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Origin and evolution of Cenozoic magmatism of Sardinia (Italy). A combined isotopic (Sr–Nd–Pb–O–Hf–Os) and petrological view

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ABSTRACT

The Cenozoic igneous activity of Sardinia is essentially concentrated in the 38–0.1 Myr time range. On the basis of volcanological, petrographic, mineralogical, geochemical and isotopic considerations, two main rock types can be defined. The first group, here defined SR (subduction-related) comprises Late Eocene–Middle Miocene (~38–15 Ma) igneous rocks, essentially developed along the Sardinian Trough, a N–S oriented graben developed during the Late Oligocene–Middle Miocene. The climax of magmatism is recorded during the Early Miocene (~23–18 Ma) with minor activity before and after this time range. Major and trace element indicators, as well as Sr–Nd–Pb–Hf–Os–O isotope systematic indicate complex petrogenetic processes including subduction-related metasomatism, variable degrees of crustal contamination at shallow depths, fractional crystallization and basic rock partial melting. Hybridization processes between mantle and crustal melts and between pure mantle and crustally contaminated mantle melts increased the isotopic and elemental variability of the composition of the evolved (intermediate to acid) melts. The earliest igneous activity, pre-dating the Early Miocene magmatic climax, is related to the pushing effects exerted by the Alpine Tethys over the Hercynian or older lower crust, rather than to dehydration processes of the oceanic plate itself.

The second group comprises volcanic rocks emplaced from ~12 to ~0.1 Ma. The major and, partially, trace element content of these rocks roughly resemble magmas emplaced in within-plate tectonic settings. From a Sr–Nd–Pb–Hf–Os isotopic point of view, it is possible to subdivide these rocks into two subgroups. The first, defined RPV (Radiogenic Pb Volcanic) group comprises the oldest and very rare products (~12–4.4 Ma) occurring only in the southern sectors of Sardinia. The second group, defined UPV (Unradiogenic Pb Volcanic), comprises rocks emplaced in the remaining central and northern sectors during the ~4.8–0.1 Ma time range. The origin of the RPV rocks remains quite enigmatic, since they formed just a few Myr after the end of a subduction-related igneous activity but do not show any evidence of slab-derived metasomatic effects. In contrast, the complex origin of the mafic UPV rocks, characterized by low $^{206}Pb/^{204}Pb$ (17.4–18.1), low $^{143}Nd/^{144}Nd$ (0.51232–0.51264), low $^{176}Hf/^{177}Hf$ (0.28258–0.28280), mildly radiogenic $^{87}Sr/^{86}Sr$ (~0.7044) and radiogenic $^{187}Os/^{188}Os$ ratios (0.125–0.160) can be explained with a mantle source modified after interaction with ancient delaminated lower crustal lithologies. The strong isotopic difference between the RPV and UPV magmas and the absence of lower crustal-related features in the SR and RPV remain aspects to be solved.

1. Introduction

During the Cenozoic, a widespread igneous activity developed in the Mediterranean area, mostly within the Alpine suture zone and partially along the older Variscan suture in central Europe (e.g., Carminati et al., 2012; Duggen et al., 2005; Harangi et al., 2006; Lustrino and Wilson, 2007; Lustrino et al., 2011, and references therein). Most of the volcanological, mineralogical and geochemical features observed in the various circum-Mediterranean igneous districts are well represented in the island of Sardinia, which is thus a key-locality for magmatic and geodynamic studies on the basis of several considerations:

1) The island acted as the foreland of the earlier Alpine Orogeny and the hinterland of the Apennine subduction system (e.g., Carminati et al., 2012).

