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Crustal Melting in the Alborán Domain: Constraints from Xenoliths of the Neogene Volcanic Province

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Abstract. Metapelitic xenoliths enclosed in the Crd-Grt-bearing lavas of the Neogene Volcanic Province of SE Spain retain evidence of partial melting and relevant information on the mechanisms and P-T conditions of crustal anatexis, preserved by rapid exhumation and cooling during eruption. Both at El Joyazo and Mazarrón, microstructures show that anatexis was accompanied by foliation development, implying that the xenoliths represent portions of a deforming crystalline basement, partially molten before being enclosed in the dacite.

At El Joyazo, the xenoliths have a marked restitic composition, are made of Bt-Pl-Sil-Grt-graphite (±Ilm, Crd, Her, Qtz), and contain abundant leucogranitic glass. Primary glass inclusions in all minerals indicate that the whole restite assemblage crystallised in the presence of melt, which is only possible by a disequilibrium melting mechanism due to very rapid heating rates. Variable degrees of graphite crystallinity point to syn-anatectic crystallisation of graphite, implying that the main stage of anatexis took place under fluid-present conditions. Further melting of biotite to hercynitic spinel was probably fluid-absent. Mass balance calculations among glasses, xenoliths and probable metapelitic protoliths from the basement of the Betic Cordillera indicate degrees of melting in the range of 35-60 wt. %.

Crustal anatexis took place at 5-7 kbar, 850 ± 50 °C, and was followed by a further melting stage at T>900°C, probably when the xenoliths were already incorporated into the dacite. Calculated pressures approximate the actual Moho depth in the region (ca. 21 km), and suggest that partial melting of the xenoliths occurred close to the crust-mantle boundary. The very high temperatures, the absence of HP relicts, and the syn-anatectic pseudomorphs of sillimanite after andalusite observed in many xenoliths at Mazarrón, are difficult to reconcile with a model of decompression melting, and rather suggest regional scale (isobaric) heating related to emplacement at shallow depth of asthenospheric mantle and/or mantle derived magmas.
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1 Introduction

The Alborán domain (Fig. 1a), comprising the Alborán Sea in the western Mediterranean, the on land internal Betic Cordilleras of southern Spain and the Rif Chain of Morocco, is a late Tertiary extensional basin which developed synchronously with the convergence between African and Eurasian plates.

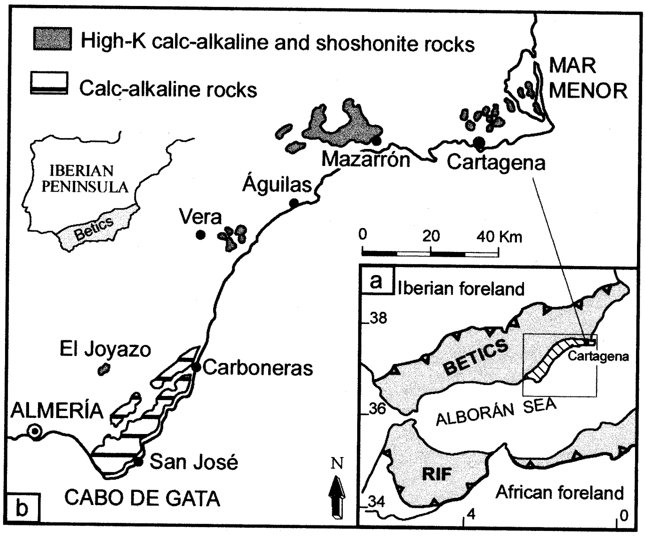

Fig. 1. The Neogene Volcanic Province of SE Betic Domain. **a)** Geographic location and schematic tectonic elements of the Alborán domain; box indicates area enlarged in (b) and diagonal pattern the Volcanic Province. **b)** The main edifices of the Miocene volcanics (after López Ruiz and Rodríguez Badiola, 1980)

The geodynamic history of the region has been dealt with by Comas et al. (1999) and the reader is referred to this comprehensive review for an updated list of relevant work. In brief, the Alborán domain is characterised by anomalous, high heat flow values, high positive Bouguer anomalies and seismic wave attenuation (Torne et al., 2000 and references therein), which suggest the presence of asthenospheric mantle and/or large bodies of mantle derived magmas at shallow depths. Recent investigations, including the multidisciplinary studies of the ODP leg 161 (Comas et al.,

