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Evaluating the paleomagnetic reliability in fold and thrust belt studies

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Abstract: Paleomagnetic data are essential for a real 3D understanding of fold and thrust belts and are a unique kinematic indicator to help understand the processes of lateral transference of deformation. In association with the bedding surface it is one of the very few natural indicators able to unambiguously relate the deformed and undeformed stages. However, paleomagnetic data are sometimes misinterpreted or ignored. An analysis of the implicit assumptions in paleomagnetic studies of fold and thrust belts reveals three possible sources of error with an intrinsic structural (geometric) control; 1) overlapped paleomagnetic directions (laboratory isolation failures), 2) rock volume deformation passively recorded by the paleomagnetic vector (non rigid-body behaviour), and 3) incorrect restoration of beds in non-coaxial structures (bedding correction failures in conical, plunging folds, etc). The different errors can be detected by applying simple geometric techniques like the stereographic scattering, the inclination vs. dip and the declination vs. strike diagrams, the fold test, the small circle reconstruction during unfolding and the geometry of the dispersion of the net tectonic rotation axes. Finally, a list of reliability criteria is proposed to evaluate the quality of investigation focused on the characterization of vertical axis rotations in fold and thrust belts.

Keywords: paleomagnetism, fold and thrust belts, assumptions, errors, resolution, reliability.

Paleomagnetism is the study of the ancient Earth magnetic field (EMF) recorded by ferromagnetic minerals present in most rocks of the crust. Since the EMF is a global and absolute reference system, paleomagnetic vectors can be used to reconstruct the plate tectonic arrangement (Van der Voo, 1993). Below the plate-scale, paleomagnetism is also useful for reconstructing microplates, terranes or block positions/rotations or large orogenic processes like the origin of the curvature; the oroclinal bending.

Paleomagnetism has been used to detect absolute magnitudes of rotation on the FTB scale since the early sixties (Norris and Black, 1961), but the definitive beginning of the application to detect VARs began during the eighties; since then, the number of data has been growing exponentially in most FTBs. The great advantage of the paleomagnetic record, when a primary origin can be unambiguously guaranteed (but not only then), is that the difference between the paleomagnetic declination in the hanging wall and the footwall (or the stable part of the plate for the same age) represents the best way to obtain the absolute magnitude of the vertical axis rotation accommodated by this thrust (independently of its origin). Other kinematic indicators, derived from the analysis of the strain or stress tensors, cannot always guarantee the achieving of the primary orientation if the original (pre-deformational) location is to be reconstructed. VARs in FTBs are most commonly related to the differential displacement of thrust sheets (McCaig and McClelland, 1992; Allerton, 1998; Pueyo *et al.*, 2004; Soto *et al.*, 2006; Sussman *et al.*, *in review*) and are reported in most fold-thrust belts.

Many present paleomagnetic studies on small-scale of, say, a few kilometers of fold and thrust front, have proved useful in providing kinematic indications that allow us to obtain: 1) the punctual characterization of the rotation magnitude of a thrust, which is related to a local (near-field; Allerton, 1998) or regional (far-field) gradient of displacement of the thrust system, 2) the lateral variation of this magnitude along-strike within the same thrust (e.g. caused by oblique ramps), 3) the punctual value of the rotation velocity of a thrust (in the case of syntectonic sedimentation; Pueyo *et al.*, 2002a), 4) the location of the pivot points responsible for the rotational movement of the thrust that allows the shortening estimate from cross section to be corrected thanks to the out of plane movement across the section (Pueyo *et al.*, 2004; Sussman *et al.*, *in review*), 5) the lateral migration velocity of these pivot-points (in the case of diachronous lateral transfer of deformation in thrust fronts with syntectonic deformation), 6) moreover, detailed paleomagnetic analyses performed in isolated structures has allowed us to understand the kinematic model in complex geometries such as conical folds (Sellés, 1988; Pueyo *et al.*, 2003a), plunging folds (Zotkevich, 1972; Stewart, 1995; Pueyo *et al.*, 2002b) or fold closures (Stewart and Jackson, 1995), 7) it is also a potential tool to set the relative timing of superposed folding (Weil, 2006). A special mention is merited when the rocks appear remagnetized during the deformation (especially if they are partially reset), the paleomagnetic information offers intermediate snapshots of the deformation that also allows 8) the unravelling of different rotational movements (Pueyo *et al.*, 2007), 9) the separating of deformation caused by cover and basement thrusts rotational activity (Oliva and Pueyo, 2007), and 10) the reconstruction of basin or thrust geometries for the time of the remagnetization allows for partial restorations (Soto *et al.*, 2008). In conclusion, the paleomagnetic vectors together with the bedding planes represent a real 3D reference system that relates the deformed and undeformed stages allowing a truly 3D understanding of the evolution of fold and thrust belts.

