Per. Mineral. (2004), *73*, 105-134 http://go.to/permin
SPECIAL ISSUE 1 : A showcase of the Italian research in petrology: magmatism in Italy

PERIODICO di MINERALOGIA
established in 1930

An International Journal of
MINERALOGY, CRYSTALLOGRAPHY, GEOCHEMISTRY,
ORE DEPOSITS, PETROLOGY, VOLCANOLOGY
and applied topics on *Environment, Archaeometry* and *Cultural Heritage*

The Cenozoic igneous activity of Sardinia

MICHELE LUSTRINO[1,2,*], VINCENZO MORRA[3*], LEONE MELLUSO[3], PIETRO BROTZU[3], FOSCO D'AMELIO[3], LORENZO FEDELE[3], LUIGI FRANCIOSI[3], ROBERTO LONIS[4] and ALFREDO MASSIMO PETTERUTI LIEBERCKNECHT[3]

[1] Dipartimento di Scienze della Terra, Università degli Studi di Roma La Sapienza, P.le A. Moro, 5, 00185 Rome, Italy
[2] CNR-Istituto di Geologia Ambientale e Geoingegneria (IGAG), Rome, Italy
[3] Dipartimento di Scienze della Terra, Università degli Studi di Napoli Federico II, Via Mezzocannone, 8, 80134 Naples, Italy
[4] Progemisa S.p.A., Via Contivecchi, 7, 09122 Cagliari, Italy

ABSTRACT. — During the Cenozoic, the island of Sardinia was the location of two different magmatic episodes: 1) a Oligocene to Miocene (hereafter OM) cycle ~32-15 Ma and 2) a Pliocene to Quaternary (hereafter PQ) cycle (~5-0.1 Ma). These two volcanic cycles differ in many aspects: 1) geographic occurrence [the OM rocks occur almost exclusively in a graben structure called the *Fossa Sarda* (Sardinian Trough) that cuts the entire island from north to south, whereas the PQ rocks are scattered throughout the island]; 2) petrography (the OM rocks are mostly porphyritic, whereas the PQ rocks are mostly aphyric); 3) geochemical affinity (the OM rocks are mostly subalkaline with a tholeiitic to calcalkaline character, whereas the PQ rocks are mostly sodic alkaline with fewer tholeiitic types); 4) major element compositions [the OM rocks are mostly dacites to rhyolites with fewer basaltic andesites, andesites and rare basalts while the PQ rocks are mostly hawaiites, mugearites and basaltic andesites, with both SiO_2-oversaturated and SiO_2-undersaturated evolved types (rhyolites and phonolites); moreover, for a given SiO_2, OM rocks have higher CaO, lower TiO_2 and lower Na_2O compared to the PQ rocks]; 5) trace element abundances and ratios (the OM rocks have lower HFSE and REE contents and higher La/Nb and Zr/Nb ratios compared to the PQ samples); 6) Sr isotopic composition (the OM rocks have $^{87}Sr/^{86}Sr$ generally > 0.7047, whereas the PQ rocks have $^{87}Sr/^{86}Sr$ generally < 0.7050). $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ ratios of the OM rocks (from 0.5127 to 0.5122 and from 18.52 to 18.71, respectively) fall within the range of the PQ samples (from 0.5129 to 0.5122 and from ~17.5 to 19.42, respectively).

The OM rocks show geochemical features typical of magmas emplaced in subduction-related settings. They are believed to have been generated within the mantle wedge developed above a west-directed subduction of (Mesogean?) oceanic lithosphere below the southern continental margin of Europe. On the other hand, the PQ volcanic rocks were emplaced concurrent with the formation of the Tyrrhenian Sea and share some geochemical similarities with magmas emplaced in within-plate (anorogenic) tectonic settings, although they exhibit peculiar characteristics.

The PQ rocks can be divided into two groups: one group (Unradiogenic Pb Volcanics = UPV) has relatively high $^{87}Sr/^{86}Sr$ (0.7043-0.7051), low $^{143}Nd/^{144}Nd$ (0.5124-0.5126), and is characterised by the least radiogenic Pb isotopic composition so far recorded in Italian (and Circum-Mediterranean) Cenozoic igneous rocks ($^{206}Pb/^{204}Pb$ = 17.36-18.07); these are the most widespread volcanic rocks and crop out in central and northern Sardinia. The other group (Radiogenic Pb Volcanics = RPV) has chemical and Sr-Nd-Pb isotopic ratios indicative of a

* Corresponding authors,
E-mail: michele.lustrino@uniroma1.it;
vincenzo.morra@unina.it

markedly different source ($^{87}Sr/^{86}Sr$ = 0.7031-0.7040; $^{143}Nd/^{144}Nd$ = 0.5127-0.5129; $^{206}Pb/^{204}Pb$ = 18.8-19.4), and crop out only in the southern part of the island. The less differentiated rocks of the two groups also show distinct trace element contents and ratios (e.g. Ba/Nb>14, Nb/U <38 and Ce/Pb <20 for the UPV; Ba/Nb<9, Nb/U >45 and Ce/Pb >24 for the RPV).

The transition from igneous cycles with orogenic (s.l.) to anorogenic (s.l.) geochemical features is relatively common throughout the entire circum-Mediterranean area; in other places this shift of chemical compositions has been related to «slab detachment» and/or the development of «slab window» processes. In this paper, to explain the geochemical differences between the OM and PQ volcanic products of Sardinia, we propose the involvement of different mantle sources: an asthenospheric mantle source slightly modified by subduction-related metasomatism for the OM rocks and a lithospheric mantle source strongly modified during ancient times (possibly during Hercynian orogenesis) for the great majority of the PQ volcanic rocks.

RIASSUNTO. — Durante il Cenozoico la Sardegna fu interessata da due grandi cicli magmatici; il primo durò dall'Oligocene al Miocene (ciclo OM; ~32-15 Ma), mentre il secondo iniziò nel Pliocene e continuò sino al Quaternario (ciclo PQ; ~5-0,1 Ma). I due cicli possono essere distinti sulla base di numerose osservazioni: le rocce OM affiorano quasi esclusivamente in una struttura di tipo graben che taglia la Sardegna da Nord a Sud (la cosiddetta *Fossa Sarda*), mentre le rocce PQ sono distribuite praticamente in tutti i settori dell'isola; da un punto di vista petrografico le rocce OM mostrano una tessitura tipicamente porfirica mentre le rocce PQ variano da debolmente porfiriche ad afiriche; le rocce del ciclo OM sono principalmente subalcaline (tholeiitiche e calcalcaline) e sono rappresentate per lo più da litotipi differenziati decisamente sovrassaturi in SiO_2 (daciti e rioliti prevalentemente in facies ignimbritica) con minori volumi di andesiti basaltiche ed andesiti ed ancor più rari basalti, mentre le rocce PQ sono per la maggior parte ad affinità alcalino-sodica (~80 % degli affioramenti) con più rari prodotti tholeiitici e transizionali (~20 %); rispetto alle rocce PQ, le rocce OM sono caratterizzate da contenuti più elevati in CaO, contenuti più bassi in TiO_2, Na_2O, HFSE and REE e da più alti valori dei rapporti La/Nb e Zr/Nb; da un punto di vista isotopico le rocce OM mostrano valori del rapporto $^{87}Sr/^{86}Sr$ sempre superiori a 0.7040, mentre le rocce PQ mostrano valori dello stesso rapporto generalmente intorno a 0,7044; i rapporti $^{143}Nd/^{144}Nd$ delle rocce OM (da 0,5127 a 0,5122) si sovrappongono ai valori delle rocce PQ (da 0,5129 a 0,5122); i valori del rapporto $^{206}Pb/^{204}Pb$ delle rocce OM (da 18,52 a 18,71) sono generalmente più elevati di quelli delle rocce PQ (da 17,5 a 19,42).

Da un punto di vista geochimico, le rocce appartenenti al ciclo OM presentano somiglianze con magmi generati in ambiente di tipo collisionale; le ipotesi più accreditate indicano le sorgenti di questi magmi nel cuneo di mantello sviluppatosi a partire dall'Oligocene in seguito alla subduzione verso ovest di litosfera oceanica (Mesogea?) al di sotto del margine continentale europeo. L'origine del ciclo PQ, invece, viene legata ai movimenti distensivi responsabili tra l'altro dell'apertura del Mar Tirreno come bacino di retroarco; le rocce PQ mostrano, da un punto di vista geochimico, analogie con i magmi generati in ambienti intraplacca.

