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Significance of styles of epicontinental shale sedimentation in the Belt basin, Mid-Proterozoic of Montana, U.S.A.

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ABSTRACT

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Within the strongly shale dominated sediment fill of the Mid-Proterozoic Belt basin a large variety of shale types can be distinguished. Sedimentological investigations of several formations have yielded valuable data about lateral associations of shale types as well as about the principal mechanisms of shale deposition. Depositional environments of shales in the Belt basin range from red bed mudstones of ancient flood plains to deep water mudstones in a turbidite setting. Graded silt/mud couplets are ubiquitous in most shales of the Belt basin. However, they differ in detail and can be related to a variety of depositional processes, such as low-density turbidity currents, sheet floods, storms, and wave reworking. In several formations there is evidence that microbial mats colonized the sediment surface and probably protected the sediment surface from erosion.

Shales from comparable Phanerozoic settings generally lack the silt/mud couplets that are so commonly observed in shales from the Belt basin and other Proterozoic epicontinental basins. This difference probably reflects the proliferation of bioturbating organisms in the Phanerozoic. The absence of benthic microbial mats in Phanerozoic shales is probably due to the evolution of metazoan grazers towards the end of the Proterozoic.

Introduction

Shales, despite the fact that they form more than 60% of the worlds sediments, are an understudied sediment type, and have long been considered the "interbedded" and "taken for granted" matrix between lithologies of greater scientific or economic interest (Potter et al. , 1980, p. 3). However, recent studies of shales (e.g. Jackson, 1985; Schieber, 1986a, 1989b; Davis et al., 1989) have shown that careful investigation of shales can yield valuable new insights into the origin of many sedimentary basins. Particularly in the case of basins that are strongly shale dominated it is imperative that close attention be paid to sedimentary features of shales. Otherwise large portions of the basin history will remain unknown, even if sandstone and carbonate units are investigated in detail.

A good example of a shale-dominated basin is the Mid-Proterozoic Belt basin of the northwestern U.S.A. and southwestern Canada (Fig. 1). Because of the absence of bioturbating organisms in the Mid-Proterozoic, primary sedimentary structures are undisturbed and can be utilized to deduce conditions and processes of sedimentation. In this paper sedimentary features of Beltian shales that were deposited in environments ranging from terrestrial to deep basinal are reviewed and discussed.

The Belt Supergroup and its Canadian equivalent, the Purcell Supergroup, constitute a thick (20 km), primarily terrigenous clastic sequence that was deposited between 1450 and 850 m.y. ago (Harrison, 1972). Whether the Belt basin was connected to the Proterozoic world ocean (Price, 1964; Harrison, 1972), or whether it was an inland body of water (Stewart, 1976; Sears and Price, 1978),

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Fig. 1. Location map. Stipple pattern indicates location of present day Belt basin. The eastward extension of the basin is also known as the Helena embayment.

has been an ongoing debate for almost a century. Recently a lacustrine interpretation of the Belt basin has been promoted by Winston (1986a), based on a comparison of sedimentary features with lacustrine sediments elsewhere. Cressman (1989) on the other hand, based on a Proterozoic plate reconstruction by Piper (1982), palinspastic restorations, tectonic subsidence analysis, and a stratigraphic study of the Prichard Formation (Fig. 2), came to the conclusion that, even though the Belt basin is located on continental crust, it formed a narrow gulf that was connected to the Proterozoic ocean. According to Cressman (1989) the initial Belt basin was fairly deep during most of Prichard deposition, shallowed toward the end of Prichard deposition, and was filled with shallow-water to subaerial deposits for the remainder of Belt sedimentation. Winston's (1986a) lacustrine interpretation is based primarily on a comparison of facies and sedimentary cycles in the Missoula Group (Fig. 2) with those of the lacustrine Green River Formation (Eocene). However, if the Belt basin during Missoula time was a shallow Gulf as proposed by Cressman (1989), tidal influence was probably strongly attenuated, and the distinction between shallow marine or lacustrine facies can not be made on sedimentologic criteria alone. Geochemical considerations, such as the question of the source for the large quantities of magnesium in the dolomites of the "Middle Belt Carbonate" (Grotzinger, 1986), as well as sulfur isotope studies of sedimentary pyrites (Strauss and Schieber, 1990), suggest that, even though an epicratonic setting is indicated, the Belt basin was nonetheless connected to the Proterozoic ocean.

Fine-grained terrigenous clastics, which ha undergone various degrees of greenschist metamorphism and are commonly mapped as argillites, dominate the sediment fill of the Belt basin. Unmetamorphosed sediments occur only in the easternmost exposures of the sequence. However, a low-grade metamorphic overprint has not obscured any of the details of primary sedimentary structures (Schieber, 1990). Therefore, all the fine-grained clastics described in this report will be discussed as shales, regardless of metamorphic overprint. Detailed mapping, stratigraphic, and sedimentologic studies of the Belt Supergroup are still not completed, but considerable progress towards an understanding of sedimentary setting and basin evolution has been achieved in the last two decades (Winston, 1986b). Though most investigators have concentrated their efforts on the

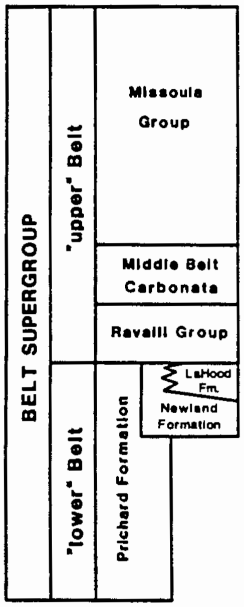

Fig. 2. Nomenclature and stratigraphic overview of the Belt Supergroup. The exact lateral relationship between Newland Formation and Prichard Formation is unknown because Laramide intrusions separate the two formations. However, observations in at least one limited outcrop area, the Highland Mountains, suggest that they are interdigitating (Thorson, 1984).

investigation of sandstone and carbonate units (e.g. McMannis, 1963; Smith and Barnes, 1966; Winston, 1973, 1986a; Horodyski, 1976a, b; Eby, 1977; White et al., 1977; Grotzinger, 1986) sufficient progress has also been made towards an understanding of the various shale units of the sequence to warrant a review of shale sedimentation in the Belt basin. Because the shales that are described in this review have been discussed and pictured in prior publications (Huebschman, 1973; Schieber, 1986a, 1987, 1989b, 1990; Winston, 1986a; Cressman, 1989), only line drawings that summarize the various sedimentary features are presented here.