However, paleomagnetic data are sometimes ignored or misinterpreted by structural geologists. This is partially due to the misunderstanding of the processing of paleomagnetic data together with the meaningless interpretations proposed in some works as well as the suspicion of non-resolution of the method. The mixing-up of working scales (local structure, thrust sheet, orogen or plate) has also contributed to this confusion. All these facts have generated some scepticism in part of the scientific community. This paper analyzes the inherent paleomagnetic assumptions in the study of fold and thrust belts and the different sources of error that can obscure and reduce its potential as a valuable kinematic indicator. The way to detect and to avoid these errors, the variables controlling them and a list of reliability criteria are proposed at the end.

Paleomagnetic assumptions and sources of error

Inherent assumptions of paleomagnetism in fold and thrust belts (FTB) are similar, as they are in any paleomagnetic study, but they can be specified one step further.

1) For a given period of time, the EMF behaves as a geocentric axial dipole.

Source of error: 0) Secular variations insufficiently averaged out. In sedimentary piles, a sufficient number of samples (10-15) along a ≈10 ka lapse (equivalent thickness) will guarantee this assumption and, initially, the paleomagnetic population of vectors should give the distinctive *fisherian* (Fisher, 1953) dispersion around the mean value.

2) Natural mechanisms of magnetic field acquisition (detritic, chemical, thermal…) may be efficient to provide to the ferromagnetic minerals an accurate field orientation recording.

Source of error: A) Inclination flattening. Shallower inclinations than expected were detected very early in paleomagnetic studies (Van Andel and Hospers, 1966). If this is caused by sediment load, the inclination error can be corrected (Tauxe, 2005). In any case, this kind of error will not affect the declination component (Fig. 1a).

Source of error: B) Structural control over overlapped directions. The ability of the laboratory procedures in the isolation of the original paleomagnetic vectors is another implicit assumption related to the efficient natural record. The natural remanent magnetization (NRM) depends upon the nature of the magnetic carriers and the geological history of the rock and is always a multi-component vector. The thermal or alternating field demagnetization methods do not always succeed in isolating these components. The common case when a folded rock is affected by the recent overprint of the present geomagnetic field merits special attention (Dinarès-Turell and McClelland, 1991; Rodríguez-Pintó and Pueyo, *in preparation*). Demagnetization circles (DC) analysis may enable the original component to be unravelled, hence providing a lower scattering than the younger overprint (Halls, 1978; Bailey and Halls, 1984; McFadden and McElhinny, 1988). This typology can be a source of large errors in tectonic interpretations if the classic end-point analysis is used instead of the DC to fit the paleomagnetic directions. In this case, the overlapped direction will be controlled by the structural position that will depend on the angular relationships between the original vector (including its polarity), the fold axis and the present field as well as the actual dip of the sampled bed (Figs. 1b and 2b). All of them together may strongly deflect the declination and the inclination and also alter the fold and reversal test results (Rodríguez-Pintó and Pueyo, *in preparation*).

3) The EMF memory may remain stable through geological time. Although many physical and chemical

