Palaeomagnetism in fold and thrust belts: use with caution

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Abstract: The application of palaeomagnetism in fold and thrust belts is a unique way to obtain kinematic information regarding the evolution of these systems. However, since many potential problems can affect the reliability of palaeomagnetic datasets and their interpretations, such data should be used with caution. In this paper, we thoroughly review the sources of error from palaeomagnetism with a particular focus on deciphering vertical-axis rotations and the assumptions behind the method. Recent investigations have demonstrated that the age of the magnetization and syn-folding results from the fold test must also be carefully examined: factors such as internal deformation, deficient isolation of components (i.e. overlapping) or incorrect restoration procedures may produce apparent syn-folding results. In fact, the restoration procedure used to return the palaeomagnetic signal to the palaeogeographic coordinate system may itself inhibit accurate estimations of vertical-axis rotations when complex deformation histories induce different, non-coaxial, deformation axes. We recommend the auxiliary use of the inclination v. dip diagram as an efficient tool for identifying many errors. Finally, to determine accurate vertical axis rotations, the reference direction should honour standard reliability criteria and would ideally be measured within the undeformed foreland of the thrust system. In this paper, we review five decades of palaeomagnetic research in fold and thrust belts by concentrating on maximizing standard reliability criteria procedures to reduce uncertainty and increase confidence when applying palaeomagnetic data to unravel the tectonic evolution of fold and thrust belts.

Palaeomagnetism is the study of Earth's ancient magnetic fields as recorded in the stratigraphic archive. Given that the magnetic field is a global reference system, a palaeomagnetic signal can be used to reconstruct relative motions of geological elements on a range of spatial scales. On a global scale, palaeomagnetism can track the position of tectonic plates as they move in time (e.g. Opdyke 1995; Irving 2005). At the scale of orogenic systems, palaeomagnetism can be used to quantify processes such as oroclinal bending, plate indentation or escape tectonics (Eldredge *et al.* 1985; Van der Voo 2004; Weil & Sussman 2004 and many others). At smaller scales, such as thrust sheets, palaeomagnetism can be applied to detect rotations associated with structural deformation (i.e. differential shortening). Rotations about a horizontal axis (i.e. tilt) are responsible for folding in the cross-section plane and are usually straightforward to characterize using stratigraphic horizons (bedding surfaces). Moreover, vertical axis rotations (VARs) are more difficult to detect and quantify. For instance, to fully define VARs in a thrust sheet, it is necessary to compare palaeomagnetic vectors in both the hanging wall and the footwall of a thrust. VARs comprise an especially valuable dataset since other kinematic indicators typically do not allow for the determination of rotations about a vertical axis.

The conceptual application of palaeomagnetic techniques to detect relative motions in fold and thrust belts (FTBs) was first described by Norris & Black (1961), who proposed the use of palaeomagnetism to decipher the origin of along-strike changes associated with the Lewis Thrust sheet in western Montana. Other early authors (see reviews by Hospers & Van Andel 1969; Tarling 1969) applied

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this idea and the technique has since grown in its utilization (see Van der Voo & Channell 1980; Kissel & Laj 1989; Sussman & Weil 2004).

The causes of VARs at the thrust fault scale are commonly associated with differential displacement along strike (McCaig & McClelland 1992; Allerton 1998; Pueyo *et al.* 2004; Soto *et al.* 2006; Sussman *et al.* 2012). Locally, non-cylindrical and non-coaxial folding (Sellés-Martínez 1988; Allerton 1994; Pueyo *et al.* 2003*a*), superposed folding (Hirt *et al.* 1992; Weil *et al.* 2000; Mochales *et al.* 2016) and plunging folds (Stewart 1995; Pueyo *et al.* 2002*a*) may also play a key role. FTBs may also be affected by significant secondary VARs during later orogenic processes including (Fig. 1) piggy-back movements during thrust stacking (Oliva-Urcia & Pueyo 2007*a*, *b*), indentation (Achache *et al.* 1983; Thomas *et al.* 1994; Collombet *et al.* 2002), buttressing (Grubbs & Van der Voo 1976; Eldredge & Van der Voo 1988), oroclinal

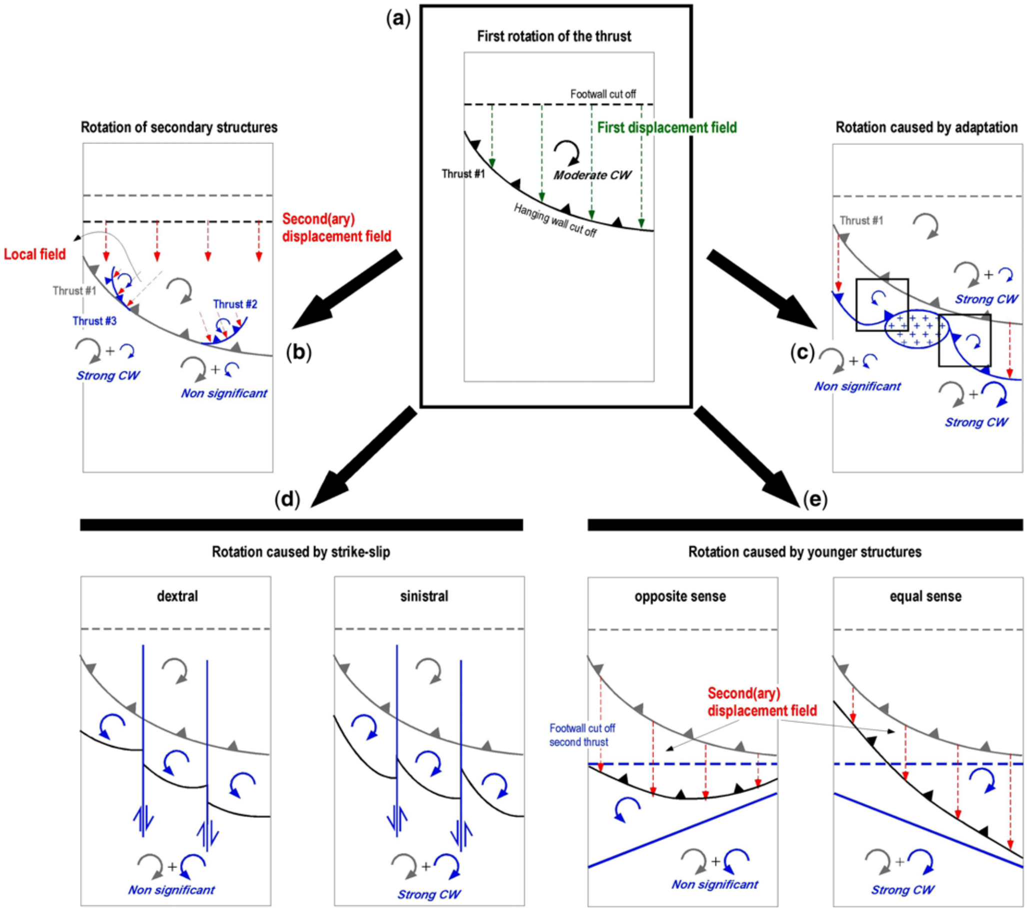

Fig. 1. Superimposed VARs in FTBs. (**a**) A given segment of a FTB contains a lateral shortening gradient with an associated VAR (as attested by the displacement field in green). (**b**) However, later deformation processes, shown in blue, may affect the primary VAR record, shown in grey (second displacement field is shown in red). For example, younger or coeval smaller structures could accommodate additional rotations in both senses (local displacement field induces the local rotation). (**c**) The progress of deformation may also incorporate previous anisotropies such that the FTB will undergo additional rotations (here the second displacement field could be homogeneous). (**d**) A similar process can occur with strike-slip motion: here, the sense of fault movement conditions the VAR. (**e**) FTB evolution can be characterized by sequences of different thrusts, with hanging-wall (piggyback) sequences being most typical. In these cases, every thrust may have accommodated different VARs. All of these processes are scale-independent and may take place at a number and range of scales. The complete VAR affecting a segment of an FTB will be the cumulative addition of all these processes and must be unravelled taking into account the structural and tectonic history.

bending (Eldredge *et al.* 1985; Weil & Sussman 2004) and strike-slip rearrangements (Ron *et al.* 1984; Nur *et al.* 1986).

Palaeomagnetic and structural investigations should be coordinated as a best practice method in deciphering and delineating the many physical processes associated with deformation. Unravelling the complex spatial–temporal deformation processes responsible for along-strike changes associated with thrust movement is an important research topic in structural geology (Hindle & Burkhard 1999; Strayer & Suppe 2002; Wilkerson *et al.* 2002; Hnat *et al.* 2008; Adam *et al.* 2013; Muñoz *et al.* 2013). Palaeomagnetic techniques play a key role in providing geometric and kinematic information in orogenic belts to comprehend deformation patterns in four dimensions.

VARs have been reported in most orogenic belts investigated for such data, for example Himalaya and Tibet (Bazhenov *et al.* 1999; Dupont-Nivet *et al.* 2002; Schill *et al.* 2002; Crouzet *et al.* 2003), Zagros (Smith *et al.* 2005; Aubourg *et al.* 2008), Taurides and Aegean (Kissel *et al.* 1993; Duermeijer *et al.* 2000; van Hinsbergen *et al.* 2007; **Çinku *et al.* 2015**), Carpathian (Márton *et al.* 2007, **2015**; Dupont-Nivet *et al.* 2005), Alps (Collombet *et al.* 2002; Sonnette *et al.* 2014; Cardello *et al.* 2015), Pyrenees (Sussman *et al.* 2004; Oliva-Urcia & Pueyo 2007*a*; Oliva-Urcia *et al.* 2010, 2012*a*, *b*; Muñoz *et al.* 2013; Izquierdo-Llavall *et al.* 2015) Cantabrian (Weil *et al.* 2001; Weil 2006), Betics, Rif and Atlas (Platt *et al.* 2003; Mattei *et al.* 2006; Moussaid *et al.* 2015), Calabrian Arc (Channell *et al.* 1990; Speranza *et al.* 1999; Cifelli *et al.* 2007, 2008*a*, *b*), Apennines (Speranza *et al.* 1997; Muttoni *et al.* 1998; Satolli *et al.* 2005; Caricchi *et al.* 2014), North American Cordillera (Beck 1980; Eldredge & Van der Voo 1988; Conder *et al.* 2003; Sears & Hendrix 2004; Harlan *et al.* 2008), Appalachians (Bayona *et al.* 2003; Ong *et al.* 2007; Hnat *et al.* 2008), Andes (Roperch & Carlier 1992; MacFadden *et al.* 1995; Prezzi *et al.* 2004; Richards *et al.* 2004; Rousse *et al.* 2005; Arriagada *et al.* 2006; Rapalini 2007; **Japas *et al.* 2015**; Rapalini *et al.* 2015) and New Zealand (Nicol *et al.* 2007).

