THE CENOZOIC MAGMATIC ACTIVITY IN SARDINIA: CHRONOLOGY AND GEODYNAMIC SIGNIFICANCE

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GEOLOGICAL SETTING AND INTRODUCTION

Two cycles of igneous activity developed in Sardinia during the Cenozoic: 1) rocks with calcalkaline affinity and "subduction-related" tectono-magmatic characteristics were emplaced during the Upper Eocene-Middle Miocene (38-12 Ma); 2) rocks with geochemical features typical of within-plate volcanism were emplaced during the Upper Miocene-Quaternary (12-0,1 Ma) period (Lustrino *et al.*, 2004, 2009, and references therein). The products of the first cycle crop out in the Sardinian Trough (N-S), in the (W-E) Cixerri, Narcao and Funtanazza grabens (Brotzu *et al.*, 1997a). This magmatism developed in an extensional geodynamic context that induced the opening of the Sardinian Trough, the Sardinia-Corsica microplate separation from Europe, its counter-clockwise rotation and the opening of the Ligurian-Provençal back-arc basin (30-15 Ma; Lustrino *et al.*, 2009 and references therein), related to the Appennine-Maghrebide subduction system and the slab rollback (Carminati *et al.*, 2012). The opening of the Ligurian-Provençal back-arc basin had its highest spreading rate at ~22-18 Ma (Gattacceca *et al.*, 2007) when the magmatic activity reached its peak (Lecca *et al.*, 1997, and references therein).

This is a petrological, geochemical and isotopic study of calcalkaline rocks cropping out in the Cixerri half-graben, in Monastir and in Monte Nureci, part of the Arcuentu volcanic complex. A new data set was added to the already studied volcanic rocks cropping out in the other Sardinian districts, in order to build up a more comprehensive database on the "calcalkaline" volcanic cycle. New $^{40}Ar/^{39}Ar$ ages of representative samples were carried out to update the age span of the calcalkaline activity in southern Sardinia.

SAMPLING AND ANALYTICAL TECHNIQUES

Lava domes crop out in the Cixerri half-graben (Fig. 1). The westernmost domes, southwest of Villamassargia village, are part of Cixerri district (26 samples), the easternmost, near Siliqua town, belong to Punta Su Silixianu (1 altered sample) and Siliqua districts, where 5 samples were collected from the Acquafredda lava dome and 4 from the Monte Truxionis lava dome. The andesitic lava domes intruded the Paleozoic bedrock (sandstone of Nebida formation) and the Cixerri formation, locally with slight thermo-metamorphic effects. They have porphyritic textures with euhedral plagioclase and amphibole phenocrysts 3-4 cm-long.

Few igneous products crop out in Monastir district: the dyke, the lava dome and the xenolith found in the lava were collected. The lava dome appears reddish because of the groundmass alteration, porphyritic with plagioclase and amphibole phenocrysts. The dyke is porphyritic with small phenocrysts of plagioclase.

Holocrystalline rocks crop out near the bedrock in Monte Nureci, they vary from coarse- to medium-grained and represent the intrusive products of the Arcuentu volcanic complex (Fig. 1).

The samples were cut with a diamond blade circular saw and reduced in smaller fragments with a chipmunk jaw crusher in the DiSTAR laboratories. Thin sections for each sample were prepared to perform petrographic studies and to obtain the chemical composition of mineral phases with an Oxford Instrument Microanalysis Unit, equipped with an INCA X-act detector and a JEOL JSM-5310 microscope (SEM-EDS). The chips were washed in deionized water, dried and pulverized in a low-blank agate mortar. Four grams of powder were glued with MOWIOL and dried at 100°C in order to prepare the pellets. The pressed pellets of the samples and of part of the literature rocks (North Sardinia, Montresta, Sindia, Arcuentu, Sulcis, Capo Frasca and Marmilla districts) were analysed with XRF (X-Ray Fluorescence) to acquire the chemical composition of each sample and to obtain a homogeneous database. The powder of representative samples was analysed with the Inductively Coupled Plasma-

Mass Spectrometry (ICP-MS) method in the Activation Laboratories (Canada) to determine the trace element composition of the bulk rocks. Two representative samples were selected for dating with $^{40}Ar/^{39}Ar$ method, which was performed in the Western Australian Argon Isotope Facility at Curtin University (Perth, Australia) on separated amphibole and plagioclase grains selected by hand-picking on sieved fractions. The Sr and Nd were separated in 26 representative samples of the studied rocks and literature samples by cation-exchange chromatographic techniques in the DiSTAR laboratories, where the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ were measured with the Triton Plus instrument.