Shale types of the Belt Supergroup

In this section the present knowledge of shale sedimentation in the Belt basin will be summarized. The various studies encompass most major stratigraphic units of the Belt Supergroup. A summary of stratigraphic nomenclature in the Belt Supergroup is given in Fig. 2.

Shales of the lower Belt Supergroup

The lower Belt Supergroup as defined by Harrison (1972) comprises almost half of the exposed sequence and it consists essentially of the various members of the Prichard Formation (Cressman, 1985) in the central and western portions of the basin, and of the LaHood Formation (McMannis, 1963), Neihart Quartzite (Schieber, 1989a), Chamberlain Shale (Walcott, 1899), and Newland Formation (Schieber, 1985) in the eastern part of the basin. If the definition and classification of shales is used as proposed by Potter et al. (1980, p. 14), about 85% of the lower Belt Supergroup consists of shale.

Newland Formation shales

The Newland Formation, a stratigraphic unit consisting of interstratified shale and carbonate packages, contains probably the most thoroughly studied shales of the Belt basin. Its sediments were deposited in an eastern extension of the Belt basin, the so called Helena embayment (Fig. 1). With respect to the narrow Gulf that Cressman (1989) envisions the Belt basin to have been, the Helena embayment was located deep inside the Gulf, and therefore tidal action was probably weak or absent. This conclusion is further supported by the observation that sediments for which a reasonable case for tidal influence on deposition can be made are only found in the northern portion of the Belt basin (Horodyski, 1976a, b) towards the opening of the presumed gulf, and by the general paucity of definite tidal deposits elsewhere in the Belt basin (Grotzinger, 1986). Naturally, a lacustrine interpretation of the Belt Supergroup (Winston, 1986a) would completely eliminate the possibility of tidal influence. A brief overview of the sedimentary history of the Helena embayment is given in Schieber (1986b).

In outcrop six main shale facies types have been distinguished in the Newland Formation, and detailed investigations allow subdivision into several more facies types (Schieber, 1985). Identification of shale facies types is based on easily observable features, such as mechanical strength, carbonate content, silt content, and sedimentary features. Wide variations of major constituents (quartz silt, clay, carbonate) within any given facies type do not allow facies differentiation based on composition alone (Schieber, 1989b). Instead, textural features were chosen to differentiate between facies types, because textural features are much more closely related to conditions of sedimentation than compositional features. Shale facies types in the Newland Formation have been described and discussed in considerable detail by Schieber (1986a, 1989b) and their pertinent features are summarized in Fig. 3. Facies relationships from shoreline to basin centre, variations in sediment sources, and differences in the mode of sediment supply are also taken into account.

Sedimentary features that are important for the interpretation of the depositional environment of these shales are:

(A) *Graded silt / mud couplets*. These contain a basal silt layer with parallel lamination, ripple cross-lamination, and graded rhythmites (Reineck and Singh, 1980, p. 120; Aigner and Reineck, 1982), that grades upwards into dolomitic clayey shale. Graded silt/mud couplets may contain a layer of intraclasts (shale) and extraclasts

