

Acquisition of anhysteretic remanence and tensor subtraction from AMS isolates true palaeocurrent grain alignments

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Abstract: Anisotropy of magnetic susceptibility (AMS) is commonly used to detect subtle palaeocurrent directions. A Proterozoic subarkose shows extreme anomalous inverse AMS fabrics that cannot be attributed to the well-known effect of single-domain magnetite. This was confirmed by anisotropy of anhysteretic remanent magnetization (AARM). Further, by subtracting increasing proportions of the AARM tensor from the AMS tensor the paramagnetic/diamagnetic response of the silicate fabric was isolated. This reveals an inverse quartz fabric but analysis of the results shows that two grain alignments are present. A prominent inverse magnetic fabric is due to quartz long axes aligning with current flow revealed by the difference $[AMS] - [AARM]$. This is due to the avalanche flow of concentrated sand dispersions down the slip-face of cross-stratified units. Dispersive pressure caused by grain interactions and shear within the fluid produces a subhorizontal resultant force that aligns grains by frictional freezing during deposition. In some samples AARM isolates a secondary feeble alignment of magnetite nearly perpendicular to bedding. This is due to suspension rainout and sweeping by the reverse circulation separation eddy that supplies additional material to the top of the sand laminae. It particularly affects fine grains such as magnetite that infiltrate the framework's pores to produce a secondary population of vertically oriented grains.

Anisotropy of magnetic susceptibility (AMS) has been used to identify palaeocurrent directions from sedimentary rocks since about 1961. Tarling & Hrouda (1993) summarized the principal discoveries. Minimum principal susceptibility is normally almost perpendicular to bedding. Maximum susceptibility may define the current grain alignment at slow velocities (<1 cm/s) whereas faster currents may roll grains so that their long axes and maximum susceptibilities are perpendicular to flow. The magnetic foliation may also imbricate, tilting upstream depending on the hydrodynamic conditions. The effects of inverse magnetic fabrics have not been considered previously for sedimentary fabrics. From the viewpoint of fabrics and magnetic anisotropy these studies make one or two assumptions that have been resolved in studies of metamorphic rocks (Borradaile & Henry 1997). The first is that the rock's AMS is controlled by the orientation distribution of grains whose shape is coaxial and congruent with the grain's AMS ellipsoid. Considerable errors arise where inverse fabrics occur because of the presence of single-domain (SD) magnetite (Jackson & Tauxe 1991) or matrix minerals such as calcite (Rochette 1988). Sec-

ondly, it is assumed that AMS is due to one mineralogical or magnetic response. In the early literature, it was commonly assumed that traces of magnetite accounted for the entire AMS signal. Later, the importance of the paramagnetic contribution was realized (Borradaile 1987; Borradaile *et al.* 1990) and subsequently the importance of even a diamagnetic matrix has been realized (Hrouda 1986); Hrouda's case will be extended here. Commonly, two or even more equally significant magnetic sub-fabrics may coexist. These may be due to different paramagnetic, diamagnetic or ferromagnetic accessory minerals, and it is even possible that they may have different orientation distributions. For example, one mineral may be aligned parallel to current flow and another perpendicular to it, depending on their hydrodynamic behaviour. One can isolate the orientation distribution of the ferromagnetic component by applying anhysteretic remanent magnetizations (ARMs) in different directions to detect the anisotropy of ARM (AARM). The complexities that arise in a coarse-grained subarkose with palaeocurrent directions well known from macroscopic sedimentation structures will be illustrated.

Sedimentary processes

Samples were obtained from a drill core through the Matinenda Formation, north of Elliot Lake, Ontario (Fralick & Miall 1989, fig. 1). Matinenda Formation fluvial sandstones and conglomerates form the basal portion of the Palaeo-Proterozoic Huronian Supergroup. Sediments were deposited by channel-dominated braided streams in a broad NNW–SSE orientated palaeo-valley (Fralick & Miall 1989). The subarkose comprises 90% quartz, largely strained, about 10% heavily altered feldspar and traces of opaque minerals. The coarse-grained sand, which dominates this portion of the formation, was transported via small- and medium-scale dunes on channel floors. All samples were of trough cross-stratified, coarse-grained sandstones produced by this dune migration (e.g. Fig. 1). Sampling was confined to five depositional events within a single

channel, with two samples from each small-scale, trough cross-stratified set, *c.* 20 cm thick. Major bedding planes were at 90° to the drill-core axis and foreset slopes vary from 26° to 32° and are shown dipping arbitrarily to 'north', on the stereogram (broken line, Fig. 2a). Magnetic core samples were drilled along the axis of the larger diameter field core.