Le rocce PQ possono essere divise in due gruppi: il primo (Unradiogenic Pb Volcanics = UPV) è caratterizzato da valori del rapporto isotopico di $^{87}Sr/^{86}Sr$ relativamente elevato (0,7043-0,7051), basso $^{143}Nd/^{144}Nd$ (0,5124-0,5126) e il più basso valore del rapporto $^{206}Pb/^{204}Pb$ mai riscontrato tra le rocce cenozoiche italiane e circum-mediterranee (17,36-18,07). Questo gruppo comprende la grande maggioranza delle rocce PQ (> 99% degli affioramenti) che affiorano nella Sardegna centrale e settentrionale. L'altro gruppo (Radiogenic Pb Volcanics = RPV), comprendente solo gli affioramenti nel settore meridionale dell'isola, mostra rapporti isotopici di Sr-Nd-Pb nettamente differenti ($^{87}Sr/^{86}Sr$ = 0,7031-0,7040; $^{143}Nd/^{144}Nd$ = 0,5127-0,5129; $^{206}Pb/^{204}Pb$ = 18,8-19,4). Le rocce più primitive dei due gruppi mostrano anche contenuti e rapporti tra elementi in traccia incompatibili molto diversi (es., Ba/Nb>14, Nb/U <38 e Ce/Pb <20 per le rocce UPV; Ba/Nb<9, Nb/U >45 e Ce/Pb >24 per le rocce RPV).

La transizione da un'attività magmatica con caratteristiche geochimiche «orogeniche» verso una con caratteristiche «anorogeniche» è relativamente comune nell'area circum-mediterranea; i processi più comunemente invocati per spiegare questa transizione sono lo «slab detachment» e/o lo «slab windows». In Sardegna viene invece proposta per ciascuno dei due cicli una genesi in sorgenti di mantello diverse: 1) mantello astenosferico leggermente modificato da fluidi rilasciati dalla litosfera oceanica in subduzione per i magmi del ciclo OM e 2) sorgente litosferica fortemente modificata da eventi metasomatici antichi (preferibilmente l'orogenesi ercinica) per la maggior parte dei magmi del ciclo PQ.

KEY WORDS: *Petrology, geochemistry, Sardinia, Alpine orogenesis, HIMU, EMI, EMII, geodynamics, Mediterranean Sea.*

INTRODUCTION

The volcanism of Sardinia is an important component of any comprehensive petrogenetic model for the circum-Tyrrhenian area, by virtue of its geographic position, the wide range of chemical composition of its igneous products and the wide time span of igneous activity (~32-0.1 Ma). With a few exceptions (e.g., Cioni *et al.*, 1982; Di Battistini *et al.*, 1990; Montanini *et al.*, 1994), until a few years ago, there were few detailed geochemical-petrological investigations of Sardinian igneous rocks, the only scientific papers being mostly published during the 1970s. More recently, an increasing amount of papers on igneous rocks became available (e.g., Morra *et al.*, 1994, 1997; Brotzu, 1997; Lustrino *et al.*, 1996, 2000, 2002; Gasperini *et al.*, 2000; Mattioli *et al.*, 2000; Downes *et al.*, 2001; Franciosi *et al.*, 2003). Based on these studies, a complex petrological scenario emerged, and a large number of hypotheses have been proposed in order to explain the origin of igneous activity in relation to Alpine geodynamics and the mantle sources characteristics of these magmas.

The island of Sardinia (Fig. 1) records two distinct igneous episodes during Oligocene-Miocene and Plio-Quaternary times. These cycles produced magmas with different petrographic, volcanological and geochemical characteristics. The Oligo-Miocene (hereafter OM) volcanic products (~32-15 Ma; Araña *et al.*, 1974; Savelli *et al.*, 1979; Montigny *et al.*, 1981; Beccaluva *et al.*, 1985; Morra *et al.*, 1994; Lecca *et al.*, 1997; Deino *et al.*, 2001; Speranza *et al.*, 2002; authors' unpublished data) are almost exclusively subalkaline, (Fig. 2) ranging from tholeiitic to calcalkaline with trace-elements subduction-related signatures (Morra *et al.*, 1994, 1997; Brotzu *et al.*, 1997a, b; Lonis *et al.*, 1997; Downes *et al.*, 2001; Franciosi *et al.*, 2003). On the other hand, the Plio-Quaternary (hereafter PQ) volcanic rocks (~5-0.1 Ma) are mildly to strongly alkaline (mostly with sodic character) to subalkaline (with tholeiitic affinity; Fig. 2), showing

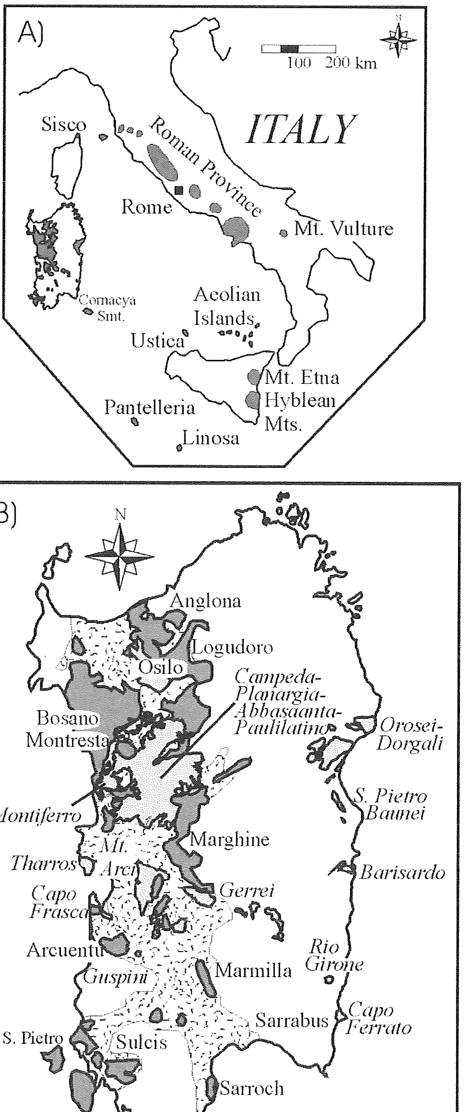

Fig. 1 – Simplified sketch maps of: A) Italian Plio-Quaternary Volcanic provinces; B) Sardinian igneous districts (in italics): Oligo-Miocene (with orogenic geochemical affinity; dark grey field) and Plio-Quaternary (with anorogenic geochemical affinity; light grey field). Modified from Lustrino *et al.* (2002).

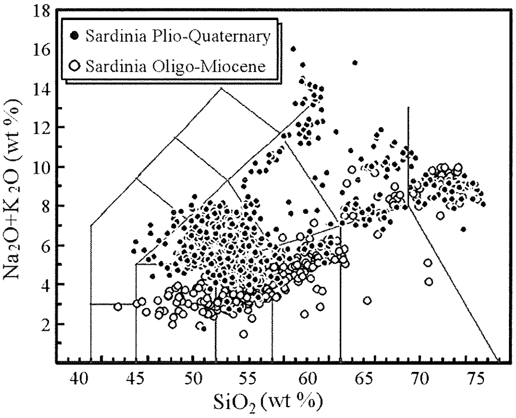

Fig. 2 – Total alkali vs. silica diagram (Le Bas *et al.*, 1986) for Oligo-Miocene (orogenic s.l.) and Plio-Quaternary (anorogenic s.l.) igneous rocks of Sardinia. References given in the text.

peculiar within-plate geochemical signatures (Lustrino *et al.*, 1996, 2000, 2002).

The study of the Cenozoic igneous rocks of Sardinia allows the investigation of the geochemical signature of this sector of the European sub-continental mantle, as well as the petrological evolution of the western Mediterranean area for several reasons: 1) the most mafic rocks of both igneous cycles have compositions akin to primitive melts (Morra *et al.*, 1997; Lustrino *et al.*, 2002; Franciosi *et al.*, 2003); 2) the PQ Sardinian volcanic rocks are often associated with mantle xenoliths that provide direct insights into the sub-continental lithospheric mantle composition (Lustrino *et al.*, 1999, 2004; Beccaluva *et al.*, 2001); 3) Sardinia was involved in two major tectonic events that reworked the European sub-continental mantle (Hercynian and Alpine orogenesis); 4) the transition from orogenic s.l. to anorogenic s.l. magmatism (a relatively common feature in many other circum-Mediterranean igneous provinces) can be investigated in detail.

