



# Chemical, petrological and mass balance constraints on the textural evolution of pelitic enclaves

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## ABSTRACT

Reaction histories in xenoliths are commonly based on textural analysis alone and are often highly disputed. In this paper we propose a more rigorous approach that combines textural analysis, reaction balance calculations and quantitative  $P$ – $T$  pseudosections using model reactions. Examples highlighting the power of this approach are: disequilibrium behaviour of plagioclase in a partial melting reaction; and the relation between biotite–plagioclase intergrowths replacing garnet and biotite patches overgrowing ilmenite.

An important message is that textural analysis in xenoliths, and probably also in other rock types, must be complemented by chemical (compositions and reaction balance) and petrological (coherent  $P$ – $T$  projections or pseudosections) constraints to distinguish between alternative generic possibilities. This method sheds new light on a discussion on the melt volume produced during biotite dehydration melting in migmatites.

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## 1. Introduction

Textural analysis is a powerful technique to distinguish reactants and products in many metamorphic reactions (e.g. Carmichael, 1969; Spry, 1969; Kriegsman and Hensen, 1998; Vernon, 2004, 2007) and is critical in defining the sense of  $P$ – $T$  paths (e.g. Corbett and Phillips, 1981; Hand et al., 1994; Hensen et al., 1995; Vernon, 1996; Cenk et al., 2002; Álvarez-Valero and Kriegsman, 2007). It does, however, suffer from a number of limitations: (i) whereas the role of major phases is commonly straightforward, the role of minor phases may be more difficult to discern and this is vitally important for some accessory phases used for direct dating of the textures (see papers in Vance et al., 2003); (ii) phases that have been completely consumed are often not considered; (iii) the number of phases required to balance the reaction can only be assessed through a qualitative or (semi)quantitative chemical approach; and (iv) phases that have not been totally consumed but no longer record their initial compositions. Hence, textural analysis can provide constraints on metamorphic processes, but is generally insufficient for a complete description.

On the other hand, chemical analysis alone can give first-order estimates of thermodynamic properties such as pressure and tempera-

ture, but cannot define (except through local zoning in minerals such as garnet) the sense of reaction progress along the  $P$ – $T$  path (e.g. isobaric heating versus cooling, isothermal decompression versus burial). In most cases, the determination of  $P$ – $T$  vectors requires textural information, such as defining reactants and products, or defining successive mineral assemblages. In addition, many key parameters of rock histories, e.g. trace element distributions or isotopic compositions (including age patterns) require contextual information (see papers in Vance et al., 2003).

In this paper we provide examples from pelitic enclaves in fossil volcanic suites within the Neogene Volcanic Province (NVP) of the Betic Cordillera (SE Spain). After Zeck's (1970) seminal work, the area has recently been reinvestigated in detail (e.g. López-Ruiz and Rodríguez-Badiola, 1980; Fernández-Soler, 1996; Benito et al., 1999; Cesare et al., 1997, 2003a,b, 2009; Cesare and Gómez-Pugnaire, 2001; Álvarez-Valero et al., 2005, 2007; Álvarez-Valero and Kriegsman, 2007, 2008). Here, we focus on problematic textures that were not or insufficiently discussed in previous papers. We will pursue a multidisciplinary approach of combining petrography (textures), petrology ( $P$ – $T$  pseudosections) and chemistry (mineral chemistry, reaction balance).

Vernon (2007) discussed the textural evolution of pelitic xenoliths/enclaves using examples from, amongst others, the NVP. Some of his conclusions are that garnets in these xenoliths/enclaves are not peritectic, and that the high-Al pelitic enclaves are not restites to the host dacitic magma. We emphasize here that such conclusions cannot be arrived at with confidence by textural analysis alone, and that much can be gained by systematically combining textural and chemical analysis, including reaction balancing and calculating volume ratios of product phases.

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## 2. Geological setting

The Alborán Basin, located between the Betic Cordillera and the Moroccan Rif, formed by syn- to late orogenic extension on the site of a former mountain belt (Balanyá and García-Dueñas, 1987). Currently, it is widely recognized as a key area for the understanding of the origin and geodynamic evolution of the Betic Cordillera (e.g. Benito et al., 1999; López-Ruiz et al., 2002; Platt et al., 2003). It is thus a focus for petrological, geochemical and geophysical investigations. Although many conflicting models have been advanced for the origin of the Alborán Basin (see Doblas et al., 2007), the current tectonomagmatic models favour extensional hypotheses, as originally proposed by Doblas and Oyarzun (1989), and upwelling of plume-contaminated sublithospheric material replacing the delaminating subcontinental lithospheric mantle during the post-collisional transition from a subduction-related to an intraplate setting (Duggen et al., 2005).

The NVP is the most important volcanic domain of continental Spain (Fig. 1), related to the Betic Cordillera and the Alborán Sea (Zeck, 1970; Fernández-Soler, 1996). Scattered volcanic outcrops occur within a 250 km long, NE-trending zone from Cabo de Gata (southwestern limit) to Mar Menor (northeastern limit). Some lavas include up to 15 vol.% crustal material (Zeck, 1970). The high-K calc-alkaline volcanic series of El Hoyazo, Mazarrón and Mar Menor contains the most abundant xenoliths of residual partially melted crust (Zeck, 1970; Cesare et al., 1997; Álvarez-Valero and Kriegsman, 2007). The crustal xenoliths were transported to the surface from depth by volcanic processes and were rapidly quenched, thus presenting a frozen image of deep-crustal processes that operated in SE Spain during the Neogene.