Palaeomagnetic analyses of FTBs usually aim to obtain geometric and/or kinematic information. To date, most palaeomagnetic studies of FTBs have focused on determining rotation magnitudes at distributed locations within thrust sheets, observing along-strike variations of VARs (Otofuji *et al.* 1985; Butler *et al.* 1995; Hnat *et al.* 2008) or differential block rotations (Nur *et al.* 1986; Mattei *et al.* 1995; Thöny *et al.* 2006; Pueyo *et al.* 2007). Detailed applications at smaller scales such as sigmoidal or curved folds are now more frequent (Smith *et al.* 2005; Rouvier *et al.* 2012; Rodríguez-Pintó *et al.* 2016), but applications for superposed folding (Bonhommet *et al.* 1981; Weil 2006; Mochales *et al.* 2016), non-cylindrical folding and non-coaxial superposed folding geometries (Zotkevich 1972; Sellés-Martínez 1988; Stewart 1995; Pueyo *et al.* 2003*a*, *b*), as well as fold closures (Stewart & Jackson 1995), have not been widely published. On the other hand, kinematic information can be deduced when syn-orogenic sedimentary sequences are dated using magnetostratigraphic records. With such datasets, thrust timing, displacement velocities and other parameters can be determined (Sempere *et al.* 1990; Burbank *et al.* 1992; Powers *et al.* 1998; **Oliva-Urcia *et al.* 2015**). In combination with fission tracks, accurate exhumation velocities (Beamud *et al.* 2011 among many references) can be constrained. However, understanding the kinematics that accompany rotational processes, such as rotational velocities, is still enigmatic. Despite the importance of determining rotational velocity for understanding the four-dimensional nature of deformation, there are very few such datasets for either orogens (Duermeijer *et al.* 2000; Mattei *et al.* 2004) or individual thrusts (Pueyo *et al.* 2002*b*; Mochales *et al.* 2012; Rodríguez-Pintó *et al.* 2016). Rotational velocity can be obtained only if syn-tectonic sedimentation and rotation were simultaneous; however, this results in dispersion of the palaeomagnetic declination, requiring coordinated structural analyses to understand the deformation process and pattern. Finally, rotations are governed by a pivot point, that is, the physical rotation axis about which a part of the hanging wall is displaced. Determining the location and evolution of the pivot point is key to understanding the kinematics of FTBs (Bates 1989; McCaig & McClelland 1992; Allerton 1994, 1998; Pueyo *et al.* 2004; Sussman *et al.* 2012); we recommend more research on this topic.

Palaeomagnetic analyses of FTBs require integration with structural and tectonic data to achieve reliable, quantitatively constrained interpretations. For instance, some researchers have already shown the importance of VARs for palinspastic reconstruction of FTBs (Bourgeois *et al.* 1997; Arriagada *et al.* 2006, 2008; Muñoz *et al.* 2013; Ramón 2013). Palaeomagnetic rotations have also been used to correct errors caused in shortening estimates in balanced sections (Pueyo *et al.* 2004; Oliva-Urcia & Pueyo 2007*b*; Sussman *et al.* 2012), to validate rotations deduced by anisotropy of magnetic susceptibility (Pueyo-Anchuela *et al.* 2012), or as an additional constraint in 3D restoration (Ramón *et al.* 2012, 2015*a*, *b*). Some recent studies have tackled the qualitative reconstruction of FTBs derived from inverted extensional basins (partial restoration in 2D) using remagnetization components that represent snapshots of the deformation history (Villalaín *et al.* 2003, **2015**; Soto *et al.* 2008). These studies show the great potential for numerically combining palaeomagnetism and structural datasets at the FTB scale.

Despite the wide range of applications for understanding the evolution of FTBs, palaeomagnetic datasets should be used with caution. This paper reviews issues associated with the field and laboratory procedures associated with collecting, measuring, processing and interpreting palaeomagnetic data, as well as the application of palaeomagnetic techniques to FTBs. We also suggest best practice approaches to help minimize the problems and to increase the reliability of the palaeomagnetic data. While several of the issues reported here are common and/or well known and have been presented in the classic paper by Van der Voo (1990), we believe an updated review will help reinvigorate attention to these topics.

Determination of vertical-axis rotations: common problems and solutions

The successful application of palaeomagnetism is based on three assumptions (e.g. Butler 1992): (A) over long periods of time, the Earth's magnetic field behaves like a geocentric axial dipole (GAD hypothesis); (B) the ferromagnetic minerals (s.l.) contained in the rocks efficiently record the Earth's magnetic field during rock formation and can be isolated and measured in the laboratory; and (C) the palaeomagnetic signal recorded in the rocks remain stable over geological time. Here we review common scenarios that may void the three main assumptions (above) as well as other secondary assumptions (grouped as D) that, if not met, make the palaeomagnetic results invalidate the method. Scenarios may include issues related to global reference, structural position, restoration methods, statistics and deformation events, etc. Whenever possible, we offer solutions to mitigate such complications.

A.1. The signal does not represent the geocentric axial dipole field

For sedimentary sequences, sampling within a stratigraphic thickness equivalent to *c.* 10 ky timeframe might be sufficient to represent the GAD, as models for secular variations of the magnetic field during the last eight millennia predict fulfillment of this assumption (Pavón-Carrasco *et al.* 2010). A population of 10–15 palaeomagnetic samples should yield the distinctive fisherian (Fisher 1953) dispersion around the mean value and confidence parameters within expected reliability boundaries (Van der Voo 1990). An additional problem may occur if the magnetic field displays a significant non-dipolar component, as has been proposed for certain periods of Earth history (Van der Voo & Torsvik 2001). If this hypothesis is true (a matter of debate: Tauxe & Kent 2004; Meert 2009), then the rotations deduced from palaeomagnetic data in FTB in those periods may be questioned.

B.1. There is not a primary palaeomagnetic signal or the signal is weak

A primary component is defined as the record of the Earth magnetic field at the time of rock formation. In some scenarios, the Earth's magnetic field was not efficiently recorded or the palaeomagnetic signal is of poor quality. This can occur when there is an insufficient amount of ferromagnetic minerals and/or those minerals are not stable. In this instance, the blocking mechanism is ineffective (e.g. some detrital rocks) and/or subsequent processes (e.g. dolomitization, shock magnetization, burning, exhumation) erased or disturbed the original palaeomagnetic record and no new stable or nonsense magnetization is produced. Unfortunately, negative results and/or the attempts to alleviate them are seldom published and thus similar problems have not been fully understood for mitigation in future studies. Perturbation of a primary magnetization by remagnetization is discussed in C1.

B.2. The palaeomagnetic signal cannot be fully isolated

Isolation of two or more components of remanence can be complicated when magnetizations of different ages are simultaneously demagnetized in the laboratory, since available techniques (alternating fields or thermal) cannot always successfully distinguish among them (overlapping of unblocking spectra). For instance, palaeomagnetic data from tilted strata affected by a secondary overprint that overlapped the original signal may result in unreliable palaeomagnetic directions once bedding is restored (Fig. 2). This can manifest as large errors in declination and inclination, and inexact palaeomagnetic age determinations as estimated from fold test results (Rodríguez-Pintó *et al.* 2011, 2013). The simultaneous demagnetization of two overlapping components yields a demagnetization circle, represented as a great circle on an equal area projection. The intersection of girdles signifies the less scattered component (Khramov 1958; Halls 1976). This technique can be very useful in determining the primary component in a scenario with overlapping components, (Halls 1978; Bailey & Halls 1984), but only when the primary component is the less scattered one. The demagnetization circle method searches for the grouping of great circle intersections; since the number of intersections of n planes is an exponential function ($[n^2 - n]/2$),

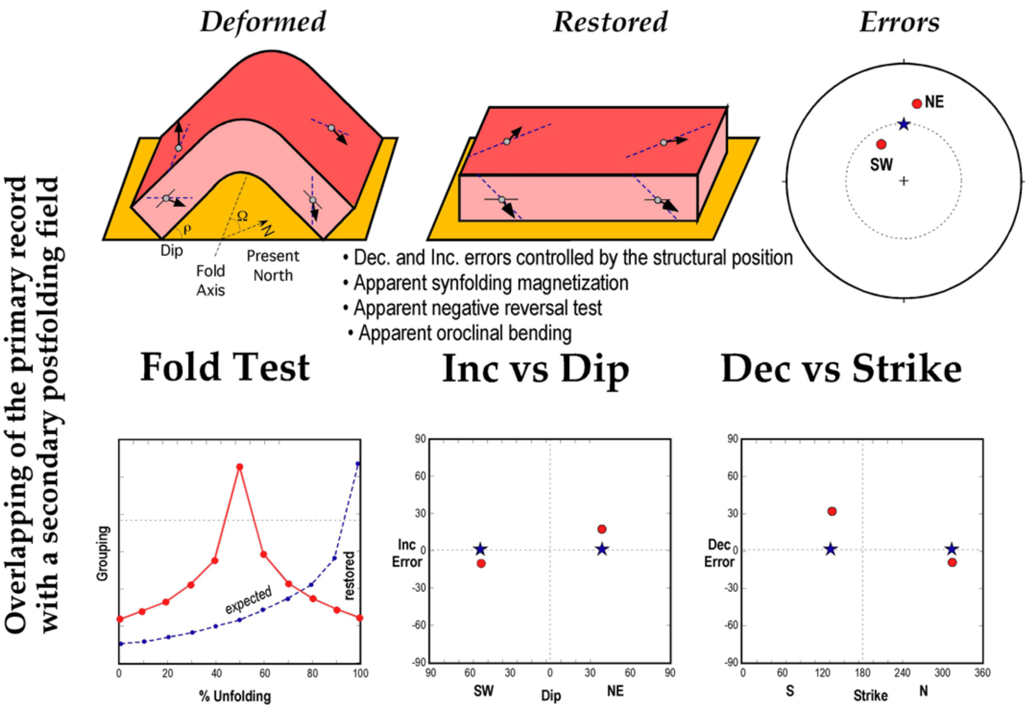

Fig. 2. Errors caused by overlapping of palaeomagnetic components. A primary (pre-folding) record could not be distinguished from a post-folding overprint. Ideally, the discontinuous line (and blue star in the stereonet) would have been obtained, but the overlapped vector is strongly conditioned by the structural location of the sampling sites along the fold geometry. The overlapped vectors may display both declination and inclination errors (compared with the expected result) and will produce anomalous results in the fold test (apparent syn-folding), in a plot of inclination v. dip of the bed, and in the oroclinal test (declination v. strike). Although not shown, the polarity of the primary and secondary components also plays an important role.

the application of the Fisher statistics to this population cannot be compared to standard populations of vectors derived from direct estimation. The problem of achieving a statically comparable result using the combination of remagnetization circles and direct observations was tackled by McFadden & McElhinny (1988).

C.1. The primary palaeomagnetic signal has not been stable during the geological time due to remagnetization

Sources of recently acquired secondary magnetizations include lightning, insolation, burning, blasting, viscous overprinting of the present-day field and/or sampling-induced magnetizations. However, ancient secondary magnetizations (remagnetizations; Elmore *et al.* 2012) reveal physicochemical changes in the rock volume related to significant geological processes. Remagnetizations were described in earlier palaeomagnetic studies (Creer 1962) and a historical review was compiled by Van der Voo & Torsvik (2012). In ideal cases, the information that secondary magnetizations provide can be very useful as snapshots of deformation processes and can help temporally constrain tectonic events (Cullen *et al.* 2012; Çinku *et al.* 2013; Kirscher *et al.* 2013; Izquierdo-Llavall *et al.* 2015). In addition, secondary magnetizations can allow for the dating of hydrothermal events or orogenic fluid migration (Evans *et al.* 2000; Elmore *et al.* 2001; Ribeiro *et al.* 2013) and can assist in constraining the time of burial diagenesis (Blumstein *et al.* 2004; Aubourg *et al.* 2012). However, a great disadvantage of using remagnetizations is that the palaeohorizontal reference frame is absent, thus limiting the potentiality of palaeomagnetism as a 3D reference indicator and reducing accuracy for determining VARs. Recently developed techniques for determining the ages of illitization (Nemkin *et al.* 2015) may allow for the accurate timing of the remagnetization and, thus, can help overcome associated problems.

