

Geochemistry of the dolerite dyke swarm of the Alpujárride Complex (Betic Cordilleras, Spain): evidence on subduction-related Miocene magmatism emplaced by back-arc hyperextension

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ABSTRACT

The dolerite dykes intruding the Alpujárride Complex (Betic Cordilleras, Spain) provide key insights into the geodynamic processes associated with the Alpine hyperextension and exhumation of the Ronda peridotites. The dykes are classified as sub-alkaline tholeiitic basaltic andesites and suggest an origin in a back-arc basin setting. Whole-rock geochemistry points to derivation by 3–20% partial melting of a spinel-bearing, depleted mantle source (N-MORB to transitional) at depths < 90 km, metasomatized by slab-derived fluids. The absence of adakitic signature rules out the slab melting and suggests fluid release under relatively low thermal conditions at shallow to intermediate depths, where dehydration reactions dominate over slab-melting. Although published U-Pb zircon ages for dolerite dykes range from ~33 to 19 Ma, field relationships and metamorphic constraints indicate emplacement at ~22–19 Ma, coeval with or shortly after the high temperature - low pressure (HT-LP) metamorphism of the Internal Zone of the Betics. This timing suggests that subduction-related magmatism in an extending back-arc basin, likely triggered by subducted slab rollback or lithospheric delamination, offers a tectonic link between mantle melting and hyperextension during the Alpine evolution of the Betic-Rif orogen.

KEYWORDS | Betic Cordilleras. Alpujárride Complex. Dolerite dykes. Geochemistry. Tectonics.

INTRODUCTION

The Betic-Rifean belt (southern Spain and northern Morocco) exemplifies an Alpine collisional orogen modified by extensional collapse in the convergent setting

between Iberia and Africa since Mesozoic times. This belt outlines the Gibraltar Arc around the Alboran Sea (Fig 1A), which is floored by a very thin continental crust. It is worth noting that the orogen exhibits features of an older hyperextended margin, including extreme thinning

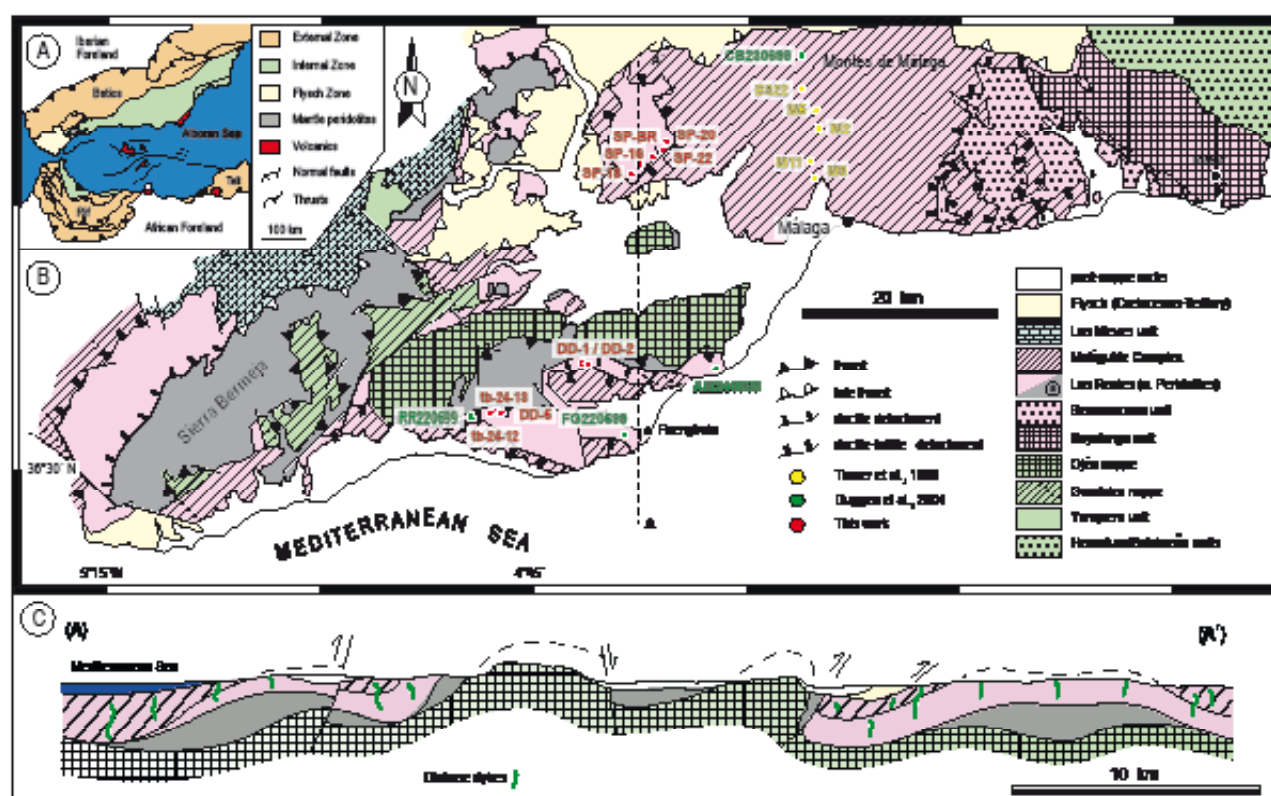


FIGURE 1. A) Tectonic map of the Betic-Rifean arc. B) Geological map of the western part of the Betic Cordilleras (modified from Esteban *et al.*, 2013) and C) geological cross-section, showing the location of dolerite dykes within the Alpujárride and Maláguide complexes).

of metamorphic isograds (Argles *et al.*, 1999; Loomis, 1972a; Torres-Roldán, 1979; Tubía, 1988, 1994) and the presence of large exhumed subcontinental mantle fragments, as exemplified by the world-class Ronda peridotites (mostly lherzolites and several types of sparse pyroxenites; Obata, 1980). However, no consensus exists regarding the exhumation mechanisms of the Ronda peridotites and the contribution of pre- and syn-orogenic deformation events. Multiple models have been proposed to explain the exhumation and tectonic emplacement of the Ronda ultramafic massifs, invoking processes such as mantle diapirism (Loomis, 1972b, 1975; Obata, 1980), extrusion of a mantle wedge during tectonic transpression (Darot, 1974; Mazzoli and Martín-Algarra, 2011; Tubía, 1994; Tubía *et al.*, 2013), tectonic inversion of a thinned back-arc basin during slab roll-back, extensional collapse, and hybrid models combining several of those processes (Bessière *et al.*, 2021; Davies *et al.*, 1993; Garrido *et al.*, 2011; Pedrera *et al.*, 2020; Précigout *et al.*, 2013; Tubía *et al.*, 1997; Tubía *et al.*, 2004; Van der Wal and Vissers, 1993). Disagreement also persists on the timing of extension, with proposed ages ranging from Palaeozoic (Kornprobst, 1976), Mesozoic (Michard *et al.*, 1997; Pedrera *et al.*, 2020) or even Cenozoic (Garrido *et al.*, 2011; Hidas *et al.*, 2015), and on the emplacement of a thrust nappe involving peridotites and metamorphic rocks

at middle crustal depths (e.g. Díaz Alvarado *et al.*, 2024; Esteban *et al.*, 2011; Sánchez-Rodríguez and Gebauer, 2000). This was followed by extensional tectonics, which can be identified by the formation of the western Alboran basin and associated volcanism that persisted until recent times in the eastern part of the Betic orogen, particularly in the Alboran Sea (e.g. Duggen *et al.*, 2004; Platt *et al.*, 2003).

In this work, we present a comprehensive geochemical dataset for the neglected dolerite dyke swarm intrusive into the Los Reales nappe, the upper tectonic unit of the Alpujárride Complex. The new analyses are treated together with previous data from dykes in the overlying Maláguide Complex, with a view to provide new constraints on extensional processes and their connection to a large-scale geodynamic scenario.

GEOLOGICAL SETTING

The Betic Cordilleras constitute the northern branch of the Betic-Rifian orogen, the westernmost part of the Mediterranean Alpine Orogen, which surrounds the Alboran Sea around the Strait of Gibraltar (Fig. 1A). Classically, they are divided into External Zones,

Internal Zones, and minor units such as the Betic Dorsal and Flysch Nappes (Vera, 2004). The External Zones consist predominantly of deformed Mesozoic and Cenozoic sedimentary rocks, originally deposited on the southern Iberian paleomargin. In contrast, the Internal Zones, focus of this work, comprise several tectonic complexes, mainly made up of metamorphic rocks of Paleozoic and Triassic ages. These complexes are from bottom to top the Nevado-Filábride, Alpujárride and Maláguide.