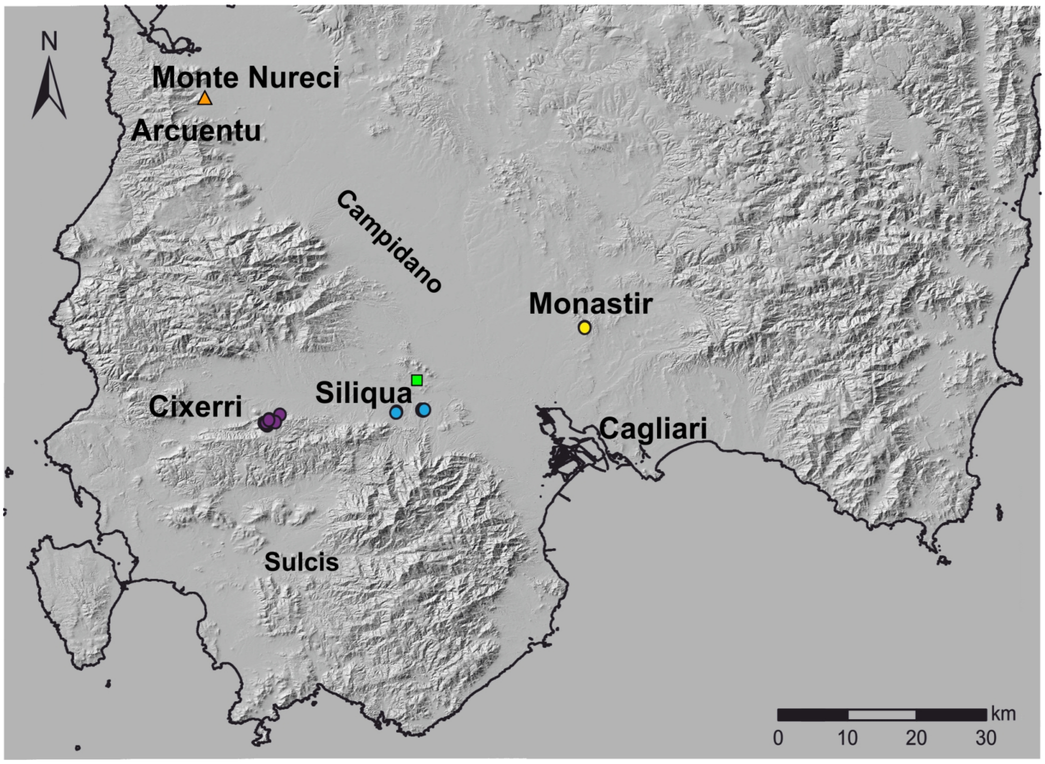

Fig. 1 - 10m DEM (Digital Elevation Model; Tarquini *et al.*, 2007) of southern Sardinia with the location of the collected samples.

RESULTS AND DISCUSSION

Ages

Plagioclase and amphibole grains hand-picked from a Cixerri andesite yielded an age of 21.52±0.73 Ma and 21.31±0.05 Ma, respectively. Plagioclase grains separated from the Monastir dyke yielded a plateau age of 30.89±1.26 Ma. The results of $^{40}Ar/^{39}Ar$ dating confirm the wide time span of calcalkaline igneous activity in southern Sardinia and the peak of activity at 22-18 Ma with the emplacement of many lava domes in the Cixerri half-graben. The products of Monastir district represent an early period of activity.

Classification and magmatic evolution

The rocks of Cixerri, Siliqua, Punta Su Silixianu and Monastir districts vary in composition from basaltic andesites to dacites, overlapping the composition of the rocks of the other Sardinian districts which vary from basalts to rhyolites. They have porphyritic texture with plagioclase, amphibole and minor clinopyroxene phenocrysts, set in a micro- to cryptocrystalline groundmass composed by the same mineral phases plus alkali feldspar and quartz (Fig. 2a-b). The sequence of crystallization is opaque oxides → plagioclase ± clinopyroxene

→ amphibole ± mica → alkali feldspar / quartz. Plagioclase and amphibole phenocrysts show normal, reverse or oscillatory zoning. The abundance of amphibole is a peculiar feature of Siliqua and Cixerri lava domes. The mineral phase composition is comparable to that observed in the literature data, except for the absence of orthopyroxene in Cixerri and Siliqua rocks.

The intrusive rocks of Monte Nureci are olivine gabbronorites and gabbronorites. The coarse-grained olivine gabbronorites are made up of euhedral to subhedral plagioclase, clinopyroxene, orthopyroxene, olivine and accessory amphibole, mica, apatite and opaque oxides (Fig. 2c-d). Pyroxene and olivine are unzoned cumulus phases. The gabbronorite contains also rare alkali feldspar and quartz, zoned clinopyroxene and plagioclase.

