DETERMINATION OF BASINWIDE PALEOCURRENT PATTERNS IN A SHALE SEQUENCE VIA ANISOTROPY OF MAGNETIC SUSCEPTIBILITY (AMS): A CASE STUDY OF THE MID-PROTEROZOIC NEWLAND FORMATION, MONTANA

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ABSTRACT: It has been demonstrated that in shales of the Mid-Proterozoic Newland Formation the long axis of the AMS ellipsoid A) coincides with the flow azimuth indicated by macroscopic paleoflow indicators and B) is inclined in an upcurrent direction. Following this finding, oriented samples were collected from the Newland Formation and its lateral equivalents over the entire extent of the southeastern Belt basin, the so-called Helena embayment. Two successive stratigraphic units were sampled to determine possible changes in paleocurrent patterns with changing basin configuration. The study resulted in the recognition of coherent paleocurrent patterns that are consistent with earlier stratigraphic and sedimentologic studies. The described investigation is the first of its kind to apply the AMS method to shales on a basinwide scale, and its success suggests that this method could also be successfully applied to paleocurrent investigations of other basins that contain extensive shale sequences.

INTRODUCTION

In the study of sedimentary basins, knowledge of paleocurrent or paleocirculation systems has always been of great value for the understanding of basin history (Potter and Pettijohn, 1977), allowing predictions about facies trends, active structural features, and location of source regions. In the past, paleoflow information has been derived from shale sequences in a variety of ways (e.g. Potter et al., 1980; Schieber and Ellwood, 1988), utilizing interbedded sandstones and carbonates, alignment of fossils and detrital quartz grains, and lateral distribution of detrital components. Drawbacks are that paleoflow indicators of interbedded sandstones and carbonates may not be representative of paleoflow in the shale itself, and that other methods require either fortuitous circumstances (such as oriented fossils), or are very time consuming because of extensive field (detailed mapping) or laboratory work (microscopy).

That anisotropy of magnetic susceptibility (AMS) of sediments is a reliable paleoflow indicator has been demonstrated in several studies of sands and sandstone (e.g. Rees, 1965; Rees et al., 1968; Hamilton and Rees, 1971; Taira and Lienert, 1979; Hrouda, 1982) and modern marine muds (e.g. Ellwood and Ledbetter, 1979; Ellwood, 1980). Although these studies have shown that the AMS method is accurate and easily applicable, the study by Schieber and Ellwood (1988) was the first to test its applicability to shales. In that study close agreement between AMS principal azimuths and macroscopic paleocurrent indicators in shales of the Mid-Proterozoic Newland Formation was found in a suite of unoriented handspecimens. Although the study did not provide actual paleocurrent information for the Newland Formation, it did indicate its suitability for a regional study of AMS fabrics as a basis for basin scale paleocurrent analysis.

GEOLOGIC SETTING

The shale dominated Newland Formation occurs in an eastern extension of the Belt basin, the Helena embayment (Fig. 1), and has been subdivided into a lower member (dolomitic shales) and an upper member (interstratified packages of shales and carbonates) by Nelson (1963). Harrison (1972) correlated the Newland Formation with the Prichard Formation of the lower Belt Supergroup. Stratigraphic and sedimentologic features of Proterozoic sediments in the Helena embayment are summarized by Schieber (1985, 1986). At the base of the upper member an interval of shales with interbedded feldspathic sandstones has been informally termed the "Newland Transition Zone" (Schieber, 1985). This interval marks a distinct change of lithology, sedimentation conditions, and facies patterns. It is interpreted to mark an episode of regression and uplift in the hinterland as a result of a change in basin configuration from a wide gentle depression to an east-west trending half-graben (Schieber, 1986, 1990). In the latter configuration fan-delta sandstones and conglomerates of the LaHood Formation (McMannis, 1963) were shed into the basin from the south along an east-west trending basin bounding fault. Northward the amount of shale in the LaHood Formation increases and it interfingers with fine-grained sediments of the upper member of the Newland Formation (Fig. 2). Given the above mentioned change of basin configuration and facies patterns, one might also expect to see changes in paleocurrent patterns between the lower and upper member of the Newland Formation. Therefore, samples for this study were collected from both stratigraphic units, in order to see if coherent paleocurrent patterns as well as their changes through time can be recognized using the AMS method.

PREVIOUSLY AVAILABLE PALEOFLOW INFORMATION

A small number of paleoflow directions was recorded in a study of storm sand deposits (medium to coarse sandstone) in the upper member of the Newland Formation (Schieber, 1987). The orientations of scour marks, flute casts, and erosional rills were measured, as well as proximality trends based on sandstone/shale ratio and abundance of sandstone beds (results summarized in Fig. 1). The data indicate that sandstones in the southern Big Belt Mountains were derived from the south, whereas sandstones in the northern Big Belt Mountains and Little Belt Mountains were derived from the north. Sedimentary structures indicative of paleoflow directions are very rare in the LaHood Formation, the lateral equivalent of the upper member of the Newland Formation along the southern basin margin (Schieber, 1990). However, decreasing grain size and bed thickness of sandstones and conglomerates towards the north, as well as a parallel decrease in the sandstone/shale ratio (Fig. 1), strongly suggest south to north sediment transport (McMannis, 1963; Boyce, 1975).

