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Magnetic fabrics in L–S tectonites: How many specimens?

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ABSTRACT

Single large blocks (10–30 kg) of homogeneously strained, fine-grained slate or schist with homogeneous fabrics reveal subtle but sometimes significant variations in magnetic fabric from large numbers (up to 100) of closely spaced cylindrical cores. Traditional samples of three to six cores per block or per site may suffice for low precision, regional determinations of fabric orientations, if suitably fine-grained and homogeneous. However, for the most precise definition of anisotropy of magnetic susceptibility axes (AMS), small sample sizes (<15 cores) yield inconsistent orientations and shapes of the mean tensor. Coarse grain size would exacerbate these shortcomings since individual cores fail to sample the fabric representatively and inter-specimen variation may exceed inter-site variation in AMS. Fine-grained homogeneous rocks most successfully yield reproducible AMS orientations, and more especially AMS shapes. The optimum number of cores is best determined by experimentation since it depends on fabric heterogeneity, mineral proportions and grain-size variations at the inter-site and intra-site level.

1. Introduction

Magnetic fabrics usually anisotropy of magnetic susceptibility (AMS) and to a lesser extent anisotropy of anhysteretic remanence (AARM) are rapid and precise techniques that determine the cryptic preferred orientation of rock-forming minerals (AMS) and remanence-bearing minerals (AARM) (Borradaile and Henry, 1997; Fuller, 1963; Hrouda, 1982; Jackson and Tauxe, 1991; Rochette et al., 1992). AMS determines a mean preferred orientation of minerals, weighted by their bulk susceptibility and by their mineral-anisotropy (Borradaile, 1987a). AARM determines a mean orientation of remanence-bearing grains dependent on shape (magnetite), domain structure and specific remanence. With decreasing confidence, AMS and AARM may isolate orientations of finite strain axes, the shapes of fabric ellipsoids and more rarely the approximate shapes of strain ellipsoids (Borradaile and Jackson, 2004). Previous work showed that finite strain magnitudes do not correlate with AMS magnitudes, from general arguments as well as specific case studies (e.g., Borradaile, 1991; Borradaile and Mothersill, 1984). The parameters Pj (1 = isotropic) and Tj (+1 = oblate; −1 = prolate) are used to characterize magnetic fabric ellipsoid shapes (Jelínek, 1981) on the polar plot (Borradaile and Jackson, 2004). 95% confidence regions for the mean tensor axes are shown on the stereograms (Jelínek, 1978) for both raw and normalized tensors (Borradaile, 2001). The following terminology is relevant and accords best with statistical practice. The *specimen* is the single right-cylindrical core (25 mm diameter × 22 mm height) used to measure AMS or AARM. The *sample* is the *number of specimens* (cores) used to determine a reproducible mean fabric. The sample may be selected randomly or in some dedicated fashion from a large *block* of rock (several kilograms), or from a *site* (=outcrop).

Our focus is on the variability of magnetic fabric within and between blocks and sites. It is not our intention to discuss the accuracy of AMS fabric determination in a single specimen (one right cylinder). This is known to be a reproducible procedure for the tectonites we use, with moderate susceptibilities ($\kappa = 300$ to 600 μSI), since the noise level of the AMS instrument is <0.2 μSI. Of course, reproducibility cannot lead us to deduce much about the accuracy.

The parallelism of AMS axes with the L–S fabric elements (L = lineation, S = foliation) is usually unquestioned for tectonites that are homogeneously strained at the hand-specimen scale, such as slates and schists of fine to medium grain-size. This is acceptable and proven where we may make reasonable inferences concerning mineral proportions, crystallography and the geometrical relationship between tensors describing magnetic anisotropy and crystallographic axes. Exceptional minerals that produce inverse or blended normal-inverse fabrics, such as single-domain magnetite and diamagnetic-paramagnetic rocks with very low susceptibilities ($\kappa \sim 0$) are excluded from this study. The shape of the AMS ellipsoid is more loosely associated with fabric shape in the L–S scheme.

