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Storm-dominated epicontinental clastic sedimentation in the Mid-Proterozoic Newland Formation, Montana, U.S.A.

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With 9 figures in the text

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Abstract: The Newland Formation, a shale dominated Mid-Proterozoic sequence, occurs in the Big Belt and Little Belt Mountains, USA. Within this sequence two types of storm deposits were recognized: A) medium to coarse grained hummocky cross-stratified sandstones, B) silt/mud couplets in the shales. These storm deposits probably formed in response to storms of variable strength. Evaluation of possible transport processes shows that the storm sands were probably deposited during unusually strong storms by basinward flowing gradient currents, and the available data suggest that these sandstones were at least partially transported in bedload. The sandstones were probably derived from nearshore sandbars and show systematic lateral changes in frequency of occurrence, mean bed thickness, and cumulative thickness of sandstone, from basin margin to basin centre. Silt/mud couplets were probably the products of relatively weak storms, and from comparison with modern examples one may conclude that they were probably carried into the basin in suspension.

Zusammenfassung: Die Newland Formation, eine mittelproterozoische schiefertonreiche Sedimentabfolge, ist in den Big Belt und Little Belt Mountains, Montana, USA, aufgeschlossen. Zwei verschiedene Typen von Sturmablagerungen wurden in diesen Sedimenten festgestellt: A) mittel- bis grobkörnige Sandsteine mit »hummocky cross-stratification«, B) gradierte siltig-tonige Lagen in den Schiefertonen. Diese Sturmlagen wurden von Stürmen unterschiedlicher Stärke erzeugt. Eine Abwägung der verschiedenen möglichen Transportprozesse ergibt, daß die Sturmsande während sehr starker Stürme von Gradientenströmungen abgelagert wurden. Es ist möglich, daß diese Sande zumindest teilweise in Rollfracht transportiert wurden. Die Sturmsande weisen vom Beckenrand zum Beckenzentrum systematische laterale Änderungen in Häufigkeit, durchschnittlicher Sandlagendicke und gesamter Sandsteindicke auf. Die Erosion küstennaher Sandbänke lieferte das Ausgangsmaterial für diese Sturmsande. Gradierte siltig-tonige Lagen wurden vermutlich von relativ schwachen Stürmen abgelagert. Es ist wahrscheinlich, daß diese feinkörnigen Sturmlagen, ähnlich wie vergleichbare Rezentbeispiele, in Schwebfracht in das Sedimentationsbecken transportiert wurden.

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Introduction

Shales and sandstones of the Mid-Proterozoic Newland Formation, Montana, U.S.A., contain sedimentary structures that indicate that a significant portion of these sediments was deposited by storms. Sandstone beds in the Newland Formation superficially resemble turbidites, yet the observed sedimentary structures in the sandstone beds are not typical of deposits formed by turbidity currents. The shales contain siltsone beds and silt/mud couplets that show great similarity to storm deposits in recent shelf muds (Reineck & Singh 1980).

A variety of mechanisms has been proposed to explain offshore sediment transport during storms. Gadow & Reineck (1969) proposed sediment transport by suspension clouds for storm deposits of the North Sea, Hamblin & Walker (1979) and Hayes (1967) proposed sand transport by density currents, and Nelson (1982) reported bedload transport for storm sands from the Bering Sea. The storm deposits of the Newland Formation were most likely transported in suspension and bedload.

Relationships between storm sand distribution and paleoshorelines as shown in this study support previous work on interpretation of proximality in ancient and recent storm deposits (Johnson 1978, Goldring & Bridges 1973, Aigner & Reineck 1982, Dott & Bourgeois 1982).

Geologic setting

The Belt Supergroup was deposited in the epicontinental (Stewart 1976) Belt basin between 1450 and 650 m. y. ago (Harrison 1972). The Newland Formation occurs in a subbasin of the Belt basin, the so-called Helena embayment (Fig. 1), and has been subdivided into a lower member (mainly dolomitic shales) and an upper member (interstratified packages of shales and carbonates) by Nelson (1963). In the Little Belt Mountains and the northern Big Belt Mountains the upper member of the Newland Formation is approximately 500 m thick, and shale packages comprise about 70% of the stratigraphic sequence (Schieber 1985). Harrison (1972) correlates the Newland Formation with the Prichard Formation of the Lower Belt Supergroup. Stratigraphic and sedimentologic features of the Proterozoic sediments in the Helena embayment were investigated by Schieber (1985), and a brief overview is given in Schieber (1986a).

The lower and upper member of the Newland Formation are separated by a shale unit that contains beds of feldspathic sandstones. This unit was deposited during an episode of regression and uplift in the hinterland, and is informally called the "Newland Transition Zone" (or NTZ). In the northernmost exposures of the NTZ the most conspicuous lithologies are very coarse feldspathic sandstones in erosional channels and quartz pebble conglomerates. These sandstones are interbedded with shales, may contain mudchips and may have mudcracks on bedding planes. The amount of sandstone in the NTZ decreases towards the south, and hummocky cross-stratified sands are the lateral equivalents of the nearshore sandstones described above. Aside of the NTZ, sandstone beds are rare in the Newland Formation.

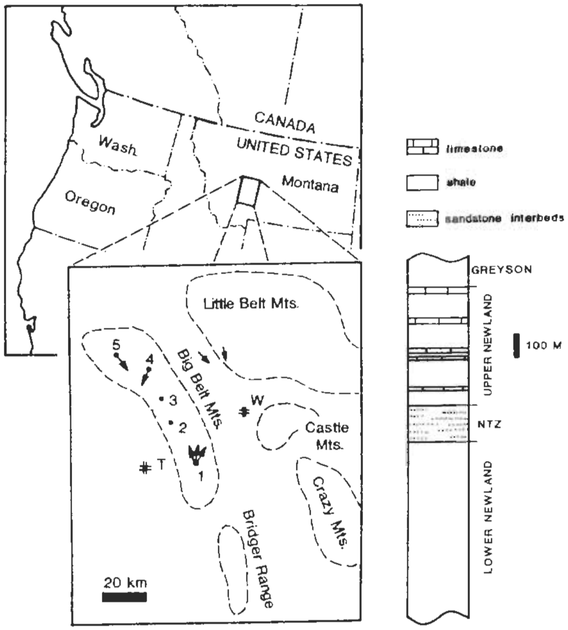

Fig. 1 Location of study area. Belt basin outlined by stipple pattern. The Helena embayment is the eastern extension of the basin. Enlarged portion of map shows mountain ranges and stratigraphic sections mentioned in the text. Explanation of symbols: 1 – Deep Creek section, 2 – Duck Creek section, 3 – Confederate Gulch section, 4 – Avalanche Creek section, 5 – Trout Creek section, T – Townsend, W – White Sulphur Springs, arrows indicate paleoflow directions in sandstones. To the right of the enlarged map portion a summary stratigraphic section of the Newland Formation in the Big Belt Mountains is shown.