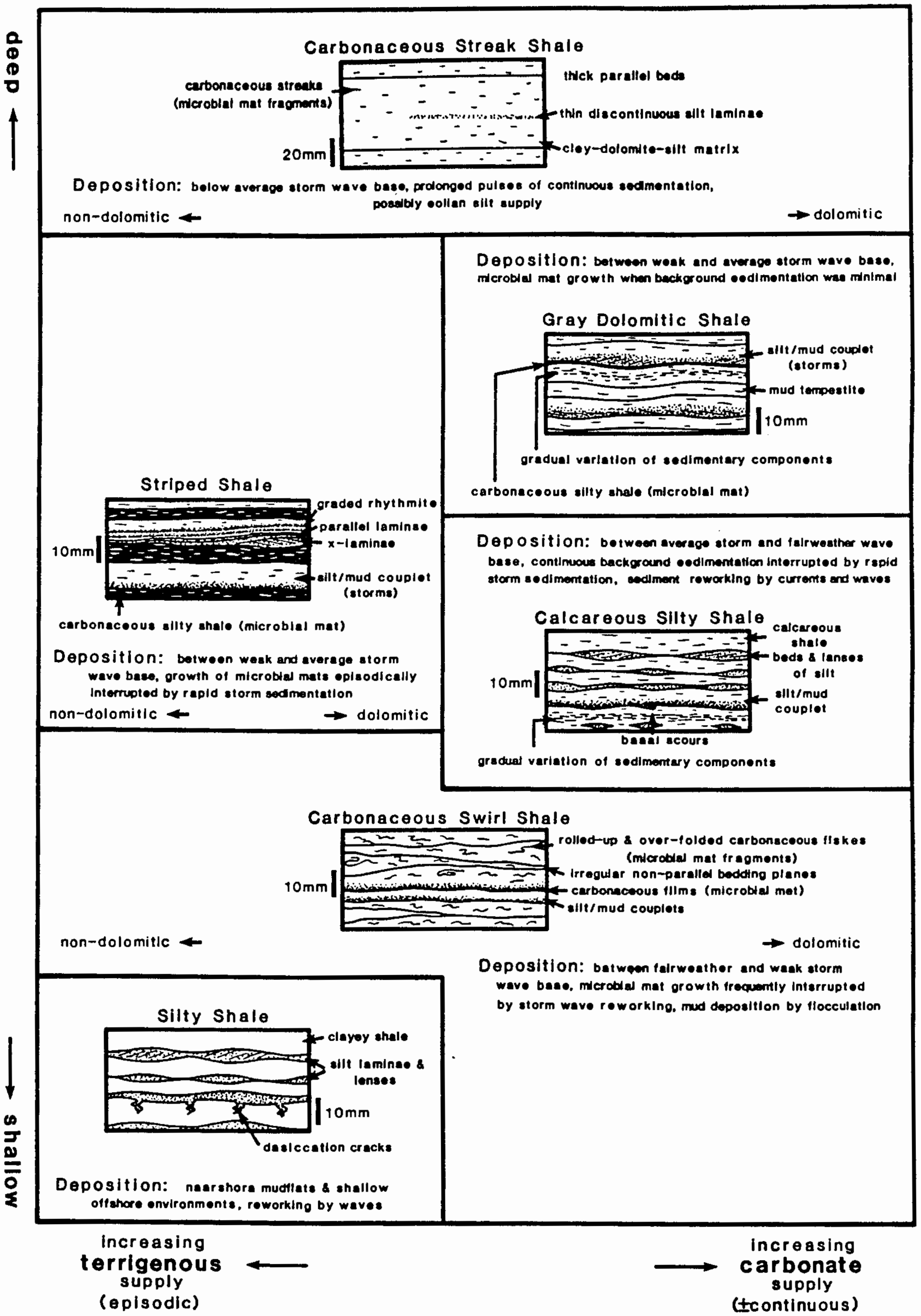

Fig. 3. Summary of shale facies features in the Newland Formation and envisioned depositional setting. Facies are arranged along a basin margin to basin centre transect according to depth of deposition and energy level of environment. Two types of sediment supply (terrigenous vs. carbonate) and continuous vs. episodic sedimentation are taken into consideration.

(carbonate) at the base and form clast/silt/mud triplets (Schieber, 1986a). Silt/mud couplets are interpreted as storm layers because of close similarities to storm deposits in modern muddy shelf seas, such as the North Sea (Reineck et al., 1967; Gadow and Reineck, 1969; Aigner and Reineck, 1982), the Gulf of Gaeta (Reineck and Singh, 1971), and the prodelta region of the Niger delta (Allen, 1965). Shales with abundant silt/mud couplets also contain sporadic beds of hummocky cross-stratified (HCS) sandstone (Schieber, 1987), an independent indication of storm-wave activity (Harms et al., 1975). HCS sandstones probably represent very exceptional major storms, whereas graded silt/mud couplets were the result of more frequent, weaker storms (Schieber, 1986a).

(B) *Laminated carbonaceous silty shale beds.* These beds are characterized by high contents of organic carbon (up to 5% TOC), and consist of alternating carbonaceous laminae, drapes of dolomitic clayey shale, and tiny lenses of silt. The internal wavy-crinkly laminae of these beds are very unlike those of deeper water hemipelagic shales (e.g. Conant and Swanson, 1961; O'Brien, 1989) and strongly resemble lamina structures from modern microbial mats (Horodyski et al., 1977; Krumbein and Cohen, 1977). In keeping with a microbial mat interpretation, mechanical behaviour of these beds during soft sediment deformation suggests that they behaved like a tough leathery membrane, rather than like a soupy organic muck. These beds were studied and described in detail by Schieber (1986a), and are interpreted as the deposits of benthic microbial mats.

(C) *Lenticular to wavy bedding.* This bedding type consists of alternating silt and clay laminae (0.2–3 mm thick). Silt laminae have sharp bases and tops. Silt layers are wavy or consist of individual lenses and may show low-angle cross-lamination, and load casts and scours at the bottom. Shales that are characterized by lenticular to wavy bedding are associated with siltstones and sandstones that contain features suggestive of deposition in very shallow water, such as mudcracks, clay galls, and erosive channels. Lenticular to wavy bedding is typical for nearshore tidal deposits (Reineck and Singh, 1980, p. 114), but because tidal currents were either weak or absent in the Helena embayment (see introduction and Schieber, 1989b) it is assumed that they are the result of intermittent wave action (Reineck and Singh, 1980, p. 115).

(D) *Erosion surfaces.* Apart from small scours at the base of silt beds, more continuous erosion surfaces with several centimeters of relief are also observed. These may be overlain by shale, but may also be overlain by lenses of cross-laminated silt and sand that have sharp basal and top contacts, and are interpreted as the product of intermittent strong currents (Schieber, 1989b). Erosion surfaces such as these are quite common in shallow shelf sequences and may result from many different types of flow. However, the observation that these sand lenses are of the same composition as the hummocky cross-stratified sandstone beds found interbedded with shales of the Newland Formation (Schieber, 1987) suggests the possibility that storm-generated currents may be responsible for these erosion surfaces as well.

(E) *Irregular bedding and unordered fabric.* Shales with these features have irregular nonparallel and slightly undulose bedding planes, show small-scale soft sediment deformation, and contain shale intraclasts. Mica flakes and clays are not aligned parallel to bedding, and may even be oriented perpendicular to bedding. Because of absence of bioturbation in the Mid-Proterozoic, and because of the abundant indications of storm-influenced sedimentation in the Newland Formation, the unordered fabric is interpreted to be due to rapid flocculation of clays from a storm-induced suspension.

(F) *Gradational variations of sedimentary components.* Within thicker shale beds one can observe gradual variations in the content of carbonaceous flakes (of microbial origin), clay, and dolomite. Gradual compositional changes are a typical feature of periodic sedimentation (Einsele, 1982a), and may for example indicate primary subtle variations in the supply of the various sedimentary components, dilution of one component by another, and may even be due to diagenetic redistribution of for example carbonate minerals. Uniform carbonate distribution in several of the studied thin sections implies that simple diagenetic carbonate redistribution cannot be called upon to explain the gradual variations. Explanation of variability as either productivity or dilution cycles (Einsele, 1982b), or as a combination of both, will require further detailed investigations. However, no matter what the ultimate cause of these variations may turn out to be, the absence of features indicative of erosion and omission implies that sedimentation, though variable, was essentially continuous. Thus, these shale beds indicate that there was a component of continuous background sedimentation in addition to the more readily recognized episodic storm-induced sedimentation.

Depositional environments of the six facies types in Fig. 3 were interpreted according to presence, absence, and relative abundance of above features. Information from interbedded sandstone and carbonate units was incorporated into the interpretation (Schieber, 1989b).

Striped shales were interpreted as representing microbial mat growth (Schieber, 1986a) that was episodically interrupted by storm deposition of silt/mud couplets. Alternation of different lithologies led to the characteristic striped appearance of these shales (Fig. 3). Rare hummocky cross-stratified sandstone beds in these shales were probably deposited by storms of exceptional magnitude, whereas the much more frequent silt/mud couplets were due to storms of average intensity. Therefore, and because of the absence of any signs of emergence, these shales were probably deposited between fairweather and storm wave base.