REGIONAL GEOLOGICAL SETTING

The opening of the Mediterranean Sea during the Tertiary and the associated igneous activity is part of the Alpine orogenesis linked to the collision of Africa (Gondwana) towards Europe (Laurasia; e.g., Doglioni *et al.*, 1998; Rosenbaum *et al.*, 2002a). The circum-Mediterranean area is a geodynamically complex region characterized during the last 30 Ma by a magmatic activity with a wide range of chemical compositions, from strongly alkaline (with sodic to potassic and ultrapotassic character) to subalkaline (tholeiitic and calcalkaline; Wilson and Bianchini, 1999; Lustrino, 2000b; Peccerillo and Lustrino, 2004).

Up to lower Oligocene, the Sardinia-Corsica block was in continuity with the southern European continental margin (Provence, France). During upper Oligocene-lower Miocene times, the block started to rotate counter-clockwise and then moved eastwards as consequence of the opening of the Ligurian-Provençal back-arc basin (Vigliotti and Langenheim, 1995; Séranne, 1999; Speranza *et al.*, 2002). The formation of this basin is considered to be related to the subduction of African oceanic lithosphere (Ionian Sea; Catalano *et al.*, 2001; Speranza *et al.*, 2002) under the European continental margin toward the NNW (Beccaluva *et al.*, 1994 and references therein). All these tectonic movements are part of the larger framework of Alpine orogeny, developing from lower Cretaceous to the present (Rosenbaum *et al.*, 2002b). During the Eocene-early Oligocene, Alpine compressional stresses were followed by transtensive and extensional regimes (Hyppolite *et al.*, 1993; Carmignani *et al.*, 1994; Lecca *et al.*, 1997). The cause of this change from an overall compressional domain to the development of extensional basins some 30 Ma ago remains an unresolved question (Jolivet *et al.*, 1999); according to Rosenbaum *et al.* (2002b) back-arc extension in the western Mediterranean Sea was a result of slower convergence between Africa and Europe. These extensional movements were responsible for Oligocene rift system development in southern Europe and in Sardinia led to: 1) counter-clockwise rotation and eastward translation of the Sardinia-Corsica block, coeval with the opening of the Ligurian-Provençal and Balearic back-arc basins (Doglioni *et al.*, 1998; Gueguen *et al.*, 1998; Speranza *et al.*, 2002); 2) formation, within Sardinia, of an Oligo-Miocene rift system (the so-called *Fossa Sarda;* Sardinian Trough), a graben-like structure that crosses the whole Island from north to south.

«Orogenic» magmatic activity is associated with the opening of these back-arc basins in Spain, France, Sardinia and Ligurian-Provençal sea; the age of the igneous activity ranges from ~32 to ~15 Ma (Beccaluva *et al.*, 1985; Martì *et al.*, 1992; Morra *et al.*, 1994; Lecca *et al.*, 1997; Rollet *et al.*, 2002). The Sardinian magmatism occurs along and within the *Fossa Sarda,* and reached a climax of activity between 21 and 18 Ma (e.g., Lecca *et al.* 1997; Morra *et al.*, 1997; Deino *et al.*, 2001). The volcanic products are both subaerial and submarine, mainly consisting of dacitic to rhyolitic ignimbrites, andesite lava flows and, subordinately, basalts. The explosive and effusive products are interlayered and partially contemporaneous; plutonic rocks (mostly gabbros and diorites) are very rare. In S. Pietro and S. Antioco islands, as well as in the Sulcis mainland (SW Sardinia; Fig. 1), mildly peralkaline rhyolites (comendites) were also erupted during the final stages of the OM volcanic cycle (Araña *et al.*, 1974; Morra *et al.*, 1994).

During the Langhian (~15 Ma) the eastward translation of the Sardinia-Corsica block stopped (e.g., Speranza *et al.*, 2002). As a consequence, the opening of the Ligurian-Provençal and Balearic basins on the western side of Sardinia also terminated. The oceanization processes subsequently continued on the eastern side of Sardinia, with the opening of the Tyrrhenian Sea. The Sardinia-Corsica block can be thus considered as a continental lithospheric slice isolated during the extensional movements that produced a lithospheric boudinage (e.g., Carminati *et al.*, 1998; Gueguen *et al.*, 1998). The migration of the locus of extension from the Ligurian-Provençal to the Tyrrhenian basins has been considered a continuous process, without time gaps between the rifting episodes (e.g., Zarki-Jakni *et al.*, 2004).

Igneous activity in the embryonic western Mediterranean Sea did not stop: the youngest igneous rocks of the OM cycle of Sardinia (~15 Ma; SW Sardinia; Araña *et al.*, 1974; Morra *et al.*, 1994) are contemporaneous with the Sisco lamproite in NE Corsica (~15 Ma; Civetta *et al.*, 1978) that marks the first evidence of the Tyrrhenian Sea opening.

The Oligocene-lower Miocene marine sediments of the *Fossa Sarda*, formed as consequence of marine ingression caused by base-level drop, rift-related, vertical movements, were uplifted up to 700 m above sea level (e.g., Mt. Santo, Logudoro; Lecca *et al.*, 1997) during the middle-upper Miocene. According to Cavazza *et al.* (2001), the Sardinia-Corsica block uplifted about 2 km as a single block together with the Alpine Corsica thrust sheets during the late Early Miocene. The exact beginning and end of these vertical movements are not well constrained. Apatite fission track thermochronology suggests cooling of Hercynian and Alpine igneous and metamorphic units of Corsica mostly between ~30 and ~11 Ma. These data indicate relatively rapid cooling from > 120°C to surface temperatures associated with denudation; this has been alternatively related to: 1) base-level subsidence linked to rifting and continental break-up in the Ligurian-Provençal basin in the western Corsica and 2) ~14-11 Ma surface uplift (evidenced by Eocene shallow marine sediments at elevations up to 700 m) associated with Tyrrhenian Sea opening (Zarki-Jakni *et al.*, 2004).

The origin of the Sardinia-Corsica Miocene (-Pliocene?) block uplift remains highly debated. Only recently a model able to reconcile the vertical movements and the jump of tectono/magmatic waves from west to east of the Sardinia-Corsica block has been proposed (Doglioni *et al.*, 2004). According to these authors, the uplift is a consequence of the Ligurian-Provençal basin opening: the oceanization of this basin (occurred between ~21-15 Ma; Rollet *et al.*, 2002) depleted the upper mantle and resulted in a lightening of the residual mantle. This residual mantle, less dense than undepleted mantle, when displaced toward east would cause a mass deficit. Its relative buoyancy would result in an uplift of the crustal block (Doglioni *et al.*, 2004) as observed for other asymmetric oceanic rifts, characterized by the uplift of the continent to the east (e.g., Red Sea; Doglioni *et al.*, 2003).

In the western continental margin of the Tyrrhenian Sea, Plio-Quaternary extensional movements resulted in the development of a rift system (Campidano graben in SW Sardinia), N-S oriented fault system in the Sarrabus area (SE Sardinia) and anorogenic magmatism throughout the island.

In summary, the Oligocene-Quaternary tectonic evolution of Sardinia is as follows: middle Oligocene- lower Miocene (Aquitanian) subsidence (with ~1200 m total vertical movements) and marine ingression related to the formation of the *Fossa Sarda* rift system (and the Ligurian-Provençal basin formation); Miocene-(Pliocene?) uplift (up to 700 m vertical movement), followed by Plio-Quaternary subsidence and formation of the Campidano graben in SW Sardinia (associated with the formation of the Tyrrhenian Sea).