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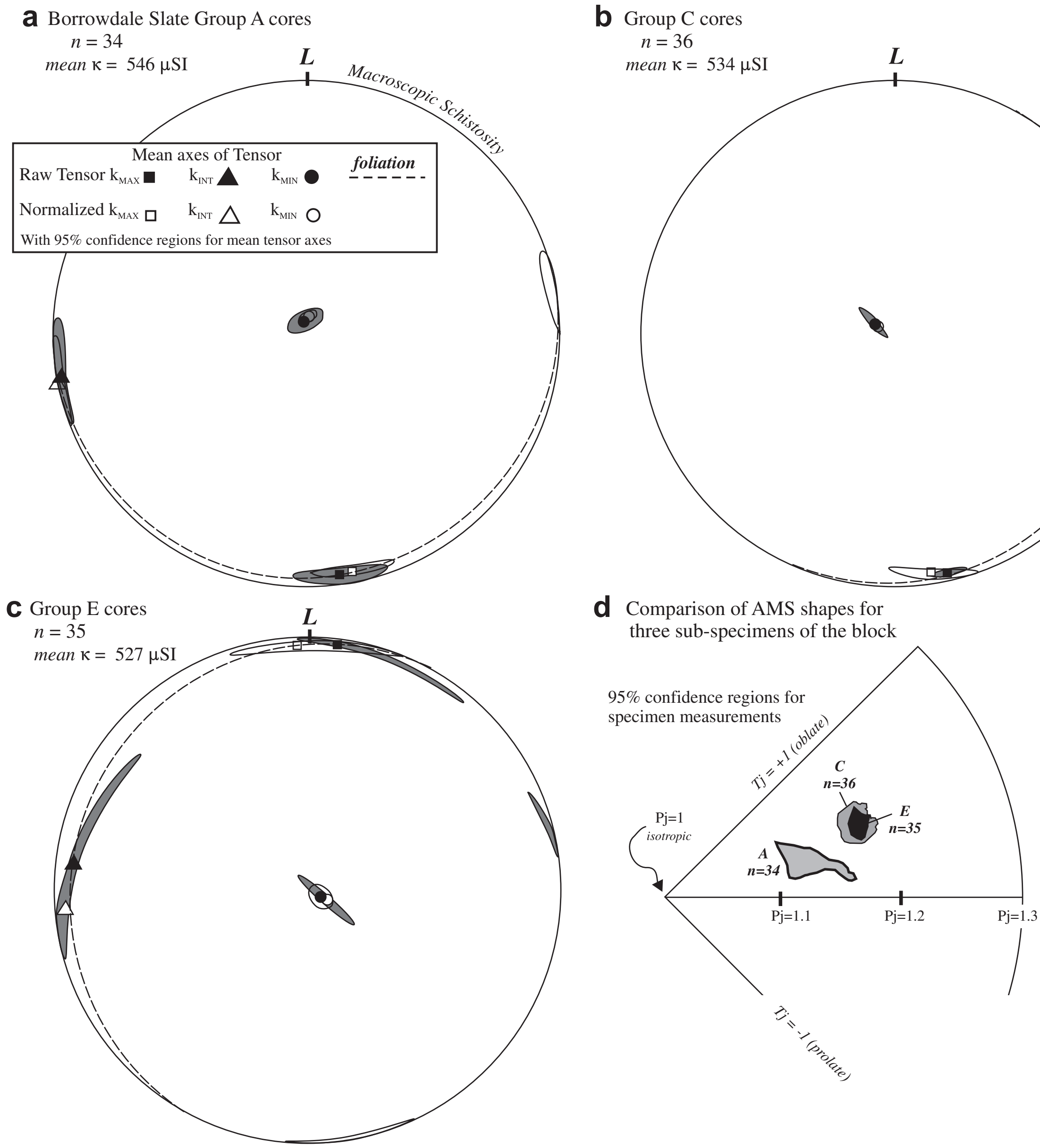

Fig. 1. A large slab of Borrowdale volcanic slate yielded 105 closely spaced cores, drilled perpendicular cleavage. The stereograms show the mean AMS tensor in fabric coordinates with the macroscopic cleavage horizontal and the visible lineation North-South. The mean tensor axes are shown with their 95% confidence regions shaded (raw specimen tensors) and unshaded (normalized specimen tensors). (a–c) Adjacent sub-samples with mean tensor orientations. (d) AMS ellipsoid shape ranges for the three adjacent sub-samples. Lower hemisphere, equal area projection used here and subsequently.