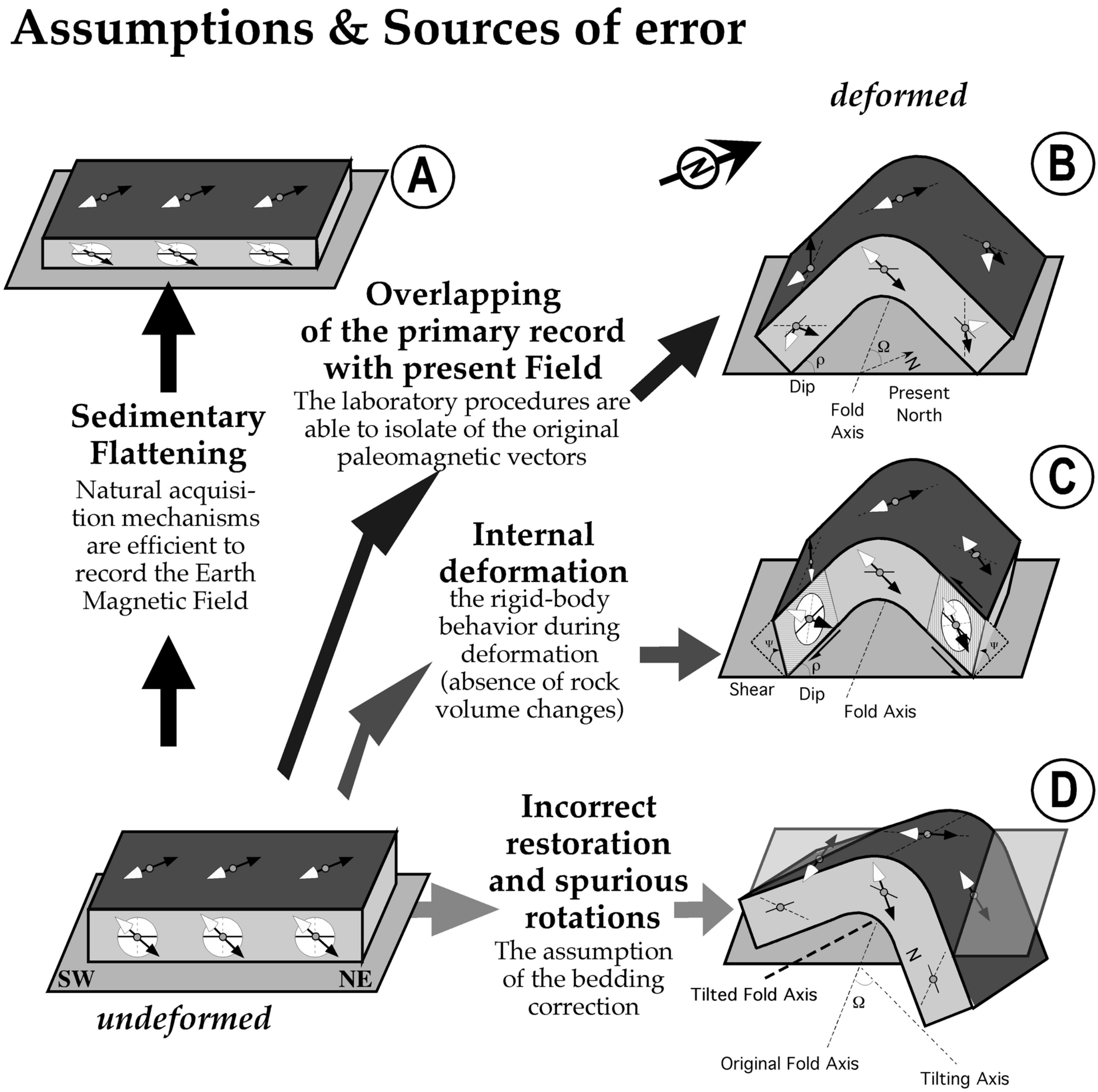

Figure 1. (A) Sedimentary flattening error, (B) Structural control and modelized errors on overlapped paleomagnetic directions (Rodríguez-Pintó *et al., in review*); the present geomagnetic field overlaps the original vector, both vectors have the same intensity, (C) Structural control of deformed paleomagnetic directions and derived errors, (D) Structural control of the magnitude of angular errors (declination) in incorrectly restored paleomagnetic directions. A plunging fold derived from an oblique tilting of a previous horizontal axis has been restored by the simple bedding correction.

