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3D Analysis of an Ordovician igneous ensemble: A complex magmatic structure hidden in a polydeformed allochthonous Variscan unit

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ABSTRACT

The basal units of the allochthonous complexes of NW Iberia represent a fragment of the external edge of Gondwana subducted and subsequently exhumed during the Variscan collision. The structural analysis carried out in orthogneissic massifs of the southern part of one of these, the Malpica–Tui Unit, reveals the generation of recumbent folds and associated axial planar foliation during their exhumation. These folds nucleated in irregular igneous bodies that were initially deformed during the subduction event and show east to southeast vergence. Down-plunge projection of surface data and a series of regularly spaced cross-sections have been used to build 3D models of the two main bodies of orthogneiss, of calc-alkaline and peralkaline compositions respectively. The first is presently a lens-shaped body folded in a recumbent syncline, whereas the peralkaline gneiss, also affected by a train of asymmetric recumbent folds in the south, exhibits in the north a fold-like structure which is interpreted as inherited from its primary geometry, that of a ring dike pluton.

1. Introduction

Establishing the geometry of granitic plutons may provide clues about their emplacement mechanisms and tectonic setting. 3D geometries are usually obtained combining structural and AMS analyses with gravity and magnetic modelling. These techniques are applied successfully to the study of plutons either undeformed or deformed during their emplacement, that is, to syn- to post-kinematic granite massifs (Bouchez et al., 1990; Yenes et al., 1999; Simancas et al., 2000; Aranguren et al., 2003; Neves et al., 2003; Talbot et al., 2004, 2005).

The original shape of strongly deformed granitic gneisses is much more difficult to establish. Deformation of igneous bodies with contrasted viscosity inside a shear zone can include rotation, shortening, flattening, and stretching, and can be accompanied by folding, boudinage, and the development of relative discrete shear zones from crystal to crustal scale. The whole gneissification of kilometre-scale granitic massifs implies deep changes in their geometry that often obscures what kind of igneous intrusion they represent. The reconstruction of the original shapes is usually impossible, as it would need a detailed knowledge of the finite strain for the whole volume of the bodies to carry out a three dimensional restoration.

However, even when strongly flattened and/or stretched, the chronological order of emplacement of different plutons can be established using cross-cutting relationships, and hints on their primary geometry can arise from their deformed shapes. Initially rounded, equidimensional plutons may become folded, specially when deformation is polyphasic, which adds complexity to the correct interpretation of the plutons. In that case, a structural study using basic geometrical techniques can be applied to identify fold geometry and separate folds from primary igneous geometries. Linkage between primary igneous geometries and room available during emplacement allows certain shapes of igneous bodies to be related to particular stress regimes, and ultimately to specific geodynamic contexts. As there is also a connection between magmatic associations and geodynamic context (Pitcher, 1993; Barbarin, 1999), magma type can be used as a helpful guide to envisage the original igneous structure at the light of these relations.

This is the case presented here, where two orthogneisses of different composition are strongly deformed and folded, and where their folded geometries and mutual relationships, combined with the peculiar composition of one of the massifs, permits the original shape of both massifs to be envisaged.

2. Geological setting

The allochthonous complexes of NW Iberia represent a nappe stack where three main groups of allochthonous units have been

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distinguished (Martínez Catalán et al., 2007). The upper units are pieces of a Cambro-Ordovician ensialic island arc (Andonaegui et al., 2002; Santos et al., 2002; Abati et al., 2003), the middle units are ophiolitic, and represent the suture of the Rheic Ocean (Díaz García et al., 1999; Pin et al., 2002, 2006; Arenas et al., 2007; Sánchez Martínez et al., 2007), and the basal units derive from distal parts of the Gondwanan continental margin. The basal units experienced extension and rift-related magmatism during the Ordovician (Ribeiro and Floor, 1987; Pin et al., 1992), subduction at the beginning of the Variscan collision (Van Calsteren et al., 1979; Santos Zalduegui et al., 1995; Rodríguez et al., 2003) and exhumation driven by crustal-scale thrusting accompanied by recumbent folding, and tectonic denudation during the Variscan orogeny (Gil Ibarguchi and Ortega Gironés, 1985; Arenas et al., 1995; Martínez Catalán et al., 1996, 1997; Rubio Pascual et al., 2002).

This study is centred in the southern part of the Malpica–Tui Unit, one of the basal allochthonous units that crops out in the western part of Galicia, in NW Iberia (Fig. 1). The Malpica–Tui Unit shows the characteristics of a thinned continental crust, and consists of a thick terrigenous pile of sediments intruded by a bimodal suite of granitic and basic magmas of Ordovician age deformed during the Variscan orogeny (Van Calsteren et al., 1979; García Garzón et al., 1981; Santos Zalduegui et al., 1995). The granitic rocks include felsic and biotitic gneisses with calc-alkaline affinities (tonalites, granodiorites and high-K granites), a mildly alkaline association composed of metaluminous alkali-feldspar quartz-syenites and granites, peraluminous alkali-feldspar granites and peralkaline granites (Rodríguez Aller, 2005). The protoliths of the alkaline and peralkaline gneisses seem to be younger than the calc-alkaline gneisses because they lack the widespread basic intrusions included in the felsic and biotite gneisses and in the metasediments.