AARM ellipsoids, both in orientation and shape, relate less closely to whole rock L–S fabrics. Here, we test these assumptions using sampling-scale experiments. In the first case, a single large block of a chlorite-slate yields 105 cores, compared in three adjacent subgroups. In the second case, a severely strained, medium-grained, greenschist facies sandstone is compared at the inter-site level (20 sites) and at the intra-site level (2 blocks with a total of 66 cores). Previous studies show both tectonites were shortened by more than 60% perpendicular to S (Borradaile, 1987b).

2. Borrowdale volcanic slate experiment, northern England

The Borrowdale Volcanic slate is a well-known chlorite-slate, commonly with ash laminae or volcanic lapilli that crops out in the English Lake District. The present block studied was massive and selected for the high degree of homogeneity at eye-level and absence of any textural or compositional heterogeneity. Individual minerals are not visible to the naked eye. The slab possessed a well-defined slaty cleavage and a feeble mineral lineation (L) within the cleavage (S), indicating an S >> L fabric type. In other locations the shapes of volcanic lapilli as well as the variation in their rim-thickness indicate shortening of >60% perpendicular to cleavage (Borradaile, 1987b; Borradaile and Mothersill, 1984). The following stereograms of mean AMS and mean AARM axes are presented in fabric coordinates with the macroscopically estimated L-direction North-South. AMS and AARM were determined using Sapphire Instruments units SI2B and SI4, respectively and remanence was measured in a Molspin magnetometer. The large block was divided into 3 sub-blocks, A; C and E, cut parallel to L and then drilled perpendicular to S, yielding a total of 105 closely spaced cores. Each of A, C and E yielded a similar number of cores and very tightly defined orientations for the AMS axes (Fig. 1a–c). The shaded zones