THE OLIGO-MIOCENE MAGMATIC ROCKS OF SARDINIA

Oligo-Miocene (~32-15 Ma) magmatic activity of Sardinia occurred in the central-western sector of island, almost exclusively along the *Fossa Sarda* (Fig. 1) and is mostly concentrated between ~21-18 Ma (Savelli *et al.*, 1979; Beccaluva *et al.*, 1985; Lecca *et al.*, 1997; authors' unpublished data). The climax of volcanic activity is coeval with the period of maximum extension and oceanic spreading of the Ligurian-Provençal basin (~21-16 Ma; Rollet *et al.*, 2002; Speranza *et al.*, 2002). The volcanic products of this cycle have mostly subalkaline affinity (both tholeiitic and calcalkaline); dacitic to rhyolitic ignimbrites are volumetrically the most common products, followed by andesitic, basaltic andesitic and, finally, basaltic lavas. These rocks crop out in northern (Anglona, Logudoro and Bosano districts), central (Marghine) and southern Sardinia (Arcuentu, Marmilla, Sarroch and Sulcis districts). Currently, most of the whole rock analyses available in the literature are concentrated on the basic-intermediate rock types (basaltic andesite to andesite), with few studies on the acid types (dacite to rhyolite).

A short summary of the most important OM igneous districts of Sardinia is reported below.

Anglona (~21-18 Ma). Andesitic lava domes with interbedded small ignimbritic horizons are overlain by volcaniclastics and pillow lavas of andesitic composition. A small microdioritic intrusive body (associated with a hydrothermal porphyry copper system) occurs in the Calabona area (Alghero; Giraud *et al.* 1979) and marks the beginning of the Cenozoic igneous activity in Sardinia (~32 Ma; Montigny *et al.* 1981). Above this, welded ignimbrites, small andesitic lava flows and ash/pumice deposits are present (Lecca *et al.*, 1997). In the Osilo area, andesitic horizons are associated with epithermal gold mineralization. There are no major and trace elements data, as well as isotopic measurements on the volcanic products of this district.

Logudoro-Bosano (~24-16 Ma). In this area at least four volcanic phases have been identified (Coulon, 1977; Lecca *et al.*, 1997). The oldest rocks consist of andesitic domes followed in the upper part by lava flows overlain by variably welded rhyolitic ash and pumice flow deposits and dacitic to rhyolitic lava domes. The youngest products are small andesitic and dacitic to rhyolitic intrusions into marine sediments of Langhian age. The least evolved effusive rocks only occur close to Sindia and Montresta towns (NW Sardinia). The volcanic sequence of Sindia (Lonis *et al.*, 1997) is made up of basalt to andesite lava domes and lava flows associated with local epiclastic breccias and ash flows. In the Montresta area the volcanic outcrops are mostly High Alumina Basalts (HAB; MgO < 7 wt %; Al_2O_3 > 16 wt %) and High Magnesia Basalts (HMB; MgO > 7 wt %; Al_2O_3 < 16 wt %), basaltic andesites and rare andesite with tholeiitic character are also found (Morra *et al.*, 1997; Franciosi *et al.*, 2003).

Marghine-Barigadu (~21-19 Ma). The central sector of Sardinia is characterized by sequences of andesitic lava flows followed by densely welded ignimbrites and, finally, by ash and pumice pyroclastic flows with variable degrees of welding. Major and trace element analyses are scarce; isotopic data are totally lacking.

Arcuentu (~30-17 Ma). The volcanic sequences of Arcuentu (SW Sardinia) are, from the bottom to the top: basaltic to andesitic domes and lava flows (~30-24 Ma), effusive and explosive products emplaced in submarine environments (~23-21 Ma), effusive and pyroclastic andesites (~21-18 Ma), and finally basaltic dykes and sills (~18-17 Ma; Assorgia *et al.*, 1984; Lecca *et al.*, 1997). This is the best studied OM district in terms of major and trace element, as well as Sr-Nd-Pb-O isotopic data (Brotzu *et al.*, 1997a; Downes *et al.*, 2001; Franciosi *et al.*, 2003).

Marmilla (~19-17 Ma). The volcano-sedimentary succession (~300 m thick) is mainly made up of pyroclastic units rarely interbedded at the top with andesitic lava flows (Lecca *et al.*, 1997). In southern Sardinia, primitive HMB pillow lavas have been recognized in the early Burdigalian volcano-sedimentary succession of the Villanovaforru area (Mattioli *et al.*, 2000; authors' unpublished data). Most of the volcanic activity of this district is associated with strong alteration and precious metal concentration (gold, copper, manganese) exploited for industrial purposes (e.g., Lustrino *et al.*, 2004).

Sarroch (~24-22 Ma). In the Sarroch district (southernmost Sardinia), pyroclastic and epiclastic andesitic breccias and conglomerates with subordinate basalts of calcalkaline affinity occur. Intrusive magmatic bodies of (gabbronoritic to gabbrodioritic in composition) and late-stage dykes have been also found (Conte, 1997). Only Sr isotopic compositions have been determined for this district (Conte, 1997).

Sulcis (~28-15 Ma). The Sulcis area is located in SW Sardinia outside the Sardinian Trough. The volcanic products can be grouped into a «lower» and an «upper» sequence. The lower sequence (~28-17 Ma) is made up of dioritic sub-volcanic bodies with associated porphyry copper mineralization, basaltic andesitic and andesitic lava domes and flows, with subordinate basalts and rarer pyroclastic and epiclastic breccias. The upper sequence (~18-15 Ma) consists of dacitic, rhyolitic and comenditic products, mainly ignimbrites. All together, the Sulcis volcanic rocks show an almost complete range of compositions from basalt to rhyolite with a SiO_2 gap from ~58 to ~66 wt % (Araña *et al.*, 1974; Morra *et al.*, 1994; Brotzu *et al.*, 1997a).

Neighbouring areas. High-K calcalkaline dacitic to rhyolitic ignimbrites of Burdigalian age (~19 Ma) have been reported by Ottaviani-Spella *et al.* (1996) from south Corsica (Balistra and Tre Paduli areas). These occurrences represent the northern continuation of the Miocene Sardinian ignimbrites and demonstrate that the Oligo-Miocene Sardinian arc extended northwards. To the NE, Burdigalian (~17.2-16 Ma) andesitic rocks dredged during the MARCO cruise along the western Corsican margin indicate arc-type volcanism. On the basis of trace element similarities between these dredged samples and Sardinian OM andesites, Rossi *et al.* (1998) proposed a link to the same subduction system. Isolated magnetic anomalies in the Ligurian sea have been interpreted as basaltic seamounts within an unroofed upper mantle (Rollet *et al.*, 2002).

Mascle *et al.* (2001) reported analyses of volcanic rocks dredged from a previously unknown ~12 Ma old submerged volcano, named Cornacya seamount, close to SE Sardinia, in the Tyrrhenian Sea. Although highly altered (LOI up to 23 wt %), these samples exhibit shoshonitic to lamproitic petrographic and geochemical features, roughly similar to the ~15 Ma old Sisco lamproite in NE Corsica. These two occurrences of Langhian shoshonitic to lamproitic melts are the first magmatic rocks related to the opening of the Tyrrhenian Sea (Mascle *et al.*, 2001).

In summary, dacitic to rhyolitic ignimbrites are the prevailing products of the OM igneous activity, followed by andesitic, basaltic andesitic and, finally, basaltic lavas with tholeiitic to calcalkaline character; basic plutonic rocks (gabbros and diorites) are very rare.

THE PLIO-QUATERNARY VOLCANIC ROCKS OF SARDINIA

The PQ magmatism is generally linked to normal faults related to the coeval opening of the Tyrrhenian Sea. In some cases, OM magmatic vents were re-activated during PQ times (e.g., Mt. Arci; Cioni *et al.*, 1982). From north to south, the PQ volcanic districts in the eastern sector of Sardinia are (Fig. 1):

Orosei-Dorgali and S. Pietro Baunei (~3.6-2.0 Ma). The rocks comprise alkaline lavas (~80 % of outcrops; mostly hawaiites plus rarer alkali basalts and mugearites) with fewer tholeiitic types (~20 % of outcrops; mostly basaltic andesites; Lustrino *et al.*, 2002). Some localities are characterized by the presence of abundant mantle xenoliths (Beccaluva *et al.*, 2001; authors' unpublished data).

Barisardo (no radiometric age available). This small outcrop (~5 km^2), located south of S. Pietro Baunei (central-eastern Sardinia), is made up of hawaiites/mugearites plus rarer transitional basaltic andesites (Lustrino, 1999; Lustrino *et al.*, 2000).