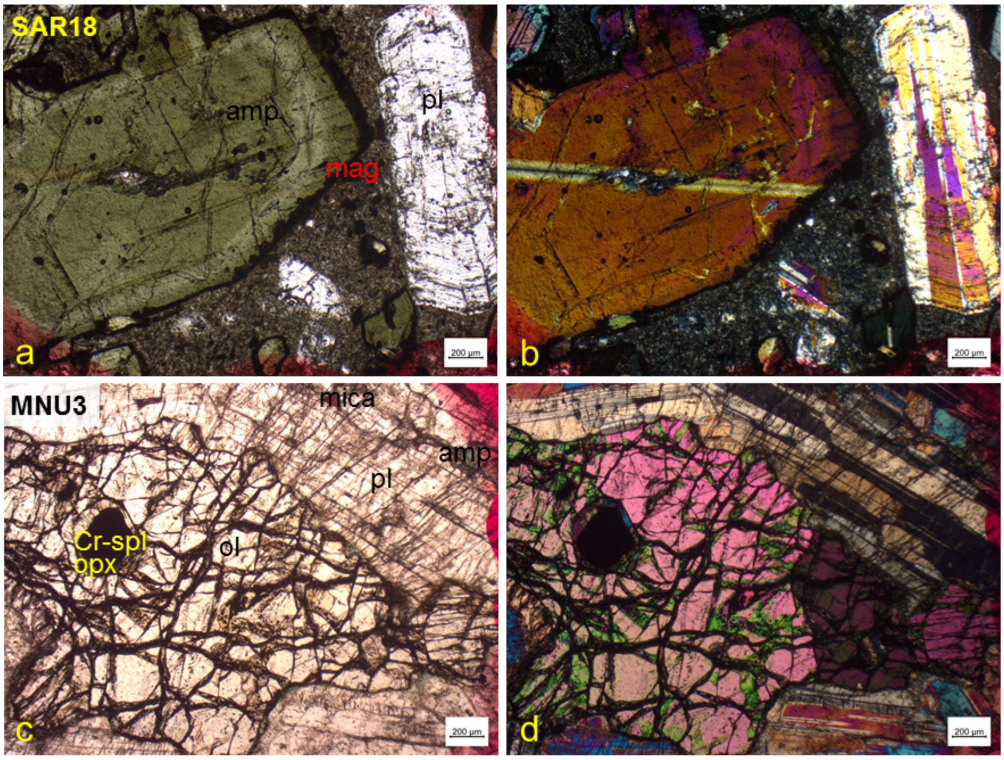

Fig. 2 - Thin section microphotographs with plane polarized light (a-c) and crossed polarizers light (b-d). View of zoned amphibole and plagioclase phenocrysts set in a cryptocrystalline groundmass of a basaltic andesite from Cixerri district (a-b). View of plagioclase and olivine with Cr-spinel inclusion in a coarse-grained olivine gabbronorite from Monte Nureci (c-d). Abbreviations from Whitney & Evans (2010).

The Sardinian rocks show calcalkaline and high-K calcalkaline affinity, as confirmed by the early crystallization of opaque oxides. They have subduction-related features like the Pb peak and the Ti-Nb-Ta troughs in the multi-element diagram normalized to the primitive mantle and fall in the arc array in the Nb/Yb *vs*. Th/Yb diagram (Fig. 3a).

The major- and trace-elements variations point to magma evolution driven by fractional crystallization of the observed phenocryst phases. The Dy/Yb ratio decreases with silica increase in Cixerri rocks, suggesting a significant role for amphibole fractionation in Cixerri magmas, differently from the magmas of other Sardinian districts. Mass balance calculations point out that amphibole is the main mafic phase removed from the Cixerri magmas in the basaltic andesite-andesite transition (35% of the removed assemblage). The high abundance of amphibole has been explained with the high H_2O content in Cixerri melts, calculated with the thermobarometer and hygrometer of Ridolfi *et al.* (2010) applied on amphibole (up to 9 wt.%), differently from the other districts ($H_2O_{melt} \approx 5$ wt.%). The calculated pressure of amphibole crystallization indicates two main ranges of pressure where crystallization took place (~3-4 kbar and ~7-8 kbar) pointing to a polybaric plumbing system.

