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Folding, strain and Graham's fold test in palaeomagnetic investigations

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Summary. Graham's fold test is an important test of stability of magnetization and is widely used in palaeomagnetic studies. The change in dispersion of palaeomagnetic directions achieved by 'returning' layers to their original orientation can give an indication of the relationship between the time of deformation and of magnetization acquisition. However, McElhinny's criteria for application of the test are regarded by McFadden & Jones to be inappropriate. Additionally, simple rotation of directions about the strike of the layer may not be a sufficient procedure. The rock type and style (and amount) of deformation may often appreciably affect the orientation of a vector or magnetic direction during deformation. Hence detailed observations are necessary to provide the basis of the steps used in applying the fold test. Apparent failure of the test may not indicate the absence of pre-deformation stable magnetization in a rock.

Although Graham's fold test is important in palaeomagnetic (and related tectonic) investigations of deformed rocks, application of the test may be very complex.

1 Introduction

Graham (1949) reported a study of the stability of magnetization in sedimentary rocks and included two simple but elegant tests of stability. These field tests in palaeomagnetism are generally referred to as (Graham's) fold test (or tilt test) and the conglomerate test. McElhinny (1964) prepared a technique to assess the significance of the fold test, but McFadden & Jones (1981, p. 58) have concluded that that technique is 'invalid', especially because it is too stringent. However, there may be an additional cause for care in using the fold test.

Graham's (1949) fold test has been extended to any layer (bed, flow, dyke or vein, sill) which was formerly planar, and is now widely used in palaeomagnetic investigations. However, in many cases the fold test should not be considered as simply a tilt test (rotation about a layer's strike direction, which is an external reference).

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Briefly, the fold or tilt test is applied by 'returning' the layer to its presumed original orientation and rotating the direction of magnetization an equal amount and in the same sense. If magnetic directions from 'opposite' limbs of a fold come together, then it is assumed generally that magnetization was acquired prior to folding. Various techniques may be used for rotating or correcting directions, but they generally involve rotation about the strike of the layer.

Although the fold test is widely used, the cautionary note sounded by Graham (1949, pp. 156–157) concerning the need for detailed consideration of effects of various deformation styles on magnetic directions has apparently not been followed up in detail. Tarling (1971, p. 48) observed that the 'tilt correction may not be simple as complex rotations may also be involved', but did not elaborate, other than to point out the importance of plunge correction and bedding tilt distortion caused by differential compaction (p. 60). It is this point (*cf*. Tarling 1971, p. 48) which will be considered here. Simple rigid body tilting of layers will generally only tilt the direction of magnetization with no change in the angular relationship between the layer's plane and the direction of magnetization. However, as recorded by Graham (1949), during folding this angular relationship may change – even with stable magnetization. If such changes occur then some failed fold tests may not indicate lack of primary remanence (*cf.* McFadden & Jones 1981).

2 Fold styles

Folds (and folding) have been classified in a number of ways, and different fold styles or types are recognized. The geometrical effects of multiple folding will not be considered at any length here. A common two-fold classification is that which divides folds into concentric or parallel folds and similar or shear folds (Fig. 1). Such a classification of style and fold development is likely to be too simple for most field observations as shear occurs in both types. Nevertheless, these two styles will be a useful basis for this discussion.

Factors which influence the style of fold developed during deformation include rock competency (influenced by rock type, depth and temperature), relative and absolute layer thickness and duration of deformation. Ultimately all such factors need to be considered, even in the context of palaeomagnetism, but it is necessary first to understand the basic geometrical relationships.

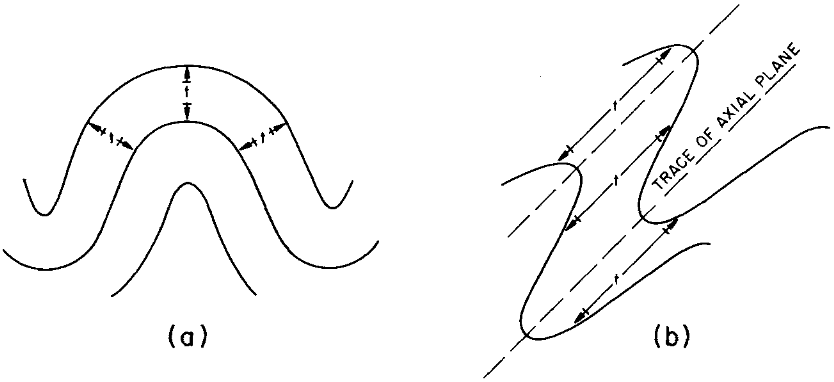

Figure 1. (a) Concentric or parallel folds – in which layer thickness t remains constant around the fold. In cores of tight folds faulting is common. (b) Similar folds – in which the apparent thickness t parallel to the trace of the axial plane remains constant. The folds may develop by shear or slip along planes parallel to the axial plane, and/or by compression perpendicular to the axial plane.

