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# GEOCHEMICAL CHARACTERISTICS AND MANTLE SOURCES OF THE OLIGO-MIOCENE PRIMITIVE BASALTS FROM SARDINIA: THE ROLE OF SUBDUCTION COMPONENTS

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ABSTRACT

During the Oligo-Miocene, the Island of Sardinia was covered by the products of voluminous magmatic activity, with a typical subduction-related signature. The mafic rocks of the Montresta (north) and Arcuentu (south) volcanic districts include primitive high MgO basalts whose trace element and Sr-, Nd- and Pb-isotope compositions constrain the nature and role of subduction-related components in the Tertiary Sardinian volcanism. The geochemical and isotopic data require an approximate degree of partial melting of 15% of a MORB-like depleted mantle prior to enrichment, and the input of two subduction components in the mantle wedge consisting of fluids from subducted oceanic crust (altered MORB) and fluids from subducted sediments. Ratios among trace elements which are variably compatible with fluid and melt phases (i.e. Th/Pb, Th/Nd and Sr/Nd) exclude the contribution of melts from the subducted slab. Models based on isotopic ratios indicate that the pre-subduction depleted mantle source of Sardinia magmas was enriched by 0.1-0.5% MORB fluid and less than 0.1% sediment fluid. The geochemical and isotopic compositions of the Montresta volcanic rocks are homogeneous, whereas those of the Arcuentu show quite heterogeneous characters, suggesting variations in mantle source over the long time-span (about 13 Ma) of volcanic activity in this district.

## INTRODUCTION

The genesis of subduction-related magmas is a matter of debate because of the great variability of the factors involved. Chemical variations observed in orogenic magmas world-wide are related to the interplay of mantle wedge composition, nature of slab-derived component(s), partial melting processes, and interactions between magmas and overlying lithosphere (e.g., Pearce and Peate, 1995).

The mantle source (wedge) generally has MORB-like composition (e.g., Münker, 2000) although OIB-like mantle sources have sometimes been proposed (e.g., Peate et al., 1997). Many authors (Bizimis et al., 2000; Dorendorf et al., 2000) hold that the main slab component is represented by hydrous fluids deriving from dehydration of subducted oceanic crust; others hypothesise that partial melting of slab sediments produces hydrous melts, later migrating into the overlying mantle wedge (Turner et al., 1997; Elburg and Foden, 1998).

In some cases, the composition of subduction-related orogenic magmas reflects multiple slab components (Class et al., 2000; Macdonald et al., 2000; Münker, 2000, and references therein), whose amount in the mantle wedge is estimated to vary from less than 1% (Stolper and Newman, 1994) to more than 20% (Ayers, 1998). These components are considered to be responsible for peculiar patterns of incompatible trace elements, generally characterised by strong Large Ion Lithophile Elements (LILE) enrichment with respect to High Field Strength Elements (HFSE) (Turner et al., 1997; Pearce et al., 1999; Walker et al., 2001, and references therein). This feature is related to the different behaviour of LILE (non-conservative) and HFSE (conservative) in aqueous fluids (e.g., Pearce and Peate, 1995). LILE generally have slab-fluid partition coefficients <1; HFSE are generally retained in the slab. However, if the main slab component is represented by water-rich melts rather than fluids, elements such as Zr, Nb and Ta may be considered non-conservative (Brenan et al., 1995a; 1995b; Becker et al., 2000).

The Oligo-Miocene orogenic magmatic rocks from northern (Montresta) and southern Sardinia (Arcuentu) include high-Mg basalts (HMB) with geochemical features typical of near-primary melts (Brotzu et al., 1997a; Morra et al., 1997). These rocks give us a good opportunity to investigate their mantle sources on the basis of geochemical data on trace elements and isotopes. The aim of this study was to identify and model the subduction-related components (fluids or melts from sediments or oceanic crust) involved in their genesis.

Readers are referred to previous works by Morra et al. (1994; 1997), Brotzu et al. (1997a; 1997b), Lonis et al. (1997), and Downes et al. (2001) for a full listing and the petrological modeling of the geochemical features of the Sardinian Oligo-Miocene volcanic rocks. In particular, according to Morra et al. (1997), the main subduction component of magmas from the northern district (Montresta) is a fluid from subducted oceanic crust, whereas Downes et al. (2001) believe that 2-10% bulk pelagic sediments are involved in the genesis of the southern volcanic rocks (Arcuentu district).

## GEOLOGICAL BACKGROUND

The Island of Sardinia (Fig. 1) records two distinct volcanic phases during Oligocene-Miocene and Plio-Pleistocene times, which produced igneous rocks with differing petrographic and geochemical features. The Oligocene-Miocene volcanic rocks (32-15 Ma; Montigny et al., 1981; Beccaluva et al., 1985; Morra et al., 1994) have calc-alka-

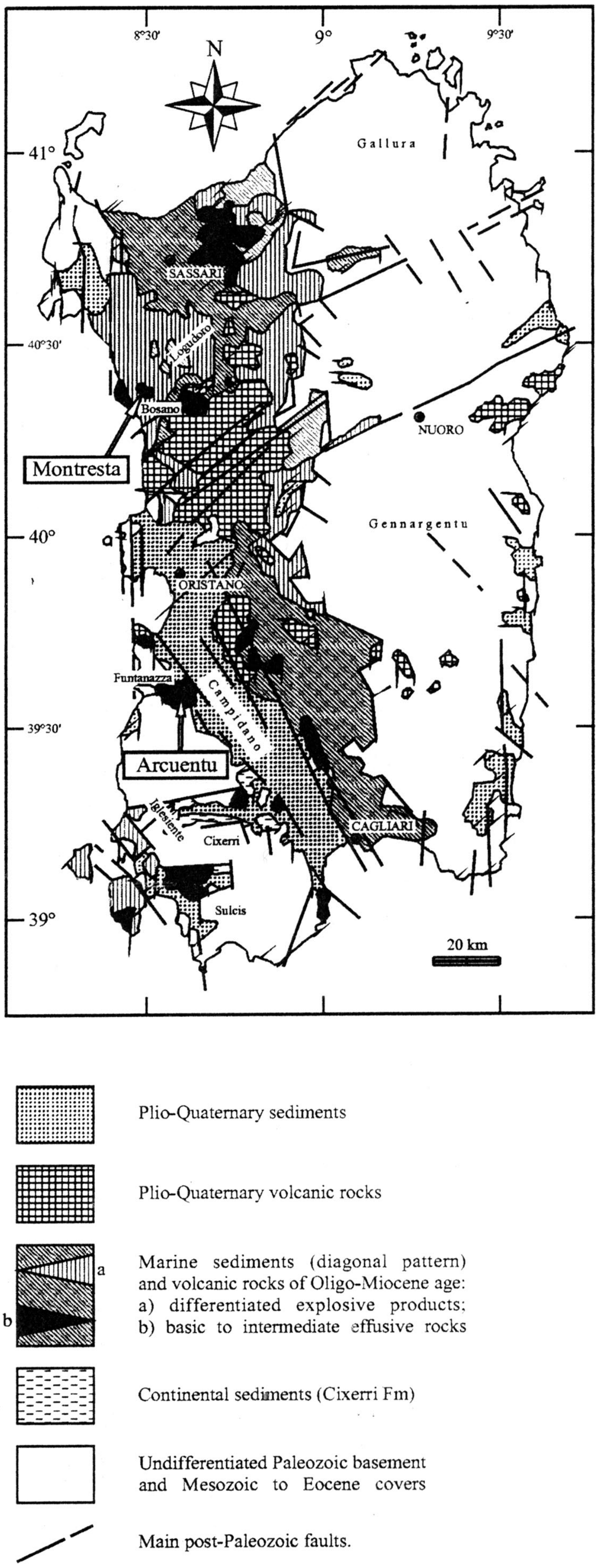


Fig. 1 - Geological sketch map of Sardinia, after Morra et al. (1997), modified.

line to tholeiitic serial affinity and subduction-related signatures (Morra et al., 1994; 1997; Lonis et al., 1997), whereas the Plio-Pleistocene ones (~5-0.1 Ma) have sodic alkaline to tholeiitic serial affinity and within-plate geochemical signatures (Lustrino et al., 1996; 2000; 2002).