The foreset laminae were deposited by avalanches originating near the crest lines of the dunes. Concentrated suspensions were maintained by dispersive pressure caused by collisions (Lowe 1982) or close approaches (Rees 1968). In these circumstances, grains will align to minimize angular momentum transfer caused by collision. This results in a preferred orientation with long axes parallel to the movement direction and the short axis near the direction of maximum velocity gradient (Rees 1968). An imbrication will also develop as the resistance to shear of the dispersion creates pressure (Bagnold

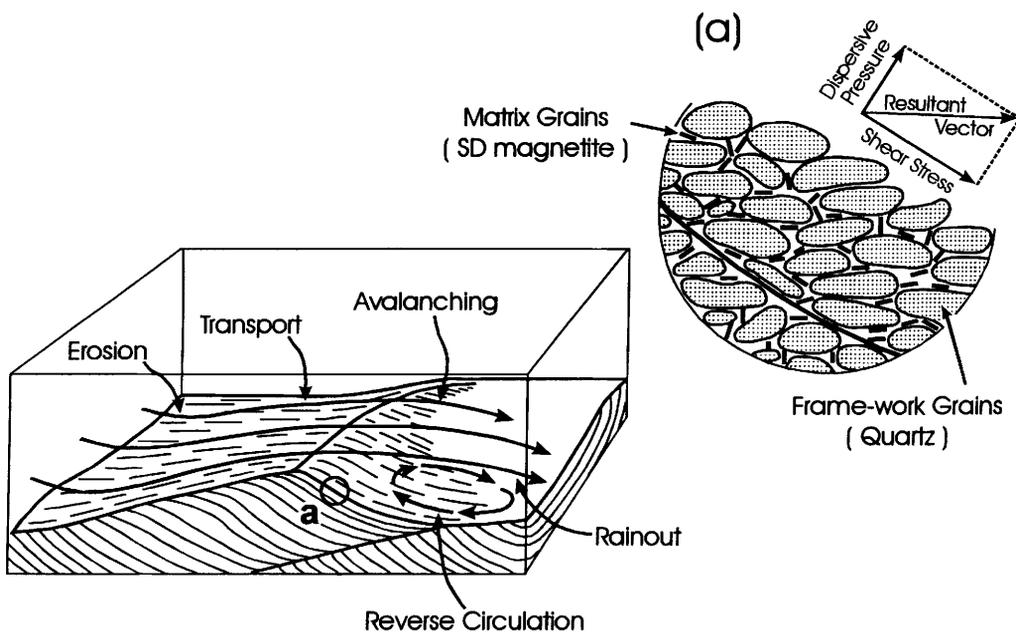


Fig. 1. Processes controlling grain orientation in trough cross-stratification formed by downstream migration of a discontinuously crested dune. Water flowing over the crest of a dune upstream from the dune shown loses contact with the bed. Where contact is regained the force results in a zone of erosion. Sand entrained from this scour and other grains reaching the bed from intermittent suspension travel as a traction carpet up the surface of the dune and avalanche down the lee slope depositing downstream-dipping laminae. Between sporadic avalanche events grains are delivered to the lee slope by rainout into the slower-moving water immediately behind the dune. The reverse circulation separation eddy that develops here serves to sweep material onto the surface of the laminae. During an avalanche grains align with long axes parallel to the resultant vector produced by the two main forces operating in the flow: shear stress and dispersive pressure. The enlargement in (a) shows that matrix grains, such as fine magnetite, added to the top of the laminae through rainout and traction by the separation eddy will infiltrate pore spaces and acquire steep orientations. Other matrix grains may align parallel to the framework grains during sedimentary compaction.

