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Facies and deposition of a mixed terrigenous-carbonate suite in a Mid-Proterozoic epicratonic sea: The Newland Formation, Belt Supergroup, Montana, U.S.A.

By

Jürgen Schieber, Arlington/Texas

With 12 figures in the text

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Abstract: Carbonate rocks of the Newland Formation are characterized by a relatively large content of terrigenous matter (up to 50%). Simultaneous terrigenous clastic and carbonate sedimentation is indicated by lateral facies associations and small scale relationships between shale and carbonate beds. Main lithofacies types are: (A) "molar tooth carbonates" (fine crystalline dolostone interbedded with shales), deposited in a nearshore mudflat to lagoonal setting; (B) cherty dolostone (minor clay content) with cryptalgal laminations, deposited nearshore in an intermittently exposed setting; (C) bedded limestone, deposited in a probably storm-wave dominated shallow offshore setting; (D) heterolithic limestone (limestone-marl cycles), deposited in a storm-dominated shallow offshore setting; (E) millimetre-laminated limestone, a "starved basin" facies that was deposited far offshore.

Facies distribution within the basin was primarily controlled by water depth (implying energy of depositional environment as well as distance from shoreline) and proximity to the source of terrigenous material. Carbonate-siliciclastic mixing involved simultaneous operation of "Punctuated Mixing", "Facies Mixing", and "In Situ Mixing" processes. Microbial mats were probably important factors in carbonate production. Because of their ability to thrive even under conditions of considerable siliciclastic sedimentation they were most likely the reason why carbonate production in nearshore environments was not negatively affected by influx of large proportions of terrigenous clastics.

Zusammenfassung: Karbonatgesteine der Newland Formation enthalten relativ große Mengen terrigener Komponenten (bis 50%). Laterale Faziesbeziehungen und Beobachtungen der Beziehungen zwischen Karbonat- und Tonsteinbänken sind ein Anzeichen, daß Karbonate und terrigene Sedimente gleichzeitig im Becken abgelagert wurden. Die Hauptfaziestypen sind: (A) "Molar Tooth Carbonates" (feinkristalline Dolomite mit zwischengelagerten Tonsteinen), die in küstennahen Watten und Lagunen abgelagert wurden; (B) "Cherty Dolostone" (geringer Tongehalt) mit "cryptalgal laminations",

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abgelagert im Küstenbereich mit gelegentlichem Auftauchen; (C) "Bedded Limestone", abgelagert im Flachwasserbereich mit Sedimentaufarbeitung durch Sturmwellen; (D) "heterolithic Limestone" (Kalkbänke mit Mergelzwischenlagen), abgelagert im Flachwasserbereich mit Sedimentaufarbeitung durch Sturmwellen; (E) "Millimetre-Laminated Limestone", küstenferne Ablagerung (Hungerbeckenfazies).

Die beckenweite Faziesverbreitung war hauptsächlich durch die Wassertiefe (Energieniveau des Ablagerungsraums und Küstenferne ist hier mit einbegriffen) und die Nähe zur terrigenen Sedimentzufuhr kontrolliert. Drei Prozesse, "Punctuated Mixing", "Facies Mixing", und "In Situ Mixing", waren an der Mischung von Karbonaten und terrigenen Sedimenten beteiligt. Mikrobenmatten waren vermutlich ein wichtiger Faktor in der Karbonatproduktion. Wegen ihrer Fähigkeit, auch unter starker terrigener Sedimentation zu gedeihen, waren sie vermutlich der Grund, daß Karbonatproduktion im Küstenbereich von starker terrigener Sedimentzufuhr nicht negativ beeinflußt wurde.

Introduction

Terrigenous clastic sedimentation has an inhibiting effect on both modern and ancient carbonate secreting organisms, and that circumstance led to the long held generalization that sediments consisting of a mixture of carbonate and terrigenous material should rarely form. This perception is also illustrated by the way in which sedimentology texts are subdivided in chapters on carbonate and terrigenous clastic sedimentation. However, as recent research has shown, mixed siliciclastic and carbonate sediments are quite common in modern as well as in ancient sequences (McIlreath & Ginsburg 1982; Doyle & Roberts 1988). Mount (1984) identified four basic processes that cause mixing of carbonate and siliciclastic sediments: (A) mixing generated by rare storms ("Punctuated Mixing"); (B) mixing along the margins of contrasting facies ("Facies Mixing"); (C) in situ accumulation of calcareous organisms in siliciclastic sediments ("In Situ Mixing"); (D) erosion of carbonate source terranes. The Newland Formation of the Belt basin is an example of a Mid-Proterozoic mixed carbonate-clastic sequence where primary carbonate production is indicated even in environments that experienced very large contributions of siliciclastic material. Carbonate production under those conditions is probably directly or indirectly tied to microbial mats, wich in the Precambrian played an important role in carbonate precipitation and accumulation through photosynthetic removal of carbon dioxide and trapping and binding of fine carbonate sediment (Boggs 1987). Microbial mats can prosper even in presence of abundant siliciclastic sedimentation (Bauld et al. 1980; Javor & Castenholz 1981; Gerdes et al. 1985) and were probably responsible for continued carbonate production in shallow nearshore environments of the Newland Formation.

Geologic setting

The Newland Formation of the Mid-Proterozoic Belt basin occurs in the Helena embayment, an eastern extension of the Belt basin (Fig. 1). The first description of the Newland Formation dates back to Walcott (1899), who described type localities and originally named it the Newland Limestone. Regional mapping of the formation in the 1960's showed that the formation consists of intercalated packages of carbonates and shales (Nelson 1963), and because the overall carbonate content of the formation is definitely below 50% the name Newland Formation was proposed instead (Birkholz 1967). The Newland Formation in the study area consists of a lower member of mono-

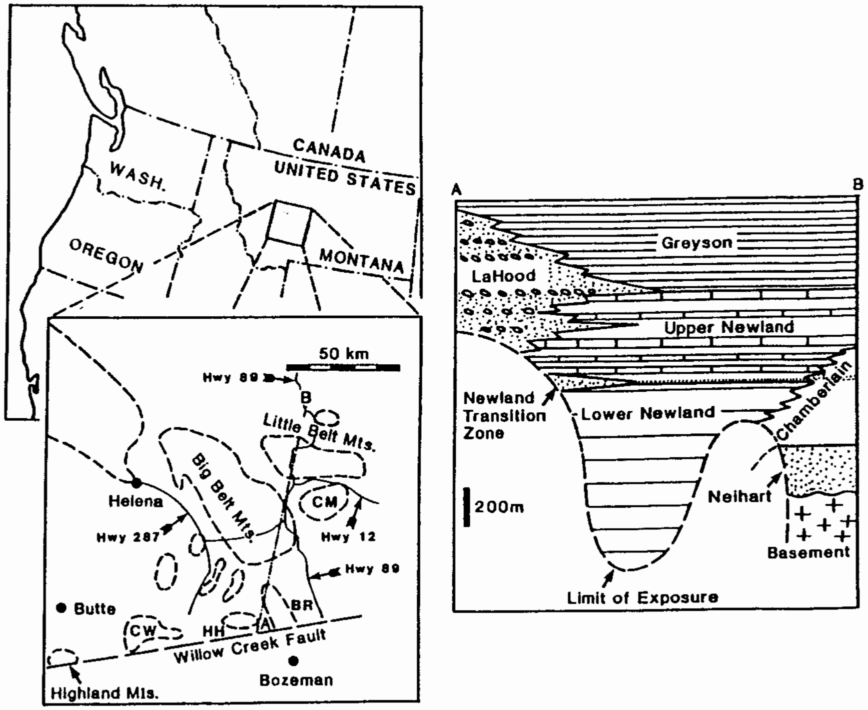

Fig. 1. Location of study area and stratigraphic overview. Belt basin outlined by stipple pattern. The Helena embayment is the eastern extension of the basin. Enlarged map shows outcrop areas of rocks of the Belt Series (areas enclosed by dashed lines), major cities, and principal highways (Hwy) in the study area. Explanation of symbols: HH = Horseshoe Hills; CW = Cardwell-Whitehall area; BR = Bridger Range; CM = Castle Mountains. The stratigraphic overview for the Helena embayment represents a generalized restored cross-section along line AB in the enlarged map portion.

tonous gray dolomitic shales, and an upper member consisting of alternating shale units (some ten to over 100 m thick) and carbonate units (10-70 m thick). Shales with sandstone interbeds mark the transition between lower and upper member and have informally been referred to as the Newland Transition Zone (SCHIEBER 1987). With deposition of the upper member of the Newland Formation the Helena embayment probably developed into an east-west trending half graben (SCHIEBER 1990). The southern margin of that half graben was a syndepositional fault, north of which coarse clastic alluvial fan to deltaic sediments of the LaHood Formation were deposited. A brief overview of the sedimentary history of the Helena embayment is given in SCHIEBER (1986).