The Sardinian Oligo-Miocene volcanism is considered to be related to the subduction of African oceanic crust under the European continental margin towards NNW (Beccaluva et al., 1994); the Eocene-Early Oligocene Alpine compressive phase was followed by transtensive and extensional regimes (Hippolyte et al., 1993; Carmignani et al., 1994) which, during Oligocene, caused faulting and rifting in the western European continental crust. In Sardinia these extensional stresses led to: 1) formation of the Oligo-Miocene rift system (the so called *Fossa Sarda*) crossing the whole island from north to south with a length of about 220 km; 2) translation southwards and counterclockwise rotation of the Sardinia-Corsica continental microplate, with coeval opening of the Balearic back-arc basin (Doglioni et al., 2002; Speranza et al., 2002).

Orogenic magmatic activity took place from the Valencia Trough to southern Sardinia over a time-span ranging from ~32 to ~15 Ma (Beccaluva et al., 1985; Martì et al., 1992). The Sardinian volcanism occurring along and within the Fossa Sarda reached its climax of activity between 21 and 18 Ma. Products are subaerial and submarine, and mainly consist of andesitic to rhyolitic ignimbrite and, subordinately, of basaltic lava. The explosive and effusive products are interlayered and partially contemporaneous. Peralkaline rhyolite also occurs in the islands S. Pietro and S. Antioco, as well as in the Sulcis mainland (SW Sardinia) (Morra et al., 1994).

## MAJOR AND TRACE ELEMENT GEOCHEMISTRY

Major and trace element abundances for high-Mg basalts (HMB) from Sardinia are listed in Table 1. The HMBs from Montresta are primitive rocks with MgO >7% and $Al_2O_3$ <16%, (according to the definition of Kersting and Arculus, 1994), and with geochemical features (i.e. Mg# ~0.70) similar to near-primary mantle melts (e.g., Frey et al., 1978). The mafic rocks from the Arcuentu complex may also be classified as HMBs and, on the basis of their Ni and Cr contents, considered as moderately evolved melts. When compared with Montresta HMBs, the Arcuentu basalts show higher $SiO_2$ contents and are slightly more porphyritic (about 15% phenocrysts).

In the analysed basalts, LILE are enriched relative to LREE (Light Rare Earth Elements), with Ba/La ranging from 10 to 23. As shown in Fig. 2 the Arcuentu lavas have stronger enrichment in Cs, Rb, Ba, Th and K than the Montresta samples. Both LILE and LREE are enriched relative to HFSE, with Ba/Nb ratios ranging from 24 to 83 and La/Nb from 2 to 4. Hf and Zr are depleted relative to Sm and Nd, and Pb/Ta and Th/Ta (from 13 to 36, and from 4 to 13 respectively) are much higher than average N-MORB (Pb/Ta = 2.3 and Th/Ta = 0.9; Sun and McDonough, 1989). Nb/Ta (~14) and Zr/Hf (~33) are also slightly lower than N-MORB (~17 and 36), whereas Nb/Yb (0.8-1.4) are slightly higher (N-MORB ~0.76). Rare earth elements (Fig. 3) show relatively flat chondrite-normalized patterns, with total concentrations ranging from 36.4 up to 43.8; HREE are from 6.8 to 10.2 times chondritic values, while $(La/Yb)_n$ and $(Gd/Yb)_n$ range respectively from 2.0 to 2.5 and from 1.1 to 1.3.

Table 1 - Analytical results for selected basalts from Sardinia. Major element data are from Brotzu et al. (1997a) and Morra et al. (1997). Mg# = (Mg/Mg+Fe'').

| | Montresta | | | Arcuentu | |
|---|---|---|---|---|---|
| | KB 24 | KB23 | KB13 | AR280 | RL116 |
| $SiO_2$ | 47.36 | 47.14 | 48.18 | 51.11 | 50.79 |
| $TiO_2$ | 0.79 | 0.77 | 0.74 | 0.75 | 0.63 |
| $Al_2O_3$ | 15.19 | 15.36 | 15.33 | 15.21 | 15.83 |
| $Fe_2O_{3t}$ | 10.43 | 10.81 | 11.12 | 9.76 | 10.86 |
| MnO | 0.19 | 0.19 | 0.12 | 0.18 | 0.18 |
| MgO | 11.02 | 11.02 | 8.95 | 9.28 | 7.64 |
| CaO | 11.85 | 11.81 | 12.72 | 10.04 | 9.88 |
| $Na_2O$ | 2.14 | 2.14 | 1.78 | 1.96 | 2.26 |
| $K_2O$ | 0.45 | 0.45 | 0.51 | 0.54 | 0.67 |
| $P_2O_5$ | 0.26 | 0.28 | 0.23 | 0.09 | 0.08 |
| LOI | 0.32 | 0.03 | 0.32 | 1.09 | 1.18 |
| Sum | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Mg# | 0.70 | 0.69 | 0.64 | 0.68 | 0.61 |
| Be | 0.35 | 0.7 | 0.18 | 0.13 | 0.36 |
| V | 315 | 309 | 311 | 255 | 299 |
| Cr | 793 | 756 | 345 | 701 | 202 |
| Co | 53.7 | 52.7 | 40.9 | 36.4 | 42.5 |
| Ni | 229 | 220 | 82 | 116 | 127 |
| Cu | 93.4 | 119 | 77.5 | 84.9 | 97.4 |
| Zn | 93.5 | 92.0 | 81.4 | 77.0 | 91.2 |
| Ga | 16.4 | 16.1 | 15.6 | 15.1 | 15.5 |
| Ge | 1.35 | 1.38 | 1.35 | 1.11 | 1.26 |
| Rb | 7.13 | 7.78 | 10.7 | 13.3 | 21.7 |
| Sr | 450 | 450 | 371 | 192 | 186 |
| Y | 15.5 | 16.6 | 16.0 | 17.5 | 19.4 |
| Zr | 38.1 | 35.2 | 33.5 | 50.4 | 42.5 |
| Nb | 1.97 | 1.85 | 1.81 | 2.38 | 1.47 |
| Mo | 0.09 | 0.23 | 0.20 | 0.51 | 0.59 |
| In | 0.04 | 0.03 | 0.03 | 0.05 | 0.03 |
| Sn | 0.74 | 0.55 | 0.47 | 0.37 | 0.49 |
| Cs | 0.08 | 0.15 | 0.20 | 0.36 | 0.54 |
| Ba | 49.1 | 46.2 | 51.1 | 153 | 123 |
| La | 4.20 | 4.53 | 4.39 | 6.55 | 6.27 |