1999 and references therein) have contributed to a detailed knowledge of the lithospheric structure in the area, revealing that the floor of the Alborán sea is covered by a very thin continental crust, that increases in thickness towards the Betic domain. The depth of Moho in the Alborán domain has been recently mapped from 3D modelling of gravity, heat-flow and elevation data (Torne et al. 2000), and is shown to increase from <12 km to ca. 35 km in the internal zones of the Betic Cordillera. Based on the above geodynamic features, the thinned, hot crust of the Alborán domain is, and has been since the onset of extension, a potential setting for HT-LP metamorphism, partial melting and generation of anatectic magmas, especially of granitoid composition.

Evidence in favour of crustal melting is indeed widespread throughout the Alborán domain, both onshore and offshore, and provided by:

1- Leucogranite dykes of Sierra Cabrera (Zeck et al., 1992) and ODP Site 976 (Soto and Platt, 1999);

2- High-grade metamorphic rocks and migmatites of the Betic Cordillera and the Alborán sea floor (e.g. Platt and Whitehouse, 1999; Soto and Platt, 1999);

3- High-K calc-alkaline, Grt-Crd-bearing dacites and rhyolites in the Neogene Betic basins (Molin, 1980);

4- Calc-alkaline andesites of the Caldear volcanic group of Sierra de Gata, interpreted as partial melts from an amphibolitic source (Zeck et al., 1998), and thought to constitute large areas of the Alborán sea floor.

Regardless of the existing dispute on the origin of many products of the Neogene Volcanic Province (see for example the alternative models proposed by Benito et al., 1999; Turner et al., 1999, and Zeck, 1970), as well as on their age, all the above occurrences bear significance on the crustal melting processes in the region, and each one gives unique information owing to its own peculiar features (plutonic or volcanic, felsic or mafic, onshore or offshore). However, scarce attention has been paid to the crustal xenoliths that occur in the Grt-Crd-bearing, high-K volcanics: in fact, after the detailed petrographic work of Zeck (1968; 1970) only recently they have been reconsidered (Benito et al., 1999; Cesare et al., 1997, Cesare and Maineri, 1999; Cesare, 2000).

This paper describes the main petrologic features of the xenoliths in the volcanic edifice of El Joyazo (also called Cerro del Hoyazo), with some additions from the area of Mazarrón. The aim is to demonstrate how these rocks put further constraints on melting processes in the Alborán domain, and therefore need to be considered in the large scale geodynamic reconstruction and modelling.

2 Geological Setting and Petrography

Grt-Crd-bearing lavas are typical products of the high-K calc-alkaline to shoshonitic series of the Neogene Volcanic Province of southern Spain (Fig. 1b). They form scattered, generally small edifices, aligned along a NE-SW trending belt extending for ca. 150 km from Almeria to Mar Menor. The age of this volcanism is upper Miocene, and available radiometric ages are in the range 6.2 - 8.9 Ma (Turner et al., 1999).

A discussion of the origin of these magmas is beyond the purpose of this study; here it will suffice to recall that, despite the existence of competing genetic models pointing to an essentially crustal origin (Zeck, 1970; Munskgaard, 1984) or to a relevant contribution of mantle material (Benito et al., 1999; Turner et al., 1999), these rocks contain geochemical evidence of partial melting of the continental crust. This is further supported by the presence of Al-rich crustal xenoliths, which are particularly abundant at El Joyazo, ENE of Almeria (Fig. 1b).

At El Joyazo, the calc-alkaline lava is a porphyritic dacite, which consists of a rhyolitic glassy matrix >50 vol.% and phenocrysts <1mm of plagioclase (An_{80}), cordierite (Mg_{45}) biotite, ortho- and clino pyroxene. The rock also contains abundant single xenocrysts of garnet, biotite, cordierite (Mg_{50}), sillimanite, spinel, quartz, as well as larger rock fragments made up of the same minerals.

The xenoliths of El Joyazo have been characterised by Zeck (1968, 1970), who gave a very detailed petrographic description and distinguished three types: Grt-Bt-Sil gneiss, Qtz-Crd gneiss and Spl-Crd rocks (mineral abbreviations after Kretz, 1983); the total content of restitic material (xenoliths and xenocrysts) is approximately 10-15 vol % of the lava (Zeck, 1992).

