GR Letter

The onset of the assembly of Pangaea in NW Iberia: Constraints on the kinematics of continental subduction

Rubén Díez Fernández [a,*], José R. Martínez Catalán [a], Ricardo Arenas [b], Jacobo Abati [b]

[a] Departamento de Geología, Universidad de Salamanca, 37008 Salamanca, Spain
[b] Departamento de Petrología y Geoquímica and Instituto de Geología Económica, Universidad Complutense/Consejo Superior de Investigaciones Científicas, 28040 Madrid, Spain

ABSTRACT

Excellent exposures of high-pressure rocks developed in a Variscan continental subduction system outcrop in NW Iberia. The kinematic criteria provided by the high-pressure metamorphic fabrics can be used to infer tectonic flow within the deep sections of this system. The dominant trend of the ductile flow is oblique to that of the orogenic belt, indicating oblique continental subduction. Its azimuth, a few tens of degrees clockwise relative to the orogenic trend, suggests dextral transpression between Gondwana and Laurussia during continental subduction that took place at the Upper Devonian, and provides a consistent kinematic reference for the earliest assembly of Pangaea in NW Iberia.

Keywords:
Assembly of Pangaea
Continental subduction kinematics
Tectonics
NW Iberia

1. Introduction

The oldest evidence on the plate kinematics of a given continent–continent assembly lies in its continental subduction record preceding collision, and the high- to ultrahigh-pressure (HP/UHP) belts so formed are witness of such processes. Exhumed continental blocks develop a strong overprint of the subduction record as they return to shallower lithospheric levels (e.g. Ring et al., 2007; Zhang et al., 2009; Hacker et al., 2010), where such evidence is mostly preserved in small and disconnected lenses (e.g. eclogite pods; Teyssier et al., 2010), commonly as mineral relicts within a dominant low- to medium-pressure metamorphic matrix. Indeed, recent modeling predicts large-scale nappe-folding during the process (e.g. Gerya et al., 2002; Warren et al., 2008) that would distort any former geological record (Díez Fernández et al., 2011a). For these reasons, unraveling the earliest kinematic events in ancient collisional orogenies is one of the most critical topics in tectonics, and requires significant structural and metamorphic insights.

The supercontinent Pangaea assembled from the collision between Gondwana and Laurussia, following the closure of the Rheic Ocean during the Upper Paleozoic (Matte, 1986; Scotese, 1997; Stampfli and Borel, 2002; Martínez Catalán et al., 2009). The Variscan Belt represents that part of this amalgamation preserved in Europe, which started with the subduction of the Gondwana plate in the Upper Devonian (e.g. Schulmann et al., 2005; Ballèvre et al., 2009; Abati et al., 2010). Kinematic data for this event are lacking. Variations in the PT conditions of the first HP metamorphic event along this margin indicate a west-dipping (present coordinates) polarity for the continental subduction in NW Iberia (Martínez Catalán et al., 1996). There is a lack of consistent indicators of along-strike components during the subduction, so ideas about the early relative plate movement between the two main landmasses involved in the assembly of Pangaea are highly speculative (e.g. Arenas et al., 2009).

Exposures of well-preserved Variscan HP rocks are rare, but where they occur they provide evidence for the kinematics of continental subduction. We present *in situ* kinematic criteria from the best outcrops of eclogite rocks developed in the section of the Variscan subduction system exposed in NW Iberia, Spain. The data are accompanied by a detailed field analysis and a regional tectonometamorphic synthesis in order to constrain their plate tectonic significance.

2. Geologic setting

The allochthonous complexes of NW Iberia comprise a nappe stack of allochthonous units, in which the Neoproterozoic and Paleozoic geodynamic evolution of the northern peri-Gondwanan realm is preserved as a collage of exotic terranes that delineate a piece of the suture zone of the Rheic Ocean (Fig. 1; Martínez Catalán et al., 2009). The peripheral and outermost domains are placed on top. The uppermost thrusts consist of an imbricated Cambro-Ordovician continental

* Corresponding author. Tel.: +34 923 294488; fax: +34 923 294514.
E-mail addresses: georuben@usal.es (R. Díez Fernández), jrmc@usal.es (J.R. Martínez Catalán), arenas@geo.ucm.es (R. Arenas), abati@geo.ucm.es (J. Abati).