The lack of primitive samples in the studied districts hampered a detailed investigation on the magma sources, as already done for Montresta and Arcuentu districts where HMBs (High Magnesium Basalts) occur (Morra *et al.*, 1997; Downes *et al.*, 2001; Franciosi *et al.*, 2003; Lustrino *et al.*, 2013), identifying a N-MORB-like source variably enriched by slab fluids and low amount of sediment fluids (< 0.1%) as magma source in the mantle. However, the flat HREE (Heavy Rare Earth Element) patterns of the studied rocks in the chondrite normalized REE diagram, suggest a magma source in the spinel peridotite stability field. The lower HREE content in the most primitive rocks of the Sardinian districts compared to the Atlantic N-MORB (Normal Mid Ocean Ridge Basalts) points to a *depleted* N-MORB-like source metasomatized by the fluids coming from the subducting slab and sediments, which were rich in elements such as Rb, Ba, Pb, Sr and poor in HFSE (High Field Strength Elements), Zr, Hf, Nb, Ta, Ti. Comparing the samples with the same evolution degree from different districts, some distinctions can be observed, particularly between Siliqua and Cixerri rocks. The Siliqua rocks have higher Sr, Ba, Pb, Nb concentrations and Sr/Y, $(La/Yb)_N$, $(La/Sm)_N$ ratios than rocks from Cixerri and other districts (Fig. 3b-c-d). The higher mobile elements contents and trace element ratios in the Siliqua rocks could also suggest that the input of subducted sediments in Siliqua mantle source was more relevant.

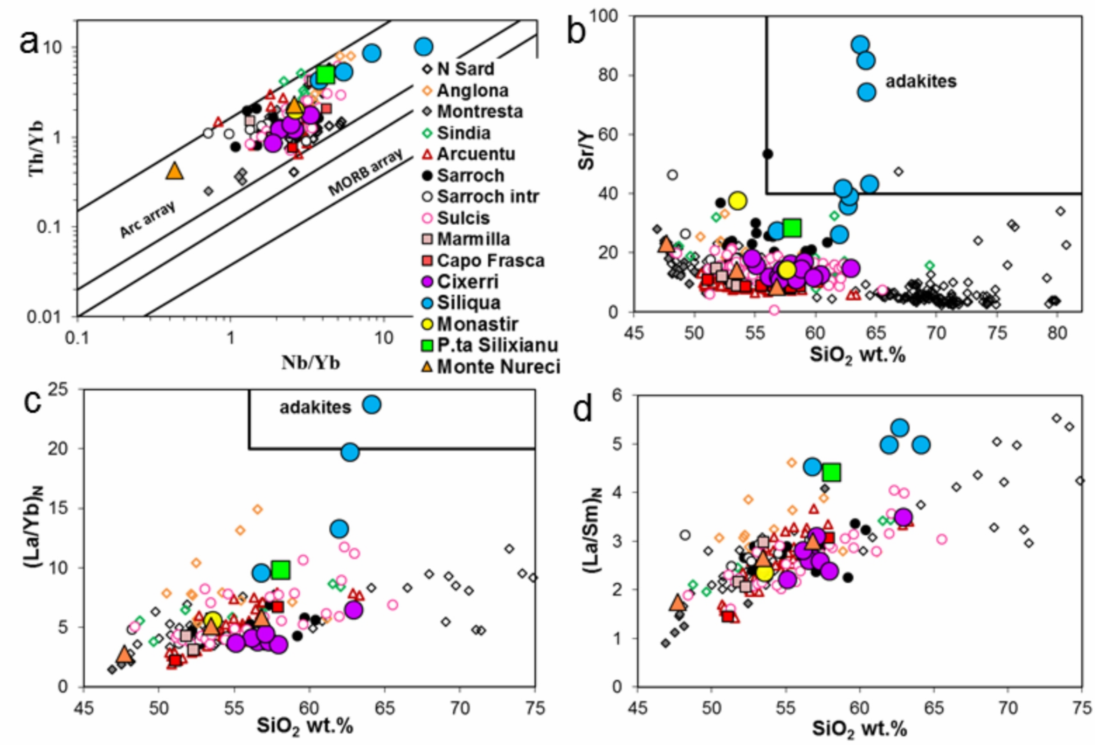

Fig. 3 - a) Nb/Yb *vs*. Th/Yb with MORB and Arc array from Pearce *et al.* (1995) b) SiO_2 (wt.%) *vs*. Sr/Y, c) SiO_2 (wt.%) *vs*. $(La/Yb)_N$, d) SiO_2 (wt.%) *vs*. $(La/Sm)_N$ diagrams for the rocks from Cixerri, Siliqua, Monastir, Punta Su Silixianu and Monte Nureci districts, compared to literature data: North Sardinia (Marrazzo, 2008; Guarino *et al.*, 2011; Tecchiato *et al.*, 2018), Anglona (Beccaluva *et al.*, 2013), Montresta (Morra *et al.*, 1997; Franciosi *et al.*, 2003), Sindia (Lonis *et al.*, 1997), Arcuentu (Brotzu *et al.*, 1997b; Downes *et al.*, 2001; Franciosi *et al.*, 2003), Sarroch and Sarroch intrusive (Conte, 1997), Sulcis (Brotzu *et al.*, 1997a; Conte *et al.*, 2010; Ronga, 2011; Lustrino *et al.*, 2013), Marmilla and Capo Frasca (Fedele, 2002; Lustrino *et al.*, 2013). N = normalized to the chondrite (Anders & Grevesse, 1989). The adakites field is taken from Defant & Drummond (1990) and Moyen (2009).

