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Flexural folding of linear elements by non coaxial axes of deformation in fold and thrust belts: restoration and errors

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With 2 Figures

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1. Introduction

The combined use of linear elements (paleocurrents, stress directions, paleomagnetic vectors) and bedding planes in fold and thrust belts is an excellent way to restore geological structures to the non-deformed stage. In this sense paleomagnetic analysis have demonstrated to be a suitable and successful technique for determining rotations from its earliest application (NORRIS & BLACK 1961), vertical axis rotation in particular. The orientation of the local paleomagnetic vector will be related to its reference vector by means of the deformation processes undergone by that portion of the thrust belt. This is not always possible with other structural indicators because they do not have an "absolute" reference system to contrast local deviations. Deformation processes (simple shear, pure shear, translation, rotation) affecting a non-deformed, primary 3D element (E.g. a pair composed by a paleomagnetic reference vector and a horizontal bedding plane) will generate the observed deformation stage. *As in so many problems in structural geology, the* key between these two stages *lies in proper deciphering of geometry and sequences of structural events* (ELLIOT 1976).

Internal deformation processes (simple and pure shear) during folding that affect the orientation of lines have been investigated in several cases (e.g. RAMSAY 1961, LOWRIE & al. 1986, STAMATAKOS & KODAMA 1991). However *the study of the structural evolution of thrust belts is in a large measure the study and interpretation of finite rotations* (*external* deformation) (MC CAIG & MC CLELLAND 1992). The combinations of these rotations (vertical and horizontal) together with translations over discontinuity planes will be responsible for the final geometry of these systems. The variables that sinthetize the *external* deformation processes can be reduced to the number, sequence, orientation and magnitude of the deformation axes that have affected the initial non-deformed rock volume (horizontal plane and reference vector). In fold and thrust systems these axes are controlled by the geometry and interactions of the thrust plane (rock's anisotropy) and the displacement field (geodynamic forces). When more than one deformation and non-coaxial axes affect a rock volume, this will result in complex geometries like superposed, interference, forced, plunging or conical folding (Fig. 1).

2. Restoration

Restoration should strictly follow the reverse order of the deformation processes. However in most cases this is merely based on the bedding correction (BC). This correction presupposes that the observed bedding plane was tilted by the bedding strike as rotation axis for an angle equal to the dip. As this assumption is not necessarily true, the restored orientation of a line is "infected" by an error (apparent vertical rotation of MAC DONALD 1980, or spurious rotation, PUEYO 2000). In the example (Fig. 1) many deformation axes (A, B, C and D) have acted in the hanging wall (stage 4). The true restoration (e.g. of the light region) should start removing the effect of the last rotation

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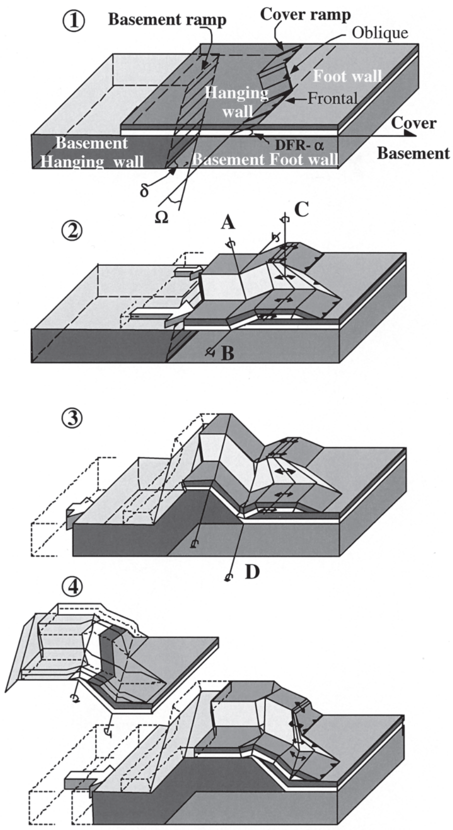

Fig. 1: Progressive deformation stages in a hypothetical thrust system with interactions of basement and cover rocks. The geometry of fault propagation folds (1 & 2) is controlled by the geometry of the thrust plane (mechanically compatible with the local stress field). Notice that there is a difference of shortening at both sides of the oblique ramp that will produce a vertical axis rotation (C) and will be responsible for the conical geometry observed in the hanging wall. A basement thrust deforms the cover system (3 and 4, the later with detail of the foot wall geometry). Non-coaxial deformation (obliquity) is produced by the different anisotropy of the basement and cover rocks (for a given and equal oriented stress field, like in the figure) and will originate plunging and interference structures in the hanging-wall. A to D are the deformation (external rotation) and non-coaxial axes.

axis, D; then B and A. Because vertical axis rotations are almost impossible to contrain with field data; C will be detected when the process is finished and the local paleomagnetic vector is contrasted with the paleomagnetic reference.

