THE COINCIDENCE OF MACROSCOPIC PALEOCURRENT INDICATORS AND MAGNETIC LINEATION IN SHALES FROM THE PRECAMBRIAN BELT BASIN[1]

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ABSTRACT: Paleocurrent flow direction in shale sequences can be inferred from sedimentary structures of associated lithologies, from orientation of fossils, from alignment of silt and sand-sized particles in shales, from mapping of scalar properties of a shale sequence, and from the orientation of concretions. Not all of these methods relate to shale properties directly, and most of them are very time-consuming and may even require fortuitous circumstances to be applicable. Consequently, even though shales constitute about 60% of all sediments, paleocurrent data from shale sequences are sparse. Thus, in order to improve our understanding of the evolution of sedimentary basins, it would be beneficial to have an accurate and conveniently applicable method of paleocurrent determination for shales.

The anisotropy of magnetic susceptibility (AMS) of a number of shale samples from the Precambrian Belt Supergroup carries a fabric-related magnetic lineation that coincides with paleocurrents indicated by cross-laminated silt beds within the shales. Magnetic foliation decreases as dolomite content increases because of diagenetic dolomite growth, but magnetic lineation is only slightly affected. These data indicate that primary flow direction as represented by AMS measurement of these samples is preserved and therefore the AMS method can provide a rapid and accurate way to determine current-flow systems in shale-dominated sedimentary basins.

INTRODUCTION

Numerous paleocurrent studies in sandstone and carbonate sequences have shown that it is always of great value in a basin analysis project to get as much data as possible on the paleocurrent system within a sedimentary basin (Potter and Pettijohn 1977). However, in contrast to sandstones and carbonates, shale sequences are notorious for their paucity of directional sedimentary structures. Therefore, paleocurrent studies of shale sequences are quite rare (Potter et al. 1980), even though shales comprise approximately 60% of all sedimentary rocks. In the past, the following approaches were taken to study paleocurrent systems of shale sequences:

1) to utilize primary sedimentary structures in siltstones, sandstones, and carbonate rocks that are intercalated with the shales;
2) to measure the orientation of fossils within the shale itself;
3) to measure the shape orientation of silt-sized particles within shale beds;
4) to map scalar properties of a shale sequence to detect sediment-dispersal patterns; and
5) to measure the orientation of concretions.

The first method, measuring the directional properties of sedimentary structures, has probably been used the most extensively and, for initial studies, is probably the best path to follow. The basic assumption behind this approach is that the shale paleocurrent system is not significantly different from that in the associated sandstones and carbonates. This assumption, however, is not necessarily true (Potter and Pettijohn 1977). For example, in ancient shelf sequences, beds of sandstones and skeletal carbonates are found within shale sequences. Probably the majority of these beds are storm deposits (Johnson and Baldwin 1986). The storm-generated current systems that transport these beds are of short duration and are distinctly different from the current systems that operate during fairweather periods (Swift et al. 1983). Thus, if one uses intercalated sandstone and carbonate beds to infer the paleocurrent system of shales, one might get a strongly biased understanding of paleocurrent systems in mud-dominated shelf sequences.

The second method, fossil orientations, has been used successfully in studies of several shale-dominated basins (e.g., Ruedemann 1897; Seilacher 1960; Zangerl and Richardson 1963; Jones and Glendening 1968; Jones and Dennison 1970). However, fossils are by no means abundant and equally distributed in all shales, and therefore, this method is only applicable to fossiliferous shale sequences. Furthermore, there are many shale-rich basins of Precambrian age for which this method is not applicable because of the complete lack of orientable fossils. Also, determination of paleocurrents from fossil orientations is time-consuming and often requires that the researcher be skilled in paleoecology (Potter et al. 1980).

The third method utilizes the long-axis orientation of silt-sized grains in shales as an indicator of current direction (utilizing thin sections cut parallel to bedding). Only in a few studies has this technique been utilized (Piper 1972; Hakes 1976), probably because it is extremely time-consuming.