The *gray dolomitic shales* were probably deposited at a comparable water depth because of the common presence of storm deposited silt/mud couplets (Fig. 3). The paucity and thinness of microbial mat deposits in this facies is probably due to continuous background sedimentation during most of deposition (gradual variations in sedimentary components, see Fig. 3). The latter probably led to increased turbidity in the water column. Only when background sedimentation was essentially absent could microbial mats colonize the sediment surface.

The *carbonaceous swirl shales* were deposited in shallower water, as indicated by probably frequent wave reworking. Frequent wave reworking in the carbonaceous swirl shale facies is indicated by poor development and survival of microbial mats (microbial mat deposits are thin and commonly eroded), and irregular non-parallel bedding plan (Fig. 3). Water depth was shallower than for t prior two facies types, probably between fairweather and weak storm wave base.

The *silty shale* facies is characterized by lenticular and wavy bedding (Fig. 3) and was probably deposited in fairly shallow water. Associated siltstones and sandstones with mudcracks, clay galls, erosive channels, and wave ripples suggest deposition on mudflats and in very shallow offshore environments.

Lenticular and wavy bedding is also found in the *calcareous silty shale* facies, but it is less prominent than in the silty shale facies. The presence of silt/mud couplets and erosion surfaces indicates deposition above average storm wave base, and the presence of lenticular and wavy bedding suggests deposition close to fairweather wave base. Frequent reworking is also indicated by the absence of microbial mat deposits. A continuous background sedimentation component is indicated by gradual variations in sediment components (Fig. 3), and probably contributed to suppression of microbial mat growth.

The *carbonaceous streak shales* are thickly be ded (3–20 cm thick) and contrast in that respe considerably from all the above mentioned shale types (bed thickness rarely in excess of a few centimeters). Thickness of beds, lack of sorting, and gradual variations in the concentration of sedimentary components indicate that individual shale beds were deposited from prolonged pulses of more or less continuous sedimentation, probably derived in part from deltaic systems in the south of the Helena embayment. The presence of thick hummocky cross-stratified sandstone beds in this facies, coupled with the complete absence of silt/mud couplets suggests that only the strongest storms were able to reach the bottom, and that deposition occurred below average storm wave base (Schieber, 1989b).

Carbonate production and terrigenous sedimentation were contemporaneous during deposition of the upper member of the Newland Formation. This circumstance is clearly demonstrated by terrigenous sediment components and shale clasts in carbonate units (Schieber, 1985), by dolostone and limestone clasts within shales (in particular the base of clast/silt/mud triplets), and also by the significant amounts of fine-grained dolomite within the shales (Schieber, 1989b). Carbonate influx was more or less continuous, whereas terrigenous influx was essentially episodic because of the probably semi-arid climate at that time (Schieber, 1985). Above statement is supported by the observation that evidence of continuous sedimentation is only found in carbonate-rich shales (Fig. 3). Arrangement of these shales along a bathymetric profile according to estimated depth of deposition leads to predictions of lateral facies associations (Fig. 3) that are borne out by stratigraphic studies in the Newland Formation (Schieber, 1989b).

Prichard Formation shales

The Prichard Formation constitutes the lower Belt Supergroup (Harrison, 1972) in most of the central and western portion of the Belt basin. The Newland Formation is considered the eastern equivalent of the upper portion of the Prichard Formation (Fig. 2).

An exploration of sedimentary features in shales of the Prichard Formation was conducted by Schieber (1990). The Prichard Formation contains in many places thin to medium bedded fine sandstone beds that are interpreted as turbidites on the basis of flute casts, grading, climbing ripples, and incomplete Bouma sequences (Höy, 1984; Cressman, 1985). The latter author interpreted the bulk of the Prichard Formation as a deep-water, prodeltaic sequence. Sedimentary features that are encountered in shales of the Prichard Formation are briefly described below.

(A) *Thick silt / mud couplets*. These have been observed throughout most of the Prichard Formation (Cressman, 1985, 1989), are approximately 5–30 mm thick, and have a layer of even to undulose silt at the base that is in gradational contact with an overlying layer of mud. The silt portion may show ripple cross-lamination, parallel lamination, and so-called "fading ripples" (Stow and Shanmugam, 1980). The mud portion is in many places structureless, but may also contain thin regular silt laminae (0.1–0.4 mm thick) and indistinct discontinuous silt laminae of similar thickness. Cressman (1989) refers to this couplet type as "graded siltite–argillite couplets".

(B) *Thin silt / mud couplets*. These are 1–5 mm thick and have a layer of fine to medium siltstone at the base that grades upwards into clayey shale. The basal contact is sharp and commonly shows load and flame structures. Silt to clay grading is the only visible sedimentary feature within these couplets. These thin couplets are included in the "graded siltite–argillite couplets" of Cressman (1989).

(C) *Wavy-lenticular silt laminae*. These consist of thin laminae (0.3–2 mm thick) of coarse silt to fine sand (sharp bottoms and tops) that alternate with clay laminae. Typically these laminae occur as "sets" or "bundles of approximately 3–15. No grading was observed within single laminae or sets of laminae. From published descriptions it appears that argillites containing such laminae were probably described as "lined rock" by Cressman (1989).

(D) *Massive shale beds*. These beds are essentially structureless, up to 20 mm thick, and show internal gradational variations in the content of sedimentary components (clay, carbonaceous flakes). This type of shale beds probably constitutes the bulk of what Cressman (1989) describes as argillite.

(E) *Even silt laminae*. These occur within massive shale beds, are 0.25–1 mm thick, and have indistinct lower and upper boundaries. They occur as single laminae or as bundles of closely spaced laminae. Argillites with this type of laminae are probably also included in Cressman's (1989) "lined rock" variety.

(F) *Even colour banding*. Some thin intervals of the Prichard Formation are characterized by colour-banded siltstones that consist of even light-coloured silt laminae (1–20 mm thick) alternating with dark silt laminae that contain appreciable amounts of organic matter and clay (now recrystallized to micas). The boundaries between silt laminae are indistinct. These banded intervals can be traced for at least 400 km across the basin. Cressman (1989) described these colour banded siltstones as "laminated silty argillites".