3. Errors

Several forward models of plunging folds have been performed from an initial non-deformed stage (pair vector-bedding plane). Underlying *assumptions* during modelisation of flexural folds in the stereonet are: (1) The bedding plane in the non-deformed stage was horizontal. (2) A paleomagnetic reference vector was contained in this non-deformed bed (primary). (3) The angular relation between the line and the plane does not change during the deformation (no internal deformation). (4) The bedding is dimensionless and the development of geometries has not space-problems (thickness is zero). (5) There is no vertical axis of rotation. Therefore, after BC, the deflection with the reference will be always an apparent vertical rotation (error). (6) Two non- coaxial and horizontal axes of deformation acting at different times are responsible for the finite deformation.

4. Discussion

It is obvious that the true restoration would return the line and its plane to the original position, however the application of the BC will generate an error (apparent vertical rotation) in the orientation of the "restored" line. These models have allowed to *demonstrate* that: A) the error is independent of the orientation of the line with regard to the deformation axes; any line will undergo the same error for a given structural position in a given fold (W and d values). This is the azimutal independence of Chan (1988). B) the error is only dependent upon the magnitudes of the deformation axes (a and d) as well as their relative orientation (W: obliquity) (Fig. 2). C) For a given fold (same value of W and d) errors are asymmetrical for symmetrical positions on the folded surface; $|Error_{a}|$ ¹ $|Error_{-a}|$ (except for W = 90°). D) The application of the fold-test without considering complex geometrical and kinematics histories (Graham 1949) may generate erroneous deductions between the age of the paleomagnetic vector and the age of the folding (demonstrated by Stewart 1995 for W = 90°).

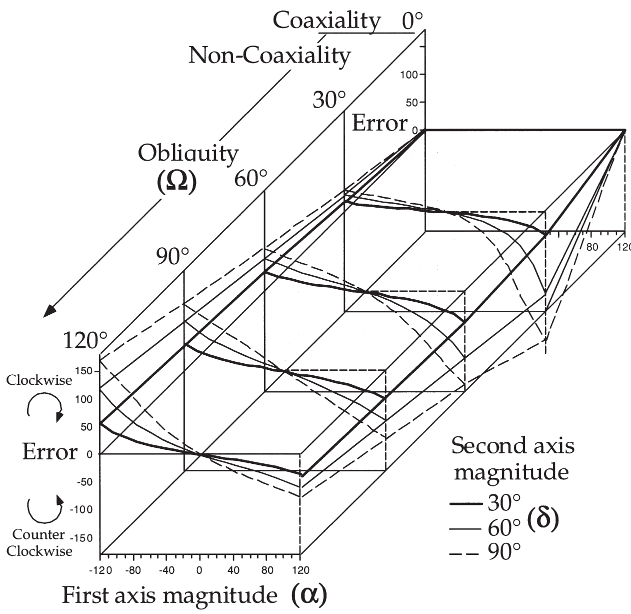

Fig. 2: Apparent vertical axis rotation values (errors) encountered after application of the BC in structures generated by horizontal and non-coaxial axes of deformation. First axis magnitude (a) represents the degree of folding (degree of flank rotation). Symmetrical limb positions of a given fold will have opposite values (+ or – sign). 0 represents the hinge position. Obliquity (O) is the angle between the deformation axes (0 when they are coaxial). The magnitude of the second axis (d) represents, for example, the tilting caused by the frontal forelimb of the basement thrust (Fig. 1 – stages 3 and 4).

On the other hand two non-coaxial and horizontal axes of deformation will generate different kinds of plunging folds in many cases. The plunge of a fold is usually removed assuming that it was acquired by a tilting perpendicular to the fold axis azimut. This can be very often an erroneous correction (Cummins 1964). By removing the plunge with such an operation the relative age deformation-magnetization error will be avoided, but the final orientation of vectors will be affected with an error that can be very large. This error is, in most cases, larger than the one produced by the application of the BC (Pueyo 2000).

The solution and correct restoration, in all cases, have to be based on a good control of the geometry and kinematics of folding. Vertical axis rotations are very difficult to control, even with paleomagnetic analysis, the lack of control during restoration of flexural folded structures may imply the input of considerable errors. The model presented herein is applicable to any linear element (stress directions, paleocu-rrents,...) recorded in sedimentary rocks and folded passively.

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