SAMPLING AND DATA AQUISITION

Oriented samples of the Newland Formation were collected from 32 sites in the Big Belt and Little Belt Mountains, as well as from 4 sites in the southern part of the Helena embayment (Fig. 1). During an initial field test a small number of oriented samples were drilled in outcrop, and strike and dip of shale beds was recorded. Splintering of cores during drilling seriously hampered sampling. Collection of oriented hand specimens and later sample processing and coring in the lab at UTA turned out to be much more efficient and allowed measurements from outcrops that otherwise would not have yielded data.

Cores were measured for AMS in a low-field torsion fiber magnetometer (see King and Rees, 1962 for a discussion of the method), and a tilt corrected AMS ellipsoid was calculated for each core. Further information and a discussion of magnetic fabric data is given by Schieber and Ellwood (1988). Ninety percent of the AMS measurements reported in Table 1 were made on cores drilled from oriented hand specimens. Although most data in this study come from shales, in places where sandstones are abundant and form resistant ledges AMS measurements were also performed on sandstone samples. The proportion of sandstone data in a site is indicated in the rightmost column of Table 1 (SS%).

RESULTS

Samples of an AMS pilot study of Newland Formation shales (Schieber and Ellwood, 1988) showed magnetic fabric elements typically inclined (imbricated) opposite to flow direction, suggesting that principal axis (K1) inclination and declination can be used to determine paleoflow direction. This assumption is the basis for interpretation of data from the present study. Site means of K1 azimuths for 31 sites and 4 composite sites (pool data from closely adjacent outcrops) are presented so that the angle given in Table 1 points in the interpreted paleoflow direction.

Data from hand specimen cores typically show well defined clustering (e.g. sample 1 in Fig. 3), but in a small number of specimens anomalous appearing data distributions were observed. For example, in sample 5 (Fig. 3A) measurements from core 5-1 plot almost 90 degrees from the azimuth defined by the other two cores. Causes for such a deviation could be