Grt-Bt-Sil xenoliths occur as rounded enclaves generally <20 cm in size, with medium grain size and a marked foliation on hand specimen; ruby garnet crystals up to 15 mm in diameter are very common. The main mineral assemblage consists of biotite (Mg_{35}), garnet (Mg_{15}), sillimanite, plagioclase (An_{30-35}), glass, apatite, graphite. Cordierite (Mg_{50}) ilmenite, hercynitic spinel (Mg_{20}) and sanidine may also be present (Cesare et al., 1997; Cesare, 2000). Among the peculiarities of these rocks are the abundance of graphite and rhyolitic glass, and the virtual absence of quartz; the latter suggests silica depletion through melt extraction.

Based on field observations, bulk chemical data and petrographic evidence (Zeck, 1970) and isotopic data (Munskgaard, 1984) the xenoliths and the enclosing dacite are regarded to have a common origin and have been interpreted to represent restites and anatectic melt from partial melting of (semi-)pelitic rocks, respectively.

In the area of Mazarrón, Crd-bearing lavas are broadly similar to those of El Joyazo, and contain phenocrysts of sanidine ($Or_{80}Ab_{20}$), plagioclase (An_{74-84}) and biotite; the latter is typically zoned with high-Mg (Mg_{85}), low-TiO_2 (3 wt%) cores, and low-Mg (Mg_{45-60}), high- TiO_2 (up to 6 wt%) rims. Among the xenocrysts, garnet is rare and hercynite and sillimanite less common than at El Joyazo, whereas cordierite (Mg_{40-60}) and andalusite are abundant.

Crustal xenoliths in the lavas of Mazarrrón display a greater mineralogical variability, characterised by the common occurrence of cordierite and andalusite. Among others, Grt-Bt-Sill-Pl-Crd±Spl and Crd-And-Sill-Bt–Pl-Spl±Kfs assemblages are frequently observed; in the latter type hercynitic spinel typically occurs in symplectic intergrowths with andalusite.

Recent studies have concentrated on the Grt-Bt-Sil

xenoliths of El Joyazo (Cesare et al., 1997; Cesare and Maineri, 1999; Cesare, 2000), with the aim of constraining the textural evolution and microchemical relationships between mineral phases and melts during the anatectic event(s). In the sections below, the main results concerning evidence and mechanisms of crustal melting are summarised and integrated with new data from the locality of Mazarrón. Unless specified, the description and discussion relate to the Grt-Bt-Sil xenoliths, the most abundant at El Joyazo.

3 Textural evidence of syntectonic melting of the xenoliths

Cesare et al. (1997) reported some first evidence of syntectonic melting of the xenoliths, including anastomosing of foliation around garnet, bending of biotite crystals which contain glass inclusions, presence of an earlier foliation, occurrence of interstitial glass in strain shadows. A more definitive proof is provided by the textures presented in Figure 2, which are preserved within plagioclase porphyroblasts occurring in both El Joyazo and Mazarrón xenoliths. In the example from El Joyazo, a porphyroblast of garnet is included in plagioclase, in which an evident crenulation foliation is slightly deflected around the garnet (Fig. 2a). Close up views (Fig. 2b and 2c) reveal the presence of primary glass inclusions in both garnet and in the graphite-rich, helicitic foliation of plagioclase. The plagioclase porphyroblasts in one xenolith from Mazarrón (Fig. 2d) contain an earlier, internal foliation at a high angle to the main foliation of the rock; the latter is defined by fibrolite- and biotite-rich folia, and by thin glass layers. Also in this case the earlier foliation in plagioclase contains glass inclusions and graphite (Fig. 2e). In both cases, the textural aspect (shape and 3D-orientation) of glass inclusions indicates primary trapping, i.e. entrapment during growth of the host mineral. As melt occurs both inside and outside the plagioclase porphyroblasts, it is concluded that development, or deflection, of the main foliation occurred in the presence of a melt phase. Because strain can be hardly transferred to xenoliths when they are immersed in a melt-rich crystal mush (the dacitic magma), the above textures are evidence that melting took place when the crust was a coherent body, and test for the regional scale at which the process occurred.