Petrography

The sandstones are composed of well rounded quartz and carbonate grains (0.25–1.0 mm). The carbonate grains vary in abundance from 20% to 40% and consist of oolites, grainstone fragments, and fragments of fine crystalline limestone and dolostone. The sandstones may contain up to 30% feldspars (mainly K-spar), but typically they contain between 5% and 15%. The sandstones are cemented by overgrowth quartz, chert, and sparry calcite or dolomite, and are typically well sorted.

The sandstones are very weathering resistant because of predominant quartz cement, and for this reason internal sedimentary structures of sandstone beds are in many places not very prominent. Therefore line drawings were used in this paper to highlight sedimentary features in outcrop photos.

The shales consist mainly of illite, quartz and dolomite, and are distinctly bedded. The thickness of individual beds ranges from a few mm to several cm. A summary of shale compositions can be found in SCHIEBER (1986b), and detailed descriptions are given in SCHIEBER (1985).

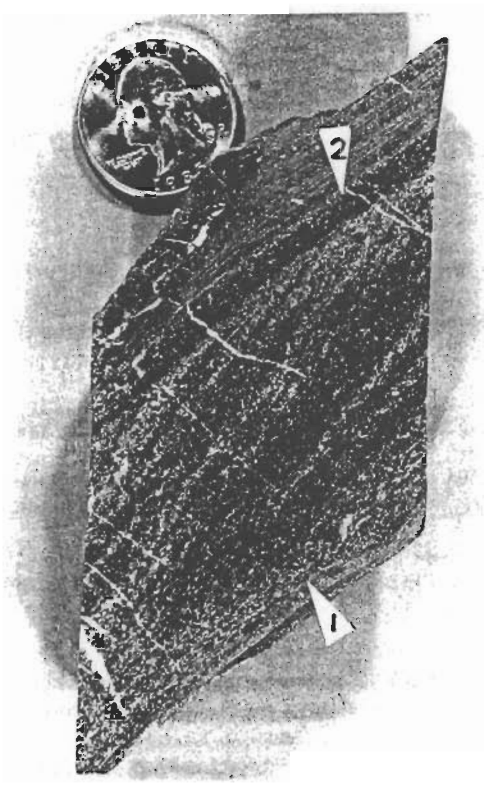

Fig. 2. Drill core sample of cross bedded sandstone. Base of bed marked by arrow 1, top of bed marked by arrow 2. Coin is 24 mm in diameter.

Sedimentary structures

Sandstones

The sandstones occur interbedded with shales and range in thickness from 1 cm to 150 cm. They occur mostly as tabular, sheet-like bodies, or as horizons of sandstone lenses. In some areas they are channel-fill deposits (width up to 3 m, depth up to 0.5 m). Sandstone sheets are persistent throughout the extent of the outcrop and can commonly be traced for several tens of metres.

All sandstone beds have a sharp base and most of them also have a sharp top. Basal contacts are mostly undulate and in places may display flute marks, rope-like scour marks, and also narrow, deeply incised furrows that resemble gutter casts. In the inner parts of the basin gradational upper contacts are more common and best developed on the thickest sandstone beds. On the whole, however, normal grading in sandstone beds is not the rule but rather the exception. In basin-marginal areas no gradational upper contacts were observed. Sandstones may show cross-stratification with bedsets of 4–20 cm thickness (Fig. 2) and individual crossbeds that are between 2–20 mm thick. Two different types of cross-stratification were observed. The first type is low-angle cross-stratification in which the cross-laminae are parallel to the lower set boundary or the base of the bed. It resembles hummocky cross-stratification (HCS) as defined by HARMS et al. (1975) and DUKE (1985), and is the prodominant type of cross-stratification in the Newland sandstones (Fig. 3, Fig. 4). In the second type the cross-laminae terminate against the lower set boundary (Fig. 2) and foreset inclinations are steeper (inclinations as steep as 28° were observed). This type of cross-stratification fits the definition of planar cross-bedding as given by REINECK & SINGH (1980), and in the remainder of the paper we will simply refer to it as cross-bedding. If found, cross-bedding occurs most commonly in the lower portions of sandstone beds, but beds that formed in basin-marginal areas may show cross-bedding throughout the thickness of the bed. Thinner sandstone beds may consist of only a single bedset (Fig. 2). Additional sedimentary structures are small current ripples and parallel, draping laminae of fine sand in the upper portions of sand beds (Fig. 5). These parallel laminae may in places grade upwards into mudstone. In places discontinuous mud drapes (up to several cm thick) occur within sandstone beds (Fig. 5). Some beds consist of overlapping lenses of sandstone (up to 60 cm long and up to 10 cm thick).

Inspection of a large number of sandstone beds showed that the various sedimentary strctures are arranged in a systematic vertical succession if found together in the same bed, and that an idealized sequence of sedimentary structures can be constructed that resembles those proposed by DOTT & BOURGEOIS (1982) and WALKER et al. (1983) for hummocky cross-stratified (HCS) sandstones. Hummocky cross-stratification and cross-bedding can be found in the lower portions of thicker sandstone beds. They are followed by current ripples, par-