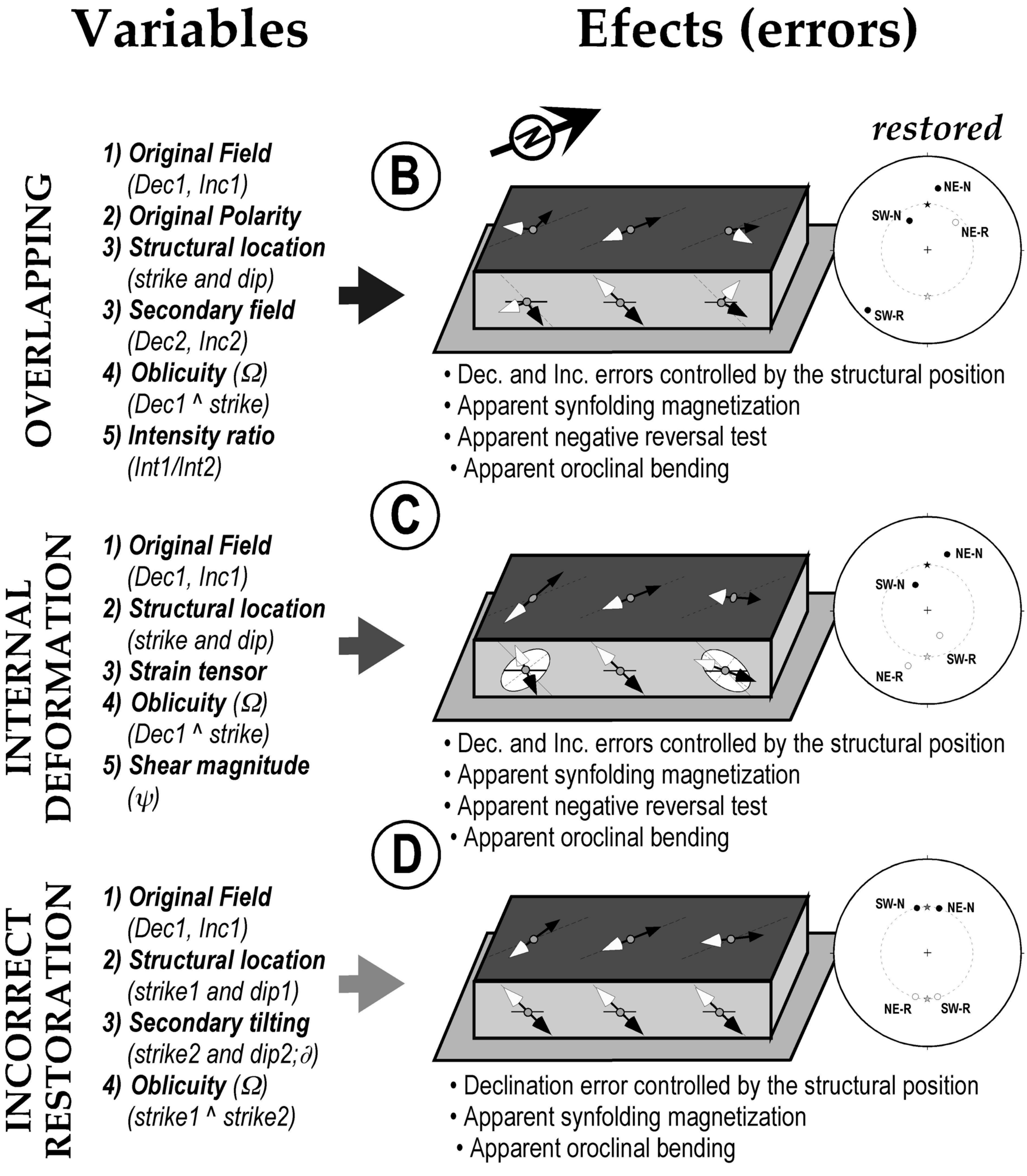

Figure 2. Variables and effects (after restoration) of the different types of structural errors (B: overlapping, C: internal deformation, D: incorrect restoration). Stereonets of restored data; paleomagnetic vectors should converge with their respective references (black and white stars) depending upon the original polarity, but they change according to the structural position (opposite fold flanks were considered; NE and SW).

processes may totally or partially reset the original information (i.e. remagnetizations), the paleomagnetic analyses can guarantee that many rocks of the Earth's crust fulfill this assumption.

Source of error: C) Internal deformation of the rock volume. Another inherent assumption is the rigid-body behaviour during deformation, i.e. the absence of rock volume changes that would modify the original paleomagnetic information. Any external rotational movement will be accurately detected during the resolution of the method if the assumption is true. However, internal (rotational) deformation of rock volumes are common and their possible influence on paleomagnetic vectors was detected during the eighties (Lowrie *et al.*, 1986; Van der Pluijm, 1987; Kodama, 1988; Stamatakos and Kodama, 1991; Borradaile, 1997). The simple or pure shear mechanisms related, for example, to flexural folding will deform the original paleomagnetic information (Figs. 1c and 2c). Similar to the overlapped directions, the final deformed vectors will depend upon the original vector, the fold axis and the magnitude of shear. Therefore, the rock volume deformation will modify the paleomagnetic declination and inclination as well as the fold and reversal tests.

