Tectonophysics 630 (2014) 75–90

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Dyke intrusion into a pre-existing joint network: The Aiguablava lamprophyre dyke swarm (Catalan Coastal Ranges)

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ARTICLE INFO

Article history:
Received 22 March 2014
Received in revised form 8 May 2014
Accepted 9 May 2014
Available online 17 May 2014

Keywords:
Mafic dyke
Fracture
Joint
Paleostress analysis
Variscan basement

ABSTRACT

A structural analysis has been performed in the Upper Permian lamprophyric dyke swarm of Aiguablava (Costa Brava, NE Iberia). Emplacement of sub-vertical dykes is related to the presence of a widespread joint network, mostly developed during the cooling and decompression of the late Variscan leucogranitic host rocks. The joint pattern consists on multiple sub-vertical joint sets among which two orthogonal sets at ≈N23° and ≈N113° are predominant. A sub-horizontal set is also prominent. The sub-vertical dykes have a mean N100°–N125° trend, which corresponds to the trend of one of the main joint sets. However, dyke segmentation is noticeable at the Dm- to cm-scale, and this is inferred to be related to dyke propagation and emplacement along the variably oriented pre-existing joints. A mean robust sub-horizontal NNE–SSW net dilation direction was measured from matching dyke jogs, markers in the host rock and analysis of maximum dyke thicknesses, and this is in line with the minimum principal stress axis ($_3$) derived from a three-dimensional paleostress analysis from dyke orientations. The inferred maximum principal stress axis ($_1$) is sub-vertical, indicating that dykes intruded under conditions of tectonic extension. Furthermore, a Mohr construction allowed calculation of the stress ratio $\varphi = 0.29$ (close to a prolate stress ellipsoid) and a driving pressure ratio $R' = 0.27$, which corresponds to a magmatic pressure almost equal to the intermediate principal stress axis, σ_2. It is inferred that many of the pre-existing joint sets were exploited by the magma, the WNW–ESE joint set (normal to σ_3) being the most favorable for dyke emplacement. The present study highlights the structural control of a pre-existing fracture network on emplacement of the Aiguablava lamprophyres in the upper crust during late Permian NNE–SSW brittle extension.

1. Introduction

Magmatic dykes provide data about sources and location of magma reservoirs, magma transport (e.g. Bons et al., 2001; Brown, 2010; Clemens and Mawer, 1992; Vanderhaeghe, 1999), intrusion and emplacement mechanisms (e.g. Brown and Solar, 1999; Cadman et al., 1990; Hutton, 1988) and are important kinematic markers in both, deformed mid- and lower crustal domains (e.g. Druguet et al., 2008; Hanmer and Passchier, 1991) and in the upper crust (e.g. Airoldi et al., 2011; Babiker and Gudmundsson, 2004; Cadman et al., 1990; Glazner et al., 1999; Paquet et al., 2007). Furthermore, dyke swarms, particularly mafic ones, are essential for the interpretation of geodynamic processes and paleogeographic reconstruction of continents (e.g., using paleomagnetic and geochronological studies; Ernst et al., 1995; Halls, 1982; Hanski et al., 2006; Srivastava, 2011), and in determining magmatic flow and regional paleostress conditions (Anderson, 1951; Delaney et al., 1986; Hoek, 1991; Hou, 2012; Neff, 1973; Ode, 1957; Platten, 2000; Pollard, 1973; Rubin, 1995).

Lamprophyres are among this kind of intrusive rocks which typically form dyke swarms. They are generally grouped as porphyritic rocks with ferromagnesian phenocrysts (biotite, amphibole or pyroxene) and usually contain feldspar, which is confined to the groundmass (Le Bas and Streckeisen, 1991). Although lamprophyre and lamprophyric rocks have no petrogenetic significance (Mitchell, 1994), their singular nature has generated wide interest in geological research during the last three decades. This is especially because of their importance in deep-mantle studies and their supposed association with kimberlites and lamproites (Woolley et al., 1996).