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3 Rotation of vectors during folding

Ramsay (1961) discussed the effects of folding on the orientation of planar, and hence linear, features within layers, using cross-bedding as a particular example. The geometrical techniques outlined by Ramsay (1961) may be applied to palaeomagnetic directions in tilted and folded layers when remanence is carried by detrital grains (i.e. DRM) – remanence carried by pigment or other CRM may not be affected in the same way. Simple rigid body tilting about one axis, which may develop in fault block tilting, may not seriously influence directions relative to a layer surface. Strong deformation and metamorphism of rocks may cause remagnetization, and hence is not considered here.

If rocks have been folded by flexure without compression with a horizontal axis of rotation parallel to the strike of the layers, then simple rotation of a layer about its strike will generally 'return' it to its original orientation. Correction for non-plunging concentric folds and for tilted layers simply involves rotation of the lineation or palaeomagnetic direction about the fold axis or strike of the layers. The term 'tilt correction' is herein restricted to such a correction. Ramsay (1961) noted that the error in lineation direction caused by not correcting for dips of up to 25° does not exceed 3° – but in palaeomagnetic studies angular errors may arise in several ways and hence all such errors should be eliminated whenever such a simple correction can be applied. For steep dips such declination errors may exceed 50°. The error varies with the layer's dip and the angle between the lineation (e.g. a lineation created by the trace of the cross-bedding on a vertical plane) and the flexural fold axis (Ramsay 1961, pp. 85–86).

Unfolding of layers in a plunging concentric fold must take into account the orientation of both the layer and the fold axis. Hence the fold should first be 'unplunged' before the tilt correction is applied. As an example, it can be shown that neglect of a shallow 10° plunge would cause a declination error of 5° for a dip of 60° and 10° for a dip of 90° (after Ramsay's 1961, fig. 5, p. 89). In overturned limbs the errors become more serious.

Shear may occur between and parallel to layers in flexure folding, and hence rotation of directions could occur, whereas in similar or shear folding the shear movement, if it occurs, does so on shear surfaces parallel to the axial plane (Fig. 1). Stereographic plots showing effects of shear folding may be complicated (e.g. Ramsay 1961). As it is necessary to recognize original geometrical relationships in the layers, and also the orientation of imposed tectonic axes, external reference lines such as present strike direction are inadequate for reconstructions to obtain original palaeomagnetic directions in similar folds. Ramsay (1961) has described the techniques, and extended his discussion to include the effects of simple compression and of shear folding an inclined surface. Even for compression of 10 per cent modification of a vector direction could exceed 10° (*cf.* Ramsay 1961, fig. 8).

Fig. 2 shows the effects that flexure folding may exert on the orientation of palaeomagnetic (especially DRM) directions, and Fig. 3 the effects of shear folding. Table 1 contains a summary of reorientation effects on primary directions induced by folding. As the dip of the layer becomes steeper, so the angle between the layer surface and the palaeomagnetic inclination changes – becoming asymmetrical on opposite limbs. If the fold has been compressed, the angular error is generally even more severe.

Table 1 indicates, especially for layer dips in excess of 30°, that the inclination of the palaeomagnetic vector measured from the layer surface is noticeably different for flexure folding and shear folding. Ramsay (1961, fig. 12) illustrated the angular error in a lineation direction (*cf.* that of a palaeomagnetic direction or its trace) resulting from unfolding shear folds by flexure fold techniques. For the geometric configurations used by Ramsay (1961) the error ranges from 0° to 140°, being less than 5° in about 26 per cent of the examples used (percentage determined here).