The Alpujárride Complex crops out almost continuously from east to west across the Internal Zones. It comprises several tectonic nappes that differ from one transect to another. Lithologically, the complex presents metapelites at its base, presumably of Paleozoic or Permo-Triassic age, affected by a metamorphism of variable intensity. The upper part consists of a marble formation, dated as Middle or Upper Triassic (Kozur and Simon, 1972; Kozur *et al.*, 1985). Based on progressively increasing metamorphic P-T conditions, lithological features and tectonic position, the Alpujárride Complex has been subdivided into three principal tectonic units: the Lower, Intermediate and Higher Alpujárrides nappes (Tubía *et al.*, 1992). Significantly, the Intermediate Alpujárrides locally preserve relics of eclogitized rocks sandwiched between metapelitic and carbonate formations (Tubía and Gil-Ibarguchi, 1991). These eclogites have been interpreted as products of subduction-related metamorphism of Jurassic mafic protoliths that reached minimum depths of approximately 60 km (Tubía *et al.*, 1997). A Miocene age of 19.9 ± 1.7 Ma has been proposed for the temperature peak of the high-pressure metamorphism, probably having occurred shortly after the maximum P conditions, as suggested by Sánchez-Rodríguez and Gebauer (2000).

The evolution of the Betic-Rifian orogen was driven by the African-Iberian plate convergence since Late Mesozoic. In this context, at Miocene-Pliocene time, the Alboran basin and adjacent Internal Zones experienced considerable extension while shortening occurred in the External Zones (García-Dueñas *et al.*, 1992; Platt and Vissers, 1989; Platt *et al.*, 2003). This extension, accompanied by calc-alkaline volcanism, has been dated at 15 – 2.7 Ma (K-Ar ages; Bellon *et al.*, 1983; Di Battistini *et al.*, 1987; Duggen *et al.*, 2004; Nobel *et al.*, 1981). In the central and western Internal Zones, an earlier igneous activity linked to Paleogene-Neogene extension is recorded by dolerite dykes ranging in age from 22–23 Ma (K-Ar; Torres-Roldán *et al.*, 1986) to over 33 Ma (33.6 to 17.4 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ ages of Duggen *et al.*, 2004; Platzman *et al.*, 2000; Turner *et al.*, 1999; 33.1 Ma U-Pb SHRIMP zircon age of Esteban *et al.*, 2013).

THE BASIC DYKE SWARM

The dyke swarm consists of dolerites, which cross-cut the structurally highest Alpujárride nappes (Los Reales nappe and its eastern counterpart, the Benamocarra unit), and the lower part of the overlying Maláguide Complex (Fig. 1B, 1C). The Los Reales nappe is an allochthonous sheet formed by the Ronda peridotites overlain by a continental metamorphic crust that includes, from bottom to top, acid granulites (kinzigites), migmatites and micaschists. The Ronda peridotites are bounded by two main lithospheric shear zones. The upper shear zone is concordant with the structure of the Los Reales metamorphic cover, which shows isograds broadly parallel to lithological contacts and regional foliation, a steep P-T gradient, and clear evidence of strong crustal thinning associated with isothermal decompression at *ca.* 22 Ma (e.g. Argles *et al.*, 1999; Esteban *et al.*, 2011; Platt and Vissers, 1989; Précigout *et al.*, 2013; Tubía, 1994; Zeck, 1996). This shear zone is interpreted as a large-extensional detachment that contributed to the exhumation of the Ronda peridotites. In contrast, the lower shear zone structurally underlying the Sierra Bermeja (Fig. 2A) and Sierra Alpujata (Fig. 2B) massifs, observed along thousands of meters in the Guadaiza tectonic window and the Ojén nappe, respectively, is marked by a dynamothermal metamorphic aureole formed at the expense of the underlying middle continental crust. This aureole, which cuts the regional structure of the Guadaiza and Ojén nappe, is mainly composed of strongly mylonitized, cordierite-bearing migmatites and is parallel to the mylonitic foliation developed in the peridotites during their hot thrust-related emplacement. The timing of emplacement of the Ronda peridotites has been directly constrained by zircon U-Pb dating of, among other materials, the metamorphic and the leucocratic dykes derived from partial melting of the crust during emplacement of the Ronda peridotites. These leucocratic dykes intrude the overlying peridotites. However, zircons from the metamorphic aureole of the Guadaiza nappe yield U-Pb ages of *ca.* 290–300 Ma (Acosta-Vigil *et al.*, 2014; Díaz-Alvarado *et al.*, 2024), apparently indicating a Permian migmatite formation. This apparent age discrepancy can be reconciled, as previously proposed by Tubía (1988), by distinguishing, from the structural and petrographic point of view, two metamorphic events: an Alpine event affecting the upper part of the sequence leading to the metamorphic aureole formation, and a pre-Alpine HT metamorphic event recorded from bottom to top of the crustal sequence, leading to Istan migmatite formation. Consistent with this interpretation, detrital zircon U-Pb ages of *ca.* 290 Ma obtained from quartzites interlayered within Triassic marbles in both, Ojén and Guadaiza, nappes (Esteban *et al.* 2022, 2023) have been interpreted as a late-Variscan metamorphic zircon population associated with the anatexis and migmatization of crustal sequence. Moreover,



FIGURE 2. A) Panoramic view of the Sierra Bermeja massif emplaced over the Guadaiza nappe. B) Panoramic view of the Sierra Alpujata massif, showing the superposition of Sierra Alpujata peridotite massif over quartz-feldspathic mylonites of the Ojen Nappe.

the common observation in the upper migmatites of the Guadaiza nappe of new zircon crystals or rims around older zircon cores, yielding (*e.g.* Esteban *et al.*, 2011; Sánchez-Rodríguez and Gebauer, 2000), was interpreted as a second partial melting of the metapelite sequence of the Guadaiza nappe during the hot emplacement of the peridotites, implying that the metamorphism reached temperature high enough to promote a second event of partial melting. A more recent but similar interpretation of Variscan and Alpine superposed HT metamorphism can arise from well constrained U-Pb of the metamorphic cover of the Ronda peridotites in the Betic and in the Rif, as similar Permian and Miocene ages have been obtained (*e.g.* Massonne, 2014; Zeck and Whitehouse, 2002; Zeck and Williams, 2001), suggesting that HT metamorphism is partly inherited from the Variscan Orogeny and is subsequently overprinted by a HT Alpine metamorphism. Therefore, the coexistence of inherited Variscan and Alpine high-temperature metamorphic overprints can be considered as a widespread feature in the western Alpujárride nappes. The Benamocarra unit displays only of schists. The Maláguide Complex consists

of schists with late to post-kinematic andalusite, phyllites, greywackes interlayered with strongly folded limestones of Devonian age (“calizas alabeadas”), greywackes with slates and an unconformable post-Visean conglomerate (“Conglomerado de Marbella”) crowning the Paleozoic sequence. Overlying this sequence are Permo-Triassic red beds and a reduced Mesozoic to Cenozoic cover (Azema, 1961; Mäkel, 1985).

The dolerite dykes are restricted to the Los Reales nappe and the Maláguide Complex. They cross-cut the migmatites and the overlying lithologies of the Los Reales nappe, as well as the lower part of the Maláguide Complex up to the “calizas alabeadas”. Neither the Ronda peridotites nor the underlying Ojén and Guadaiza nappes contain dolerite dykes (Fig. 1C). It could be considered that the lack of dykes in the materials listed above could be attributed to rheological reasons. However, regional geology data allows us to rule out that interpretation, because the metapelitic sequences are similar in the Ojén, Guadaiza and Los Reales nappes. It seems, thus, logical to expect the same rheological behaviour in the three Alpujárride nappes.

The dolerite dyke swarm is composed of two sets of subvertical dykes with different orientations. They intrude at high angle to the regional foliation, cutting across folds and schistosity of the host rocks (Fig. 3A). Less often, sills are also found in the Maláguide and Alpujárride complexes. The contacts between the dykes and the country rocks are mainly sharp and planar (Fig. 3A), but lobulated contacts are observed when the dolerite dykes cut across leucogranites (Fig. 3B). Dykes in the Maláguide Complex display a mean E–W strike, while those emplaced in the Los Reales nappe and Benamocarra unit show a N10 °E strike (Cuevas *et al.*, 2006; Tubía, 1988). Dyke thickness varies from 10 cm to 4 m (Fig. 3A, B). Fresh dykes are greyish green in colour and exhibit a great mineralogical and textural homogeneity. They are usually fine-grained, porphyritic to sub-ophitic plagioclase-hornblende dolerites with minor amounts of clinopyroxene or interstitial quartz and rare biotite (Torres-Roldán *et al.*, 1986). A few dykes from the Alpujárride are coarse-grained (Fig. 3C) dolerites with clinopyroxene as the major mafic mineral and minor chlorite and epidote. Pyrrhotite with minute inclusions of magnetite can be recognised on fresh, polished samples, whereas hematite is commonly observed in altered samples (Calvo *et al.*, 2001). The

finding of feldspar spherulites and vesicles filled with calcite, chlorite and quartz points to very shallow intrusion depths. Paleomagnetic studies of dykes show that the absolute value of the clockwise rotations observed are approximately equal in the Maláguide and Alpujárride Complex (Calvo *et al.*, 2001; Platzman and Platt, 2004; Platzman *et al.*, 2000). This fact confirms that the relative perpendicular orientation of the two dyke sets is of primary intrusive origin.