Rio Girone (no radiometric age available). This very small outcrop is represented by a ~50 m^2 neck of Na-basanite which exhumes small ultramafic mantle xenoliths (Lustrino *et al.*, 1996, 1999, 2000). This neck intrudes Paleozoic phyllites and is located along a NS fault running roughly parallel to the shore line.

Capo Ferrato (~5.9-5.0 Ma). This outcrop represents the earliest known volcanic activity of the PQ cycle of Sardinia. The main rock types are intermediate to evolved alkaline rocks (mugearites and trachytes; Brotzu *et al.*, 1975; Lustrino *et al.*, 2000; Petteruti-Lieberknecht *et al.*, 2003; authors' unpublished data).

In the central-western sector, the scenario is more complicated, with the presence of large volcanic complexes (Montiferro and Mt. Arci), widespread basaltic plains (Campeda-Planargia-Abbasanta-Paulilatino) and monogenic spatter/cinder cones (Logudoro). From north to south they are:

Logudoro (~3.1-0.1 Ma). The northernmost outcrops of the PQ volcanic cycle of Sardinia are also the youngest ones (as young as 0.1 Ma). This district is mostly made up of small central vents and cinder-spatter cones outcropping over an area of ~500 km^2 (Beccaluva *et al.*, 1976; Lustrino, 1999; Gasperini *et al.*, 2000; Lustrino *et al.*, 2000; Petteruti-Lieberknecht *et al.*, 2003).

Campeda-Planargia-Abbasanta-Paulilatino basaltic plains (~3.1-2.0 Ma). These basic to intermediate lava flows represent the largest PQ volcanic plateaux in Sardinia (~850 km^2). These volcanic rocks, partially covering other volcanic complexes (Montiferro, to the west) and cinder cones (Logudoro, to the north), include tholeiitic (basaltic andesites) and mildly alkaline lavas (hawaiites, mugearites; Beccaluva *et al.*, 1975; Lustrino, 1999; Lustrino *et al.*, 2000).

Montiferro (~3.9-1.6 Ma). This volcanic complex (~400 km^2) is made up of basic to intermediate (basanites, hawaiites, mugearites) and differentiated products (trachytes, phonolites), occurring mainly as lava flows and domes with a total thickness up to 300 meters. The less differentiated alkaline rocks entrain mafic and ultramafic xenoliths (both of mantle and cumulus origin) as well as crustal xenoliths (Di Battistini *et al.*, 1990; Lustrino, 1999; Lustrino *et al.*, 2000; Beccaluva *et al.*, 2001; authors' unpublished data).

Gerrei (~3.8-2.1 Ma). The volcanic rocks of this district (central-southern Sardinia) are mostly basaltic andesites and hawaiites (Lustrino *et al.*, 1996, 2000; Lustrino, 2000a).

The alkaline rocks commonly host centimetric to decimetric mantle xenoliths (Lustrino *et al.*, 1999).

Capo Frasca-Tharros (no radiometric age available). These are small outcrops at the southern and northern tips, respectively, of the Oristano Gulf (central-eastern Sardinia). The rocks are basaltic andesites with tholeiitic affinity (Lustrino, 1999; Lustrino *et al.*, 2000; Petteruti-Lieberknecht *et al.*, 2003). In the Capo Frasca area, the PQ basaltic andesites overly OM volcanic rocks (authors' unpublished data).

Mt. Arci (~3.8-2.6 Ma). This is a volcanic complex located along the north-eastern side of the Campidano graben, with abundant dacitic to rhyolitic lava flows (Beccaluva *et al.*, 1974; Cioni *et al.*, 1982; Montanini *et al.*, 1994; Lustrino, 1999; Petteruti-Lieberknecht *et al.*, 2003). Among the PQ volcanic rocks of Sardinia, the Mt. Arci products show two peculiarities: 1) this is the only place where felsic SiO_2-oversaturated volcanic rocks are present and 2) the complex is made up of volcanic rocks belonging both to OM and PQ volcanic cycles.

Guspini (no age available). This is a very small alkaline neck (about 100 m^2) of hawaiitic composition outcropping on the western branch of the Campidano Graben (Lustrino *et al.*, 2000).

In summary, the PQ volcanic rocks have mainly basic to intermediate compositions; however, differentiated products (both SiO_2-oversaturated and SiO_2-undersaturated) also occur. Both subalkaline and alkaline magma types are present. The alkaline rocks are mildly to strongly alkaline mainly with sodic affinity, although some slightly potassic types are also found (Lustrino *et al.*, 1996). The subalkaline rocks are less primitive than their alkaline counterparts and show a tholeiitic character (Lustrino, 1999; Lustrino *et al.*, 2002).

DISCUSSION

The following discussion of the petrogenesis and geodynamic significance of the OM and PQ magmatic cycles in Sardinia is divided in two parts: the first is devoted to identifying similarities and differences between the products of the two cycles in terms of major and trace elements as well as radiogenic and stable isotopic systematics. In the second part, particular attention is paid to constrain the causes of the geochemical peculiarities of the products belonging to these two cycles.

Similarities and differences between the OM and PQ igneous rocks of Sardinia.

The OM and PQ igneous rocks of Sardinia are characterized by a wide chemical spectrum of composition, from basic (with very few ultrabasic) to acid types (Fig. 2; Table 1 and 2). A complete list of whole rock major and trace element as well as isotopic data of the Cenozoic igneous rocks of Sardinia can be requested to the first author. The first striking difference between the two groups is the prevailing alkaline character of the PQ rocks compared with the subalkaline composition of the OM products. Moreover, among the PQ rocks, two different liquid lines of descent can be recognized (Fig. 2): one evolving towards strongly SiO_2-undersaturated evolved differentiates (phonolites of Montiferro), the other towards slightly SiO_2-undersaturated to SiO_2-saturated compositions (trachytes of Capo Ferrato and Mt. Arci). The few strongly SiO_2-oversaturated felsic PQ rocks (dacite and rhyolite of Mt. Arci) show petrographic, geochemical and isotopic characteristics either of mixing products between mantle melts and crustal material or pure crustal anatectic partial melts, rather than differentiated products of tholeiitic liquids (Cioni *et al.*, 1982; Montanini *et al.*, 1994; Petteruti-Lieberknecht *et al.*, 2003).

The OM and PQ igneous rocks of Sardinia can be distinguished in Harker-type variation diagrams using MgO as a differentiation index (Fig. 3). Strong differences between the two groups exist for TiO_2, Na_2O, K_2O and P_2O_5 (more abundant in the PQ than OM rocks) and

TABLE 1

Major and trace elements and Sr-Nd-Pb isotopic ratios of representative OM samples.
Rock types: B = basalt; HMB = high-MgO basalt; HAB = high Al_2O_3 *basalt; BA = basaltic andesite; A = andesite; Com = comendite. Sources: (D 76) = Dostal et al., 1976; (M 94) = Morra et al., 1994; (B 97a) = Brotzu et al., 1997a; (B 97b) = Brotzu et al., 1997b; (L 97) = Lonis et al., 1997; (M 97) = Morra et al., 1997; (D 01) = Downes et al., 2001; (F 03) = Franciosi et al., 2003.*