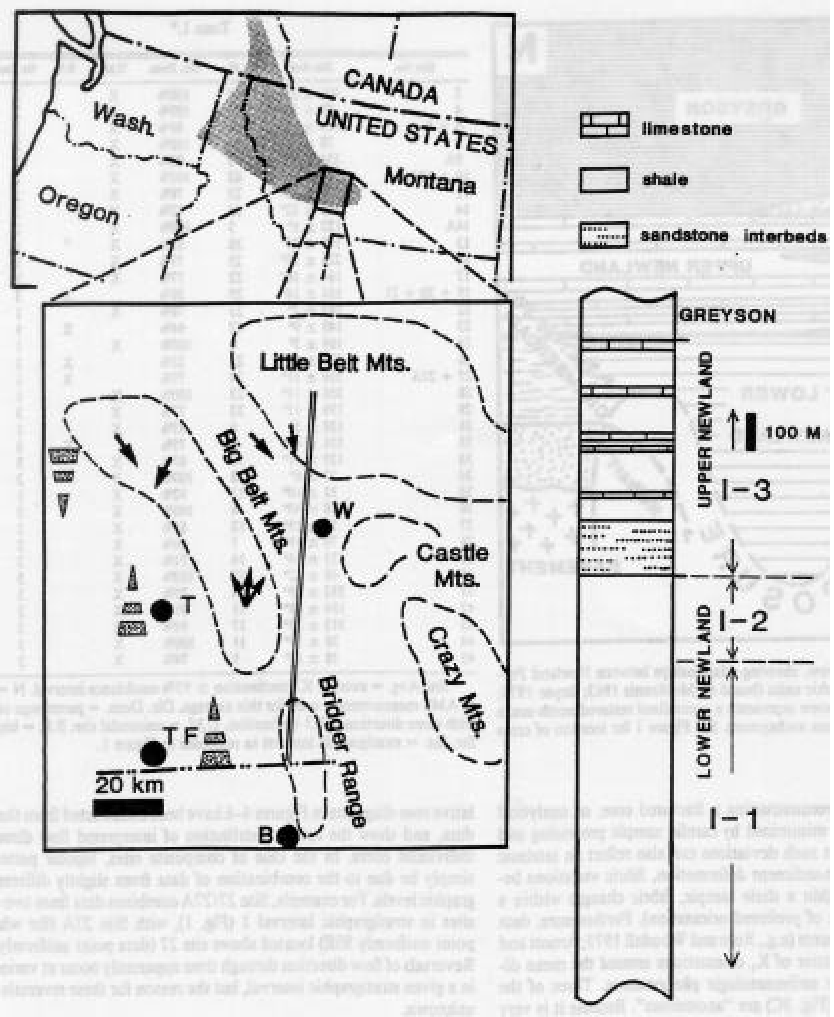

Figure 1: Location map and stratigraphic overview. Belt basin outlined with stipple pattern. The enlarged map portion comprises the Helena embayment, and shows major geographic features of the study area. B = Bozeman, TF = Three Forks, T = Townsend, W = White Sulphur Springs. Solid arrows indicate paleoflow directions in sandstones. Tapered arrows with stipple pattern indicate decreasing sand content, decreasing thickness of sand beds, and decreasing sand/shale ratio. The two opposed arrows to the left of the Big Belt Mountains indicate sandstone trends for the Newland Formation. The dashed-double-dotted line that runs through the center of the Bridger Range marks the southern boundary of the LaHood Formation. The arrow to the left of the Bridger Range indicates sandstone trends for the LaHood Formation. Thicknesses in the generalized stratigraphic column are approximate because of lateral thickness changes in the Newland Formation. I-1 = interval 1 (data in Fig. 4); I-2 = interval 2 (data in Fig. 5); I-3 = interval 3 (data in Fig. 6).

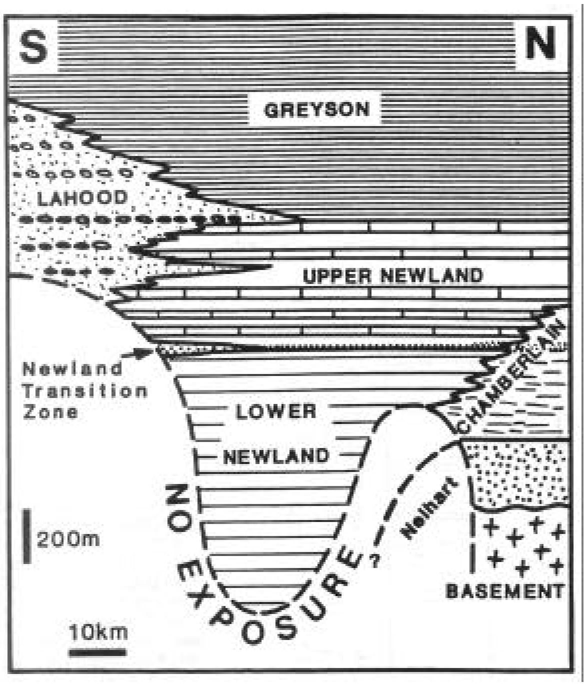

Figure 2: Stratigraphic overview, showing relationships between Newland Formation and adjacent stratigraphic units (based on McMannis, 1963; Boyce, 1975; and Schieber, 1985). The overview represents a N-S oriented generalized restored cross-section through the Helena embayment. The cross section runs from the middle of the Bridger Range to the northern edge of the Little Belt Mountains (see enlarged map in Fig. 1).

TABLE 1.*

Site No.	Site Avg.	N	Dir. Dom.	U.M.	B.P.	Str. Int.	SS%
2	101 ± 24°	8	100%	X		2	0
4	89 ± 24°	21	100%	X		3	0
6 + 8	113 ± 15°	44	89%	X		3	0
9	78 ± 29°	14	100%	X		2	0
9A	334 ± 71°	6	83%	X		1	0
10 + 10A	91 ± 10°	62	100%	X		2	0
11	138 ± 48°	23	78%	X		3	17
14	125 ± 22°	16	75%	X		3	13
14A	125 ± 6°	3	100%	X		2	0
15	166 ± 21°	26	81%	X		1	0
16	226 ± 28°	25	79%	X		1	0
17	164 ± 18°	22	77%	X		3	0
19 + 20 + 21	164 ± 14°	29	59%		X	3	3
22	163 ± 7°	23	78%	X		1	0
23	148 ± 9°	42	64%		X	1	0
24	169 ± 3°	6	100%	X		1	0
26	338 ± 31°	21	55%		X	3	35
27 + 27A	336 ± 31°	24	75%		X	1	0
28	358 ± 14°	23	100%	X		1	0
29	196 ± 11°	32	77%	X		3	50
31	138 ± 3°	6	83%	X		1	0
32	331 ± 46°	8	75%		X	3	63
33	123 ± 41°	15	87%	X		3	0
34	27 ± 6°	13	100%	X		3	0
35	31 ± 10°	12	92%	X		1	0
36	18 ± 40°	6	100%	X		3	0
37	59 ± 13°	12	83%	X		2	0
38	70 ± 19°	7	86%	X		2	0
39	123 ± 14°	14	71%	X		3	100
40	48 ± 22°	23	100%	X		3	100
41	332 ± 39°	24	75%	X		3	62
42	184 ± 16°	11	91%	X		3	0
43	313 ± 25°	17	94%	X		3	0
44	38 ± 19°	11	100%	X		3	100
45	18 ± 16°	9	78%	X		3	56

Site Avg.= average K1 declination +95% confidence interval. N= number of AMS measurements used for this average. Dir. Dom.= percentage of samples with same direction of k1 inclination. U.M.= unimodal site; B.P.= bipolar site. Str. Int.= stratigraphic interval in reference to Figure 1