4 Conditions of crustal melting (how?)

The xenoliths of El Joyazo contain abundant information on how melting of the crust took place, and how peculiar the behaviour of these rocks was. Conventional Grt-Bt and Grt-Crd thermobarometry on the main assemblage of the xenoliths (Grt-Bt-Sil-Pl-melt±Crd) indicates equilibration at 850 ± 50 °C and 5-7 kbar; similar P-T values are also derived from the Spl-Crd xenoliths. As concerns pressure, experimental studies on partial melting of graphitic pelites (B. Cesare and M. Schmidt, unp. data) suggest that 7 kbar may be a more realistic value to account for the observed

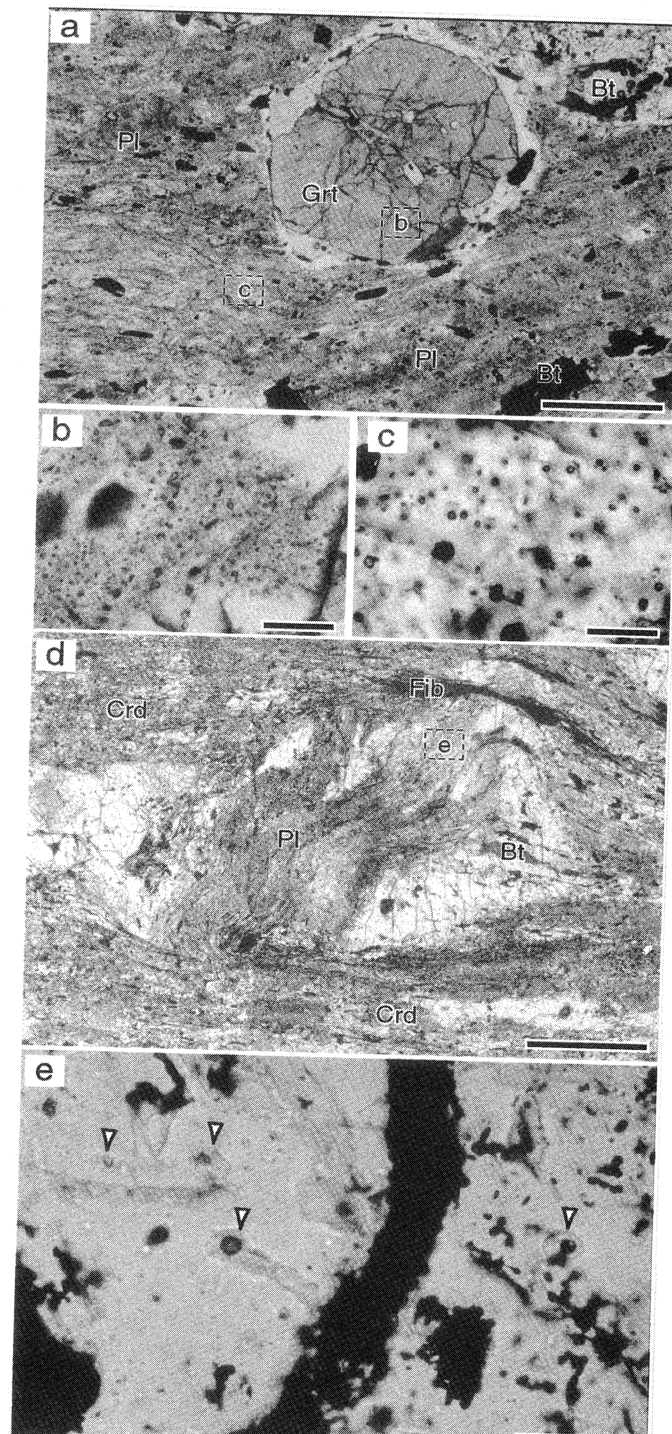

Fig. 2. Photomicrographs illustrating evidence of syntectonic melting of xenoliths at El Joyazo (a, b, c) and Mazarrón (d, e). **a)** Garnet crystal (Grt) included in a porphyroblast of Plagioclase (Pl). In the lower half, a subhorizontal crenulation foliation bends around the garnet, implying that foliation is coeval or younger than the garnet. Boxes (b) and (c) indicate areas enlarged in the next two pictures. Scale bar 4 mm. **b)** Glass inclusions with negative crystal shape within garnet from (a). The textural appearance of the inclusions indicates primary trapping, i.e. growth of garnet in the presence of melt. Scale bar ca. 100 μm. **c)** Glass inclusions in plagioclase, with similar features as in (b). Scale bar ca. 100 μm. **d)** Porphyroblast of plagioclase wrapped by a subhorizontal main foliation, outlined by fibrolite folia, in a Crd-Bt-Spl-Sil-(And) xenolith. The plagioclase contains a slightly crenulated internal foliation at a high angle to the external foliation. Box (e) indicates area enlarged in the next picture. Scale bar 1 mm. **e)** Round to irregular glass inclusions associated with graphite within plagioclase porphyroblast from (d). Scale bar ca. 50 μm.

composition of phases and abundance of garnet.

Despite the well equilibrated chemical composition of the minerals in xenoliths, Cesare and Maineri (1999) discussed in detail evidence of disequilibrium during partial melting. Firstly, the presence of primary glass inclusions in all minerals, explained as the result of rapid, disequilibrium melting of low- to medium-grade metapelites: owing to extremely fast heating, these rocks by-passed equilibrium transitions through upper amphibolite-facies conditions, and were directly transformed into a restitic assemblage and its coexisting anatectic melt. Disequilibrium is also testified by the presence of four textural generations of graphite, each showing a different degree of