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Cenozoic Italian magmatism – Isotope constraints for possible plume-related activity

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ABSTRACT

Assessment of the isotope systematics and the magmatotectonic history of mainly Cenozoic igneous rocks from Italy shows them to be inconsistent with subduction-related magmatism. We attempt to fit these data into an alternative model involving long-term, recurrent plume activity that extended over a period of about 100 Ma, that involved mantle expansion and subsequent mixing between isotopically-distinct, mantle components. Sr, Nd and Pb isotopic compositions of Cenozoic Italian igneous rocks, rather than being random, reflect binary mixing involving a common end-member similar to FOZO. Most isotopic data from along the entire length of Italy, from the Aeolian Islands to the Alpine belt, define a Main Italian Radiogenic Trend (MIRT), characterized by mixing between FOZO and a highly radiogenic Sr, mantle end-member (ITEM, ITalian Enriched Mantle). Data from the Adria foreland, Sicily and the south-western Tyrrhenian Sea and Sardinia deviate from MIRT suggesting mixing with other components, perhaps HIMU and EM1. Both the absence of pure DMM, and the presence of isotopic end-members not recognized in present-day consuming-plate margins are incompatible with subduction-related models. Two models are discussed, one in which ITEM is attributed to melting of pre-Alpine sediments/upper continental crust entrained in a FOZO-like mantle and the other to widespread metasomatic activity involving deep-seated plume activity. In the latter, the widespread nature of FOZO is attributed to a late Triassic–early Jurassic plume that preceded the opening of the Alpine Tethys and led to modification of the lithosphere and/or asthenosphere. Late Jurassic–early Cretaceous plume activity produced mantle expansion and the opening of the Alpine Tethys. A new phase of plume activity started during the Oligocene with the opening of the western and central Mediterranean Basins. Stretching and large-scale extension of the Mediterranean lithosphere was caused by the progressive eastward growth and volume increase of a plume head trapped within the Transition Zone. Plume-generated fluids/melts enriched in K–Ca–CO_2–H_2O, produced mantle sources capable of generating widespread alkaline, mafic, and carbonatitic magmatism. Lithospheric unloading controlled the Tyrrhenian and peri-Tyrrhenian magmatic activity.

1. Introduction

Since the acceptance of a plate tectonic model to the Tyrrhenian–Apennine system of Italy (e.g. Malinverno and Ryan, 1986), the Neogene to Quaternary magmatism in Italy has been attributed to subduction, accommodated by the eastern migration of a westerly-dipping slab, involving conventional trench retreat and back-arc extension (Doglioni et al., 1997; Wortel et al., 2003; Faccenna et al., 2004 among others). However, the general picture is made more complicated by the large chemical and isotopic variation of the associated magmatism. Compositions range from sub-alkaline to alkaline basalts, ultrapotassic mafic to ultramafic rock-types, reflecting different processes and/or mantle sources with very depleted to highly enriched radiogenic isotopic signatures. The presence of leucitites, kamafugites, carbonatites, lamprophyres and lamproites, typical of intraplate associations, as well as the isotopic compositions of many of the igneous rocks, challenge any subduction-related model. As a consequence, authors have been forced into creating complex geodynamic scenarios where the subducted slab had been cross-cut, pierced or straddled by a rising plume (see Gasperini et al., 2002 and reference therein). Several articles have questioned the involvement of subduction-related processes in Italy and have, instead, proposed intra-continental passive rifting (e.g. Cundari, 1979, 1994; Lavecchia, 1988; Locardi

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and Nicolich, 1988; Lavecchia and Stoppa, 1996). A more recent model involves a trapped plume which has physically expanded the asthenospheric mantle in the western and central Mediterranean, leading to lithospheric stretching and associated magmatism without any involvement of subduction (e.g. Bell et al., 2004; Lavecchia and Creati, 2006; Bell et al., 2006; Lavecchia and Bell, 2011). This Mediterranean plume might have initiated in the Atlantic at deep levels and migrated to shallower depths in the western and central Mediterranean areas and regions elsewhere (e.g. Hoernle et al., 1995; Oyarzun et al., 1997; Piromallo et al., 2008; Duggen et al., 2009).

Recent evidence for plume activity in Italy, an idea by no means new (e.g. Vollmer, 1976), involves the recognition of isotopic mantle components found in OIBs, especially FOZO (FOcus ZOne, see Hart et al., 1992), but not in subduction-related environments (Bell et al., 2004, 2005; Cadoux et al., 2007). Other plume-related or intraplate mantle components that may have played a role in Italy are HIMU (e.g. Wilson and Patterson, 2001; Gasperini et al., 2002; Harangi et al., 2006; Rotolo et al., 2006; Lustrino and Wilson, 2007; Beccaluva et al., 2007; Bianchini et al., 2008) and EMI (e.g. Lustrino et al., 2000; Downes et al., 2001). A strongly enriched mantle component, named ITEM (ITalian Enriched Mantle) and never found in subduction environments, has also been recognized along the length of Italy, from the Aeolian Islands to the Alps (Bell et al., 2005, 2006; Owen, 2008). Characterized by an extremely high $^{87}Sr/^{86}Sr$ (>0.7220, initial ratio), it is mostly seen in Oligocene lamprophyres from the western Alps (Venturelli et al., 1984; Owen, 2008).

In this paper, based on an updated regional database of published and unpublished Sr, Nd and Pb isotope analyses (Table 1 and references therein), we assess the minimum number of isotopic end-members needed to explain the mixing trends for the Italian igneous occurrences (peninsular Italy plus the Alps, Sardinia, Sicily and the Tyrrhenian Sea), from Late Cretaceous to present day. We then discuss the role of plume activity and its direct or indirect interaction with the asthenosphere and the lithosphere in controlling mantle source modification, magmatism, and tectonics. We take into consideration the overall long-term magmatotectonic history since Cretaceous times, but specifically focus on the late Miocene–Quaternary extensional phase that opened up the central Mediterranean and generated lithospheric stretching, unloading and resulting volcanism. This is then followed by an assessment of the evolution of the Mediterranean through the use of chemical geodynamics, an approach pioneered by Allègre (1982).

