Introduction: Palaeomagnetism in fold and thrust belts: new perspectives

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Palaeomagnetism, that is, the study of the ancient magnetic field recorded in rocks, is the only vectorial indicator in the Earth sciences that is capable of associating geological bodies with their original location (primary vectors) or with intermediate locations (secondary vectors) during their geological history. For this reason, palaeomagnetism has played a key role in supporting continental drift theory.

Beyond tectonic plate-scale applications, palaeomagnetism has become a fundamental tool for assessing the evolution of mountain ranges owing to its unique potential for quantifying vertical axis rotations (VAR). Since the pioneering applications of authors such as Norris & Black (1961) and Tarling (1969), palaeomagnetism has been applied to problems at a variety of scales in many orogenic systems (e.g. Elredge *et al.* 1985; Kissel & Laj 1989; Weil & Sussman 2004; Elmore *et al.* 2012). In particular, palaeomagnetic data have been increasingly used as key quantitative information for determining the timing, distribution and magnitude of vertical axis rotations (Van der Voo & Channell 1980; McCaig & McClelland 1992; Allerton 1998).

Together with structural analyses, palaeomagnetic investigations help to unravel the deformation history of fold and thrust belts, For instance, palaeomagnetism in growth strata has shed much light not only on the kinematics of folding and thrusting but also on the deformation timing such that quantitative geological reconstructions can be accomplished even in four dimensions (Pueyo *et al.* 2004; Arriagada *et al.* 2008; Ramón *et al.* 2012). These approaches reduce the levels of uncertainty of other structural variables, such as shortening and internal deformation.

Overall, this Geological Society Special Publication compiles contributions presenting recent developments in palaeomagnetism, in terms of both methodology and applications of palaeomagnetic studies to fold and thrust belts. The scientific breadth of this volume includes:

- compilations and overviews of fold and thrust belts with abundant palaeomagnetic data;
- case studies showing how palaeomagnetic data are used in understanding the kinematic evolution of geological structures at different scales;
- case studies showing how magnetostratigraphy contributes to the assessment of the magnitude and the timing of vertical axis rotations and deformation rates;
- studies of complex tectonic structures, including the integration of palaeomagnetism with anisotropy of magnetic susceptibility (AMS) and/or structural analyses; and
- analyses pertaining to data reliability, resolution analysis and error sources.

The volume starts with two papers that present large palaeomagnetic datasets (Fig. 1); the Western Carpathians (**Márton *et al.* 2015**) and the Western and Central Mediterranean arcs (**Cifelli *et al.* 2016**). In both cases, synthetic and robust palaeomagnetically deduced VARs are used to constrain the kinematic and geodynamic evolution in these regions.

The second part of the volume presents a suite of papers focused on different structural and tectonic