C.2. The palaeomagnetic signal has not been stable over geological time owing to reorientation of palaeomagnetic vectors

Even for scenarios in which the palaeomagnetic record is of good quality and has survived over geological time, other processes may disturb the palaeomagnetic vectors. If the third assumption of record stability over time is met, complete stability of the palaeomagnetic signal can still only be achieved if a rock volume behaves like a rigid solid. However, in some cases, palaeomagnetic vectors are reoriented. During lithostatic loading sediments may lose volume during burial and subsequently palaeomagentic vectors will undergo inclination shallowing (van Andel & Hospers 1966); published solutions can help account for inclination shallowing (Kodama 1997; Tauxe 2005; Bilardello & Kodama 2010). On the other hand, reorientation is significantly more complicated when a rock volume is subject to penetrative, internal tectonic deformation. Simple and pure shear strain are common during tectonic deformation (i.e. during flexural folding) and their possible influences on palaeomagnetic vectors has been described by many researchers (Perroud 1982; Facer 1983; Lowrie *et al.* 1986; Cogné 1987; van der Pluijm 1987; Kodama 1988; Stamatakos & Kodama 1991; Borradaile 1997; Oliva-Urcia *et al.* 2010, among others). Error correction caused by internal deformation is not straightforward owing to the difficulty in knowing the deformation tensor (magnitude and orientation of the strain axes). Thus, identification of this problem is critical (Fig. 3) and any dataset from an FTB with penetrative internal tectonic deformation has to be considered cautiously.

D.1. The palaeomagnetic reference direction is unknown

Estimates of VARs require comparison with a coeval palaeomagnetic reference direction for the same tectonic element. As such, estimates may be inaccurate if the age of a remagnetization cannot

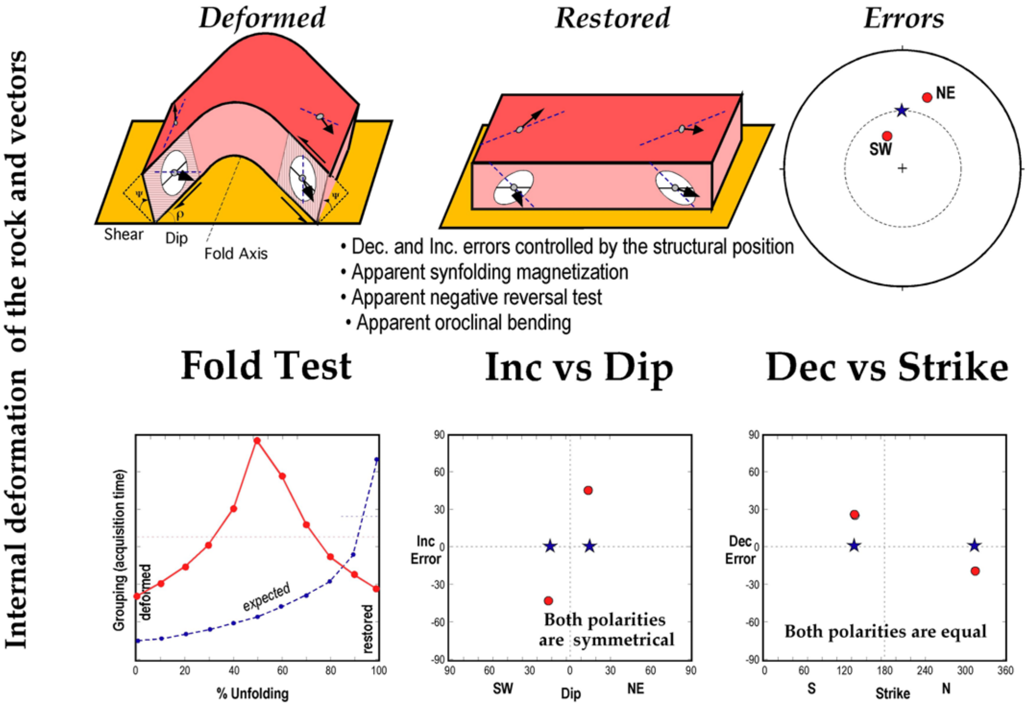

Fig. 3. Errors caused by internal deformation of rocks. In this case, flexural folding in the fold limbs produced simple shear and deformed the original palaeomagnetic vectors. Similar to the problem of overlapped directions, the final deformed vectors will depend upon the original vector, the fold axis orientation, and the magnitude of shear. Internal deformation will modify the palaeomagnetic declination and inclination as well as results from fold and reversal tests and will produce erroneous interpretations of palaeomagnetic datasets if it is not taken into account. This spurious effect may be critical in the detection and mitigation of these kinds of errors. In this case, the magnetic polarity did not exert any influence.

be associated with a specific (and well-dated) deformation event and must be deduced from apparent polar wander paths.

The absence of well-constrained palaeomagnetic references will decrease the reliability of the palaeomagnetic data to determine VARs. This occurs when either primary or secondary palaeomagnetic datasets are compromised, such as when references for the same tectonic element and equal age are not reliable or do not exist. In these scenarios, comparison between the hanging wall and footwall of the thrust system will only yield relative rotations between them.

D.2. Lack of a palaeohorizontal reference (such as bedding planes)

Bedding planes usually represent a palaeohorizontal reference in sedimentary rocks and some volcanic rocks (i.e. ignimbrites, basaltic flows). In terms of primary magnetizations, the bedding plane is the only surface that allows for confident restoration of the palaeomagnetic data to the ‘palaeogeographic reference system’ or reference frame in which the VARs are estimated. In fact, the combination of a stratigraphic horizon and palaeomagnetic vectors is the only 3D marker that can be related both before and after the deformation. Therefore, in the absence of palaeohorizontal references, or with uncertain palaeohorizontal markers in some stratigraphic surfaces (i.e. in delta fans, cross-bedding, channels, some igneous bodies or in remagnitized rocks) the reliability of the palaeomagnetic data to provide an accurate VARs or palaeolatitudes is reduced.

D.3. Cylindrical bedding correction to restore the palaeomagnetic data

Mountain building processes may rotate, translate and/or distort rock volumes several times and in several different ways. Non-coaxial deformation may produce conical and plunging folds, superposed folding, forced folds, fold closures and/or oblique thrust ramps along with any kind of superimposed deformation. The cylindrical bedding correction, for example, involves tilting the palaeomagnetic vector and the bedding plane by the bedding strike for an angle equal to the dip. This correction will return the vectors to palaeohorizontal but does not guarantee proper restoration to the palaeogeographic reference system (Fig. 4). In scenarios for which several deformation events have affected a given location, restoration should follow the reverse chronological order of the deformation events (restoration is not commutative; Ramsay 1960). Therefore, application of the bedding correction in complex parts of FTBs will generate an error in the declination component (‘apparent rotation’ by MacDonald 1980; Chan 1988; ‘spurious rotation’ by Pueyo *et al.* 2003*b*) as well producing errors in results of the fold test or in the strike v. declination (oroclinal) diagram. Quantifying these errors in different scenarios was an active structural geology research topic in the 1960s (Norman 1960; Ramsay 1960, 1961; Stauffer 1964; Cummins 1964, 1966), but has attracted little attention since (Zotkevich 1972; Scott 1984; Bazhenov 1988; Sellés-Martínez 1988; Setiabudidaya *et al.* 1994; Stewart 1995; Weinberger *et al.* 1995; Pueyo *et al.* 2003*a*, *b*). A full understanding of the deformation sequence (derived from a thorough structural analysis) is critical in order to perform the correct restoration sequence with the palaeomagnetic data and to determine accurate estimates of VARs.

D.4. Resolution, accuracy and statistical significance of VARs in FTBs

In order to characterize VARs in parts of FTBs sharing similar structural trends, several sites must be investigated to obtain a reliable palaeomagnetic signal. In addition, detailed studies regarding the statistical significance of the palaeomagnetic data from a structural point of view (i.e. the number of sites needed to characterize a trend-domain, dip-domain in terms by Suppe 1985) still need to be standardized. Pastor-Galán *et al.* (2016) have recently simulated the relationship between the site standard deviation (confidence angle) and the number of sites needed to define the curvature of an orocline; 12–13 sites may be enough to characterize 45° of structural bend when the α_{95} of those sites is below 10°, but the number of sites rises to 50 if $\alpha_{95} < 20°$. These results indicate that the characterization of segments of a FTB with variable trends would require at least five sites for every 15° of strike of the thrust.

D.4. Multiple rotations

A common problem with interpreting palaeomagnetic data from FTBs is the superposition of different rotational processes (Fig. 1). For a scenario with a given thrust that initially underwent variable shortening along strike (i.e. rotations), secondary and/or passive younger rotational movements would superpose and must be first determined and then subtracted because VARs are additive and commutative and require complete structural and geometric understanding of the deformation processes and their timing. Unresolved multiple rotations may affect the oroclinal bedding diagram and will add noise to the estimation of the oroclinal slope (Yonkee & Weil 2010).

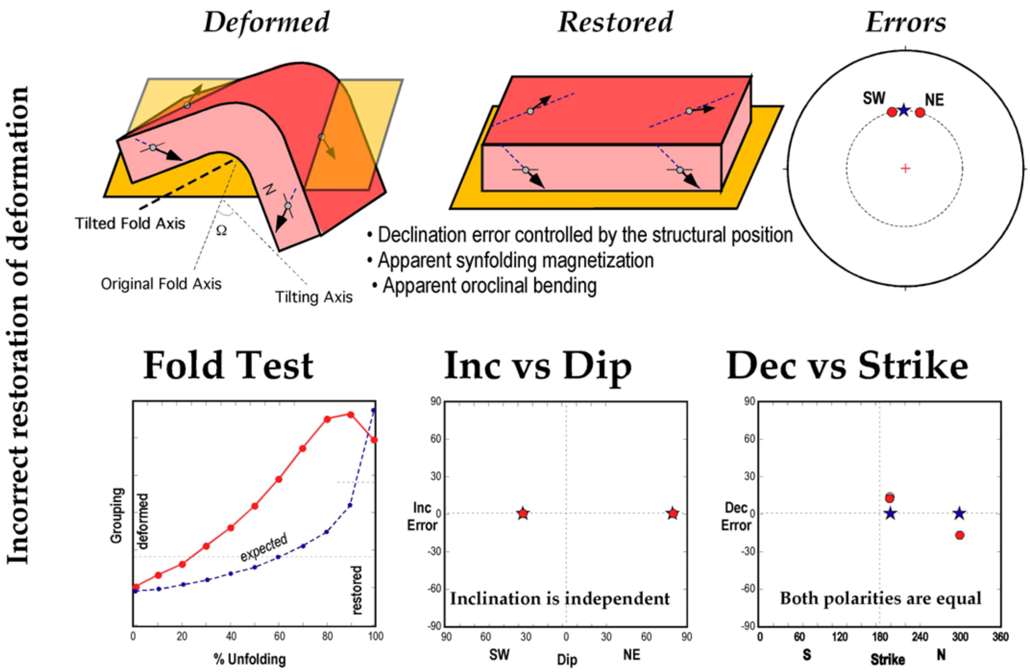

Fig. 4. Errors caused by application of the bedding correction in areas of superposed folding. The fold from previous examples maintains the primary palaeomagnetic signal but has undergone a secondary tilting. The application of the bedding correction will produce anomalies in the declination component and in the fold test, but not in the reversal test or in the inclination v. dip diagram. Here the magnetic polarity has no influence.

Palaeomagnetic data and FTBs: key steps

In order to mitigate the difficulties and challenges presented in the previous section, we discuss techniques that cover all elements (i.e. data collection, processing and interpretation), of palaeomagnetic analysis. Proposed best practice steps and procedures, of which most are well accepted by the palaeomagnetic community, are specified below:

(1) *Sampling sites.* A sampling site is a location from which individual palaeomagnetic samples are collected. A site should be geo-referenced with precision and samples (10–15 for each site) should be collected from homogeneous rock types such that a consistent palaeomagnetic signal can be obtained. In addition, several meters of stratigraphic section (5–10 m or more, depending upon inferred sedimentation rates) should be sampled to average secular variation, thus fulfilling the GAD assumption. Some lithologies (i.e. condensed pelagic carbonates) may meet this requirement in a few centimetres. Ideally, the stratigraphic position and age of the sampling site should be determined and reported in detail, including the stratigraphic age and the magnetic polarity stratigraphy. In addition, the site should be structurally uniform with constant and well-characterized bedding planes (ideally all samples will contain bedding planes allowing for fisherian calculation of the mean plane; Fisher 1953). Both the regional and local structural settings must be properly characterized. On the other hand, drilling in multiple directions at the outcrop scale during the sampling can be key for detecting spurious components in the laboratory.

