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GRAIN-SCALE DEFORMATION AND THE FOLD TEST - EVALUATION OF SYN-FOLDING REMAGNETIZATION

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Abstract. The paleomagnetic fold test examines for pre-, syn- or post-folding (re)magnetization. Generally, passive limb rotation is used to restore folded units to their original position, and the position of the Fisherian maximum determines the relationship between folding and magnetization. In a more complete analysis, the reorientation of material lines in different fold models is used. However, the magnetic vector should not be considered a material line as it represents the sum of vectors in individual magnetic carriers and does not cross grain boundaries. Therefore, the role of grain-scale deformation mechanisms was examined, using two end members: rigid-body rotation (spin) and homogeneous strain.

From this study it is concluded that (1) the Fisherian maximum will in general occur before complete unfolding, (2) the sign of the inclination may change during unfolding and, consequently, 'cross-over' unfolding is not representative of syn-folding remagnetization, (3) statistical analysis will not necessarily produce significant results. A number of recommendations are given, which include: stepwise unfolding (and unplunging) should be carried out routinely; local, rather than regional, fold tests should be performed; both limbs and the hinge of a single folded layer should be examined in order to determine the active deformation mechanisms that will enable corrections to be carried out; in addition to Fisherian statistics, the angle between magnetic vector and bedding across a fold should be measured and used for correction.

Introduction

The paleomagnetic fold test is used to determine timing of acquisition of magnetization relative to folding in deformed rocks (Graham, 1949). Three different relationships can be recognized: pre-, syn- and post-folding; they represent aquisition of magnetization before, during and after folding, respectively. Tests to identify pre- and post-folding magnetization have long been used (McElhinny, 1964; McFadden and Jones, 1981). More recently, stepwise unfolding has been applied to document syn-folding remagnetization (e.g. McCabe *et al.*, 1983; McClelland Brown, 1983; Schwartz and Van der Voo, 1984; Kent and Opdyke, 1985; Scotese, 1985; Miller and Kent, 1986). In contrast to earlier applications where tectonic tilt was corrected by rotating in-situ measurements over the total dip angle of deformed beds, stepwise unfolding utilizes a sequence of steps to examine the behavior of the magnetic vector in deformed rocks. At each step the mean and Fisher (1953) precision parameter (McElhinny, 1964; McFadden and Jones, 1981) are determined and when a statistically significant maximum occurs at partial unfolding, syn-folding remagnetization is concluded. For this analysis it is assumed that the angle between the magnetic vector and bedding remains constant during folding. In Figure 1 the shape of possible stepwise unfolding curves are illustrated schematically, with the maximum K value occurring in the range from 0-100%.

Facer (1983) has examined the fold test in view of flexural slip/flow and shear folding (for these and other folding mechanisms see Ramsay, 1967; Hobbs *et al.*, 1976). However, in this approach the magnetic vector is considered a material line in the rock, i.e. a line that physically connects two points before and after deformation. Consequently, reorientation of the magnetic vector is assumed to be analogous to deformed cross bedding in folded rocks (Ramsay, 1961). This approach presents an improvement on passive limb rotation (for example, Spariosu *et al.*, 1984); however, it places considerable constraints on the possible reorientation of the magnetic vector as will be shown below, and is therefore not a suitable application of Ramsay's (1961) technique.

The measured magnetic vector in a sample represents the sum of magnetic directions in individual magnetic carriers, rather than a line crossing grain boundaries (van der Pluijm, 1986). In this paper, the material line approach is therefore not adopted, and the effect of deformation on the reorientation of the magnetic vector at the scale of individual grains will be examined. It will be shown that grain-scale deformation may result in significant deflection of magnetic directions in deformed rocks, and this has implications for the interpretation of fold test results and specifically for syn-folding remagnetization.

Deformation mechanisms

To examine the effect of grain-scale deformation we first have to establish the possible deformation mechanisms. Two end members will be considered here: (1) rigid-body rotation, and (2) homogeneous strain. When rigid-body rotation is active, grains rotate without changing shape; homogeneous strain is the mechanism where strain is produced by grain shape changes only. Clearly, in natural rocks both deformation mechanisms may be active. However, considering these two mechanisms separately will allow for a clearer illustration of the effect of these processes. A somewhat confusing terminology is associated with rotational components of deformation; here, rigid-body rotation equates with spin, and rotation associated with homogeneous strain is shear-induced vorticity (Lister and Williams, 1983). Note that on the grain scale the magnetic vector is considered a passive marker that tracks the deformation of the host.