In the fourth method, the basinwide distribution of certain shale components, such as quartz silt; the amount of plant debris; and the abundance of certain clay minerals, such as kaolinite (Parham 1966), are determined and related to paleogeography, provenance, and paleocirculation patterns. However, practically all such studies have been made in very young oceanic sediments (e.g., Hollister and Heezen 1972; Jones 1985; Ledbetter and Balsam 1985) because it is very important that exact lateral comparisons can be made.

In the fifth method, orientation of concretions, the underlying assumption is that concretion orientation is a response to fabric anisotropy of the host sediment, which

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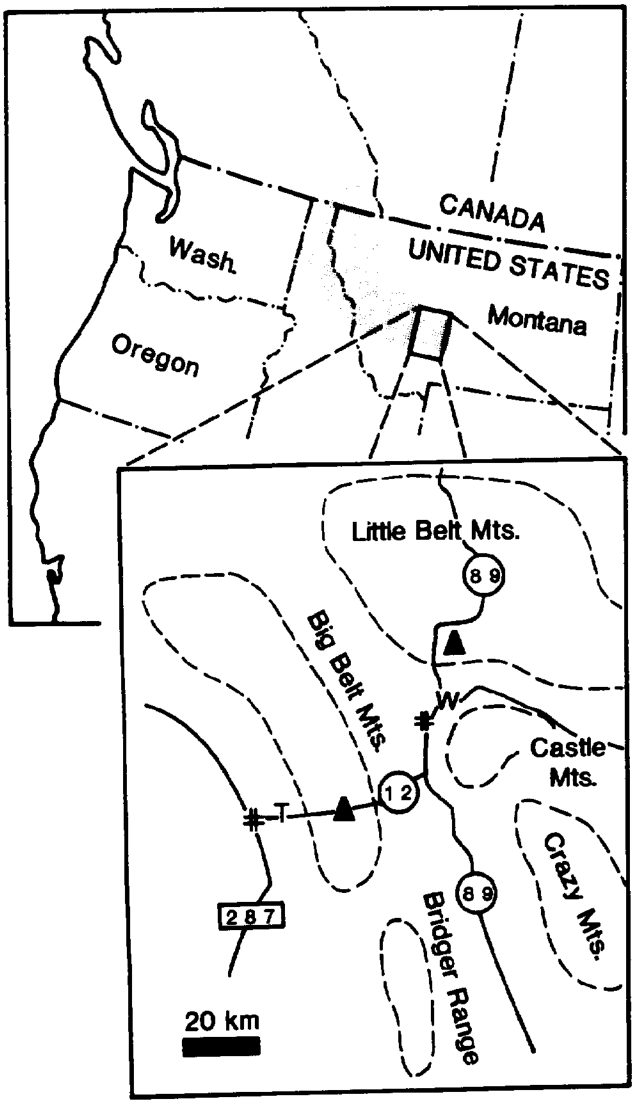

FIG. 1.—Location of study area. Enlarged portion of map shows location of sample localities (triangles) within Little Belt and Big Belt mountains. T = Townsend; W = White Sulfur Springs. Solid lines are roads (road numbers in circles or rectangles).

in turn is caused by the depositing currents. However, concretions in shales may also grow irregularly or be oriented parallel to fractures, and may not always be as well aligned as in the few published examples where this approach was used (Colton 1967; Sperling 1967). Furthermore, without unusually well-exposed bedding planes (a rare occurrence in shale outcrops), it is very difficult to see preferred nodule orientation.

In summary, we conclude that the first method (using associated lithologies) is at best of limited value for determining paleocurrent systems in shales. The other reported methods often require fortuitous circumstances for success, such as the occurrence of orientable fossils, or concretions, or are very time-consuming, requiring extensive field (detailed mapping) or laboratory (microscopy) time. Thus, before comprehensive paleocurrent

FIG. 2.—Cross-laminated, starved silt ripple within shale. Samples were cut so that a three-dimensional view of cross-laminae was always available for paleocurrent determination. The coin is 19 mm in diameter.

studies of shale sequences become an integral part of every basin study, a method of paleoflow determination in shales needs to be employed that is easily applicable, rapid, accurate, and objective.