The subject of this paper are the carbonate units of the upper member of the Newland Formation. These carbonates can contain considerable amounts of terrigenous clastic material, and conversely the interbedded shales may contain large proportions of fine crystalline carbonate material (primarily dolomite). Stratigraphic studies in the Little Belt and Big Belts Mountains show that even though carbonate units are generally of considerable lateral continuity, they may pass laterally into shales (SCHIEBER 1985). Facies characteristics and depositional environment of shales in the Newland Formation have been described by SCHIEBER (1989).

In earlier reconstructions of basin history the Belt basin was thought of as a cratonic reentrant of the Proterozoic ocean onto the North American craton (HARRISON et al. 1974). In an epicontinental sea of that type, with a wide connection to the main ocean, one might expect to see recorded in the sediments ample evidence of tidal influence on sedimentation (SHAW 1964). However, such evidence is sparse and practically always equivocal. More recent studies (STEWART 1976; SEARS & PRICE 1978; PIPER 1982) suggest that the Belt basin actually was an epicratonic basin, and that another landmass was located along the western edge of the basin. The latter studies helped to revive a landlocked interpretation of the Belt Series. In publications by WINSTON (1986) sedimentary facies and cycles of the Belt basin are compared with lacustrine sediments of the Eocene Green River Formation, and it is concluded that the similarities warrant a lacustrine interpretation of the Belt Series. However, because physical processes recorded in ancient lake sediments are quite similar to processes associated with marine environments, the distinction between lacustrine deposits and those of microtidal epicontinental seas is problematic and can not be decided based on sedimentologic studies alone (GROTZINGER 1986). Further arguments against a lacustrine interpretation were advanced by CRESSMAN (1989) as a result of a study of the Prichard Formation, a western equivalent of the Newland Formation. By combining subsidence analysis, palinspastic restoration, and stratigraphic and sedimentologic studies, he concluded that a river approximately the size of the modern Mississippi was draining into the Belt basin from the south, furnishing sediment for submarine fans that measured roughly 400 km's across. Because such features are incompatible with deposition in a lake, Cressman concluded that the Belt basin was a gulf that was connected to the Proterozoic ocean. In PIPER's (1982) reconstruction of a Proterozoic supercontinent the present Belt basin would have been epicratonic, but might have had in the north a connection/seaway to the Proterozoic ocean. In such a scenario the influence of tides would be greatly diminished or absent, furnishing a possible explanation for the paucity of tidal features in the Belt Series. Geochemical considerations also suggest that the Belt basin, though epicontinental, should have been connected to the Proterozoic ocean. For example, it is quite unlikely that the granitic gneisses of the Belt source terranes could have supplied the necessary magnesium to produce the large amounts of early dolomite in Belt carbonates (GROTZINGER 1986). Strongly negative $\delta^{34}S$ values of early diagenetic pyrite in shales of the Newland Formation also suggest that the Belt "sea" was connected to the Proterozoic ocean (STRAUSS & SCHIEBER 1990). Weighing the various arguments for and against a lacustrine Belt basin, I personally prefer its interpretation as an epicratonic sea that was connected to the Proterozoic ocean.

Well-rounded fresh feldspars that are found in moderate to abundant quantities in sandstone beds of the Newland Formation as well as major element compositions of Newland shales (SCHIEBER 1985, 1987) indicate that the prevailing climate was probably arid to semi-arid.

Facies description and interpretation

Carbonates in the Newland Formation are compositionally dominated by microsparite, probably a recrystallization product of original micrite. Five major facies types and two additional subfacies types have been distinguished, based on mineralogy, clay content, intra- and extraclasts, and sedimentary features. Approximately 1500 samples and 350 petrographic thin sections were examined. Selected samples were stained with Alizarin Red-S to distinguish calcite from dolomite. Diagenetic and geochemical features of these carbonates were discussed in a previous publication (SCHIEBER 1988).

Molar tooth carbonate facies

This facies consists of fine crystalline, even to slightly undulose beds (5-100 cm thick) of dolostone and dolomitic limestone (carbonate content 70% to less than 50%). Carbonate packages as much as 5 m thick alternate with shale packages (some metres to 10 m thick). Internal lamination of carbonate beds is typically discontinuous wavy with alternating lighter and darker laminae (0.05-0.3 mm thick). Darker laminae may be strongly carbonaceous, take on a wavy-crinkly continuous appearance, and contain fine crystalline (3-10 microns), irregularly shaped, impure dolomite. These laminae may also contain fine crystalline dolostone peloids (10-100 microns in size). The lighter laminae are even to wavy-lenticular, coarser in grain size, and contain variable amounts of equidimensional calcite grains (approximately 10 microns in size), quartz silt, dolomite crystals, mica flakes, and clays.

The facies is characterized by so called "molar tooth structures" (or MTS), an extraordinarily diverse group of calcite filled structures that was first described from the Belt Series by BAUERMAN (1885). EBY (1977) conducted the most important recent study of MTS. The common denominator of all "molar tooth structures" is that they are all filled by equidimensional calcite grains (approximately 10 microns in size) that are identical to the equidimensional calcite found in the host rock. In the Newland Formation the following types of MTS (EBY 1977) were recognized:

1) Vertical Ribbons: most abundant, 1-5 mm wide, may extend as much as 20 cm vertically. They may cut across an entire bed, or taper out with depth (Fig. 2). On surfaces perpendicular to bedding they appear crumbled, fractured, ptygmatically folded (Fig. 2), offset, and "telescoped", owing to compaction of the sediments after ribbon formation. On bedding planes the interconnected ribbons produce polygonal and incomplete shrinkage crack patterns (Fig. 3), with repeated cracking producing several superimposed crack systems.

Fig. 2. Sideview of a bed of "molar tooth carbonate". Arrows A, B, and C point to shrinkage cracks within this bed that are filled with clear equidimensional calcite and belong to the vertical ribbon variety of "molar tooth structures". The cracks occur within three different horizons in the bed. Downward tapering nature of cracks is particularly well displayed by the crack pointed out by arrow B, Cracks marked with arrows A and B show well developed ptygmatic deformation of cracks because of compaction. Bed is approximately 25 cm thick.

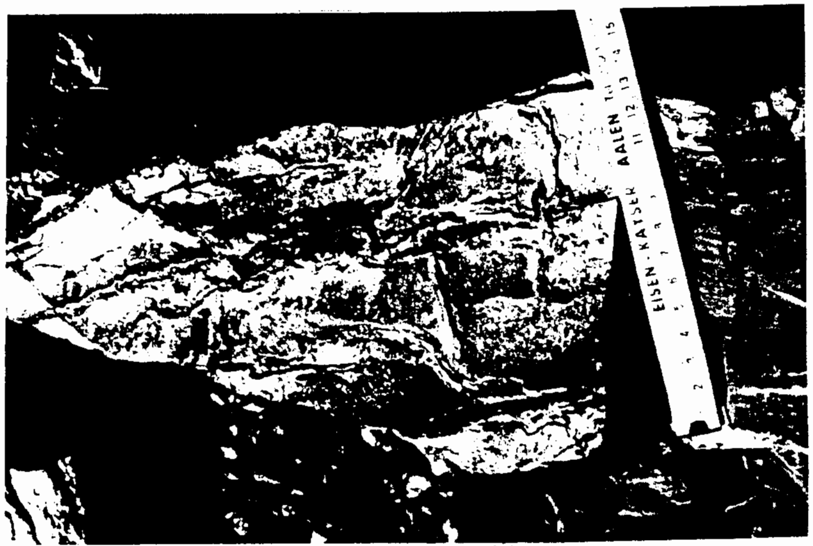

Fig. 3. Vertical ribbons on bedding surface of MTS carbonate bed form polygonal and incomplete shrinkage cracks. Ruler has centimetre divisions.