(1) core orienting errors, (2) errors in reconstructing a fractured core, (3) analytical errors. These can be minimized through careful sample processing and replicate measurements. However, natural causes for such deviations are possible as well (soft sediment deformation, fabric variations between successive layers of shale sample, fabric changes within a given layer, original lack of preferred orientation), reflecting an intrinsic property of the sample. Furthermore, that scatter of K1 orientations around the mean direction is possibly a primary sedimentologic phenomenon is suggested by data from flume deposited sediments (e.g. Rees and Woodall, 1975; Arnott and Hand, 1989). Three of the cores measured for site 17 (Fig. 3C) are "anomalous". Because it is very difficult to determine whether their "anomalous" fabric reflects an intrinsic sample property or is due to procedural artifacts, one may be tempted to simply eliminate these data. However, for above reasons and because the site mean does not change appreciably when the "anomalous" samples are excluded (Fig. 3D), the small number of "anomalous" measurements was included in the calculation of site means.

All examined sites show either unimodal or bipolar distribution of K1 orientations (Table 1). Column four of Table 1 (Directional Dominance) gives the proportion of K1 axes at a given site that are inclined opposite to the interpreted paleoflow direction given in column two. In a number of sites all K1 axes are inclined in the same direction (Directional Dominance = 100%), and the interpreted paleoflow direction was the same throughout the sampled interval. In other sites a proportion of samples suggest flow opposite to the dominant paleoflow direction. Where it happens this typically is observed between samples from different layers within a given outcrop, and may indicate paleoflow reversal within the sequence. In a small number of cases it also occurs between cores from a single sample, in which case it might indicate flow reversal between individual layers of a shale sample. On Figures 4, 5, and 6, sites where more than two thirds of all K1 inclinations point in the same general direction are shown as single arrows, whereas those where less than two thirds point in the same direction are shown as double ended arrows. These sites are listed as unimodal vs bipolar respectively in Table 1. However, the cumulative rose diagrams in Figs. 4, 5, and 6 have been constructed from the original data, and show the actual distribution of interpreted flow directions of individual cores. In the case of composite sites, bipolar patterns may simply be due to the combination of data from slightly different stratigraphic levels. For example, site 27/27A combines data from two adjacent sites in stratigraphic interval 1 (Fig. 1), with site 27A (data point uniformly SSE) located above site 27 (data point uniformly NNW). Reversals of flow direction through time apparently occur at various scales within a given stratigraphic interval, yet the actual reason for these reversals remains unknown.

Paleocurrent Patterns

The purpose of this study was to see if it would be possible to detect within the Newland Formation paleocurrent patterns as well as their possible change in the course of basin evolution. Figure 1 shows that the Newland Formation was subdivided into three intervals for that purpose. Interval 1 and 2 together comprise the lower member of the Newland Formation, whereas interval 3 is identical to the upper member of the Newland Formation as defined by Nelson (1963). Interval 1 comprises the bulk of the lower member of the Newland Formation, and interval 2 forms its uppermost 100 meters in the Little Belt Mountains and is also characterized by occurrences