In this study we have examined the usefulness of anisotropy of magnetic susceptibility (AMS) data from shales as recorders of depositional current orientations. A large variety of postdepositional or postdiagenetic factors may alter initially produced (primary) AMS data. These include elements such as compaction and bioturbation (not important in Precambrian rocks) as postdepositional but prelithification factors. Later magnetic crystal growth or grain realignment in response to tectonic stresses, fluid migration through the sediment, redox reactions, and other factors may alter primary orientations in sediments. An excellent review on the AMS subject including problem areas involving work on sedimentary rocks was published by Hrouda (1982). Despite these potential complications, our data show that shale paleoflow directions can indeed be predicted from AMS data and indicate that the AMS method has great potential to become a widely used tool in paleocurrent studies of shale basins.

Our results may also help to place constraints on AMS measurements from shales and slates of structurally deformed terrains. Such studies have attributed changes in linear elements of deformed shales to changes in deformational magnitude (e.g., Lamarche and Rochette, in press). However, our data demonstrate that some small changes in magnetic lineation can be attributed to diagenetic processes rather than to tectonic events.

STUDY MATERIALS

The shale samples on which we have conducted AMS measurements were collected from outcrops of the Mid-Proterozoic Newland Formation in the Big Belt Mountains and Little Belt Mountains of west-central Montana (Fig. 1). The Newland Formation belongs to the Belt Supergroup (Harrison 1972), which is about 6 km thick in the study area and consists of about 80% shale. The stratigraphic sequence comprises the basal Neihart Quartzite, the Chamberlain Shale, the Newland Limestone (or Newland Formation), and the Greyson Shale. Samples were chosen that contained macroscopic paleocurrent indicators, such as starved ripples (Fig. 2) and cross-laminated silt beds, in order to compare magnetic fabric orientations to paleoflow directions.

Shale samples consist of variable amounts of three in-

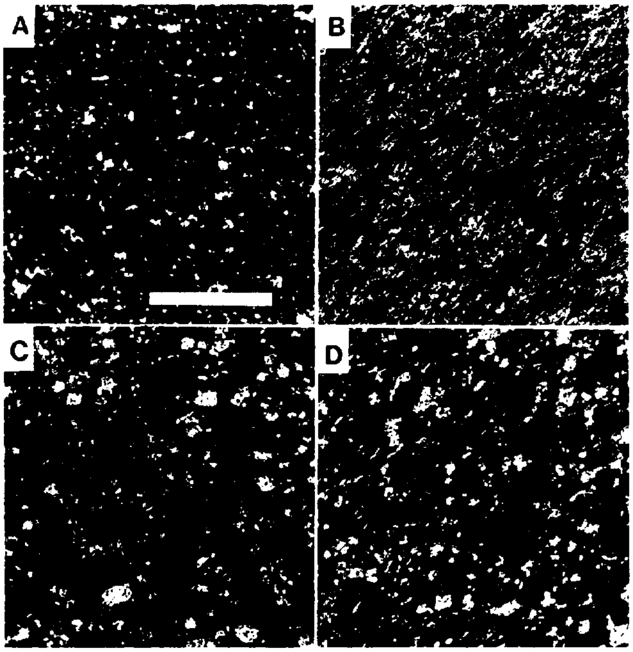

FIG. 3.—Photomicrographs of two shale specimens (crossed polarizer and analyzer). A) Shale with low dolomite content, laminations oriented parallel to the polarizer. Bright specks are dolomite crystals. B) Same specimen as in A, but rotated by 45°. Sample appears much brighter in this position, and foliation is clearly visible. C) Shale with high dolomite content. Bright specks are dolomite crystals. D) Same specimen as in C, but rotated by 45°. Brightness did not increase, and foliation is much more weakly developed than in the dolomite-poor sample. All photos were taken under the same magnification. Scale bar is 100 μm long.

terlaminated rock types, gray dolomitic shale, siltstone, and silty carbonaceous shales. Of these three components the gray dolomitic shales form the bulk of each sample, and the siltstones make up between 3 and 30% of the sample. Laminae of silty carbonaceous shales are absent in several samples, and if they are present, they constitute only between 1 and 10% of the sample. Even though appreciable amounts of siltstone may occur in these samples, their bulk composition is dominated by clay-size constituents (60% or more), and therefore, they can appropriately be classified as shales (Potter et al. 1980). The shales of the Newland Formation were described in detail by Schieber (1985), and specific petrographic and sedimentological aspects, such as the interlamination of rock types, are described in Schieber (1986, 1987).