2) Blob Structures: spherical-elliptical to tube-like bodies (1-10 mm diameter) and irregular blobs.

3) Horizontal Ribbons: discontinuous horizontal layers (1-5 mm thick). They are of very minor importance in the Newland Formation.

4) Fragmental Ribbon and Blob Hash: lenses, lensy layers (up to 20 cm thick), and depression fills on erosion surfaces, consisting of MTS fragments (0.5-30 mm in size) in a fine carbonate mud matrix.

Sedimentary features and depositional environment

Polygonal and incomplete shrinkage crack patterns formed by vertical ribbons suggests that volume loss, be it by desiccation, water loss, or synaeresis, is responsible for these cracks. Deformation of the vertical ribbons requires that the host sediment was still soft when the cracks formed. Incomplete crack patterns are commonly associated with synaeresis, but PLUMMER & GOSTIN (1980) point out that no precise relationship can be drawn between the morphology of any one fossilized mudcrack and the conditions of its formation. These authors also point out that polygonal and multigeneration synaeresis cracks are rare in the geologic record. Modern analogs of crack patterns as found in the Newland Formation occur in the Coorong dolomites of Australia (VON DER BORCH 1976; VON DER BORCH & JONES 1976), and on Andros Island in the Bahamas (GINSBURG & HARDIE 1975). In the Coorong dolomites the cracks form shortly after exposure of lagoonal carbonate muds, mainly in response to dewatering of the sediment. Narrow and well defined discontinuous fractures that may merge into a polygonal pattern form in carbonate mud of a yoghurt like consistency. Cracks on Andros Island occur in intertidal carbonate muds as a result of dewatering during low tide, extend downwards for as much as 30 cm, and form polygonal and incomplete crack systems. These recent examples of incomplete and polygonal shrinkage cracks suggest that vertical ribbons in MTS carbonates may similarly have formed during subaerial exposure and dewatering of soft carbonate muds.

Blob structures, are interpreted by Eby (1977) to represent gas escape structures, in analogy to similar appearing gas bubbles and gas escape channels (due to decay of buried organic matter) described from modern sediments (Reineck & Singh 1980). Horizontal ribbons, a rare feature in MTS carbonates of the Newland Formation, may have originated as sheet cracks owing to sediment shrinkage (Eby 1977). The great form variability of MTS strongly suggests a multiple origin for these structures.

Infilling with equidimensional calcite is probably one of the most intriguing features of the various types of MTS. In a detailed study Eby (1977) found evidence that MTS were initially filled with calcium sulphate (either from overlying waters or from interstitial pore waters), and that subsequently the sulphates were replaced by calcite. Such a scenario allows open spaces of all shapes and origins to be filled with the same material, consistent with the commonly assumed multiple origin and the observed uniform infilling of MTS. Analogous infilling of mudcracks with evaporite minerals has been described from intertidal dolomites of the Permian of Texas (Lucia 1972, anhydrite filled cracks) and from the Coorong carbonates (halite fills) of Australia (Von der Borch 1976).

Fig. 4. Edgewise conglomerate in MTS carbonate facies. Erosive base of bed is outlined by black ink dashes, top of bed is marked by arrows A, B, and C. Bed thickens in centre of photo (below arrow B), because flat carbonate clasts stand on edge (form a fan-like pattern). Cap of marker pen is 50 mm long.

MTS carbonates also contain in places intraformational conglomerates (up to 10 cm thick), consisting of platy carbonate fragments (up to 10 cm long and up to 1 cm thick, angular to subrounded edges) that are in many places oriented subparallel to bedding, but may also show imbrication and fan-like, swirly patterns with the pebbles standing on edge (Fig. 4). In recent carbonate environments flat pebble conglomerates are derived from dried out carbonate mud on levees and algal mats (Shinn et al. 1969), are a common feature of shallow marine environments, and are thought to result from strong wave and current action during storms (Wilson 1975). Erosion surfaces overlain with beds of MTS hash are probably of the same origin as the intraformational conglomerates. In addition to intraformational conglomerates and MTS hash beds, MTS carbonates contain wavy cross-laminated silt layers with internal reactivation surfaces probably also due to storms.

Current generated sedimentary features in MTS carbonates suggest deposition in very shallow water. Polygonal crack patterns of vertical ribbons, as well as a suggestion of evaporitive infilling of these cracks, strongly suggests that at times and in places the carbonate mud surface was subaerially exposed. Internal laminae of MTS carbonate beds bear considerable resemblance to stromatolite microstructures described by Bertrand-Sarfati (1976). Even though no other features indicative of stromatolite growth (such as domal buildups) were found, it is possible that this internal lamination is due to microbial mat colonization of the sediment surface.

In summary one may say that MTS carbonates were probably deposited in a very shallow nearshore setting, that carbonate muds underwent episodes of subaerial exposure, that microbial mats potentially colonized the sediment surface, and that occasional storms caused erosion and reworking of surface sediments.

Cherty dolostone facies

This facies consists of medium bedded dolostone (beds 1-15 cm thick, average 4 cm) with variable amounts of irregular chert nodules (up to 10 cm size) that appear dark gray to black in outcrop. Even to undulose alternating light and dark gray laminae (1-10 mm thick) that are accentuated by differential weathering (light gray laminae contain up to 20% authigenic silica) characterize the dolostones.

The light gray laminae (0.5-3 mm thick) consist of abundant rounded dolostone peloids (30-50 microns, sorting good to very good). Peloid outlines may in places still be sharp, but in most places diagenetic recrystallization has produced diffuse grain outlines. Areas between peloids are filled with coarser sparry dolomite (5-20 microns) and authigenic silica. These laminae show lateral thickness variations and may be graded with silt to very fine sand sized material at the bottom. Dark gray laminae (0.5-2 mm thick) consist mostly of dolomite crystals (10-100 microns in size), contain randomly distributed tiny pyrite grains, and have a slightly brownish appearance in transmitted light because of finely dispersed organic matter. Remnants of very thin carbonaceous laminae have been found in these laminae in samples with strong silicification.

Massive dolostone beds (1-10 cm thick) that are interbedded with laminated dolostones are a subfacies of the cherty dolostone facies. Faint internal laminae (0.1-1 mm thick) of these beds are spaced 2-25 mm apart and consist of silt to sand sized particles (primarily dolostone, but also shale clasts and detrital quartz).

Sedimentary features and depositional environment

Fig. 5. Typical outcrop appearance of laminated dolostones of the cherty dolostone facies. Arrow points out chert nodule. Hammer handle is 18 cm lang.

Fig. 6. Laminated dolostone of the cherty dolostone facies with low amplitude domes (pointed out by arrows) that are interpreted as small domal stromatolites. Hammer handle is 18 cm long.

The laminated dolostones (Fig. 5) closely resemble cryptalgal laminated dolostones as described by **Halley** (1975), **Armstrong** (1975), and **Erikson** (1977). Supporting evidence for the presence of microbial mats during carbonate accumulation is furnished by sets of laminae that may show low amplitude (never in excess of 5 cm) uparching and doming (Fig. 6), and polygonal ridges on bedding planes that appear to be due to uparching of laminae beneath those ridges (Fig. 7). The polygonal surface patterns resemble "incipient mudcracks" from subaerially exposed algal flats (**Conybeare & Crook** 1968), where drying out of algally bound sediment leads to uparching of layers and mudcrack formation is prevented by internal cohesion of the algal mat. Under assumption of a microbial mat origin, the dark gray laminae (containing carbonaceous matter and pyrite) can be interpreted as remnants of microbial laminae, whereas light gray (peloidal) laminae may represent sedimentation onto microbial laminae by intermittent currents. In a few locations flat pebble conglomerates were found that are thought to represent dried out carbonate muds that were eroded and redeposited during storms (**Wilson** 1975).