This paper examines the Aiguablava lamprophyric dyke swarm in the Catalan Coastal batholith of NE Iberia from a structural point of view. The high quality exposures and the variety and clarity of structures bring evidence for intrusion of the dyke swarm into a pervasive fracture network in the host rocks, and this stands out as the main emplacement model recognized since the last decade (Carreras and Gimeno, 2000; Enrique, 2009; Gimeno, 2002; Passchier, 2007). Indeed, the area has become a classic locality to observe the cross-cutting elationships between different generations of dykes and joint sets (Druguet et al., 2013). However, except for preliminary work by

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http://dx.doi.org/10.1016/j.tecto.2014.05.015

Martínez-Poza et al. (2012), no systematic and exhaustive structural analysis of the dykes has been performed. In contrast, several petrological and geochronological studies have been carried out (Enrique, 2009; Enrique et al., 2012; Esteve et al., 2014; San Miguel Arribas, 1952; San Miguel de la Cámara, 1936; Solé et al., 2003; Ubide, 2013; Ubide et al., 2008, 2010).

Self-propagating dyke-fractures (Lister and Kerr, 1991; Spence and Turcotte, 1985) and dyke intrusion into previously fractured rocks became established in the 1980's as two end-member mechanisms for dyke transport and emplacement. The fundamentals of the second of these mechanisms were established by Delaney et al. (1986) and Pollard (1987). They gave some criteria for the identification of dykes intruded along pre-existing fractures and formulated the condition for fracture re-opening. Accordingly, for dyke emplacement, magmatic pressure (P_m) must equal or exceed the tectonic normal stress (σ_n) acting on the fracture surface.

$$P_m \geq \sigma_n. \quad (1)$$

Later works by Baer et al. (1994) and Jolly and Sanderson (1995) provided feasible methods to measure the relative magmatic pressure and state of stress during dyke emplacement, using dyke orientation data. The relationship between dyke and vein emplacement and fracture networks has been broadly investigated in subsequent studies (André et al., 2001; Gudmundsson et al., 2002; Hoek, 1991; Le Gall et al., 2005; Mazzarini and Isola, 2007; Tokarski, 1990; Ziv et al., 2000).

The objectives of this research are to characterize the three-dimensional relationships between the pre-existing jointing and the lamprophyric dykes and to determine the geo-mechanical conditions associated with the intrusion of the dyke swarm. The following methodologies have been applied to achieve the above objectives: (i) statistical measurement of fracture networks using a circular scanline method on aerial orthophotographs, (ii) characterization of dyke intrusion patterns at different scales and differently oriented exposure surfaces, (iii) estimation of the net dilation direction for the dyke swarm applying a stereographic analytical technique, (iv) 3-D analysis of the stress state during dyke emplacement by the combined use of stereographic projections and Mohr circles, and (v) estimation of the amount of regional extension from scanlines on photographs.

2. Geological and petrological settings

The studied lamprophyre dyke swarm in the Aiguablava pluton (Costa Brava) is part of the Catalan Coastal Ranges batholith in NE-Spain (Fig. 1). The Catalan Coastal Ranges batholith, emplaced into late Neoproterozoic and Paleozoic rocks at intermediate and shallow crustal levels, is composed of several magmatic intrusions, with compositions varying from granodiorite to monzogranite to leucogranite. The estimated age of the batholith is Lower Permian (Enrique, 1990), corresponding to the late- to post-Variscan magmatism that is also represented by other granitoid plutons in the basement of the Pyrenees. The Aiguablava pluton was dated as ≈288 Ma (Ferrés, 1998; Losantos et al., 2000).

The Aiguablava pluton is made of a pinkish medium to fine-grained biotite leucogranite, mainly composed of quartz, K-feldspar and sodic plagioclase, with minor biotite and garnet as accessory minerals (Enrique, 1990; Gimeno, 2002). A widespread network of aplite–pegmatite veins is associated with this intrusive body. The presence of miarolitic cavities suggests that magma crystallization occurred in the shallowest parts of the magmatic system. Towards the north, this leucogranite intrudes into K-feldspar megacryst-bearing granodiorite and into phyllites of the Begur massif, where these rocks are also crosscut by the lamprophyric dykes (Enrique, 2009).