The gray dolomitic shale beds consist essentially of illite, dolomite, quartz silt, and minor amounts of muscovite flakes. Individual shale beds range in thickness from a few millimeters to 35 mm. The quartz silt content is 5% or less, the dolomite content ranges from 15% to 55%, and the remainder of the rock consists of illite. The dolomite crystals are anhedral to rhombic in outline, and range in size from 2 to 20 microns. When dolomite content is low, the shale shows preferred extinction parallel to bedding under a petrographic microscope (Fig. 3A and B), and as dolomite content increases, this effect gradually diminishes (Fig. 3C and D). The bright specks in Figure 3 (dolomite) are larger in the dolomite-rich sample, suggesting that dolomite crystal size increases with dolomite content. However, examination of a large number of petrographic thin sections shows that the latter is not the case, but rather that with increasing dolomite content, clusters of dolomite crystals (larger specks) become more abundant.

Siltstone beds are between a few millimeters and 20 mm thick, and consist of quartz silt, dolosiltite, dolomitic peloids, and a few percent of muscovite flakes. The porespace between detrital grains is filled by dolomite crystals and quartz. Sedimentary structures of siltstone beds include graded rhythmites, parallel lamination, and cross-lamination (Schieber 1985; 1986).

The silty carbonaceous beds range in thickness from 1–4 mm, consist of carbonaceous laminae that alternate with dolomitic-clayey laminae, and contain tiny lenses and stringers of silt. These shales were described in detail by Schieber (1986).

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

It is now well established that the AMS method can be very useful as a tool in helping to solve a large variety of geological problems (e.g., Bhatal 1971). One area where the method has been extensively applied is in the study of experimental and natural unlithified sediments and, to a lesser extent, in the study of sedimentary rocks (e.g., Hrouda 1982).

AMS is commonly expressed as an ellipsoid with principal axes, K_1 (maximum), K_2 (intermediate), and K_3 (minimum), which in general terms reflect the physical orientation of magnetic elements in a single sample. In sediment samples, the AMS ellipsoid elements have been shown to reflect the petrofabric orientation (Taira and Lienert 1979), which results from any physical process orienting grains in the sediments, such as current flow, compaction, and diagenesis.

Much of the AMS work on terrigenous sediments has concentrated on flume studies using sand- or silt-sized particles (e.g., Rees 1965; Rees and Woodall 1975), although some papers have been published for natural sediments which report flow-orientation data determined using the AMS method (von Rad 1971; Taira and Lienert 1979). While a few AMS studies on shales have been reported (e.g., Hounslow 1985), data for shales are not abundant and interpretations of these data generally do not focus on problems like defining flow direction but rather deal with problems of progressive deformation from shale to slate fabrics (e.g., Rochette and Vialon 1984).

Bioturbation

Recent AMS work on experimental and natural sediments has shown that bioturbation can produce unexpected AMS azimuthal orientations (Ellwood 1984; Chernow et al. 1986). One of these effects is probably the partial or total disruption of a primary-flow-controlled fabric. The Mid-Proterozoic-age shale samples from the Belt basin were not influenced by bioturbation and are,