| | Montresta | | | Arcuentu | |
|---|---|---|---|---|---|
| | KB 24 | KB23 | KB13 | AR280 | RL116 |
| Ce | 10.5 | 11.2 | 10.7 | 14.1 | 10.5 |
| Pr | 1.68 | 1.84 | 1.59 | 1.92 | 1.76 |
| Nd | 7.93 | 9.18 | 7.81 | 7.91 | 8.00 |
| Sm | 2.26 | 2.59 | 2.44 | 2.20 | 2.17 |
| Eu | 0.77 | 0.84 | 0.82 | 0.78 | 0.75 |
| Gd | 2.34 | 2.49 | 2.56 | 2.58 | 2.42 |
| Tb | 0.38 | 0.46 | 0.43 | 0.43 | 0.48 |
| Dy | 2.44 | 2.84 | 2.77 | 2.91 | 3.05 |
| Ho | 0.58 | 0.64 | 0.56 | 0.60 | 0.65 |
| Er | 1.42 | 1.57 | 1.51 | 1.55 | 1.68 |
| Tm | 0.25 | 0.27 | 0.23 | 0.24 | 0.29 |
| Yb | 1.43 | 1.55 | 1.60 | 1.76 | 1.82 |
| Lu | 0.25 | 0.28 | 0.25 | 0.28 | 0.29 |
| Hf | 1.13 | 1.14 | 1.01 | 1.42 | 1.30 |
| Ta | 0.14 | 0.13 | 0.13 | 0.17 | 0.11 |
| W | 0.02 | 0.05 | 0.03 | 0.16 | 0.17 |
| Pb | 1.80 | 1.95 | 1.88 | 4.00 | 4.03 |
| Th | 0.54 | 0.63 | 0.59 | 1.11 | 1.43 |
| U | 0.13 | 0.12 | 0.12 | 0.22 | 0.28 |
| Ba/La | 12 | 10 | 12 | 23 | 20 |
| Ba/Nb | 25 | 25 | 28 | 64 | 84 |
| Eu/Eu* | 1.03 | 1.01 | 1.00 | 1.01 | 1.00 |
| La/Nb | 2.1 | 2.4 | 2.4 | 2.7 | 4.3 |
| Nb/Ta | 14 | 14 | 14 | 14.00 | 13 |
| Nb/Yb | 1.38 | 1.19 | 1.13 | 1.35 | 0.81 |
| Nd/Pb | 4.4 | 4.7 | 4.1 | 2.0 | 2.0 |
| Pb/Ta | 13 | 15 | 14 | 23 | 37 |
| Sr/Nd | 57 | 49 | 47 | 24 | 23 |
| Th/Nd | 0.07 | 0.07 | 0.08 | 0.14 | 0.18 |
| Th/Pb | 0.30 | 0.32 | 0.31 | 0.28 | 0.35 |
| Th/Ta | 3.86 | 4.85 | 4.54 | 6.53 | 13.00 |
| Ti/V | 15 | 15 | 14 | 17 | 12 |
| Zr/Hf | 34 | 31 | 33 | 35 | 32 |

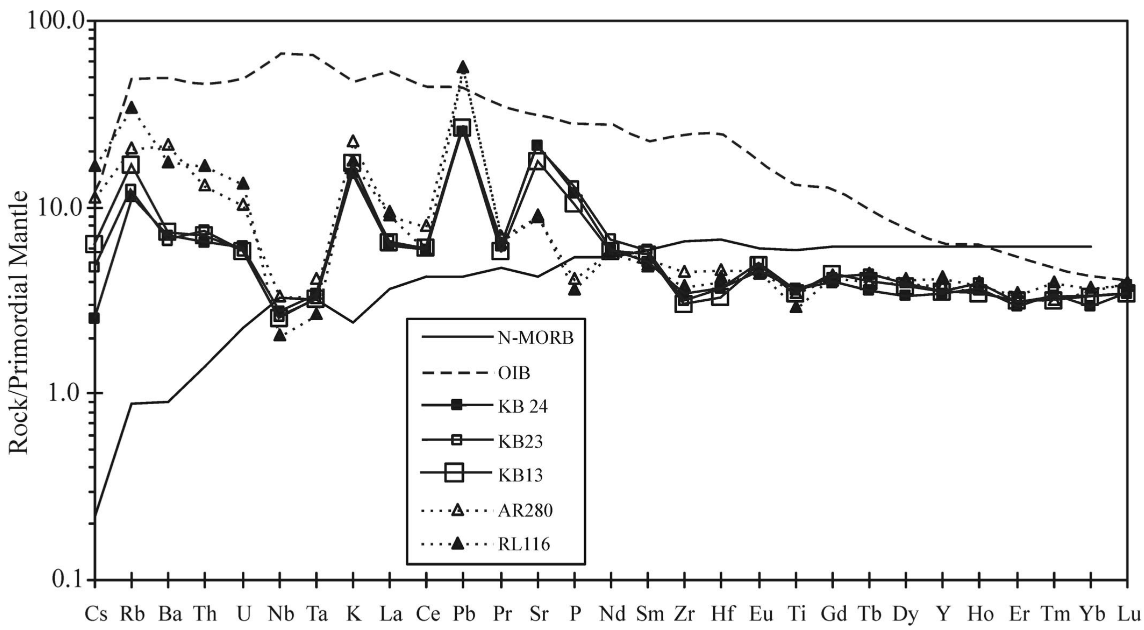


Fig. 2 - Primordial mantle-normalized trace element diagram of Montresta and Arcuentu samples. Normalization values after Sun and McDonough (1989).

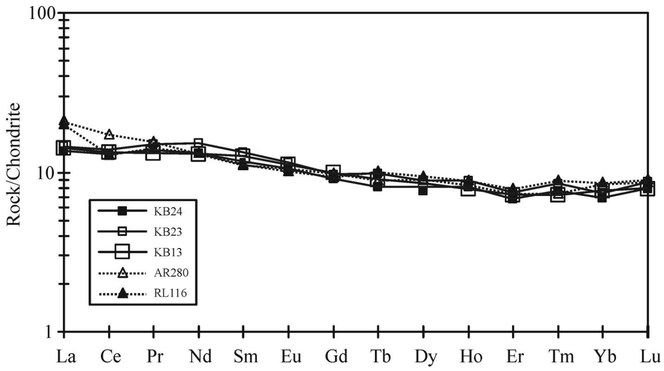


Fig. 3 - Chondrite-normalized REE diagram for Oligo-Miocene basalts from Sardinia. Normalization values after Boynton (1984).

## Sr-Nd-Pb ISOTOPE SYSTEMATICS

Sr-, Nd- and Pb-isotope data of Oligo-Miocene mafic volcanic rocks from Sardinia are listed in Table 2, together with initial isotope ratios recalculated at 18 Ma. Initial Sr-, Nd- and Pb-isotope ratios are plotted on conventional isotope-isotope covariation diagrams in Figs. 4 and 5.

In the initial $^{87}Sr/^{86}Sr$ versus initial $^{143}Nd/^{144}Nd$ diagram (Fig. 4) the rocks from Montresta cluster together in the upper left quadrant, close to Bulk Earth at 18 Ma. They lie very close to the field of mafic volcanic rocks from the Aeolian Arc. The rocks from Montresta are also similar in their Sr-Nd isotope systematics to some volcanic rocks cored from the Tyrrhenian seafloor. The values are distinct from those of the potassic alkaline rocks belonging to the Campanian Magmatic Province (Fig. 4).