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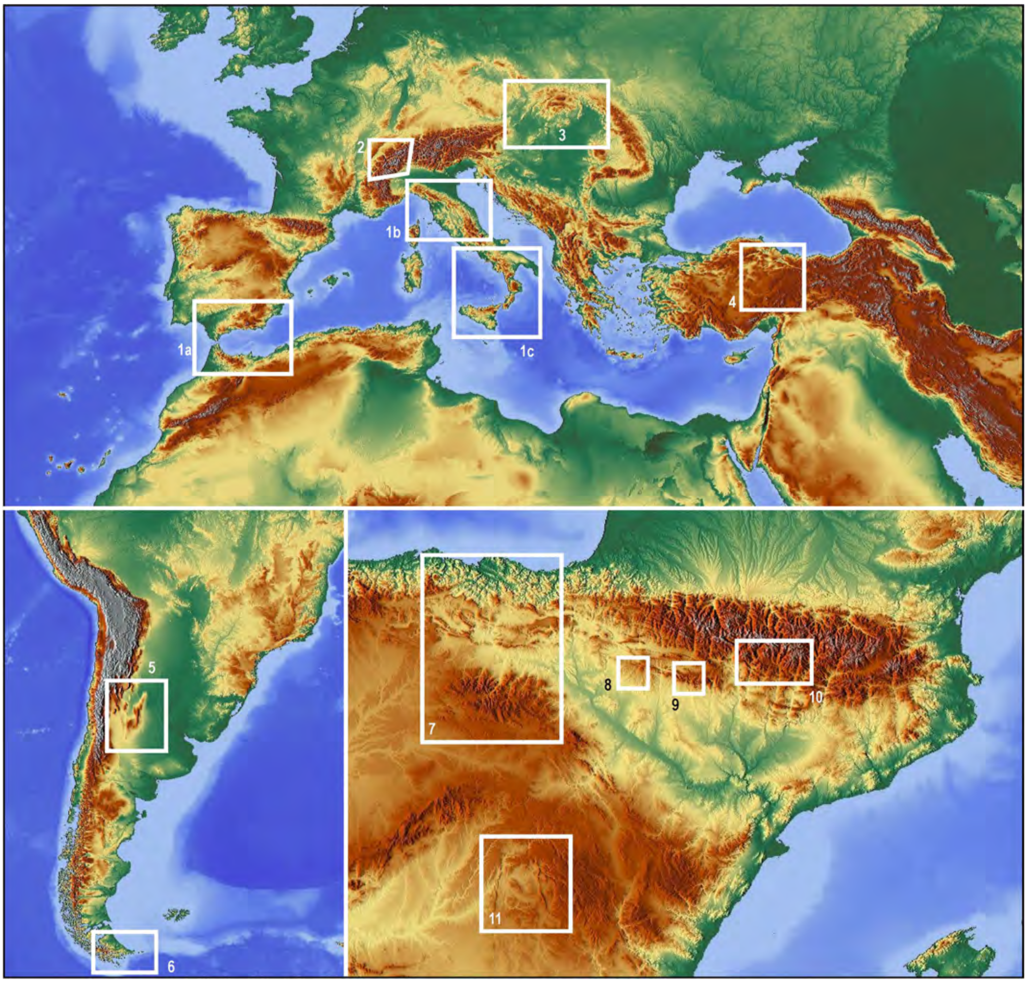

Fig. 1. Topographic map with the locations of the study area comprising this volume: **1a**, Betics and Rif arc; **1b**, Apeninnes; **1c**, Calabrian arc (Cifelli *et al.* 2016); **2**, Alps (Cardello *et al.* 2015); **3**, Western Carpathians (Márton *et al.* 2015); **4**, Central Anatolia (Cinku *et al.* 2015); **5**, Pampean Ranges (Japas *et al.* 2015); **6**, Patagonia (Rapalini *et al.* 2015); **7**, Polientes, Cabuerniga and Cameros basins (Villalaín *et al.* 2015); **8**, Western Pyrenean External Sierras (Oliva-Urcia *et al.* 2015); **9**, Pico del Aguila Anticline (Anastasio *et al.* 2015); **10**, Cotiella (Garcés *et al.* 2015); **11**, Altomira Range (Valcárcel *et al.* 2015). Source map: http://www.maps-for-free.com (licensed under the Creative Commons Attribution-Share Alike 2.0 Generic licence.).

problems in the Andes, Pyrenees, the Iberian Range, the Alps and Anatolia. **Rapalini *et al.* (2015)** show new data focused on unravelling the primary or secondary nature of the Patagonian orocline, **Japas *et al.* (2015)** discuss Neogene rotations measured in the Andean Precordillera fold and thrust belt. **Oliva-Urcia *et al.* (2015)** present a new magnetostratigraphic section from the southwestern portion of the Pyrenean main thrust that allows for both the refinement of the chronostratigraphy of the region and dating of primary folding and thrusting events. The Pico del Aguila anticline, in the central part of the basal thrust, is the target of the paper by **Anastasio *et al.* (2015)**, which uses AMS and published chronostratigraphy to decipher fold kinematics. The work by **Cardello *et al.* (2015)** in the Helvetic Alps and that by **Valcárcel *et al.* (2015)** in the Southern Iberian Range share some common features in that they represent detailed studies of individual structures and aim to obtain well-constrained kinematic models. These papers both integrate their palaeomagnetic data with structural, tectonic and AMS data, and bracket the limitations of their palaeomagnetic analyses. **Cinku *et al.***

(2015) investigate the palaeomagnetic rotations that occurred in the Kırşehir block during the closure of the remnant of the northern branch of the Neotethys Ocean, in the İzmir–Ankara–Erzincan suture zone, from Late Cretaceous to Middle Eocene times.