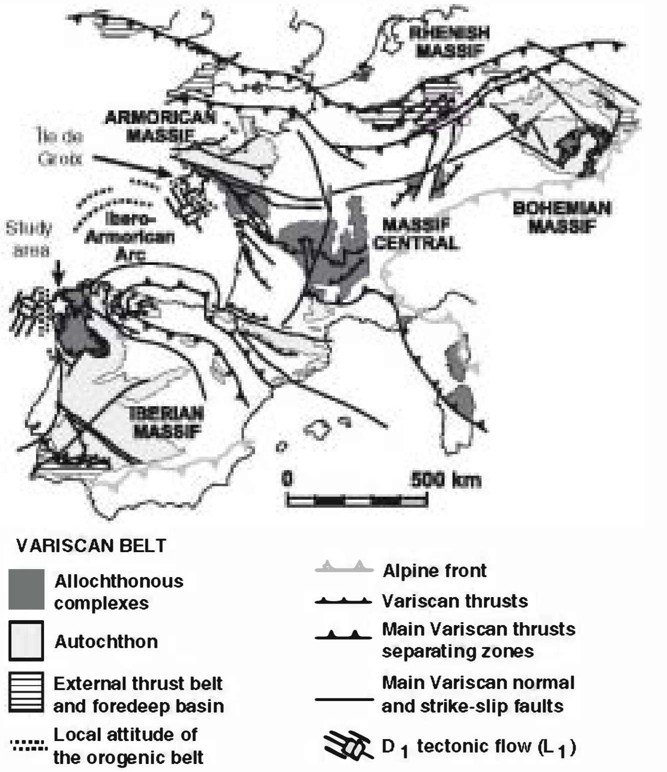

Fig. 1. Location of the study area in the Variscan belt. The orientation of D_1 tectonic flow in relation to the trend of the orogenic belt is shown. Data from NW Iberia (published in this article) and from Île de Groix, France (Philippon et al., 2009).

arc detached from Gondwana (Abati et al., 1999; Gómez Barreiro et al., 2007). The middle units are ophiolitic, and represent vestiges of Rheic Ocean lithosphere (Sánchez Martínez et al., 2009). The basal units outline the most external part of the Gondwana margin (Díez Fernández et al., 2010; Díez Fernández et al., 2011b). The allochthonous pile rests on top of a parautochthonous imbricate thrust sheet that occupies an intermediate position in the regional structural pile, separating the allochthonous complexes from the autochthonous series of the Iberian Massif (Martínez Catalán et al., 2007).

Variscan deformation started in the basal units, and developed under HP/UHP conditions (D_1; Díez Fernández et al., 2011a). This event records the subduction of Gondwana beneath an accretionary complex and Laurussia (Fig. 2), and is the focus of this article.

3. The relicts of continental subduction

The basal units include large, lens-shaped, orthogneiss massifs surrounded by albite-bearing schists and paragneisses, and alternating with mafic rocks (Fig. 3a). The metamorphic conditions reached within the subduction wedge range between blueschist and eclogite facies, whereas the early exhumation (D_2) developed under amphibolite to

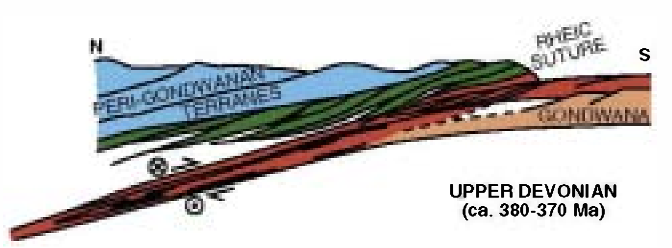

Fig. 2. Continental subduction model for the northern Gondwana margin exposed in NW Iberia.