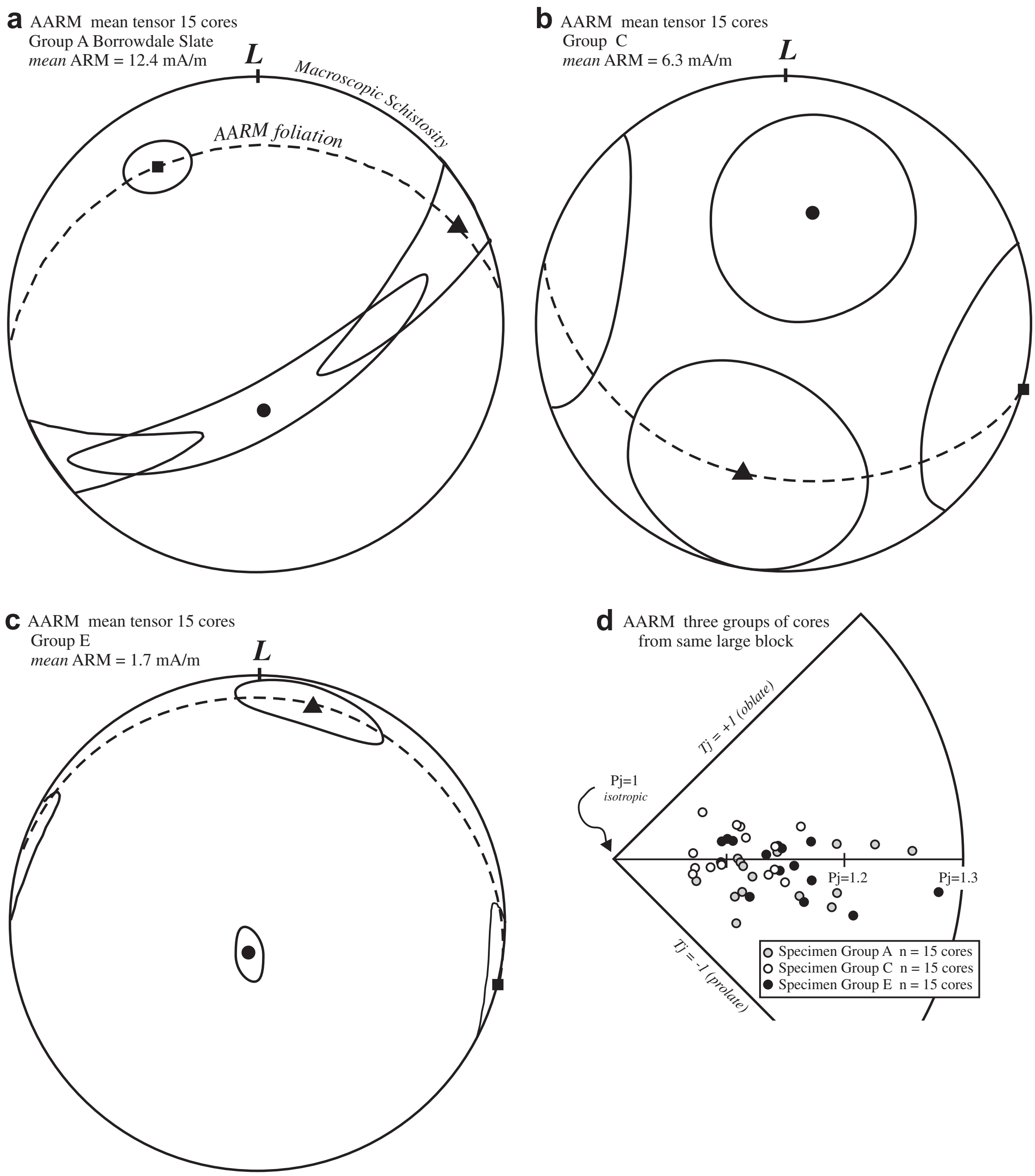

Fig. 2. AARM data for the same large slab of Borrowdale volcanic slate. The confidence regions are only shown for the raw specimen tensors since in AARM data, due to magnetite alone, we do not expect outliers due to mineralogical variation.

are the 95% confidence regions around the mean tensor axes. These are "raw" calculations using the actual AMS axial magnitudes. The calculation for the mean tensor and it confidence regions was also calculated for the normalized tensor, in which each specimen AMS axis magnitude is divided by the mean susceptibility for the specimen. Thus, each AMS ellipsoid reduces to a unit susceptibility tensor. For this rock, the normalized mean tensors differ little because the bulk susceptibilities are rather uniform and devoid of serious magnitude-outliers. The most important conclusion from the comparison of these specimens is that despite large and homogeneous samples, the mean tensors do differ in orientation.

The shapes of the AMS ellipsoids for the three sub-samples are presented on the polar plot (Borradaile and Jackson, 2004) with the 95% confidence region for the *sample* shown. Subgroups C and E agree well but the adjacent part of the specimen (A) yields notably less eccentric and more neutral AMS ellipsoid shapes.

AARM is a more demanding technique and not all specimens are conducive to measurement (Jackson et al., 1988, 1989; McCabe et al., 1985). Suitable data were obtained using an AF field decaying from 100 mT with a simultaneous DC bias field active over the AF range from 60 mT down to zero (Sapphire Instruments SI4 demagnetizer). The DC field applied over the 60 mT to zero decay window was 1 mT (The same conditions were used for the Seine sandstone experiment, below.) Pseudo-single domain and multi-domain magnetite carries the AARM in these specimens (Nakamura and Borradaile, 2001). Fig. 2 presents data on 15 cores from each of the adjacent sub-blocks, A, C and E. Only E provides an AARM fabric partly consistent with the AMS fabric; the magnetic foliation is similar but the k_{MAX} axis is not. Apart from those differences in orientation, the AARM fabrics have different shapes as shown by their confidence regions (Fig. 2a–c); (a) reveals an L > S fabric, (b) is L = S and (c) is S > L. Both the polar plots (Fig. 1d *cf.* Fig. 2d) and the