Sample	KB 24	KB13	SD1	SIN43	V 1199	ST46	AR280	MU-36IG	1531
Locality	Montresta	Montresta	Sindia	Sindia	Narcao	Arcuentu	Arcuentu	Sulcis	Bosano
Source	M 97-F 03	M 97-F 03	L 97	L 97	B 97a	D 01	B 97b-F 03	M 94	D 76
Type	B (HMB)	B (HMB)	B (HAB)	A	BA	B (HMB)	B (HMB)	Com	B (HAB)
SiO_2	47.5	47.2	49.1	60.6	53.3	51.3	51.7	73.4	45.1
TiO_2	0.79	0.77	1.02	0.69	1.00	0.58	0.76	0.28	1.25
Al_2O_3	15.2	15.4	18.2	16.8	18.1	14.6	15.4	13.1	18.4
Fe_2O_3	10.5	10.8	11.1	7.0	10.3	10.6	9.87	2.95	13.0
MnO	0.19	0.19	0.20	0.12	0.16	0.18	0.18	0.08	0.18
MgO	11.1	11.0	6.95	2.88	3.55	10.1	9.38	0.17	6.76
CaO	11.9	11.8	10.2	6.10	9.82	10.0	10.15	0.16	12.1
Na_2O	2.15	2.14	2.19	2.75	2.47	1.89	1.98	4.88	2.32
K_2O	0.45	0.45	0.92	2.91	1.16	0.59	0.55	5.03	0.67
P_2O_5	0.26	0.28	0.22	0.17	0.22	0.09	0.09	0.02	0.18
LOI	0.32	0.32	1.63	1.51	1.91	0.72	1.09	0.63	1.62
Mg#	0.70	0.69	0.58	0.47	0.44	0.67	0.68	0.11	0.53
V	315	309	324	119	224	265	255	5	-
Cr	793	756	19	-	24	268	701	7	-
Co	53.7	52.7	-	-	23	-	36.4	-	-
Ni	229	220	16	7	21	148	116	-	-
Rb	7.13	7.78	16	95	50	18.1	13.3	210	24
Sr	450	450	513	395	423	193	192	21	495
Y	15.5	16.6	20	25	24	15.4	17.5	54	-
Zr	38.1	35.2	67	178	138	37	50.4	633	-
Nb	1.97	1.85	6	10	5	1.8	2.38	77	-
Cs	0.08	0.15	-	-	-	-	0.36	-	-
Ba	49.1	46.2	196	493	551	128	153	179	-
La	4.20	4.53	15.17	29.85	21.40	4.60	6.55	62.00	7.50
Ce	10.5	11.2	32.7	59.7	56.1	11.4	14.1	27.5	17.7
Pr	1.68	1.84	-	-	-	-	1.92	-	-
Nd	7.93	9.18	18.34	26.66	20.00	6.40	7.91	54.00	12.50
Sm	2.26	2.59	4.51	5.44	6.62	1.79	2.20	11.30	3.15
Eu	0.78	0.84	1.35	1.33	1.29	0.61	0.78	0.71	1.04
Gd	2.34	2.49	3.72	4.49	6.42	1.84	2.58	9.21	3.71
Tb	0.38	0.46	-	-	-	-	0.43		0.63
Dy	2.44	2.84	3.56	3.99	2.33	-	2.91	9.17	-
Ho	0.58	0.64	-	-	-	-	0.60		0.74
Er	1.42	1.57	1.82	2.31	2.03	-	1.55	4.43	-
Tm	0.25	0.27	-	-	-	-	0.24		-
Yb	1.43	1.55	1.90	2.46	2.68	1.44	1.76	4.95	1.94
Lu	0.25	0.28	0.29	0.42	0.37	0.27	0.28	0.69	0.30
Hf	1.13	1.14	-	-	-	1.10	1.42	-	-
Ta	0.14	0.13	-	-	-	0.07	0.17	-	-
Pb	1.80	1.95	6	14	-	2.80	4.00	12	-
Th	0.54	0.63	4	15	-	2.20	1.11	-	-
U	0.13	0.12	-	-	-	0.22	0.22	-	-
$^{87}Sr/^{86}Sr$	0.70414	0.70426	0.70519	0.70592	0.70628	0.70538	0.70625	0.70669	0.70440
$^{143}Nd/^{144}Nd$	0.51274	0.51271	-	-	-	0.51269	0.51260	-	-
$^{206}Pb/^{204}Pb$	18.703	18.707	-	-	-	-	18.609	-	-
$^{207}Pb/^{204}Pb$	15.631	15.644	-	-	-	-	15.651	-	-
$^{208}Pb/^{204}Pb$	38.408	38.663	-	-	-	-	38.697	-	-

TABLE 2

Major and trace elements and Sr-Nd-Pb isotopic ratios of representative PQ samples.
Rock types: Alk B = Alkali basalt; BSN = basanite; BA = basaltic andesite; H = Hawaiite; M = mugearite; R = rhyolite; T = trachyte; TD = trachydacite. Sources: (M 94) = Montanini et al., 1994; (G 00) = Gasperini et al., 2000; (L 00) = Lustrino et al., 2000; (L 02) = Lustrino et al., 2002.

Sample	MGV76	MGV89	ALP6	MGV249	BL 3	LOG 1	A196	A25	CF
Locality	Orosei Dorgali	Orosei Dorgali	Rio Girone	Guspini	Logudoro	Logudoro	Mt. Arci	Mt. Arci	Capo Ferrato
Source	L 00	L 02	L 00	L 00	G 00	G 00	M 94	M 94	L 00
Type	Alk B	BA	BSN	H	H	M	TD	R	T
SiO_2	48.0	52.7	45.8	49.3	49.2	54.8	69.1	74.7	61.4
TiO_2	1.76	1.86	3.13	3.12	2.34	2.15	0.58	0.11	0.89
Al_2O_3	15.7	16.9	15.2	15.8	16.4	16.2	14.8	14.1	16.8
Fe_2O_3	10.2	11.0	11.7	11.4	10.3	9.16	3.36	1.44	6.68
MnO	0.14	0.14	0.16	0.14	0.14	0.11	0.04	0.05	0.12
MgO	10.9	3.60	7.55	5.03	7.93	4.38	1.11	0.08	1.26
CaO	8.49	8.77	10.4	8.58	7.40	5.98	1.83	0.62	3.41
Na_2O	3.61	3.42	3.49	3.46	3.29	4.23	4.18	3.80	4.81
K_2O	0.82	1.31	2.23	2.48	2.43	2.27	4.73	5.05	4.22
P_2O_5	0.38	0.30	0.39	0.77	0.56	0.63	0.20	0.09	0.37
LOI	1.59	1.46	1.22	1.23	1.41	0.61	0.21	0.40	2.18
Mg#	0.706	0.424	0.592	0.499	0.634	0.518	0.427	0.112	0.298
V	192	165	251	228	165	147	31	-	29
Cr	427	279	212	152	195	141	33	3	-
Co	52	39	44	39	44	35	-	-	6
Ni	298	168	126	87	125	78	20	5	-
Rb	21.2	21	49	57	51.8	48.8	161	227	97
Sr	690	536	907	902	870	933	234	25	302
Y	17	18	28	24	19	20	30	35	42
Zr	159	134	223	260	242	251	222	99	507
Nb	31	20	70	72	51	45	28	44	77.3
Cs	0.81	0.51	1.55	1.45	0.71	0.54	-	-	0.68
Ba	648	507	528	620	1037	882	704	131	1046
La	26.51	20.35	47.06	49.28	46.00	41.50	-	19.60	67.41
Ce	52.0	39.4	96.4	95.5	87.0	82.7	-	46.7	130.4
Pr	6.16	4.71	12.14	10.80	9.96	9.78	-	-	14.99
Nd	25.17	19.81	46.58	47.86	39.60	41.50	-	20	58.13
Sm	4.87	4.37	8.27	9.37	8.09	8.77	-	6.03	10.74
Eu	1.63	1.57	2.53	2.85	2.44	2.63	-	0.38	2.81
Gd	4.36	4.42	7.02	7.39	6.22	6.70	-	5.25	9.30
Tb	0.60	0.60	1.01	0.94	0.79	0.85	-	-	1.43
Dy	3.22	3.30	5.66	5.16	4.12	4.11	-	5.30	7.84
Ho	0.55	0.66	0.88	0.89	0.69	0.72	-	-	1.48
Er	1.47	1.59	2.26	2.38	1.74	1.81	-	2.61	4.00
Tm	0.20	0.23	0.35	0.30	0.20	0.22	-	-	0.64
Yb	1.16	1.36	1.97	1.89	1.36	1.41	-	2.32	3.97
Lu	0.18	0.22	0.30	0.27	0.21	0.17	-	-	0.61
Hf	3.46	3.31	4.80	6.04	5.32	5.31	7.90	4.20	11.77
Ta	2.05	1.41	4.51	5.01	3.57	2.89	3.30	3.00	5.51
Pb	3.05	4.01	4.00	3.36	4.90	6.80	23	37	11.77
Th	3.39	2.93	5.91	6.31	7.55	5.75	17	16	14.94
U	0.79	0.64	1.30	1.58	1.25	0.92	4.40	6.80	3.48
$^{87}Sr/^{86}Sr$	0.70442	0.70453	0.70401	0.70315	0.70423	0.70469	0.70597	0.71529	0.70487
$^{143}Nd/^{144}Nd$	0.51257	0.51254	0.51285	0.51289	0.51251	0.51240	0.51219	0.51221	0.51271
$^{206}Pb/^{204}Pb$	17.860	17.738	19.230	19.422	17.757	17.548	-	-	18.840
$^{207}Pb/^{204}Pb$	15.596	15.531	15.640	15.665	15.601	15.549	-	-	15.657
$^{208}Pb/^{204}Pb$	37.942	37.894	39.100	39.135	37.917	37.650	-	-	38.977