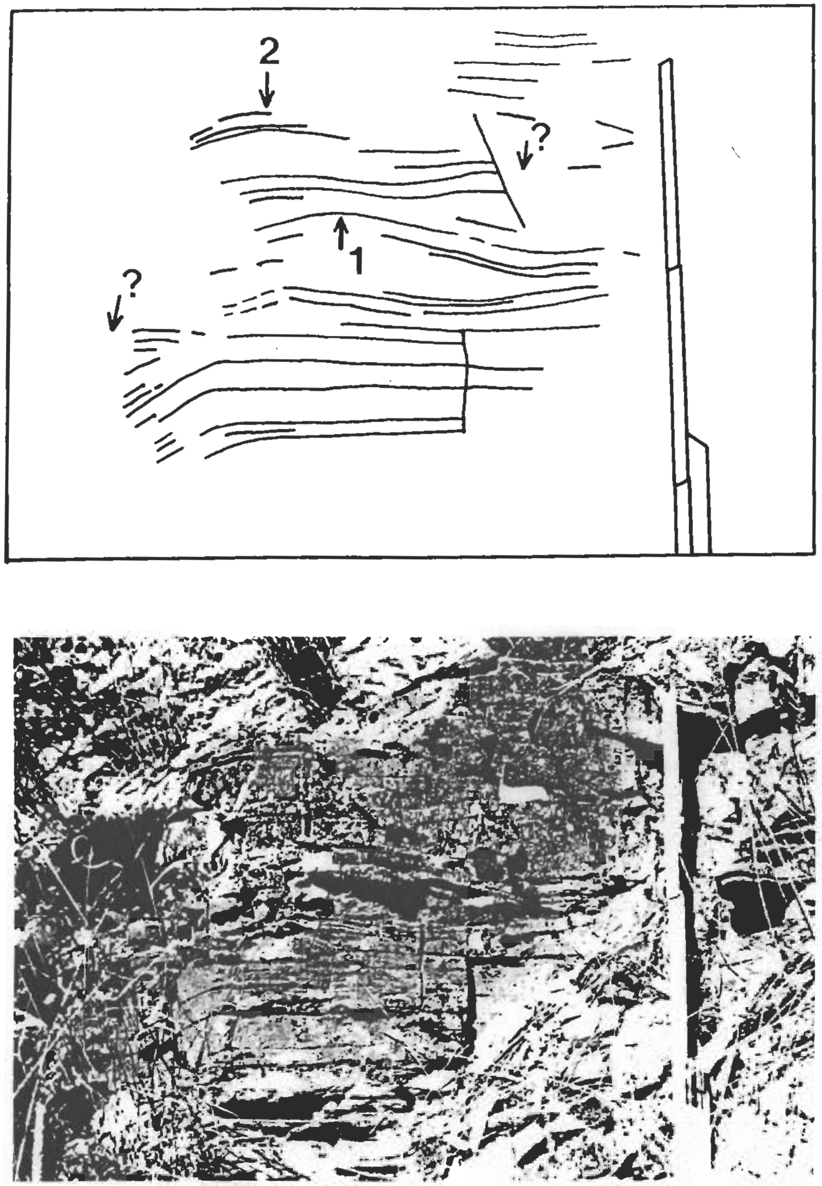

Fig. 3. Hummocky cross-stratification in Newland sandstone bed. Visible bedding features outlined in line drawing. Hummocks indicated by arrows (number 1 and 2). Locations of other probable hummocks indicated by arrows with question mark. Ruler is 50 cm long.

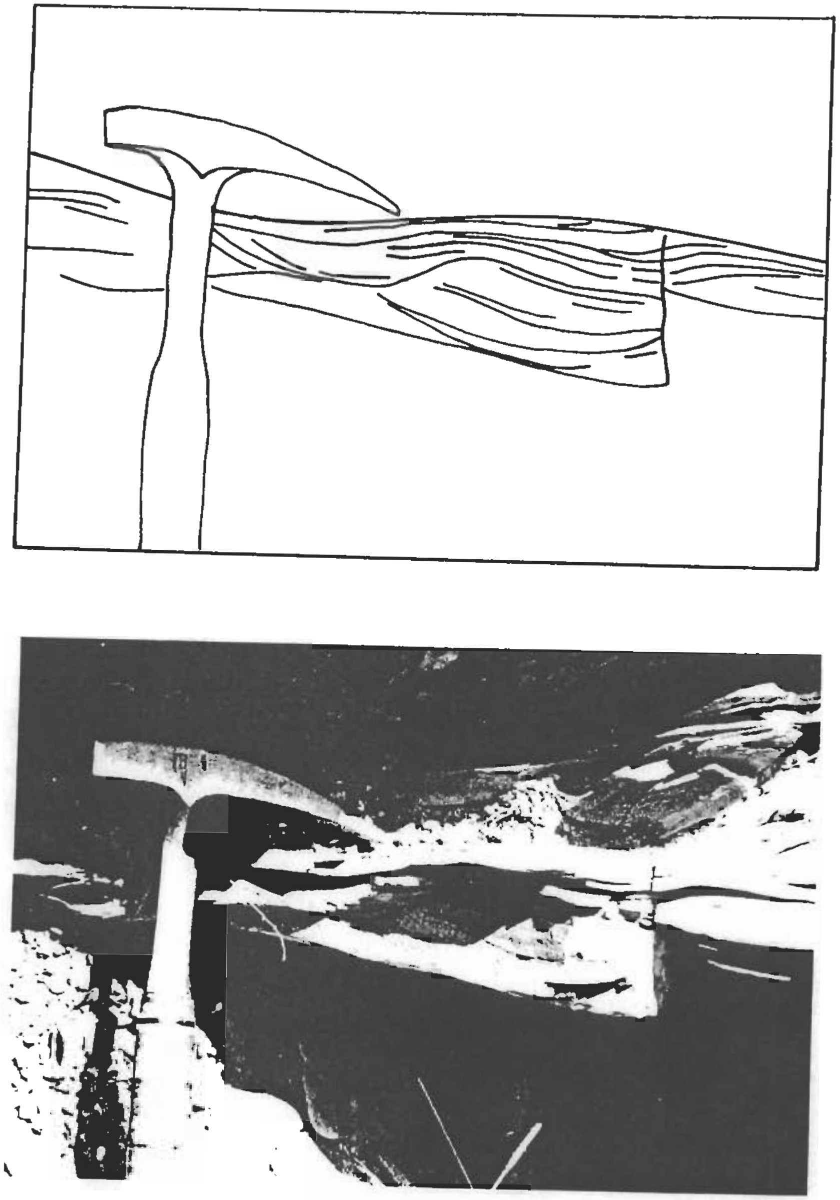

Fig. 4. Thin sandstone bed with hummocky cross-stratification. Laminations highlighted in line drawing. Hammer head is oriented upsection in this and all other figures.