4) A paleomagnetic vector restored to the ancient reference system (paleo-horizontal) allows the quantifying of the vertical-axis rotations at the studied point (declination difference with the expected direction). The bedding plane represents a reliable paleohorizontal reference in sedimentary rocks.

Source of error: D) The bedding correction in complex areas. The standard tilt correction (or bedding correction) presupposes a tilting by the bedding strike for an angle equal to the dip. This assumption is seldom true in complex portions of fold and thrust belts where non-coaxial axes of deformation have acted (conical and plunging folds, overlapped folding, forced folds, fold closures, oblique thrust ramps, etc). Therefore, the incorrectly restored paleomagnetic vector will be deflected in its declination component (apparent rotation, MacDonald, 1980; Chan, 1988; spurious rotation, Pueyo, 2000) as well as in the fold test or in the strike vs. declination diagram (Figs. 1d and 2d). The magnitude of errors (for non-coaxial structures) will depend upon the initial fold geometry, the secondary tilting and the relationship between them (obliquity). The quantification of these kinds of error in different geometries was an active structural geology research topic during the sixties, with few exceptions (Sellés, 1988; Stewart, 1995; Pueyo *et al.*, 2003a, b, among others), not much attention has been paid to it during the processing of paleomagnetic data in fold and thrust belts.

Control of potential errors

The magnitude of the aforementioned sources of error has a strong structural control led by the fold geometry; overlapped and strained vectors and the incorrect use of the bedding correction in complex structures. Although these relationships may be complex, it is straightforward to detect them by basic geometric techniques (Fig. 3). In this section some methods to detect potential errors are given; once they are obvious, an appropriate structural modeling of the case study should be done to remove the paleomagnetic bias. The ability of these techniques to recognize errors is based on the sampling in different positions of an individual fold.

Paleomagnetic scattering geometry in the spherical space

An expected paleomagnetic distribution coming from a lithologically (similar rock magnetism) and structurally (equal bedding and mechanical answer to deformation) homogeneous sampling point should display a *Fisherian* (Fisher, 1953) scattering on the sterographic projection. This scattering should be perfectly conical, with circular section, around the mean. Lithostatic load may cause an inclination shallowing (error type B) that will produce an elliptical geometry of the dispersion. In contrast, the ellipse axes will have a structurally controlled orientation in deformed vectors (non rigid body behaviour; error type C).

The inclination vs. dip (ID) diagram

Both variables should be independent if the aforementioned assumptions are valid. However, two error types with a structural control (B and C) will exhibit inclination-dip relationships (Fig. 3). The performance of this diagram along a section of sites perpendicular to a fold axis will easily rule out both situations if an arbitrary assignation of a positive dip for one limb and a negative one for the other is given. Internal deformation of the rock volume (error type C) will produce a distinctive signal depending on the fold flank position (both polarities will undergo the same deflection). On the other hand, in the folded and overlapped components (error type B), the inclination error added to each polarity will be different for the same structural position and different positions in the fold geometry will cause different inclination errors for a given polarity (Rodríguez-Pintó and Pueyo, *in preparation*).

The declination vs. strike (DS) diagram

All structurally controlled errors (B, C and D) will induce tendencies in this diagram. As in the inclination, the declination error of an overlapped direction (type B) will depend on the structural variables (fold axis geometry), the degree of overlap and the