Secondly, the folding mechanism has to be determined. It is outside the scope of this contribution to discuss the various fold models, but flexural flow/slip is generally considered a reasonable model for rock types we are concerned with in paleomagnetic studies (sandstones, limestones, volcanics). The main distinction between flexural slip and flexural flow is that deformation is localized or more evenly distributed, respectively. For simplicity only rotations in symmetrical folds as seen in the fold profile plane (perpendicular to the fold axis) will be considered. Results obtained from this analysis are, with some modification, also valid for asymmetrical folds, and the analysis can easily be extended into the third dimension. Note that layer-parallel shortening at the onset of deformation, prior to limb rotation, will not play a role for the determination of timing of magnetization using the fold test. However, analysis of pole positions from vector inclination will be affected.

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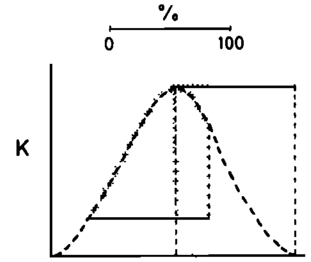

Fig. 1. Composite diagram giving possible Fisher precision parameter curves during stepwise unfolding. Shaded area shows a maximum before 100% unfolding is reached.

Rigid-body rotation

During rigid-body rotation grains do not change shape but strain is produced by shear along discrete surfaces, such as grain boundaries (particulate flow; Borradaile, 1981). Angular rotation of particles in a deforming layer is opposite to limb rotation as is schematically illustrated in Figure 2a. The angle of rotation of a particle with respect to bedding (β) is a function of (1) amount of shear and (2) coupling between particles. In addition, changes in other parameters, such as area change ($l_0 x w_0 \neq l_1 x w_1$) or the relationship between Z_1 and Z_0 will affect the amount of rotation angle β. These various parameters will be discussed below.

The amount of bulk shear during flexural flow has been calculated by a variety of workers. For example, Ramsay (1967, figure 7-57) shows the angular shear (β) as a function of dip angle (Ψ) for constant area and Z_1=Z_0 cos Ψ (Figure 2b, curve 4). Williams and Schoneveld (1981) calculated curves for constant area and Z_1=Z_0 (Figure 2b, curve 2). Both curves assume perfect coupling between particles, expressed as β=tan Ψ (rad), which places an upper limit on the amount of rotation. Alternatively, curves can be calculated for folding in a viscous fluid model; the relationship between rotation and angular shear is β=½tan Ψ (rad), i.e. half-coupling (Rosenfeld, 1970; Ghosh and Ramberg, 1978). Curves 1 and 3 in Figure 2b follow this equation using the same parameters as for curves 2 and 4, respectively. In terms of strain components, curves 2 and 4 are simple shear only, and curves 1 and 3 a combination of simple and pure shear.

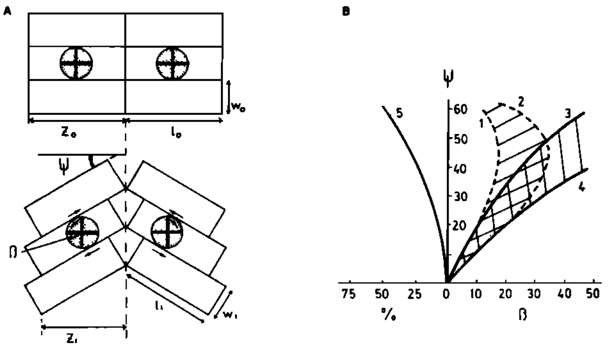

Fig. 2. Rigid-body rotation of particles during folding. Rotation of rigid particles is opposite for both limbs of a fold (a). In (b) the amount of rotation (β) with respect to bedding as a function of limb dip Ψ is plotted. Curves 1 and 2 give amounts for half and full coupling, respectively, when constant area and Z1=Z0 are assumed; curves 3 and 4 give values for half and full coupling, respectively, when constant area and Z1=Z0 cos Ψ are used; curve 5 equates percentage of shortening strain to limb dip. See text for discussion.

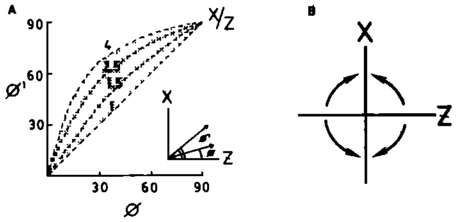

Fig. 3. Reorientation of the magnetic direction during homogeneous strain of the magnetic carrier. In (a) the angular change is plotted as a function of the axial strain ratio (X/Z). As a result of homogeneous strain the magnetic direction will always be reoriented into the direction of the minimum principal strain; however, its location in one of the quadrants determines the sense of rotation (b).