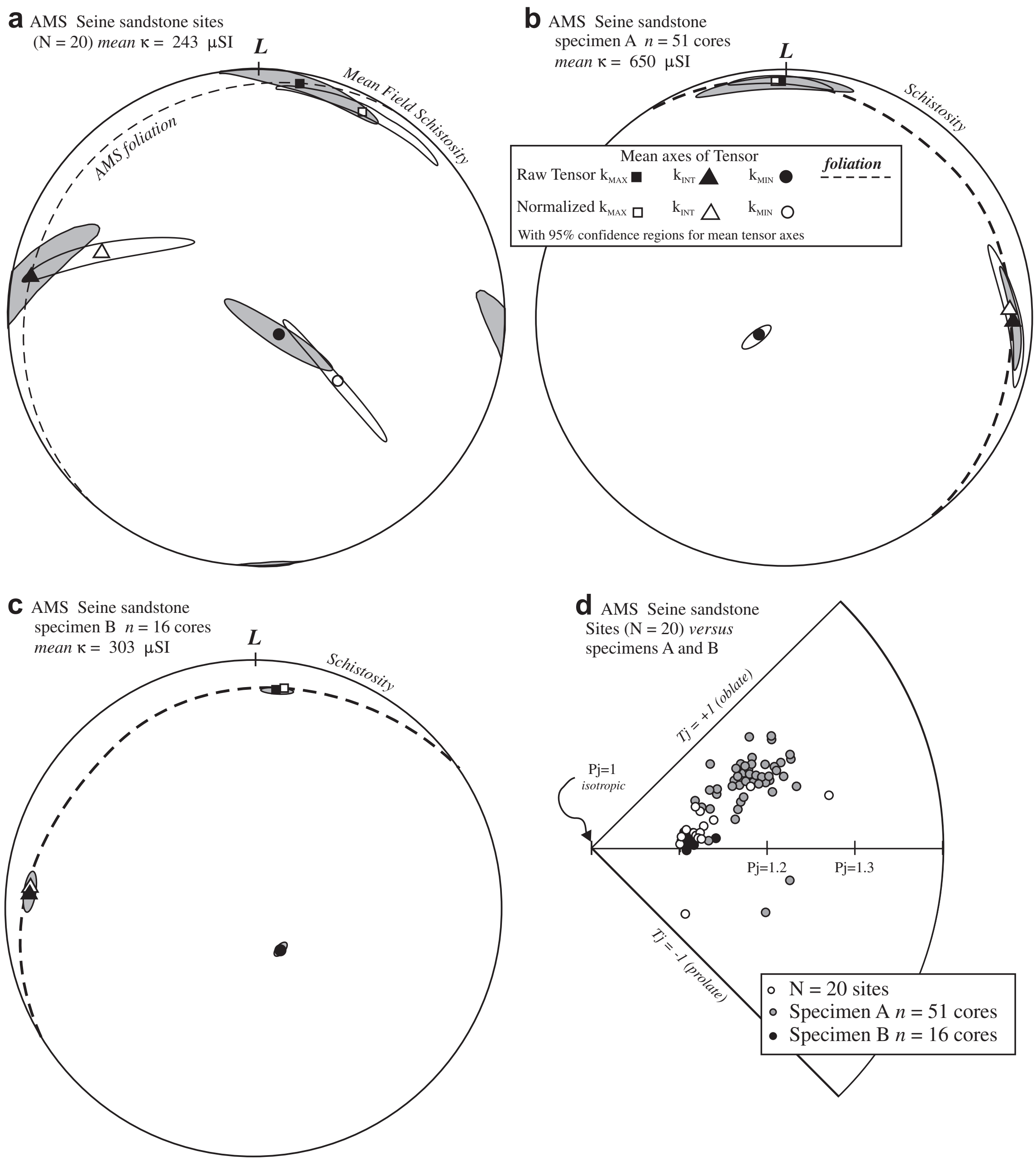

Fig. 3. (a) A regional sample of 20 sites of Seine meta-sandstone is compared with intra-site AMS variation for two large hand specimens (b–c).

shapes of the AARM confidence regions verify that the AARM fabrics are notably less oblate than the AMS fabrics. This is, of course, a reflection of the magnetic symmetry of the magnetite grain shapes being more prolate than that of the AMS of chlorite (Borradaile and Jackson, 2004).