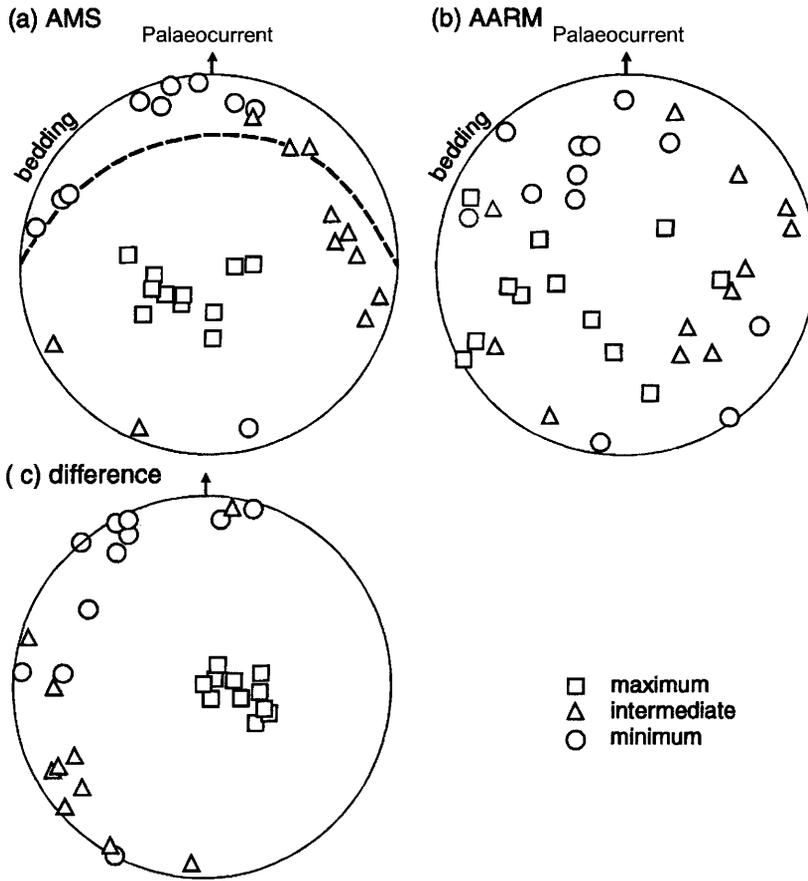


Fig. 2. The AMS fabric orientations shown on equal-area lower-hemisphere stereonets. Bedding is horizontal in all cases. (a) The AMS summing the induced magnetization anisotropy for all grains (quartz and magnetite). (Note the inverse fabric with maximum susceptibility perpendicular to bedding and minimum susceptibility parallel to movement direction.) The average avalanche slope is shown by a broken line. (b) The ARM anisotropy that records only the fabric contributions of very fine SD magnetite. This shows also an inverse fabric, but a weaker one. The grains' alignments are less well developed because some grains may have settled into steep pore spaces and adhered to the near-vertical pore walls (see text). (c) The AMS contribution of the framework (quartz) grains alone, revealed by subtracting (b) from (a). As quartz has an inverse fabric the maximum susceptibility is perpendicular to bedding and the minimum susceptibility is parallel to flow.

1954). This results in a shear stress (T) in the plane of shear, and a dispersive pressure (P) normal to that plane (Fig. 1). The resultant force on the grain acts at an average angle of $\tan^{-1}(T/P)$ to form an imbrication angle of 18° , $T/P = 0.32$, for purely inertial particle collisions. Where viscous drag of the intergranular fluid dominates, the imbrication angle is 37° , $T/P = 0.75$ (Hamilton *et al.* 1968; Rees 1968). Experimental results (Hamilton *et al.* 1968; Ellwood & Howard 1981), and data from non-lithified foreset laminae (Rees 1968; Taira &

Lienert 1979) and lithified foreset laminae (Potter & Mast 1963) corroborate this theory. One minor, unexplained discrepancy is the tendency, within a foreset unit, for the long axis orientations to deviate consistently in one direction on the plane of layering, from the movement direction defined by the maximum slope of the foresets (Potter & Mast 1963).

The average preferred orientation discussed above should apply to all grains transported by the concentrated dispersions because the same forces are expected to affect all moving particles.