The amount of particle rotation in natural rocks, and therefore of rotation of the magnetic vector, will lie within the two shaded fields of Figure 2b. When the area remains constant, the relationship between Z_1 and Z_0 will dominate the final amount of rotation, which, for simple fold structures, will lie in the area between curves 3 and 4. Coupling may be closer to perfect in carbonates than in sandstones and volcanics, especially at small grain sizes. Consequently, even at moderate bedding dips, considerable rotation of the magnetic direction is possible; for example, rotation angle β may be more than 45° at a limb dip of 40°.

The rotation of the magnetic vector associated with rigid-body rotation of the carriers has two important consequences. (1) In contrast to the material line approach to rotation of the magnetic vector (Facer, 1983), the vector may actually rotate through the dipping bedding surface; in other words, a 'down' magnetic vector may change to 'up'. This excludes the application of 'cross-over' unfolding (McCabe *et al.*, 1983; Scotese, 1985) as a synfolding discriminator (see also Kodama, 1986a). (2) Because the rotation angle is equal in magnitude but of opposite sign on the limbs of a fold, the angular difference is twice that of the rotation. In practice, this will produce a maximum well before 100% unfolding (see also Kodama, 1986b).

Homogeneous strain

Grains will be actively deformed during homogeneous strain which results in grain elongation in the direction of the minimum principal strain axis of the strain ellipsoid (the extension direction, X). As a consequence, the magnetic vector will always rotate toward the X-direction (Figure 3b). In Figure 3a the rotation of the vector for a number of strain ratios (1 to 4, representing 0 to 50% shortening strain) is plotted. For example, a magnetic vector originally at an angle ϕ of 40° to the shortening direction (Z) and an X/Z strain ratio of 2 (≈30% shortening strain) will result in a vector at an angle ϕ' of 59° from Z, i.e. a rotation angle of 19°. The rotation angle will be equal in magnitude but of opposite sign on the limbs of a symmetrical fold.

During limb rotation, the angle between magnetic vector and Z-axis changes, and thus the amount of rotation will be different for the two limbs, i.e. the magnetic vector does not remain symmetrical with respect to the strain axes. Consequently, although all vectors rotate toward the X-direction, their angular rotation will be different and hence stepwise unfolding will produce a maximum before 100% unfolding.

Conclusion and Recommendations

The analysis of pre- and post-folding (re)magnetization in paleomagnetism has been remarkably successful. However, recent applications of stepwise unfolding to determine synfolding remagnetization should be carried out with caution.

From the above it follows that a peak in Fisher precision parameter values can be reached before 100% unfolding. This peak can be tested for statistical significance, but a positive test does not necessarily imply syn-folding remagnetization. Both of the above mechanisms can produce statistically significant maxima while the magnetization was acquired prior to folding.

A statistical test on the position of the maximum K-value compared to the 100% unfolding value is not significant because, as shown earlier, in general a maximum may be reached before complete unfolding. Note that this maximum need not be much away from 100%. Alternatively, secondary magnetization may be acquired during the first few percent of folding and because the resulting maximum is not statistically significant, pre-folding (primary) magnetization may be erroneously concluded.

A conclusive distinction between pre-, post- and syn-folding (re)magnetization can only be made when the angular difference between magnetic vector orientations from both limbs after unfolding is greater than can be accounted for by deformation mechanisms, such as rigid-body rotation and homogeneous strain. Because these mechanisms can account for considerable differential rotation of the magnetic vector, this condition will generally only be met for magnetizations acquired at a late stage of folding, or when independent constraints, for example from microscopic examination, can be placed on the role of grain-scale deformation mechanisms.

In summary, it is believed that, even in relatively open folds, grain-scale deformation mechanisms can significantly hinder the interpretation of fold test results.

Recommendations

Samples from limbs of folds are generally used to determine timing of magnetization. However, when samples from the hinge zone are included, a considerably better knowledge of active deformation mechanisms may be obtained. Consequently, pre-, syn- or post-folding (re)magnetization may be concluded because the role of active deformation mechanisms can be assessed to a much greater detail.

Stepwise unfolding (e.g. 10% intervals) should be performed routinely rather than one-step (100%) unfolding. Furthermore, unfolding of plunging folds should include simultaneous unplunging in equivalent increments when the fold plunge is a primary fold characteristic (e.g. doubly-plunging folds).

A distinction should be made between regional and local fold tests. The former test applies limb averages obtained from various layers, while in the latter case only a single layer is examined at different positions within one fold structure. Using the local fold test an understanding of active deformation processes may be obtained and hence misinterpretation of the data can be avoided.

In addition to the determination of the Fisher precision parameter during (stepwise) unfolding, the angle between magnetic vector and layering for both limbs and the hinge of a fold should be incorporated, and used for correction.

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