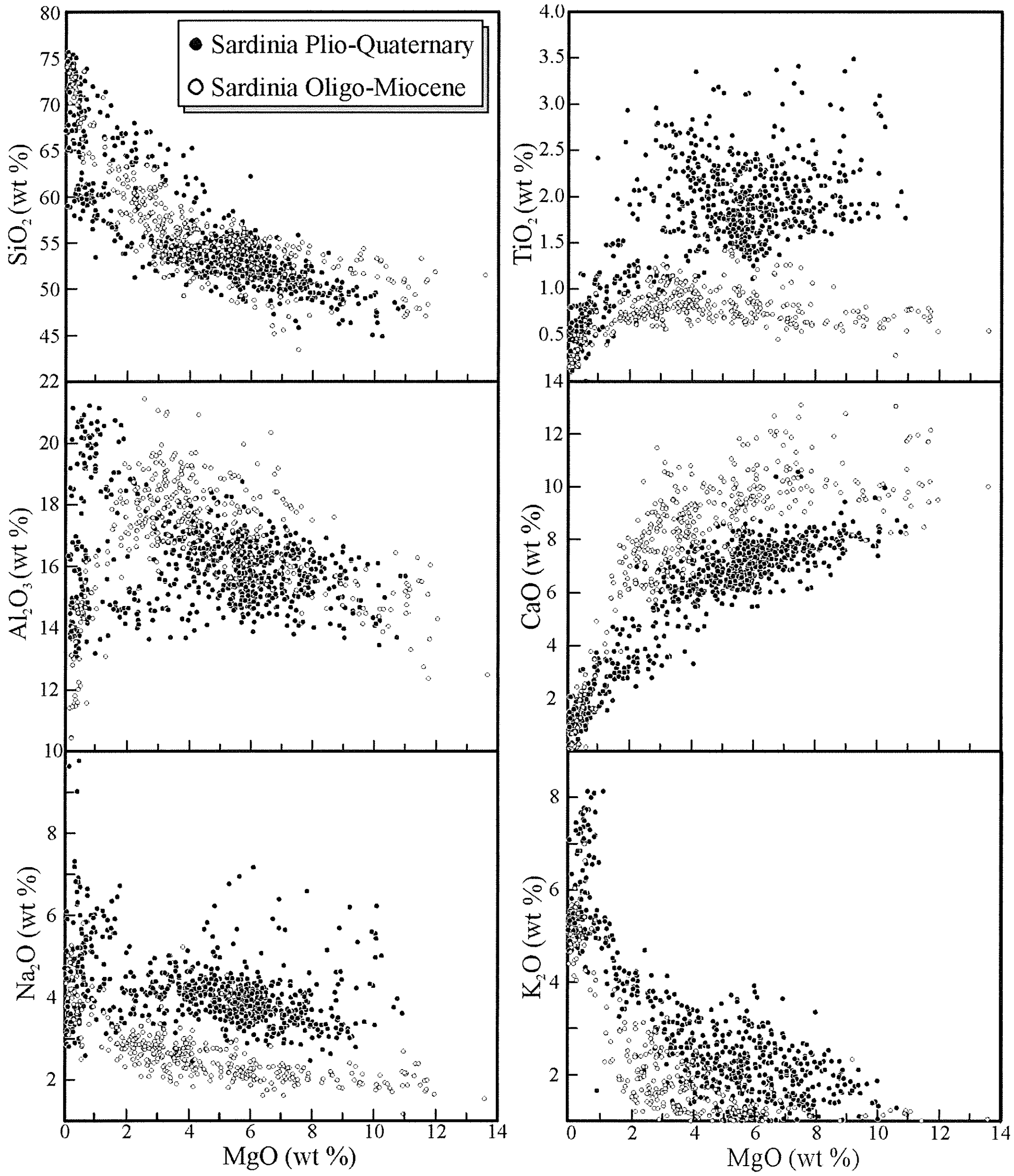

Fig. 3 – Selected major elements vs. MgO variation diagrams for Oligo-Miocene (orogenic s.l.) and Plio-Quaternary (anorogenic s.l.) igneous rocks of Sardinia. References given in the text.

in CaO (more abundant in the OM than PQ rocks) for a given MgO.

The transition elements Sc, V and Cu are more enriched in the OM compared to the PQ rocks, whereas Co is depleted; Cr largely overlaps in the two groups, with the most mafic OM rocks (MgO > 6 wt %) being characterized by generally higher Cr than the PQ group. Ni and Zn are always lower in the OM rocks compared to PQ products. All these elements

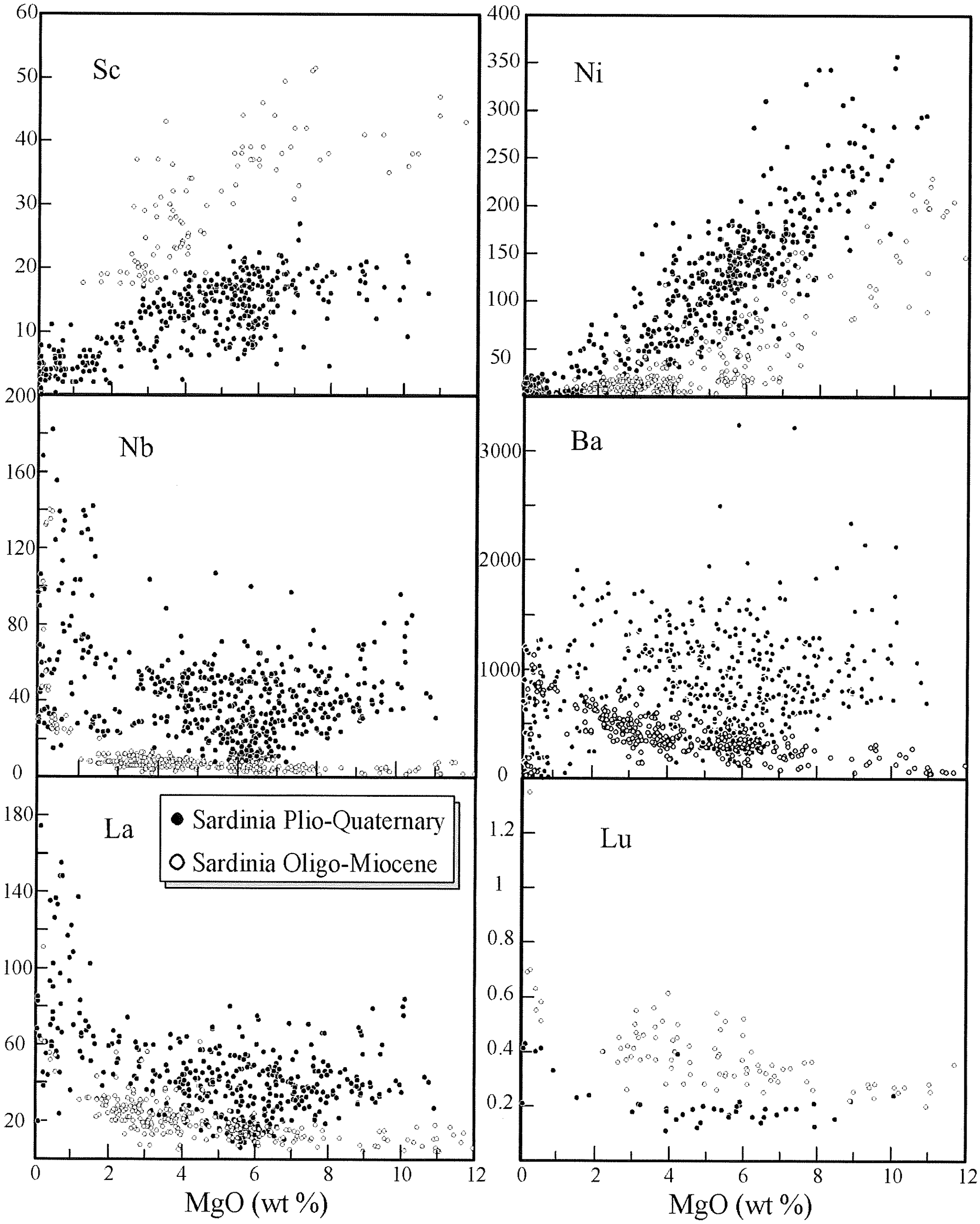

Fig. 4 – Selected transition (Sc and Ni), high field strength (Nb), large ion litophile (Ba) and rare earth elements (La and Lu) vs. MgO variation diagrams for Oligo-Miocene (orogenic s.l.) and Plio-Quaternary (anorogenic s.l.) igneous rocks of Sardinia. References given in the text.

are correlated with MgO, albeit with considerable scatter (Fig. 4).