(2) *Network of rotations.* The distribution of the sites within a structural domain designed to estimate the rotation magnitudes needs to be carefully planned. Ideally, sites within individual folds, thrusts and other faults should be selected to meet the following criteria. (a) Sites should contain rocks with good-quality palaeomagnetic signals based on pilot campaigns. (b) Sufficient sites are chosen to allow for a robust rotation estimate (mean and error) of the structural trend. (c) Sites should be evenly distributed to account for along-strike changes in order to add certainty to the statistical significance of the results. (d) Sufficient sites are

chosen along the full arc of a fold or thrust width to permit achieving statistically significant fold tests. Individual folds (at any scale) with different dips within the fold surface must be sampled in every thrust unit to ensure a reliable result of the fold test. Thus, regional scale fold tests are undesirable because they may be biased by numerous sources of errors. (e) In syn-orogenic sediments, sites should be evenly distributed within the stratigraphic sequence of the hanging-wall, potentially allowing for characterization of the rotational velocity of the associated thrust.

(3) *Laboratory procedures.* In order to meet standards for a successful laboratory campaign, a number of published criteria should be met. (a) A sufficient number of demagnetized samples per site will assure a reliable site mean characterization; between 10 and 15 specimens usually yields confident results (Kirschvink 1980; Van der Voo 1990). (2) Detailed pilot alternating field (AF) or thermal (TH) demagnetizations, or combinations of those approaches, help to define the unblocking coercivity and temperature spectrums. (3) Characteristic directions and demagnetization planes must be defined with at least four or five demagnetization steps (Kirschvink 1980). (4) Rock magnetic carriers should be unambiguously identified. While there are many possibilities (low/high temperature magnetization/susceptibility runs, hysteresis loops, FORC diagrams, etc.), thermal demagnetization of three-component isothermal remanent magnetization (IRM) (Lowrie 1990), although a qualitative approach, yields a useful definition of demagnetization strategy.

(4) *Sample level characterization.* The fitting of individual (specimen) demagnetization results should follow some published/accepted criteria, as follows. (a) Vector directions must be fitted by principal component analyses (PCA) after visual inspection of demagnetization diagrams and the maximum angular deviation (MAD) should be below 15° (Kirschvink 1980). (2) Demagnetization circles (Halls 1978), defined by two remanences, can be used to double check the PCA fitting of the directions and may help to define overlapping components of remanence. Other ancillary methods (or combinations of them), such as linearity spectrum analysis (Schmidt 1982), stacking routine (Scheepers & Zijderveld 1992) and virtual palaeomagnetic directions (Pueyo 2000; Ramón 2013), may be very useful to understand the palaeomagnetic behaviour from a global perspective and to obtain a first-order palaeomagnetic signal. Individual directions or planes should be obtained using standard PCA analysis (see a partial compilation in https://magwiki.wikispaces.com/Paleomagnetic+and+Rock+Magnetic+Software). In addition, rock density should be always calculated from standard samples to help the processing of some rock magnetism experiments. Further, palaeomagnetists should consider (and publish) the petrophysical properties like density (ρ), magnetic susceptibility (k) or the natural remanent magnetization (NRM) of their samples because of their potential additional value in exploration geophysics.

(5) *Site level characterization. Next statistical level includes the characterization of the mean palaeomagnetic vector for a site.* (a) Fisher (1953) statistics, mean and confidence parameters (α_{95}, k and R) have been widely used by palaemagnetists for decades. As proposed by Van der Voo (1990), the α_{95} value, which may have structural implications in shortening estimates, should be lower than 10° (never higher than 15°). The precision parameter (k) should be larger than 20. (b) To double check the correct application of the Fisher (1953) distribution, the orientation tensor (Bingham 1974; Scheidegger 1965) could be calculated at the site scale. Ratios between eigenvectors (Tauxe 1998) could ascertain the suitability of the Fisher (1953) distribution and thus could detect possible sources of error (i.e. overlapping, internal deformation, improper restoration). (c) Mean bedding planes or other structural markers should be fitted using Fisher (1953) or Bingham (1974) statistics (depending upon the nature of the indicator) and should be reported in publications.

(6) *Restoration of site means.* The palaeomagnetic vectors must be corrected to the palaeogeographical reference system for the time when their magnetization was blocked in. This is accomplished as follows. (a) The geometry of folds and thrusts should be accurately defined. Bedding measurements within the area (exceeding the sampling sites) should be collected during fieldwork to characterize fold axes and thrust planes, as their geometry (i.e. conical or cylindric folds, and oblique, lateral or frontal thrusts) may be key to performing an appropriate restoration. (b) Restoration of the palaeomagnetic vectors must strictly follow the reverse order of the deformational sequence because deformation processes are non-commutative and may impart errors in the final estimation of VARs. (c) While a kinematic model to understand the structures is needed, it is also likely that palaeomagnetic analyses will help to improve such a model.

(7) *Combined palaeomagnetic and structural analyses*. A key factor during palaeomagnetic data processing is derived from the application of the fold test (Graham 1949), which assesses the relative age between folding and magnetization acquisition. (The fold test is a powerful and effective technique that could be extended to analysing other structural indicators.) Collecting a wide distribution of palaeomagnetic data obtained along fold surfaces is critical for minimizing many potential sources of errors in the application of the fold test. (a) All sampling sites should unequivocally belong to the same fold. (b) Results of many fold tests show that statistical approaches (McElhinny 1964; McFadden & Jones 1981; McFadden 1990, 1998; Bazhenov & Shipunov 1991; Tauxe & Watson 1994; Shipunov 1997; Weil & Van der Voo 2002; Enkin 2003) will bring similar results in case of postfolding and prefolding magnetizations. In these cases, progressive unfolding techniques or the small circle intersection method (SCI: Waldhör 1999; Waldhör & Appel 2006) will also yield similar results. (c) However, 'syn-folding' magnetizations derived from any method must be carefully evaluated because significant sources of errors will produce an apparent syn-folding result in the fold test (i.e. partially overlapped components, internally deformed vectors or incorrectly restored directions). In these circumstances, the use of auxiliary methods such as evaluation of trends in the declination v. strike diagram and/or the inclination v. dip plot (Figs 2, 3 & 4) will help distinguish between real syn-folding remagnetizations and apparent ones. (4) Real syn-folding magnetizations should be better defined by the SCI method because the progressive and proportional untilting technique assumes a kinematic model that may not represent how the structure developed (Cairanne *et al.* 2002; Delaunay *et al.* 2002). The results derived from the SCI approach may help to accurately reconstruct the geometry of the fold when remagnetization took place (Villalaín *et al.* 2003, 2015). (5) Palaeomagnetic declinations without inclination errors are usually represented as cones on geological maps (Mochales & Blenkinsop 2014) and are an informative way to visualize VARs and their relationship to the structure. However, the α_{95} must be converted to the A95 angle (Demarest 1983) to avoid a declination underestimation caused by latitude.

(8) *Palaeomagnetic reference and rotation confidence*. Accurate quantification of VAR magnitudes requires a high-quality reference field direction. To determine absolute rotation values, angles from a deformed area should be contrasted against a palaeomagnetic reference direction obtained in a close and undeformed part of the tectonic element. Reference data from the undisturbed foreland basin of the FTB will most often yield the best result. Relative VAR values in the hanging wall can be estimated from the data obtained from rocks in the footwall of the thrust.

Conclusion: reliability of palaeomagnetic data in fold and thrust belts

Considering the complexities of obtaining reliable VARs from palaeomagnetic data in FTBs, it is important to follow the philosophy of the reliability criteria established by Van der Voo (1990) and Opdyke and Channell (1996) to evaluate the quality of palaeopoles and the quality of magnetostratigraphic sections, respectively. We present and update these quality criteria as a best practice approach for using palaeomagnetic data to characterize VARs in FTBs:

(1) The age(s) of the rock(s), timing of deformation (i.e. folding, thrusting and rotation) and timing of acquisition of magnetization must be known.

(2) A minimum of five sites (10 is desirable) per thrust unit (10–15 samples per site), with a site mean characterized by $\alpha_{95} \leq 10^\circ$ (never $> 15^\circ$) and $k > 20$ (never < 10). In cases with variable structural trends (along-strike changes), at least five sites should be targeted fir every 15° of trend domain.

(3) Detailed demagnetization procedures must isolate all magnetization components and allow for a trusted calculation of remanence directions with demagnetization circles fitted by PCA (Kirschvink 1980). More than four or five steps must be involved to fit vectors and planes (respectively) and a MAD $< 15^\circ$ is desirable. The use of auxiliary methods (demagnetization circles, stacking routine, linearity spectrum, virtual directions, etc.) is recommended to best interpret the palaeomagnetic signal. Combined use of difference and resultant vectors should be carried out to facilitate the detection of instrument problems.

(4) Stability (field) tests and error-control techniques (i.e. conglomerate-, reversal- and fold tests and the small-circle intersection method) should be performed to support the timing of magnetization acquisition. Additionally, strike v. declination and dip v. inclination diagrams should be plotted to detect and to try to avoid errors, especially for syn-folding magnetizations.

(5) The geometry, kinematics and timing of all structures studied should be known to avoid restoration errors and apparent results in the fold and reversal tests and in the declination (rotation) deflection. This information is critical to restoring multiple rotations.

(6) When an inclination error is found, its origin (i.e. compaction, internal deformation and overlapping of directions) must be determined by means of geometric techniques. Identifying the source of the inclination error is critical to mitigate possible errors that may also affect declination.

(7) Rotations must be compared with a reliable palaeomagnetic reference direction obtained from the undeformed foreland (absolute VAR) or in the nearest footwall (relative VAR). Multiple rotations must be taken into account.

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References

Achache, J., Courtillot, V. & Besse, J. 1983. Paleomagnetic constraints on the late Cretaceous and Cenozoic tectonics of southeastern Asia. *Earth and Planetary Science Letters*, **63**, 123–136.

Adam, J., Klinkmüller, M., Schreurs, G. & Wieneke, B. 2013. Quantitative 3D strain analysis in analogue experiments simulating tectonic deformation: integration of X-ray computed tomography and digital volume correlation techniques. *Journal of Structural Geology*, **55**, 127–149.

Allerton, S. 1994. Vertical-axis rotation associated with folding and thrusting: an example from the eastern Subbetic zone of southern Spain. *Geology*, **22**, 1039–1042.

Allerton, S. 1998. Geometry and kinematics of vertical-axis rotations in fold and thrust belts. *Tectonophysics*, **299**, 15–30.

Arriagada, C., Roperch, P., Mpodozis, C. & Fernandez, R. 2006. Paleomagnetism and tectonics of the southern Atacama Desert (25–28 S), northern Chile. *Tectonics*, **25**, TC4001–TC4026.

Arriagada, C., Roperch, P., Mpodozis, C. & Cobbold, P.R. 2008. Paleogene building of the Bolivian Orocline: tectonic restoration of the central Andes in 2-D map view. *Tectonics*, **27**, TC6014–TC6027.

Aubourg, C., Smith, B., Bakhtari, H.R., Guya, N. & Eshraghi, A. 2008. Tertiary block rotations in the Fars arc (Zagros, Iran). *Geophysical Journal International*, **173**, 659–673.