The two mafic rocks from Arcuentu lie to the right of Bulk Earth at 18 Ma, and are very similar to calc-alkaline and shoshonitic rocks from the Aeolian Arc and to shoshonitic rocks from the Campanian Magmatic Province. In of Fig. 4, the field of Sr and Nd isotope data determined by Downes et al. (2001) on Oligo-Miocene volcanics from Arcuentu (southern Sardinia) is reported for comparison.

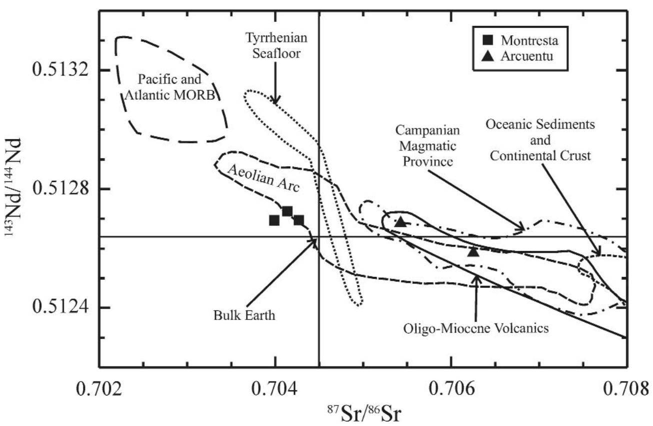


Fig. 4 - $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ covariation diagram for Sardinia mafic rocks. Sr and Nd isotope values for Bulk Earth calculated at 18 Ma, according to CHUR model (Faure, 1986, and references therein). Data sources: Arcuentu volcanics, Downes et al. (2001); Aeolian Arc, Ellam et al. (1989), Esperança et al. (1992), Francalanci et al. (1993), Del Moro et al. (1998), De Astis et al. (2000); oceanic sediments, White et al. (1985), Woodhead and Fraser (1985), Ben Othman et al. (1989). For Pacific and Atlantic MORB, Tyrrhenian seafloor, Campanian Magmatic Province and continental crust (Calabria), see references quoted in D'Antonio et al. (1996; 1999), Conticelli et al. (2002) and Pappalardo et al. (2002).

In the initial $^{206}Pb/^{204}Pb$ versus initial $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ covariation diagrams (Fig. 5), the mafic rocks from Sardinia make a near vertical array, which lies at a high angle with respect to the Northern Hemisphere Reference Line (NHRL; Hart, 1984); the array is well above the NHRL in the $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ plot. In both diagrams, the Montresta and Arcuentu rocks fall in the fields of oceanic pelagic sediments and upper continental crustal rocks, and are distinct from both Pacific and Atlantic MORB. Furthermore, they look similar to the least radiogenic (in terms of Pb isotopes) calc-alkaline rocks from the Aeolian Arc (Ellam et al., 1989; Francalanci et al., 1993; Del Moro et al., 1998; De Astis et al., 2000) and potassic alkaline rocks from the Campanian Magmatic Region (D'Antonio et al., 1996; 1999). The more evolved Oligo-Miocene rocks from Sardinia (crosses in Fig. 5), plotting well within the continental crust field, have been interpreted as contaminated magmas (Caron and Orgeval, 1996).

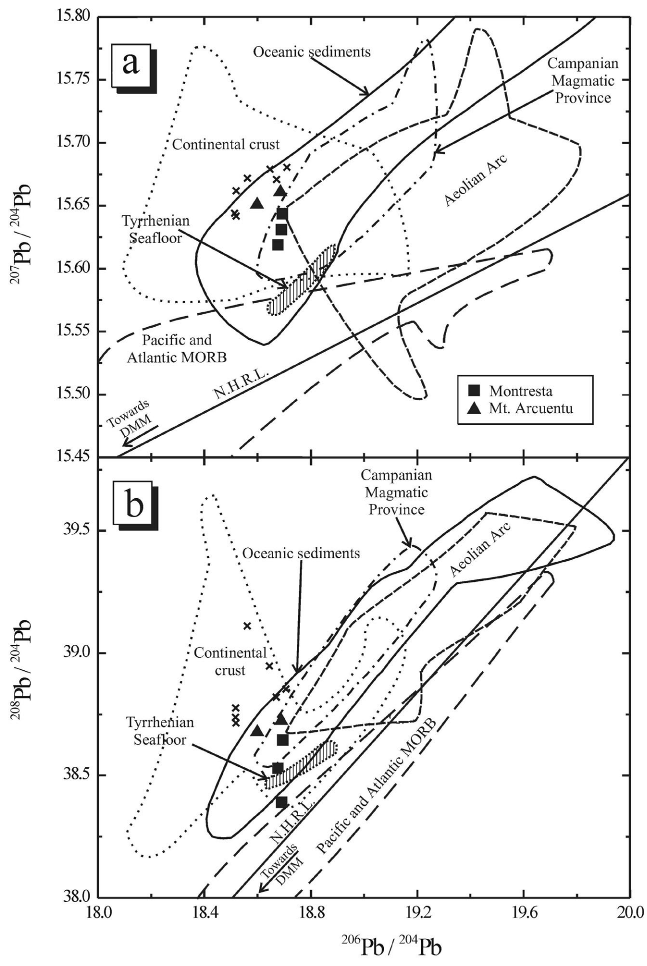


Fig. 5 - $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ (a) and $^{208}Pb/^{204}Pb$ (b) covariation diagrams for analysed mafic rocks from Sardinia. Crosses- Sardinian Andesitic rocks from various localities (Caron and Orgeval, 1996). N.H.R.L.- Northern Hemisphere Reference Line (Hart, 1984). Data sources: Aeolian Arc, Ellam et al. (1989), Esperança et al. (1992), Francalanci et al. (1993), Del Moro et al. (1998), De Astis et al. (2000); oceanic sediments, White et al. (1985), Woodhead and Fraser (1985), Ben Othman et al. (1989). For Pacific and Atlantic MORB, Tyrrhenian seafloor, Campanian Magmatic Province, and continental crust (Calabria), see references quoted in D'Antonio et al. (1996, 1999), Conticelli et al. (2002) and Pappalardo et al. (2002).

Table 2 - Sr-Nd and Pb isotope composition of selected basalts from Sardinia. Subscript "$_{18}$" indicates isotope ratios recalculated at 18 Ma.

| Sample | $^{87}Sr/^{86}Sr$ | $^{143}Nd/^{144}Nd$ | $^{206}Pb/^{204}Pb$ | $^{207}Pb/^{204}Pb$ | $^{208}Pb/^{204}Pb$ | $^{87}Sr/^{86}Sr_{18}$ | $^{143}Nd/^{144}Nd_{18}$ | $^{206}Pb/^{204}Pb_{18}$ | $^{207}Pb/^{204}Pb_{18}$ | $^{208}Pb/^{204}Pb_{18}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| KB24 | 0.70414 | 0.51274 | 18.703 | 15.631 | 38.408 | 0.70413 | 0.51271 | 18.690 | 15.630 | 38.390 |
| KB23 | 0.70399 | 0.51271 | 18.688 | 15.619 | 38.549 | 0.70398 | 0.51269 | 18.677 | 15.618 | 38.530 |
| KB13 | 0.70428 | 0.51271 | 18.707 | 15.644 | 38.663 | 0.70426 | 0.51269 | 18.695 | 15.643 | 38.645 |
| AR280 | 0.70631 | 0.51260 | 18.609 | 15.651 | 38.697 | 0.70625 | 0.51258 | 18.599 | 15.650 | 38.681 |
| RL116 | 0.70551 | 0.51270 | 18.702 | 15.661 | 38.747 | 0.70542 | 0.51268 | 18.689 | 15.660 | 38.726 |

## DISCUSSION

The new trace element and Sr-, Nd- and Pb-isotope data of the analysed HMBs from Montresta and Arcuentu are consistent with derivation from a slightly depleted mantle source region modified by subduction processes (Table 2; Figs. 2, 3, 4, 5). Furthermore, in the Sr-Nd and Pb-Pb covariation diagrams (Figs. 4, 5), these rocks appear to be very similar to the least radiogenic volcanic rocks from the Aeolian Arc and Campanian Region. The latter have isotopic characteristics currently interpreted as derived from subduction-modified mantle source regions (e.g., Francalanci et al., 1993; Del Moro et al., 1998; D'Antonio et al., 1999; De Astis et al., 2000).