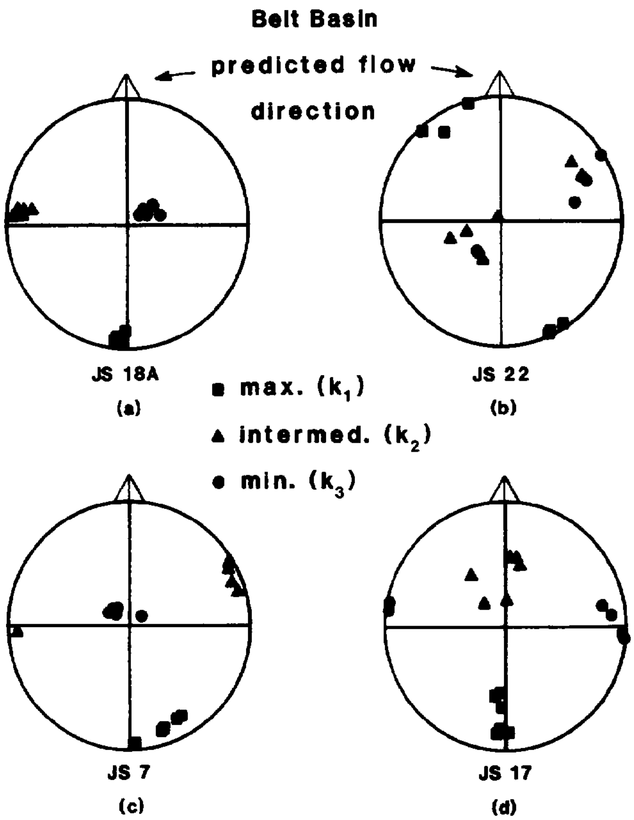

FIG. 4.—Lower-hemisphere equal-area AMS plots of samples from the Belt basin. a = best case (see text and Table 1). b = worst case. c = the general fabric pattern. d = a case of anomalous fabric similar to that in b.

therefore, an ideal choice for a study that aims to evaluate AMS flow indicators in shales.

METHODS AND RESULTS

Shales often do not have good sedimentary structures which can be used to indicate flow direction. In order to test the AMS method for the purpose of paleoflow determination, one of us (JS) determined the direction of dip of cross-laminae of siltstone beds in our shale samples and drew an arrow on ten hand samples to indicate his best estimate of paleoflow directions in each sample. It should be noted here that the paleocurrent arrows give only relative directions, because original sample orientations were not recorded during sample acquisition. Cores approximately equal to 2.4 cm in diameter were drilled from these samples (a total of 49 cores; see Table 1) and an oriented (fudicial) line drawn on each core was aligned with the flow arrow. The AMS was then measured using low-field torsion fiber magnetometers, and an average AMS ellipsoid was calculated for each hand sample from all cores drilled from that sample. The data are given in Table 1. Dolomite content was determined by acid digestion, and clay content was calculated from the Al_2O_3 content of each sample (determined by XRF) based on illite composition taken from Deer et al. (1966). The parameter

TABLE 1.

Sample #	N	Dolo/Clay	$\bar{H}$ (%)	$\Delta\bar{D}$	$\bar{F}$	$\bar{L}$	$\bar{V}$	$\bar{K}_3$Inc
JS 7	5	0.50	8.3	19.4°	6.4	1.8	61.3°	77.5°
JS 9*	6	–	1.0	3.4°	0.6	0.4	51.7°	75.4°
JS 10*	3	–	1.9	0.5°	1.1	0.8	49.9°	80.0°
JS 15	4	1.62	1.9	27.7°	0.6	1.2	35.3°	80.8°
JS 17	6	1.66	1.8	4.3°	1.0	0.8	47.3°	4.9°
JS 18A	5	1.83	2.4	4.2°	1.4	1.0	49.1°	74.8°
JS 18B*	4	–	2.1	7.2°	1.0	1.2	42.6°	32.7°
JS 19	4	0.66	6.0	4.8°	4.4	1.6	59.2°	86.2°
JS 22	6	1.68	1.5	28.0°	0.8	0.7	46.5°	21.1°
JS 24	6	1.29	4.4	14.5°	3.0	1.4	51.5°	77.1°

N = number of cores measured per sample; Dolo/Clay = dolomite to clay ratio; $\bar{H}$ (%) = average total anisotropy; $\Delta\bar{D}$ = average angular difference between predicted flow direction and orientation of K_1; $\bar{F}$ = average foliation; $\bar{L}$ = average lineation; $\bar{V}$ = average shape parameter after Graham (1966); if V > 45° oblate, if V < 45° prolate; $\bar{K}_3$Inc = inclination of K_3 (pole to magnetic foliation) relative to bedding planes in the sample; and * = samples that do not contain dolomite and are therefore not plotted in Figure 6. JS 9 and 10 are siltstone samples, and JS 18B is a limestone sample. These samples are plotted in Figure 5.