2. Magmatotectonic framework

Fig. 1 schematically shows the geometry and tectonic location of the western (e.g. Algerian and Provençal-Ligure Basins) and central (e.g. Tyrrhenian Sea) Mediterranean Basins and of the Alpine-Betic and Apennine-Maghrebide compressional chains. Table 1 summarizes the isotopic data, the tectonic phases and associated igneous activity. The late Cretaceous–Paleocene compressional phase, which was essentially amagmatic, lead to the progressive consumption of the Alpine Tethys with formation of the internal sheets of the Europe-verging Alpine-Betic thrust belt. It was, only subordinately, accompanied by two cycles of lamprophyric activity, one at the end of the early Cretaceous (∼110–90 Ma) and the other during the late Cretaceous and the early Paleocene (∼80–60 Ma) (Vichi et al., 2005). The first cycle is well represented in southern Tuscany (Faraone and Stoppa, 1990), while the second is recognized at several isolated localities including Calceranica and Corvara in Badia in the south-eastern Alps (68–70 Ma), Nuraxi Figus in south-eastern Sardinia (62–60 Ma), Punta delle Pietre Nere in Puglia (70 Ma, Conticelli et al., 2002) and La Queglia in Abruzzo (58–54 Ma) (see Stoppa, 2008 and references therein) (Fig. 2).

The late Paleocene–Eocene collisional stage between the Africa and Europe continental plates, which pre-dated the Mediterranean extensional phase, produced the nucleation of Africa-verging Alpine sheets. This phase was coeval with basaltic volcanism in the Veneto foreland of the south-eastern Alps (Macera et al., 2003; Beccaluva et al., 2007) and with lamprophyric volcanism in the south-eastern (Val Fiscalina, 34 Ma) and the south-western Alps (Sesia-Lanzo, Combin and Biellese, 29–33 Ma) (see Stoppa, 2008 and references therein). In Oligocene–early Miocene times a narrow belt of calc-alkaline activity developed along the Peri-Adriatic lineament in the Alps, the French coast in Provençe and in south-eastern Sardinia (e.g. Pamić et al., 2002).

At the beginning of late Oligocene times, the extensional process lead to the progressive opening of the Mediterranean wide-rift basins and extension started to dominate over compression. The Neogene to Quaternary Mediterranean phase also involved fold-and-thrust belt tectonics, with formation of the Apennine-Maghrebide belt, but the compressional structures were always confined outward from the progressively eastward-stretching and thinning lithospheric domains (Fig. 1). Two distinct deformational stages, separated by a tectonic break, may be distinguished: the late Oligocene–early Miocene, Ligure–Balearic stage (∼25 to ∼16 Ma) and the middle Miocene–Quaternary, Tyrrhenian stage (∼13 Ma to present) (Lavecchia and Bell, 2011). The Tyrrhenian stage led to the progressive stretching and thinning of the roots of the pre-existing Alpine chain and to the progressive involvement in the compressional tectonics of the Adriatic foreland terranes, as well as formation of the Apennine fold-and-thrust belt. At present, the Tyrrhenian Sea is characterized by a thinned lithosphere which reaches a minimum thickness of only 30 km in its southern bathyal plane, containing the Magnaghi, Vavilov and Marsili volcanoes. In Fig. 2 it is evident that most of the Tyrrhenian and circum-Tyrrhenian magmatic occurrences lie within the thinned lithosphere domain encompassed by the 50 km lithosphere–asthenosphere contour line (Fig. 2; see Panza et al., 2007). Most rocks in the western and southern sides of this domain are sodic basalts (Ustica, Etna, Hyblean Plateau and some of the Tyrrhenian ODP dredged samples). In the Tyrrhenian basinal area (Magnaghi, Vavilov, Marsili), most volcanic rocks are transitional basalts, but along the eastern rift side (from the Aeolian Islands to Campania, Latium and Tuscany), potassium-rich products dominate. They consist of lamproites in Tuscany, of near silica-saturated and leucite-free rocks (trachybasalts plus calc-alkaline rocks) in the Aeolian insular arc, and of silica-undersaturated, leucite-rich, high potassium rocks (leucitites and melilitites; olivine melilitite/kamafugites) within the Roman–Campanian Province. Both saturated and undersaturated trends co-exist in the same province (Conticelli et al., 2007 and references therein). Mid Pleistocene carbonatitic monogenic centres occur within the Intra-montane Ultra-alkaline Province (IUP) of central Italy and at Vulture, both underlain by unthinned lithospheric where the lithosphere–asthenosphere boundary lies at a depth of nearly 90–110 km (e.g. Stoppa and Woolley, 1997; Lavecchia et al., 2006 and references therein).

An independent extensional phase, still active, developed mainly in Mio-Pliocene times, led to the opening of the north-westerly striking, narrow Sicily Channel thrust system, which cross cuts the Sicily-Maghrebide rift system and continues north-west as the Campidano graben in Sardinia (Corti et al., 2006). These relationships are shown in Figs. 1 and 2. The associated Na-alkaline activity, typical of intra-plate rift related magmatism, started during late Miocene times (e.g. Graham Bank, still active), climaxing during the Pleistocene at Linosa and Pantelleria and within the Campidano graben in Sardinia. Associated with extensional tectonics unrelated to the Tyrrhenian opening, such magmatism also characterizes the Hyblean foreland in south-eastern Sicily. For recent reviews, the