The sum of above observations suggests deposition in shallow water with times of subaerial exposure. Microbially laminated dolomites are commonly thought to indicate intertidal flat environments (**Logan** 1961), but because tidal activity was probably insignificant during Newland deposition it is preferred to envision deposition in very shallow water on gently sloping carbonate mudflats where changing wind patterns could have led to intermittent subaerial exposure.

Massive dolostone beds may contain cross-laminated wavy layers and lenses of silt and sand ($\leq$ 2 cm thick), in places abundant enough to warrant description

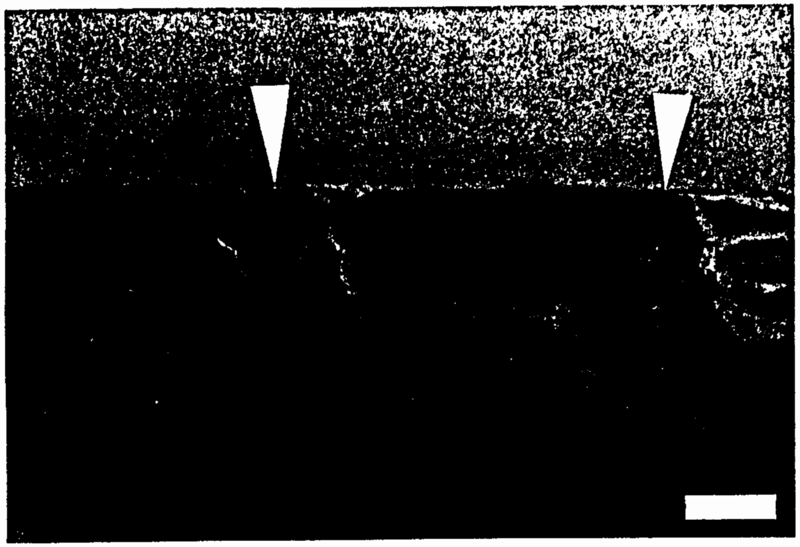

Fig. 7. Etched slab of laminated dolostone that shows polygonal ridges on the surface. Uparching of laminae beneath two of these ridges (pointed out by arrows) resemble small stromatolites. Scale bar in lower left corner is 1 cm long.

as wavy and lensoidal bedding (Reineck & Wunderlich 1968). This observation indicates an environment where periods of current activity alternated with slack water conditions, and because of the intimate association with laminated dolostones it is assumed that massive dolostones were deposited in shallow subaqueous settings within and adjacent to algal mudflats.

Millimetre-laminated limestone facies

Sets of millimetre-laminae (0.3-1 mm thick, Fig. 8), that are parallel to slightly wavy and distinguished by variations in colour, crystal size, and micrograding, characterize this facies. Lamina sets can consist of several tens of these laminae. Individual laminae consist of microsparite (5-40 microns, average 20 microns) with interlocking irregular grains. Detrital quartz (silt to sand size), peloids, shale fragments, and detrital micas, can be found in the bottom parts of laminae. Tiny streaks of organic matter (possibly microbial mat fragments) that are more abundant towards the top of laminae probably cause their gray colour. Compositionally most of the laminae can be classified as mudstones, but in places coarser particles are abundant enough to permit a wackestone classification (Dunham 1962). Sets of millimetre-laminae are interbedded with massive limestone beds (Fig. 8) of the same type as found in the bedded limestone facies (described below).

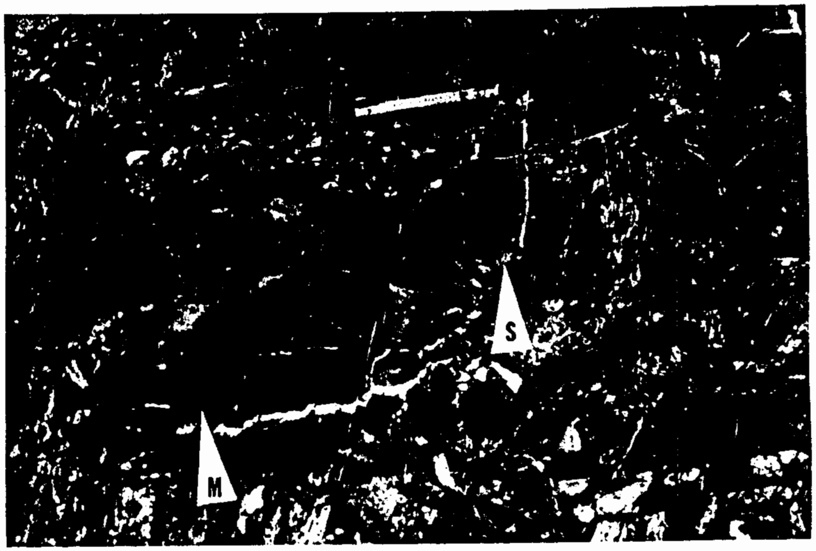

Fig. 8. Outcrop of millimetre-laminated limestone facies. Sets of millimetre laminae are of darker colour (pointed out by arrow M), interbedded massive limestone beds are of lighter gray colour (pointed out by arrow S). Ruler is 22 cm long.

Bedded limestone facies

This facies consists predominantly of even to slightly undulose beds (4-25 cm thick) of microsparitic limestone (interlocking irregular calcite crystals, 10-40 microns, average 20 microns). Peloids (50-150 microns in size) with diffuse grain boundaries and quartz silt occur in variable amounts and are concentrated in indistinct internal laminae (2-15 mm apart). Compositionally the limestones range from mudstone to wackestones (Dunham 1962). This facies may in places also contain thin sets of millimetre-laminae. Authigenic feldspars and irregular to elliptical-lenticular chert nodules (similar to those in cherty dolostone facies) also occur.

Sedimentary features and depositional environments

Both millimetre-laminated limestone and bedded limestone facies can be found interbedded and as lateral equivalents of each other, and their sedimentary features and depositional setting are therefore discussed together.

Millimetre-laminated limestones closely resemble thinly laminated basinal carbonates as described by Hoffman (1973), Enos (1974), Wilson (1975), and Hemleben (1980). Laminae form as a result of small sediment pulses from nearshore areas, alternating with longer periods of very slow deposition (organic-rich tops of laminae), and have also been referred to as "starved basin" facies (Wilson 1972).

In contrast, the bedded limestones contain a higher abundance of coarser material (peloids, quartz sand and silt, shale fragments) that in places has been reworked into ripples (lenticular and wavy bedding) by wave action as indicated by form discordant internal structure, opposing dips of foreset laminae in superimposed ripples, and laminae spreading from the top of ripples (Boersma 1970). Interbedding of ripples with carbonate mud indicates alternating conditions of slack water and wave action, and in light of the abundance of storm deposits in terrigenous units of the Newland Formation (Schieber 1986, 1987) the latter was probably storm induced as well.

An integrated interpretation of the two facies in question suggests that a predominance of millimetre-laminae indicates distal, basinal deposition, whereas a predominance of bedded limestones indicates closer proximity to the shoreline and shallower water. Stratiform solution collapse breccias, restricted to single beds within outcrops, were also found in the bedded limestone facies. They suggest post-depositional removal of layers of evaporite minerals that originally precipitated from the water column, and indicate hypersaline conditions in the Helena embayment.

Fig. 9. Outcrop of heterolithic limestone facies. Resistant limestone beds are separated by less resistant calcareous shale beds. Arrow points out a horizon of carbonate concretions. Hammer is 31 cm long.