Above sedimentary features are summarized in Fig. 4. Lateral associations of sedimentary features in the Prichard Formation have not been investigated to date, thus only generalized statements as to the conditions of shale sedimentation in the Prichard Formation can be made. Even though the author observed possibly wave reworked siltstones in the Aldridge Formation (Canadian equivalent of Prichard Formation) and sandstone beds with possible hummocky cross-stratification in the mid-Prichard quartzites (unit E of Cressman, 1985), the bulk of the Prichard Formation lacks these features and it can safely be assumed that it was deposited below storm wave base. As to the maximum depth of Prichard deposition, there are at present no data available that would allow an estimate to be made with any degree of confidence. However, Cressman (1989), by interpreting a quartzite member of the Prichard Formation as a submarine fan deposit, and by analogy with modern submarine fans of similar size, suggested that the depth of deposition of the Prichard Formation might have been as large as 2500 m.

Accumulation of the Prichard Formation h been likened to turbidite deposition in front c large river delta (Cressman; 1984). The *thick silt/mud couplets* (Fig. 4) show considerable resemblance to fine-grained turbidites as described by Stow and Shanmugam (1980). Considering that sandy turbidites are common in the Prichard Formation (Cressman, 1984), it is plausible to interpret the thick silt/mud couplets that are so common throughout the sequence as fine-grained turbidites. Indirect evidence, such as the abundance of mud, the complete absence of carbonates, and geochemical data led Cressman (1989) to believe that Prichard sediments were supplied to the Belt basin by a large river, and that the turbidites of the Prichard Formation are related to deltaic deposition. With this premise in mind, the thick silt/mud couplets could, for example, be interpreted as the deposits of muddy density flows that entered the basin during major river floods.

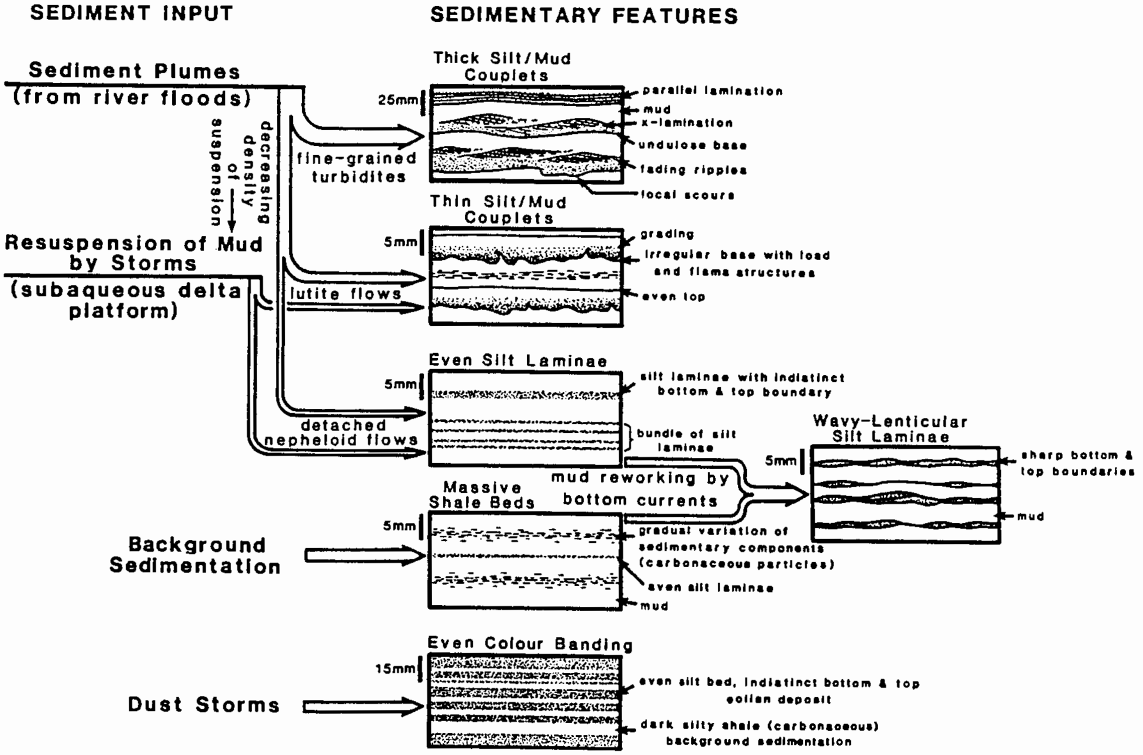

Fig. 4. Summary of sedimentary features and envisioned depositional processes for shales from the Prichard Formation.

In keeping with an overall turbidite interpretation one might of course assume that the *thin silt / mud couplets* are part of the proximal–distal continuum commonly found in turbidite sequences, and are simply distal equivalents of thick silt/mud couplets. However, except for grading, basal load casts, and flame structures, the thin silt/mud couplets seem to lack other sedimentary features that have been observed in muddy turbidites (Stow and Shanmugam, 1980). In particular, when Stow and Shanmugam's (1980) "standard sequence" for fine-grained turbidites is applied to the thick silt/mud couplets, the latter may exhibit complete $T_0 - T_7$ sequences (the bioturbated T_8 division is necessarily absent in Precambrian sediments) as well as a whole spectrum of partial sequences. In contrast, the thin silt/mud couplets do not exhibit variability with respect to the observed sequence of sedimentary structures and are in comparison very thin. The absence of any internal sedimentary features but grading (Fig. 4) implies that transporting currents were very weak or absent. Thus, though one could still interpret them as very distal, fine-grained turbidites, there is the possibility that they are of different origin. For example, storms that resuspended fine sediment on the adjacent shelf/prodelta, as well as river floods could have given rise to short lived lutite flows (very low-density and low-velocity turbidites; McCave, 1972) that can be expected to deposit very thin graded layers in deeper parts of the basin.