ANALYTICAL METHODS

Whole-rock analyses were performed at the Activation Laboratories Ltd. in Ancaster, Ontario, using a combination of their standard preparation and analytical package (for more details see the 4Lithores package at www.actlabs.com). After crushing and pulverizing the samples to 95% passing 105 μ m, lithium metaborate/tetraborate fusion, followed by nitric acid digestion was employed for sample preparation. Major and some selected trace elements (Ba, Be, Sc, Sr, V, Y and Zr) were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) and other trace elements and rare-earth element by inductively coupled plasma mass spectrometry (ICP-MS).

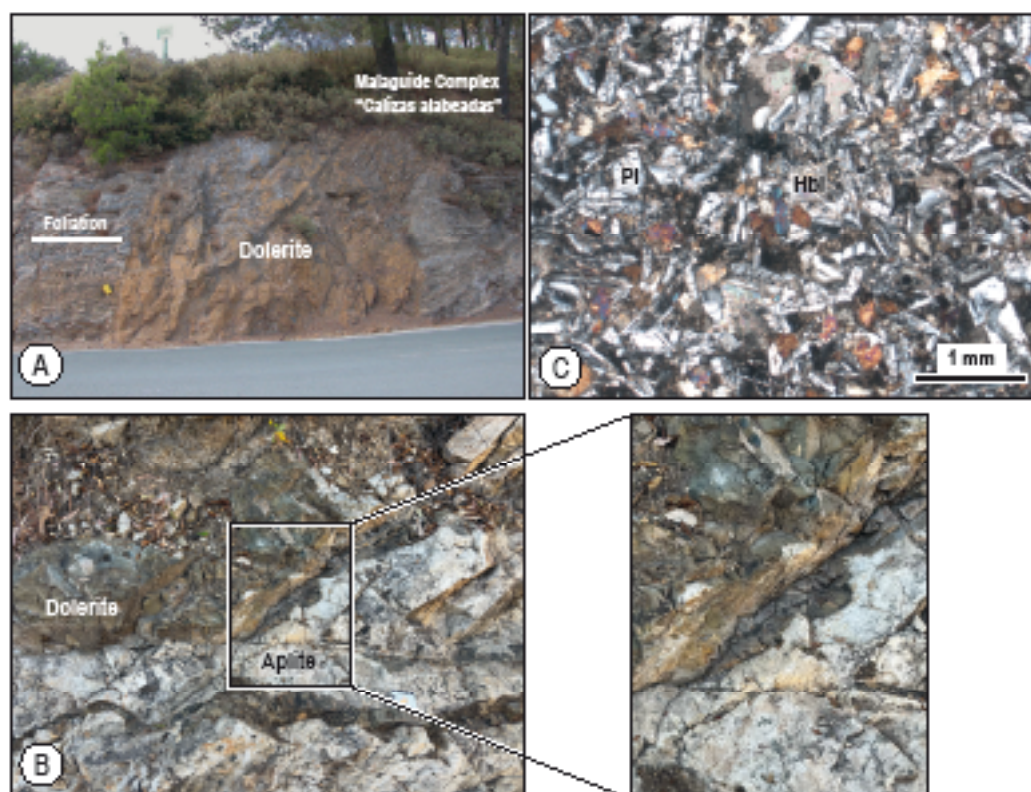


FIGURE 3. A) Field photograph of dolerite dykes intruded within the “calizas alabeadas” of the Maláguide Complex. B) Detailed outcrop views of dolerite dykes intruded within aplitic dykes (note the lobulated borders of the dolerite dykes). C) Photomicrograph of a coarse-grained dolerite dyke of the Alpujárride Complex.

GEOCHEMISTRY

Geochemical graphs were generated using PetroGram, an Excel-based petrology program for modelling of magmatic processes (Gündüz and Asan, 2021). Table I presents the whole-rock major oxides, trace and rare-earth element (REE) data for ten new representative dolerite dykes from the Alpujárride Complex (DDAC). To discuss their origin and tectonic setting, we have plotted these geochemical data along with those of dolerite dykes from the Málagaide and Alpujárride Complex reported by Duggen *et al.* (2004), Fernández-Fernández *et al.* (2007), Pedraza *et al.* (2025), Torres-Roldán *et al.* (1986) and Turner *et al.* (1999). Sample locations, when available from published sources, are shown in Figure 1.

From field and petrographic observations, it is observed that many dykes exhibit visible alteration, whereby their compositions may have been modified by late- or post-crystallization fluid-rock interactions. Consequently, mobilization of major, trace, and REE elements must be considered. The dolerite dykes of the Alpujárride Complex generally exhibit loss on ignition (LOI) values of less than 3% (Table I, except for DD-1) and chemical index of alteration (CIA) values of 38–44, comparable to those of unaltered basalts (Nesbitt and Young, 1982). The possible effects of post-magmatic alteration can also be evaluated. Thus, in the $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ vs. $[100 * \text{K}_2\text{O} / (\text{Na}_2\text{O} + \text{K}_2\text{O})]$ diagram of Hughes (1972) the DDAC plot within the igneous spectrum field and, consequently, they are inferred to have undergone minor post-magmatic alteration. Analysed samples also show a small range of Ce/Ce* ratios $[\text{Ce}_{\text{CN}} / ((\text{La}_{\text{CN}})^{0.667} * (\text{Nd}_{\text{CN}})^{0.333})]$, between 0.86 and 1.08, and lack of carbonization and silicification processes, pointing to minor alteration and apparently limited light rare earth elements (LREE) mobility (Polat *et al.*, 2002).

The samples studied have moderate SiO_2 (51.6–54.5%) and low total alkali (2.4–3.5%) contents, which are typical of sub-alkaline basaltic andesite (Fig. 4A; Irvine and Baragar, 1971; Le Bas *et al.*, 1986). They display high Al_2O_3 (15.6–16.5%) and variable contents of CaO (8.7–12.5%), Fe_2O_3 (7.2–9%) and MgO (4.7–7.5%). The $\text{Mg}^\#$ values (magnesium index) range from 34 to 48%, suggesting moderate igneous fractionation.

In the AFM diagram (Irvine and Baragar, 1971), the samples align along a Fe-enrichment trend, consistent with tholeiitic affinity. Similarly, in the Zr/TiO₂ vs. SiO_2 and Nb/Y diagrams of Winchester and Floyd (1977), the Zr/Ti vs. Nb/Y diagram (Fig. 4B) of Pearce (1996) and the TiO₂ vs. $\text{Zr}/(\text{P}_2\text{O}_5 * 10,000)$ diagram of Winchester and Floyd (1977), the samples are consistently classified as tholeiitic andesite-basalts.

Harker variation diagrams (Fig. I A-D) of SiO_2 versus major and trace elements reveal linear relationships, confirming that the studied dolerites have not been strongly influenced by post-magmatic alterations. The observed negative correlations between SiO_2 and major (MgO, CaO) and trace elements (Cr, Ni, Co) indicate that the fractional crystallization of olivine, orthopyroxene and clinopyroxene could have played a significant role during the evolution of the tholeiitic magma.

Additionally, to assess the post-magmatic mobility of trace elements, rare earths (REE) and high field strength elements (HFSE), we have plotted these versus Zr (Fig. I E-I), which is known for its limited mobility during metamorphism and alteration. The HFSE and REE elements show a positive correlation with Zr, though some significant differences can be observed:

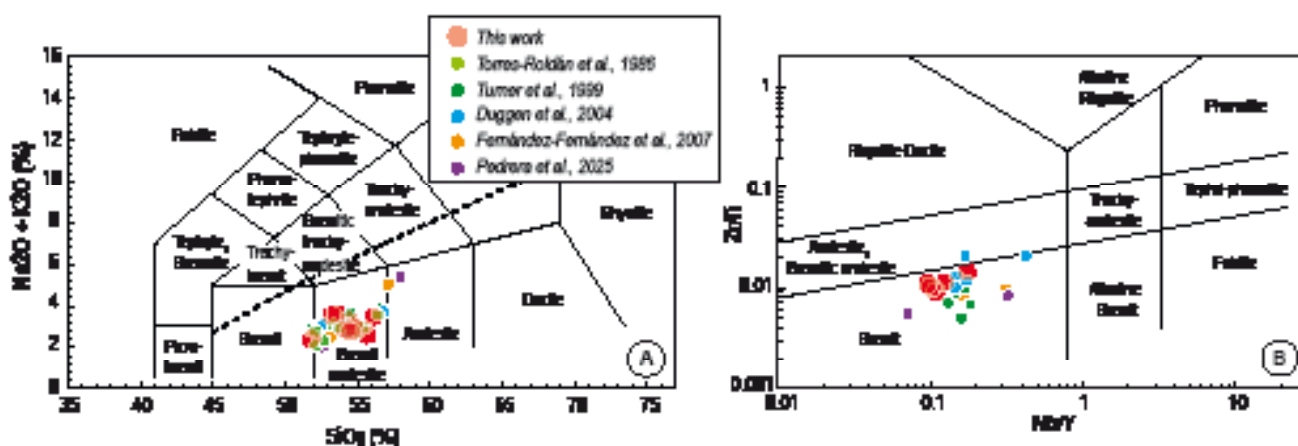


FIGURE 4. A) Total alkali content ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) vs SiO_2 (Lebas *et al.*, 1986) and B) Zr/Y vs Nb/Y (Winchester and Floyd, 1977) classification plot for Alpujárride and Málagaide dolerites.