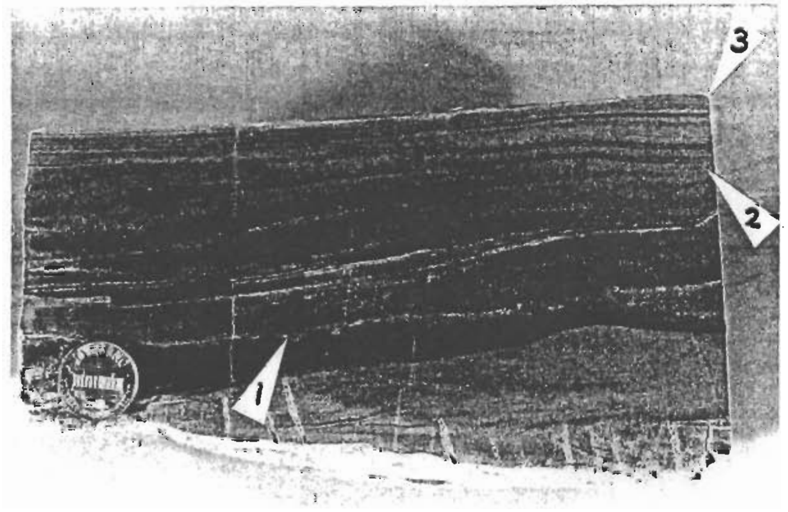

Fig. 5. Draping parallel laminae (between arrows 2 and 3) at top of sandstone bed. Erosive base (arrow 1) cuts into underlying mud drape (dark gray). Mud drape pinches out at back side of sample, causing an amalgamated sandstone bed. Coin is 19 mm in diameter.

allel lamination and finally the graded top portion. Beds that were deposited in a basin-marginal setting commonly lack the upper portion of the described sequence and consist only of hummocky cross-stratified and/or cross-bedded sandstone (Fig. 6). In thick, distally deposited sandstone beds the whole sequence of sedimentary structures can be found. Parts of this sequence may be missing (particularly the part with current ripples is fairly rare), but the vertical order of sedimentary structures remains the same.

Shales

The Newland Formation contains several different types of shale facies (Schieber 1984, 1985). Shales of the Newland Formation are thinly bedded (beds are a few mm to a few cm thick) and commonly contain siltstone beds of similar thickness. Sedimentary features of siltstone beds are essentially the same in the various shales facies types, and a detailed description of these features was presented by Schieber (1986b). Therefore only a brief description of such features will be given in this paper.

The siltstones occur as wavy layers and lenses that may show internal cross-lamination, parallel lamination, and graded rhythmites. Careful inspection shows that many siltstone beds have gradational contacts to the shale bed that

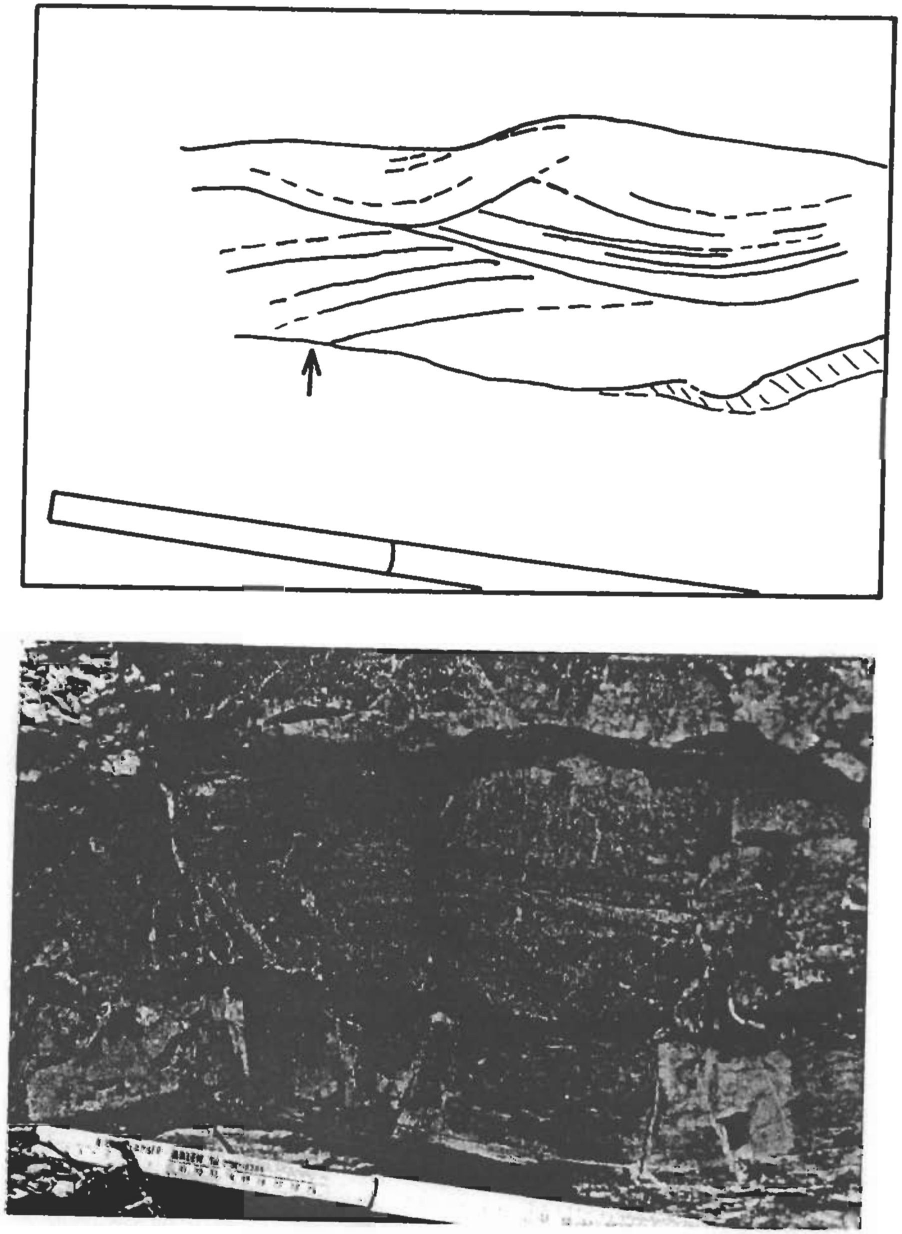

Fig. 6. Hummocky sandstone bed with cross-beds in the basal portion that possibly formed from sand transported in bedload. Bedding highlighted in line drawing. Arrow indicates where basal cross-beds terminate on basal erosion surface. Ruler has cm divisions.