Thus, both the larger grains, resting on one another to form the framework, and the smaller grains infilling pores between framework grains will have, on average, similar orientations if the grains travelled in the same dispersion. However, matrix grains and some framework grains will probably be added to the top of the laminae after deposition (Fig. 1). This is accomplished through rainout into the separation eddy and reverse flow, traction transport by the separation eddy. During deposition of the avalanche, smaller grains concentrate near the bottom of the flow because of the effect of dispersive pressure (Lowe 1976, 1982). This may leave the upper portion of the laminae deficient in matrix so that small grains supplied by the separation eddy infiltrate the pore space. This may apply particularly to micron-sized magnetite. Since the average pore wall will be perpendicular to the layer, it may align the small particle in this direction, producing a sieve texture. This grain orientation will be perpendicular to the avalanche slope but will be represented by only a small percentage of suitably small grains (Fig. 1a).

One other sedimentary process has implications for the magnetic fabrics of the Matinenda sandstones. Early Palaeo-Proterozoic weathering, which supplied the detritus, occurred in an oxygen-deficient atmosphere (Cloud 1973; Holland 1973). This resulted in a very limited oxidation of iron in iron-bearing mineral phases during weathering. An indication of this is the large amount of detrital pyrite in the Matinenda Formation. Its contribution to the magnetic fabric is negligible because it is both a trace mineral and diamagnetic. However, the same geochemical environment enhanced the survival of fine-grained magnetite in the erosion-transportation system. This resulted in a sedimentary fabric indicator for the very fine-grained portion of a rock that would not normally be so well developed in younger rocks where detritus formed under a more evolved atmosphere.

Magnetic anisotropies

AMS records the directional variation of induced magnetization in all minerals. This encompasses paramagnetic minerals such as micas, clays, and mafic silicates with susceptibilities $< 2000 \mu\text{SI}$. Higher values are due to inclusions of ferromagnetic impurities. In contrast, the remainder of the rock matrix may be composed of diamagnetic minerals such as quartz, calcite and feldspar with very feeble anisotropies and a small diamagnetic susceptibility of approximately $-14 \mu\text{SI}$. Finally, remanence-bearing minerals occur as traces in

low concentrations, but they are highly susceptible; e.g. magnetite has a mean susceptibility of $2.8 \times 10^6 \mu\text{SI}$.

The anisotropies are weak so that current directions may be very poorly determined because the slightest contamination by a few poorly oriented grains of higher susceptibility causes spurious anisotropy directions. Moreover, calcite, because of the parallelism of its *c*-axis and minimum susceptibility, could cause an inverse AMS with maximum susceptibility perpendicular to bedding (Rochette *et al.* 1992). The susceptibility anisotropy of quartz has been reported as both inverse and normal, depending on the origin of the samples (Hrouda 1986). Unfortunately, the size and shape of the samples was not given and studies of natural crystals are unlikely to be helpful, as the slightest contamination by inclusions can mask the intrinsic AMS of the quartz lattice. Hrouda (1986) quoted anisotropies of k_{ab}/k_c at 1.014 and 1.028 for synthetic quartz, which are probably more accurate reflections of the anisotropy of the pure lattice. Thus, synthetic quartz has a susceptibility of $-14.8 \mu\text{SI}$ along the *c*-axis and $-14.5 \mu\text{SI}$ in orthogonal directions. The susceptibility of remanence-bearing minerals, loosely called 'ferromagnetic' in this paper, is very high, up to $2.8 \times 10^6 \mu\text{SI}$ for magnetite, so that microscopic traces of this mineral can swamp a conflicting but more significant palaeocurrent fabric of matrix silicates. Thus, it is very difficult to determine the matrix anisotropy (and infer palaeocurrent directions) where the matrix has low susceptibility. A further complication is that the most common remanence-bearing mineral, magnetite, has an anisotropy strongly influenced by 'magnetic grain size'. If the magnetite grain responds in a multidomainal (MD) manner, its long axis will produce the maximum low field susceptibility and its short axis will yield the smallest susceptibility. However, if the grain shows single domainal (SD) response, it is already saturated in its long axis so that this will appear as the minimum susceptibility direction (Stephenson *et al.* 1986; Jackson 1991). This generates inverse fabrics in which the minimum susceptibility defines the alignment of SD magnetite grains.