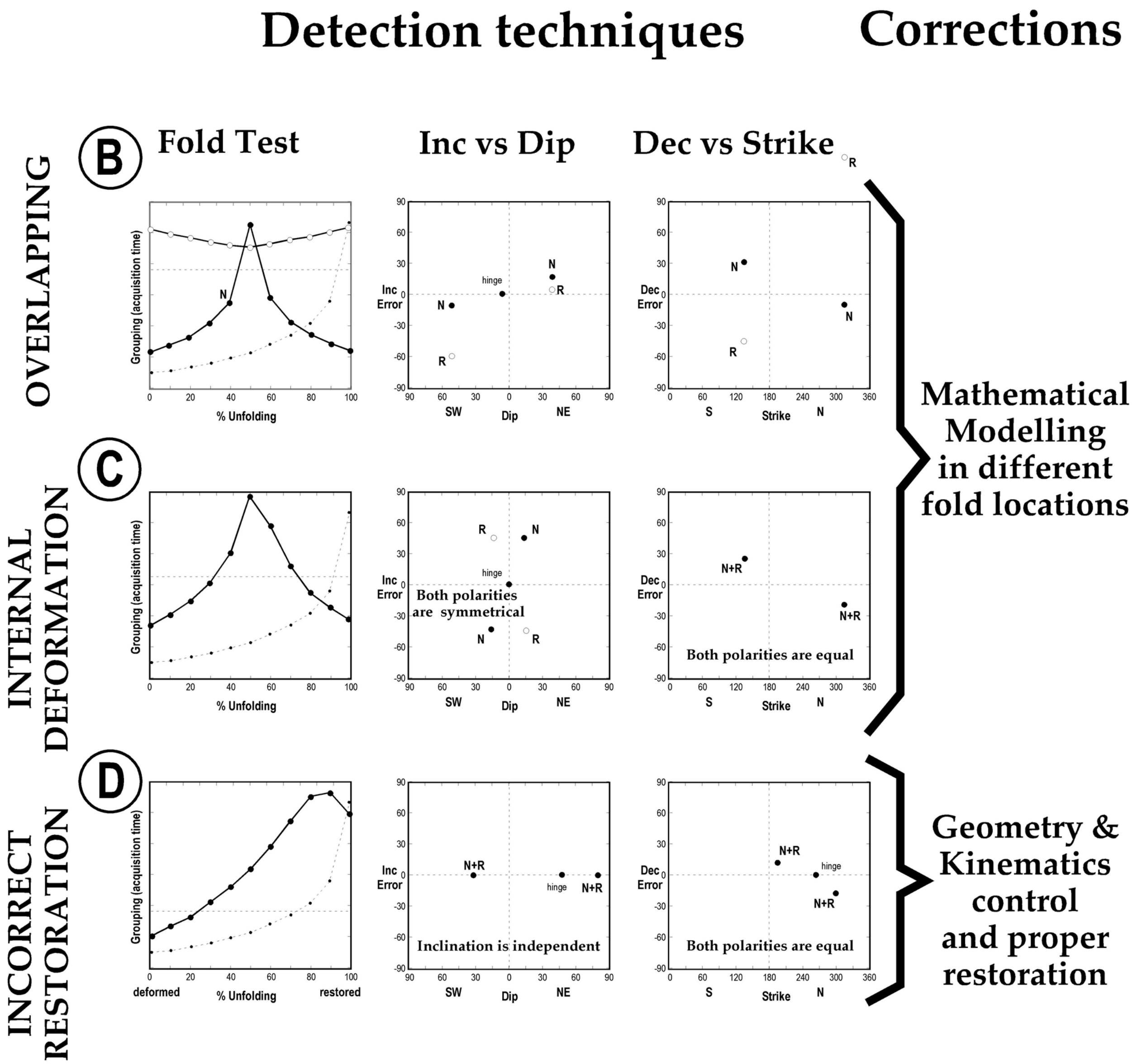

Figure 3. Detection techniques of structurally induced errors (B: overlapping, C: internal deformation, D: incorrect restoration). The expected fold test (best grouping at 100% unfolding) contrasts with the observed data; systematic synfolding magnetizations. Magnetic polarities (black, normal; white, reverse) have been separately considered in the case of vector overlapping. Note that the inclination vs. dip and the declination vs. strike relationships can help to isolate the error source.

magnetic polarity. Similar relationships will be found with deformed vectors (type C) where the deformation tensor will play a key role. In contrast with the ID diagram, the incorrectly restored (bedding corrected) vectors will impart errors in this diagram. Their magnitude will depend, for cylindrical structures, on the angular relationship between the two deformation axes (i.e. folding and tilting) and the degree of horizontal rotational deformation of both. The problem of the DS diagram is the existence of real VARs that can mask the detection of errors. Therefore, better sensitivity identifying errors will be achieved by combining the ID and DS diagrams.

The fold test and the small circle intersection method

Graham's fold test (Graham, 1949) and the numerous papers on its assumptions, statistical treatment and significance (see overview by Weil and Van der Voo, 2002) as well as the more recent small-circle intersection method (see overview in Waldhör and Appel, 2006), provide a fundamental tool for paleomagnetic data analysis (Van der Voo, 1990, 1993). Basically, the fold test searches for the relative timing of the magnetization and folding to be achieved. Two extreme results can be derived (being unaffected by any error source): a prefolding and postfolding age of magnetization. However, any synfolding acquisition inference should be carefully analysed by other techniques since the three structurally controlled sources of error will yield this outcome and may mask the real result.