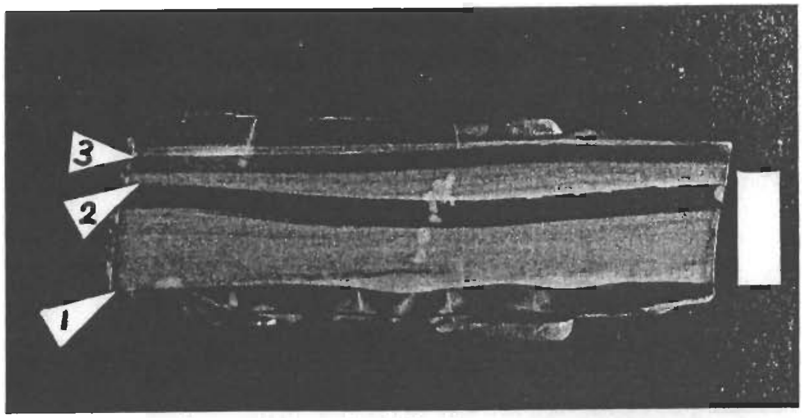

Fig. 7. Storm layers in cut specimen of shale from lower member of Newland Formation. Arrows 1 through 3 point out the bases of 3 successive silt/mud couplets. Note low angle cross-lamination and parallel lamination. Scale bar is 20 mm long.

overlies them, thus forming silt/mud couplets. In places siltstones overlie lenses and beds of lithoclasts (1–20 mm in size), thus forming clast/silt/mud triplets. Erosive bottom contacts may be found at the base of comparatively thick clast and silt beds, but non-erosive bottom contacts are the most common ones. Figure 7 shows silt/mud couplets from shales of the Newland Formation.

Distribution and source of sandstones

Basin configuration

Figure 8 shows the paleogeography of the Helena embayment during deposition of the NTZ. The southern margin of the embayment is defined by the east-west trending outcrop belt of the LaHood Formation (McMannis 1963), an alluvial fan to deltaic deposit (Boyce 1975) that accumulated north of a syndepositional fault zone. The depositional margin of the northern part of the embayment has been eroded, but the distribution of silty shales and nearshore sandstones in the NTZ of the Little Belt Mountains indicates an east-west to west-north-west trending basin margin. West-north-west trending carbonate facies belts in the upper member of the Newland Formation indicate that shoreline trends were similar to those during NTZ deposition (Schieber 1985).

Source of sandstone

The shales that are interbedded with the sandstones of the NTZ do not contain grains of the size and type as found in the sandstone beds. Thus the sandstone beds can not have been created by winnowing of mud and must be considered an allochthonous deposit.

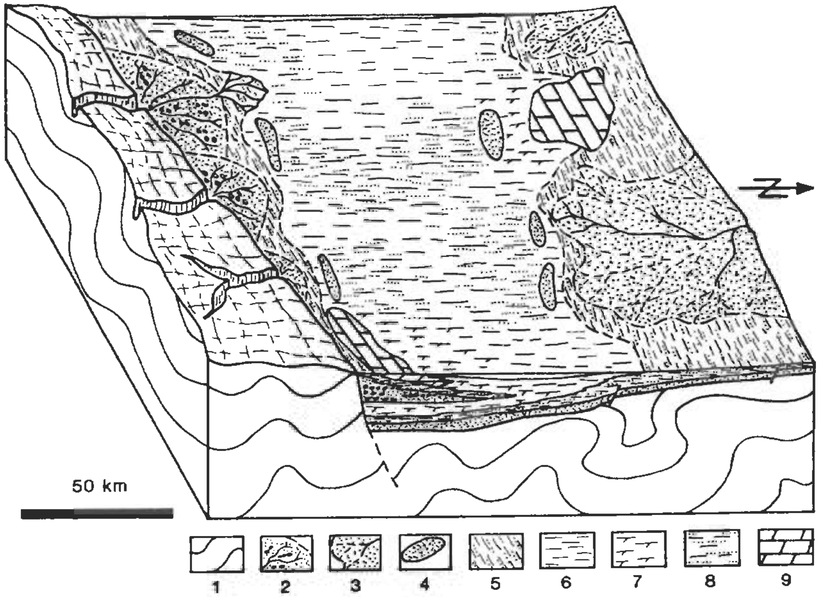

Fig. 8. Simplified paleogeographic sketch of the Helena embayment during deposition of the NTZ. Explanation of symbols: 1 – metamorphic basement, 2 – alluvial fan facies association, 3 – fan-delta facies association, 4 – offshore sand bar, 5 – silty shale (nearshore), 6 – basinal shale with silt/mud couplets, 7 – same shale in dolomitic facies, 8 – shale with sandstone beds, 9 – fine crystalline dolostone (mudflats).

Parallel to depositional strike, the abundance of sandstone in the NTZ is variable and seems to depend on proximity to point sources of sand. In one locality near the northern basin margin, a large sand body, which also contains carbonate pebbles and flat pebble conglomerates, crops out for about 2.5 km parallel to depositional strike, and may extend up to 5 km in intermittent exposures. Available drill hole data show that this sand body migrated basinward with time, and that its long axis most likely was parallel to depositional strike. The most apparent sedimentary structures are cross-bedding and abundant erosion surfaces. This sandbody is interpreted as a shallow marine sandbar which formed parallel to the paleoshoreline. There is some indication (from scattered outcrops) that several comparable sandstone bodies existed along the northern basin margin. Because the bar sands are petrographically identical to the assumed storm-sands, they are regarded as the source for the storm-sand sheets.

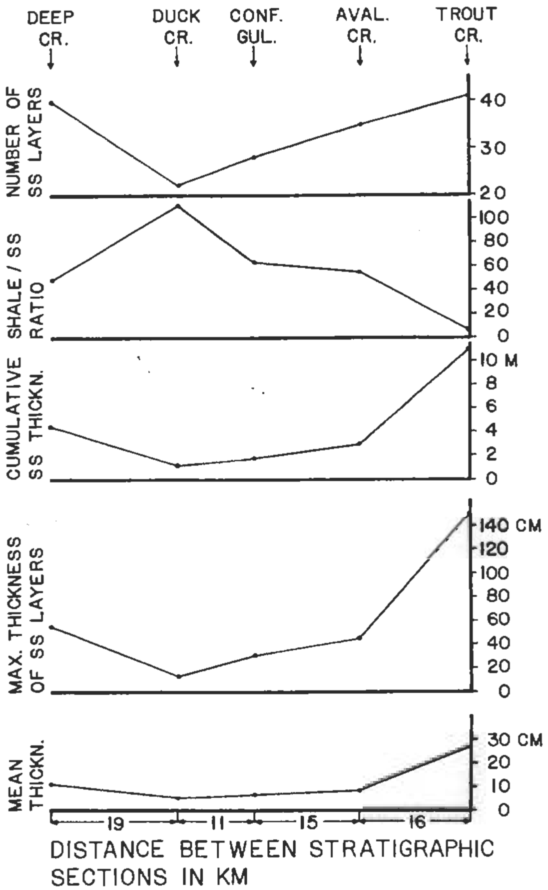

Fig. 9. Lateral variations in the number of sandstone beds, cumulative sandstone thickness, mean thickness of sandstone beds, maximum thickness of sandstone beds, and shale/sandstone ratio in the NTZ of the Big Belt Mountains.