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2) In Sardinia two different igneous phases developed during the Cenozoic, the oldest (Late Eocene–Middle Miocene) is considered to be related to the originally NW-directed Apennine subduction system, whereas the youngest (Middle Miocene–Quaternary) volcanism seems geochemically unrelated to active or recent subduction processes (e.g., Lustrino et al., 2007a, 2009, 2011; Fig. 1).
3) The igneous rocks, essentially in volcanic facies, cover about one-fourth of the island (Fig. 1), making their investigation relatively easy and statistically relevant.
4) The most recent "anorogenic" products often carry mantle xenoliths, therefore providing direct evidence on the composition of the local shallow sub-continental mantle (e.g., Rocco et al., 2012, and references therein).
5) More than 99% of the "anorogenic" products show unique geochemical compositions compared to the rest of the "anorogenic" lavas of the circum-Mediterranean area in terms of BSE-like Sr, sub-chondritic Nd and very low $^{206}Pb/^{204}Pb$ isotopes (e.g., Lustrino et al., 2007a).

Former studies have evidenced the peculiar isotopic composition of the Cenozoic igneous rocks of Sardinia, even though a comprehensive Sr–Nd–Pb–Hf–Os–O isotopic study is still missing. This paper presents thirty-four new Sr-, thirty new Nd-, thirty new Pb-, seventeen new Hf-, seven new Os- and fifteen new O-isotopic ratios for the most representative samples of both "orogenic" and "anorogenic" rocks. Our new results are integrated with published and new major- and trace-element and isotopic data of Sardinian rocks, in order to examine the petrological and geodynamic processes associated with their origin.

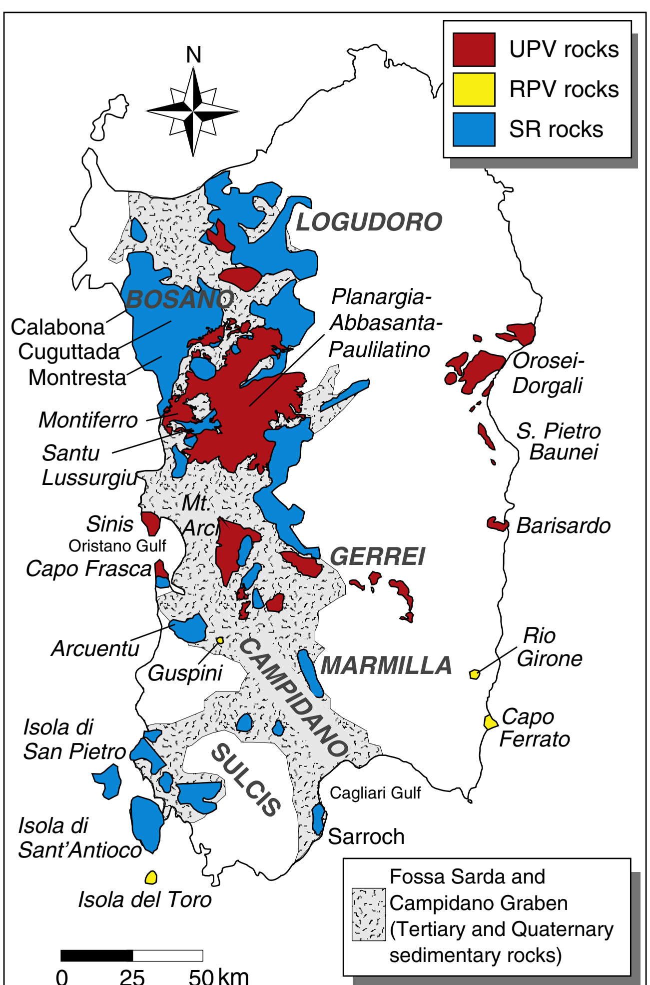

Fig. 1. Simplified geological map of Sardinia, showing the main Cenozoic igneous outcrops. Modified from Lustrino et al. (2009).