The net tectonic rotation axis distribution

The net tectonic rotation axis (NTRA) is the only one that relates the non-deformed initial stage (horizontal bedding plane and reference vector; p_o and m_o) to the deformed one (observed vector *in situ* and its bedding plane; m_f and p_f). It represents the finite rotation axis of deformation, and the spatial distribution of these axes for a different location of a given fold can be used to detect any source of the aforementioned errors (Pueyo, 2000). Possible distributions in the spherical space include: 1) the NTRA are horizontal and equal for all structural positions; paleomagnetic vectors do not show any error source and do not display VAR either, 2) the NTRA scatter along a great vertical circle dependent upon the structural position; paleomagnetic vectors are free from errors and they record an equal magnitude of VAR, 3) the NTRA scatter within any inclined plane; paleomagnetic vectors have undergone multiple axes of horizontal rotations (error source E) and maybe VAR, and 4) the NTRA scatter along small circles; paleomagnetic data are either affected by overlapping (type C) or by internal deformation (type D).

Reliability criteria on the thrust scale

Following the philosophy of the reliability criteria established by Van der Voo (1990) to evaluate the quality of paleopoles, a paleomagnetic investigation focused on the characterization of vertical axis rotations in an individual thrust sheet should meet some additional and specific criteria:

1) rock, deformation (folding, thrusting and rotation) and magnetization ages are known;

2) a minimum of 5 sites (10 is desirable) per thrust unit (10-15 specimens per site). Site means characterised by $a_{95} \leq 10°$ (never >15°) and k>20 (never <10). If needed, scatter anisotropy controlled on the site scale (eigenvector analysis);

3) detailed demagnetization isolating all magnetization components and allowing a reliable calculation of directions and demagnetization circles, which should be fitted by PCA (Kirschvink, 1980). Combined use of difference and resultant vectors are always preferable to detect instrumental problems. More than 4 steps involved in the calculation (vectors and planes) and MAD<10° (never >15°);

4) field test and error-control techniques. Conglomerate, reversal, fold test and the small-circle intersection method have to be performed to support the magnetization age. Additional strike vs. declination and dip vs. inclination diagrams and the dispersion of the NTR axis should be performed to avoid errors in case of synfolding remagnetizations;

5) structural control. Fold and thrust geometry and kinematics should be known in order to avoid restoration errors and the subsequent implications in the fold test and the declination (rotation) error;

6) the origin of the inclination error has to be identified from among compaction, internal deformation and overlapping of directions by means of geometric techniques;

7) rotations have to be contrasted to an appropriate reference in the undeformed foreland (absolute VAR) or in the nearest footwall (relative VAR).

Conclusions and future perspectives

Paleomagnetic analysis can contribute to the real understanding and quantification of deformation patterns in 3D of fold and thrust belts. Besides classic assumptions of paleomagnetism, the application to FTB presupposes: 1) the absence of internal deformation (rigid body assumption), 2) the perfect laboratory isolation of folded components, and 3) the bedding correction to the ancient reference system is not necessarily true in FTBs. These suppositions are the origin of the three more common sources of error. These deflections will have a strong structural control that will help to identify and filter them in order to make the paleomagnetic database reliable. Suggested detection techniques include the evaluation of the stereographic scattering, the assessment of the inclination vs. dip and the declination vs. strike diagrams, the critical evaluation of syntectonic magnetizations in the fold test and in the small-circle intersection method as well as the inspection of the stereographic dispersion of finite axes of rotation. A paleomagnetic procedure and a list of reliability criteria are proposed as a workflow.