### Crustal contamination

Brotzu et al. (1997a) argue that the evolution of the Arcuentu magmas, from HMB to andesite, was mainly driven by polybaric fractional crystallization in closed systems. On the contrary, for the Montresta magmas, evolution solely driven by fractional crystallization is unlikely, although the $(^{87}Sr/^{86}Sr)_{18}$ values show a progressive increase with $SiO_2$, ranging from 0.70398 (HMB) to 0.70520 (andesite) (Morra et al., 1997). Increase in initial $^{87}Sr/^{86}Sr$ with differentiation has also been recorded in other Oligo-Miocene volcanic districts of Sardinia (Dupuy et al., 1974; Morra et al., 1994; Brotzu et al., 1997b; Lonis et al., 1997). Recently, Downes et al. (2001) pointed out that the $^{87}Sr/^{86}Sr$ variations in the Arcuentu magmas are not correlated with their differentiation, noting a roughly positive correlation of $^{87}Sr/^{86}Sr$ with $SiO_2$, and a poor correlation with MgO. From these observations, Downes et al. (2001) infer a mantle source enriched by melts from siliceous sediments as the major cause of the high, variable $^{87}Sr/^{86}Sr$ ratios. Such an enrichment, on the basis of Sr and O isotopic data, would imply 2 to 10% contribution from oceanic sediments. Other authors (Morra et al., 1994; 1997; Brotzu et al., 1997b; Conte, 1997; Lonis et al., 1997) have pointed out that assimilation-fractional crystallization was the main process in the evolution of the Sardinian Oligo-Miocene orogenic magmas. In order to examine this process, all available data on Sardinian orogenic rocks are plotted in the $SiO_2$ and MgO vs. $^{87}Sr/^{86}Sr$ diagrams (Fig. 6a, b). The clear positive correlation of $^{87}Sr/^{86}Sr$ with $SiO_2$ is visible, as well as a negative correlation with MgO, for all rocks including those from Arcuentu, together with remarkable differences between Sr data by various authors (Dupuy et al., 1974; Morra et al., 1994; 1997; Brotzu et al., 1997b; Conte, 1997; Lonis et al., 1997) and those by Downes et al. (2001). These differences may be related to a higher degree of crustal contamination for the more evolved samples from Arcuentu, or to other causes, evaluation of which is beyond the scope of this paper. Sr isotope variations, for all available data, suggest that contamination played a significant, although variable, role in the evolution of all Sardinian orogenic magmas, including those of the Arcuentu complex. Moreover, crustal contamination for Sardinian andesitic magmas has been proposed by Caron and Orgeval (1996) on the basis of Pb isotope ratios.

However, the only primitive rocks from Sardinia which are thought to be poorly contaminated, may provide good information on the nature of the source.

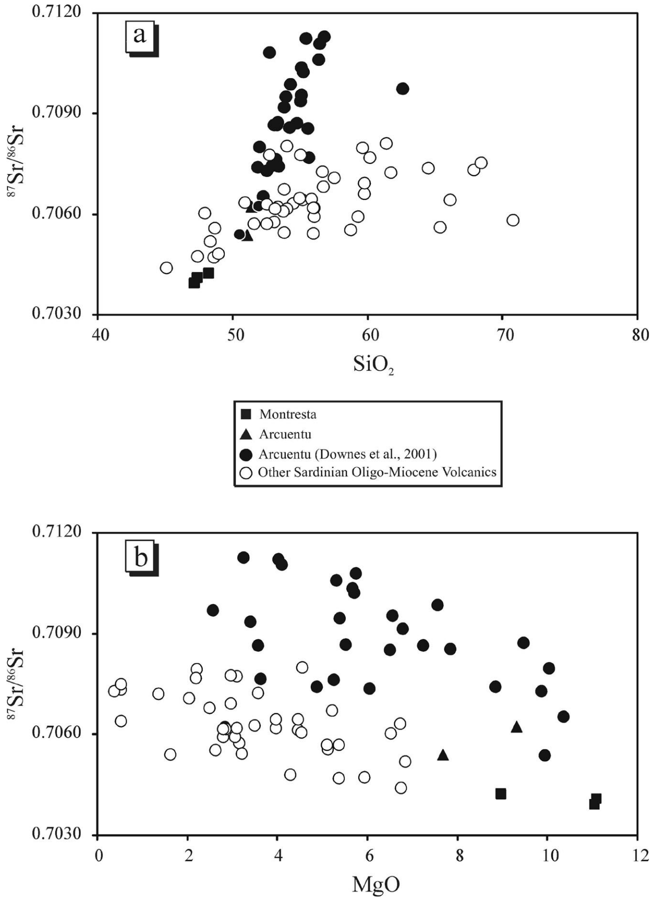


Fig. 6 - $^{87}Sr/^{86}Sr$ versus $SiO_2$ (a) and MgO (b) diagrams for Sardinia Oligo-Miocene volcanic rocks. Data source: this work, Dupuy et al. (1974), Morra et al. (1994; 1997), Brotzu et al. (1997b), Conte (1997), Lonis et al. (1997), Downes et al. (2001).

### Pre-enrichment mantle source

The mantle sources of the primitive magmas extruded in the Arcuentu and Montresta volcanic districts have been presumed to be located within the spinel stability field (Brotzu et al., 1997a; Morra et al., 1997). For the Montresta primitive magmas, Morra et al. (1997) proposed a degree of partial melting of a N-MORB-like source of about 15%.

In order to investigate the composition of the Sardinian mantle wedge prior to subduction enrichment, HFSE concentrations in primitive rocks were considered. HFSE are not substantially mobilised by acqueous fluids during subduction due to their low mobility (e.g., Brenan et al., 1995b; Pearce et al., 1999; Walker et al., 2001). Moreover, the oceanic sediments have low concentration in HFSE (e.g. Plank and Langmuir, 1998). Low HFSE contents may therefore be interpreted as the result of mantle-wedge depletion due to previous melting events, particularly when a back-arc basin is present (e.g. Elliott et al., 1997).

For the mafic rocks of this study, ratios of some elements such as Ti, V, Zr, Nb and Ta were used to investigate the mantle sources prior to subduction. The average value of the Nb/Ta ratio for depleted upper mantle has been calculated at about 15.5 (Jochum et al., 1997), whereas the chondritic value is about 17. The Arcuentu and Montresta basalts have average Nb/Ta ratios of ~14, indicating a N-MORB-like depleted source for the Sardinian primitive melts. The Ti/V ratio is about 15 for Montresta and about 12 for sample RL116 from Arcuentu; these values are lower than those of MORB (~25; Sun and McDonough, 1989). Ti/Zr is about 130, very similar to that of MORB (≈130; Sun and McDonough, 1989) for the Montresta rocks and lower, around 90, for the Arcuentu volcanic rocks. The low Ti/V ratios for Sardinia mafic rocks with respect to typical MORB may be related to sources slightly depleted in Ti relative to V during partial melting of mantle (i.e., Ti is highly incompatible and V is moderately compatible with respect to spinel and clinopyroxene). The Ti/V ratio should therefore reflect slight differences in mantle source with respect to those of MORB. The great difference in the Ti/Zr ratio in the Montresta and Arcuentu rocks is problematic. For Montresta mafic rocks, the Ti/Zr ratio close to N-MORB indicates a similar mantle source as well as similar degrees of partial melting. Instead, the low Ti/Zr of Arcuentu rocks may partly be due to depletion in Ti by extraction of basaltic melts during previous melting events.