Aubourg, C., Pozzi, J.-P. & Kars, M. 2012. Burial, claystones remagnetization and some consequences for magnetostratigraphy. *In*: Elmore, R.D., Muxworthy, A.R., Aldana, M.M. & Mena, M. (eds) *Remagnetization and Chemical Alteration of Sedimentary Rocks*. Geological Society, London, Special Publications, **371**, 181–188, http://doi.org/10.1144/SP371.4

Bailey, R.C. & Halls, H.C. 1984. Estimate of confidence in paleomagnetic directions derived from mixed remagnetization circle and direct observational data. *Journal of Geophysics*, **54**, 174–182.

Bates, M.P. 1989. Palaeomagnetic evidence for rotations and deformation in the Nogueras Zone, central southern Pyrenees, Spain. *Journal of the Geological Society, London*, **146**, 459–476, http://doi.org/10.1144/gsjgs.146.3.0459

Bayona, G., Thomas, W.A. & Van der Voo, R. 2003. Kinematics of thrust sheets within transverse zones; a structural and paleomagnetic investigation in the Appalachian thrust belt of Georgia and Alabama. *Journal of Structural Geology*, **25**, 1193–1212.

Bazhenov, M.L. 1988. Analysis of the resolution of the paleomagnetic methoid in solving tectonic problems. *Geotectonics*, **22**, 204–212.

Bazhenov, M.L. & Shipunov, S.V. 1991. Fold test in paleomagnetism: new approaches and reappraisal of data. *Earth and Planetary Science Letters*, **104**, 16–24.

Bazhenov, M.L., Burtman, V.S. & Dvorova, A.V. 1999. Permian paleomagnetism of the Tien Shan fold belt, Central Asia: post-collisional rotations and deformation. *Tectonophysics*, **312**, 303–329.

Beamud, E., Muñoz, J.A., Fitzgerald, P.G., Baldwin, S.L., Garcés, M., Cabrera, L. & Metcalf, J.R. 2011. Magnetostratigraphy and detrital apatite fission track thermochronology in syntectonic conglomerates: constraints on the exhumation of the South-Central Pyrenees. *Basin Research*, **23**, 309–331.

Beck, M.E. 1980. Paleomagnetic record of plate-margin tectonic processes along the western edge of North America. *Journal of Geophysical Research: Solid Earth (1978–2012)*, **85**, 7115–7131.

Bilardello, D. & Kodama, K.P. 2010. A new inclination shallowing correction of the Mauch Chunk Formation of Pennsylvania, based on high-field AIR results: implications for the Carboniferous North American APW path and Pangea reconstructions. *Earth and Planetary Science Letters*, **299**, 218–227.

Bingham, C. 1974. An antipodally symmetric distribution on the sphere. *Annals of Statistics*, **2**, 1201–1225.

Blumstein, A.M., Elmore, R.D., Engel, M.H., Elliot, C. & Basu, A. 2004. Paleomagnetic dating of burial diagenesis in Mississippian carbonates, Utah. *Journal of Geophysical Research: Solid Earth (1978–2012)*, **109**, B04101–B04116.

Bonhommet, N., Cobbold, P.R., Perroud, H. & Richardson, A. 1981. Paleomagnetism and cross-folding in a key area of the Asturian Arc (Spain). *Journal of Geophysical Research: Solid Earth (1978–2012)*, **86**, 1873–1887.

Borradaile, G.J. 1997. Deformation and paleomagnetism. *Surveys in Geophysics*, **18**, 405–435.

Bourgeois, O., Cobbold, P.R., Rouby, D., Thomas, J.C. & Shein, V. 1997. Least squares restoration of Tertiary thrust sheets in map view, Tajik Depression, Central Asia. *Journal of Geophysical Research, B, Solid Earth and Planets*, **102**, 27553–27573.

Burbank, D.W., Vergés, J., Muñoz, J.A. & Bentham, P. 1992. Coeval hindward-and forward-imbricating thrusting in the south-central Pyrenees, Spain: timing and rates of shortening and deposition. *Geological Society of America Bulletin*, **104**, 3–17.

Butler, R.F. 1992. *Paleomagnetism: Magnetic Domains to Geologic Terranes*. Blackwell, Boston, MA.

Butler, R.F., Richards, D.R., Sempere, T. & Marshall, L.G. 1995. Paleomagnetic determinations of vertical-axis tectonic rotations from Late Cretaceous and Paleocene strata of Bolivia. *Geology*, **23**, 799–802.

Cairanne, C., Aubourg, C. & Pozzi, J.P. 2002. Synfolding remagnetization and the significance of the small circle test: examples from the Vocontian trough (SE France). *Physics and Chemistry of the Earth*, **27**, 1151–1159.

Cardello, G.L., Almqvist, B.S.G., Hirt, A.M. & Mancktelow, N.S. 2015. Determining the timing of formation of the Rawil Depression in the Helvetic Alps by paleomagnetic and structural methods. *In*: Pueyo, E.L., Cifelli, F., Sussman, A.J. & Oliva-Urcia, B. (eds) *Palaeomagnetism in Fold and Thrust Belts: New Perspectives*. Geological Society, London, Special Publications, **425**. First published online July 22, 2015, updated August 18, 2015, http://doi.org/10.1144/SP425.4

Caricchi, C., Cifelli, F., Sagnotti, L., Sani, F., Speranza, F. & Mattei, M. 2014. Paleomagnetic evidence for a post-Eocene 90° CCW rotation of internal Apennine units: a linkage with Corsica-Sardinia rotation? *Tectonics*, **33**, 374–392.

Chan, L.S. 1988. Apparent tectonic rotations, declination anomaly equations and declination anomaly charts. *Journal of Geophysical Research*, **93**, 12151– 12158.

Channell, J.E.T., Oldow, J.S., Catalano, R. & d'Argenio, B. 1990. Paleomagnetically determined rotations in the western Sicilian fold and thrust belt. *Tectonics*, **9**, 641–660.

Cifelli, F., Mattei, M. & Rossetti, F. 2007. Tectonic evolution of arcuate mountain belts on top of a retreating subduction slab: the example of the Calabrian Arc. *Journal of Geophysical Research*, **112**, B09101–B09120.

Cifelli, F., Mattei, M. & Porreca, M. 2008*a*. New paleomagnetic data from Oligocene-upper Miocene sediments in the Rif chain (northern Morocco): insights on the Neogene tectonic evolution of the Gibraltar Arc. *Journal of Geophysical Research*, B02104, http://doi.org/10.1029/2007JB005271

Cifelli, F., Mattei, M. & Della Seta, M. 2008*b*. Calabrian Arc oroclinal bending: the role of subduction. *Tectonics*, **27**, TC5001–TC5015, http://doi.org/10.1029/2008TC002272

Çinku, M.C., Hisarli, Z.M. *et al.* 2013. Evidence of Early Cretaceous remagnetization in the Crimean Peninsula: a palaeomagnetic study from Mesozoic rocks in the Crimean and Western Pontides, conjugate margins of the Western Black Sea. *Geophysical Journal International*, **195**, 821–843.

Çinku, M.C., Hisarli, M. *et al.* 2015. Evidence of Late Cretaceous oroclinal bending in north–central Anatolia: palaeomagnetic results from Mesozoic and Cenozoic rocks along the İzmir–Ankara–Erzincan Suture Zone. *In*: Pueyo, E.L., Cifelli, F., Sussman, A.J. & Oliva-Urcia, B. (eds) *Palaeomagnetism in Fold and Thrust Belts: New Perspectives*. Geological Society, London, Special Publications, **425**. First published online August 3, 2015, updated August 14, 2015, http://doi.org/10.1144/SP425.2

Cogné, J.P. 1987. Paleomagnetic direction obtained by strain removal in the Pyrenean Permian redbeds at the 'Col du Somport' (France). *Earth and Planetary Science Letters*, **85**, 162–172.

Collombet, M., Thomas, J.C., Chauvin, A., Tricart, P., Bouillin, J.P. & Gratier, J.P. 2002. Counterclockwise rotation of the Western Alps since the Oligocene; new insights from paleomagnetic data. *Tectonics*, **21**, 1401–1415.

Conder, J., Butler, R.F., DeCelles, P.G. & Constenius, K. 2003. Paleomagnetic determination of vertical-axis rotations within the Charleston–Nebo salient, Utah. *Geology*, **31**, 1113–1116.

Creer, K.M. 1962. A statistical enquiry into the partial remagnetization of folded Old Red Sandstone rocks. *Journal of Geophysical Research*, **67**, 1899–1906.

Crouzet, C., Gautam, P., Schill, E. & Appel, E. 2003. Multicomponent magnetization in western Dolpo (Tethyan Himalaya, Nepal); tectonic implications. *Tectonophysics*, **377**, 179–196.

Cullen, A.B., Zechmeister, M.S., Elmore, R.D. & Pannalal, S.J. 2012. Paleomagnetism of the Crocker Formation, northwest Borneo: implications for late Cenozoic tectonics. *Geosphere*, **8**, 1146–1169.

Cummins, W.A. 1964. Current directions from folded strata. *Geological Magazine*, **101/2**, 169–173.

Cummins, W.A. 1966. Conical folding and sedimentary lineations. *Geological Magazine*, **103**, 197–203.

Delaunay, S., Smith, B. & Aubourg, C. 2002. Asymmetrical fold test in the case of overfolding: two examples from the Makran accretionary prism (Southern Iran). *Physics and Chemistry of the Earth*, **27**, 1195–1203.

Demarest, H.H. 1983. Error analysis for the determination of tectonic rotation from paleomagnetic data. *Journal of Geophysical Research: Solid Earth (1978–2012)*, **88**, 4321–4328.

Duermeijer, C.E., Nyst, M., Meijer, P.T., Langereis, C.G. & Spakman, W. 2000. Neogene evolution of the Aegean arc: paleomagnetic and geodetic evidence for a rapid and young rotation phase. *Earth and Planetary Science Letters*, **176**, 509–525.

Dupont-Nivet, G., Butler, R.F., Yin, A. & Chen, X. 2002. Paleomagnetism indicates no Neogene rotation of the Qaidam Basin in northern Tibet during Indo-Asian collision. *Geology*, **30**, 263–266.

Dupont-Nivet, G., Vasiliev, I., Langereis, C.G., Krijgsman, W. & Panaiotu, C. 2005. Neogene tectonic evolution of the Southern and Eastern Carpathians constrained by paleomagnetism. *Earth and Planetary Science Letters*, **236**, 374–387.

Eldredge, S. & Van der Voo, R. 1988. Paleomagnetic study of thrust sheet rotations in the Helena and Wyoming salients of the northern Rocky Mountains. *Geological Society of America Memoirs*, **171**, 319–332.

Eldredge, S., Bachtadse, V. & Van der Voo, R. 1985. Paleomagnetism and the orocline hypothesis. *Tectonphysics*, **119**, 153–179.

Elmore, R.D., Kelley, J., Evans, M. & Lewchuk, M.T. 2001. Remagnetization and orogenic fluids: testing the hypothesis in the central Appalachians. *Geophysical Journal International*, **144**, 568–576.

Elmore, R.D., Muxworthy, A.R. & Aldana, M. 2012. Remagnetization and chemical alteration of sedimentary rocks. *In*: Elmore, R.D., Muxworthy, A.R., Aldana, M.M. & Mena, M. (eds) *Remagnetization and Chemical Alteration of Sedimentary Rocks*. Geological Society, London, Special Publications, **371**, 1–21, http://doi.org/10.1144/SP371.15

Enkin, R.J. 2003. The direction-correction tilt test: an all-purpose tilt/fold test for paleomagnetic studies. *Earth and Planetary Science Letters*, **212**, 151–166.

Evans, M.A., Elmore, R.D. & Lewchuk, M.T. 2000. Examining the relationship between remagnetization and orogenic fluids: central Appalachians. *Journal of Geochemical Exploration*, **69**, 139–142.

Facer, R.A. 1983. Folding, strain and Graham's fold test in palaeomagnetic investigations. *Geophysical Journal International*, **72**, 165–171.