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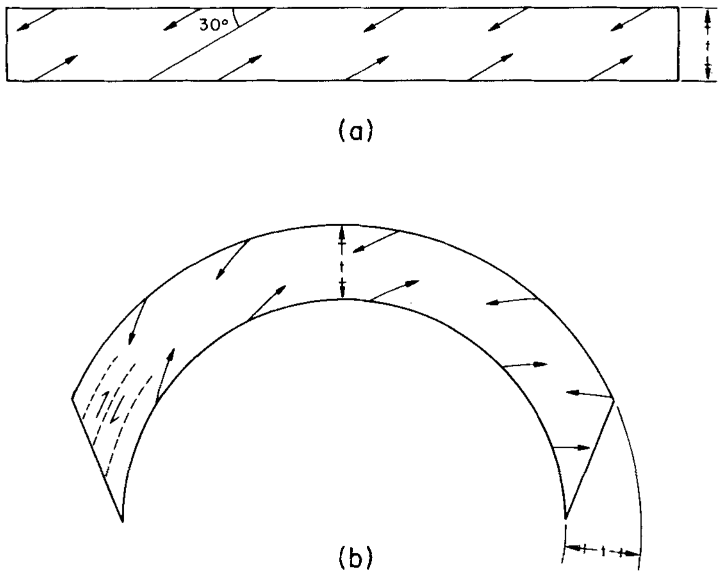

Figure 2. Effects of flexure folding on palaeomagnetic (DRM) directions (modified after Ramsey 1961, fig. 14). (a) Initial orientation, showing 'normal' and 'reversed' inclinations. (b) Orientation after flexure folding of the layer and the inclinations. The thickness *t* of the layer remains constant and all internal movement is along planes parallel to the layer surface (dashes), with shear sense shown. This shear could rotate remanence-carrying grains. The radius of curvature of the folded surface is 9*t*.

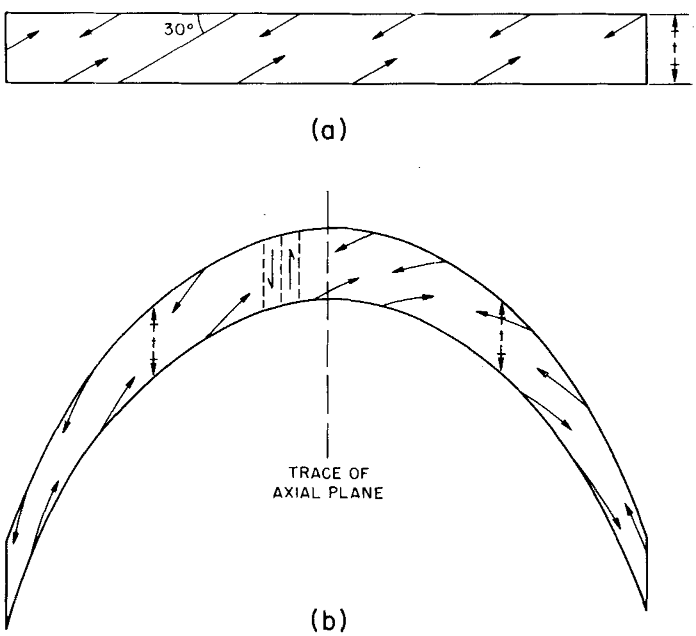

Figure 3. Effects of shear folding on palaeomagnetic (DRM) inclination (modified after Ramsay 1961), fig. 16). (a) As for Fig. 2 (a). (b) Orientation after shear folding, with vertical axial plane, showing inclination orientations. The thickness is modified as shown, with shear (? rotation) along directions parallel to the axial plane, with the sense as shown.

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Table 1. Modification of palaeomagnetic (DRM) directions by folding and compression.

	Flexure folding		Shear folding	
	No compression	50 per cent compression	No compression	50 per cent compression
Dip of beds	Angle between inclination and layer surface			
90° N	10°	5°	0°	0°
60° N	14°	20°	13°	20°
30° N	21°	38°	23°	38°
0	30°	54°	30°	55°
30° S	39°	71°	30°	66°
60° S	44°	62°	17°	44°
90° S	46°	29°	0°	0°

Notes:

Fold axis oriented east–west.

Angle between the perpendicular to palaeomagnetic declination and the fold axis is 60°. If this angle is 30°, data in this table would be similar. (Adapted from figs 15 and 17 of Ramsay 1961, fig. 15 being based on

$$\theta = \sin^{-1}\left[\frac{(r+t)\sin\{\phi[1-r/(r+t)]\}}{\sqrt{[\![r^2+(r+t)^2-2r(r+t)\cos\{\phi[1-r/(r+t)]\}]\!]}}\right]-90°$$

where

θ is the angle an original vertical makes with the folded layer of thickness t;
r is the radius of curvature of the inner surface (*cf.* Fig. 2); and
ϕ is the angle of dip of the inner surface in Fig. 2 (*cf.* pp. 92, 95 and fig. 14 of Ramsay 1961.)

