PETROLOGIC STUDY OF THE POST-HERCYNIAN DYKE MAGMATISM IN CALABRIA AND SICILY

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INTRODUCTION AND GEOLOGICAL SETTING

During the late Paleozoic - early Mesozoic, huge volumes of plutonic and volcanic rocks, as well as widespread basic to acidic dyke swarms, were produced, mostly related to the extensional tectonic regime established during the final stages of the Hercynian orogeny, causing wrenching and faulting of the crust and subsequent continental break-up leading to the definitive Jurassic opening of the Tethys ocean (*e.g.*, Wilson *et al.*, 2004).

In south-western Europe the produced magmatic rocks show a well defined time distribution in terms of magmatic affinity (calc-alkaline, alkaline and tholeiitic; Orejana *et al.*, 2008 and references therein). Calc-alkaline magmas were indeed produced during the Permo-Carboniferous whereas magmatic affinity shifted to alkaline during the late Permian - middle-late Triassic. Generally, alkaline and calc-alkaline magmatism did not coexist. Finally, minor volumes of tholeiitic magmas were produced, but not earlier than the late Triassic.

Wide variations in geochemical affinity and compositions of produced magmas can be related to a number of factors: type, composition, depth and melting degrees of the involved sources, reflecting in turn different tectonic settings and mantle heterogeneity; composition of parental magmas; differentiation processes during the magma ascent (*e.g.*, fractional crystallization, magma mixing, crustal contamination, AFC).

The sources potentially involved in the widespread and voluminous post-Hercynian magmatic event were either the lithospheric mantle as the asthenosphere, the continental crust and the subducted oceanic slab (*e.g.*, Lorenz & Nicholls, 1984; Finger & Steyrer, 1990, 1991; Bonin *et al.*, 1993; Traversa *et al.*, 2003). This latter, according to some authors, would have played a dominant role, especially in the production of the calc-alkaline magmas (*e.g.*, Cameron *et al.*, 2003). Nevertheless, most authors discard such contribution since subduction is considered to have been too old to influence the post-collisional magmatic activity (*e.g.*, Cocherie *et al.*, 1994; Rottura *et al.*, 1998; Cortesogno *et al.*, 2004).

Products of Hercynian post-collisional dyke magmatism occur in the Calabria Peloritani Orogen (CPO) and in the western-central Sicily, showing a geochemical affinity ranging from calc-alkaline to tholeiitic and alkaline, respectively.

Calabrian dykes have been collected from five different locations of Serre Massif, one of few places in the world where a nearly complete section of continental crust, with an overall thickness of about 30 km, is exposed (Schenk, 1980, 1984, 1990). The crustal section is made up of (from the bottom to the top):

a) lower crustal metagabbros, felsic and mafic granulites, and metapelitic migmatites (Schenk, 1980, 1984, 1990; Acquafredda *et al.*, 2006);

b) large bodies of late Hercynian metaluminous to weakly peraluminous quartz-diorites, tonalites and granodiorites, and minor strongly peraluminous granodiorites and granites, forming the Serre batholith, intruded in between the lower and upper crustal metamorphic rocks (Rottura *et al.*, 1990; Caggianelli *et al.*, 2007 and references therein);

c) greenschist to amphibolite facies metasedimentary and minor metavolcanic sequences, forming the uppermost crustal levels (Colonna *et al.*, 1973; Atzori *et al.*, 1977; Acquafredda *et al.*, 1987; Angì *et al.*, 2010).

Studied dykes intrude the paragneiss and phyllite basement as well as the late Hercynian granitoids, with lenticular or tabular shapes and individual thickness ranging between 0.3 and 10 m.

Sicilian dykes have been sampled in two different sectors of the Sicilian-Maghrebian orogenic chain, composed of a thin-skinned south-verging fold and thrust belt developed during the Late Cretaceous -

Quaternary Africa-Europe collision (Dewey *et al*., 1989; Ben Avraham *et al*., 1990; Mazzoli & Helman, 1994; Tortorici *et al.*, 2009). One dyke outcrop is located in central Sicily where the Sicilide complex is observed, and the other one in western Sicily where the Permian to Palaeogene carbonates and Miocene (up to Early Tortonian) terrigenous deposits, deriving from the southern Neo-Tethyan margin (Catalano & D'Argenio, 1978; Mascle, 1979), dominate and are overlain by thrusted rock units of the Sicilide Complex, including the Numidian Flysch.