The dacites of the Acquafredda lava dome have a peculiar chemical composition: they have low concentration of Y and HREE (HREE<10 times chondrite). They can be classified as *adakites* following Defant & Drummond (1990) and Moyen (2009) (Fig. 3b-c). The Acquafredda dacites represent the first finding of *adakites* in Sardinia in the Cenozoic subduction-related magmatic cycle.

Adakite formation is commonly thought to be caused by slab melting of hot and young lithosphere (Defant & Drummond, 1990; Moyen, 2009). This is not the case for the Acquafredda *adakites,* because the Cenozoic igneous activity in Sardinia is related to the NW-ward directed subduction of the ancient Tethys Ocean (Rollet *et al.*, 2002; and references therein). The similar isotopic composition between the Acquafredda *adakite* and the calcalkaline samples of the area point to a common source; therefore, the *adakites* could be the product of re-melting, at high pressures, where amphibole is stable, of an amphibole-bearing arc rock with isotopic composition similar to the basaltic andesite of Siliqua (Fig. 4b).

The genesis of Acquafredda *adakites* was modelled in a two-step process: 1) fractional crystallization of plagioclase, amphibole, orthopyroxene and magnetite from the basaltic andesite to obtain the andesite of Acquafredda; 2) low degree of re-melting (f = 20%) of the removed assemblage. The match between the modelled magma and the *adakite* REE patterns confirms that Acquafredda *adakites* could derive from re-melting of an amphibole-bearing intrusive rock represented by the removed assemblage in the basaltic andesite-andesite transition, with amphibole as residual phase of the melting, which retained HREE.

The olivine gabbronorites of Monte Nureci have mafic phases with high Mg# and plagioclase with high anorthite content, suggesting that these phases fractionated by a mafic magma with relatively high Mg#. The chemical analyses of these mineral phases were used to model, with a mass balance calculation, the evolution for fractional crystallization from a basaltic andesite to an andesite of Arcuentu. The low sum of squares of the residuals (R^2 = 0.05) and the relative abundance of the mineral phases in the removed assemblage (40% plagioclase, 27% clinopyroxene, 22% orthopyroxene, 10% olivine) that broadly matches the modal abundances of the olivine gabbronorites, point to a genetically link between the Monte Nureci intrusive rocks and the overlying lavas of the Arcuentu district. Moreover, the isotopic composition of Monte Nureci rocks matches that of the Arcuentu basaltic andesites (Fig. 4), confirming that the Monte Nureci intrusive rocks derive by mineral accumulus from an Arcuentu magma with basaltic andesite composition.

The $^{87}Sr/^{86}Sr_i$ *vs*. $^{143}Nd/^{144}Nd_i$ diagram (Fig. 4a) of the rocks of the Sardinian districts highlights the following: 1) the Cixerri rocks have higher $^{87}Sr/^{86}Sr_i$ and lower $^{143}Nd/^{144}Nd_i$ than Siliqua samples. It can be due to the isotopically different magma sources or to different degrees of crustal assimilation; their roughly parallel trends suggest that, although with slightly different degrees of assimilation, the primitive magmas were isotopically different; 2) the basaltic andesite of Monastir has the same $^{87}Sr/^{86}Sr_i$ and lower $^{143}Nd/^{144}Nd_i$ than Montresta HMBs pointing to different magma sources and mantle heterogeneity under Sardinia.

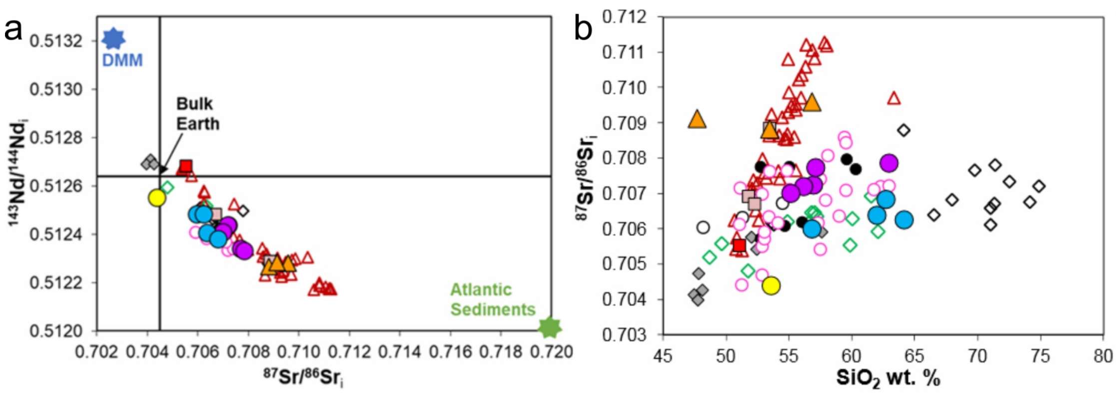

Fig. 4 - a) $^{87}Sr/^{86}Sr_i$ *vs*. $^{143}Nd/^{144}Nd_i$ diagram, b) SiO_2 (wt.%) *vs*. $^{87}Sr/^{86}Sr_i$ diagram for the studied rocks (Cixerri, Siliqua, Monastir, Monte Nureci, Arcuentu, Sindia and Sulcis) integrated with literature data. Symbols and references as in Fig. 3. DMM (Depleted MORB Mantle) and Atlantic sediments (Downes *et al.*, 2001 and references therein).