Heterolithic limestone facies

Gray to buff weathering limestone beds (5-60 cm thick, average 20 cm) that are separated by partings of calcareous silty shale (1-40 cm thick, average 20 cm) are characteristic of this facies (Fig. 9). Limestone beds are wavy undulose, may be lateral equivalents of horizons of flat carbonate concretions, and have sharp contacts with shale interbeds (Fig. 9). They consist predominantly of calcite microspar (10-80 microns, average 30 microns, interlocking irregular grains) and contain as much as 15% detrital components (quartz silt, well rounded coarse quartz, feldspar grains, siltstone fragments, ooids and other rounded carbonate particles, streaks of organic matter). Diagenetic silicification is common (Schieber 1988), but not as well developed as in the cherty dolostone facies.

Heterolithic rippled limestone facies

This is a subfacies of the heterolithic limestone facies and is distinguished primarily by the presence of flat pebble conglomerates, sandstones, and siltstones. Interstitial authigenic silica is common and may constitute locally up to 20% of the rock. Fine internal laminae, spaced 1-15 mm apart, are rich in silt to sand sized material (quartz, carbonate particles, shale clasts).

Fig. 10. Outcrop photo of heterolithic rippled limestone facies. Lenses (arrow A) and wavy layers (arrow B) of silt and sand are enhanced by differential weathering. Note the clearly concretionary nature of carbonate beds (light gray). Ruler is 22 cm long.

Fig. 11. Closeup photo of silt lens with internal cross-lamination. The silt lens in the centre of the photo shows opposing dips of foreset laminae, cross-stratal off-shoots, and bundle-wise upbuilding. These features are interpreted to indicate wave action during ripple formation. Ruler has centimetre divisions.

Siltstones and sandstones in this facies consist of variable amounts of rounded limestone and dolostone particles (most abundant), oolites, fragments of molar tooth carbonate, shale clasts, chert, quartz grains (10-30%), feldspars, and mica flakes. Quartz grains in the coarse sandstone beds are conspicuously well rounded and are identical to those found in storm sand beds within shale units of the Newland Formation (Schieber 1987). Flat pebble conglomerates are mixed to variable amounts with coarse sand. Pebbles are platy, may reach 15 cm in size, and exhibit a range of lithologies (microsparitic limestone, molar tooth carbonate, dolostone, shale).

Sedimentary features and depositional environments

Silt and sand in the heterolithic rippled limestone facies occurs as lenses and wavy layers from a few mm to 50 mm thick (Fig. 10), may exhibit internal cross-laminae (Fig. 11), and may resemble lenticular and wavy bedding. Basal contacts may be erosional as well as non-erosional. Especially in thicker layers, form-discordant internal structure, intricately interwoven cross-lamination, bundle-wise upbuilding, opposing dips of foresets in successive ripples, and cross stratal off-shoots are common (Fig. 11) and indicative of wave activity (Boersma 1970; in Reineck & Singh 1980, p. 103). Interbedded layers of carbonate mud suggest that periods of quiescence alternated with periods of current and wave activity.

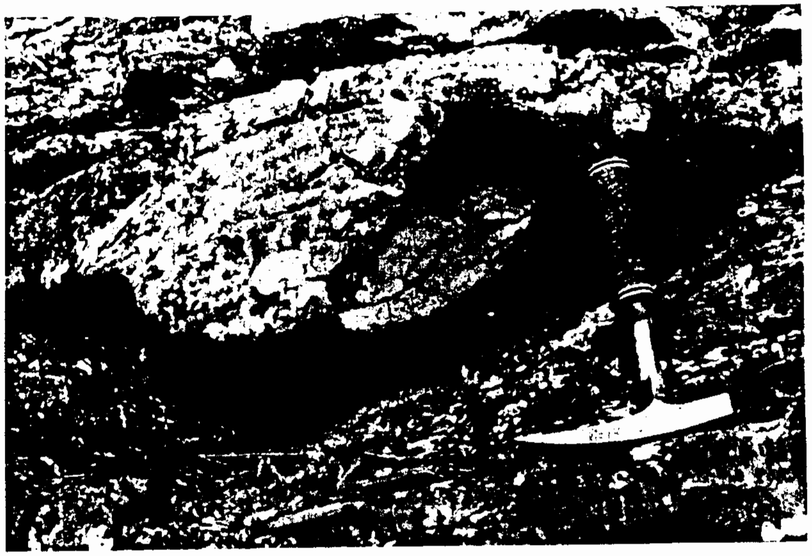

Fig. 12. Outcrop photo of sand-filled erosional channel in heterolithic rippled limestone facies. Hammer handle is 18 cm long.

Symmetrical ripples with spill-over lobes were observed at the top of coarse sandstone beds and indicate sediment reworking by storms and deposition between fairweather and storm wave base (Seilacher 1982).

Flat pebble conglomerates and pebbly sandstones are found in erosional channels (Fig. 12) that may be as wide as 2 m and as deep as 0.5 m. Conglomerates are clast supported and may show imbrication of pebbles. Pebbly sandstones commonly show planar crossbedding and may show symmetrical straight crested ripples at the tops of these channel fills. In carbonate environments, channel fills such as these may be related to tidal currents (Conybeare & Crook 1968; Wilson 1975). However, unlike tidal channels, the erosional channels in the Newland carbonates do not show any indication of lateral migration, appear to have been cut and filled during a single event, and in cross-sections they resemble storm-produced gutter casts from shallow marine Triassic carbonates in SW-Germany (Aigner & Futterer 1977). Considering the common occurrence of storm deposits throughout the Newland Formation a storm origin is also assumed for these debris filled erosional channels.

Obviously, deposition of heterolithic limestones occurred with a strong terrigenous component to overall sedimentation, and therefore the landward equivalents of this facies should also contain abundant terrigenous material. From the presence of flat pebbles and molar tooth carbonate fragments we may assume that it was deposited basinwards of molar tooth carbonate mudflats, and that storms eroded nearshore sediments and transported mud as well as coarse clastic sediments deeper into the basin.

The essential absence of silt and sand beds and of current created features in the heterolithic limestone facies suggests that this facies was deposited at a greater distance from the shoreline than the heterolithic rippled limestone facies and at a greater water depth.

The observed limestone-shale interbedding strongly resembles limestone-marl cycles described elsewhere. In the latter bedding can be produced through periodic increase in detrital silicate supply, periodic dissolution of carbonate, diagenetic processes, and climatic fluctuations (Einsele 1982). The lateral change from limestone beds to concretion horizons suggests that carbonate beds in the heterolithic limestone facies have definitely a diagenetic component to their origin and possibly grew concretionary in a calcareous mud during early diagenesis.

A conceptual model of carbonate sedimentation in the Newland Formation

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, by dolostone and limestone clasts within shales, and also by the significant amounts of fine grained dolomite within the shales (Schieber 1989).

In comparison to non-storm layers, storm layers in shales of the Newland Formation contain significantly more carbonate matter. The latter is overall dominated by fine grained dolomite, but also contains silt to pebble size particles (Schieber 1989). Considering that storms were probably the major agent to redistribute sediments from nearshore areas into the basin throughout Newland deposition, and further taking into account the observation that carbonate horizons in the Newland Formation decrease in thickness towards the basin centre (Schieber 1985), it is reasonable to conclude that the nearshore areas dominated overall carbonate production in the basin.

Facies distribution and basin configuration during deposition of major carbonate intervals in the upper member of the Newland Formation were reconstructed from sixteen measured stratigraphic sections (Schieber 1985). Facies distribution as well as sedimentary features indicate that nearshore environments were dominantly carbonate mudflats of the molar tooth carbonate facies. Keeping in mind that microbial photosynthesis was probably a major factor in the Proterozoic to create physiochemical conditions for carbonate precipitation, potential stromatolite-like internal laminations in the MTS facies are further suggestion of enhanced carbonate production in nearshore areas.