Five stratigraphic sections of the Newland Formation were measured in the Big Belt Mountains (Fig. 1). In these sections the occurrence and thickness of each sandstone bed in the NTZ was recorded. The section line runs approximately perpendicular to the paleoshoreline and Fig. 9 shows the systematic changes in the frequency of sandstone beds, cumulative sandstone thickness, shale to sandstone ratio, maximum thickness of sandstone beds, and mean thickness of sandstone beds. Essentially, the number of sandstone beds as well as the amount of sandstone decreases towards the basin centre. A small number of paleocurrent orientations were collected by measuring directions of flute casts, orientation of erosive channels, and the dip direction of cross-beds at the base of sandstone beds (because basal cross-beds have the highest potential to have escaped later reworking). These data indicate that sandstones in the southern Big Belt Mountains were derived from the south, whereas sandstones in the northern Big Belt Mountains and the Little Belt Mountains were derived from the north (Fig. 1).

Evaluation of transport mechanisms

The presence of hummocky cross-stratification (HCS) in the sandstones strongly suggests that storms played a major role in the formation of these sandstone beds (Harms et al. 1975, Dott & Bourgeois 1982; Duke 1985).

In the case of modern storm deposits, storm-surge ebbcurrents (Nelson 1982), density currents (Hayes 1967), seaward return of suspension clouds (Gadow & Reineck 1969, Reineck & Singh 1972), and wind forced coastal downwelling (Swift et al. 1983) are most commonly cited as probable transport agents of storm deposits. Allen (1982) introduced the term "offshore flowing gradient current", meaning seaward flowing bottom currents that are caused by the wind forced set-up of the sea surface against the shore. These gradient currents cause offshore sediment transport during storms and are principally the same as the "coastal downwelling" described by Swift et al. (1983). Yet, even though in recent storm deposits the transport mechanisms are accessible to investigation, controversy exists as to the mechanisms that created specific deposits (see e. g. Reineck & Singh 1972, concerning storm deposits described by Hayes 1967).

Suspension currents

Many investigators have been vexed by the problem of the transport mechanism in ancient storm deposits, and a major point of controversy seems to be whether or not density currents play a role in transporting storm sands in shallow seas (Walker et al. 1983, Aigner & Reineck 1982).

Hamblin & Walker (1979) propose that retreating sandladen storm surges give rise to density currents. They assume that above storm wave base, wave reworking of turbidites forms HCS sandstones, and that turbidites are formed where these sandstones were deposited below storm wave base. Storm waves do indeed bring a lot of sediment in suspension in nearshore areas, and that sediment is carried offshore during surge retreat (Gadow & Reineck 1969, Nelson 1982). However, in areas where near bottom concentrations of suspended sediment were measured during storms (Swift et al. 1983), sediment concentrations were one order of magnitude lower than required for the autosuspension criterion of Pantin (1979). The stirring effect of waves in a shallow sea may prevent formation of a separate turbid bottom layer, and for that reason Pettijohn et al.

(1972) consider it unlikely that turbidity currents can get started in shallow seas. Pantin (1979) states that conditions for autosuspension (and hence turbidity currents) of fine silt should occur quite frequently in those areas of shallow seas where bottom gradients are 1:100 or steeper. In the case of coarser grain sizes and shallower slopes, storm induced turbidity currents are considered unlikely.

Offshore flowing gradient currents and storm-surge ebb-currents

Both types of currents are a response to storm set-up of the sea surface against the shore. However, whereas gradient currents flow for the whole duration of a storm, storm-surge ebb-currents are restricted to the relaxation period after storms. The water mass that is moved due to offshore flowing gradient currents (or coastal downwelling) vastly exceeds the water mass moved due to storm-surge ebbflow (Swift et al. 1983), especially in the case of major storms that last for several days. One may therefore assume that gradient currents have a greater potential for offshore movement of large quantities of sediment than have storm-surge ebb-currents.

Seaward returning suspension clouds

Suspension clouds are due to wave induced high water turbulence and were observed to effect offshore transport of sediment in the North Sea (Gadow & Reineck 1969, Reineck & Singh 1972). Suspension clouds move offshore with tidal currents or storm-surge ebb-currents and loose their suspended sediment load as turbulence decreases. The North Sea storm deposits are of fairly fine grain size (coarse silt to very fine sand), and it is questionable if significant amounts of coarser grains (such as in the storm sands of the Newland Formation) could be carried offshore by such a mechanism.

Application to the Newland Formation

Sandstones

HCS sandstones are found in the central portions of the Helena embayment and that implies that storm wave base reached the bottom in the centre of the basin. Dott & Bourgeois (1982) estimate that HCS may be expected in water as deep as 80 m. If one assumes a 100 m water depth in the centre and a 40 km distance between basin centre and shoreline for the Newland Formation (Fig. 8), then one arrives at a bottom gradient of 1:400. Because of the small wave fetch of the Helena embayment storm wave base was probably considerably shallower, and the actual bottom gradient even smaller than figured above. As discussed in a preceding section, the small bottom gradient as well as the medium to coarse grain size of the sandstones make it appear highly unlikely that the storm sands in the Newland Formation were transported into the basin by turbidity currents

(Pantin 1979). Similarly, the comparatively coarse grain size of the sandstones makes it appear quite unlikely that seaward returning suspension clouds played a major role in the offshore transport of sand.

The storm sands of the Newland Formation were transported deep into the Helena embayment (Figs. 1, 8, 9) and relatively thick layers of sand accumulated, testifying to the transport of significant volumes of sand. Because offshore flowing gradient currents have a high potential for offshore movement of substantial amounts of sand (see above) it is assumed that they, rather than storm-surge ebb-currents, were the transport agents for storms sands in the Newland Formation.

Shales

Siltstone beds, silt/mud couplets, and clast/silt/mud triplets in the Newland shales have the same sedimentary structures and are very similar in appearance to storm deposits in modern shelf muds of the North Sea and the Gulf of Gaeta, Italy (Reineck et al. 1967, Gadow & Reineck 1969, Reineck & Singh 1971, Schieber 1986b). Gadow & Reineck (1969) and Reineck & Singh (1972) suggested that the North Sea storm deposits were transported by seaward returning suspension clouds, whereas Aigner & Reineck (1982) suggested that offshore flowing gradient currents played a role in the deposition of North Sea storm deposits as well.

The storm sand beds are an indication that storms probably did generate offshore flowing gradient currents during deposition of the Newland Formation. Thus, it is not unreasonable to assume that storm deposits in the shales were deposited from gradient currents as well. Because of the fine grained nature of the storm deposits in the Newland shales, suspension clouds and even density currents (Pantin 1979) are also viable transport mechanisms. However, gradient currents would have been flowing regardless of the competition of other transport mechanisms and most likely were the dominating force in sediment transport (Swift et al. 1983).