while the heavy rare earth elements (HREE) display a strong positive correlation (from Sm to Lu), the light rare earth elements (LREE) (from La to Nd) exhibit a more scattered yet still positive correlation with Zr. Regarding the HFSE, tantalum (Ta) and hafnium (Hf) show a strong positive correlation with Zr, while elements such as thorium (Th) and uranium (U) denote also a slight positive but more scattered correlation. These patterns suggest limited albeit differing mobilities of these elements during post-magmatic events. Conversely, the large ion lithophile elements (LILE) consistently show a scattered distribution, reflecting significant element mobility.

C1 chondrite-normalized REE patterns (C_N) and N-MORB (NM_N) normalized multi-element variation diagrams are presented in Figure 6. The DDAC exhibits low total rare-earth element (Σ REE) concentrations, ranging from 27 to 45 ppm (34.3 ppm on average; Table I) with REE abundances 10 to 30 times those of C1 chondrite (Fig. 5A; Sun and McDonough, 1989). The samples display gently sloping REE patterns, with $(La/Yb)_{CN}$ values ranging from 1.1 to 2.9. They are characterized by a weak enrichment in LREEs, indicated by $(La/Sm)_{CN}$ ratios of 0.9 to 1.8, and a relatively flat distribution of HREEs, with $(Gd/Yb)_{CN}$ values between 1.1 and 1.5. Eu/Eu^* values vary from 0.9 to 1.1, thus suggesting that plagioclase fractionation or accumulation can be discounted. On the N-MORB normalized multi-element variation diagrams (Fig. 5B; Sun and McDonough, 1989), the samples feature a strong enrichment in LILE (e.g., K, Rb, Ba, Th) relative to HFSEs (e.g., Zr, Hf, Ta, Y, Nb). Additionally, negative Nb and positive Ce anomalies are observed. Enrichment in LREE, negative anomalies in fluid-immobile HFSE and Th enrichment correspond to signatures intermediate between those of N-MORB and continental crust, thus pointing to a possible back-arc setting.

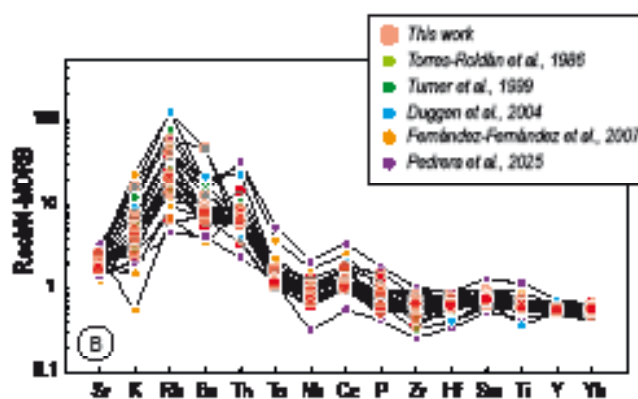
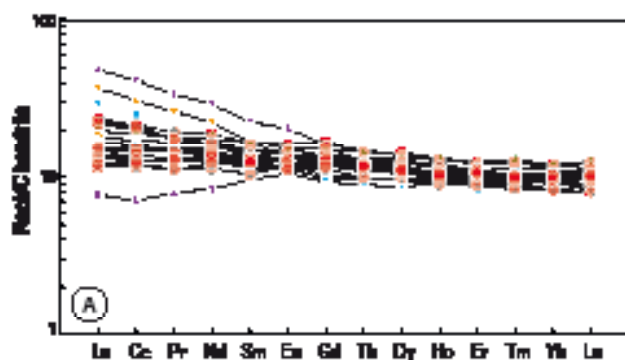


FIGURE 5. A) Chondrite normalized REEs patterns and B) N-MORB spider diagrams of Alpujárride and Maláguide Dolerites.

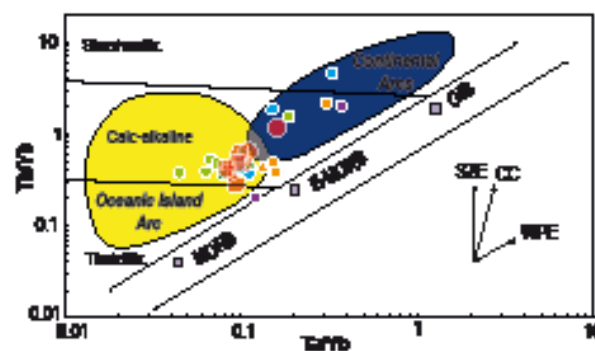


FIGURE 6. Th/Yb vs Ta/Yb (after Pearce, 1983) for Alpujárride and Maláguide dolerites. Vectors indicate the influence of subduction components (SZE), within-plate enrichment (WPE) and crustal contamination (CC).

DISCUSSION

Petrogenetic constraints

According to the geochemical Harker diagrams presented above, there is a broad similarity of trends for the immobile and incompatible or even major elements, which suggest a minor amount of crustal contamination (Fig. 1). Yet, the moderate enrichment in LREEs (Fig. 5A) and large ion lithophile elements (LILE), such as Rb, Ba, Sr and the depletion in high field strength elements (HFSE), such as Nb and Ta (Fig. 5B) suggest that the parental magmas were probably derived from subduction magmatism related to partial melting of a mantle wedge with possible additions of slab-derived fluids and/or sediment-derived melts where apparently the crustal contamination played a negligible role. The Nb/Th vs. La/Nb, and Th/Nb vs. La/Sm relationships, together with the Nb/La values indicate a volcanic arc signature with limited crustal contamination. In the Th/Yb vs. Nb/Yb (Pearce, 2008; not shown) and Th/Yb vs. Ta/Yb (Fig. 6; Pearce, 1983) diagrams used for detection of crustal signatures in the magmas, the samples

studied are enriched in Th/Yb relative to the MORB-OIB array, pointing to a subduction contamination component from a depleted N-MORB or transitional mantle source. This is also consistent with their high Zr/Nb (average of 22.7) and Y/Nb (average of 8.4) ratios (N-MORB: Zr/Nb = 31.75; Y/Nb = 12.04 / E-MORB: Zr/Nb = 8.79; Y/Nb = 2.7; Sun and McDonough, 1989).

Fluids derived from the dehydration of the oceanic crust and silicate melts from subducted sediments are considered the primary sources for components of crustal contamination in mantle wedges over subducted slabs. The enriched lithospheric mantle can be traced back to an ancient subduction zone, where partial melting of the mantle occurred after or during the slab subduction. The melts released by the hydrated oceanic crust are enriched in LILEs such as potassium and rubidium, while being depleted in HFSEs like niobium (Nb) and tantalum, since these are less mobile and tend to be retained in the subducted slab. In contrast, silicate melts can mobilize most incompatible elements, resulting in significant incorporation of LREEs and thorium into the mantle

wedge (Tatsumi and Eggins, 1995; Woodhead *et al.*, 2001). Consequently, mantle sources metasomatized by slab melts or subduction-related fluids exhibit different trace element signatures that let them to be tracked leading to higher Th/Yb and La/Yb ratios (Hawkesworth *et al.*, 1993; Pearce and Peate, 1995; Stern, 2002), among others. (Hf/Sm)_{PMN} and (Ta/La)_{PMN} ratios of DDAC range from 0.88 to 1.08 and 0.56 to 0.96, respectively (Fig. 7A). In the (Hf/Sm)_{PMN} vs. (Ta/La)_{PMN} diagram (Fig. 7A; La Flèche *et al.*, 1998), the dolerite dykes define a trend toward the volcanic arc basalts, extracted from a hydrated mantle source. The samples analysed denote a relatively wide range of U/Th (0.17–0.75), Th/Zr (0.01–0.04), Ba/La (7.7–80.4) and Sr/Nb (51.2–111.1) ratios, alongside consistent with Th/Nb (0.21–0.68), Nb/Zr (0.03–0.09) and Th/Yb (0.28–1.17) ratios. The observed trends in U/Th vs Th/Nb (Fig. 7B), Ba/La vs Th/Yb (Fig. 7C) and Nb/Zr vs Th/Zr (Fig. 7D) diagrams align with fluid-like component enrichments suggesting that the lithospheric mantle was metasomatized by slab-derived hydrous fluids (Hawkesworth *et al.*, 1993; Pearce and Peate, 1995; Saunders *et al.*, 1991; Stern, 2002) released by dehydration reactions from shallow to intermediate depths