The outcrop from central Sicily (Leonforte area) consists of a sill intruded into the Ladinian Lercara Formation, here consisting of 6 m of a well bedded pelagic sequence of cherty siltites and tuffites (Grasso & Scribano, 1985; Grasso *et al.*, 1993), and passing upwards to 10 m of black shales and micritic limestones, assigned to the Mufara Formation and dated to the Early Carnian on the basis of palaeontological data (Grasso & Scribano, 1985; Grasso *et al*., 1993).

The second study area, in western Sicily, consists of two different dyke outcrops occurring in the Lercara area. Studied dykes are intruded within a middle-late Triassic shale-sandstone sequence belonging to the Lercara Formation (Montanari, 1968; Cirilli *et al*., 1990; Carcione *et al*., 2004; Carcione, 2007).

Field and petrographic features, mineral chemistry, whole-rock major and trace elements and Sr-Nd isotopic composition of both Calabrian and Sicilian dykes have been investigated with the aim to develop a petrogenetic model able to explain their origin and evolution, as well as to try defining a geodynamic context for studied magmatic rocks in the frame of the different phases of magmatic activity that, starting from the initial collapse of the European Hercynian Belt, were sequentially involved in the continental breakup of Pangea and in the subsequent oceanization processes leading to Tethys formation.

RESULTS AND DISCUSSION

Calabrian dykes

The studied Calabrian dykes outcrop in five different location of Serre Massif (Mammola, Antonimina, Foletti Valley, San Todaro, and Villaggio Zomaro) and samples have been labelled as LMA, PDL, A, F, ST, and VZ, respectively. All samples suffered an extensive hydrothermal alteration causing partial or, in some cases, total replacement of the primary mineralogical assemblage by secondary phases (*e.g.*, chlorite and/or actinolite after pyroxene; chlorite after biotite; albite after plagioclase).

Calabrian dykes show a porphyritic texture with a P.I. in the range of 7-25%. The most mafic lithotypes (LMA, PDL, A and F samples) are mainly formed by pyroxene phenocrysts (mostly augite and minor diopside) in a groundmass formed by plagioclase (mainly albitic in composition) and amphibole (Tschermakite and Mg-Hastingsite in LMA samples, Mg-Hornblende in F samples, Tschermakite and Mg-Hornblende in A samples). Noteworthy is the presence of quartz *ocelli* in LMA and PDL samples, in some cases mantled by clinopyroxene and amphibole and occasionally embayed.

The most felsic dykes (ST and VZ samples) consist of albitic plagioclase, K-feldspar, quartz, chloritized biotite and white mica. ST samples separate in two different sub-groups: Group I, characterized by a fine to medium-grained matrix, lack of primary white mica and low amounts of secondary one; Group II characterized by a medium-grained quartz-rich matrix and by the presence of primary white mica.

Calabrian dykes range in composition from basaltic andesites (LMA-PDL groups), andesites (A-F groups) to dacites-rhyodacites (VZ-ST groups), all showing a medium- to high-K calc-alkaline affinity.

Significant differences in major and trace elements composition have been detected among the ST samples that may be again divided into two subgroups (SiO_2-poor and SiO_2-rich) reflecting the observed petrographic features. The former group shows many similarities in terms of major and trace elements composition with the intruded metaluminous to weakly peraluminous Serre granitoids, generally interpreted as resulting from the interaction of mantle-derived magmas with lower-crustal melts (Schenk, 1980; Rottura *et al*., 1990).

On the whole, all dykes show similarities with the late Carboniferous - lower Permian calc-alkaline dykes of the Sardinia-Corsica domain - SCD (Atzori & Traversa, 1986; Atzori *et al*., 2000; Traversa *et al*., 2003) and show typical features of subduction-related magmas (*e.g.*, Pearce, 1983), such as LILE enrichment, HFSE depletion, peaks at Rb, Pb and Th, and troughs at Nb-Ta and Ti, indicative of orogenic geodynamic contexts, strongly contrasting with the post-collisional tectonic setting envisaged for the emplacement of the dykes. In fact, the studied calc-alkaline dykes, intruding Hercynian metapelites and late-Hercynian undeformed granitoid rocks, were likely generated in a post-collisional extensional context, characterized by lithosphere thinning promoting astenosphere upwelling (*e.g.*, Caggianelli *et al*., 2007; Angì *et al*., 2010).

This is indeed the same general framework envisaged for dykes of roughly similar composition widespread in western Europe, such as those from the SCD (Atzori & Traversa, 1986; Atzori *et al*., 2000; Traversa *et al*., 2003), for which a transition from a compressive to extensional geodynamic setting and variable extents of crustal contamination of mantle magmas derived from subduction-modified lithospheric mantle sources, have been invoked to explain their geochemical features.