$\Delta\bar{D}$ in Table 1 represents the angular difference between the predicted flow direction (the arrow drawn on the sample) and the measured long-axis (K_1) orientation. Examples of AMS distributions for these hand samples are given in Figure 4. The examples reported here include the best case (Fig. 4a), the worst case (Fig. 4b), a typical case (Fig. 4c), and cases of anomalous sedimentary fabric, which are discussed below (Fig. 4b and d).

DISCUSSION

Our primary goal in this study was to evaluate how closely the predicted flow directions compared to measured AMS long-axis orientations. In no case is the difference between the two as great as 30°, and in the two cases where $\Delta\bar{D}$ is relatively large (e.g., 28°, Table 1), this difference is probably due to poor structural resolution of the mean flow direction for that particular hand sample, and thus the probable error is in initial placement of the arrow (see above) on the sample. Clearly, the correspondence reported here between directions is excellent, and we suggest that the AMS method is a very productive and rapid way of identifying paleoflow directions in shales. Reproducible results can be obtained, even though $\bar{K}$ susceptibilities are low. $\bar{K}$ is indicative of the magnetic constituents in the sample and is defined as

$$\bar{K} = \frac{(K_1 + K_2 + K_3)}{3}. \qquad [1]$$

AMS data for sedimentary rocks are expected to show a general foliated (bedded) character. In that case, the K_1 and K_2 axes lie in a plane subparallel to bedding, and the minimum (K_3) axes are oriented perpendicular to bedding and therefore have a near-vertical orientation. Our data conform to this expected axial distribution (e.g., steep K_3 inclinations; Table 1) with the exception of a few "anomalous" samples (Fig. 4). Petrographic work combined with the AMS has allowed us to identify the reasons why the

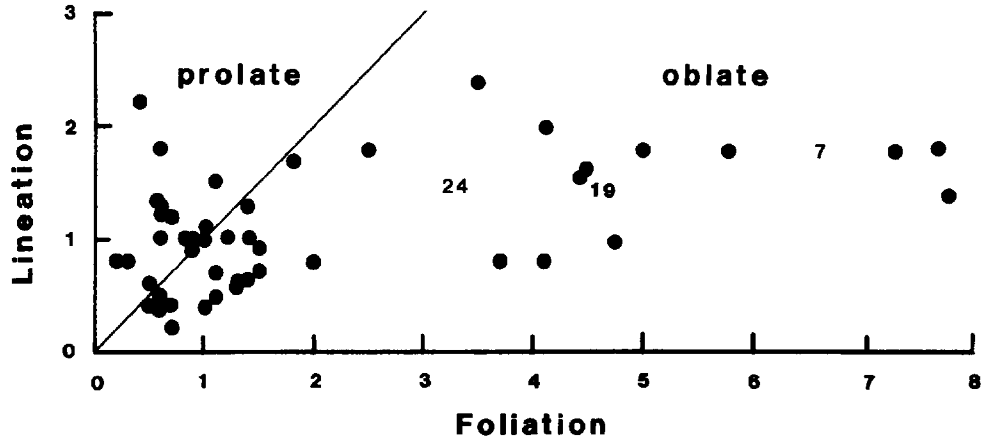

FIG. 5.—AMS lineation versus foliation. Note that the prolate (mainly lineated fields) versus oblate (mainly foliated) fields are defined in the diagram by the solid line. The general distribution of data from samples 7, 19, and 24 is indicated by a number.

magnetic fabric is anomalous in these few samples, and our analysis is discussed in the following paragraphs.