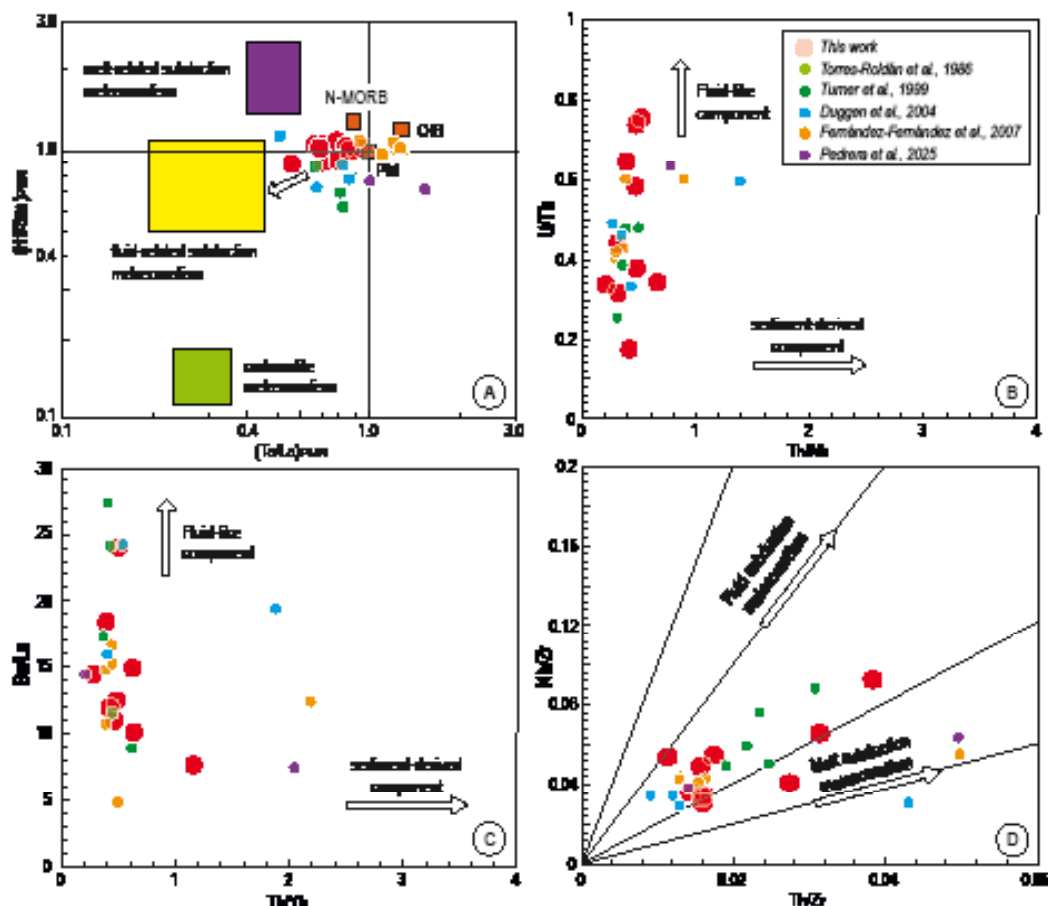


FIGURE 7. A) (Hf/Sm)_{PMN} vs (Ta/La)_{PMN}, B) U/Th vs Th/Nb, C) Ba/La vs Th/Yb and D) Nb/Zr vs Th/Zr displaying that Alpujárride and Maláguide dolerites were metasomatized by slab-derived hydrous fluids rather than by sediment-derived melt components.

under relatively low-temperature conditions (Elliot, 2003; Peacock, 1990). All these features with their relative flat REE patterns ($(\text{La/Yb})_{\text{CN}} = 1.1\text{--}2.9$) and the lack of significant LREE and Th enrichment do point that slab melting did not play a major role in the genesis of the DDAC magmas and can point to some important implications of thermal state. Although shallow subducted slabs can undergo partial melting and generate adakitic magmas, this process typically produces melts with high Sr/Y and La/Yb ratios and strongly fractionated REE patterns due to the retention of heavy rare earth elements in residual garnet (Defant and Drummond, 1990; Martin *et al.*, 2005), geochemical features that are not observed in the studied samples. The predominance of a hydrous fluid signature, characterized by high LILE/HFSE but without significant LREE/Th enrichment from sediment melts, places constraints on the subduction zone geometry during dyke genesis. These patterns are consistent with melting of a mantle wedge fluxed by fluids released from a subducted slab at shallow to intermediate depths (<100–150 km), where dehydration reactions dominate over slab-melting (Elliot, 2003; Elliott *et al.*, 1997; Hawkesworth *et al.*, 1997; Peacock, 1990). This thermal state is compatible with a nascent or reorganizing subduction system, such as

during slab rollback and back-arc extension in the Western Mediterranean. Future studies incorporating boron isotope systematics could quantitatively constrain the proportion and source of this fluid.

Tectonic setting

The chemical composition of the DDAC provides insights into the tectonic setting of the protoliths using trace element discrimination diagrams. In the Ti/Y vs. Nb/Y diagram (Pearce, 1982), low ratios indicate a MORB or volcanic arc basalt component. This is further supported by the Zr/Y vs. Ti/U diagram (Pearce and Gale, 1977) and the Ti vs. Zr diagram (Fig. 8A; Wang *et al.*, 2016), which are employed to differentiate between within-plate basalt, with arc-like geochemical features and true arc basalts. In both diagrams our samples plot within the fields of plate margin and volcanic arc basalts, respectively, thereby ruling out a within-plate tectonic setting. In the Tb-Th-Ta (Fig. 8B; Cabanis and Thieblemont, 1988) and Y-La-Nb (Fig. 8C; Cabanis and Lecolle, 1989), the DDAC samples plot mainly within the back-arc basalts (BAB) or aligned between BAB and Island Arc Tholeiites (IAT). In the Th_{CN} vs Nb_{CN}

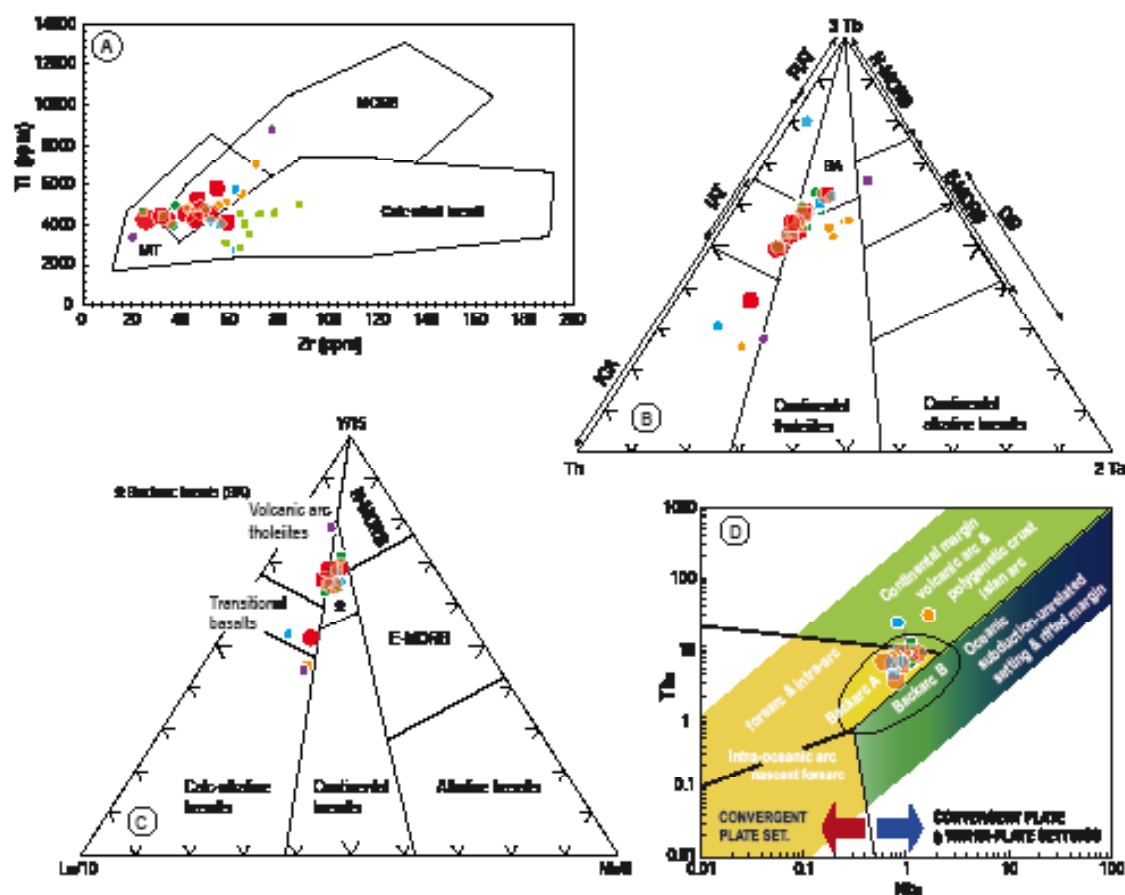


FIGURE 8. A) Ti vs Zr, B) Th-3xTb-2xTa, C) La/10–Y/15–Nb/8 and D) Th_{NMN} vs Nb_{NMN} tectonic discrimination diagrams for the dolerite samples, showing their main back-arc basalt affinity.

diagram (Fig. 9D; Saccani, 2015), the studied samples plot in the back-arc basalts (Type A), characterized by the input of subduction-derived crustal components, whereas in the Ti/V vs Ti/1000 diagram (Shervais, 1982) the samples plot between IAT and MORB/BAB fields.