The fine grained nature of dolomite in the MTS facies suggests that dolomite formed very early in diagenesis. Possible present day analogs of the MTS carbonates, the mudflats and lagoons of the Coorong area (Von der Borch & Lock 1979), produce significant amounts of primary calcium carbonate as well as dolomite that is potentially of primary origin (Von der Borch & Jones 1976) or at the very least formed during very early diagenesis. Similarly, authigenic silica in the MTS carbonates is reminiscent of early diagenetic silicification found in Coorong dolomites (Peterson & Von der Borch 1965). Though there are similarities between MTS carbonates and this potential modern analog with respect to sedimentary features, microcrystalline dolomite, and authigenic silica, climatic conditions were probably not identical between MTS carbonates and Coorong dolomites. The Coorong dolomites are deposited in a warm humid environment, whereas the interpretation of MTS as calcite replaced calcium sulphate and the presence of stratiform solution collapse breccias suggest general hypersalinity of the basin waters and a dryer climate. Such an interpretation is also in agreement with the arid to semi-arid paleoclimate assessment made in the section on the geologic setting of the Newland Formation.

Some of the nearshore carbonate production was probably swept deeper into the basin and probably was the main source of the fine crystalline dolomite that is common in most Newland shales. Considering the indications of evaporitic conditions and hypersalinity and the presence of stratiform solution collapse breccias in the bedded limestone facies, it seems feasible that the offshore limestones owe their origin at least in part to direct precipitation of calcite from the water column. Geochemical investigations have shown these offshore carbonates to contain relatively large concentrations of strontium (up to 2836 ppm Sr). Considering that calcite in equilibrium with seawater contains approximately 1200 ppm Sr vs 8300 ppm Sr of aragonite (Veizer 1978), as well as the fact that these limestones have undergone diagenetic recrystallization, it appears likely that at least a portion of the calcite in these limestones recrystallized from precursor aragonite.

Comparatively large amounts of terrigenous material were obviously supplied to nearshore carbonate mudflats, but with no apparent negative influence on carbonate production. Terrigenous sedimentation merely served to dilute the carbonate component of the MTS carbonate facies. Sedimentary features, such as cryptalgal lamination, incipient mudcracks, and small domal stromatolites, place the cherty dolostone facies at a similar overall water depth as the MTS carbonate facies, but the considerably smaller content of terrigenous material indicates that they were deposited at a greater distance from the input of terrigenous material. Lateral facies associations (Schieber 1985) show that the cherty dolostone facies was deposited basinward of the MTS carbonate facies.

Lateral facies associations in carbonate units of the Newland Formation further indicate that bedded limestones occur basinward of cherty dolostones and that millimetre-laminated limestones occur basinward of bedded limestones. The application of WALTHER's Law of Facies to vertical facies associations within stratigraphic sections suggests the same lateral facies relationship. Proximal to distal relationships between MTS carbonates and heterolithic limestones can not be established as clearly, mainly because these limestones occur predominantly in the upper portion of the upper member of the Newland Formation, where post-Precambrian erosion has removed the basin marginal deposits. However, the common occurrence of fragments of MTS carbonates within coarse clastic beds of the heterolithic rippled limestone facies suggests that the latter was deposited seawards of MTS carbonates. The presence of current and wave generated sedimentary features in the heterolithic rippled limestone facies suggests that the latter was deposited in shallower water and closer to the shoreline than the heterolithic limestone facies. Because of the abundance of shale interbeds, the heterolithic limestones could not have been basinward lateral equivalents of either the cherty dolostone, the bedded limestone, or the millimetre-laminated limestone facies.

In summary, there appear to be two main variables that controlled carbonate facies development: (1) water depth (encompassing also energy level of environment and distance to shoreline); (2) the amount of terrigenous sediment input along the shoreline. In the envisioned model the MTS carbonates are deposited on nearshore mudflats, and in case of thin shale interbeds (small terrigenous input) cherty dolostones, bedded limestones, and mm-laminated limestones are deposited successively further offshore and in deeper water. If nearshore mudflats receive large amounts of terrigenous input (thick shale interbeds in MTS carbonates) heterolithic rippled limestones and heterolithic limestones are deposited successively further offshore and in deeper water. Vertical facies contacts between carbonate units and shale units are commonly gradational (SCHIEBER 1985), an indication of gradational lateral transitions between carbonate and shale facies.

The paucity of stromatolites in Newland carbonates

Considering the overall shallow epicontinental setting of carbonate deposition in the Newland Formation, a curious situation exists when one compares stromatolite abundance and diversity in the Newland Formation with other carbonate sequences of similar age. Particularly, Proterozoic carbonate sequences around the world contain a wide variety of diagnostic stromatolite forms (CLOUD & SEMIKHATOV 1969; PREISS 1976), that owe their distinctive appearances to the interplay between hydrological and physico-chemical conditions of the environment as well as the mat community on the stromatolite growth surface. A number of these stromatolite forms are actually diagnostic and widespread enough to allow intra- and interbasinal correlation of Proterozoic carbonate sequences (WALTER 1976; PREISS 1976), and are typically of columnar-branching morphology. Examinations of stromatolite form variability in modern environments indicates that the later morphologies require high energy depositional settings and are best developed on coastal headlands where wave and/or tidal scouring are at a maximum (HOFFMAN 1976).

In carbonates of the Newland Formation practically all stromatolite occurrences are of the planar-stratiform type, an indication of low energy conditions and weak wave and tidal scour (HOFFMAN 1976). Only in the Altyn Limestone, an approximate lateral equivalent of the Newland Formation in the northern Belt basin, have columnar and branching stromatolites been observed (HORODYSKI 1976a).

Another major carbonate unit within the Belt Series, the "Middle Belt Carbonate Interval" (HARRISON 1972), also exhibits a much lower diversity of stromatolite forms when compared to Proterozoic carbonate sequences elsewhere (EBY 1977). Among the few recognized columnar and branching stromatolite forms of interbasinal character are *Conophyton*, *Jacutophyton*, and *Baicalia* (HORODYSKI 1976b), and these have only been found in the northern portion of the basin. The only other stromatolite forms found are domal and mound-shaped stromatolites. EBY (1977) suggested that strongly elevated salinity of basin waters was the cause for the paucity of distinctive Mid-Proterozoic stromatolite form genera in the "Middle Belt Carbonate Interval". Increased salinity of basin waters is indicated by the presence of cerebroid ooids, halite casts, and presumably calcitized evaporites (MTS).

Increased salinity of basin waters is also indicated for the time interval of Newland deposition by presence of MTS and stratiform solution collapse breccias. Additionally, silicified evaporites have been described from its northern equivalent, the Altyn Limestone (WHITE 1977). Thus, basinwide conditions of increased salinity, as well as low levels of wave and tidal current activity may have been responsible for the very strong dominance of planar-stratiform stromatolites in the Newland Formation. The occurrence of columnar-branching stromatolites in the northern part of the basin may actually be an indication of a northern seaway connection to the Proterozoic ocean (see section on geologic setting). Tidal influences from the Proterozoic ocean would in this case have been strongest in the northern portion of the basin (Altyn Limestone), and weakest or absent on the southern and southeastern portions of the basin (Newland Formation).

Conclusion

The Newland Formation was deposited in an epicratonic basin under arid to semi-arid climate conditions. Carbonate depositional environments range from nearshore mudflats to distal "starved basin" facies. Storms played an important role in the redistribution of carbonate material from nearshore to basinal environments and their deposits are found in all facies types. Nearshore carbonate mudflats probably dominated carbonate production in the basin, and carbonate precipitation was most likely linked to metabolic processes of microbial mats. Basin waters were probably hypersaline, and in offshore environments direct carbonate precipitation from the water column may have been important. Contemporaneous terrigenous sedimentation was not detrimental to carbonate production on nearshore mudflats, probably because of the ability of microbial mats to prosper even under conditions of strong siliciclastic sedimentation. Main controls on carbonate facies development are (a) water depth (related to energy level of environment and distance from shoreline) and (b) the amount of terrigenous input along the shoreline.