greenschist facies conditions (Rodríguez et al., 2003). The HP mineral assemblage (S_1) in the metasedimentary rocks consists of quartz + phengite + garnet ± rutile ± epidote in the lower structural sections (Díez Fernández et al., 2011a), and chloritoid + garnet ± glaucophane + phengite + paragonite + chlorite + epidote + rutile + illmenite + quartz in the upper sections (López-Carmona et al., 2010). These assemblages usually occur as mineral trails within syn-exhumation albite porphyroblasts (Arenas et al., 1995), and have not been considered for kinematic analysis.

A foliation developed in most of the orthogneisses during the earliest stages of exhumation (Díez Fernández et al., 2011a), but relict coronitic garnets in igneous biotite provide evidence for the subduction event (Gil Ibarguchi, 1995). More importantly, non-retrogressed HP fabrics can be found in tonalitic orthogneisses, which also enclose subconcordant lenses of eclogite. Both the tonalitic orthogneisses and the eclogites are exposed together in the Malpica-Tui Complex north of the Fervenza reservoir (Fig. 3a and b), where they represent large bodies, several hundreds of meters thick that escaped retrogression during exhumation.

The D_1 assemblage (S_1) of the tonalitic orthogneisses includes omphacite + garnet + quartz + zoisite + phengite + rutile + kyanite ± apatite ± zircon, and defines a tectonic banding in which quartz-rich layers alternate with melanocratic layers and lenses with nemato-lepidoblastic texture (Fig. 4a). The eclogites are fine- to medium-grained rocks with grano-nematoblastic texture. S_1 consists of garnet + omphacite + zoisite + rutile + phengite + quartz + kyanite (Fig. 4b). S_1 is the main foliation within the HP bodies, and its minerals define a mineral and a stretching lineation (L_1). These rock types provide clues to the metamorphic and deformational conditions at P > 2 GPa (2.4–2.6 GPa and 615 °C; Rodríguez et al., 2003), and the age of the oldest dated Variscan deformation (372 ± 3 Ma; Abati et al., 2010). In the tonalitic orthogneisses, chlorite, white mica and epidote may occur within D_1-garnet, whereas in the eclogites, glaucophane may be trapped within D_1-garnet (Fig. 4c). Such inclusions witness previous colder conditions in a HP prograde P-T-t path, suggesting that S_1 represents a fossil relict of the continental subduction.

4. Kinematic criteria and structural framework

The sense of rotation of the vorticity vector of the D_1 tectonic flow was determined by using offset mesoscopic and microscopic features in S_1. Kinematic criteria include σ-type porphyroclasts and lenses, asymmetrical boudinage, SC composite foliation or C′ fabrics, and intrafolial asymmetrical recumbent folds (Fig. 4d and e). S_1 is a flat-lying foliation bent into open upright synforms (see local orientation in Fig. 3a) and shows consistent top-to-the-NE shear-sense (Fig. 3c). D_1 folds axes have NW–SE trends (120º/16º) and are perpendicular to L_1, the mean trend of which in the tonalitic orthogneisses and eclogites is 30º/21º (Fig. 3c), thus constraining the D_1 tectonic flow to a NE–SW vector.

The early exhumation of the basal units was driven by large fold-nappe structures (D_2). Progressive exhumation started with the Fervenza thrust, which was followed by the propagation towards the foreland of a train of recumbent folds, and replaced by the Lalín-Forcarei thrust (Fig. 3d; Díez Fernández et al., 2011a). These events preceded the emplacement of the suture zone onto the Gondwana mainland by out-of-sequence thrusting (D_3; Martínez Catalán et al., 2002). Crustal thickening was followed by the gravitational collapse of the collisional wedge (D_4; Gómez Barreiro et al., 2010; Díez Fernández et al., accepted), wrench tectonics and upright folding (D_5), and oroclinal bending (Weil et al., 2000). In the light of such a complex scenario, the interpretation of the D_1 flow relies on whether or not the relative orientations of the indicators were modified during the exhumation.