Fisher, R.A. 1953. Dispersion on a sphere. *Proceedings of the Royal Society, London*, **A217**, 295–305.

Graham, J.W. 1949. The stability and significance of magnetism in sedimentary rocks. *Journal of Geophysical Research*, **54**, 131–167.

Grubbs, K.L. & Van der Voo, R. 1976. Structural deformation of the Idaho-Wyoming overthrust belt (U.S.A.), as determined by Triassic paleomagnetism. *Tectonophysics*, **33**, 321–336.

Halls, H.C. 1976. A least-squares method to find a remanence direction from converging remagnetization circles. *Geophysical Journal International*, **45**, 297–304.

Halls, H.C. 1978. The use of converging remagnetization circles in paleomagnetism. *Physics of the Earth and Planetary Interiors*, **16**, 1–11.

Harlan, S.S., Geissman, J.W., Whisner, S.C. & Schmidt, C.J. 2008. Paleomagnetism and geochronology of sills of the Doherty Mountain area, southwestern Montana; implications for the timing of fold-and-thrust belt deformation and vertical-axis rotations along the southern margin of the Helena Salient. *Geological Society of America Bulletin*, **120**, 1091–1104.

Hindle, D. & Burkhard, M. 1999. Strain, displacement and rotation associated with the formation of curvature in fold belts; the example of the Jura arc. *Journal of Structural Geology*, **21**, 1089–1101.

Hirt, A.M., Lowrie, W., Julivert, M. & Arboleya, M.L. 1992. Paleomagnetic results in support of a model for the origin of the Asturian Arc. *Tectonophysics*, **213**, 321–339.

Hnat, J.S., van der Pluijm, B.A., Van der Voo, R. & Thomas, W.A. 2008. Differential displacement and rotation in thrust fronts: a magnetic, calcite twinning and palinspastic study of the Jones Valley thrust, Alabama, US Appalachians. *Journal of Structural Geology*, **30**, 725–738.

Hospers, J. & Van Andel, S.I. 1969. Palaeomagnetism and tectonics, a review. *Earth-Science Reviews*, **5**, 5–44.

Irving, E. 2005. The role of latitude in mobilism debate. *Proceedings of the National Academy of Science, USA*, **102**, 1821–1828.

Izquierdo-Llavall, E., Sainz, A.C., Oliva-Urcia, B., Burmester, R., Pueyo, E.L. & Housen, B. 2015. Multi-episodic remagnetization related to deformation in the Pyrenean Internal Sierras. *Geophysical Journal International*, **201**, 891–914.

Japas, M.S., Ré, G.H., Oriolo, S. & Vilas, J.F. 2015. Palaeomagnetic data from the Precordillera fold and thrust belt constraining Neogene foreland evolution of the Pampean flat-slab segment (Central Andes, Argentina). *In*: Pueyo, E.L., Cifelli, F., Sussman, A.J. & Oliva-Urcia, B. (eds) *Palaeomagnetism in Fold and Thrust Belts: New Perspectives*. Geological Society, London, Special Publications, **425**. First published online August 18, 2015, http://doi.org/10.1144/SP425.9

Khramov, A.N. 1958. *Paleomagnetism and Stratigraphic Correlation*. Gostoptechizdat, Leningrad.

Kirscher, U., Zwing, A., Alexeiev, D.V., Echtler, H.P. & Bachtadse, V. 2013. Paleomagnetism of Paleozoic sedimentary rocks from the Karatau Range, Southern Kazakhstan: multiple remagnetization events correlate with phases of deformation. *Journal of Geophysical Research: Solid Earth*, **118**, 3871–3885.

Kirschvink, J.L. 1980. The least-squares line and plane and the analysis of the paleomagnetic data. *Geophysical Journal of the Royal Astronomical Society*, **62**, 699–718.

Kissel, C. & Laj, C. 1989. *Paleomagnetic Rotations and Continental Deformation*. NATO ASI Science Series C, **254**. Kluwer Academic Publishers, Dordrecht.

Kissel, C., Averbuch, O., de Lamotte, D.F., Monod, O. & Allerton, S. 1993. First paleomagnetic evidence for a post-Eocene clockwise rotation of the Western Taurides thrust belt east of the Isparta reentrant (Southwestern Turkey). *Earth and Planetary Science Letters*, **117**, 1–14.

Kodama, K.P. 1988. Remanence rotation due to rock strain during folding and the stepwise application of the fold test. *Journal of Geophysical Research, B, Solid Earth and Planets*, **93**, 3357–3371.

Kodama, K.P. 1997. A successful rock magnetic technique for correctng paleomagnetic inclination shallowing: case study of the nacimiento formation, New Mexico. *Journal of Geophysical Research: Solid Earth (1978–2012)*, **102**, 5193–5205.

Lowrie, W. 1990. Identification of ferromagnetic minerals in a rock by coercitivity and un-blocking temperature properties. *Geophysics Research Letters*, **17**, 159–162.

Lowrie, W., Hirt, A.M. & Kligfield, R. 1986. Effects of tectonic deformation on the remanent magnetization of rocks. *Tectonics*, **5**, 713–722.

MacDonald, W.D. 1980. Net tectonic rotation, apparent tectonic rotation and the structural tilt correction in paleomagnetism studies. *Journal of Geophysical Research*, **85**, 3659–3669.

MacFadden, B.J., Anaya, F. & Swisher, C.C. 1995. Neogene paleomagnetism and oroclinal bending of the central Andes of Bolivia. *Journal of Geophysical Research: Solid Earth*, **100**, 8153–8167.

Márton, E., Tischler, M., Csontos, L., Fuegenschuh, B. & Schmid, S.M. 2007. The contact zone between the ALCAPA and Tisza-Dacia megatectonic units of northern Romania in the light of new paleomagnetic data. *Swiss Journal of Geosciences*, **100**, 109–124.

Márton, E., Grabowski, J., Tokarski, A.K. & Túnyi, I. 2015. Palaeomagnetic results from the fold and thrust belt of the Western Carpathians: an overview. *In*: Pueyo, E.L., Cifelli, F., Sussman, A.J. & Oliva-Urcia, B. (eds) *Palaeomagnetism in Fold and Thrust Belts: New Perspectives*. Geological Society, London, Special Publications, **425**. First published online August 12, 2015, http://doi.org/10.1144/SP425.1

Mattei, M., Funiciello, R. & Kissel, C. 1995. Paleomagnetic and structural evidence for Neogene block rotations in the Central Apennines, Italy. *Journal of Geophysical Research: Solid Earth (1978–2012)*, **100**, 17863–17883.

Mattei, M., Petrocelli, V., Lacava, D. & Schiattarella, M. 2004. Geodynamic implications of Pleistocene ultrarapid vertical-axis rotations in the Southern Apennines, Italy. *Geology*, **32**, 789–792.

Mattei, M., Cifelli, F., Rojas, I.M., Crespo-Blanc, A., Comas, M., Faccenna, C. & Porreca, M. 2006. Neogene tectonic evolution of the Gibraltar Arc; new paleomagnetic constrains from the Betic chain. *Earth and Planetary Science Letters*, **250**, 522–540.

McCaig, A.M. & McClelland, E. 1992. Palaeomagnetic techniques applied to thrust belts. *In*: McClay, K.R. (ed.) *Thrust Tectonics*. Chapman and Hall, London, 209–216.

McElhinny, M.W. 1964. Statistical significance of the fold test in palaeomagnetism. *Geophysical Journal of the Royal Astronomical Society*, **8**, 338–340.

McFadden, P.L. 1990. A new fold test for palaeomagnetic studies. *Geophysical Journal International.*, **103**, 163–169.

McFadden, P.L. 1998. The fold test as an analytical tool. *Geophysical Journal International*, **135**, 329–338.

McFadden, P.L. & Jones, D.L. 1981. The fold test in palaeomagnetism. *Geophysical Journal of the Royal Astronomical Society*, **67**, 53–58.

McFadden, P.L. & McElhinny, M.W. 1988. The combined analysis of remagnetization circles and direct observations in paleomagnetism. *EPSL*, **87**, 161–172.

Meert, J.G. 2009. Palaeomagnetism: in GAD we trust. *Nature Geoscience*, **2**, 673–674.

Mochales, T. & Blenkinsop, T.G. 2014. Representation of paleomagnetic data in virtual globes: a case study from the Pyrenees. *Computers & Geosciences*, **70**, 56–62.

Mochales, T., Casas, A.M., Pueyo, E.L. & Barnolas, A. 2012. Rotational velocity for oblique structures (Boltaña anticline, Southern Pyrenees). *Journal of Structural Geology*, **35**, 2–16.

Mochales, T., Pueyo, E.L., Casas, A.M. & Barnolas, A. 2016. Restoring paleomagnetic data in complex superposed folding settings: the Boltaña anticline (Southern Pyrenees). *Tectonophysics*, **671**, 281–298, http://doi.org/10.1016/j.tecto.2016.01.008

Moussaid, B., Villalaín, J.J., Casas-Sainz, A., El Ouardi, H., Oliva-Urcia, B., Soto, R. & Torres-López, S. 2015. Primary v. secondary curved fold axes: deciphering the origin of the Aït Attab syncline (Moroccan High Atlas) using paleomagnetic data. *Journal of Structural Geology*, **70**, 65–77.

Muñoz, J.A., Beamud, E., Fernández, O., Arbués, P., Dinarès-Turell, J. & Poblet, J. 2013. The Ainsa Fold and thrust oblique zone of the central Pyrenees: kinematics of a curved contractional system from paleomagnetic and structural data. *Tectonics*, **32**, 1142–1175.

Muttoni, G., Argnani, A., Kent, D.V., Abrahamsen, N. & Cibin, U. 1998. Paleomagnetic evidence for Neogene tectonic rotations in the northern Apennines, Italy. *Earth and Planetary Science Letters*, **154**, 25–40.

Nemkin, S.R., Fitz-Díaz, E., van der Pluijm, B. & Van der Voo, R. 2015. Dating synfolding remagnetization: approach and field application (central Sierra Madre Oriental, Mexico). *Geosphere*, **11**, 1617–1628.

Nicol, A., Mazengarb, C., Chanier, F., Rait, G., Uruski, C. & Wallace, L. 2007. Tectonic evolution of the active Hikurangi subduction margin, New Zealand, since the Oligocene. *Tectonics*, **26**, 1–5.

Norman, T.N. 1960. Azimuths of primary linear structures in folded strata. *Geological Magazine*, **97**, 338–343.

Norris, D.K. & Black, R.F. 1961. Application of palaeomagnetism to thrust mechanics. *Nature (London)*, **192**, 933–935.

Nur, A., Ron, H. & Scotti, O. 1986. Fault mechanics and the kinematics of block rotations. *Geology*, **14**, 746–749.

Oliva-Urcia, B. & Pueyo, E.L. 2007*a*. Basement kinematic constrains from paleomagnetic data of remagnetized cover rocks (Internal Sierras, Southwestern Pyrenees). *Tectonics*, **26**, TC4014–TC4036.

Oliva-Urcia, B. & Pueyo, E.L. 2007*b*. Gradient of shortening and vertical-axis rotations in the Southern Pyrenees (Spain), insights from a synthesis of paleomagnetic data. *Revista de la Sociedad Geológica de España*, **20**, 105–118.

Oliva-Urcia, B., Casas, A.M., Pueyo, E.L., Román-Berdiel, T. & Geissman, J.W. 2010. Paleomagnetic evidence for dextral strike-slip motion in the Pyrenees during the Alpine convergence (Mauléon basin, France). *Tectonophysics*, **494**, 165–179, http://doi.org/10.1016/j.tecto.2010.09.018

Oliva-Urcia, B., Casas, A.M., Pueyo, E.L. & Pocoví, A. 2012*a*. Structural and paleomagnetic evidence for non-rotational kinematics in the western termination of the External Sierras (southwestern central Pyrenees). *Geologica Acta*, **10**, 1–22.