### Subduction components

The mafic rocks from Montresta and Arcuentu have rather high initial $^{143}Nd/^{144}Nd$ ratios (about 0.5127) and quite low initial $^{87}Sr/^{86}Sr$ (about 0.704-0.706) and $^{206}Pb/^{204}Pb$ ratios (about 18.7), suggesting that their source region was enriched with respect to that of N-MORB-like depleted mantle. The Sr-Nd isotope relationships of these rocks suggest that the subduction components cannot be represented only by altered oceanic crust. The Pb-isotope relationships of the Montresta and Arcuentu mafic rocks may indicate a contribution from pelagic sediments. As the isotopic composition of lead in the mantle is very sensitive to the addition of sediments, it may be inferred that the mantle source region of the Sardinian Oligo-Miocene mafic magmas was modified by even the very small contribution of a sedimentary component, as already suggested by Morra et al. (1997).

The ratios between trace elements having different behaviour in melt and fluid phases help to constrain the nature of the subduction component(s). For example, on one hand, the Sr/Nd ratio is increased by input of fluid phases, due to the different partitioning of the two elements in both sediment and eclogite fluids (i.e. eclogite/fluid: $D_{Sr}$ = 0.18, $D_{Nd}$ = 45; Brenan et al., 1995a; 1995b; sediment/fluid: $D_{Sr}$ = 0.53, $D_{Nd}$ = 3.26; Johnson and Plank, 1999). On the other hand, slab melts may be unable to modify the Sr/Nd ratio significantly, because both elements have similar partition coefficients. Furthermore Th is readily mobilised by slab melting and, therefore, a significant increase in Th/Pb may be expected. In the Sr/Nd versus Th/Pb plot of Fig.7a, HMBs from Sardinia define an array at very low Th/Pb values (average 0.31) towards high Sr/Nd, suggesting the contribution of a fluid component.

In the Th/Nd versus $^{143}Nd/^{144}Nd$ plot of Fig 7b the two arrows starting from the sediments field indicate that sediment fluid and sediment melt have opposite trends in terms of Th/Nd ratios, while the $^{143}Nd/^{144}Nd$ ratio remains unchanged; the HMBs from Sardinia lie between the MORB

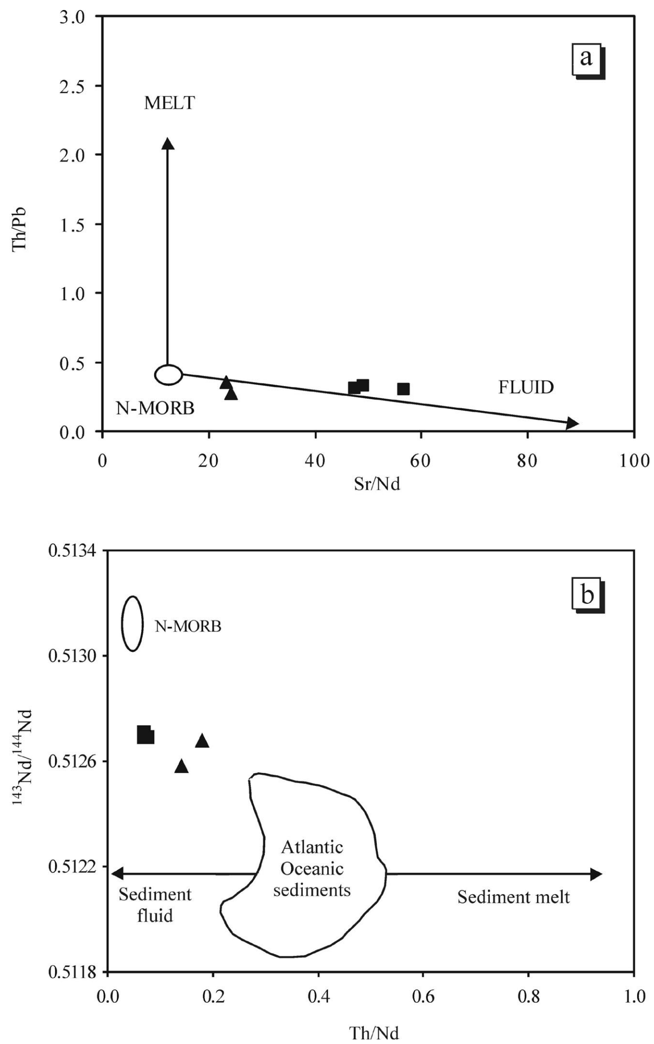


Fig. 7 - a) Sr/Nd versus Th/Pb diagram for orogenic basalts from Sardinia. Starting from a N-MORB like source, input of a melt component from subducted slab increases Th/Pb ratio, while Sr/Nd ratio varies mainly due to fluid components. Symbols as in Figs. 4 and 5.
b) Th/Nd versus $^{143}Nd/^{144}Nd$ diagram for Oligo-Miocene HMBs from Sardinia. Montresta and Arcuentu samples are consistent with mixing between N-MORB-like source and fluids from Atlantic sediments (data sources White et al., 1985; Ben Othman et al., 1989). Symbols as in Figs. 4 and 5.

field and a low Th/Nd end-member, probably represented by sediment fluids.

The contribution of fluids from altered oceanic crust and from sediments may be estimated by considering Nd/Pb and $^{206}Pb/^{204}Pb$ ratios (Fig. 8a): the Nd/Pb ratio in the mantle wedge readily changes when a MORB fluid component is added. In fact, depleted mantle generally has high Nd/Pb ratios (10-25), whereas MORB fluids are characterised by very low Nd/Pb because of the high solid/fluid partition coefficient of Nd in MORB oceanic crust, while Pb is readily mobilised in hydrous fluids (Brenan et al., 1995b; Johnson and Plank, 1999). In Fig.8a, the Nd/Pb ratio of the Arcuentu magmas may be explained by input in the mantle wedge of about 0.5 % MORB fluid and less than 0.1% sediment fluid. The Nd/Pb and $^{206}Pb/^{204}Pb$ ratios of Montresta HMBs are consistent with a contribution of MORB fluid of about 0.1%; sediment fluids may have contributed for less than 0.1%. Therefore, in the genesis of the orogenic primitive magmas of Sardinia, three end-members are probably involved: 1) depleted mantle, 2) fluids from subducted altered oceanic crust, 3) fluids from subducted oceanic sediments, similar to Atlantic Ocean sediments.