The analysis of REE ratios serves as a valuable tool for identifying the characteristics of mantle sources. The dolerite samples studied exhibit low Sm/Yb (1.07–1.49) and Tb/Yb (0.24–0.29) ratios, indicating that they likely originated from a garnet- and plagioclase-free spinel-bearing mantle source. Moreover, the low Gd/Yb_{CN} ratio (1.5–1.1) denotes partial melting of a spinel-bearing lherzolitic mantle at depths below 90 km. Moreover, considering the diagram of Nb/La vs La/Yb (Abdel-Rahman and Nassar 2004), DDAC samples denote mixed asthenosphere and lithosphere mantle components (not shown). Thus, our data indicate a depleted spinel-lherzolite mantle source that was selectively metasomatized by slab-derived fluids (see previous sections). This is the hallmark of a back-arc basin setting, where asthenospheric upwelling behind an arc interacts with fluids from the subducting slab (Pearce *et al.*, 2005; Woodhead *et al.*, 2001). Zr and La contents increase sharply with increasing Zr/Nb (Fig. 9A) and

La/Sm (Fig. 9B) ratios, as the Ce and Nb contents also do with increasing Nb/Zr (Fig. 9C) and Ce/Yb (Fig. 9D) ratios. In all these diagrams, there are continuous linear trends suggesting that the melt composition was probably controlled by different degrees of partial melting instead of crystal fractionation. The degree of partial melting that produced the parental magmas of these dolerites can be determined using REE abundances and ratios. Further insights into the melting process can be gained from the Sm/Yb vs. La/Yb (Fig. 10A), Lu/Hf vs. La/Sm (Fig. 10B), and Tb/Yb vs. Dy/Yb diagrams, among others. In all these diagrams, samples plot on or near the spinel-lherzolite melting curve, suggesting a 3–20% of partial melting. This interpretation is consistent with the observed data, since the most LREE enriched samples (SP-BR, SP-16, DD-1) correspond to lower degrees of partial melting.

Geodynamic scenario

The integration of geochemical data into a specific regional geodynamic scenario is subject to constraints arising from the geochronology of both, the dykes and the metamorphic rocks of the Alpujarride nappes, as well as from the regional geology.

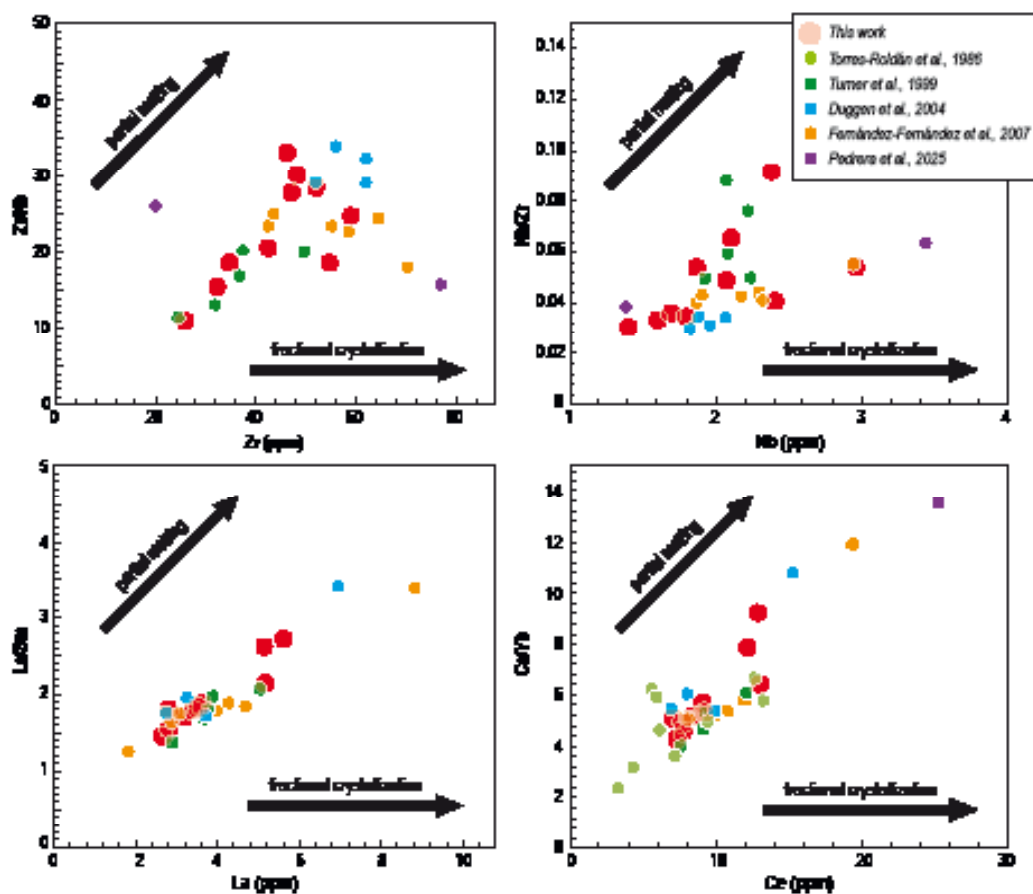


FIGURE 9. A) Zr/Nb vs Zr, B) Nb/Zr vs Nb, C) La/Sm vs La and D) Ce/Yb vs Ce diagrams showing that Alpujarride and Málagaide dolerites are controlled by partial melting.

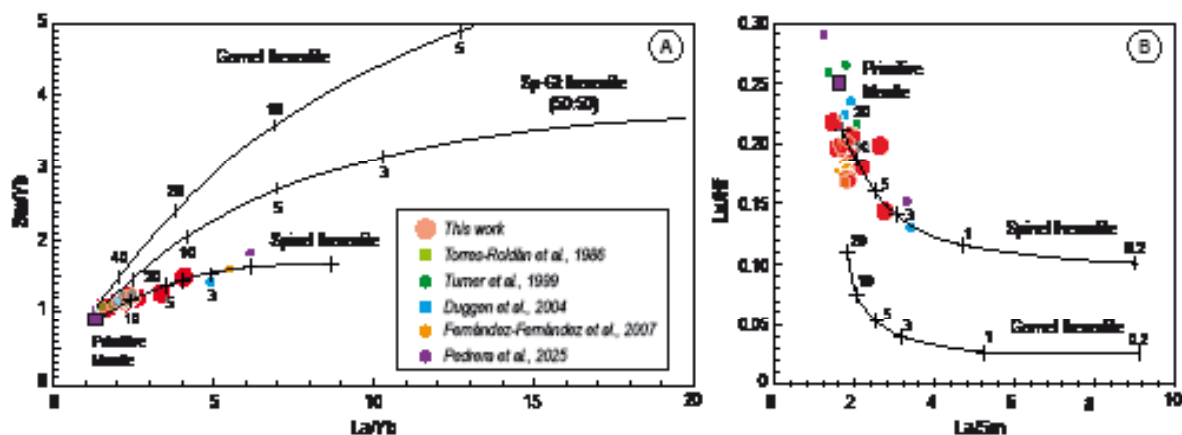


FIGURE 10. A) Sm/Yb vs La/Yb and B) Lu/Hf vs La/Sm diagrams of the dolerite dykes from the Alpujarride and Málagaide complexes. Crosses and numbers indicate the partial melting degree of the mantle source.