crystallinity measured by Laser Raman spectroscopy. The highest, granulite-grade crystallinity characterises the very fine-grained graphite associated with glass inclusions: this has been interpreted as indication of graphite precipitation during the main stage of anatexis, which took place (or initiated) under fluid-present conditions (Cesare and Maineri, 1999). In these xenoliths, the components H_2O and C (graphite) can be balanced without requiring infiltration of external hydrous fluids.

After the main anatectic stage, a further episode of melting is locally testified by the partial resorption of biotite to produce hercynitic spinel, ilmenite and melt; this quartz-absent texture has been modelled by the continuous melting reaction

$$Bt_1 + Pl_1 + Sil + melt_1 + Grt = Ilm + melt_2 + Bt_2 + Her + Pl_2$$

and mass balanced as fluid-absent in the Al-Ca-Fe-K-Mg-Mn-Na-Si-Ti system (Cesare, 2000). This second melting event is constrained at T = 900-950 °C and $P \geq 5$ kbar, and occurred under static conditions; thus it may reflect a stage when the xenoliths had already been incorporated in the deep-seated host dacite.

At El Joyazo andalusite is virtually absent (Zeck, 1968); conversely it is very common in the crustal xenoliths of Mazarrón, where it is partially to completely corroded and replaced by coarse sillimanite (Fig. 3). The presence of glass within and around the pseudomorph textures indicates that the And-Sil replacement occurred syn-anatectic.

5 Extent of crustal melting (how much?)

The highly residual composition of the xenoliths (ca. 44 wt% SiO_2, 31% Al_2O_3, 10% FeO_{tot}), suggests extraction of large volumes of anatectic granitic melt. Because the composition of this melt, preserved as glass inclusions, is known (Table 1), the extracted fraction can be calculated by mass balance, once a model protolith is chosen. Cesare et al. (1997) recognised that the xenoliths derive from fine-grained graphite-rich metapelites, and proposed the low-grade Bt-Grt phyllites of the Alpujárride basement as protholiths for the Grt-Bt-Sil xenoliths. This view has been extended by Soto and Platt (1999) to the high grade rocks in the Alborán seafloor at ODP site 976. Given the above assumption, mass balance calculations indicate that the amount of melt extracted from the xenoliths was very high, in the range 35-60 wt.%. This first order evaluation, made in the Si-Al-Fe-Mg-K-Ti system, does not balance the distribution of Ca and Na, and needs a better statistical representation of the chemistry of xenoliths, metapelitic protoliths and glasses.