The Aiguablava lamprophyric dykes can be grouped in at least three distinct petrographical types (Enrique, 2009):

(1) An extensive system of ≈N110°–N115° trending sub-vertical dykes (Figs. 1 and 2) of dark greenish-gray color and thickness varying between a few centimeters and a few meters (Figs. 3 and 4). They have been classically considered as having a predominant calc-alkaline spessartitic composition (Enrique, 2009; San Miguel Arribas, 1952; San Miguel de la Cámara, 1936), although a more recent study by Ubide et al. (2010) places these rocks between the sub-alkaline and alkaline fields. Whole-rock K–Ar dating indicates a 253 ± 5 Ma, Upper Permian age (Losantos et al., 2000). They are aphanitic to fine-grained, containing partly altered clinopyroxene, olivine and biotite phenocrysts. Calcite and chlorite are common in the groundmass together with plagioclase and amphibole. Chilled margins of aphanitic texture devoid of phenocrysts and angular xenoliths of the leucogranitic host rock are common in dm- to m-thick dykes. The local presence of vesicular texture at the dyke margins suggests dyke emplacement at a shallow crustal level (Gimeno, 2002). In some cases the thickest dykes display a rather complex internal structure consisting of either a wall-parallel textural banding or low-angle mutual cross-cuts. These features could be related to a late multi-stage dyke assembly in the evolution from the volumetrically most abundant spessartitic dykes to the less abundant bostonitic ones which are described here below.

(2) A less voluminous group of sub-vertical dykes of alkaline affinity is also recognized in the study area (bostonites; see Enrique, 2009). These are easily distinguishable from the spessartite dykes by their characteristic chocolate-brown color. Although bostonite dykes have not been dated yet, field cross-cutting relationships indicate that they postdate the spessartitic dykes (Fig. 4a). Locally, they form composite dykes combined with the spessartite ones, as observed in the Punta des Mut area (Enrique et al., 2012).

(3) Apart from the above two dyke types (spessartite and bostonite), a few sub-horizontal ultrabasic camptonite dykes of alkaline affinity are also recorded (Esteve et al., 2014; San Miguel Arribas, 1952; San Miguel de la Cámara, 1936). These were dated at ≈76 Ma (Upper Cretaceous age) by the amphibole $^{40}Ar/^{39}Ar$ method (Solé et al., 2003), and are thus unrelated in time and geodynamic context to the earlier Permian lamprophyres. In the study area they are represented in Sa Planassa zone by a single ca. 2.5 m thick sub-horizontal sheeted intrusion (Fig. 2). They have an across dyke zoned porphyritic texture characterized by the accumulation of phenocrysts (clinopyroxene and amphibole) at the base of the dykes, which is inferred to be on account of gravitational fractionation (Gimeno, 2002; Ubide et al., 2008).

On a wider regional context, mid- to late-Permian mafic calc-alkaline to alkaline magmatism is present elsewhere in the Pyrenees, the Iberian Range, the Spanish Central System, the Cantabrian Chain, the French Massif Central (Perini et al., 2004) and in the Corso-Sardo block (Ronca et al., 1999). However, there is a lack of general agreement on the geodynamic framework of these intrusions, which have mostly been interpreted from petrogenetic and geochemical approaches.

The intrusion of the latest camptonitic dykes has been interpreted in the context of the alkaline magmatism associated to the Mesozoic regional extensional event which marked the evolution on the margins between the Iberian and European plates. This process was the result of the Pangea breakup and the subsequent opening of the North Atlantic ocean. Other examples of this alkaline magmatic activity are found in other localities of the Catalan Coastal Ranges, in the Corbières massif (NE of the Pyrenees) and in the Western Pyrenees (Solé et al., 2003; Ubide, 2013).