Figure 5 shows a plot of magnetic foliation, where foliation F is defined as

$$F = \frac{(K_2 - K_3)}{\bar{K}}, \qquad [2]$$

versus magnetic lineation L, where L is defined as

$$L = \frac{(K_1 - K_2)}{\bar{K}}. \qquad [3]$$

Note that in Figure 5 the lineation data exhibit low magnitudes but overall relative uniformity, whereas foliation data may exhibit a great deal of variability. Analysis of petrographic thin sections from these samples (Fig. 3) shows that postdepositional processes, mainly the in situ recrystallization of carbonate mud to dolomite, have disrupted the initial planar fabrics but appear to have had only slight effects on lineations (dolomite/clay ratios for each shale sample are given in Table 1). One could hypothesize, as has been done by Colton (1967) with regard to oriented concretions in shales, that dolomite crystal growth was essentially parallel to linear elements in the fabric and that therefore lineation disruption was relatively insignificant. However, at present this hypothesis cannot be substantiated, because the small grain size of the dolomite crystals (2–20 μm), as well as their small size relative to the thickness of the thin sections (30 μm), makes it exceedingly difficult to determine the orientation of a statistically significant number of dolomite crystals in any given sample using standard microscopic methods. Figure 6 illustrates the "dolomite recrystallization effect" on the AMS data. There is a clear linear relationship ($r = 0.955$, significance at >0.001 level) between foliation (F) and the dolomite/clay ratio. Planar fabric disruption is apparent when dolomite percentages increase. On the other hand, lineation (L) shows very little change with increasing dolomite content and is relatively poorly correlated ($r = 0.900$, significance at >0.02 level) with the dolomite/clay ratio. The slight lineation disruption that does occur is reflected in the total anisotropy magnitude (H) exhibited by the AMS fabric data (Fig. 6), where H is defined as

$$H = \frac{(K_1 - K_3)}{\bar{K}}. \qquad [4]$$

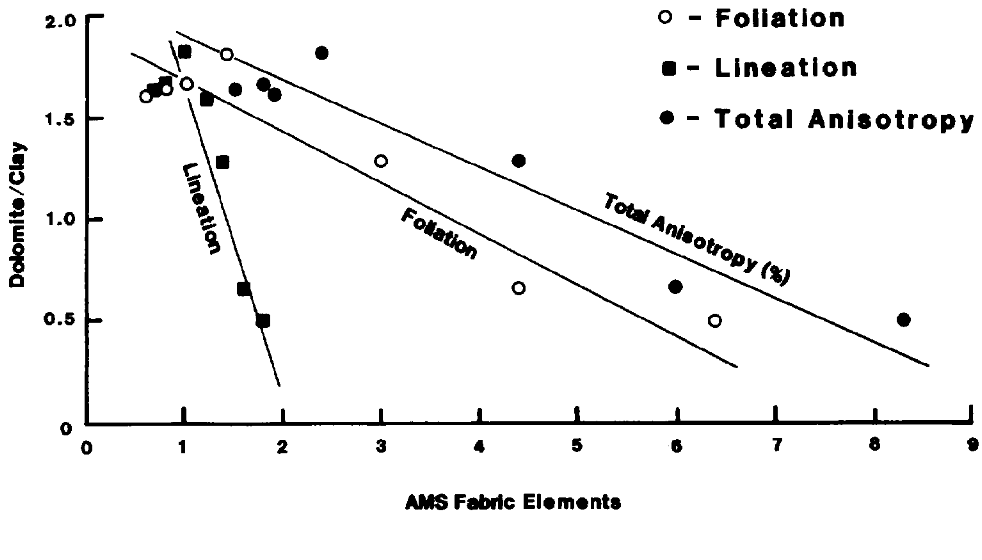

FIG. 6.—Averge foliation (F), average lineation (L) and average total anisotropy (H) data from each hand sample are plotted versus the dolomite/clay ratio for that sample. Lines are calculated from a linear regression of the data; for F, the correlation coefficient (r) is 0.955; for H, it is 0.965; and for L, it is 0.900.

These data indicate that primary-flow directions in Belt basin shale samples are preserved and can be extracted using the AMS method.

CONCLUSIONS

It is apparent from the data presented here that there is very good agreement between AMS principal azimuths and macroscopic paleocurrent indicators in Beltian shales from the Upper and Lower Newland Formation. Compared with alternative methods that determine fabric anisotropy (e.g., measuring shape orientation of silt-sized grains), this method is much less time-consuming (it takes only minutes to take an oriented core, and the AMS measurement is fully automated) and much more objective. It is our expectation that this method should also work in other shale sequences, and therefore it holds great promise as a research tool for paleocurrent studies in shale basins. In such studies oriented samples can be conveniently drilled in outcrop as long as the shales are reasonably well indurated. Collection of oriented hand samples is a possible alternative.

Additional research needs to be conducted in order to understand more clearly how magnetic lineation is preserved in these samples despite fabric disruption during diagenesis.

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