Analogous to interpretations of Newland shales (Schieber, 1989b), the absence of internal features indicative of erosion or omission as well as gradational variations in the content of sedimentary components suggests that *massive shale beds* are the product of continuous pelagic background sedimentation. *Even silt laminae* in these beds resemble thin parallel silt laminae observed in Devonian black shales of New York (O'Brien, 1989), that were interpreted as the deposits of low-density detached turbid layers. Alternative processes that could lead to such laminae are gradually shifting sediment supply by nepheloid flows (Moore, 1969), "suspension cascading" of nepheloid flows (McCave, 1972), or a combination of settling from detached nepheloid flows and pelagic background sedimentation (Stanley, 1983).

Absence of internal grading, small thickness, and sharp bottom and top contacts suggest that the *wavy-lenticular silt laminae* are not the result of distal turbidite deposition, but rather the consequence of sediment reworking by weak bottom currents (Reineck, 1974). The T_3 division in Stow and Shanmugam's (1980) fine-grained turbidite model bears resemblance to "sets" of wavy-lenticular silt laminae in Prichard shales, suggesting that alternatively these laminae might fit a fine-grained turbidite model. However, wavy-lenticular silt laminae were not observed within thick silt/mud couplets (fine-grained turbidites), thus suggesting that they are of unrelated origin. So far none of the thick and thin silt/mud couplets in the Prichard Formation have shown evidence of reworking in the top portion, an indication that bottom sediment reworking was minor and affected only the uppermost few millimetres of the sediment. It is suggested here that massive shale beds and their included even silt laminae were reworked by bottom currents to produce the wavy-lenticular silt laminae.

In the case of shales with *even colour banding*, wide areal distribution as well as even and continuous appearance of laminae suggests that these shales were deposited in deep water (Huebschman, 1973) beyond the influence of storm waves. Huebschman (1973) suggested that the silt that formed the continuous silt laminae was blown across the basin by dust storms, and that widespread surface blooms of planktonic algae supplied the carbon for the dark bands. Because the dark bands also contain more clays, it is possible that they actually reflect periods of smaller supply of eolian material when the pelagic background sedimentation of organic matter and clays formed a larger proportion of the bottom sediments. In that scenario the light bands would then represent episodes of large eolian sediment supply. Alternatively, colour-banded siltstones could also have been caused by settling of suspended sediment from river plumes that spread out over the surface. Cressman (1989) estimated that the river that supplied the bulk of Prichard sediments was in size and sediment load roughly comparable to the modern Mississippi. However, Mississippi sediment plumes deposit the bulk of their silt load in delta-front and prodelta environments, and sediment plumes typically do not extend more than 15–20 km offshore of the river mouth (Coleman and Prior, 1980). That river plumes in the Belt basin should have carried silt material hundreds of kilometres beyond the shelf edge appears highly unlikely in light of modern analogs.

A whole array of processes, such as gravity flow initiated by river floods or storm resuspension, pelagic settling, dust storms, and bottom current reworking, may have been involved to produce the observed sedimentary features in Prichard shales (Fig. 4). As for gravity flows alone, an attempt has been made to identify the deposits of muddy turbidity flows, lutite flows, and detached nepheloid flows. Given the bias in the literature towards turbidity current deposits in deep-sea environments, many might argue that most of the observed features can be explained by a natural progression in the waning of a dilute turbidity current. However, in modern environments the interplay of turbidity, traction, and hemipelagic settling mechanisms is commonly observed and produces a continuum of laminated mud types (Stanley, 1983). This being the case, it appears very unlikely that the features of Prichard shales can summarily be attributed to turbidity currents. Alternative mechanisms have to be considered as well.

Weathering and iron staining of Prichard Formation outcrops make it difficult to observe details of the reported sedimentary features in the field. Thus most observations were made on petrographic thin sections, complemented by observations on slabbed hand specimens. Future research into sedimentary features of these shales will focus on drill core studies, in order to better understand associations of sedimentary features. Results from that work should help to identify better the various depositional processes that were active during deposition of Prichard shales.

Shales of the upper Belt Supergroup

The upper Belt Supergroup (Harrison, 1972), comprising the Ravalli Group, the Middle Belt Carbonate, and the Missoula Group, contains considerable more sandstone than the lower Belt Supergroup, but overall the sequence is still dominated by shales. Winston (1984), in a study primarily directed at the Missoula Group, developed a classification scheme of rock types that also includes several categories for mudrocks. This classification scheme, which primarily focuses on sedimentary structures rather than colour and composition, was also applied by White and Winston (1984), Lemoine and Winston (1986), Slover and Winston (1986), Winston (1986a), and Winston et al. (1986) in studies of the Ravalli Group and the Middle Belt Carbonate. All the sediment types described below have a wide compositional range, from wholly terrigenous to mixed terrigenous/carbonate to carbonaceous. Descriptions are summarized from Winston (1986a). The shale-dominated rock types of Winston's classification scheme are:

(A) *Even couplet sediment type*. This sediment type consists of very fine sand and silt layers that grade upwards into clay. Couplets are between 0.3 and 30 mm thick, and are even to slightly wavy. The lower portion of the couplets contains local scours at the base, parallel lamination and climbing ripple lamination. Red varieties (hematitic) of this sediment type contain a relatively large proportion of sand and are characterized by mudcracks and mudchips, whereas the greenish (chloritic) varieties contain a relatively large proportion of mud and show considerably fewer mudcracks and mudchips.

(B) *Lenticular couplet sediment type*. This sediment type consists of lenses and wavy layers of fine sand and silt that are overlain with sharp contact by a mud layer. Bedding surfaces of sand/silt layers commonly show symmetrical wave ripples and occasionally also interference ripples. Mudcracks occur in variable amounts.

(C) *Microlamina sediment type*. This sediment type consists of millimeter-scale laminae of quartz or dolomitic silt overlain by equally thin mud laminae. The latter can contain sufficient organic carbon to give them a black colour. Couplets range in thickness from 0.5 to 3 mm. This sediment type may show soft sediment deformation, synaeresis cracks, scoured surfaces, and locally stromatolites.

(D) *Pinch and swell and couplet sediment type.* This sediment type consists of fine sand and silt at the base, grading upwards into mud. Couplets thicken and thin across outcrops and are up to 30 mm thick. The silt portions show well developed load casts into underlying mud. Silt filled synaeresis cracks are common.