Discussion of transport modes: bedload or suspension?

Sandstones

If gradient currents transported the storm sands of the NTZ, how did these currents transport the sand? In bedload, suspension, or a combination of both? Wave reworking tends to obliterate prior sedimentary structures, and therefore direct evidence as to the transport mode might not be available, regardless if the sand arrived in bedload or suspension.

Cross-bedding in sandstones from the NTZ is shown in Figs. 2 and 6. In Fig. 2 the cross-beds are tabular and extend from the top to the bottom of the bed, thus indicating lateral accretion of cross-beds and bedload transport of sand. In

HCS sandstones, the cross-laminae are usually parallel to the lower set boundary or the base of the bed (HARMS et al. 1975, HAMBLIN & WALKER 1979, DUKE 1985). The cross-laminae in the lowermost bedset of the sandstone bed in Fig. 6 terminate against the erosional base, and this suggests lateral accretion of laminae and bedload transport of sand. The relatively shallow dips of cross laminae and the tangential foresets may indicate suspension transport in addition to bedload (JOPLING 1965). In the upper part of that same sandstone bed (Fig. 6) the laminae of bedsets are essentially parallel to the lower erosion surfaces and stratification looks more similar to HCS. Thus, the upper portion of the sandstone bed has probably been reworked by waves.

HUNTER & CLIFTON (1982) suggested that HCS forms in a combined flow regime of both mean flow and wave generated oscillatory currents. This suggestion is supported by SWIFT et al. (1983) who concluded that hummocky megaripples (which they consider recent equivalents of HCS) on the Atlantic shelf were deposited by combined flow currents. DUKE (1985) questions SWIFT et al.'s (1983) identification of hummocky megaripples as modern equivalents of HCS, because of high-angle cross-bedding that he observed particularly in the lower portions of SWIFT et al.'s hummocky megaripples. DUKE suggests that the latter are merely megaripples that were partially reworked by storms waves. If by itself, the undirectional component in the combined flow regime described by SWIFT et al. (1983) would be able to transport the sands (1.5–2.2 Ø) in bedload and thus produce megaripples. Depending on the interplay between the unidirectional and the wave orbital component one might find deposits that show dominance of one component over another. The unidirectional component is storm generated, and therefore the examples shown in SWIFT et al. (1983) and reinterpreted by DUKE (1985) may indeed be sands that were transported by storm-generated currents in bedload under simultaneous wave-reworking. Thus, hummocky megaripples may be storm transported sands in which wave reworking did not go to completion and in which evidence of bedload transport (high-angle cross-bedding) was preserved in the lower portions of the beds.

The presence and orientation (Fig. 1) of erosional features such as flute marks, scour marks, and erosional channels at the base of storm sands in the NTZ indicate the offshore flow of currents with a strong unidirectional component. Similarly, the mere fact that sandstones were carried into the basin over distances of 40 km also necessitates the presence of currents with a significant unidirectional component. The internal stratification of the sandstone bed shown in Fig. 6 resembles more that of hummocky megaripples (see SWIFT et al. 1983, their fig. 5A) than that of typical HCS sandstones. It may therefore be an ancient analogue of the hummocky megaripples of SWIFT et al. (1983), and may indeed be a storm sand that was carried into the basin in bedload (or partially in bedload) and reworked by waves. It is, however, impossible to estimate the overall importance of bedload transport because of extensive reworking of the sandstones.

The preservation potential of wave generated sedimentary structures (such as HCS) is low in shallow environments (DOTT & BOURGEOIS 1982) where fair weather processes may rework storm deposits. In the NTZ, sandstones that are entirely cross-bedded were observed in localities relatively close to the shoreline where the water was presumably shallower. These may therefore be fair weather reworked storm sands. However, if fair weather currents were of a strength to move medium to coarse sand, then the nearshore NTZ should be dominated by sandstone instead of shale (Fig. 9). Storm-surge ebb-currents, which flow in an offshore direction after the storm is essentially over and when wave action is greatly diminished (NELSON 1982), could cause reworking and destruction of wave produced structures, particularly in nearshore areas where currents are strongest. Current ripples that were observed in a few places in the upper portions of sandstone beds may have formed under the influence of such currents after wave action had declined.

Settling of suspended sand from a moving water mass can create parallel laminae (REINECK & SINGH 1972), and the parallel laminated sand that is found below the graded tops of sandstone beds, as well as those that drape the top of sandstone beds (Fig. 5) may be of such an origin. Silt and mud at the top of HCS sandstones probably result from cessation of water disturbance after storms that allows settling of fine particles from suspension (DOTT & BOURGEOIS 1982). Gradational silt/mud tops of sandstone beds in the NTZ most likely formed in such a way. The absence of graded top portions in proximal Newland storm sands might also be due to storm-surge ebb-currents that prevented settling of suspended fine material in nearshore areas and swept it deeper into the basin.

Shales

Suspension transport of silt and mud requires only small current velocities (SUNDBORG 1967), and therefore silt and mud in the storm deposits of the Newland shales were most certainly transported in suspension, regardless of transport mechanism (see above) and strength of storm. The components of lithoclast beds that were found in nearshore shales (SCHIEBER 1986b) are coarse enough to have been transported in bedload.

Very weak bottom currents or wave activity in the waning stages of storms probably favoured the deposition of laminated silts and graded rhythmites from suspension, whereas somewhat stronger currents or wave activity caused their reworking into cross-laminated silts. After cessation of current and wave activity post-storm muds settled on top of the siltstone beds (formation of silt/mud couplets).

Significance of storm deposits

Recurrence frequency of storms

A look at Fig. 9 shows that on average, storm sand beds in the NTZ are separated by 4–5 m of shale. The age of the Beltian sequence in the Helena embayment is crudely bracketed by radiometric age determinations (Obradovich & Peterman 1968), and together with the knowledge of the total thickness of the sequence one can calculate that average accumulation rates were between 0.2 and 0.05 mm/year (Schieber 1985). Thus the average periodicity of storm sands lies between 20 000 and 100 000 years. If these sands were the only storm deposits in the NTZ, such time spans would seem unrealisticly large if compared with the present (Ager 1973): However, the shales contain on average about 50 silt/mud couplets per metre, thus recording a recurrence frequency of storms from 100 to 400 years. Very similar silt/mud couplets in the North Sea shelf muds have an average recurrence frequency of 50 years (Reineck et al. 1967). Thus, considering the uncertainties in the Beltian accumulation rates, recurrence frequencies of storms in the Belt basin seem comparable to recurrence frequencies in modern epicontinental seas.