3. Seine meta-sandstone experiment, northern Ontario

The Seine meta-sandstone is a strongly schistose greenschist facies, Archaean rock cropping out in North-western Ontario, 300 km west of Thunder Bay. Highly strained clastic grains are visible to the naked eye (1–3 mm) and the schistose matrix is composed of biotite and actinolite. Finite strain studies reveal that the average shortening perpendicular to cleavage is at least 70% (Borradaile, 1987a; Borradaile and Dehls, 1993). In the following stereograms the mean tensors are shown in specimen coordinates with the macroscopically estimated schistosity (S) nearly horizontal and the lineation (L) North–South. The Seine sandstone is an S > L or L > S tectonite in outcrop. As with the Borrowdale Volcanic Slate study, the mean tensors have 95% confidence regions. The raw tensors, weighted with the actual magnitudes of specimen susceptibility axes, have confidence regions that are shaded. The normalized tensor for AMS suppresses outliers since they are not weighted by individual specimen susceptibility-magnitudes; their confidence regions are shown unshaded.

We compare a site-level study ($N = 20$ sites) with detailed studies two of the blocks from those sites (A, $n = 51$ cores; B, $n = 16$ cores) (Fig. 3a–c). The stereograms compare orientations of the mean tensors. Raw tensors in all cases define the S-fabric although the symmetry of the confidence regions for the sites (Fig. 3a) is rather poor. That situation is worsened when the tensor is normalized, suggesting that the sample is not representative