Sedimentary features of above sediment types are summarized in Fig. 5. Winston (1986a) developed a sedimentological model for sediment types in the upper Belt Supergroup. According to his model, the first three sediment types described above occupy the distal end of a facies tract that reaches from alluvial aprons through sea (or lake) margin flats to basinal muds. The most proximal of above sediment types is the *even couplet type*. Its red variety is thought to have been deposited on exposed mudflats by decelerating sheetfloods, whereas the green variety is thought to represent flood-generated influxes into standing water that settled from suspension (Winston, 1986a). Further basinward, the *lenticular couplets* are probably an equivalent of wave-generated lenticular and wavy bedding in modern sediments (Reineck and Singh, 1980, p. 114). Lateral association of this sediment type with the even couplets suggests that lenticular couplets are simply even couplets that were deposited in standing water by floods and then reworked by waves. The variable amounts of mudcracks in this sediment type are in their abundance probably related to the relative depth of deposition. Finally, the *microlamina sediment type* was deposited in the central portions of the basin. It has been suggested that this sediment type reflects periodic influx of small amounts of sediment (Winston, 1986a), and that microbial mats (carbonaceous laminae) colonized the sediment surfaces between sedimentation pulses (Grotzinger, 1981).

The *pinch and swell couplets* are particularly common in the Middle Belt Carbonate and form the distal part of a clastic tongue that was shed into the Belt basin from a western source area (Winston, 1986a). Their relationship to other sediment types is not well understood, but they appear to have been deposited seaward of the lenticular couplet type and landward of the microlamina sediment type. Winston interpreted them as the result of suspension settling from turbidite interflows that moved across the basin along density contrasts in a stratified water column. He quotes the absence of traction-generated features, such as

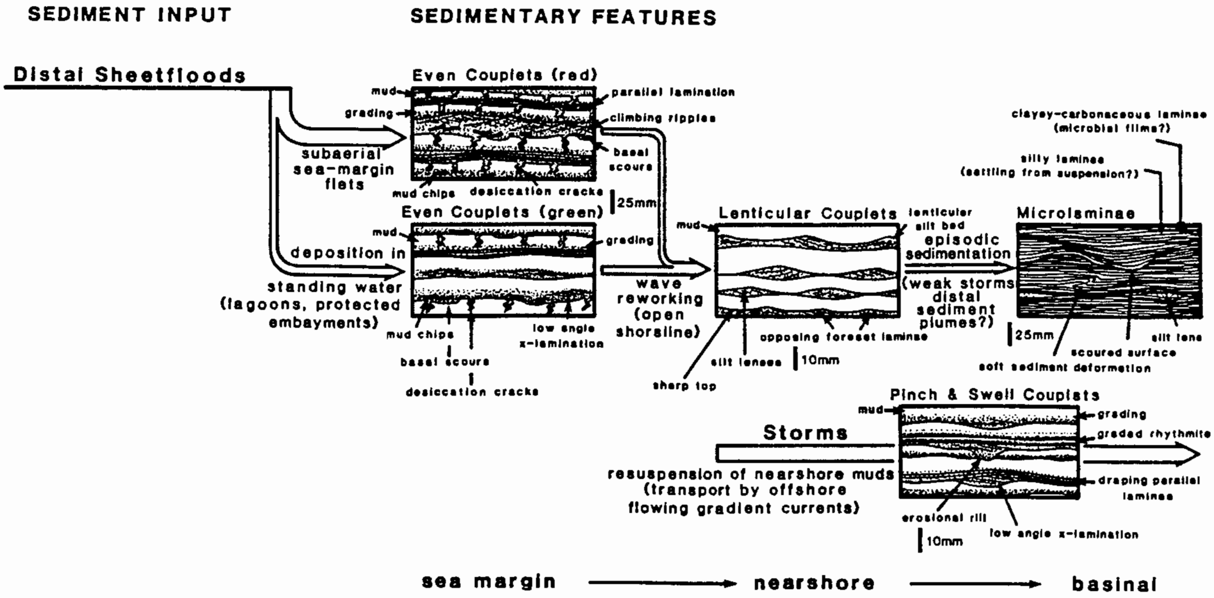

Fig. 5. Summary of sedimentary features and envisioned depositional processes for shale-dominated sediment types of the upper Belt Supergroup. Shale sediment types or facies types are arranged according to proximal vs. distal relationships as proposed by Winston (1986a).

ripple cross-lamination as evidence in favour of such an interpretation. However, Grotzinger (1986) suggested that these sediments were transported into the basin by storm-induced, offshore-flowing gradient currents (Aigner and Reineck, 1982); an interpretation that is further supported by the presence of hummocky cross-stratification in interbedded sandstones. Examination of hand specimens and thin sections of this sediment type by the author showed the presence of basal scours, low-angle cross-lamination, parallel lamination, and graded rhythmites (Fig. 5), suggesting a storm origin as proposed for silt/mud couplets in the Newland Formation (Schieber, 1986a, 1987, 1989b). A storm deposit interpretation of this sediment type places it at a water depth between fair-weather and storm wave base.

Pinch and swell structures may potentially also be the result of deformation and low grade metamorphism in Belt rocks. However, internal sedimentary features of pinch and swell couplets, such as cross-lamination, are undeformed and show that the pinch and swell appearance is a primary feature of these beds.

Summary of shale sedimentation in the Belt basin

As is evident from the preceding sections, graded sand/silt-to-mud couplets are a common feature of most shale units in the Belt Supergroup (Figs. 3, 4, and 5). Detailed examination shows that there is actually a great variety of distinguishable couplet types. Knowledge of sedimentary features within these couplets, combined with knowledge of stratigraphic relationships, makes it possible to assign environmental significance to the various couplet types. Graded couplets in shales of the Belt basin were deposited by distal sheetfloods on exposed mudflats and in shallow nearshore environments (even couplets, Fig. 5), were generated by wave action in shallow-water settings (lenticular couplets of the upper Belt Supergroup, Fig. 5; lenticular to wavy bedding in the Newland Formation, Fig. 3), were carried into the basin by offshore-flowing gradient currents during storms (pinch and swell couplets of the upper Belt Supergroup, Fig. 5; graded silt/mud couplets of the Newland Formation, Fig. 3), and were deposited by gravity flow as fine-grained turbidites (thick silt/mud couplets of the Prichard Formation, Fig. 4) and lutite flow posits (thin silt/mud couplets of the Prich Formation, Fig. 4). Obviously, careful study of couplets and recognition of their specific features in the case of Belt basin shales is an important tool in the interpretation of shale depositional environments.