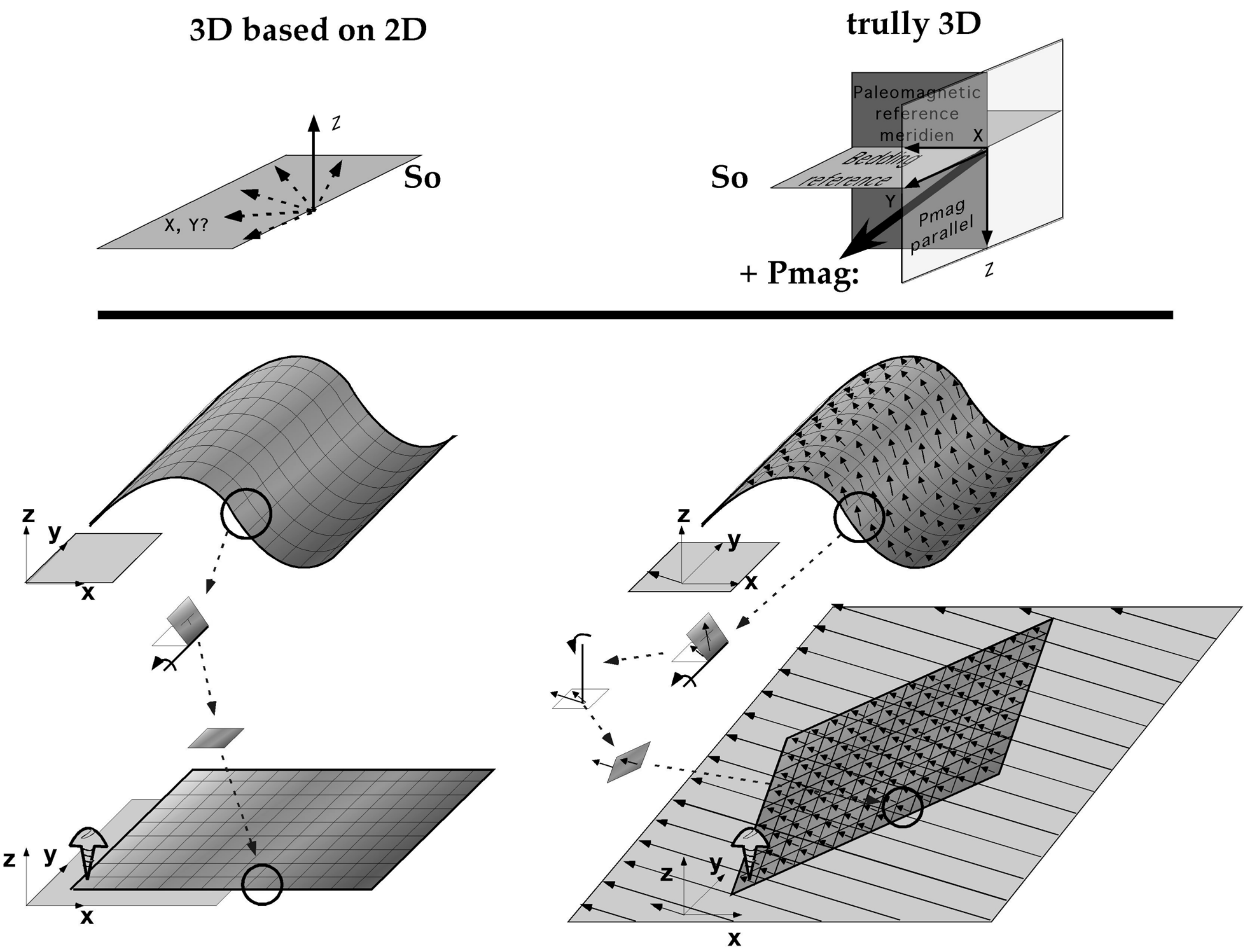

Figure 4. 3D restorations and paleomagnetic vectors. Current 3D restoration methods are based on a 2D reference frame; the bedding plane (left column). Paleomagnetism can provide a real 3D reference frame (right column). The convergence of the paleomagnetic vectors can reduce the uncertainty of the restoration and can be very useful for validating geometries and complex geological contexts.

Future developments of paleomagnetic analysis in FTBs, which represent the only accurate tool for recognising discrete magnitudes of vertical axis rotations, should focus on the temporal and spatial variability of the rotational component of deformation, which is strongly related with the lateral gradient of shortening and the lateral transference of the deformation. Within this framework, magnetostratigraphic studies of syntectonic sedimentary piles can shed clear light on this three-dimensional problem. Moreover, the paleomagnetic data should have a more active role in the 2D shortening estimation (both cross section and map view), since it allows us to correct the out-of-plane movements biasing the classic approaches (Pueyo *et al.*, 2004; Sussman *et al.*, *in review*). Finally, the paleomagnetic vector together with the bedding plane can be used as a primary 3D reference to be used in restoration and validation techniques, since they are accurately known in both the deformed and undeformed stages (Fig. 4).

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