The age of the dolerite dykes was first addressed by [Torres-Roldán et al. \(1986\)](#), who proposed an intrusion age of 22–23 Ma based on bulk-rock K/Ar analyses. Subsequently, three further studies have examined this issue using either $^{40}\text{Ar}/^{39}\text{Ar}$ data ([Duggen et al., 2004](#) and [Turner et al., 1999](#)) or U-Pb SHRIMP data on zircon ([Esteban et al., 2013](#)). As proposed by [Turner et al. \(1999\)](#) the emplacement of the dykes took place at ~ 30 –27 Ma, whereas [Duggen et al. \(2004\)](#) and [Esteban et al. \(2013\)](#) suggest older intrusion ages, at 33.6 ± 0.6 Ma and 33.1 ± 0.7 Ma, respectively. It should be noted that the $^{40}\text{Ar}/^{39}\text{Ar}$ ages range between 30 and 17 Ma ([Turner et al., 1999](#)) or 33 and 17 Ma ([Duggen et al., 2004](#)). To explain such time spans, these authors attribute the older $^{40}\text{Ar}/^{39}\text{Ar}$ ages to the dyke intrusion and the younger ones to the imprint of the regional metamorphism ([Fig. 11](#)). However, the frequent alteration of these dykes ([Torres-Roldán et al., 1986](#)) and the low Zr content in basaltic rocks call for caution when interpreting the geochronological data mentioned above. Alternatively, the timing of the dolerite swarm can also be constrained by the age of the metamorphic host rocks. This is because the dykes contain enclaves of the surrounding metamorphic rocks, and therefore their intrusion cannot predate the age of the regional metamorphism. This means that the well-established age for HT-LP metamorphism of the Los Reales nappe sets the maximum intrusion age at ~ 22 Ma ([Fig. 11](#)). As suggested by [Torres-Roldán et al. \(1986\)](#), an intrusion time slightly younger than the metamorphism opens the possibility that the emplacement of dykes in the Málagaide complex might have occurred whilst the rocks were still hot, which would explain the development of incipient retrograde metamorphic assemblages in the dykes. In this regard, the formation of lobulated contacts between dykes and aplite sills of the Los Reales nappe ([Fig. 3B](#)) also suggests similar ages for the HT-LP regional metamorphism and the dolerite intrusion.

As this type of contact requires that the host rocks were ductile during the intrusion ([Pitcher, 1993](#)), the aplites should be kept at temperature more than 350° to 475° C, the brittle-ductile transition in the continental crust, depending on fault slip rate and temperature gradient ([Aharonov and Scholz, 2019](#)).

With regard to the regional factors, it is worth noting that the metamorphic sequence of the Los Reales nappe, where the dykes are emplaced, is a sheet with reduced structural thickness (up to 5 km thick) and strongly condensed isograds, ranging from granulitic conditions close to the Ronda peridotites to greenschist facies at their uppermost levels ([Balanyá et al., 1993](#); [Loomis, 1972a](#); [Massonne, 2014](#); [Tubía, 1988](#)). The metamorphic sequence of the Los Reales nappe thus corresponds to a thinned continental crust, for which a minimum fivefold vertical attenuation has been described ([Argles et al., 1999](#)). The crustal thinning is the result of an event of late-extensional tectonics, leading to the development of ductile shear zones associated with important material omissions along the contact between the Ronda peridotite and its metamorphic cover ([Argles et al., 1999](#); [Tubía, 1994](#)) or along the contacts between migmatites and the overlying schists ([Cuevas et al., 2001](#)). The Los Reales-Málagaide boundary, which has long been recognised as extensional shear zone ([González-Lodeiro et al., 1996](#); [Lonergan and Platt, 1995](#); [Tubía et al., 1993](#)), is further evidence of this extensional event at upper structural levels and under brittle-ductile conditions.

To summarise, the region studied is characterised by: i) the presence of a dyke swarm of basaltic composition, ii) emplaced in a severely thinned continental crust, iii) during an event of extensional tectonics, iv) that was accomplished at Miocene times (~ 20 –23 Ma), and v) contributed to the exhumation of the Ronda peridotites.

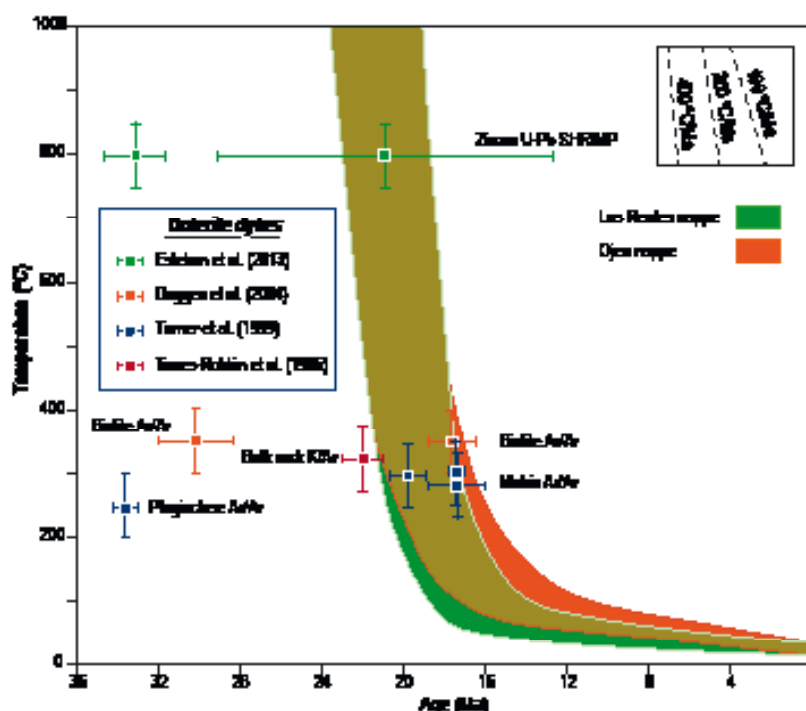


FIGURE 11. Temperature-time (T-t) cooling path for Ojén and Los Reales nappe (modified from [Esteban et al., 2004](#)) summarizing published geochronological data for dolerite dykes.

Looking at them as a whole, and further considering that the geochemical signature of the dolerite swarm points to a subduction scenario, we consider that the Early Miocene tectono-magmatic evolution of Los Reales-Maláguide group is consistent with a back-arc hyperextension in a subduction scenario, in line with the exhumation process proposed for the south Tibetan ophiolites ([Maffione et al., 2015](#)).

CONCLUSIONS

According to the data presented we conclude that:

- i) The source of the DDAC was a spinel-bearing depleted mantle source (N-MORB or Transitional-MORB) located at depths less than 90 km, lying in between the asthenosphere-lithosphere interface.
- ii) The absence of adakitic signature magmas rules out slab melting and suggests fluid release under relatively low thermal conditions at shallow to intermediate depths, where dehydration reactions dominate over slab-melting.
- iii) The melt composition was mainly controlled by partial melting degrees of 3–20% and less so by crystal fractionation of olivine and pyroxene.

iv) Tectonic discrimination diagrams, though sometimes controversial, point to the origin of the DDAC in a context of back-arc basalts or a transition zone between back-arc basalts and island arc tholeiites (IAT).

v) Similar geochemical trends for the DDMC also point to the same mantle source.

vi) A back-arc basin, induced by slab rollback or delamination of the subducted lithosphere, is proposed as the tectonic scenario for the Alpujarride and Maláguide dolerites, providing an excellent example of interaction between subduction and magma genesis in the mantle wedge.