Several of the processes proposed by Mount (1984) in a generalized model for siliciclastic-carbonate mixing in shallow shelf environments have been in effect during deposition of the Newland Formation. "Punctuated Mixing" due to storms has been a major factor to introduce carbonate matter from nearshore carbonate mudflats to areas of contemporaneous shale accumulation. "Facies Mixing" is indicated by the commonly observed gradational contacts between shale and carbonate units. The direct or indirect production of carbonates by microbial mats on nearshore mudflats with abundant terrigenous sediment supply would fall into the "In Situ Mixing" category of Mount (1984). Obviously, these three mixing processes operated simultaneously, but their effect was not necessarily uniform across the basin.

If looked at more specifically, carbonate-siliciclastic mixing in the upper member of the Newland Formation seems also to be related to basin configuration and tectonic setting. In particular, the halfgraben configuration of the Helena embayment, with a growth fault and abundant deposition of coarse terrigenous clastics along the southern basin margin (Fig. 1), and deposition of intercalated carbonates and shales in the central and northern portion, shows considerable resemblance to the carbonate-siliciclastic mixing model proposed by Walker et al. (1983). In that model a sedimentary sequence is considered as wedge-like on a regional scale, with a coarse terrigenous clastic portion in the thick end of the wedge, and a carbonate dominated portion on the opposite, thin end of the wedge. A deeper water shale basin separates the terrigenous depocentre from the carbonate depocentre. In the upper member of the Newland Formation deeper water facies (mm-laminated and heterolithic limestone) is dominant in the central portions of the Helena embayment (Big Belt and Castle Mountains, see Fig. 1), whereas shallow water facies (molar tooth carbonates and cherty dolostones) is found in several of the carbonate units of the northern Helena embayment (Little Belt Mountains). The southern portion of the embayment (Bridger Range, Horseshoe Hills, Cardwell-Whitehall district, Highland Mountains) is dominated by coarse clastic deposits of the LaHood Formation (Fig. 1), a lateral equivalent of the upper member of the Newland Formation (Schieber 1990). Thus, in general terms, the Helena embayment during deposition of the upper member of the Newland Formation can be subdivided in a southern terrigenous clastic dominated portion, a central portion of deeper water carbonates, and a northern portion of shallow water carbonates, just as required by the model of Walker et al. (1983). Distribution of shales in the upper member of the Newland Formation is also consistent with this model. A considerable portion of the shales in the Newland Formation were probably derived from the south, as indicated by south to north thinning of individual shale units and by a northward thinning of the upper member of the Newland Formation as a whole (Schieber 1985). In addition, shallow water shale facies increase in abundance northward (Schieber 1989). These trends are complemented by southward thinning and eventuel pinch-out of carbonate units within the sequence (Schieber 1985). During deposition of the upper member of the Newland Formation repeated uplifts along the southern basin margin probably caused variations in terrigenous clastic input and northward advances and retreats of clastic sedimentation. The latter led to deposition of large volumes of mixed terrigenous/carbonats sediments by "Facies Mixing", as well as producing intercalated shale and carbonate packages (Schieber 1986). Gradual transitions between shale and carbonate units indicate that "Facies Mixing" was common throughout the basin. In contrast, "Punctuated Mixing" (due to storms) was primarily of importance for carbonates and shales deposited in offshore-basinal settings of the central to northern Helena embayment. "In Situ Mixing" was mainly confined to nearshore mudflats (molar tooth carbonates) of the northern Helena embayment.

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References

Aigner, T. & Futterer, E. (1977): Kolk-Töpfe und -Rinnen (pot and gutter casts) im Muschelkalk - Anzeiger für Wattenmeer? – N. Jb. Geol. Paläont. Abh., **156**: 285-304; Stuttgart.

Armstrong, A. K. (1975): Carboniferous tidal-flat deposits of the North Flank, northeastern Brooks Range, arctic Alaska. – In: Ginsburg, R. N. [Ed.]: Tidal Deposits: 325-331; New York (Springer).

Bauerman, H. (1885): Report on the geology of the country near the fourty-ninth parallel of north latitude west of the Rocky Mountains. – Canada Geol. Surv. Rept. Prog. 1882-1884, B: 1-42; Ottawa.

Bauld, J., Burne, R. V., Chambers, L. A., Ferguson, J. & Skyring, G. W. (1980): Sedimentological and geobiological studies of intertidal cyanobacterial mats in northeastern Spencer Gulf, South Australia. – In: Trudinger, P. A., Walter, M. R. & Ralph, B. J. [Eds.]: Biogeochemistry of ancient and modern environments: 157-166; Canberra (Austr. Acad. Sci.).

Bertrand-Sarfati, J. (1976): An attempt to classify Late Precambrian stromatolite microstructures. – In: Walter, M. R. [Ed.]: Stromatolites: 251-259; Amsterdam (Elsevier).

Birkholz, D. O. (1967): Geology of the Camas Creek area, Meagher Conty, Montana. – MS thesis, Montana College Miner. Sci. Technol.: 68 p., Butte.

Boersma, J. R. (1970): Distinguishing features of wave-ripple cross-stratification and morphology. – Doct. Diss., Univ. of Utrecht: 65 p.; Utrecht.

Boggs, S. (1987): Principles of sedimentology and stratigraphy. – 784 p.; Columbus (Merrill).

Cressman, E. R. (1989): Reconnaissance stratigraphy of the Prichard Formation (Middle Proterozoic) and early development of the Belt basin, Washington, Idaho, and Montana. – U.S. geol. Surv. Prof. Pap., **1490:** 80 p.; Washington.

Cloud, P. E. & Semikhatov, M. A. (1969): Proterozoic stromatolite zonation. – Amer. J. Sci., **267:** 1017-1061; New Haven.

Conybeare, C. E. B. & Crook, K. A. W. (1968): Manual of sedimentary structures. – BMR Bull., **102:** 327 p.; Canberra.

Doyle, L. J. & Roberts, H. H. [Eds.] (1988): Carbonate-clastic transitions. – 304 p.; New York (Elsevier).

Dunham, R. J. (1962): Classification of carbonate rocks according to depositional texture. – In: Ham, W. E. [Ed.]: Classification of carbonate rocks: 108-121; Tulsa (Amer. Ass. Petrol. Geol.).

Eby, D. E. (1977): Sedimentation and early diagenesis within eastern portions of the 'Middle Belt Carbonate Interval' (Helena Formation), Belt Supergroup (Precambrian-Y), Western Montana. – Ph. D. diss., SUNY at Stony Brook: 755 p.; New York.

Einsele, G. (1982): Limestone-marl cycles (Periodites): Diagnosis, significance, causes - a review. – In: Einsele, G. & Seilacher, A. [Eds.]: Cyclic and event stratification: 8-53; Berlin (Springer).

Enos, P. (1974): Reefs, platforms and basins of Middle Cretaceous in Northeast Mexico. – Am. Assoc. Petrol. Geol. Bull., **58:** 800-809; Tulsa.

Erikson, K. A. (1977): Tidal flat and subtidal sedimentation in the 2250 M. Y. Malmani Dolomite, Transvaal, South Africa. – Sed. Geol., **18:** 223-244; Amsterdam.

Gerdes, G., Krumbein, W. E. & Reineck, H.-E. (1985): The depositional record of sandy, versicolored tidal flats (Mellum Island, southern North Sea). – J. sediment. Petrol., **55:** 265-278; Tulsa.

Ginsburg, R. N. & Hardie, L. A. (1975): Tidal and storm deposits, northwestern Andros Island, Bahamas. – In: Ginsburg, R. N. [Ed.]: Tidal Deposits: 201-208; New York (Springer).

Grotzinger, J. P. (1986): Shallowing-upward cycles of the Wallace Formation, Belt Supergroup, northwestern Montana and northern Idaho. – Montana Bur. Mines Geol., Spec. Publ., **94:** 143-160; Butte.

Halley, R. B. (1975): Peritidal lithologies of Cambrian carbonate islands, Carrara Formation, southern Great Basin. – In: Ginsburg, R. N. [Ed.]: Tidal Deposits: 279-288; New York (Springer).

Harrison, J. E. (1972): Precambrian Belt basin of northwestern United States: Its geometry, sedimentation, and copper occurrences. – Bull. geol. Soc. Amer., **83:** 1215-1240; Boulder.