A similar magmatic source is also suggested by the Sr-Nd isotopic composition of most of the studied dyke groups ($^{87}Sr/^{86}Sr_i$ from 0.7098 to 0.7254; εNd_i from -4.10 to -8.49; Fig. 1).

Conversely, the most acidic ST dacite-rhyodacitic group shows an isotopic composition ($^{87}Sr/^{86}Sr_i$ = 0.7254; εNd_i = -7.32; Fig. 1) broadly compatible with a direct crustal origin by partial melting of metasediments from the lower Serre crust. Moreover, the comparison with experimental melts composition revealed similarities with a metapelitic crustal source.

Differently, the silica-poor sub-group of ST dacite-rhyodacites likely resulted from hybridization, at variable extent, of basaltic mantle magma with pelitic metasediments.

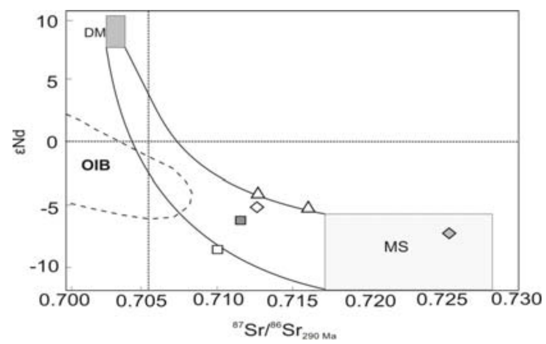

Fig. 1 - εNd *vs*. $^{87}Sr/^{86}Sr_{290\ Ma}$ diagram for Calabrian dykes. DM: depleted mantle: MS: metasediments from Calabria lower crust (Caggianelli *et al*., 1991). Curves are two possible mixing lines between DM and MS (Rottura *et al*., 1991). Squares: basaltic andesites samples; triangles: andesites samples; empty rhomb: ST silica-poor sub-group sample; filled rhomb: ST silica-rich sub-group sample.

Group VZ dacitic dykes have mineralogical and geochemical composition strongly modified by post-magmatic modifications. For this reason, various attempts to develop reliable geochemical modeling, explaining the genesis and evolution of VZ samples, resulted unsuccessful. However, the strong similarities observed between the trace element composition of the VZ samples and the other studied Calabrian dykes as well as the SCD post-collisional dykes, allow us to envisaged a comparable post-collisional tectonic context and magma source. Additionally, the "disequilibrium" textures shown by VZ samples (*e.g.*, quartz *ocelli* and dissolution textures) could be considered consistent with mixing processes between crustal- and mantle-derived melts.

FC-AFC and mixing calculations (Ersoy & Helvacı, 2010) have been carried out to define the processes involved in the evolution of the intermediate-basic Serre dykes. Results suggest that the basaltic andesites and group F andesites likely evolved by AFC processes involving stalling and fractionation of mantle-derived melts in the crust and concurrent assimilation of wall rocks similar to the lower crustal Serre metapelites.

On the other hand, group A andesites likely represent the result of simple fractionation process from the most primitive group A melts.

Sicilian dykes

Sicilian dykes from two different localities have been studied: in central Sicily, in the Leonforte area (VG samples) and in western Sicily, in the Lercara area (MA and BM samples).

Hydrothermal metamorphism affected extensively these samples, causing albitization of plagioclase and, in some cases, partial to total chlorite replacement of primary mafic mineral phases, as well as local growth of prehnite/pumpellyte grains. Primary plagioclase composition (mainly labradoritic) is preserved in the BM samples of the Lercara area, while fresh augitic, and minor diopsidic, clinopyroxene forming an ophitic texture with plagioclase, is observed in the Leonforte samples.

The studied rocks have been classified as alkaline basalts (VG samples) as well as tholeiitic basalts and basaltic-andesites (BM and MA samples, respectively).

The alkali basalts from Leonforte area have a distinctive OIB trace element character (OIB-like humped pattern, enrichments in LILE, HFSE and LREE, positive Nb-Ta and Ti anomalies) suggesting an anorogenic nature of the magmas with no involvement of crustal and/or subduction-related components. Additionally, trace element compositions are broadly similar to those of Spanish Central System alkaline suite (Villaseca *et al*., 2004; Orejana *et al*., 2008) and Triassic San Donato alkaline dykes (Barca *et al*., 2010), for which LILE-enriched mantle sources have been invoked.