2. Geological background and magmatic evolution

The geological setting and background of the island of Sardinia has been recently reviewed (e.g., Carminati et al., 2010, 2012; Lustrino et al., 2009, 2011) and for this reason only the most important aspects will be summarized here. Until the Oligocene, Sardinia and Corsica were part of the southern European paleo-margin. After a NE–SW striking rifting stage, mostly developed during the Oligocene, a ~55–60° Early Miocene counter-clockwise rotation separated the Sardinia–Corsica block from Europe (~22–15 Ma; Fig. 2; Carminati et al., 2010, 2012; Gattacceca et al., 2007, and references therein). A branch of this rifting system is now identified in the Sardinian Trough (*Fossa Sarda* in the Italian literature), a ~220 km-long, ~40 km-wide middle Oligocene-Aquitanian rift system cutting the island from north to south (Cherchi et al., 2008; Faccenna et al., 2002; Lecca et al., 1997; Fig. 1). During the Langhian (~15 Ma) the Sardinia–Corsica block rotation ceased, thereby attaining its roughly N–S oriented present position (e.g., Gattacceca et al., 2007; Speranza et al., 2002; Vigliotti and Langenheim, 1995). The rotation of the Sardinia–Corsica block was associated with the opening of the Ligurian–Provençal back-arc basin and was roughly coeval also with the clockwise rotation of the Balearic Promontory and the opening of the Valencia Trough (Fig. 2). The peak of the angular velocity coincided with the peak of magma productivity, whereas the end of the Sardinia–Corsica rotation coincided with the end of the "orogenic" igneous activity. After a few Myr of quiescence, Sardinia was affected by a reprise of igneous activity from early Late Miocene (~12 Ma) to Pleistocene (~0.1 Ma), with a peak concentrated around Middle–Late Pliocene (Beccaluva et al., 1985; Lustrino et al., 2000, 2004a, 2007a, 2007b, and references therein).

The origin of the Oligo–Miocene extensional movements recorded in the western Mediterranean basins has been related to the gravitative sinking of subducted oceanic lithosphere of the Tethyan Ocean (Ionian Sea) subducting north-westward since late Eocene, possibly coupled with an asthenospheric east-directed mantle flow (e.g., Alvarez, 1974; Beccaluva et al., 1989; Carminati et al., 2012; Gueguen et al., 1998). The oldest igneous rocks (~38 Myr; Lustrino et al., 2009; Fig. 3) are represented by a small microdiorite body from Calabona area (N Sardinia). Late Eocene–Late Oligocene igneous activity in Sardinia was sporadic, with the bulk of the orogenic igneous activity starting around 28 Ma (Lecca et al., 1997), and peaking during the 22–18 Myr time range (Beccaluva et al., 1985; Carminati et al., 2012; Gattacceca et al., 2007; Speranza et al., 2002, and references therein; Fig. 3). Rock compositions are mostly intermediate to acid subalkaline terms (essentially basaltic andesites, andesites, dacites and rhyolites), mainly resulting from explosive activity (mostly ignimbritic flows), with rare mildly alkaline compositions (shoshonites and latites) and very rare basic–ultrabasic exceptions (e.g., basalts and picritic basalts of Montresta and Arcuentu, north-western and south-western Sardinia, respectively; Morra et al., 1997; Brotzu et al., 1997b; Downes et al., 2001; Franciosi et al., 2003; Beccaluva et al., 2013). Trace element abundances and isotopic ratios of the less differentiated Late Eocene–Middle Miocene rocks led several authors to propose a derivation from a mantle wedge modified by slab-derived fluids (e.g., Conte et al., 2010; Downes et al., 2001; Franciosi et al., 2003; Guarino et al., 2011; Lustrino et al., 2009; Mattioli et al., 2000; Morra et al., 1997).

The Serravalian (~11.8 Ma) volcanic rocks of the Isola del Toro (SW Sardinia) mark an abrupt change in terms of chemistry, petrography and volcanological facies compared with the older igneous activity (Lustrino et al., 2007a, 2007b, 2009). After a ~5 Myr quiescence, the volcanic activity continued in the southern sector of Sardinia only (Capo Ferrato, Rio Girone and Guspini; Lustrino et al., 2000, 2007a). The volcanic rocks produced during the ~11.8–4.4 Ma time span define the so-called RPV (Radiogenic Pb Volcanic) group (Lustrino et al., 2000;