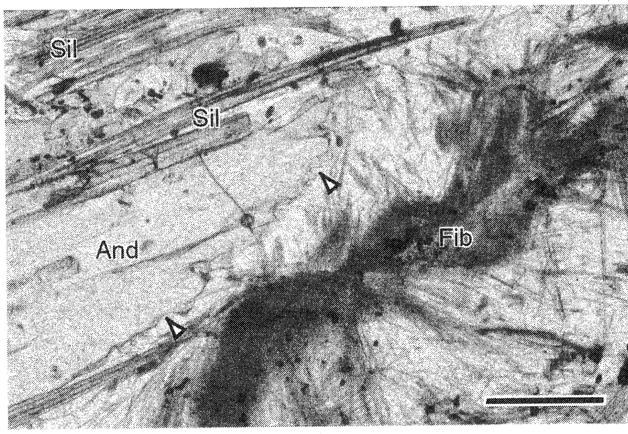

Fig. 3. Photomicrograph illustrating common textural relationships among Al_2SiO_5 polymorphs in the xenoliths at Mazarrón. A porphyroblast of andalusite (And) shows resorbed grain boundaries (arrows) and oriented replacement by prismatic sillimanite (Sil). Acicular, fibrolitic sillimanite (Fib) occurs in the rock matrix, and does not replace andalusite directly. Glass inclusions are present in the rock minerals, including andalusite. Scale bar ca. 200 μm.

Table 1. Representative electron microprobe analyses of glass inclusions and interstitial glass in the xenoliths of El Joyazo. Analyses represent averages of *n* spots.

Sample	SP 823	SP 823	SP 832	SP 832	HO 33a
Host	plagioclase	garnet	ilmenite	hercynite	Interstitial
n	6	4	2	4	3
SiO_2	77.04	76.32	72.15	72.69	73.91
TiO_2	0.06	0.10	0.52	0.20	0.13
Al_2O_3	12.83	13.88	15.08	14.54	14.48
FeO	1.05	1.76	3.06	2.40	1.49
MnO	0.04	0.07	0.03	0.03	0.02
MgO	0.14	0.09	0.31	0.29	0.03
CaO	0.13	0.51	1.51	1.06	0.77
Na_2O	1.33	2.31	3.18	2.33	1.77
K_2O	3.57	3.87	5.13	5.28	4.28
Total	96.18	98.91	100.97	98.82	96.89

6 Setting of crustal melting (where?)

Under the assumption of lithostatic pressure regimes, the values estimated by geobarometry correspond to a depth of ca. 25 km (assuming a crustal density of 2.7 g/cm^3), a value that is slightly higher than the actual Moho depth below El Joyazo (ca. 21 km, Torne et al., 2000). Because crustal thickness is considered to have changed very little since the end of extension, these depths suggest that xenoliths document crustal melting occurring immediately above the paleo Moho; this is the portion of crust where maximum temperatures, and thus maximum melt productivity, are expected.

Conditions of anatexis appear to be shallower in the xenoliths of Mazarrón, in which cordierite is widespread and far more abundant than garnet. The presence of andalusite in most xenoliths requires that pressure was below 4 kbar, that corresponds to a maximum depth of ca. 15 km.

7 Causes of crustal melting (why?)

The main driving force for crustal anatexis in the Alborán region has been often identified in decompression melting, both for high grade basement rocks (Soto et al., 1999) and calc-alkaline volcanics (Zeck, 1996). This model would be in agreement with most published P-T paths from these areas, which show roughly isothermal decompression, with the exception of the path proposed by Soto and Platt (1999), characterised by a temperature increase up to ca. 700 °C during decompression.