The positive correlation of $^{87}Sr/^{86}Sr$ with silica content (Fig. 4b) points to magma evolution in open systems, particularly remarkable at the Arcuentu volcanic complex, where the basalts to andesites have a marked increase in $^{87}Sr/^{86}Sr_i$ (from 0.70538 to 0.71127) with increasing degree of magmatic evolution. The evolution for fractional crystallization and assimilation (AFC) was modelled applying the equations of DePaolo (1981) to quantify the degree of crustal assimilation, expressed as r (r = assimilation rate/crystallization rate), supposing two different contaminants: 1) one representing the Hercynian lower crust of Calabria (Caggianelli *et al.*, 1991; Fig. 5a-c), and 2) a metabasalt of 490 Ma (Fig. 5b-d) belonging to the Sardinian bedrock (Gaggero *et al.*, 2012). A rock with composition similar to the metabasalt is likely the most reliable contaminant. The calculated r is 0.1-0.2 for Cixerri rocks (Fig. 5b) and 0.2-0.4 for Arcuentu rocks (Fig. 5d).

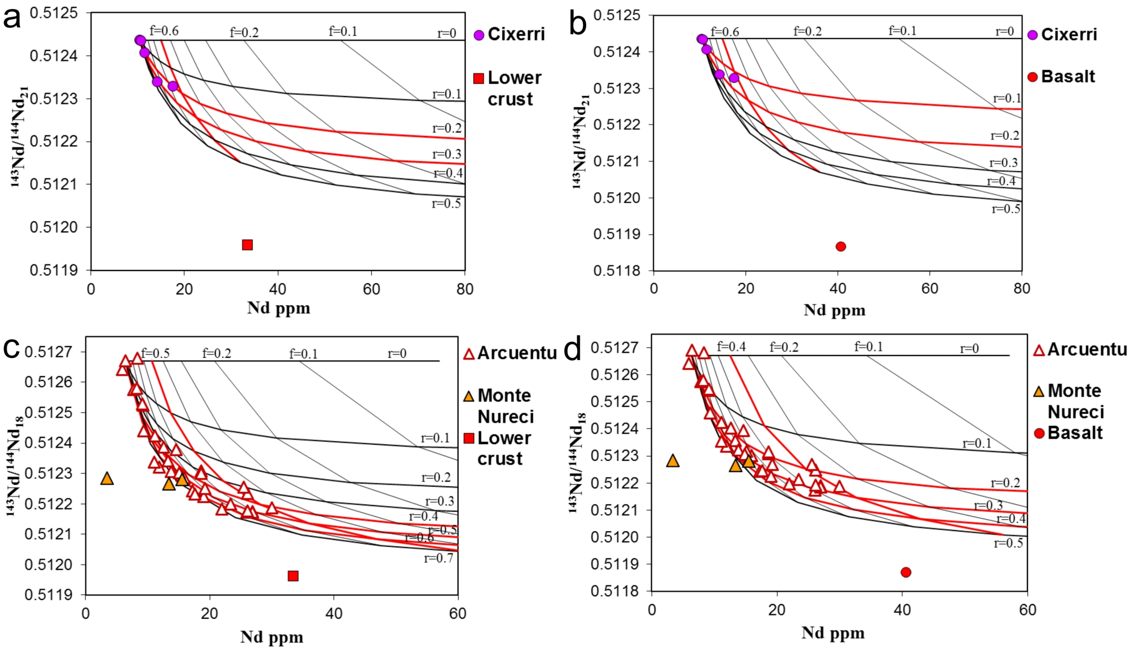

Fig. 5 - Nd (ppm) *vs.* $^{143}Nd/^{144}Nd_i$: AFC models for Cixerri rocks considering a) Lower Crust (Caggianelli *et al.*, 1991) and b) Metabasalt of 490 Ma (Gaggero *et al.*, 2012) as contaminants, AFC models for Arcuentu rocks (from this study, Downes *et al.*, 2001; Franciosi *et al.*, 2003; Lustrino *et al.*, 2013) considering c) Lower Crust and d) Motabasalt of 490 Ma as contaminants.