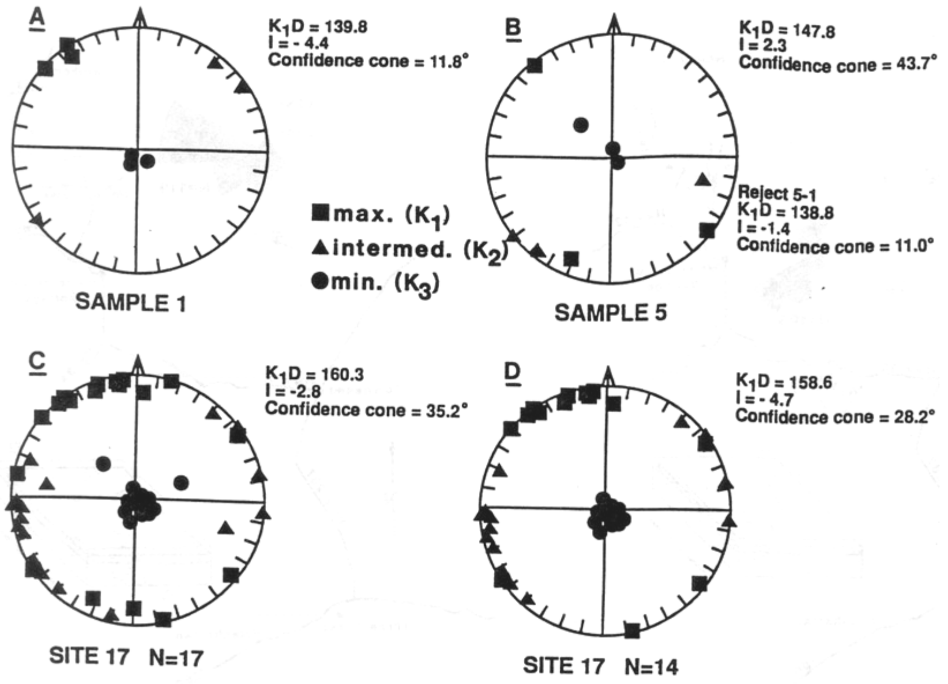

Figure 3: Lower hemisphere equal area plots of data from site 17 (only data from cores that were drilled from oriented hand specimens). K1D is the declination of the K1 axis, and I is the inclination of the K1 axis (in degrees). Figure 3A: Plot of data from hand specimen 1. This is a typical sample. Interpreted flow direction is to the SE (K1 imbrication towards NW). Figure 3B: Plot of data from hand specimen 5. One core plots almost 90 degrees from the other two cores and could be considered "anomalous" and rejected. Figure 3C: Data from all cores that were drilled from oriented hand specimens at site 17. Three of these cores yield "anomalous" data (similar cases as in Fig. 3B). Figure 3D: The same data set as in Fig. 3C, but without the three "anomalous" samples. Note the minimal change of K1D between plot 3C and 3D. In plot 3D the majority of K1 axes shows imbrication towards the NW, thus indicating that paleoflow likely was to the SE.

of variably sized cone in cone concretions (Schieber, 1985). The lower member of the Newland Formation greatly increases in thickness towards the Big Belt Mountains, and the thickness of interval 2 increases there to approximately 200 meters.

Site averages for interval 1 are shown in Figure 4. When compared with basic paleocurrent patterns of Pettijohn et al. (1987), the paleoflow pattern of interval 1 seems best described as a combined parallel-bipolar pattern, with a predominance of the southerly component. Interval 2, the uppermost portion of the lower member of the Newland Formation, shows a marked pattern change (Figure 5). The azimuth has rotated by approximately 90 degrees and the pattern is of the parallel-unimodal type. Figure 6 shows site averages for interval 3, the upper member of the Newland Formation. This figure incorporates the largest number of measurements and the pattern appears to change as one goes from south to north. The pattern in the southern third of the map may be classified as parallel-unimodal, the one in the center as parallel-bipolar, and the one in the northern third again as essentially parallel-unimodal.

Comparison with previously acquired paleoflow information

Interval 1

Because it lacks sandstone, no previous paleoflow data were available from the lower member of the Newland Formation. However, the newly acquired shale AMS data support earlier assumptions as to basin outline and paleoslope.

For example, the fact that the flow pattern in Fig. 4 does not conform in any noticeable way with the outline of the Helena embayment (Fig. 1) suggests that what is preserved of the lower member of the Newland Formation is only an erosional remnant of an originally much more extensive deposit. This agrees well with earlier suppositions that held that the lower member of the Newland Formation was probably deposited as a widespread cratonic sediment blanket or within an extensive smooth sediment-filled depression (Schieber, 1990; Reynolds, 1984). Increasing thickness of the lower member of the Newland Formation towards the south has been interpreted to indicate a gently southward dipping paleoslope (Schieber, 1985). The parallel paleocurrent pattern down this paleoslope towards the SSE (Fig. 4) is what one might expect in such a setting (Pettijohn et al., 1987).

Interval 3

The largest number of measurements was made on the upper member of the Newland Formation and its lateral equivalents. Although some general paleoflow characteristics were known previously (Fig. 1) from studies of sandstone interbeds and sandy lateral equivalents (LaHood Formation), AMS data yielded a much more detailed flow pattern (Fig. 6).

Almost 90 percent of the measurements from the southern portion of Fig. 6 (sites 40, 41, 44, 45) were made on sandstones (Table 1), primarily because sandstones were the most commonly outcropping lithology and were easily sampled. Petrofabrics of flume deposited sands (Cheel, 1990), relationships between magnetic lineation and sand grain long-axis orientation (Taira and Lienert, 1979), AMS measurements on flume-deposited sands (Rees and Woodall, 1975), and AMS studies of sands and sandstones (e.g. Hrouda, 1982; Hamilton and Rees, 1971; Rees, 1965; Rees et al., 1968) all suggest that magnetic fabrics of sandstones generally should show upstream imbrication. If K1 axes of sandstones from sites 40, 41, 44, and 45 are interpreted in this way they suggest a northerly transport direction (Table 1). These sites are in the LaHood Formation, a fan-delta sequence that prograded into the basin from an active fault along the southern basin margin (Boyce, 1975). Overall transport to the NNE as indicated by the rose diagram and the site averages (Fig. 6), is in good agreement with the previously described northward decrease in grain size, sand content, and sandstone/shale ratio (Fig. 1). AMS data of shales, although not as numerous, also indicate northward sediment transport.

In the northern part of the Helena embayment, AMS measurements indicate general paleoflow towards the southeast during deposition of the upper member of the Newland Formation (Fig. 6). However, when previously collected paleoflow data from sandstones (Fig. 1) are considered, and when AMS measurements from shales are considered separateley from the small number of AMS measurements in sandstones of that area (contribute data to sites 11, 14, and 26), a somewhat different picture emerges. In particular, AMS measurements from shales indicate predominant transport in an east-west to southeasterly direction, whereas data from sandstones (AMS plus sedimentary structures) indicate a southern to southeasterly transport direction. Sandstone beds as well as many of the shale beds in the upper member of the Newland Formation were probably deposited by storms (Schieber, 1987), as can be seen from hummocky cross-stratification in sandstones and comparison of the shales to muddy tempestites of the North Sea (Aigner and Reineck, 1982).