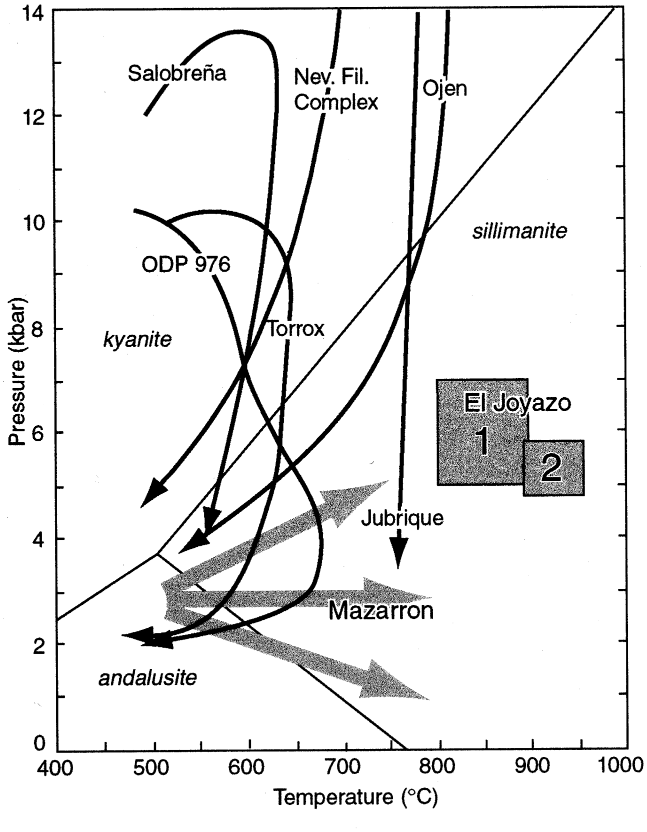

Fig. 4. Comparison of published P-T paths for various areas of the Alborán domain (thin black arrows, after Turner et al., 1999 and Gómez-Pugnaire et al., 1994), thermobarometric estimates from the xenoliths of El Joyazo (shaded boxes), and textural indications of And-Sil replacement from the xenoliths at Mazarrón (thick shaded arrows). 1: main anatectic event; 2: incongruent melting of biotite to hercynite (Cesare, 2000).

Comparison of these paths with thermobarometric estimates and textural information from the crustal xenoliths (Fig. 4), indicates that anatexis of the latter is hardly related either to decompression melting or to a slight increase of T such as in the basement of the Alborán Sea. At El Joyazo, temperatures are much higher (100-200 °C) than those reported from other areas of inferred crustal melting, and there is no petrographic evidence, such as high pressure mineral relicts, suggesting that anatexis was produced by decompression. Even if (significant) decompression had occurred prior to reequilibration at 5-7 kbar, these rocks would have been already extensively melted at the estimated temperatures of 800–900 °C, implying that the cause of melting was a relevant heat anomaly, rather than a pressure drop. At Mazarrón, the widespread syn-anatectic pseudomorphs of sillimanite after andalusite are indication of paths (shaded arrows in Fig. 4) that are incompatible with decompression alone.

As discussed by Jansen et al., 1993, we suggest that the xenoliths testify for a regional, (quasi)isobaric heating process occurring immediately above the Moho after the main phase of crustal thinning, and related to the emplacement of asthenospheric mantle and/or mantle derived magmas at shallow depth.

8 Conclusions

Most crustal xenoliths in the Grt-Crd calc-alkaline lavas of the Neogene Volcanic Province of SE Spain represent fragments of a metapelitic basement, deformed and partially melted before being enclosed in the host lavas. Thus, they derive from regional scale anatexis, and not from a thermal event induced by contact with (or enclosure by) the lava. Owing to unusual quenching of the deep crustal conditions by rapid exhumation and cooling during eruption, these rocks represent direct and unique witness of the processes of anatexis, and provide the maximum information on crustal melting processes taking place in the lower, thinned crust of the Southern Betic Cordillera.

At El Joyazo, crustal melting involved graphitic metapelites, similar to those cropping out in the Alpujárride Complex, and took place at ca. 850 °C and ca. 25 km depth, values which are likely to indicate the paleo crust-mantle boundary after Miocene crustal thinning. Melting took place (or started) under fluid-present conditions, with widespread evidence of disequilibrium, due to very high heating rates; a second stage of melting was probably fluid-absent.

Compared to other settings of Miocene crustal anatexis in the Alborán domain (e.g. Soto and Platt, 1999) the xenoliths testify for much higher temperatures and much higher degrees of melting (35-60 wt.%), which would indicate segregation of large volumes of leucogranitic magmas. Because intermediate to acidic products are very rare among the Miocene volcanics, it is likely that these melts crystallised at depth as plutonic bodies.

The study of the crustal xenoliths of the Neogene Volcanic Province, in particular those which experienced syn-anatectic deformation, provides important data, otherwise unavailable, to constrain the evolution of the crust in its deeper parts, and can help to refine or modify existing models on the geodynamic evolution of the Alborán domain.

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