The third section of this volume is devoted to new approaches for the application of palaeomagnetism to fold and thrust belts. The paper by **Garcés *et al.* (2015)** introduces a new concept for the restoration of remagnetizations to the ancient reference system in the Central Pyrenees that takes into account the geometry of unconformities that formed during the extensional-basin inversion instead of the bedding plane. **Villalaín *et al.* (2015)** present the reconstruction of highly subsident extensional basins that, in turn, reset the palaeomagnetic signal; these basins were inverted during Tertiary development of a fold and thrust belt. In this case, the geometric analysis of the remagnetized directions has allowed for reconstruction of the geometry of those basins at the time interval of the remagnetization.

While quantitative use of palaeomagnetically deduced rotations is scarce, some researchers have addressed this problem in recent years. Palinspastic restorations of orogens can be much more precise if palaeomagnetic vectors are combined with structural features in a numerical approach. This was first applied in the Bolivian orocline by Arriagada *et al.* (2008). In a similar way, the quantification of errors in shortening estimates deduced from restored and balanced sections in fold and thrust belts has been recently introduced (e.g. Pueyo *et al.* 2004; Sussman *et al.* 2012). Here, **Ramón *et al.* (2015*a*)** propose a new 3-D restoration method that combines the use of palaeomagnetic data and a parametric approach for the definition and processing of the structural surfaces. These authors demonstrate that using palaeomagnetism clearly improves the restoration result of complex geological settings. Finally, **Pueyo *et al.* (2016)** present an overview of the potential sources of error in palaeomagnetic studies applied to deformed regions, review field, laboratory and processing techniques and propose an extension of the classic reliability criteria established by Van der Voo (1990).

Future and challenges of palaeomagnetic studies in fold and thrust belts

The application of palaeomagnetism to fold and thrust belts still has many challenges that need to be met in the future:

- *Data resolution* – resolution studies on palaeomagnetic data can be found in the literature specifically applied to tectonic problems (Demarest 1983; Bazhenov 1988). However, the definition of palaeomagnetic means at the dip-domain scale (*sensu* Suppe 1985; Groshong 1999) along thrust fronts is still required, perhaps with an approach similar to that of Deenen *et al.* (2011) but more focused on the geometry of the fold and thrust belts.
- *Reliability* – many potential sources of error can affect palaeomagnetic datasets in fold and thrust belts (see **Pueyo *et al.* 2016**). Apart from other processing and laboratory problems, the effect of internal deformation, non-resolved overlapping of components or errors in the restoration of complex settings may limit the value of the palaeomagnetic vectors as a robust kinematic indicator. In this sense, some advances on demonstrating the quality and reliability of the palaeomagnetic data have been made (MacDonald 1980; Chan 1988; Sellés-Martínez 1988; Weinberger *et al.* 1995; Rodríguez-Pintó *et al.* 2011). However, numerical modelling of errors and the establishment of specific procedures are still to be set.
- *Age constraining palaeomagnetic vectors* – constraining the age of the magnetization in palaeomagnetic studies is a key variable and it is usually done via the fold test (Graham 1949; McElhinny 1964), a powerful tool that is rarely used for other classic structural indicators. The statistical significance of the fold test is mature (e.g. Tauxe & Watson 1994; McFadden 1998; Enkin 2003), but mathematical approaches to the fold test do not consider phenomena such as folding kinematics. While some authors have already considered this problem (Cairanne *et al.* 2002; Delaunay *et al.* 2002; Waldhör & Appel 2006; **Villalaín *et al.* 2015**), further advances in this regard need to be accomplished.
- *Understanding the architecture of rotated areas* – understanding of the spatial and temporal variability of rotational patterns in fold and thrust belts is still in its infancy. In this sense, integration of classic determination of VARs and magnetostratigraphic studies may shed much more light in future on these systems in 4-D.
- *Quantitative implications* – palaeomagnetic results should play a more active role in the 2-D/3-D shortening estimation (cross-section, map view, 3-D restorations, etc.), since such data account for the out-of-plane movements biasing classic approaches (e.g. McCaig & McClelland 1992; Pueyo *et al.* 2004; Sussman *et al.* 2012). In this sense, palaeomagnetic vectors, together with the bedding plane, are the only reliable 3-D reference frame to be used in 3-D restoration and validation techniques, since they are accurately known in both the deformed and undeformed stages. Although some recent works have demonstrated this (Ramón *et al.* 2012, **2015*a***, *b*),

many challenges remain. We encourage future investigators to meet such challenges.