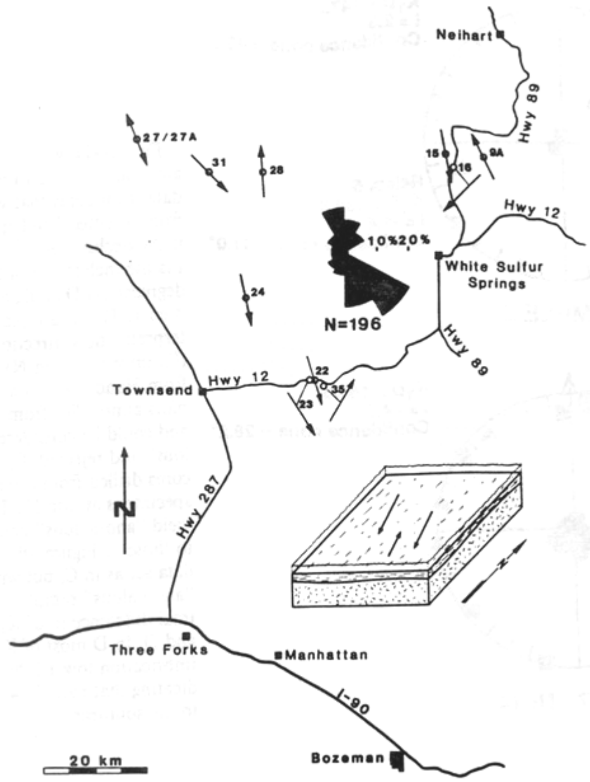

Figure 4: Map of AMS site averages for lower portion of lower member of the Newland Formation (see Fig. 1). Single arrows indicate that one direction strongly dominates, double arrows indicate bipolar sites. Sites marked by empty circles, numbers besides circle correspond to site numbers in Table 1. Inset block diagram shows schematic geologic interpretation of area with a parallel-bipolar paleocurrent pattern

In comparison with ancient storm deposits, sedimentary features (e.g. sole marks) and transport directions of Newland sandstones in the northern Helena emabyment suggest existence of an east-west trending shoreline to the north (Leckie and Krystinik, 1989), an assumption that is supported by studies of facies distribution (Schieber, 1985). However, such a comparison conflicts with observations of modern shelf seas that suggest shore-parallel to shore-oblique (geostrophically balanced) flow during storms (Swift et al., 1983). On the other hand, the observed flow directions for the shales are essentially those that would result from a geostrophically balanced storm currrent. Examination of sedimentary features and facies associations in the Newland Formation (Schieber, 1985) suggest that the northern shoreline should have been located at least several km's and probably even in excess of 10 km's north of its northernmost exposure (site 4, Fig. 6), an indication that storm induced currents in the northern Helena embayment probably were geostrophically balanced (Swift et al., 1983). Duke (1990) and Duke et al. (1991) pointed out that in that case two types of flow phenomenon have to be considered, namely a unidirectional and obliquely offshore directed bottom current, and a superimposed oscillatory wave motion that is oriented more or less normal to the shoreline. Because the bed shear stress imposed by waves is much larger than that of the offshore flowing current, the peak instantaneous shear stress is directed at a very high angle to shore. Thus the coarsest grains in the flow (medium to coarse sand for the Newland Formation) should move almost directly seaward and erosional features (flute marks) should be offshore-directed. In contrast, the suspended load will be much more strongly affected by the geostrophic flow component and move shore-oblique. The difference between overall transport directions of shales and sandstones in the Newland Formation may very well suggest that the scenario proposed by Duke et al. (1991) concerning sediment transport in storm-induced currents is valid.

