Journal of Geodynamics 101 (2016) 170–185

Contents lists available at ScienceDirect

Journal of Geodynamics

journal homepage: http://www.elsevier.com/locate/jog

Structure and tectonic setting of the SE Sardinia mafic dyke swarm. Insights for the stress state during magma emplacement in the upper crust

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ARTICLE INFO

Article history:
Received 1 November 2015
Received in revised form 15 May 2016
Accepted 30 May 2016
Available online 25 June 2016

Keywords:
Corso-Sardinian block
Dyke emplacement
Fracture
Paleostress analysis
Permian

ABSTRACT

The SE Sardinia mafic dyke swarm intruded in Permian times into the Late Variscan granitoids of the Sàrrabus massif. In order to characterize the structure of the dyke swarm and to assess the stress state and tectonic regime at the time of dyking, we have performed a multi-methodological study which encompasses paleostress analysis using the orientation distribution of dykes, estimation of crustal extension from dyke thickness/spacing ratios and true dilation direction from the matching geometry of offsets. The mean orientation of the dyke swarm is ~N150°, with secondary main trends orientated ~N77° and ~N10°. The fracture network (mostly joints) exhibits multiple orientations grouped in four or more sets, being the orientation and density patterns in granitoid and dykes significantly different. Some of the pre-existing joints were exploited by the dykes, while others were reactivated as faults during and after dyke intrusion. The paleostress analysis yielded σ_1 sub-vertical, indicating that an extensional tectonic regime predominated in the area during the emplacement of the dyke swarm. σ_3 was sub-horizontal, sub-parallel to the mean NE–SW dilation direction. The inferred relative stress magnitudes are characterized by a σ_1 much larger than the other two principal stresses. In this context, intrusion of the dyke swarm occurred under low magma pressure conditions and preferentially into a pre-existing joint network during a regional extensional event. The SE Sardinian dyke swarm has been compared with other contemporary mafic dykes of the western Mediterranean region, by attempting to restore the effects of the Neogene and eo-Alpine rotational events. The reconstruction gives a complex crustal-scale pattern in terms of dyke orientation, a fact that could be partly attributed to differential rotations associated with localized strike-slip movements that might have operated coevally with regional extension or transtension during Permian times.

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1. Introduction

Dykes are among the most interesting structural elements used in paleostress and paleostrain analysis (Anderson, 1951; Halls, 1982; Delaney et al., 1986; Pollard, 1987). This is because most dykes propagate as extension fractures that form perpendicular to the minimum principal compressive stress (σ_3) and because their geometric features are useful to constrain the tectonics of magma emplacement (Babiker and Gudmundsson, 2004; Le Gall et al., 2005; Skarmeta, 2011; Ni et al., 2016). The regional stress field and tectonic regime play an important role in dyking, but other factors like magmatic pressure and the interaction with rock layering or with pre-existing fractures also have to be taken into account (Baer et al., 1994; Rubin, 1995; Rivalta et al., 2015).

The structural patterns of mafic dyke swarms have been classically used as evidence for deciphering crustal scale tectonic settings, as shown by a large number of papers and special volumes dedicated to this topic (e.g. Halls, 1982; Parker et al., 1990; Ernst et al., 1995; Hoek and Seitz, 1995; Babiker and Gudmundsson, 2004; Hanski et al., 2006; Srivastava, 2011). When these dyke swarms are subvertical and are well exposed at outcrop scale, they are suitable to carry out tectonic analyses from aerial or satellite photographs and, thus, inferring geotectonic settings.

This is the case in southeastern Sardinia where a large mafic dyke swarm of Permian age intruded into granitoid rocks of the Sàrrabus massif. Dykes are subvertical and roughly parallel to each other in a NW-SW direction.

The main objectives of this research are to characterize the structural pattern of the SE Sardinia dyke swarm and to determine

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http://dx.doi.org/10.1016/j.jog.2016.05.012
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the tectonic conditions associated with the intrusive event. In addition, this paper aims to compare the results from this study with those previously obtained for another Permian lamprophyre dyke swarm in the Catalan Coastal batholith of NE Iberia (Martinez-Poza et al., 2014). The reason for making this correlation is that, by the time of magmatic activity in Late Carboniferous-Permian times and until the Neogene rifting event, the Corso-Sardinian block is supposed to have been closely adjacent to NE Iberia (Alvarez, 1972; Matte, 1986; Carosi and Oggiano, 2002). The methodologies used in the present study are the same as those applied to the Catalan Coastal dyke swarm. This will allow direct, mutual comparison and correlation. Furthermore, some insight is gained at plate-scale into the geodynamic evolution of the western Mediterranean region from Permian to present times.

2. Geological setting

The Paleozoic basement of Sardinia (Fig. 1a) is the result of the collision between Gondwana and Armorica plates in the South European Variscan framework. All penetrative deformation structures, metamorphism (which increases from SW to NE Sardinia) and large calc-alkaline magmatic activity belong to the Variscan cycle (Secchi and Lorrai, 2001), without any substantial effect of the Alpine orogenesis (Vaccaro et al., 1991).

In the Variscan foreland zone of SE Sardinia, dyke swarms stand out embedded in the Sàrrabus massif, a late Variscan plutonic complex composed of a sequence of different granitoid types (Brotzu and Morbidelli, 1974; Brotzu et al., 1993). This study focuses on the Permian mafic dyke swarm that is well exposed in the southern part of the Sàrrabus massif, along the coastal shore in the surroundings of Villasimius (Fig. 1).