The tonalitic orthogneiss bodies occur in the hanging wall of the Fervenza thrust, in the normal limb of a D_2 fold (Fig. 3b), in a domain free from strike-slip shear zones, and at the hinge zone of a late, open upright synform. Although the tonalitic orthogneisses are surrounded

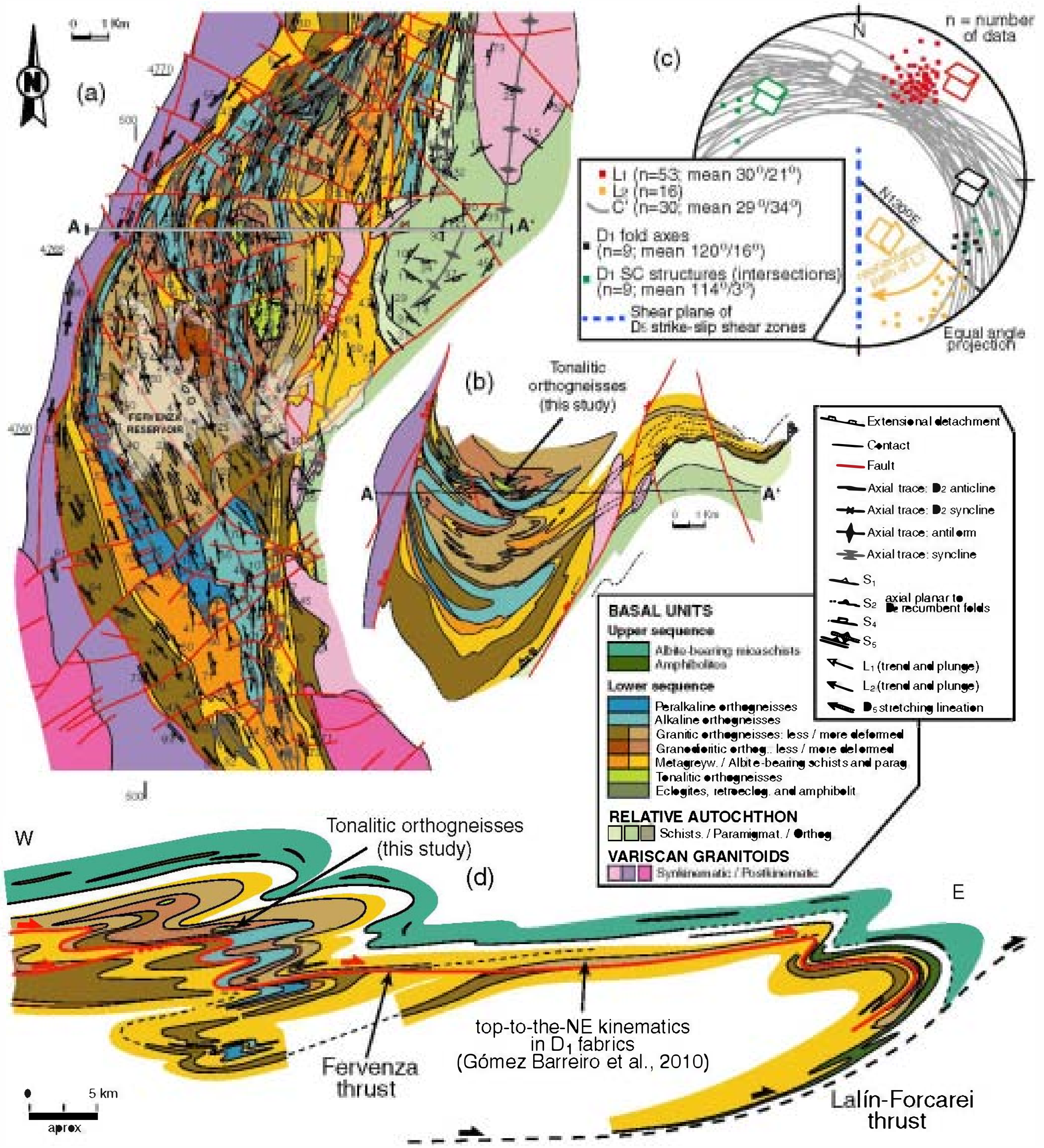

Fig. 3. (a) Geological map of the Malpica–Tui Complex around the Fervenza reservoir (UTM coordinates, Zone 29). (b) Cross-section. (c) Plot showing the orientation of D_1 structures and kinematics (equal angle projection). Orientation of L_2 bounding the HP bodies is also included. (d) Reconstruction of the structure of the basal units after D_2 exhumation event showing the position of the studied tonalitic orthogneisses (after Díez Fernández et al., 2011a).

by mylonitic felsic orthogneisses with a penetrative D_2 fabric (S_2; top-to-the-SE and -ESE), L_1 and the stretching lineation developed during D_2 (L_2) are usually oriented at very high angles to one another and may be perpendicular (Fig. 3a and c). Subsequent deformation phases did not affect this section of the Malpica–Tui Complex, which in this part of the Ibero-Armorican arc has a N–S orientation.

5. Discussion

No significant ductile reorientation of D_1 linear fabrics related to folding and/or deflection by ductile shearing has been observed in the tonalitic orthogneisses north of the Fervenza reservoir. This is supported by the near perpendicular relationship between D_1 fold

