sulphide water remains to be determined. Geochemical and petrographic analyses to follow are expected to clarify these issues.

Synsedimentary folding, faulting, and resedimentation

Laminite clearly lithified earlier than interlayered allochthonous material. Partly lithified laminite was plastically folded in the shallow subsurface or at the sediment-water interface. Centimetre- to metre-scale folds are present in locations near deep-water mounds or major synsedimentary faults and their debris, and are interpreted as the result of gravitational instability in cohesive laminite on local, subtle paleoslopes. In contrast to the uniform, flat surfaces where the laminated water-column precipitates accumulated in most of the basinal area, laminae in such locations would have accumulated parallel to underlying inclined surfaces, and been subject to deformation or catastrophic resedimentation. Healed synsedimentary faults would have developed in fully lithified laminite at the sediment-water interface, whereas faults lacking evidence of healing could have developed in lithified laminite anywhere in the buried sediment pile. Creep folds would have developed in cohesive but pliable sediment, either intrastratally, near the sediment-water interface, or, in the case of folds whose upper surfaces are truncated, at the sediment surface. Homogeneous dolostone beds and graded tabular intraclast beds might be debrites and turbidites derived from slope failure in poorly lithified laminite.

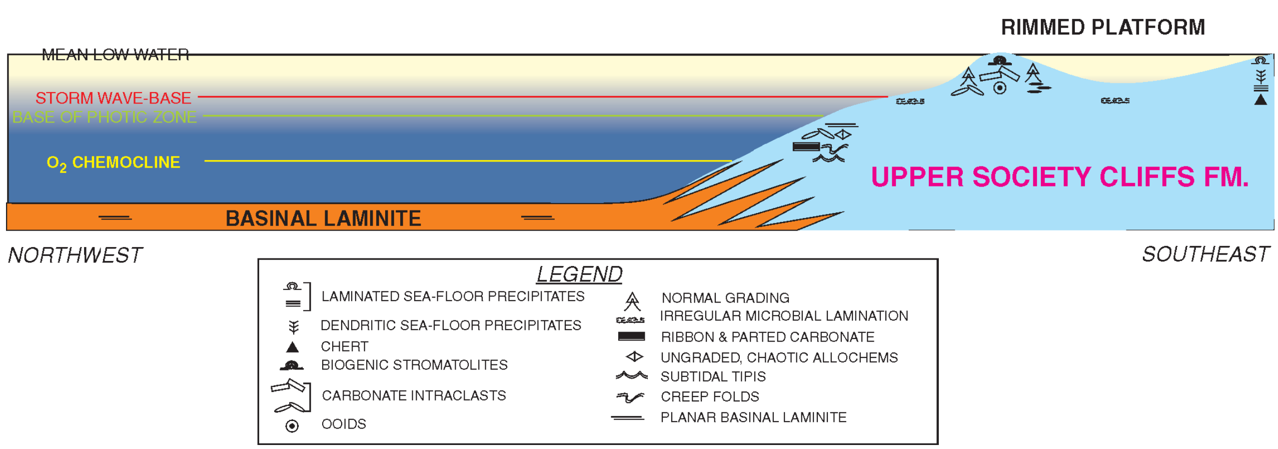

Figure 7. *Interpretation of basin configuration during deposition of Society Cliffs laminite.*

Brecciation

Early and late breccia phases are present. Comparatively early brecciation is associated with angular clasts, rare infiltration of loose sediment into breccia cracks and interstices, and rare breccia formation within creep folds. This type of brecciation clearly took place during deposition of the laminite succession, affecting strata close to or at the sediment-water interface (*see* argument in Turner, 2003a), as well as more deeply buried, lithified material. Cracks were lined with precipitated carbonate and then crosscut by identical, but demonstrably younger, generations of cracks. Later brecciation associated with coarse sparry dolomite, local sulphides, and common rounding of breccia clasts is more clearly the evidence of solution collapse.

Stratigraphic and sedimentological data emerging from the present study cannot be reconciled with previous theories regarding the long-disputed origin of laminite breccia. Previous authors noted that brecciation in the laminite facies is most pronounced in the western part of the Milne Inlet Graben (e.g. 'karsting' in Fig. 14 of Geldsetzer, 1973; Olsen, 1984); this observation led to interpretations invoking subaerial exposure and solution of evaporites or karstification as the cause for in situ breakage and collapse of lithified dolostone. In fact, although the degree of brecciation varies with location, and breccia is most common in the west, it is present wherever the laminite lithofacies is found, and through the entire thickness of the laminite succession.

The inferred collapse of lithified carbonate into volumes formerly occupied by interbedded evaporite layers as a result of later dissolution (Olson, 1984) is refuted by (1) absence of any relict evidence of evaporite minerals (e.g. moulds); (2) breccia masses that are generally at high angles to lamination, rather than stratigraphically delimited; and (3) local evidence for very early brecciation, in the form of infiltration of breccia interstices by foreign particles at or near the sediment-water interface. The former presence of now-vanished evaporites cannot be conclusively disproved, however, without further petrographic and geochemical investigation.

Meteoric karstification during or after laminite deposition is contradicted by (1) absence of meteoric fabrics or precipitates; (2) absence of solution-widened joints or pervasive rounding of brecciated material; (3) absence of identifiable exposure surfaces within the laminite succession; (4) absence of significant dissolutional or collapse-related open spaces; (5) evidence of very early breccia formation (see (3) in previous paragraph); (6) the extreme change in relative sea level (hundreds of metres) that would be required to bring meteoric water to the base of the laminite succession.