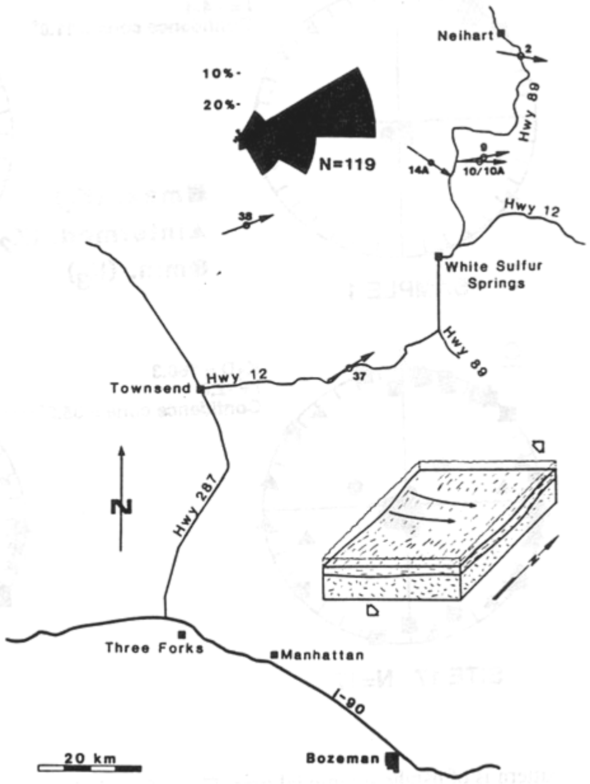

Figure 5: Map of AMS site averages for uppermost portion of lower member of the Newland Formation (see Fig. 1). Symbols as in Fig. 4. Note the strong shift of paleoflow to an easterly flow direction. Inset block diagram shows schematic geologic interpretation of area with beginning subsidence of an east-west trending trough and eastward flow along the trough axis. Open arrows indicate presumed direction of extension.

Thus, although paleoflow directions determined from shales and sandstones differ, above considerations suggest that they are nonetheless consistent with an east-west trending shoreline in the north of the Helena embayment during deposition of the upper member of the Newland Formation. With an east-west trending basin bounding fault in the south and a gradual thickening of the upper member of the Newland Formation towards the south (Schieber, 1985), the basin does indeed resemble the half-graben configuration mentioned in the introduction. The inset block diagram in Fig. 6 shows major features of the assumed paleogeography, such as the southern basin margin with alluvial fans, the central depositional trough (E-W trending), and generally shallow water along the northern basin margin. Additional sketch maps and details concerning the paleogeography of the upper member of the Newland Formation can be found in Schieber (1985, 1987). The bipolar paleocurrent pattern in the central portion of Fig. 6 is probably due to interfingering in the central portion of the basin of sediment derived from the northern and southern shorelines.

Brief mention should be given here to site 32 which is listed in Table 1 as bipolar although 75 percent of the AMS measurements suggest flow in a northerly direction. However, all the northward directed AMS data are from a hummocky cross-stratified sandstone bed. The imbrication (in off-shore direction) of magnetic fabrics and of sand grains appears opposite to what one would expect from the southward transport direction deduced from sedimentry structures and proximality trends (Fig. 1). However, the explanation may simply be that strike and dip measurements were taken from shale bedding planes rather than the more irregular sandstone surface. Thus samples from the southern portion of a hummock may show a southerly dipping fabric (suggesting northward transport), even though the fabric within individual laminae may still be inclined to the north, and thus indicate transport to the south. Therefore, although more than two thirds of the measurements at site 32 point to transport in a northwesterly direction, site 32 is nonetheless listed as bipolar in Table 1.

Interval 2

Obviously, paleocurrent patterns from the lower and upper member of the Newland Formation do indeed contrast strongly (Figs. 4 and 6), and the changing patterns are reasonably explained with a postulated change from an extensive smooth sediment-filled depression to an east-west trending half graben. Although AMS data for interval 2 (uppermost portion of lower member of Newland Formation) are comparatively sparse, the observed drastic change in flow direction from N-S to east (Fig. 5) might indicate that tectonic movements that led to half graben formation were already under way at that time. Possibly beginning extension led to initial subsidence and development of an east-west trending trough along the site of the future graben (see inset block diagram in Fig. 5).

magnetic fabric of shales

Although detrital magnetite seems to be responsible for the magnetic fabric of many sediments (e.g. Hrouda, 1982), no appreciable quantities of magnetite have been detected in shales of the Newland Formation (Schieber and Ellwood, 1988). Therefore the suggestion by Hounslow (1985) that paramagnetic phyllosilicates can define the magnetic fabric of mudrocks may well apply to the shales of the Newland Formation. Hounslow (1985) also proposed that magnetic lineation in unbioturbated shales is probably a primary feature through current alignment of sedimentary particles. Schieber and Ellwood (1988) showed that magnetic lineation in shales of the Newland Formation coincides with the paleoflow azimuth, and that magnetic fabric elements are inclined in up-current direction. Although there is for shales no previously published information regarding a correlation between magnetic fabric and petrofabric comparable to that observed in sandstones (e.g. Taira and Lienert, 1979), preliminary results of an ongoing microfabric study of Newland shales suggest that such a relationship might indeed exist.

The data presented here suggest a fairly consistent N-S oriented flow pattern in Figure 4 and an equally consistent E-W oriented pattern in Figure 5. Also, even though the pattern in Figure 6 is more variable, large areas show essentially the same flow azimuth. Strong and even perfect predominance of one inclination direction in many outcrops and especially the observation that such orientations may stay the same over large areas (see for example Figure 5, or NE portion of Figure 6), suggest in comparison with paleoflow studies from other sedimentary basins (e.g. Potter and Pettijohn, 1977) that water circulation and sediment transport over the basin floor was a likely cause for particle alignment and the resulting uniformity of magnetic fabrics.