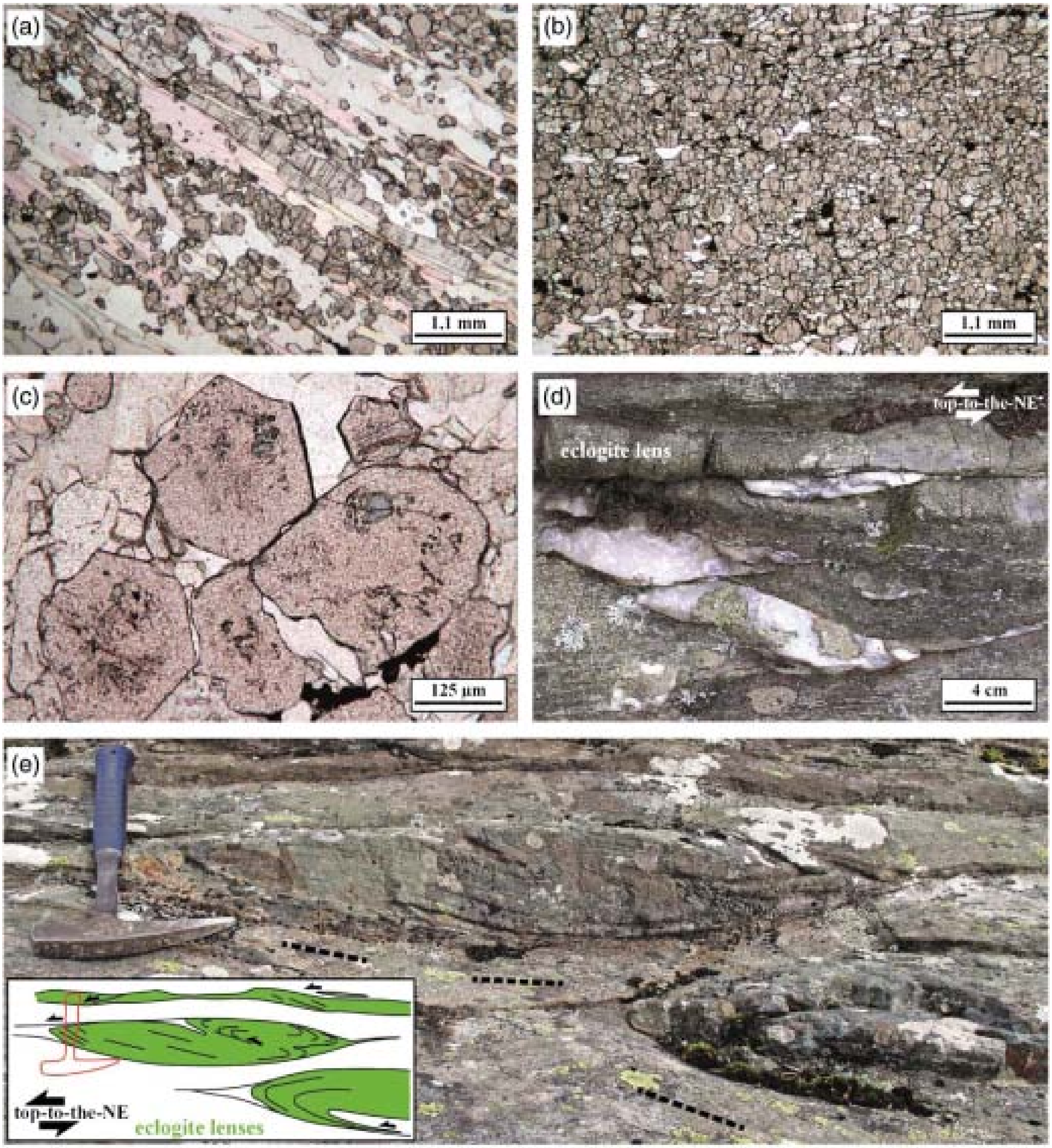

Fig. 4. (a) S_1 in the tonalitic orthogneisses. (b) S_1 in fine-grained eclogites enclosed in tonalitic orthogneisses. (c) Glaucophane relicts in D_1 garnets from eclogite. (d) Sigmoidal boudinage in quartz ribbons and segregates from tonalitic orthogneisses. (e) Structures preserved in eclogite lenses enclosed in tonalitic orthogneisses. See sketch for best visualization of kinematic criteria (sigmoidal boudinage with σ-type asymmetry boudinage and intrafolial folds, C′ fabrics, and S–C composite foliation). Stretching lineation (L_1) is shown as black dashed lines. The picture is normal to D_1 fold axes.

axes and L_1 (Fig. 3c). The data suggest passive rotation of the large, undeformed domains embedded in a viscous media. But a detailed 3D analysis of two large orthogneissic massifs in the southern part of the Malpica–Tui Complex indicate that the same regional NNE–SSW stretching during D_1 occurred there (Díez Fernández and Martínez Catalán, 2009). That study was carried out 80 to 95 km to the south of the Fervenza reservoir, and the fact that the main D_1 stretching direction is the same in both areas allows us to discard the possibility of large passive rotations. On the other hand, the analysis of quartz c-axis fabrics of tectonites provided a similar attitude for D_1 flow in the continuation of the basal units in the Órdenes Complex, to the east (Gómez Barreiro et al., 2010).