Sr-Nd isotopic composition ($^{87}Sr/^{86}Sr_i$ from 0.7060 to 0.7067; εNd_i = from 3.43 to 3.69; Fig. 2), largely similar to those of the late Permian alkaline rocks of the Pyrenees (Lago *et al*., 2004) and the Spanish Central System (SCS; Villaseca *et al*., 2004; Orejana *et al*., 2008), is compatible with a moderately depleted asthenospheric mantle source, that however had experienced a recent metasomatic enrichment event by LILE-rich fluids, likely related to convective motion in the mantle. Finally, trace elements ratios and descending REE patterns, suggest a deep, possibly garnet-bearing, astenospheric mantle source and low degrees of partial melting.

Tholeiitic samples from Lercara area show E-MORB affinities, such as HFSE enrichment and high HFSE/LILE ratio, as well as Sr and Ti negative anomalies and Th and Pb troughs in normalized trace elements patterns, consistent with an enriched asthenospheric mantle source.

Sr-Nd isotopic composition ($^{87}Sr/^{86}Sr_i$ from 0.7074 to 0.7079; εNd_i = from -1.7 to -2.2; Fig. 2) confirms the enriched character of the mantle source coupled with the interaction with crustal rocks. Several crustal

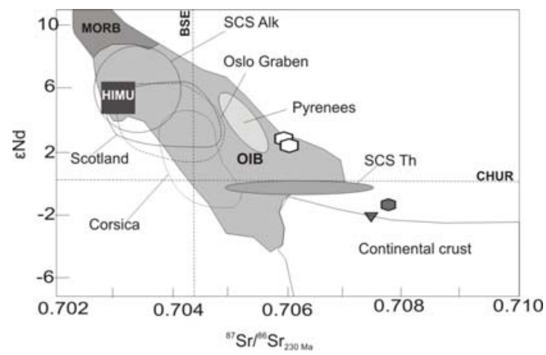

Fig. 2 - εNd *vs*. $^{87}Sr/^{86}Sr_{230\ Ma}$ diagram for Sicilian dykes. Alkaline samples: empty symbols; tholeiitic samples: filled symbols. MORB and OIB fields after Zindler & Hart (1986). Compositional fields of Pyrenees, Oslo Graben, Spanish Central System (SCS Alk: alkaline lamprophyres, SCS Th: tholeiitic dykes), Scotland, and Corsica are from Lago *et al*. (2004), Neumann *et al.* (2004), Orejana *et al.* (2008); Upton *et al.* (2004), and Bonin (2004) respectively.

signatures, indicatives of lower crust involvement (such as Th/Yb, Ta/Yb and Nb/U), have been also detected.

Moreover, AFC calculations (De Paolo, 1981) carried out in this study suggest that, although mainly fitting the pure mixing model line with the lower crust (Taylor & McLennan, 1995), the composition of many of the tholeiitic rocks would require an assimilation ratio of lower crustal rocks ranging from 20 to 40%. Similar AFC mechanisms, implying assimilation of lower-crustal rocks (granulites), have been proposed by Cebrià *et al*. (2003) to explain the composition of the Spanish Central System tholeiitic suite.

CONCLUSION

The studied magmatic rocks from southern Calabria and central and western Sicily, with calc-alkaline, alkaline and tholeiitic affinities, well represent the transition between the late Carboniferous-early Permian post-collisional geodynamic context to a Triassic purely distensive one, taking place throughout the Pangea break-up and the subsequent opening of the Tethys ocean.

The sub-alkaline low- to high-K calc-alkaline magmatism, likely mostly developed during the late Carboniferous-early Permian, is related to post-collisional Hercynian phases, taking place after the main collisional events and related to the collapse of the chain through the development of a trans-tensile stress field (Arthaud & Matte, 1977; Ziegler, 1993). Enriched lithospheric mantle sources, metasomatized by subduction-related fluids and interactions, at variable extents, with the still thickened crust, are envisaged.

Middle Triassic alkaline rocks mark the transition to a purely distensive context, no more connected with the collapse of the Hercynian belt, but rather with the post-Hercynian global re-organization of plates, wrenching and faulting of the crust that will cause the break-up of Pangea (Cortesogno *et al*., 1998; Orejana *et al*., 2008).

Lithosphere thinning, passive upwelling of hot asthenospheric mantle and melting triggered by adiabatic decompression is the most probable geodynamic setting for the generation of Sicilian alkali basalts in agreement with the scenario proposed for the emplacement of the Triassic alkali basalts of the San Donato Unit (Barca *et al*., 2010), in northern Calabria.

Finally, the studied middle to late Triassic tholeiitic magmatism is likely related to major rates of lithosphere extension and asthenosphere upwelling, and to high degrees of partial melting of a more depleted and less deep asthenospheric mantle source than that involved in the alkaline magmatism. However, the interaction between lower crustal rocks indicates that the lithospheric thinning was not still complete at the time of the tholeiitic magmatic activity.

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