CONCLUSIONS

The petrographic, geochemical and isotopic characterization of the studied igneous rocks, and their comparison with the literature data, allow to conclude that:

- all the studied samples are evolved rocks with calcalkaline affinity and the typical subduction-related patterns;
- the new $^{40}Ar/^{39}Ar$ age determination of the Cixerri domes (~21 Ma) is markedly different from that of the Monastir dyke (~31 Ma) confirming a significant time span for the calcalkaline volcanism in SW Sardinia;
- the magma evolution was governed by fractional crystallization in polybaric plumbing systems;
- significant involvement of amphibole is hypothesized for the Cixerri basaltic andesite-andesite transition, differently from the rest of the Sardinian magmatism at the same compositional range;
- the adakitic signature of the Acquafredda dacites, could be the result of re-melting, at relatively high crustal pressure, of an amphibole-bearing intrusive rock formed by the removed assemblage during the transition from the Acquafredda basaltic andesite to andesite;

- the olivine gabbronorites of Monte Nureci represent the complementary cumulate of the Arcuentu magmas in the basaltic andesite-andesite transition;

- the isotopic variability of the studied samples is related to mantle heterogeneity and to magma evolution mainly driven by fractional crystallization in open systems; crustal assimilation was lower in the Cixerri andesites than in the Arcuentu rocks, suggesting independence of the feeder systems and parental magmas at depth;

- the lack of primitive samples hampers a compelling geochemical study of the mantle sources; the lower concentration of HREE in the most primitive rocks than typical N-MORBs is likely due to an incompatible element-*depleted* signature of the mantle wedge prior to the enrichment by slab and sediment-derived fluids;

- the higher trace element concentrations (*e.g.*, Sr, Ba, Pb) and ratios in the Siliqua rocks might be due to a higher sediment-derived fluid flux in the mantle source.

REFERENCES

Anders, E. & Grevesse, N. (1989): Abundances of the elements: meteoritic and solar. *Geochim. Cosmochim. Ac*., **53**, 197-214.

Beccaluva, L., Bianchini, G., Mameli, P., Natali, C. (2013): Miocene shoshonite volcanism in Sardinia: Implications for magma sources and geodynamic evolution of the central-western Mediterranean. *Lithos*, **180-181**, 128-137.

Brotzu, P., Callegari, E., Morra, V., Ruffini, R. (1997a): The orogenic basal-andesite suites from the Tertiary volcanic complex of Narcao, S-W Sardinia (Italy): petrology, geochemistry and Sr-isotope characteristics. *Period. Mineral.*, **66**, 101-150.

Brotzu, P., Lonis, R., Melluso, L., Morbidelli, L., Traversa, G., Franciosi, L. (1997b): Petrology and evolution of calcalkaline magmas from the Arcuentu volcanic complex (SW Sardinia, Italy). *Period. Mineral.*, **66**, 151-184.

Caggianelli, A., Del Moro, A., Paglionico, A., Piccarreta, G., Pinarelli, L., Rottura, A. (1991): Lower crustal granite genesis connected with chemical fractionation in the continental crust of Calabria (Southern Italy). *Eur. J. Mineral.*, **3**, 159-180.

Carminati, E., Lustrino, M., Doglioni, C. (2012): Geodynamic evolution of the central and western Mediterranean: tectonic vs. igneous constraints. *Tectonophysics*, **579**, 173-192.

Conte, A.M. (1997): Petrology and geochemistry of Tertiary calc-alkaline magmatic rocks from the Sarroch domain (Sardinia, Italy). *Period. Mineral*., **66**, 63-100.

Conte, A.M., Palladino, D.M., Perinelli, C., Argenti, E. (2010): Petrogenesis of the high-alumina basalt-andesite suite from Sant'Antioco Island, SW Sardinia, Italy. *Period. Mineral*., **79**, 27-55.

Defant, M.J. & Drummond, M.S. (1990): Derivation of some modern arc magmas by melting of young subducted lithosphere. *Nature*, **367**, 662-665.

DePaolo, D.J. (1981): Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. *Earth Planet. Sci. Lett*., **53**, 189-202.

Downes, H., Thirlwall, M.F., Trayhorn, S.C. (2001): Miocene subduction-related magmatism in southern Sardinia: Sr-Nd-and oxygen isotopic evidence for mantle source enrichment. *J. Volcanol. Geoth. Res.*, **106**, 1-22.

Fedele, L. (2002): Il vulcanismo Cenozoico della Sardegna centrale e meridionale. Caratteristiche petrologiche e geochimiche. Master degree Thesis.

Franciosi, L., Lustrino, M., Melluso, L., Morra, V., D'Antonio, M. (2003): Geochemical characteristics and mantle sources of the Oligo-Miocene primitive basalts from Sardinia. *Ofioliti*, **28**, 105-114.