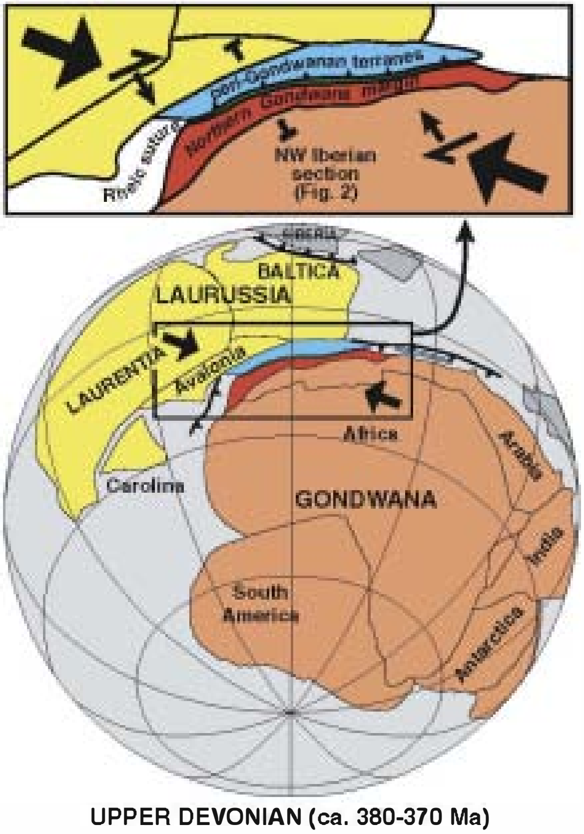

Fig. 5. Suggested global plate kinematics during the Upper Devonian. Continental mass distribution based on Winchester et al. (2002) and Gómez Barreiro et al. (2007).

Although post-subduction mylonitization deeply affected the Malpica–Tui Complex, modifying and reorienting nearly all of the earlier planar and linear fabrics towards their respective flow planes (e.g. L_2 toward D_5 shear zones; Fig. 3a and c), we conclude that the NE–SW trend preserved in the tonalitic orthogneisses is a reasonable approximation to the original D_1 flow vectors. It must be pointed out, however, that such a trend is estimated in present coordinates, and for a section of the belt with a N–S attitude.

The same Variscan continental subduction system described here is also exposed in Île de Groix, France (Fig. 1). There, Philippon et al. (2009) reported top-to-the-SE kinematics in D_1 fabrics. Coming from a small island, it is difficult to put this datum in a regional structural context since it is disconnected from the Armorican Massif. However, the Île de Groix lithologies and tectonometamorphic evolution are comparable to that of the upper sequence exposed in the basal units of NW Iberia (Díez Fernández et al., 2010), which occurs in the long, normal limb of a large D_2 fold-nappe (Díez Fernández et al., 2011a). If the structural position is equivalent in Île de Groix, and the Ibero-Armorican Arc is restored to a straight trend (Weil et al., 2000), the D_1 flow in the French section becomes similar to that preserved in NW Iberia, that is, with its azimuth rotated clockwise in relation to the trend of the orogenic belt (Fig. 1).

The interpretation of stretching lineations is always subject to some controversy, as its meaning may vary depending on the geometry of the shear zone (Passchier, 1998). The D_1 event records very deep processes in the Variscan subduction system, where a significant component of pure shear might be expected. However, our field data support the existence of a dominant component of simple shear, since L_1 and the D_1 vorticity vector are perpendicular. We cannot distinguish between monoclinic and triclinic symmetries but, in either case, the stretching lineation would tend to point to the shear direction (Lin et al., 1998).

In a suture zone, stretching normal to its regional trend would be consistent with orthogonal subduction, whereas an oblique stretching lineation would indicate strike-slip components. The NE–SW tectonic flow of the D_1 deformation in the Malpica–Tui Complex supports a combination of normal and parallel components, acting together in this particular plate boundary instead of being partitioned in separate fault zones. We consider that the flow reported here for D_1 deformation represents the coupling between the downgoing Gondwana plate and the overriding Laurussian mantle wedge in a large and wide ductile shear zone dominated by simple shear. This megastructure affected a considerable section of the subducted continental crust and developed in an oblique subduction setting with a significant component of dextral motion (Fig. 5).

Acknowledgements

The authors thank reviewers Michel Ballèvre and Brendan Murphy, as well as editor Damian Nance for many useful and constructive comments. This work was funded by research projects CGL2007-65338-C02-01 and -02/BTE of the Dirección General de Programas y Transferencia del Conocimiento (Spanish Ministry of Science and Innovation), co-financed by the European Funds of Regional Development (FEDER).

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