In order to verify the amount of sediment fluid involved in the genesis of HMBs from Sardinia, the $^{206}Pb/^{204}Pb$ vs $^{87}Sr/^{86}Sr$ plots (Fig. 8b) can considered. The Montresta samples lie on mixing line 2, between mantle source enriched by 0.1% MORB fluid (as calculated in model of Fig. 8a) and sediment fluid (SF) at less than 0.1% of oceanic sediment contribution. Samples from Arcuentu lie on mixing lines 2 and 3, between mantle source enriched by about 0.5% MORB fluid and fluid from sediments at 0.05-0.08% of sediment contribution. These estimates are far from the results of Sr and O isotope modeling by Downes et al. (2001) for Arcuentu basalts, for which the greater contribution of oceanic sediments (2% for the more mafic rocks) was inferred. Our estimates, based on Sr and Pb isotopic data, are also consistent with the absence of negative Eu anomalies (Table 1; Fig. 3); in fact, addition of 2% of oceanic sediments to a depleted mantle wedge would cause marked negative Eu anomalies, while Eu/Eu* higher than 0.95, as in Sardinian HMBs, constrains the amount of sediment component to less than 1% (McLennan and Taylor, 1981). The amount of total fluids involved in the genesis of the Sardinian magmas was too low, by itself, to trigger partial melting of mantle source (i.e. about 0.15% for Montresta; Morra et al., 1997). Melting was thus caused by adiabatic decompression of the Sardinian mantle during the climax of the extensional tectonic regime (Morra et al., 1997).

However, an alternative hypothesis can be proposed for basalt RL116 from the Arcuentu district, compared with the less evolved basalt AR280 from the same district. RL116 isotopic ratios are closer to those of Montresta samples than basalt AR280. Fig. 9a shows that basalt RL116 may be derived from a parental magma (P), similar to the Montresta HMBs, coming from a mantle source slightly more enriched in sediment component, later affected by low degrees of crustal contamination. In fact, in Fig. 9a, sample RL116 can be reproduced by crustal assimilation at about 0.4% of contamination of a lower crustal component (LC). In the Nd/Pb versus $^{206}Pb/^{204}Pb$ plot of Fig. 9b, the contribution of crustal contamination (more than 1%) is higher than that calculated in Fig. 9a. It turns out that a process of crustal contamination starting from a magma similar to Montresta basalts cannot be well constrained, essentially on the basis of our geochemical and Sr, Nd and Pb isotopic data. Therefore, variably enriched mantle sources in Sardinia are more likely. The HMBs from Montresta do have substantially homogeneous geochemical and isotopic compositions, whereas the Arcuentu samples are quite different in both trace elements (Table 1) and isotopic characteristics (Table 2), as already reported by Brotzu et al. (1997a), who pointed out “differences in mantle-derived parental magmas”. Temporal varia-

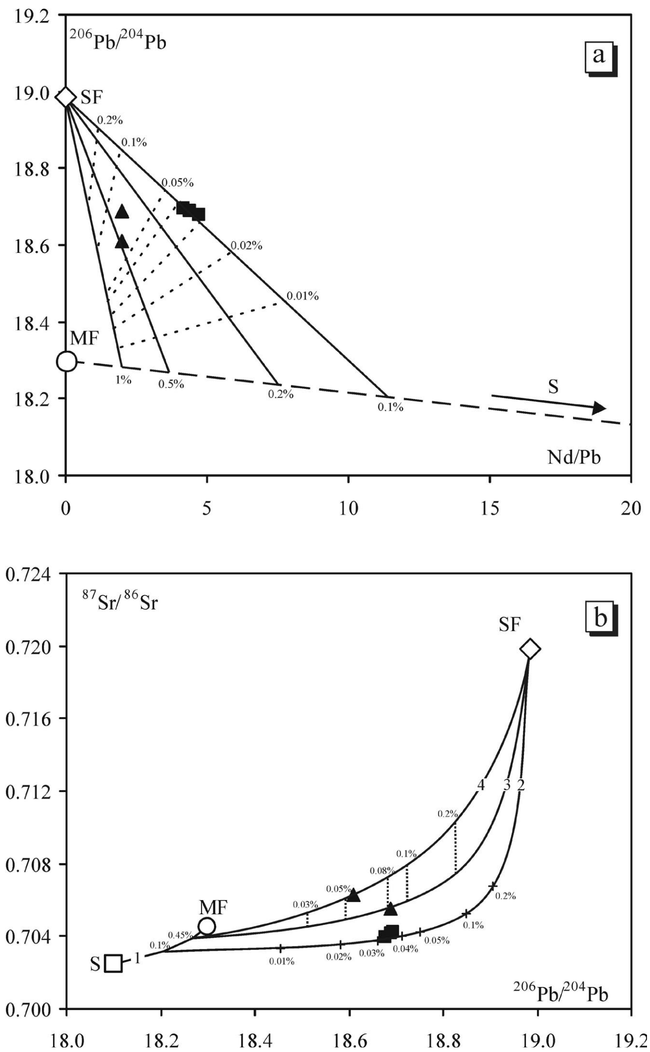


Fig. 8 - a) Nd/Pb versus $^{206}Pb/^{204}Pb$ diagrams for Mt. Arcuentu and Montresta samples. Dashed lines: mixing between depleted mantle (S) and MORB fluid (MF). Solid lines: different percentages of MORB fluid. Dotted lines: different percentages of sediment fluid (SF). Compositions of S, MF, and SF listed in Table 3. Fluid from Altered MORB calculated assuming 2% by volume of fluid and, for eclogite/fluid, $D_{Pb}$ = 0.01 (Brenan et al., 1995b) and $D_{Nd}$ = 3.26 (Johnson and Plank, 1999). Fluid from sediments calculated assuming 1% by volume of fluid and sediment/fluid partition coefficients are $D_{Pb}$ = 0.51 and $D_{Nd}$ = 3.26 (Johnson and Plank, 1999). Symbols as in Figs. 4 and 5.
b) $^{206}Pb/^{204}Pb$ versus $^{87}Sr/^{86}Sr$ diagrams for orogenic basalts from Sardinia. HMBs from Montresta lie on mixing line 2, between mantle source enriched by 0.1% MORB fluid and fluid from sediments (SF) at less than 0.05% of sediment fluid input. Isotopic ratios of Arcuentu basalts are consistent with mixing between less than 0.1% sediment fluid and mantle source enriched by about 0.5% MORB fluid. Fluid from altered MORB calculated as in Fig. 9, and eclogite/fluid partition coefficients are: $D_{Pb}$- 0.01 and $D_{Sr}$- 0.19 (Brenan et al., 1995b). Sediment fluid is calculated assuming 1% by volume of fluid, and sediment/fluid partition coefficient are: $D_{Pb}$- 0.51 (Johnson and Plank, 1999); $D_{Sr}$ (line 2)- 0.53 (Johnson and Plank, 1999); $D_{Sr}$ (line 3)- 0.37; $D_{Sr}$ (line 4)- 0.19 (Brenan et al., 1995b). Compositions of S, MF and SF listed in Table 3. Symbols as in Figs. 4 and 5.

Table 3 - Compositions of end-members used in quantitative modelling. Data sources: [A] - Elburg and Foden (1998); [B] - Taylor and Nesbitt (1998); [C] - Ben Othman et al. (1989); [D] - Class et al. (2000); [E] - Hole et al. (1984); [F] - Caggianelli et al. (1991).

| | $^{87}Sr/^{86}Sr$ | $^{144}Nd/^{143}Nd$ | $^{206}Pb/^{204}Pb$ | Sr | Nd | Pb |
|---|---|---|---|---|---|---|
| Depleted mantle (S) | 0.7025[A] | 0.5132[D] | 18.1[A] | 6[D] | 0.73[A] | 0.03[D] |
| Altered MORB | 0.7045[B] | 0.513[A] | 18.3[B] | 120[B] | 11.4[E] | 0.7[B] |
| Sediments | 0.719858[C] | 0.512061[C] | 18.985[C] | 139[C] | 43.38[C] | 31.28[C] |
| Lower Crust (LC) | 0.71587[F] | 0.51198[F] | 18.371[F] | 249[F] | 33.4[F] | 16[F] |

tions of mantle sources of Arcuentu are probable, considering that magmatic activity in this area lasted for about 13 Ma (according to available K-Ar age determinations; Montigny et al., 1981; Assorgia et al., 1984; Beccaluva et al., 1985).