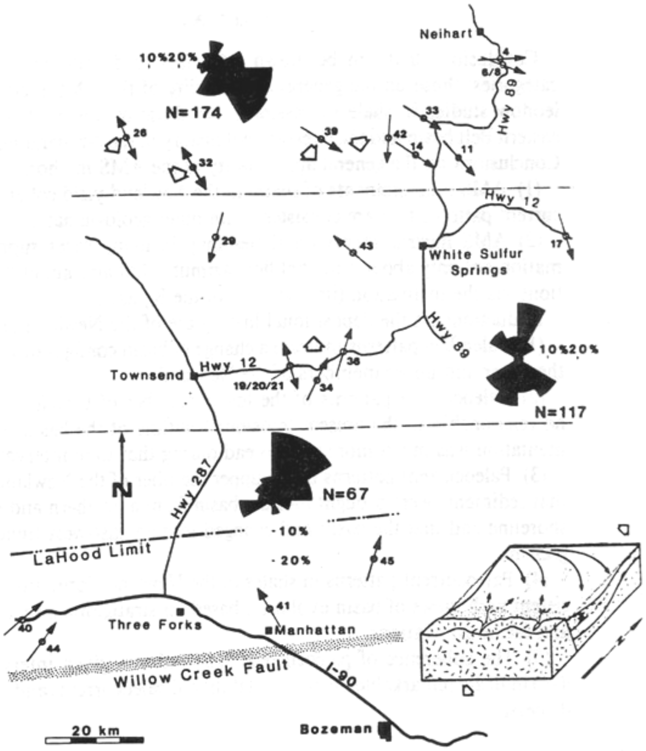

Figure 6: Map of AMS site averages for upper member of the Newland Formation (see Fig. 1). Symbols as in Fig. 4. Empty arrows indicate flow directions deduced from sedimentary structures of sandstones in outcrop. Stippled band in lower portion of diagram indicates approximate location of Proterozoic basin bounding fault. Heavy double-dotted line indicates approximate northern limit of LaHood Formation. Fine horizontal dashed-dotted lines separate the three areas (northern, central, southern) whose sites contributed to the three rose diagrams. Inset block diagram summarizes geologic interpretation of area with fan-deltas extending north from a syndepositional fault, and storm generated shore-oblique currents that carry sediment into the basin from an east-west trending northern shoreline. Open arrows indicate direction of extension

Based on above observations, the initial interpretation of AMS data from the Newland Formation (Schieber and Ellwood, 1988), namely that azimuth and inclination of the K1 axis can be utilized to interpret not only the sense but also the direction of paleoflow, appears to be justified.

Influence of Deformation and Metamorphism

Both tectonic deformation and metamorphism can produce AMS in sediments (Graham, 1966). Although the Newland Formation in general has not undergone metamorphism, locally areas with schistosity development were found near (probably synkinematic) intrusions. Samples from these areas were not utilized in this study.

Laramide deformation affected rocks of the Newland Formation, and fold axes exhibit north-south to north-westerly orientations (e.g. Skipp and Peterson, 1965; Mertie et al., 1951). If deformation had led to post-depositional AMS lineations, these should be oriented parallel to the fold axes and one might for example think that the NNW to SSE alignment of AMS azimuths in Figure 4 (interval 1) is simply a result of east-west tectonic compression. However, in that case AMS lineations should show more or less the same orientation throughout the stratigraphic sequence of a given area. The observation that within the Newland Formation one can see drastic changes in AMS lineations between successive stratigraphic units (compare for example Fig. 4 and Fig. 5) clearly refutes this supposition. Tectonic deformation was apparently insufficient to substantially alter primary petrofabrics.

CONCLUSION

Conclusions that can be drawn from this study fall into two broad categories, namely (1) those that concern the general applicability of the AMS method to paleoflow studies in shale sequences and (2) those that pertain to the evolution of the eastern Belt basin and the depositional history of the Newland Formation. Conclusions that concern the general applicability of the AMS method are:

1) The results from the Newland Formation show that AMS measurements of shales can yield coherent paleocurrent patterns that are consistent with other geologic data.
2) AMS measurements on shales may in many cases not only supply information about potential flow azimuths, but also about flow directions via the inclination (imbrication) of the K1 axis.

Deductions that pertain to Newland Formation depositional history are:

1) Paleoflow patterns indicate a change of basin configuration between the lower and upper member of the Newland Formation.
2) Paleocurrent patterns of the lower member of the Newland Formation show no relationship to the present (erosional) outline of the basin. Belt sedimentation was much more widespread during that time interval.
3) Paleocurrent patterns of the upper member of the Newland Formation suggest that sediments were brought into the basin from a northern and southern shoreline and that the basin had changed into an east-west trending half graben.
4) Paleocurrent patterns in shales of the Newland Formation are consistent with views of basin evolution that are based on stratigraphic relationships and facies associations.
5) The coherence of paleocurrent data within a given interval (Figs. 4, 5, and 6) indicate remarkable long term stability of paleocurrent and sediment dispersal systems.

Acknowledgments

Acknowledgment is made to the Donors of the Petroleum Research Fund, administered by the American Chemical Society, for primary funding of this study as well as to the Advanced Research Program of the State of Texas for additional funding.

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