Separation of magnetic fabric contributions

A few simple techniques exist for isolating the anisotropy contributions of different minerals to the overall magnetic fabric of a rock. This approach is important to understand the alignment process and the particular mineral grains

that it affected. The first, most simple, approach is the physical separation of minerals (Borradaile *et al.* 1986, 1990). Alternatively, the selective leaching of iron oxides may leave the matrix fabric intact (e.g. Borradaile *et al.* 1991; Jackson & Borradaile 1991) thus permitting its separate measurement. Finally, measurements of low field susceptibility at different frequencies can emphasize the response of different minerals according to their in-phase and out-of-phase response (Borradaile *et al.* 1991; Ellwood *et al.* 1993) or to different effective magnetic grain sizes of ferromagnetic grains (Thompson & Oldfield 1986; Jackson *et al.* 1989). However, these methods usually lack the precision needed to determine the anisotropy essential in estimating the palaeocurrent direction. Traditionally, AMS has been the preferred method, with the more recent addition of AARM. In this study, the AMS was measured in the usual way, at a low field (0.1 mT, 19 200 Hz). As a precaution, measurements were also made along the body diagonals of the sample and along the conventional 'principal plane' Girdler (1961) sample orientations. Borradaile & Stupavsky (1992) showed that this greatly increases sensitivity for practical reasons. On its own, the AMS combines the response of all minerals, paramagnetic, diamagnetic and ferromagnetic. Our samples are subarkoses so that the matrix should be characterized by a diamagnetic signal but the mean susceptibility was $+67 \mu\text{SI}$, indicating the presence of ferromagnetic contamination. (This was confirmed later by the samples' mean ARM susceptibility of 47.6 mA/m). The principal AMS directions are clearly related to sedimentary structure (Fig. 2a). However the results disagree with the commonly recognized pattern because the maximum susceptibility is perpendicular to bedding and the minimum susceptibility is parallel to the current direction. Although this has not been recorded previously in sediments, from the literature on metamorphic rocks, one recognizes this as an 'inverse fabric', caused by SD magnetite. To resolve this the AARM was measured by applying a laboratory anhysteretic remanence with a direct field of 0.1 mT while the alternating field (AF) decayed from 100 mT to zero. The anisotropy of remanence-bearing minerals is isolated in this way (Fig. 2b). The fabric is less well defined, because the fine-grained, sparse magnetites possess a weak fabric, but the inverse nature is confirmed, as most ARM maximum axes are steep.

AMS combines the magnetic response of all minerals whereas the AARM isolates the remanence-bearing ones, in this case SD magnetite. Thus, if the fabric of Fig. 2b is subtracted from

that of Fig. 2a then any remaining fabric caused by the matrix grain alignment of the sediment can be visualized. To preserve the best accuracy we subtracted the double-precision, raw susceptibility measurements made in different directions through the sample. The alternative method, using the eigenvalues and eigendirections and working backwards, introduced too many calculation errors. The first approach was to estimate the volume of magnetite in each sample from the saturation remanence of the sample. This permitted an estimate to be made of the expected low-field susceptibility contribution to AMS by the SD magnetite. Unfortunately, this introduced so many inaccuracies that when the tensors were subtracted some components were negative and some were positive so that the resultant fabric ellipsoid was indeterminate. Thus, a simpler approach was adopted. First, the AMS and AARM tensors were normalized by their mean values, to yield dimensionless ellipsoids. It is known that the AARM fabric is a significant mask over the matrix AMS signal. Thus, increasing fractions of the AARM signal were subtracted from the AMS signal in incremental experiments. When this fraction exceeded 95% of the AMS signal, the remaining fabric was a slightly enhanced sedimentary fabric (Fig. 2c), now attributed to the quartz matrix.

The inverse fabric with maximum susceptibility (>0) perpendicular to bedding is still apparent because one now sees the dominant quartz grain fabric with quartz minimum susceptibility (-14.8) parallel to its long (c) axes, defining the current lineation. The alignment of quartz c -axes has been confirmed by observing the sign-elongation with a one-wavelength retardation plate. The quartz maxima (-14.5) are thus at a high angle to both major bedding and the avalanche slopes, being slightly imbricated in the avalanche (Figs 1 and 2a). Thus, both the quartz fabric and the much weaker magnetite fabric are inverse magnetic fabrics, which still faithfully record current flow by the alignment of their long grain axes. When the magnetite fabric is isolated by AARM (Fig. 2b) its alignment is rather weak, though discernibly inverse with maximum susceptibility steep and minimum susceptibility parallel to the movement direction. As noted above, this is understood in the sedimentation literature because some very fine grains settle onto the steep pore walls at the top of the avalanche surface during rainout. The SD, micron-size magnetite falls into this category, so that some samples have their long axes oriented steeply (horizontal maximum susceptibility, as the fabric is inverse; Fig. 2c). Confining magnetic