Silt/mud couplets are 200 times more frequent than storm sands, and because the latter require stronger currents for their transportation one may speculate that the silt/mud couplets are the product of average storms, whereas the massive offshore sand transport that is recorded by the HCS sandstones was caused by extremely heavy but equally rare storms. The circumstance that storm sands are essentially only found in the NTZ probably does not mean that very strong storms only occurred during that particular time interval. Extreme storms probably occurred throughout deposition of the Newland Formation, but only during NTZ deposition were coarse sands available along the shoreline for redistribution by storms (see introduction).

Sediment redistribution by storms

Proximality trends in sandstone distribution that were recognized in this study support previous work using storm sequences for basin analysis (Brenchley et al. 1979, Goldring & Bridges 1973, Dott & Bourgeois 1982, Aigner & Reineck 1982) and complement other available data on the paleogeography of the Helena embayment (see introduction).

The sandstone interval in the Trout Creek section contains sandstone beds up to 150 cm thick (Fig. 9). Channel fill sands and amalgamation of sandstone beds (indicated by discontinuous mud drapes in sandstone beds) were observed. These sandstones fall into the shoreline association of Goldring & Bridges (1973) and are "proximal" according to Johnson (1978). The sandstone-bearing interval in the Trout Creek section is approximately 100 m thick, and is thinner than in the sections to the south (160 m at Avalanche Creek, 130 m at Confederate Gulch). This observation indicates significant storm erosion or nondeposition of shales in proximal areas, which caused a thinning of the section relative to more basinal equivalents. Sandstone occurrences in all the other sections are comparable with the open shelf association of Goldring & Bridges (1973).

In Fig. 9 the number of sandstone beds decreases from north to south, and then increases again in the Deep Creek section. The reason for this trend reversal is that we approach the southern basin margin. Along this margin the LaHood Formation (McMannis 1963), a coarse clastic alluvial fan and deltaic unit (Boyce 1975) and lateral equivalent of the Newland Formation, was deposited. The sands in the NTZ of the Deep Creek section were derived from a southerly direction (Fig. 1), probably from nearshore sands of the LaHood Formation.

The observed trends in the sandstones of the Newland Formation (Fig. 9) compare well with observations made by Aigner & Reineck (1982) on recent storm deposits of the North Sea. There the frequency of storm sands, their maximum thickness, and the mean thickness all decrease towards the basin centre; distribution maps of these parameters show isolines that follow the basin margins, and perturbations of contour lines are related to point sources of sediment.

Compared with the sandstones, proximality trends in the shales of the Newland Formation are much more difficult to quantify because of generally much poorer exposure. The shales do, however, show that storms played a major role in redistributing terrigenous sediments from the shoreline into the basin, because at least 50 % of the shales in the upper and more than 50 % of the shales in the lower member of the Newland Formation consist of silt/mud couplets (Schieber 1985, 1986b).

Vertical sequence of sedimentary structures

The idealized vertical sequence of sedimentary structures that was observed in the storm sands of the Newland Formation (see above), resembles idealized sequences proposed for HCS sandstones by Dott & Bourgeois (1982) and Walker et al. (1983). There are three main differences between their sequences and the one observed in the Newland Formation.

First, current ripples are found in the upper parts of sandstone beds instead of wave ripples as suggested by above authors (their X-division). However, even though wave ripples seem to be the most common ripple type in the upper portions of studied HCS sandstones, Dott & Bourgeois acknowledge that in some cases the rippled portion shows clear unidirectional orientation.

Second, parallel laminations of fine sand in the Newland sandstone beds seem to have formed by settling from suspension instead of by deposition under sheet flow conditions as suggested by Dott & Bourgeois (their F-division). The position of these parallel laminae below the graded silt/mud top portion, as well as their comparatively fine grain size (the hummocky beds below consist of medium to coarse sand), suggests that they indeed settled from suspension and thus might be considered part of the M-division (mudstone division) of above authors. That their M-division may show parallel lamination is acknowledged by Dott & Bourgeois (1982).

Third, there is some evidence of bedload transport in the Newland storm sands, whereas both teams of above authors have not found such evidence in their examples and assume that HCS sandstones are transported in suspension. However, the vast majority of HCS sandstones that were studied by these authors were of fine grain size (silt to fine sand) and may thus indeed have been transported in suspension. In contrast, the Newland storm sands are of medium to coarse grain size and would have required considerably stronger currents to have been transported in suspension. Thus, there is a higher potential for the Newland storm sands to have at least partially been transported in bedload.

Conclusion

Sandstones that are interbedded with shales of the Newland Formation are interpreted as storm deposits because of HCS. The bulk of the sandstones was probably transported into the basin by offshore flowing gradient currents. It is likely that at least portions of the sand were transported in bedload. Storm-surge ebb-currents may have reworked proximal sandstone beds and may have swept suspended sediment deeper into the basin.

Proximality trends were observed in distribution and thickness of sandstones. They can be related to increasing distance from the shoreline and compare well with trends observed in recent shelf seas (Aigner & Reineck 1982, Nelson 1982). Basin trends derived from storm sand distribution are in agreement with basin trends derived from the distribution of other sediments.

Tentatively an idealized vertical sequence of sedimentary structures has been established for the Newland storm sands. This sequence is similar to the ones proposed by Dott & Bourgeois (1982) and Walker et al. (1983) for HCS sandstones elsewhere. The account of sedimentary features in HCS sandstones that is given by Dott & Bourgeois (1982) shows that there is actually considerable variability from case to case. Because the sequences that are proposed by Dott & Bourgeois (1982) and by Walker et al. (1983) are the syntheses of observations from many locations, it may well be that these idealized sequences represent the effects of the whole spectrum of parameters (such as water depth, bottom gradient, grain size, wave fetch, prevailing wind directions, fluctuations in wind and current strength etc.) that may affect a storm deposited sediment bed. However, in any particular stratigraphic sequence, the relative importance of these various parameters may have strongly differed from that that is represented by generalized "ideal" sequences, thus resulting in a different sequence of sedimentary structures.

Sandstones as well as shales record storm induced sedimentation in the Newland Formation. Silt/mud couplets record storms of average strength and HCS sandstones record rare storms of extreme strength. Average storms occurred every hundred or few hundred years, whereas extremely strong storms recurred on the order of 10 000's of years. In addition to storm strength, deposition of storm sands was governed by availability of sand. More than 50% of the terrigenous sediment in the Newland Formation was deposited by storms.

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