Harrison, J. E., Griggs, A. B. & Wells, J. D. (1984): Tectonic features of the Precambrian Belt basin and their influence on post-Belt structures. – U.S. geol. Surv. Prof. Pap., **866:** 15 p.; Washington.

Hemleben, C. (1980): Allodapic limestones of the Barcaliente Formation (Namurian A) between Luna and Cea rivers (Southern Cantabrian Mountains, Spain). – N. Jb. Geol. Paläont. Abh., **159:** 223-255; Stuttgart.

Hoffman, P. (1973): Recent and ancient algal stromatolites: Seventy years of pedagogic cross-pollination. – In: Ginsburg R. N. [Ed.]: Evolving concepts in sedimentology: 178-191; Baltimore (Johns Hopkins Univ. Press).

–,– (1976): Stromatolite Morphogenesis in Shark Bay, Western Australia. – In: Walter, M. R. [Ed.]: Stromatolites: 261-271; Amsterdam (Elsevier).

Horodyski, R. (1976a): Stromatolites from the Middle Proterozoic Altyn Limestone, Belt Supergroup, Glacier National Park, Montana. – In: Walter, M. R. [Ed.]: Stromatolites: 585-597; Amsterdam (Elsevier).

–,– (1976b): Stromatolites of the Upper Siyeh limestone (Middle Proterozoic), Belt Supergroup, Glacier National Park, Montana. – Prec. Res., **3:** 517-536; Amsterdam.

Javor, B. J. & Castenholz, R. W. (1981): Laminated microbial mats, Laguna Guerro Negro, Mexico. – Geomicrobiol. J., **2:** 237-273; New York.

Lucia, F. J. (1972): Recognition of evaporite-carbonate shoreline sedimentation. – In: Rigby, J. K & Hamblin, W. K. [Eds.]: Recognition of ancient sedimentary environments: 160-191; Tulsa (Soc. Econ. Paleont. Mineral.).

McIlreath, I. & Ginsburg, R. N. (1982): Mixed deposition of carbonate and siliciclastic sediments. – In: Abstracts of papers, 11th International Congress on Sedimentology: 109-113; Utrecht (Internat. Ass. Sedimentol.).

Mount, J. F. (1984): Mixing of siliciclastic and carbonate sediments in shallow shelf environments. – Geology, **12:** 432-435; Boulder.

Nelson, W. H. (1963): Geology of the Duck Creek Pass quadrangle, Montana. – U.S. geol. Surv. Bull., **1121J:** 56 p.; Washington.

Peterson, M.N.A. & Von der Borch, C. C. (1965): Modern chert in a carbonate-precipitating locality. - Science, **149:** 1501-1503; Washington.

Piper, J. D. A. (1982): The Precambrian paleomagnetic record: The case for the Proterozoic Supercontinent. – Earth Planet. Sci. Lett., **59:** 61-89; Amsterdam.

Plummer, P. S. & Gostin, V. A. (1980): Shrinkage cracks: Desiccation or synaeresis? – J. sedim. Petrol., **51:** 1147-1156; Tulsa.

Preiss, W. V. (1976): Intercontinental correlations. – In: Walter, M. R. [Ed.]: Stromatolites: 359-370; Amsterdam (Elsevier)

Reineck, H.-E. & Singh, I. B. (1980): Depositional sedimentary environments. – 539 p.; New York (Springer).

Reineck, H.-E. & Wunderlich, F. (1968): Classification and origin of flaser and lenticular bedding. – Sedimentology, **11:** 99-104; Amsterdam.

Schieber, J. (1985): The relationship between basin evolution and genesis of stratiform sulfide horizons in Mid-Proterozoic sediments of the Belt Supergroup, Montana. U.S.A. – Ph. D. diss., Univ. of Oregon: 811 p.; Eugene.

–,– (1986): Stratigraphic conctrol of rare-earth pattern types in Mid-Proterozoic sediments of the Belt Supergroup, Montana, U.S.A.: Implications for basin analysis. – Chem. Geol., **54:** 135-148; Amsterdam.

–,– (1987): Storm-dominated epicontinental clastic sedimentation in the Mid-Proterozoic Newland Formation. – N. Jb. Geol. Paläont. Mh. **1987:** 417-439; Stuttgart.

–,– (1988): Redistribution of rare-earth elements during diagenesis of carbonate rocks from the Mid-Proterozoic Newland Formation, Montana, U.S.A. – Chem. Geol., **69:** 111-126; Amsterdam.

–,– (1989): Facies and origin of shales from the Mid-Proterozoic Newland Formation, Belt basin, Montana, U.S.A. – Sedimentology, **36:** 203-219; Oxford.

–,– (1990): Distribution of REE in the eastern Belt Supergroup (Montana, U.S.A.): Implications for stratigraphic correlations and basin evolution. – Chem. Geol., **81**: 83-98; Amsterdam.

SEARS, J. W. & PRICE, R. A. (1978): The Siberian connection: A case for the Precambrian separation of the North American and Siberian cratons. – Geology, **6**: 267-270; Boulder.

SEILACHER, A. (1982): Distinctive features of sandy tempestites. – In: EINSELE, G. & SEILACHER, A. [Eds.]: Cyclic and event stratification: 333-349; Berlin (Springer).

SHAW, A. B. (1964): Time in stratigraphy. – 365 p.; New York (McGraw-Hill).

SHINN, E. A., LLOYD. R. M. & GINSBURG, R. N. (1969): Anatomy of a modern carbonate tidal flat, Andros Island, Bahamas. – J. sediment. Petrol., **39**: 1202-1228; Tulsa.

STEWART, J. H. (1976): Late Precambrian evolution of North America: Plate tectonics implication. – Geology, **4**: 11-15; Boulder.

STRAUSS, H. & SCHIEBER, J. (1990): A sulfer isotope study of pyrite genesis: The Mid-Proterozoic Newland Formation, Belt Supergroup, Montana. – Geoch. Cosmoch. Acta **54**: 197-204; New York.

VEIZER, J. (1978): Strontium. – In: WEDEPOHL, K. H. [Ed.]: Handbook of geochemistry: 38-K-1 - 38-L-3; New York (Springer).

VON DER BORCH, C. C. (1976): Stratigraphy and formation of Holocene dolomitic carbonate deposits of the Coorong area, South Australia. – J. sediment. Petrol., **46**: 952-966; Tulsa.

VON DER BORCH, C. C. & JONES, J. B. (1976): Spherular modern dolomite from the Coorong area, South Australia. – Sedimentology, **23**: 587-591; Oxford.

VON DER BORCH, C. C. & LOCK, D. (1979): Geological significance of Coorong dolomites. – Sedimentology, **26**: 813-824; Oxford.

WALCOTT, C. D. (1899): Precambrian fossiliferous formations. – Geol. Soc. Amer. Bull., 10: 199-244; Boulder.

WALKER, K. R., SHANMUGAM, G. & RUPPEL, S. C. (1983): A model for carbonate to terrigenous clastic sequences. – Geol. Soc. Amer. Bull., 94: 700-712; Boulder.

WALTER, M. R. (1976): Stromatolites. – 790 p.; Amsterdam (Elsevier).

WHITE, B. (1977): Silicified evaporites from the Middle Proterozoic Altyn Formation, Lower Belt Supergroup of Montana. – Geol. Soc. Amer. Abstr. w. Progr., 9: 1223-1224; Boulder.

WILSON, J. L. (1975): Carbonate facies in geologic history. – 471 p.; New York (Springer).

WINSTON, D. (1986): Sedimentology of the Ravalli Group, Middle Belt Carbonate and Missoula Group, Middle Proterozoic Belt Supergroup, Montana, Idaho and Washington. – Montana Ber. Min. Geol., Spec. Publ., **94**: 85-124; Butte.

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Anschrift des Verfassers:

Dr. JÜRGEN SCHIEBER, Department of Geology, The University of Texas at Arlington
(UTA), Arlington, Texas 76019, U.S.A.