Oliva-Urcia, B., Pueyo, E.L., Larrasoaña, J.C., Casas, A.M., Román-Berdiel, T., Van der Voo, R. & Scholger, R. 2012*b*. New and revisited paleomagnetic data from Permian-Triassic red beds: Two kinematic domains in the West-Central Pyrenees. *Tectonophysics*, **522–523**, 158–175, http://doi.org/10.1016/j.tecto.2011.11.023

Oliva-Urcia, B., Beamud, E., Garcés, M., Arenas, C., Soto, R., Pueyo, E.L. & Pardo, G. 2015. New magnetostratigraphic dating of the Palaeogene syntectonic sediments of the west-central Pyrenees: tectonostratigraphic implications. *In*: Pueyo, E.L., Cifelli, F., Sussman, A.J. & Oliva-Urcia, B. (eds) *Palaeomagnetism in Fold and Thrust Belts: New Perspectives*. Geological Society, London, Special Publications, **425**. First published online August 3, 2015, updated August 21, 2015, http://doi.org/10.1144/SP425.5

Ong, P.F., van der Pluijm, B.A. & Van der Voo, R. 2007. Early rotation and late folding in the Pennsylvania Salient (U.S. Appalachians); evidence from calcite-twinning analysis of Paleozoic carbonates. *Geological Society of America Bulletin*, **119**, 796–804.

Opdyke, M.D. 1995. Paleomagnetism, polar wondering, and the rejuvenation of crustal mobility. *Journal of Geophysical Research*, **100**, B24361–24366.

Opdyke, M.D. & Channell, J.E. 1996. *Magnetic Stratigraphy*. Academic Press, San Diego.

Otofuji, Y.I., Matsuda, T. & Nohda, S. 1985. Paleomagnetic evidence for the Miocene counter-clockwise rotation of Northeast Japan – rifting process of the Japan Arc. *Earth and Planetary Science Letters*, **75**, 265–277.

Pastor-Galán, D., Mulchrone, K.F., Koymans, M.R., van Hinsbergen, D.J.J. & Langereis, C.G. 2016. Total Least Squares Orocline test: A robust method to quantify vertical axis rotation patterns in orogens, with examples from the Cantabrian and Aegean oroclines. *Lithosphere* (in press).

Pavón-Carrasco, F.J., Osete, M.L. & Torta, J.M. 2010. Regional modeling of the geomagnetic field in Europe from 6000 to 1000 BC. *Geochemistry, Geophysics, Geosystems*, **11**, 1–20, http://doi.org/10.1029/2010GC003197

Perroud, H. 1982. Relations paléomagnétisme et déformation: exemple de la région de Cabo de Penas (Espagne). *Comptes Rendus de l'Académie des Sciences Paris*, **294**, 45–48.

Platt, J.P., Allerton, S., Kirker, A., Mandeville, C., Mayfield, A., Platzman, E.S. & Rimi, A. 2003. The ultimate arc: differential displacement, oroclinal bending, and vertical axis rotation in the External Betic–Rif arc. *Tectonics*, **22**, 201–231.

Powers, P.M., Lillie, R.J. & Yeats, R.S. 1998. Structure and shortening of the Kangra and Dehra Dun reentrants, sub-Himalaya, India. *Geological Society of America Bulletin*, **110**, 1010–1027.

Prezzi, C., Caffe, P.J. & Somoza, R. 2004. New paleomagnetic data from the northern Puna and western Cordillera Oriental, Argentina; a new insight on the timing of rotational deformation. *Journal of Geodynamics*, **38**, 93–115.

Pueyo, E.L. 2000. *Rotaciones paleomagnéticas en sistemas de pliegues y cabalgamientos. Tipos, causas, significado y aplicaciones (ejemplos del Pirineo Aragonés)*. Unpublished PhD thesis, Universidad de Zaragoza.

Pueyo, E.L., Pocoví, A. & Parés, J.M. 2002*a*. Flexural folding of linear (paleomagnetic) data by non-coaxial axes of deformation: restoration and errors. *Mitteilungen Naturwissenschaftlicher Verein für Steiermark*, **132**, 35–38.

Pueyo, E.L., Millán, H. & Pocoví, A. 2002*b*. Rotation velocity of a thrust: a paleomagnetic study in the External Sierras (Southern Pyrenees). *Sedimentary Geology*, **146**, 191–208.

Pueyo, E.L., Parés, J.M., Millán, H. & Pocoví, A. 2003*a*. Conical folds and apparent rotations in paleomagnetism (A case studied in the Southern Pyrenees). *Tectonophysics*, **362**, 345–366.

Pueyo, E.L., Pocoví, A., Parés, J.M., Millán, H. & Larrasoaña, J.C. 2003*b*. Thrust ramp geometry and spurious rotations of paleomagnetic vectors. *Studia Geophysica Geodetica*, **47**, 331–357.

Pueyo, E.L., Pocoví, A., Millán, H. & Sussman, A. 2004. Map-view models for correcting and calculating shortening estimates in rotated thrust fronts using paleomagnetic data. *In*: Weil, A. & Sussman, A. (eds) *Orogenic Curvature: Integrating Paleomagnetic and Structural Analyses*. Geological Society of America, Special Papers, **383**, 57–71.

Pueyo, E.L., Mauritsch, H.J., Gawlick, H.J., Scholger, R. & Frisch, W. 2007. New evidence for block and thrust sheet rotations in the Central Northern Calcareous Alps deduced from two pervasive remagnetization events. *Tectonics*, **26**, TC5011–TC5036. http://doi.org/10.1029/2006TC0 01965

Pueyo-Anchuela, O., Pueyo, E.L., Pocoví, A. & Gil-Imaz, A. 2012. Vertical axis rotations in fold and thrust belts: comparison of AMS and paleomagnetic data in the Western External Sierras (Southern Pyrenees). *Tectonophysics*, **532–535**, 119–133.

Ramón, M.J. 2013. *Flexural unfolding of complex geometries in fold and thrust belts using paleomagnetic vectors*. Unpublished PhD, University of Zaragoza, http://zaguan.unizar.es/record/11750

Ramón, M.J., Pueyo, E.L., Briz, J.L., Pocoví, A. & Ciria, J.C. 2012. Flexural unfolding in 3D using paleomagnetic vectors. *Journal of Structural Geology*, **35**, 28–39, http://doi.org/10.1016/j.jsg.2011.11.015

Ramón, M.J., Briz, J.L., Pueyo, E.L. & Fernández, O. 2015*a*. Horizon restoration by best fitting of finite elements and rotation constraints: sensitivity to the mesh geometry and pin-element location. *Mathematical Geosciences*, **48**, 419–437.

Ramón, M.J., Pueyo, E.L., Caumon, G. & Briz, J.L. 2015*b*. Parametric unfolding of flexural folds using palaeomagnetic vectors. *In*: Pueyo, E.L., Cifelli, F., Sussman, A.J. & Oliva-Urcia, B. (eds) *Palaeomagnetism in Fold and Thrust Belts: New Perspectives*. Geological Society, London, Special Publications, **425**. First published online August 12, 2015, http://doi.org/10.1144/SP425.6

Ramsay, J.G. 1960. The deformation of early linear structures in areas of repeated folding. *Journal of Geology*, **68**, 75–93.

Ramsay, J.G. 1961. The effects of folding upon the orientation of sedimentation structures. *Journal of Geology*, **69**, 84–100.

Rapalini, A.E. 2007. A paleomagnetic analysis of the patagonian orocline. *Geologica Acta*, **5**, 287–294.

Rapalini, A.E., Peroni, J. *et al.* 2015. Palaeomagnetism of Mesozoic magmatic bodies of the Fuegian Cordillera: implications for the formation of the Patagonian Orocline. *In*: Pueyo, E.L., Cifelli, F., Sussman, A.J. & Oliva-Urcia, B. (eds) *Palaeomagnetism in Fold and Thrust Belts: New Perspectives*. Geological Society, London, Special Publications, **425**. First published online July 22, 2015, http://doi.org/10.1144/SP425.3

Ribeiro, P., Silva, P.F., Moita, P., Kratinova, Z., Marques, F.O. & Henry, B. 2013. Palaeomagnetism in the Sines massif (SW Iberia) revisited: evidences for Late Cretaceous hydrothermal alteration and associated partial remagnetization. *Geophysical Journal International*, **195**, 176–191.

Richards, D.R., Butler, R.F. & Sempere, T. 2004. Vertical-axis rotations determined from paleomagnetism of Mesozoic and Cenozoic strata of the Bolivian Andes. *Journal of Geophysical Research: Solid Earth*, **109**, B07104.

Rodríguez-Pintó, A., Ramón, M.J., Oliva-Urcia, B., Pueyo, E.L. & Pocoví, A. 2011. Errors in paleomagnetism: structural control on overlapped vectors, mathematical models. *Physics of the Earth and Planetary Interiors*, **186**, 11–22.

Rodríguez-Pintó, A., Pueyo, E.L., Barnolas, A., Pocoví, A., Ramón, M.J. & Oliva-Urcia, B. 2013. Overlapped paleomagnetic vectors and fold geometry: a case study in the Balzes anticline (Southern Pyrenees). *Physics of the Earth and Planetary Interiors*, **215**, 43–57. http://doi.org/10.1016/j.pepi.2012.10.005

Rodríguez-Pintó, A., Pueyo, E.L.M. *et al.* 2016. Rotational kinematics of a curved fold: a structural and paleomagnetic study in the Balzes anticline (Southern Pyrenees). *Tectonophysics*, **677–678**, 171–189.

Ron, H., Freund, R., Garfunkel, Z. & Nur, A. 1984. Block rotation by strike-slip faulting: structural and paleomagnetic evidence. *Journal of Geophysical Research: Solid Earth (1978–2012)*, **89**, 6256–6270.

Roperch, P. & Carlier, G. 1992. Paleomagnetism of Mesozoic rocks from the central Andes of southern Peru: importance of rotations in the development of the Bolivian orocline. *Journal of Geophysical Research: Solid Earth (1978–2012)*, **97**, 17233–17249.

Rouvier, H., Henry, B. & Le Goff, M. 2012. Mise en évidence par le paléomagnétisme de rotations régionales dans la virgation des Corbières (France). *Bulletin de la Société Geologique de France*, **183**, 409–424.

Rousse, S., Gilder, S., Fornari, M. & Sempere, T. 2005. Insight into the Neogene tectonic history of the northern Bolivian Orocline from new paleomagnetic and geochronologic data. *Tectonics*, **24**, 1–23.

Satolli, S., Speranza, F. & Calamita, F. 2005. Paleomagnetism of the Gran Sasso range salient (central Apennines, Italy): pattern of orogenic rotations due to translation of a massive carbonate indenter. *Tectonics*, **24**, 1–22.

Scheepers, P.J.J. & Zijderveld, J.D.A. 1992. Stacking in Paleomagnetism: application to marine sediments with weak NRM. *Geophysical Research Letters*, **1914**, 1519–1522.

Scheidegger, A.M. 1965. On the statistics of the orientation of bedding planes, grain axes, and similar sedimentological data. *US Geological Survey Professional Papers*, **525C**, 164–167.

Schill, E., Crouzet, C., Gautam, P., Singh, V.K. & Appel, E. 2002. Where did rotational shortening occur in the Himalayas? Inferences from palaeomagnetic remagnetisations. *Earth and Planetary Science Letters*, **203**, 45–57.

Schmidt, P.W. 1982. Linearity spectrum analysis of multicomponent magnetizations and its application to some igneous rocks from south-eastern Australia. *Geophysical Journal International*, **70**, 647–665.