Gaggero, L., Oggiano, G., Funedda, A., Buzzi, L. (2012): Rifting and arc-related early Paleozoic volcanism along the north Gondwana margin: geochemical and geological evidence from Sardinia (Italy). *J. Geol.*, **120**, 273-292.

Gattacceca, J., Deino, A., Rizzo, R., Jones, D.S., Henry, B., Beaudoin, B., Vadeboin, F. (2007): Miocene rotation of Sardinia: new paleomagnetic and geochronological contraints and geodynamic implications. *Earth Planet. Sci. Lett.*, **258**, 359-377.

Guarino, V., Fedele, L., Franciosi, L., Lonis, R., Lustrino, M., Marrazzo, M., Melluso, L., Morra, V., Rocco, I., Ronga, F. (2011): Mineral compositions and magmatic evolution of the calcalkaline rocks of northwestern Sardinia, Italy. *Period. Mineral*., **80**, 517-545.

Lecca, L., Lonis, R., Luxoro, S., Melis, F., Secchi, F., Brotzu, P. (1997): Oligo-Miocene volcanic sequences and rifting stages in Sardinia: a review. *Period. Mineral.*, **66**, 7-61.

Lonis, R., Morra, V., Lustrino, M., Melluso, L., Secchi, F. (1997): Plagioclase textures, mineralogy and petrology of Tertiary orogenic volcanic rocks from Sindia (central Sardinia). *Period. Mineral*., **66**, 185-210.

Lustrino, M., Morra, V., Melluso, L., Brotzu, P., d'Amelio, F., Fedele, L., Franciosi, L., Lonis, R., Petterutti Liebercknecht, A.M. (2004): The Cenozoic igneous activity of Sardinia. *Period. Mineral.*, **73**, 105-134.

Lustrino, M., Morra, V., Fedele, L., Franciosi, L. (2009): Beginning of the Appennine subduction system in the central-western Mediterranean: constraints from Cenozoic "orogenic" magmatic activity of Sardinia (Italy). *Tectonics*, **28**, 1-23.

Lustrino, M., Fedele, L., Melluso, L., Morra, V., Ronga F., Geldmacher, J., Duggen, S., Agostini, S., Cucciniello, C., Franciosi, L., Meisel, T. (2013): Origin and evolution of Cenozoic magmatism of Sardinia (Italy). A combined isotopic (Sr-Nd-Pb-O-Hf-Os) and petrological view. *Lithos*, **180-181**, 138-158.

Marrazzo, M. (2008): Caratterizzazione petrologica e geochimica dei prodotti del ciclo vulcanico Oligo-Miocenico della Sardegna Nord Occidentale. Ph.D. Thesis.

Morra, V., Secchi, F.A.G., Melluso, L., Franciosi, L. (1997): High-Mg subduction-related Tertiary basalts in Sardinia, Italy. *Lithos*, **40**, 69-91.

Moyen, J.F. (2009): High Sr/Y and La/Yb ratios: the meaning of the "adakitic signature". *Lithos*, **112**, 556-574.

Pearce, J.A., Baker, P.E., Harvey, P.K., Luff, I.W. (1995): Geochemical evidence for subduction fluxes, mantle melting and fractional crystallization beneath the South Sandwich Island arc. *J. Petrol.*, **36**, 1073-1109.

Ridolfi, F., Renzulli, A., Puerini, M. (2010): Stability and chimica equilibrium of amphibole in calc-alkaline magmas: an overview, new thermobarometric formulations and application to subduction-related Volcanoes. *Contrib. Mineral. Petr.*, **160**, 45-66.

Rollet, N., Déverchère, J., Beslier, M.O., Guennoc, P., Réhault, J.P., Sosson, M., Truffert, C. (2002): Back arc extension, tectonic inheritance, and volcanism in the Ligurian Sea, western Mediterranean. *Tectonics*, **21**, 1015.

Ronga, F. (2011): Petrogenesi delle vulcaniti del Sulcis (Sardegna Sud-occidentale). Ph.D. Thesis.

Tarquini, S., Isola, I., Favalli, M., Battistini, A. (2007): TINITALY, a digital elevation model of Italy with a 10 meters cell size (Version 1.0) [Data set]. Istituto Nazionale di Geofisica e Vulcanologia (INGV).

Tecchiato, V., Gaeta, M., Mollo S., Scarlato, P., Bachmann, O., Perinelli, C. (2018): Petrological constraints on the high-Mg basalts from Capo Marargiu (Sardinia, Italy): Evidence of cryptic amphibole fractionation in polybaric environments. *J. Volcanol. Geoth. Res.*, **349**, 31-46.

Whitney, D.L. & Evans, B.W. (2010): Abbreviations for names of rock-forming minerals. *Am. Mineral.*, **95**, 185-187.