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APPENDIX I

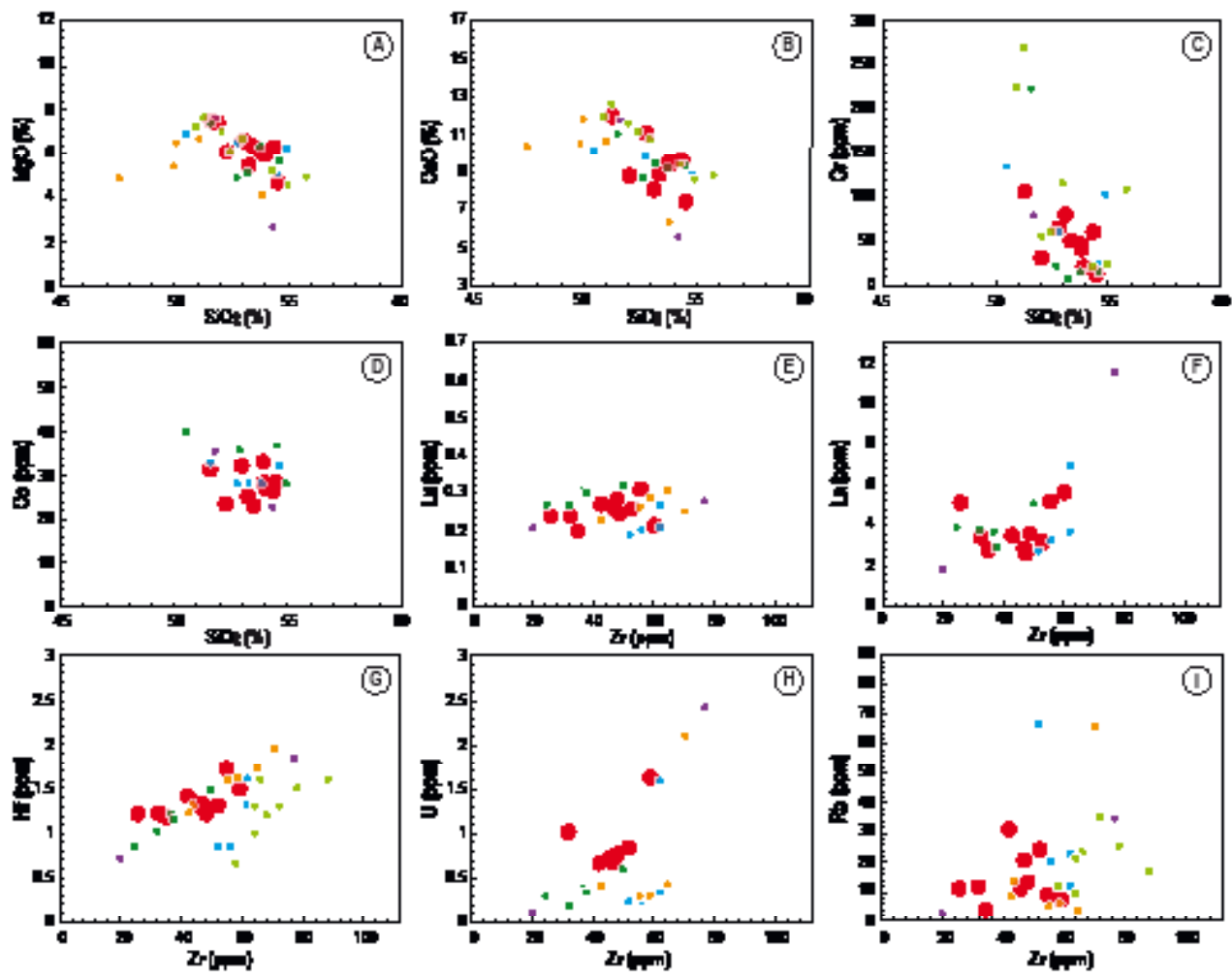


FIGURE I. Harker diagrams for the Alpujárride and Maláguide dolerites. Note the negative correlation of MgO, CaO, Cr and Co versus the SiO_2 and the slight positive and scattered correlation of Hf, U and Rb versus Zr.

TABLE I. Whole rock geochemical data of Alpujárride dolerite dykes

Sample	GP-15L	GP-16	GP-20	GP-22	GP-18	DD-1	Is-24-12	Is-24-13	DD-2	DD-5
Coordinates	36°48'15.80" N 4°47'44.80" W	36°48'30.40" N 4°48'23.67" W	36°47'3.80" N 4°48'03.80" W	36°46'18.67" N 4°48'04.40" W	36°46'10.80" N 4°48'34.07" W	36°46'35.40" N 4°48'16.80" W	36°46'40.00" N 4°48'00.00" W	36°46'46.11" N 4°48'08.27" W	36°46'35.40" N 4°48'15.00" W	36°46'00.10" N 4°48'00.27" W
SiO ₂ (Wt%)	53.95	54.53	51.63	53.95	53.00	53.27	54.01	54.39	53.48	52.29
TiO ₂	0.71	0.97	0.70	0.74	0.76	0.89	0.79	0.71	0.76	0.87
Al ₂ O ₃	16.12	15.60	16.67	16.33	15.90	15.76	16.44	16.45	16.27	16.48
FeO	8.28	9.00	8.20	8.00	7.20	8.58	8.89	8.48	8.80	8.96
MnO	0.16	0.15	0.15	0.14	0.12	0.13	0.15	0.15	0.15	0.15
MgO	6.05	4.73	7.50	5.98	6.60	5.48	6.04	6.28	6.35	6.11
CaO	10.40	8.70	12.45	10.35	11.70	9.34	10.40	10.54	9.88	9.88
Na ₂ O	2.45	3.05	2.19	2.60	2.39	2.21	2.50	2.39	2.65	3.01
K ₂ O	0.31	0.26	0.17	0.33	1.15	0.28	0.33	0.28	0.52	0.42
P ₂ O ₅	0.14	0.17	0.11	0.09	0.10	0.06	0.06	0.07	0.07	0.06
LOI	1.46	2.77	1.05	1.07	1.22	4.26	1.13	1.02	2.43	2.74
Total	99.95	99.98	100.62	96.98	100.14	99.89	100.74	100.75	100.67	100.98
Mg#	42	34	48	43	48	39	40	43	43.9	40.5
Co (ppm)	0.19	0.17	0.17	0.36	0.43	0.29	0.70	0.69	0.60	1.10
Rb	10.91	8.69	3.46	11.39	30.75	7.00	13.00	11.00	24.00	20.00
Ba	52.07	96.86	40.23	51.04	282.27	43.00	45.00	34.00	76.00	49.00
Str	150.64	151.50	180.29	154.57	230.04	222.00	149.00	145.00	176.00	229.00
Pb	5.40	2.80	4.80	4.91	6.40	5.00	5.00	5.00	5.00	5.00
Th	0.99	0.95	0.39	1.01	0.66	1.62	0.76	0.73	0.84	0.67
U	0.17	0.30	0.13	0.36	0.29	0.55	0.44	0.55	0.62	0.43
Zr	25.00	54.55	34.61	32.20	42.24	59.00	48.00	46.00	52.00	47.00
Hf	1.21	1.72	1.18	1.22	1.41	1.50	1.20	1.30	1.30	1.30
Ta	0.17	0.21	0.13	0.16	0.15	0.22	0.15	0.14	0.16	0.15
Y	0.88	0.88	num	0.88	0.88	13.80	16.10	14.90	14.60	15.70
Nb	2.38	2.96	1.87	2.11	2.07	2.40	1.60	1.40	1.80	1.70
Sc	0.88	0.88	num	0.88	0.88	30	35	35	38	37
Cr	44	12	105	41	63	80	20	60	50	30
Ni	23	20	55	25	39	20	30	30	30	20
Cu	28	28	31	33	32	25	27	26	23	23
V	214	250	223	223	205	198	249	225	229	270
W	0.88	0.88	num	0.88	0.88	1	0.5	1	1	1
Bm	0.88	0.88	num	0.88	0.88	13	13	12	13	13
Zn	62	57	73	60	67	30	50	50	50	40
Cd	54	171	64	95	12	70	90	80	30	10
La	5.13	5.86	2.79	3.42	3.91	5.60	3.60	2.84	3.86	2.65
Ce	12.15	12.96	6.96	9.03	9.14	12.80	7.66	7.29	8.38	7.76
Pr	1.64	1.81	1.07	1.34	1.37	1.63	1.22	1.04	1.21	1.17
Nd	7.52	8.79	5.15	6.48	6.66	7.38	6.20	5.61	6.37	5.98
Sm	1.97	2.43	1.57	1.94	1.94	2.07	1.94	1.84	1.87	1.85
Eu	0.75	0.99	0.67	0.73	0.84	0.63	0.70	0.64	0.67	0.74
Gd	2.85	3.43	2.27	2.74	3.13	2.48	2.58	2.38	2.52	2.70
Th	0.44	0.53	0.36	0.43	0.45	0.48	0.44	0.42	0.43	0.44
Dy	2.96	3.57	2.44	2.92	3.09	2.69	2.81	2.73	2.70	2.87
Hol	0.98	0.71	0.50	0.59	0.63	0.53	0.59	0.57	0.55	0.58
Er	1.72	2.04	1.43	1.69	1.77	1.56	1.79	1.71	1.73	1.80
Tm	0.25	0.31	0.21	0.25	0.26	0.22	0.26	0.25	0.24	0.25
Tb	1.55	2.08	1.39	1.62	1.74	1.38	1.58	1.72	1.63	1.71
Lu	0.24	0.31	0.20	0.24	0.27	0.22	0.25	0.26	0.26	0.28
REE	30.8	46.0	27.0	33.4	34.8	39.5	31.6	29.3	31.7	30.8
Co/Ce*	1.01	1.02	0.99	1.04	1.02	1.01	0.86	0.99	1.02	1.08
(La/Th) _{ch}	2.37	1.82	1.44	1.51	1.45	2.09	1.63	1.18	1.39	1.11
(La/Sm) _{ch}	1.68	1.37	1.15	1.14	1.17	1.75	1.20	1.00	1.08	0.92
(Sm/Th) _{ch}	1.52	1.40	1.35	1.40	1.49	1.43	1.35	1.14	1.20	1.31
Eu/Er*	0.97	0.98	1.09	0.97	1.04	0.87	0.96	0.93	0.94	1.02