The deposits of benthic microbial mats are a common feature in the permanently submerged portions of the basin (microlamina sediment type of the upper Belt Supergroup, Fig. 5; striped shales of the Newland Formation, Fig. 3). Except during strong storms, the microbial mats probably protected the sediment surface from erosion by bottom currents. Because microbial mats are effective environmental barriers (Bauld, 1981), they also helped to create a strongly reducing environment in the accumulating sediments and made possible the accumulation of carbonaceous shales in aerated shallow-water environments (Schieber, 1986a). The absence of microbial mat deposits can be interpreted in terms of continuous background sedimentation (reduced light penetration of the water column), or in terms of frequent wave reworking in shallow-water environments (carbonaceous sv shale).

Deeper-water shales of the Belt basin, or more specifically of the Prichard Formation, show, in addition to fine-grained turbidites and the deposits of lutite flows, features that can be interpreted as sediment reworking by bottom currents (wavy-lenticular silt laminae), nepheloid flows (even silt laminae), and deposits of wind blown dust that was carried across the basin (even colour-banded shale). Depositional processes and transport mechanisms in the Prichard Formation have been inferred from comparison with modern deep-sea sediments. Cressman's (1989) 2500 m water depth estimate is only based on comparison of Prichard sediments with modern analogs (see introduction) and therefore is very tenuous. If one considers the epicratonic setting of the Belt basin it seems unlikely that water depth during Prichard Formation deposition was anywhere near the depth of modern ocean basins. The epicratonic setting and the relatively small size of the basin probably resulted in a much smaller wave fetch and consequently much shallower wave base than is encountered in modern oceans. Under such circumstances, transport processes, such as nepheloid flows, that are known to occur in modern ocean basins at considerable depth, may well have been operative at much shallower depths.

Comparison with other Proterozoic shales

Probably the most striking two features of the Belt basin shales are the common occurrence of a wide variety of graded couplets and the deposits of benthic microbial mats. That these two features of Beltian shales are not an isolated occurrence in the Proterozoic is indicated by the presence of graded couplets in Proterozoic Shales from Australia (Moondarra Siltstone, Urquhart Shale, Gunpowder Creek Formation; personal observations), from North America (Nonesuch Shale; Elmore, 1981), and from India (Simla Slates; Singh, 1980). Most of the graded couplets in these examples resemble the graded silt mud couplets and pinch and swell couplets of the Belt basin, and were probably the result of storm deposition. Graded couplets in sea marginal environments of the Belt basin have been related to sheetfloods coming down alluvial aprons (Winston, 1986a). In the Proterozoic, basins with alluvial aprons along the shoreline seem to have been a common occurrence (Elmore, 1981; Gustavson and Williams, 1981; Neudert, 1981; Winston, 1986a) and thus shales like those along the margins of the Belt basin should be quite common in other Proterozoic basins as well.

Possible Proterozoic equivalents of the benthic microbial mat deposits in the Belt basin are known to the author from Australia (Barney Creek Formation, Urquhart Shale; personal observations), and North America (Nonesuch Shale). Detailed study of other Proterozoic shale sequences will most likely add to the list of above examples.

Conclusion

A survey of shales from the Mid-Proterozoic Belt Supergroup shows that shales of this sequence contain a wealth of sedimentary features and a large number of different shale facies types. The sedimentary features and their combinations allow the interpretation of the depositional environments of these shales.

Graded sand/silt to mud couplets were deposited in a whole range of depositional environments, from marginal marine to deep basinal. The variability of sedimentary features in these couplets reflects differing depositional processes, such as sheetfloods, storms, turbidity currents, and lutite flows, and makes them good guides to depositional environments. The common presence of graded couplets in other Proterozoic shales suggests that what has been learned from shales of the Belt basin can be applied profitably elsewhere.

Deposits of benthic microbial mats have been identified in permanently submerged shale environments from the Belt basin and appear also to be present in a number of other Proterozoic shale sequences. Presence of such deposits indicates that sedimentation was episodic rather than continuous, and also implies that the sediment surface was protected from erosion by bottom currents.

Shales that were deposited in the deepest portions of the Belt basin reflect sedimentation from muddy turbidity currents, nepheloid flows, bottom currents and windblown dust, and their sedimentary features show considerable resemblance to Phanerozoic deep-water shales and modern deep-sea muds. The shallow-water shales of the Belt basin, on the other hand, do not at all look like their Phanerozoic counterparts. Though the latter may contain silt/mud couplets comparable in origin to those of shallow-water Belt basin shales, the abundance of couplets is generally much lower. The evolution of bioturbating organisms in the Phanerozoic is probably the main reason for that difference because it greatly reduced the preservation potential of primary sedimentary structures that are so perfectly preserved in Precambrian shales.

The advent of metazoan grazers towards the end of the Precambrian is probably the main reason why benthic microbial mat deposits are essentially unknown from Phanerozoic shales. The similarity between deep water shales of the Belt sequence and Phanerozoic shales has two reasons: (1) similar processes of deep-water clastic sedimentation in the Precambrian and Phanerozoic; (2) relatively minor bioturbation of Phanerozoic deep-water clastics (Potter et al., 1980, p. 44). The latter phenomenon is probably due to the effects of relatively large sedimentation rates in turbidite basins (when compared with pelagic sediments) and of the limited nutrient supply in deep-sea settings (Seilacher, 1967). Both effects serve to limit the development of sediment-feeding infauna that typically dominates deep-water environments. In a number of Phanerozoic examples, oxygen-deficient or anoxic conditions of bottom waters probably also contributed to the preservation of primary sedimentary structures in bottom muds. Thus, whereas deep-water shales of all ages seem to show similar sedimentary features, the appearance of shallow-water shales changed considerably from Proterozoic to Phanerozoic.

It should be obvious from the examples in this paper that far from being the "uninteresting matrix" interbedded with other sediments, shales do indeed contain a wealth of information. This information actually allows meaningful interpretations of depositional environments and paleogeography, and opens up an additional dimension for basin analysis.

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