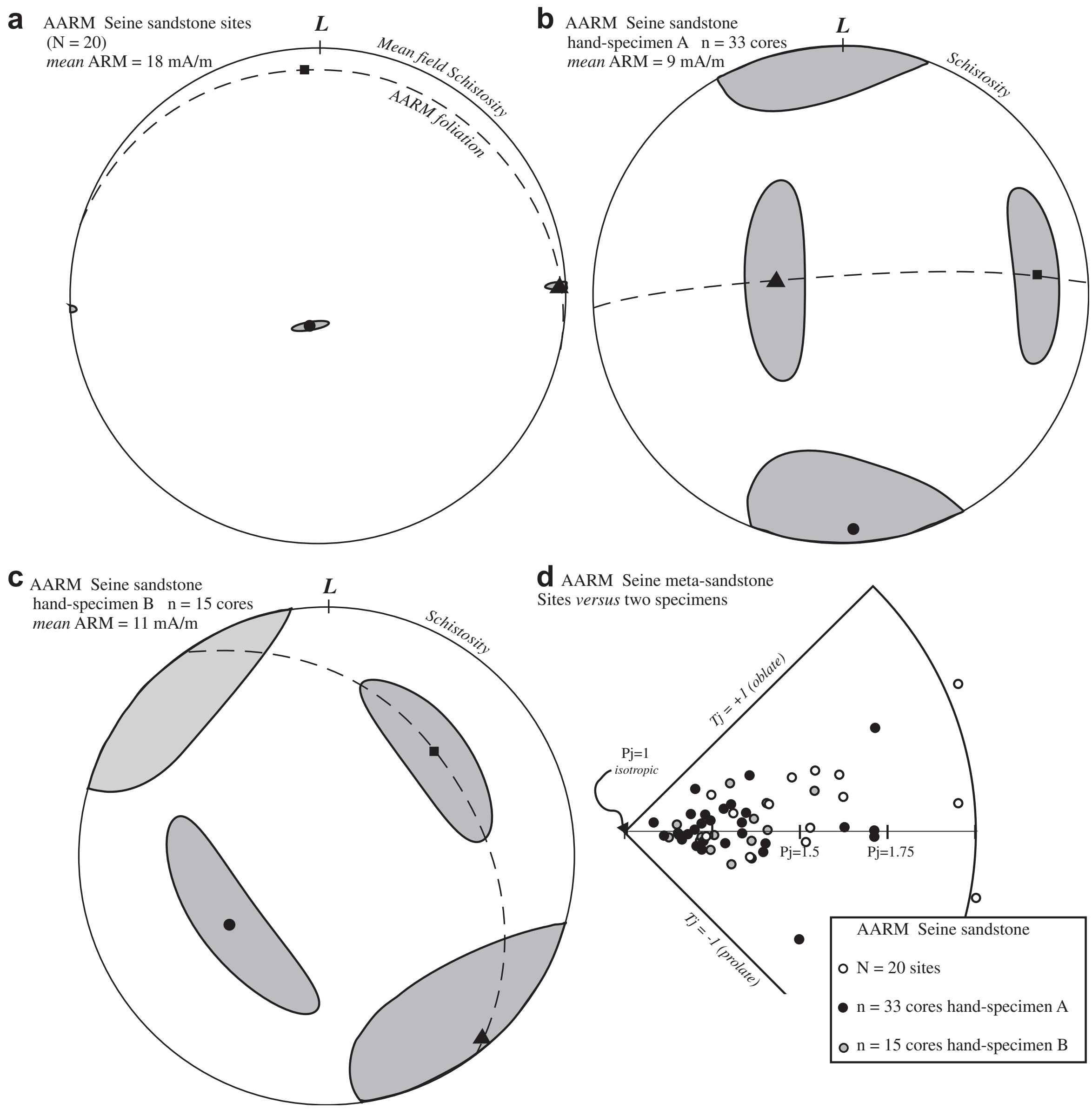

Fig. 4. AARM data for the Seine meta-sandstone.

(Borradaile, 2001). Indeed 20 sites for strained, medium-grained sandstone are probably minimal to characterize a homogeneous regional strain. In contrast, individual specimens with a high density of closely spaced cores (Fig. 3b, 51 cores; Fig. 3c, 16 cores) produce very well-defined S > L fabrics that are very consistent for the specimen. With regard to fabric shapes, specimen B (15 cores) and the 20 sites show a very similar distribution, with almost 100% overlap. In contrast, detailed sampling within specimen A shows a greater AMS shape variation than for all sites.

The contrast between sites and the two detailed specimens is even greater for AARM (Fig. 4). One core from each of 20 sites yields a very well-defined L = S distribution. On the other hand 33 cores from specimen A and 15 cores from specimen B yield poorly defined fabric orientations, incompatible with those of the "regional" study and with the AMS fabrics. Contributions from single-domain magnetite may be responsible for the discrepancies between the AARM and AMS fabrics for specimens A and B (Fig. 3b, c; Fig. 4b, c), (Potter and Stephenson, 1988; Rochette et al., 1992). With regard to AARM ellipsoid shapes, all are nearly neutral as expected for magnetite grain shapes. Although specimen B (15 cores) produces a tight cluster of shapes, specimen A (33 cores) has almost as much variation as the twenty regional samples (Fig. 4d).

4. Conclusions

A traditional test of successful sampling reproducibility is to determine that intra-site (or here intra-specimen) variation is less than the variation between sites or between specimens. In general, practice shows that three to six cores per block or per site will produce consistent results for AMS *orientations*, if the rocks are suitably fine-grained and homogeneous. However, for high precision definition of axial orientations, or for the definition of AMS shapes, larger sample sizes are required, dependent on the grain-size, mineralogical variability, heterogeneity of fabric or strain. In such cases, the optimum sample size will be the number of cores that reveal a reproducible mean fabric. In this study, the variation in AMS or AARM within large blocks (16, 51, 34, 35, 36 per block) may be similar to or larger than that between blocks or between sites.

The optimum number of cores to determine a reproducible AMS axial orientations depends on fabric homogeneity, mineral proportions and grain size (Borradaile, 1987b; Borradaile and Jackson, 2004) but will be >6 and must be determined in a pilot study. The pilot study would determine the sampling density required to achieve consistent results. Sample sizes must be larger to define a mean fabric *shape*. Some idea of the sample size required in a pilot study is shown by Fig. 3 (especially d) where the AMS-shape range for 51 closely spaced cores in one block is greater than the range for 20 different sites. Moreover, even large samples (105 cores from one block of homogeneous fine-grained slate) may fail to define a reproducible AMS ellipsoid shape (Fig. 1d).

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