4 Discussion

During folding of rocks considerable rotation of DRM-carrying grains and hence of stable magnetic directions may occur, which could introduce serious errors in palaeomagnetic studies (*cf.* Graham 1949). Tilting, either as part of simple block faulting or broad gentle folding, may not introduce significant errors, depending on rotation(s). However, it is necessary to recognize the effects of folding of previously tilted layers, because a fold with horizontal fold axis would only be generated if the axis was parallel to the strike of the beds. Plunging folds may develop in a number of ways, and the effect of plunge should be corrected for when attempting to obtain the initial configuration of vectors within the layers.

The varying effects of competency on the behaviour of rocks during folding is important, especially when studying different rock types from one fold or fold system. Folding of igneous rocks is less likely to introduce errors unless they are still cooling and hence less competent. The tendency of fine-grained rocks of sedimentary sections to be sampled for palaeomagnetic studies increases the need to correct for vector rotation – generally *not* just a simple 'tilt correction'. As palaeomagnetic studies are extended into older rocks there is an increasing need for recognizing the style of folding and correcting palaeomagnetic directions accordingly. Some published studies will serve as a basis for discussion of these points.

Graham's (1949) fold test was applied (?misapplied) by simple rotation of palaeomagnetic directions about the strike of the layering in the intrusive Giles Complex (Facer 1971 – which W. M. Schwerdtner read and prompted the present discussion). Although the gabbros, etc. of the Complex would probably behave competently during deformation, if the gravi-

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tational layers were folded into broad folds before final solidification some intergranular shear may have been imparted to the rocks. Hence, the palaeomagnetic directions may not represent true TRM directions, even with the stable remanence possibly being carried by fine-grained magnetite in plagioclase grains (*cf.* Facer 1973). Unfortunately, the style of folding and subsequent deformation in the Complex could in general not be studied during sampling for the palaeomagnetic studies and hence it is not possible to apply the fold test in the way suggested here.

McGlynn *et al.* (1974) attributed the dispersion of palaeomagnetic directions in fine-grained Nonacho sandstones to viscous partial thermoremanent magnetization (VPTRM), 'retention of a small prefolding component' (p. 36), and direction changes in the magnetic field during magnetization. Dispersion increased after 'returning' the bedding planes to horizontal (McGlynn *et al.* 1974, pp. 35–36). The bedding dips range from shallow to steep and the strike direction is variable (McGlynn *et al.* 1974, fig. 1, p. 32). Fold plunges are gentle, but variable (McGlynn 1971). Hence, the fold test probably cannot be applied simply. As folding and faulting occurred during and after sedimentation the shear deformation and compression, which locally produced 'intense cleavage' in shales (McGlynn 1971, pp. 141–142), presumably rotated remanence carriers (and magnetic vectors). Hence, although VPTRMs and other secondary magnetizations are likely to be present, prefolding directions may also be stable – but complexly redistributed.

Robertson, Roy & Park (1968, p. 1175) pointed out that there are '... Difficulties encountered in obtaining palaeomagnetic results from even mildly deformed rocks in orogenic zones ...' One difficulty is introduced by folding. Unfortunately, Graham's (1949) fold test should not be applied using simply an external reference frame – more data need to be obtained when sampling for palaeomagnetic studies. For mildly deformed rocks it may be sufficient to obtain layer orientation, and fold axis orientation if folded. For strongly deformed rocks, especially incompetent layers, detailed structural data, including the style of folding, should be combined with palaeomagnetic/tectonic studies. Unfortunately, in some cases all structural data may not be available. Graham's (1949) fold test, especially as a tilt test and for mildly folded, competent rocks, is an important test. Apparent failure of the test is not a sufficient criterion of post-folding remagnetization.

5 Conclusion

Assessment of Graham's (1949) fold test in palaeomagnetic studies shows that the style of folding and related structural orientation data must be used in applying the test. In many cases of folded sedimentary, or other incompetent, layers the use of external reference axes such as the present strike of the layer is insufficient. Simple 'return' of a layer to its original orientation does not take into account internal strain experienced by the rock. Detailed reconstruction based on all available data will often be necessary in applying the fold test. Obviously secondary magnetizations are commonly present in rocks, but failure of the fold test is not sufficient to indicate the absence or near-absence of pre-folding magnetization(s). This conclusion is similar to that of McFadden & Jones (1981, p. 58): 'there may have been many instances in which a fold test was significant but such significance was rejected on the basis of the incorrect test'. As Graham pointed out in 1949, detailed assessment of his test in some types of folding is necessary.

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