Scott, G.D. 1984. Anomalous declinations from plunging structures. *EOS Transactions AGU*, **65**, 866.

Sears, J.W. & Hendrix, M.S. 2004. Lewis and Clark line and the rotational origin of the Alberta and Helena Salients, North American Cordillera. *In*: Sussman, A.J. & Weil, A.B. (eds) *Orogenic Curvature: Integrating Paleomagnetic and Structural Analyses*. Geological Society of America Special Papers, **383**, 173–186.

Sellés-Martínez, J. 1988. Las correcciones estructural y tectónica en el tratamiento de los datos magnéticos. *Geofísica Internacional*, **27-3**, 379–393.

Sempere, T., Hérail, G., Oller, J. & Bonhomme, M.G. 1990. Late Oligocene-early Miocene major tectonic crisis and related basins in Bolivia. *Geology*, **18**, 946–949.

Setiabudidaya, D.J., Piper, D.A. & Shaw, J. 1994. Paleomagnetism of the (Early Devonian) Lower Old Red sandstones of South Wales: implications to Variscan overprinting and differential rotations. *Tectonophysics*, **231**, 257–280.

Shipunov, S.V. 1997. Synfolding magnetization; detection, testing and geological applications. *Geophysical Journal International*, **130**, 405–410.

Smith, B., Aubourg, C., Guezou, J.C., Nazari, H., Molinaro, M., Braud, X. & Guya, N. 2005. Kinematics of a sigmoidal fold and vertical axis rotation in the east of the Zagros–Makran syntaxis (southern Iran); paleomagnetic, magnetic fabric and microtectonic approaches. *Tectonophysics*, **411**, 89–109.

Sonnette, L., Humbert, F., Aubourg, C., Gattacceca, J., Lee, J.C. & Angelier, J. 2014. Significant rotations related to cover–substratum decoupling: example of the Dôme de Barrôt (Southwestern Alps, France). *Tectonophysics*, **629**, 275–289.

Soto, R., Casas-Sainz, A.M. & Pueyo, E.L. 2006. Along-strike variation of orogenic wedges associated with vertical axis rotations. *Journal of Geophysical Research (Solid Earth)*, **111**, B10402–B10423.

Soto, R., Villalain, J.J. & Casas-Sainz, A.M. 2008. Remagnetizations as a tool to analyze the tectonic history of inverted sedimentary basins: a case study from the Basque–Cantabrian basin (north Spain). *Tectonics*, **27**, TC1017–33.

Speranza, F., Sagnotti, L. & Mattei, M. 1997. Tectonics of the Umbria–Marche–Romagna Arc (central northern Apennines, Italy): new paleomagnetic constraints. *Journal of Geophysical Research: Solid Earth (1978–2012)*, **102**, 3153–3166.

Speranza, F., Maniscalco, R., Mattei, M., Di Stefano, A., Butler, R.W.H. & Funiciello, R. 1999. Timing and magnitude of rotations in the frontal thrust systems of southwestern Sicily. *Tectonics*, **18**, 1178–1197.

Stamatakos, J. & Kodama, K.P. 1991. Flexural flow folding and the paleomagnetic fold test; an example of strain reorientation of remanence in the Mauch Chunk Formation. *Tectonics*, **10**, 807–819.

Stauffer, M.R. 1964. The geometry of conical folds. *New Zealand Journal of Geology and Geophysics*, **7**, 340–347.

Stewart, S.A. 1995. Paleomagnetic analysis of plunging fold structures: errors and a simple fold test. *Earth and Planetary Science Letters*, **130**, 57–67.

Stewart, S.A. & Jackson, K.C. 1995. Palaeomagnetic analysis of fold closure growth and volumetrics. *In*: Turner, P. & Turner, A. (eds) *Palaeomagnetic Applications in Hydrocarbon Exploration and*

Production. Geological Society, London, Special Publications, **98**, 283–295, http://doi.org/10.1144/GSL.SP.1995.098.01.19

Strayer, L.M. & Suppe, J. 2002. Out-of-plane motion of a thrust sheet during along-strike propagation of a thrust ramp: a distinct-element approach. *Journal of Structural Geology*, **24**, 637–650.

Suppe, J. 1985. *Principles of Structural Geology*. Prentice-Hall, Englewood Cliffs, NJ.

Sussman, A.J. & Weil, A.B. (eds) 2004. *Orogenic Curvature: Integrating Paleomagnetic and Structural Analyses*. Geological Society of America, Special Papers **383**.

Sussman, A.J., Butler, R.F., Dinarès-Turell, J. & Vergés, J. 2004. Vertical-axis rotation of a foreland fold and implications for orogenic curvature: an example from the Southern Pyrenees, Spain. *Earth and Planetary Science Letters*, **218**, 435–449.

Sussman, A.J., Pueyo, E.L., Chase, C.G., Mitra, G. & Weil, A.J. 2012. The impact of vertical-axis rotations on shortening estimates. *Lithosphere*, **4**, 383–394.

Tarling, D.H. 1969. The palaeomagnetic evidence of displacements within continents. *In*: Kent, E.P.E., Satterthwaite, A.M.S. & Spencer, A.M. (eds) *Time and Place in Orogeny*. Geological Society, London, Special Publications, **3**, 95–113, http://doi.org/10.1144/GSL.SP.1969.003.01.06

Tauxe, L. 1998. *Paleomagnetic Principles and Practice*. Springer Science & Business Media, **1**. Dordrecht, The Netherlands.

Tauxe, L. 2005. Inclination flattening and the geocentric axial dipole hipótesis. *Earth and Planetary Science Letters*, **233**, 247–261, 15.

Tauxe, L. & Kent, D.V. 2004. A simplified statistical model for the geomagnetic field and the detection of shallow bias in paleomagnetic inclinations: was the ancient magnetic field dipolar? *Timescales of the Paleomagnetic Field*. Geophysical Monograph Series, **145**, 101–115.

Tauxe, L. & Watson, G.S. 1994. The fold test: an eigen analysis approach. *Earth and Planetary Science Letters*, **122**, 331–341.

Thomas, J.C., Chauvin, A., Gapais, D., Bazhenov, M.L., Perroud, H., Cobbold, P.R. & Burtman, V.S. 1994. Paleomagnetic evidence for Cenozoic block rotations in the Tadjik depression (Central Asia). *Journal of Geophysical Research: Solid Earth (1978–2012)*, **99**, B15141–15160 (Research, 112(B1), B01102).

Thöny, W., Ortner, H. & Scholger, R. 2006. Paleomagnetic evidence for large en-bloc rotations in the Eastern Alps during Neogene orogeny. *Tectonophysics*, **414**, 169–189.

van Andel, S.I. & Hospers, J. 1966. Systematic errors in the palaeomagnetic inclination of sedimentary rocks. *Nature (London)*, **212**, 891–893.

van der, & Pluijm, B.A. 1987. Grain scale deformation and the fold test-evaluation of synfolding remagnetization. *Geophysical Research Letters*, **14**, 155–157.

Van der Voo, R. 1990. The reliability of paleomagnetic data. *Tectonophysics*, **184**, 1–9.

Van der Voo, R. 2004. Paleomagnetism, oroclines, and growth of the continental crust. *GSA Today*, **14**, 4–9.

Van der Voo, R. & Channell, J.E.T. 1980. Paleomagnetism in orogenic belts. *Reviews of Geophysics and Space Physics*, **18**, 455–481.

Van der Voo, R. & Torsvik, T.H. 2001. Evidence for late Paleozoic and Mesozoic non-dipole fields provides an explanation for the Pangea reconstruction problems. *Earth and Planetary Science Letters*, **187**, 71–81.

Van der Voo, R. & Torsvik, T.H. 2012. The history of remagnetization of sedimentary rocks: deceptions, developments and discoveries. *In*: Elmore, R.D., Muxworthy, A.R., Aldana, M.M. & Mena, M. (eds) *Remagnetization and Chemical Alteration of Sedimentary Rocks*. Geological Society, London, Special Publications, **371**, 23–53, http://doi.org/10.1144/SP371.2

van Hinsbergen, D.J.J., Krijgsman, W., Langereis, C.G., Cornee, J.J., Duermeijer, C.E. & van Vugt, N. 2007. Discrete Plio-Pleistocene phases of tilting and counterclockwise rotation in the southeastern Aegean Arc (Rhodos, Greece); early Pliocene formation of the south Aegean left-lateral strike-slip system. *Journal of the Geological Society, London*, **164**, 1133–1144, http://doi.org/10.1144/0016-76492006-061

Villalaín, J.J., Fernández, G., Casas, A. & Gil Imaz, A. 2003. Evidence of a Cretaceous remagnetization in the Cameros Basin (North Spain): implications for basin geometry. *Tectonophysics*, **377**, 101–117.

Villalaín, J.J., Casas-Sainz, A.M. & Soto, R. 2015. Reconstruction of inverted sedimentary basins from syn-tectonic remagnetizations. A methodological proposal. *In*: Pueyo, E.L., Cifelli, F., Sussman, A.J. & Oliva-Urcia, B. (eds) *Palaeomagnetism in Fold and Thrust Belts: New Perspectives*. Geological Society, London, Special Publications, **425**. First published online October 2, 2015, http://doi.org/10.1144/SP425.10

Waldhör, M. 1999. The small-circle reconstruction in palaeomagnetism and its application to palaeomagnetic data from the Pamirs. Tuebinger Geowissenschaftliche Arbeiten. *Reihe A, Geologie, Palaeontologie, Stratigraphie*, **45**, 1–104.

Waldhör, M. & Appel, E. 2006. Intersections of remanence small circles; new tools to improve data processing interpretation in palaeomagnetism. *Geophysical Journal International*, **166**, 33–45.

Weil, A.B. 2006. Kinematics of orocline tightening in the core of an arc; paleomagnetic analysis of the Ponga Unit, Cantabrian Arc, northern Spain. *Tectonics*, **25**, 1–23.

Weil, A.B. & Sussman, A. 2004. Classification of curved orogens based on the timing relationships between structural development and vertical-axis rotations. *In*: Sussman, A.J. & Weil, A.B. (eds) *Orogenic Curvature: Integrating Paleomagnetic and Structural Analyses*. Geological Society of America, Special Papers, **383**, 1–17.

Weil, A.B. & Van der Voo, R. 2002. The evolution of the paleomagnetic fold test as applied to complex geologic situations, illustrated by a case study from northern Spain. *Physics and Chemistry of the Earth*, **27**, 1223–1235.

Weil, A.B., Van der Voo, R., Van der Pluijm, B.A. & Parés, J.M. 2000. The formation of an orocline by multiphase deformation: a paleomagnetic investigation of the Cantabria–Asturias Arc (northern Spain). *Journal of Structural Geology*, **22**, 735–756.

Weil, A.B., Van der Voo, R. & van der Pluijm, B.A. 2001. Oroclinal bending and evidence against the Pangea megashear; the Cantabria-Asturias Arc (northern Spain). *Geology*, **29**, 991–994.

Weinberger, R., Agnon, A., Ron, H. & Garfunkel, Z. 1995. Rotation about an inclined axis: three dimensional matrices for reconstructing paleomagnetic and structural data. *Journal of Structural Geology*, **17**, 777–782.

Wilkerson, M.S., Apotria, T. & Farid, T. 2002. Interpreting the geologic map expression of contractional fault-related fold terminations: lateral/oblique ramps versus displacement gradients. *Journal of Structural Geology*, **24**, 593–607.

Yonkee, A. & Weil, A.B. 2010. Quantifying vertical axis rotation in curved orogens: correlating multiple data sets with a refined weighted least squares strike test. *Tectonics*, **29**, TC3012–TC3043.

Zotkevich, I.A. 1972. Reduction of the natural remanent magnetization of a plunging fold to the ancient coordinate system in paleomagnetic studies. *Earth Physics*, **2**, 95–99.