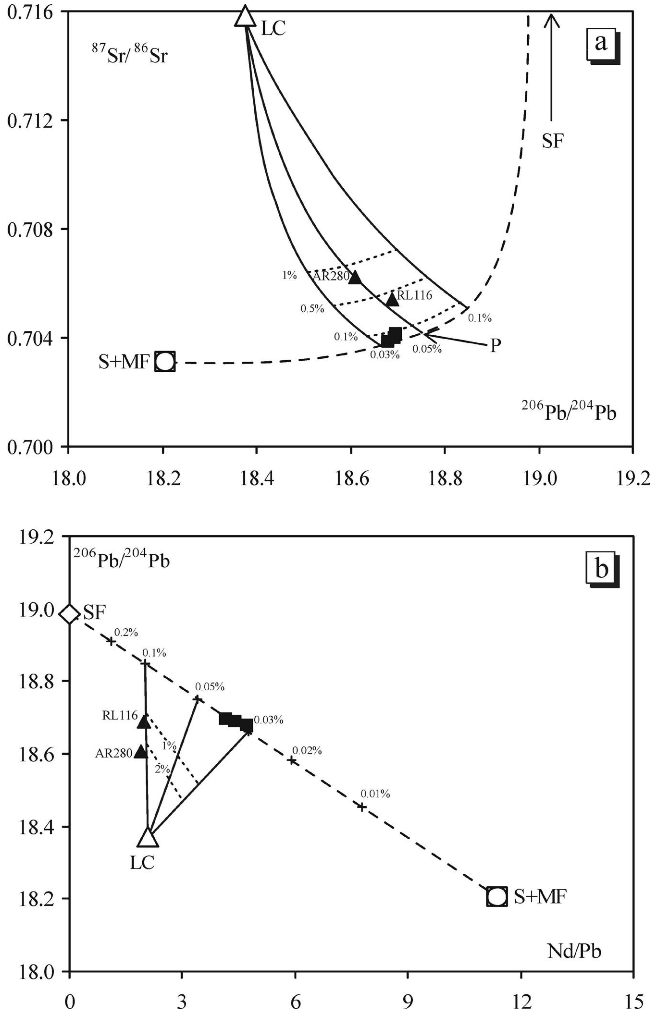


Fig. 9 - a) $^{206}Pb/^{204}Pb$ vs $^{87}Sr/^{86}Sr$ ratios of basalt RL116 from Arcuentu can be interpreted as result of about 0.4% crustal contamination of a parental magma (P) similar to Montresta basalts.
b) Nd/Pb vs $^{206}Pb/^{204}Pb$ plot does not support quantitative model of A. Nd/Pb ratio of sample RL116 indicates mantle source richer in sediment component (0.1%) and a higher degree of crustal contamination (more than 1%). In both diagrams, dashed lines represent mixing between MORB fluid enriched source (S+MF) and sediment fluid (SF). Dotted lines: equal percentages of lower crust (LC) contamination. Solid lines: equal percentages of sediment fluid. For composition of LC see table 3. Sediment fluid (SF) calculated as in Figs. 9 and 10 (mixing line 2). Symbols as in Figs. 4 and 5. See text for details.

Summarizing, the inferred mantle sources of the Oligo-Miocene orogenic magmas were slightly heterogeneous, being characterised by spatial and, possibly, temporal geochemical variations, related to variable contributions from subducted sediments and oceanic crust, as well as to different degrees of depletion of the pre-subduction mantle sources.

The strong similarity in terms of Sr-Nd-Pb isotopic compositions between the Oligo-Miocene basalts of Sardinia and the least radiogenic calc-alkaline volcanics from the Aeolian Arc, and potassic volcanics from the Campanian and Roman Regions, has already been noted. It is easy to hypothesise that the mantle source regions of the magmatism in all these areas were similar, and/or that they must have undergone similar enrichment histories. In particular, the peculiar isotopic features of volcanic rocks from the Campanian Magmatic Province may in some cases be referred to crustal contamination, although D'Antonio et al. (1999) argue that some of the least evolved rocks show radiogenic Sr and unradiogenic Nd isotopic features. It turns out that these peculiar isotopic features must have originated essentially in the mantle source regions, and this conclusion also holds for the least evolved mafic rocks from Sardinia.

## CONCLUSIONS

The geochemical and Sr, Nd and Pb isotopic features of primitive Oligo-Miocene orogenic basalts from Sardinia (Montresta and Arcuentu districts) indicate that:

- their genesis is related to the concurrence of three end-members: 1) depleted mantle wedge (MORB-like); 2) a component from subducted altered oceanic crust; 3) a component from subducted oceanic sediments;
- pre-subduction sources are very similar to N-MORB-like mantle in both Arcuentu and Montresta districts;
- ratios between trace elements such as Th/Pb, Sr/Nd and Th/Nd are consistent with the input in the mantle wedge of fluid phases from both oceanic crust and sediments, rather than melts;
- the amount of fluids from subducted oceanic crust involved in magma genesis is constrained at about 0.5% for the Arcuentu basalts and about 0.1% for Montresta;
- modeling based on $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ isotopic ratios indicate that the sediment fluid input in the mantle wedge for Arcuentu and Montresta magmas is less than 0.1 %. These values, lower than those calculated on the basis of Sr- and O-isotopes by Downes et al. (2001) for Arcuentu magmas (>2%), are consistent with the lack of negative Eu anomalies. The Arcuentu basalts are slightly heterogeneous in their geochemical and isotopic compositions, probably as a result of variations in the mantle source over the long time-span of volcanic activity in this district (about 13 Ma).

## ANALYTICAL TECHNIQUES

REEs and trace elements were determined with Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) at CRPG (Nancy, France).

Sr- and Nd-isotope analyses were performed at the CISAG (Centro Interdipartimentale di Servizio per Analisi Geomineralogiche), Naples (Italy). Samples were prepared for measurements as follows: 0.3 g of powder were strongly leached with warm 6N HCl for 30 minutes, then rinsed thoroughly in pure sub-boiling double-distilled water, and finally dissolved with high purity HF-$HNO_3$-HCl mixtures. Sr and Nd were extracted by conventional ion-exchange chromatographic techniques. The total blank was ca. 6 ng Sr and 4 ng Nd. Measurements were made using a VG354 double-collector thermal ionisation mass spectrometer running in peak jumping mode, by normalising to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$ for mass fractionation effects. The quoted error is twice the standard deviation of the mean (2σ) and is ±1*10-5. Repeated analyses of NBS-987 Sr standard yielded a mean value of $^{87}Sr/^{86}Sr = 0.71024 \pm 0.00001$ (N = 50) and the La Jolla Nd standard a mean value of $^{143}Nd/^{144}Nd = 0.511826 \pm 0.000010$ (N = 26).

Pb isotopic determinations were performed at the laboratory of the Hawaii Institute of Geophysics. Analytical procedures, blanks and uncertainties in measurements are identical to those fully reported in Lustrino et al. (2002).

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