2.1. Late Variscan magmatism

Late Variscan plutonic rocks are widespread in Sardinia and Corsica (Fig. 1a), configuring the so-called Corsica-Sardinia batholith (Rossi and Cocherie, 1991; Atzori et al., 2000; Gaggero et al., 2007). Three magmatic suites can be distinguished: (i) early Mg–K calc-alkaline monzo-diorites and monzonites, (ii) peraluminous calc-alkaline granodiorites and monzogranites with subordinate tholeiitic gabbros; and (iii) metaluminous calc-alkaline to calcic gabbros and alkaline volcanic complexes. The origin of these suites has been explained in terms of the mixing in different proportions of mantle-derived and lower crustal melts (Rossi and Cocherie, 1991; Casini et al., 2015). Several authors have grouped the plutons into syn- or late-tectonic gabbrotonalitic to gabbro-monzogranitic rocks and post-tectonic anatectic leucogranites (Bralia et al., 1981; Ghezzo and Orsini, 1982).

The southern section of the Corsica-Sardinia batholith was developed between 340 and 288 Ma (U/Pb on zircon, Cocherie et al., 2005). Pluton emplacement has been associated with a transitional context between shear-dominated transpression and post-orogenic crustal extension between Late Carboniferous and Early Permian (Gaggero et al., 2007; Carosi et al., 2012).

The Sàrrabus massif extends over an area of ~400 km^2 with characteristics of a shallow crustal level intrusion, evidenced by the low-grade regional metamorphism and the small contact metamorphism effect around plutons (Secchi and Lorrai, 2001). It is composed of several intrusive phases that revealed high-K calc-alkaline affinity. Four main different calc-alkaline plutonic units, separated by sharp contacts with a roughly N-S trend, can be distinguished in the Sàrrabus massif (Secchi and Lorrai, 2001; Fig. 1b). They are classified from the older to the younger such as follows: gabbro-tonalites, biotite- amphibole granodiorites (locally episyenitized), monzogranitic granodiorites and biotite-granodiorites. Magmatic to solid-state fabrics are conspicuous in the older facies (gabbroids, tonalites and granodiorites) whereas they are rare in the younger granites. The whole set of large plutonic bodies was emplaced in a time span from 311 to 295 Ma (Nicoletti et al., 1982; Pirinu, 1991; Brotzu et al., 1993).

2.2. The Permian dyke swarms

Later, during the Permian post-Variscan times, the granitoids from the Sàrrabus massif were intruded by voluminous NNW-SSE-trending dyke swarms of bimodal felsic and mafic character (Secchi and Lorrai, 2001). To the north of the Sàrrabus massif in central Sardinia, dykes are intruded into metamorphic basement rocks (Ronca et al., 1999). These swarms have indeed continuation to northern Sardinia and Corsica, where they display prevalent NE-SW strikes (Fig. 1a). They represent around the 25% of the volume of the Sardinia batholith (Secchi and Lorrai, 2001; Vaccaro, 1990; Vaccaro et al., 1991), ranging in thickness between ≈1 and 15 m (Atzori et al., 2000). The contrast in dyke strike between SE and NE Sardinia was interpreted by Helbing et al. (2006) to correspond with a bending structure attributed to the Alpine event. A more recent paleomagnetic study by Aubele et al. (2014) attributes such a divergence in dyke strikes to differential relative block rotations occurred during the Permian as the result of post-Variscan intra-Pangea movements.

The dykes intruded into the Sàrrabus granitoids are sub-vertical along a preferred NNW-SSE direction (N140–160°), with secondary directions at ≈N-S (Ronca et al., 1999). Comparing these trends with the late-Variscan stress patterns (Arthaud and Matte, 1975, 1977a,b), the NNW-SSE trend is parallel to the maximum compressive axis (σ_1), whereas the N-S trend matches a sinistral fault system (Ronca, 1996; Ronca and Traversa, 1996).

The dykes have been grouped in four different compositional types. They do not present any sign of Variscan ductile deformation and conform an intrusive sequence occurred during a post-collisional period of time between 290 and 260 Ma (Nicoletti et al., 1982; Pirinu, 1991; Brotzu et al., 1993; Ronca et al., 1999): (1) fine to medium grained, up to 2 m thick dykes of peraluminous two-mica aplitic-micropegmatitic leucogranites (Ronca et al., 1999), (2) 10–30 m thick dykes of biotite and biotite-muscovite porphyries, rhyolitic micrograntes and aplites (Ronca et al., 1999), (3) 0.5–10 m thick fine grained mafic dykes (porphyritic dolerites and minor lamprophyres) corresponding to calc-alkaline basalts, basaltic andesites and andesites (Ronca et al., 1999; Gaggero et al., 2007), and (4) a minor group of tholeiitic basalt dykes (Traversa and Vaccaro, 1992). Mafic dykes of the groups (3) and (4) are the most conspicuous and are the object of this study.

Rb-Sr mica ages cluster around 290–270 Ma for rhyolitic dykes, whereas a basaltic andesite sample was dated at 259 ± 3 Ma (Late Permian), further indicating that mafic dykes intruded later than the felsic ones (Ronca et al., 1999). Moreover, ^{40}Ar-^{39}Ar age determinations by Gaggero et al. (2007) for a dolerite dyke gave and age of ≈ 250 Ma. Despite the calc-alkaline affinity of the mafic dykes, an anorogenic regional extensional tectonic regime has been adopted for the emplacement of the Sardinian mafic dykes, having been related to the transition from Variscan orogenesis to the Triassic rifting event (Gaggero et al., 2007).

3. Methodology

Our analysis is based on structural data obtained from fieldwork along a W-E coastal section between Torre delle Stelle and Torre Vecchia (Fig. 1b), combined with examination of aerial photographs from the same area. The specific methodologies applied to characterize and interpret the SE Sardinia mafic dyke swarm are:

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