Geothermobarometry on the xenoliths of El Hoyazo indicates equilibration at  $850 \pm 50$  °C and  $6 \pm 1$  kbar (Cesare et al., 1997, 2003a, b; Álvarez-Valero and Kriegsman, 2007). The same  $T$  range applies at lower  $P$  (c. 4 kbar) at Mazarrón (Cesare and Gómez-Pugnaire, 2001; Álvarez-Valero et al., 2007; Álvarez-Valero and Kriegsman, 2007), whereas Mar Menor samples record even lower  $P$  at slightly higher  $T$  (Álvarez-Valero and Kriegsman, 2007, 2008). Zircon and monazite SHRIMP ages indicate that anatexis occurred at c. 9.7–8.1 Ma at El Hoyazo, c. 9.1 Ma at Mazarrón and c. 10 Ma at Mar Menor, while the eruption has been dated at c. 6.3 Ma at El Hoyazo, 9.1 Ma at Mazarrón and 9.5 Ma at Mar Menor (Zeck and Williams, 2002; Cesare et al., 2003b, 2009).

The NVP mineral equilibria are related to three successive KFMASH univariant reactions: (i)  $Bt + Sil + Qtz = Grt + Crd + Kfs + M$ ; (ii)  $Bt + Sil + Grt = Spl + Crd + Kfs + M$ ; and (iii)  $Bt + Crd + Grt = Opx + Spl + Kfs + M$  (mineral abbreviations after Kretz, 1983; M = melt). These and related divariant reactions have operated along a  $P$ – $T$  segment with increasing  $T$  and slightly decreasing  $P$  (Álvarez-Valero and Kriegsman, 2007, 2008; Álvarez-Valero et al., 2007).

## 3. Methodology

Complementary to the above studies, we here focus on problematic and ambiguous textures that were insufficiently discussed because they were felt not to be of consequence to the overall shape of the  $P$ – $T$  paths. We will pursue a multidisciplinary approach of combining petrography (textures), petrology ( $P$ – $T$  pseudosections) and chemistry (mineral chemistry, reaction balance).

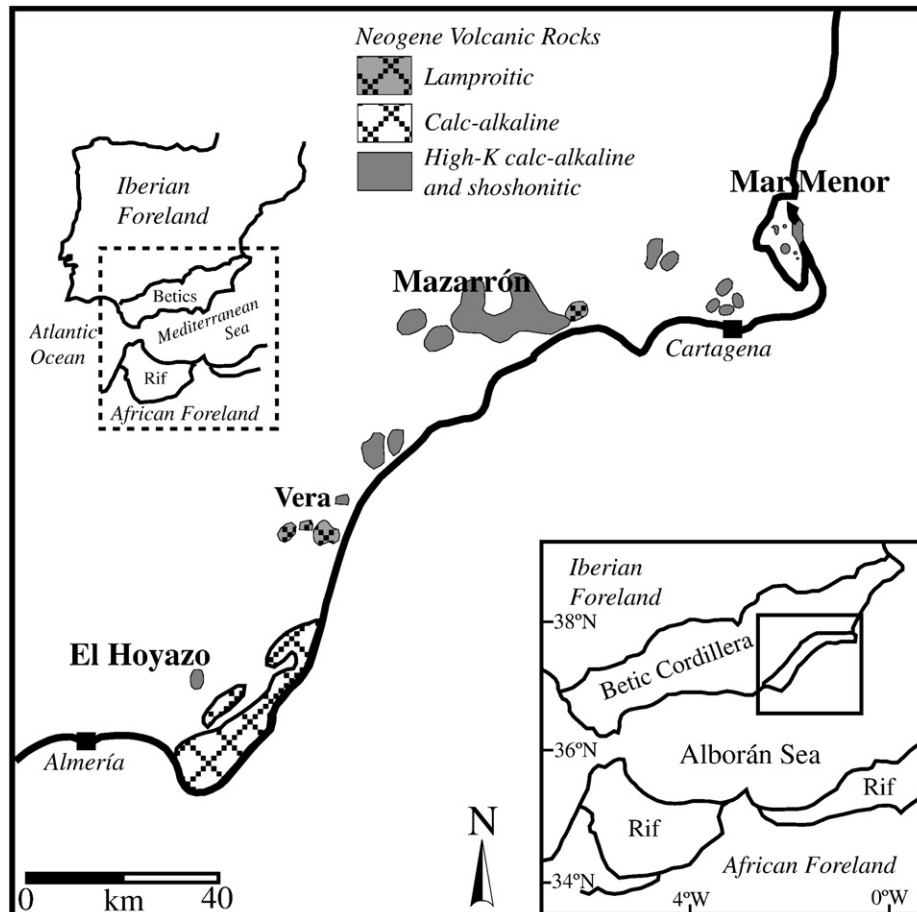


Fig. 1. Geographical location of Miocene, high-K calc-alkaline-shoshonitic volcanics of the Neogene Volcanic Province within the Alborán Domain. Sketches of the tectonic setting of the Betic-Rif Cordilleras on the upper left and lower right sides.

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