DISCUSSION

Basinal laminite

Laminite identical to that of the basinal region of the Society Cliffs Formation is described from metre-thick intervals interlayered with outer-ramp ribbon and nodular limestone in the deepest part of the Victor Bay Formation ('carbonaceous carbonates' of Sherman et al., 2000). The dark-brown-weathering laminite exhibits early soft- and brittle-deformation structures identical to those in the basinal part of the Society Cliffs Formation, and, like the Society Cliffs laminite, has a bituminous odour when freshly broken. Sherman et al. (2000) interpreted the plastic and brittle synsedimentary deformation as the result of gravitational instability on a regional carbonate slope in deep water, with carbonate supplied in suspension from a storm-affected, shallower source area, and interpreted the facies in general as recording times of high organic productivity. Although many breccias in the Society Cliffs laminite are located in areas interpreted as having been affected by slopes near reactivated rift faults or deep-water mounds, this is not the case for the bulk of areas occupied by the basinal laminite lithofacies.

The contrasting lithofacies, paleoenvironments, and depositional styles of the Society Cliffs and Victor Bay formations have been used to illustrate the breadth of carbonate sediment types and platform styles prevalent during the Mesoproterozoic transition from seafloor-precipitate-dominated Paleoproterozoic carbonate systems to lime-mud-dominated Neoproterozoic and Phanerozoic systems (Sherman et al., 2000). It is not surprising that one of the few lithofacies that these two systems have in common is one that was deposited in the deepest parts of the two successive basins, in a setting beyond the effects of variable organic productivity, insolation, substrate, and evaporation- and circulation-related seawater chemical effects — a setting deeper than all physical and chemical interfaces and limits in the water column. Although an interval of significant erosion separates the two depositional phases, at least one aspect of the Society Cliffs basin was re-established during Victor Bay Formation deposition: the deep-water, anoxic, carbonate laminite facies. Although it is not possible to compare their respective paleowater depths, it is clear that basinal waters like those inferred to have occupied the western part of the upper Society Cliffs basin also episodically impinged on the Victor Bay outer ramp.

Origin of breccias

Given the pronounced lack of evidence for the most common causes of brecciation (meteoric karstification, evaporite solution), a demonstrably unusual depositional setting, and clearly early and repetitive brecciation events, more exotic origins for this phenomenon must be considered. Molar-tooth structure, a form of early cracking that is found in Precambrian shallow marine carbonate rocks (James et al., 1998) has been attributed to spontaneous, episodic evasion of gases generated by bacterial degradation of organic matter in the shallow subsurface (Furniss et al., 1998) prior to sediment compaction, possibly triggered by synsedimentary seismicity (Pratt, 1998). In the Society Cliffs Formation, however, host rock and cracking style do not closely resemble those of molar-tooth carbonates, laminite brecciation clearly post-dates complete sediment lithification in most cases, and brecciation generally is not layer-specific as in molar-tooth structure. Given that deep-water mound growth during early Society Cliffs time is inferred to have resulted from the geographically focused evasion of gases from deep within the underlying sediment pile (*see* Turner, 2004b), that both shale and laminite in the western Milne Inlet Graben are organic-rich, and that there is evidence of ongoing minor tectonism, it is possible that, in late Society Cliffs Formation time, the brecciation of laminite, and even the precipitation of fracture-lining carbonate, resulted from continual, unfocused, explosive evasion of gas through brittle carbonate rocks.

Implications for oceanic chemistry

The anoxic basinal setting inferred for the Society Cliffs laminite from its organic-rich, ferroan, benthos-free, pyrite-poor and sulphate-mineral-free composition might have conformed approximately to the conditions presented by Canfield (1998) for a sulphate-limited anoxic Mesoproterozoic deep ocean water mass with significant dissolved iron. The interpretation of the Society Cliffs deep-water basin as having been anoxic, and the lack of evidence of sulphates, concur with data from other deep-water basins (Canfield, 1998; Anbar and Knoll, 2002; Shen et al., 2003) to the effect that the global Mesoproterozoic ocean was stratified, with anoxic, sulphate-poor water at depth. The Borden Basin has been interpreted as a continental-margin rift (Jackson and Iannelli, 1981), and would likely have been hydrologically linked to the world ocean. If further geochemical analysis supports this interpretation, this basin would represent an example of deep-water carbonate deposition below an anoxic chemocline in the Mesoproterozoic 'Canfield ocean'.

Implications for base-metal mineralization

Mineral exploration in the Milne Inlet Graben has focused on finding Mississippi Valley-type (i.e. late) mineralization in the Society Cliffs dolostone, and to a much lesser extent, on sedex potential in Arctic Bay shale. Demonstration that the Milne Inlet Graben contained an anoxic deep-basin water mass throughout the deposition of laminite (also a demonstrated time of intermittent tectonism), during deposition of 'carbonaceous carbonates' in the Victor Bay Formation, and likely also during deposition of Arctic Bay and Victor Bay shales, could broaden the basin's sedex prospectivity to include the entire Arctic Bay through lower Victor Bay shale and carbonate succession in the western Milne Inlet Graben.

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