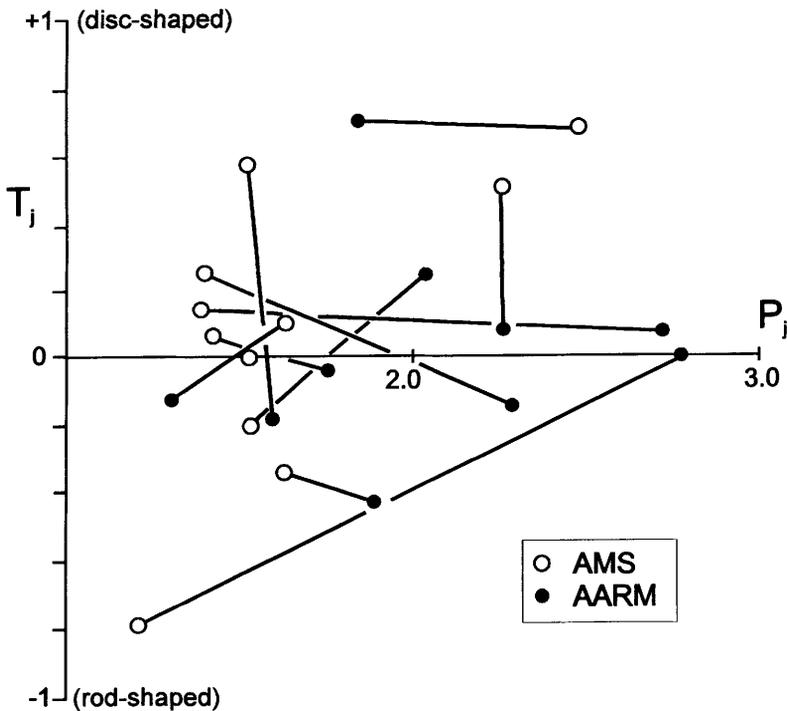


Fig. 3. The Jelinek (1981) fabric plot. This shows the symmetry or shape of the fabric ellipsoids (disc or planar fabrics, $T = +1$; rod shape or constricted, linear fabrics, $T = -1$) and their intensity ($P_j = 1 =$ isotropic). Anisotropy of remanence (AARM) is generally more intense than AMS in the same sample and tends to have a more neutral shape ($T \approx 0$) than the AMS fabric. However, there is no consistent relationship between AMS and AARM for a sample, as shown by the crossing tie-lines.

fabric studies to AMS would probably have led to the conclusion that an inverse magnetite fabric caused the signal. However, by subtracting most of the magnetite signal it was possible to recognize an underlying, still stronger inverse fabric caused by a preferred alignment of diamagnetic quartz-grain framework with c -axes parallel to the current alignment direction.

In the analysis of current directions usually only the eigendirections of the anisotropy tensor are of interest, i.e. the grain alignment and foliation. However, it may also be of value to consider the strength and symmetry of the alignment in some circumstances. For this purpose, the Jelinek plot (Jelinek, 1981) provides a clear separation of symmetry (planar or constricted alignments) from intensity (isotropic v. extremely eccentric alignment distributions). The AARM and AMS for the samples are illustrated separately (Fig. 3). Generally AARM has higher eccentricities (P_j) due to the strong remanence anisotropy of magnetite, but the AARM and AMS ellipsoids are not systematically related for the samples. On the other hand, the quartz grains (millimetre

size) would have greater inertia and there would have been less disturbance of their trajectories because of turbulence. Concerning symmetry, 8 of 11 samples have planar quartz fabrics ($T_j > 0$), emphasizing the bedding component of the current alignment. Six of 11 samples show a linear distribution ($T_j < 0$). This should not be taken to reflect the degree of current alignment because the intrinsic anisotropy of the grains must also be taken into account.

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