One of the main features of the Malpica–Tui Unit and other units occupying the lower position of the allochthonous tectonic pile is the record of an early Variscan high-pressure metamorphic event (Gil Ibarguchi and Ortega Gironés, 1985; Rodríguez et al., 2003) related to subduction with a west-directed component. Subduction was followed by exhumation and emplacement toward the east, over their relative autochthon which represents relatively inner parts of Gondwanan continental margin (Martínez Catalán et al., 1996, 1997; Rubio Pascual et al., 2002).

3. Variscan deformation events

Three main phases of deformation can be recognized in the Malpica–Tui Unit. The first (D_1) is only identified as an internal fabric ($S_i = S_1$) included in porphyroblasts (Fig. 2). But it is important because that fabric is the one associated to the high-pressure metamorphic event. The second phase (D_2) is associated to the main tectonic foliation (S_2), and related to recumbent folding and the exhumation of the unit by thrusting. The third deformation phase (D_3) gave rise to upright folds that bent the main foliation and produced fold-interference patterns.

3.1. *Relicts of early-Variscan subduction (D_1)*

Aligned internal fabrics (S_i) in blasts of albite in metasediments and of plagioclase in amphibolites, plus the presence of S_2 crenulation cleavage in the metasediments (Fig. 3a), prove the existence of an initial phase of deformation (D_1) strong enough to generate a planar tectonic fabric (S_1) and consequently to modify the original shape of the igneous bodies.

In the metasediments, the stable mineral assemblage consists of quartz, white mica, garnet, and rutile preserved in S_2 crenulated microlithons (Fig. 3b) and in the core of albite porphyroblasts (Fig. 3c). Stable growth of garnet without biotite, the presence of rounded reabsorbed turbid garnets and the atoll-like texture of those not included in the porphyroblasts support initial conditions of high pressure and low to medium temperature (Higashino, 1990; Otsuki and Banno, 1990; Takasu and Dallmeyer, 1990). These are in accordance with similar conditions established in other basal units of NW Iberia (Munhá et al., 1984; Schermerhorn and Kotsch, 1984; Gil Ibarguchi and Ortega Gironés, 1985; Díaz García, 1990; Arenas et al., 1995; Martínez Catalán et al., 1996; Rodríguez Aller, 2005). The assemblage in the metasediments is compatible with the inclusions of garnet, amphibole, rutile, chlorite, epidote and quartz inside the plagioclase of amphibolites, although this is not a characteristic high-pressure association in the metabasites. Even if there are no eclogite or blueschist facies indicators in the southern part of the Malpica–Tui Unit, small-sized garnet and rutile included in the porphyroblasts of plagioclase and absent in the matrix are a typical feature of retrogressed high-pressure metabasites in the northern parts of the unit (Gil Ibarguchi and Ortega Gironés, 1985).

Because of the lack of quantitative data, a conservative estimation of the pressure has been made based on the absence of eclogite assemblages in the metabasites and the scarce development of garnet in the metasediments compared with other related basal allochthonous units in NW Iberia (Arenas et al., 1995). Accordingly, we suggest a minimum pressure of 1 GPa during D_1, in a context of continental subduction. This interpretation confers an exhumative character to the second deformation phase (D_2), which moved the unit from these burial conditions to the amphibolite facies domain, and which was followed by further depressurization and heating during D_3.

3.2. *The regional fabrics (D_2)*

This phase is responsible of large recumbent folds affecting the orthogneisses and of the regional foliation (S_2) and lineation (L_2). The main foliation in the metasediments appears as a schistosity defined by statistically oriented quartz, biotite and white mica, subparallel or oblique to a compositional layering (S_0, Fig. 3d), and including albite porphyroblasts. When oblique to S_0, an intersection lineation can be observed.

The granitic orthogneisses include augen, planar, linear, planolinear and mylonitic varieties, pointing to heterogeneities in the deformation and perhaps to original textural and mineralogical heterogeneities in the igneous rocks. Index minerals and geochemical and textural features make it possible to map different gneissic bodies which may represent either single or composite related intrusions. Three main kinds of intrusive magmas can be distinguished: calc-alkaline, alkaline and peralkaline (Floor, 1966; Rodríguez Aller, 2005). All of them show a gneissic foliation and a mineral lineation formed by an alternation and alignment of quartz-feldspathic bands and different ferromagnesian minerals depending on the composition. These index and other secondary minerals are oriented and aligned, individually or in aggregates, parallel to the main foliation and lineation.

The largest massif in the study area is a biotite orthogneiss (Fig. 4) with calk-alkaline affinity containing biotite and lesser amounts of green amphibole (hornblende) as ferromagnesian index minerals (Fig. 3e). For the alkaline orthogneiss, cropping out in the southern part of the study area (Fig. 4), the index minerals are biotite and an alkaline green amphibole (hastingsite), both occurring generally in the same proportion but sometimes with one of them dominating among the ferromagnesian phases (Fig. 3f).

The peralkaline orthogneisses include riebeckite (blue amphibole) and/or aegirine (green pyroxene) as main index minerals, whereas astrophyllite occurs sometimes as a minor constituent of the rock (Fig. 3g). Occasionally, these gneisses crop out related with