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References

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

ANASTASIO, D., PARÉS, J.M., KODAMA, K.P., TROY, J. & PUEYO, E.L. 2015. Anisotropy of magnetic susceptibility (AMS) records synsedimentary deformation kinematics at Pico del Aguila anticline, Pyrenees, Spain. *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 June 16, 2015, http://doi.org/10.1144/SP425.8

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**, 1–14.

BAZHENOV, M.L. 1988. Analysis of the resolution of the paleomagnetic method in solving Tectonic Problems. *Geotectonics*, **22**, 204–212.

CAIRANNE, G., 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, Parts A/B/C*, **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 palaeomagnetic 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 version published online August 18, 2015, http://doi.org/10.1144/SP425.4

CHAN, L.S. 1988. Apparent tectonic rotations, declination anomaly equations and declination anomaly charts. *Journal of Geophysical Research*, **93**, 12 151– 12 158.

CIFELLI, F., CARICCHI, C. & MATTEI, M. 2016. Formation of arc-shaped orogenic belts in the Western and Central Mediterranean: a paleomagnetic review. *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 February 17, 2016, http://doi.org/10.1144/SP425.12

CINKU, 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 version published online August 14, 2015, http://doi.org/10.1144/SP425.2

DEENEN, M.H.L., LANGEREIS, C.G., VAN HINSBERGEN, D.J.J. & BIGGIN, A.J. 2011. Geomagnetic secular variation and the statistics of palaeomagnetic directions. *Geophysical Journal International*, **186**, 509–520.

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, Parts A/B/C*, **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.

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.

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

ELREDGE, S.; BACHTADSE, V. & VAN DER VOO, R. 1985. Paleomagnetism and the orocline hypothesis. *Tectonphysics*, **119**, 153–179.

GARCÉS, M., GARCÍA-SENZ, J., MUÑOZ, J.A., LÓPEZ-MIR, B. & BEAMUD, E. 2015. Timing of magnetization and vertical-axis rotations of the Cotiella massif (Late Cretaceous, South Central Pyrenees) *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 23, 2015, http://doi.org/10.1144/SP425.11

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

GROSHONG, R.H., JR, 1999. *3-D Structural Geology*. Springer-Verlag, Heidelberg.

JAPAS, M.S., RE, 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

KISSEL, C. & LAJ, C. 1989. Paleomagnetic rotations and continental deformation. *NATO ASI Science Series C*, **254**, Kluwer Academic Publishers, Boston.

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.

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

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

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

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

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

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 version published online August 21, 2015, http://doi.org/10.1144/SP425.5

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) *Special Publication on Orogenic Curvature: Integrating Paleomagnetic and Structural Analyses*. Geological Society of America, Boulder, CO, **383**, 57–71.

Pueyo, E.L., Sussman, A.J. & Oliva-Urcia, B. & Cifelli, F. 2016. Palaeomagnetism in fold and thrust belts: use with caution. *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 7, 2016, http://doi.org/10.1144/SP425.14

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., Pueyo, E.L., Caumon, G. & Briz, J.L. 2015*a*. 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

Ramón, M.J., Briz, J.L., Pueyo, E.L. & Fernández, O. 2015*b*. Horizon restoration by best fitting of finite elements and rotation constraints: sensitivity to the mesh geometry and pin-element location. *Mathematical Geosciences*, 1–19.

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

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.

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

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

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, http://doi.org/10.1130/L177.1

Tarling, D.H. 1969. The palaeomagnetic evidence of displacements within continents. *In*: Kent, P.E., Satterthwaite, E. & 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. & Watson, G.S. 1994. The fold test: an Eigen analysis approach. *Earth and Planetary Science Letters*, **122**, 331–341.

Valcárcel, M., Soto, R., Beamud, E., Oliva-Urcia, B., Muñoz, J.A. & Biete, C. 2015. Integration of palaeomagnetic data, basement-cover relationships and theoretical calculations to characterize the obliquity of the Altomira–Loranca structures (central Spain). *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 21, updated version published online September 3, 2015, http://doi.org/10.1144/SP425.7

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

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

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

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

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.