Large Ion Lithophile Elements (LILE), such as Sr and Ba, are much more enriched in the PQ rocks compared to the OM group; on the other hand, Rb shows a similar concentration range. The OM rocks show almost constant Sr values down to 4 wt % MgO, followed by a slight increase and a final decrease, whereas Ba and Rb are negatively correlated with MgO. The PQ samples show significant scattering of LILE, particularly evident for Sr (not shown) and Ba (Fig. 4).

High Field Strength Elements (HFSE), Nb, Ta, Hf and Zr (and Ti) are systematically higher in the PQ rocks compared to the OM group; only Y shows the same abundance. The OM rocks with MgO > 2 wt % show relatively uniform HFSE content, with very low concentration of Nb (< 13 ppm), Zr (< 200 ppm) Hf (< 5 ppm) and Ta (< 0.8 ppm), with slight negative correlation with MgO. The PQ rocks with MgO > 2 wt % show a much wider spread of compositions of the same elements (Nb ~10-70 ppm; Zr ~95-350 ppm; Hf ~3-8 ppm; Ta ~0.5-4 ppm). Y shows limited variation (from ~15 to ~30 ppm for both groups with MgO between 2 and 12 wt %; not shown).

Rare Earth Elements (REE) show a complex behaviour: the light REE (LREE; from La to Sm) are more enriched in the PQ than in the OM rocks; the middle REE (MREE; from Eu to Dy) largely overlap between the two groups; the heavy REE (HREE; from Er to Lu) are more enriched in the OM samples compared to the PQ rocks. OM rocks show weak negative correlation between all the REE and MgO, whereas such a correlation can be seen in the PQ rocks for LREE only; MREE (not shown) and HREE in PQ rocks are almost constant and with subtle variation (Fig. 4).

The PQ rocks with MgO > 4.5 wt% show relatively uniform chondrite-normalized REE patterns, with minimum variation among the various districts (Fig. 5). We have chosen to filter our database of PQ rocks (more than 800 analyses) at values > 4.5 wt% MgO in order to include also the tholeiitic rocks (characterized by lower MgO compared to alkaline lavas; Lustrino, 1999; Lustrino *et al.*, 2002). $(La/Lu)_N$ ranges from ~7.4 to ~31.8 and shows correlation with the alkalinity of the rock. Eu/Eu* ranges from around 1 to slightly positive values (Eu/Eu* from ~0.95 to ~1.20). The OM rocks show a larger spread of data, with chondrite-normalized REE patterns ranging from nearly flat [$(La/Lu)_N$ from 1.7 to 2.2 in Capo Frasca and Montresta] to slightly LREE-enriched [$(La/Lu)_N$ up to 4.7 in Arcuentu]. Negative Eu anomalies are evident in almost all the samples (Eu/Eu* from 1.05 to 0.67, with > 95% of samples with Eu/Eu* < 1; Fig. 5). The most striking feature shown in Fig. 5 is a crossing chondrite-normalized REE pattern between PQ and OM igneous rocks, with PQ rocks having higher LREE and lower HREE than OM rocks.

Primitive mantle-normalized incompatible trace element diagrams for the less evolved (MgO > 4.5 wt %) PQ rocks belonging to the UPV group of Lustrino *et al.* (2000) are shown in Fig. 6a. This group (UPV = Unradiogenic Pb Volcanics) represents the great majority of the PQ rocks (> 99% of outcrops) and is present in central-northern Sardinia. Some common trace element key features are (Fig. 6a): a) positive peaks of Ba, Sr, Pb and Y; b) absence of positive peaks at Nb-Ta, as instead observed for the other circum-Mediterranean Cenozoic anorogenic igneous rocks (Lustrino, 2003). The southernmost PQ samples, by far less abundant than the UPV, are named RPV (Radiogenic Pb Volcanics) by Lustrino *et al.* (2000). These rocks (outcropping in only three small localities) show very different incompatible trace element patterns (Fig. 6b): the Rio Girone basanite and Guspini hawaiite show HIMU-OIB-like patterns with positive peaks for Nb-Ta and no Ba-Pb peaks, although with less marked K negative anomalies compared to typical HIMU-OIBs (e.g., Hofmann, 1997). The Ba-Sr-Eu troughs of the other RPV sample (Capo Ferrato; not shown) are related to the most differentiated character of this sample (mugearite) and suggest feldspar removal.

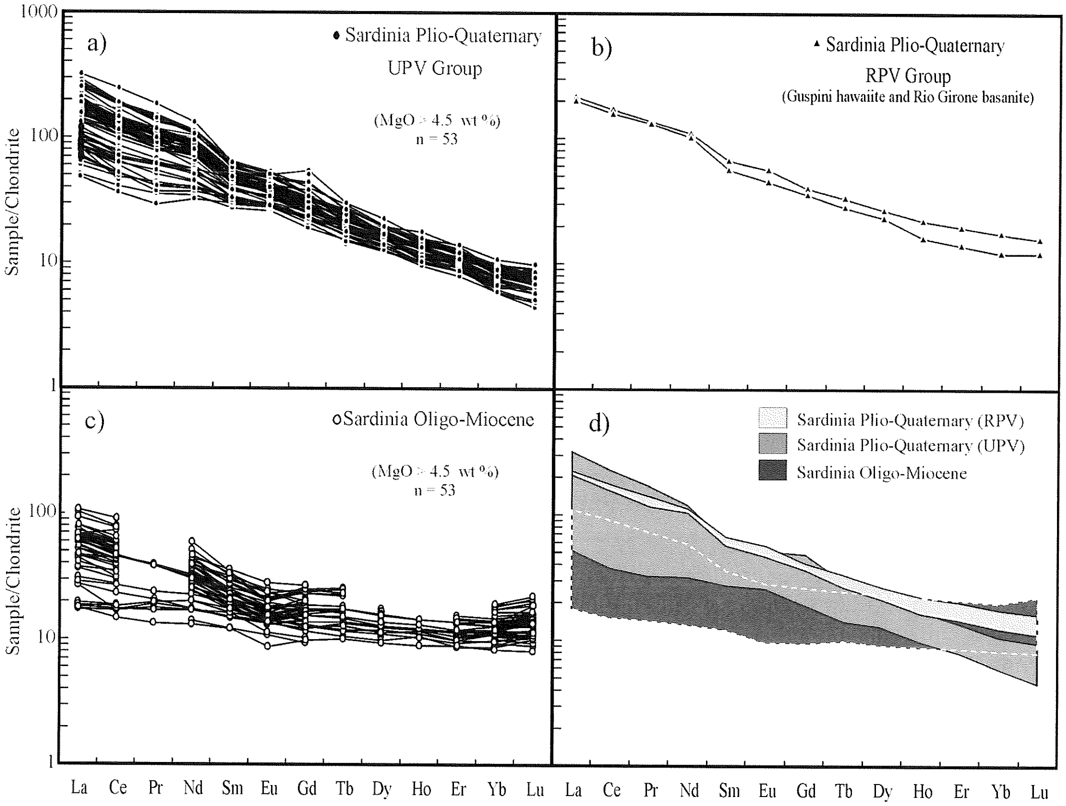

Fig. 5 – Chondrite-normalized REE patterns for: a) Plio-Quaternary rocks (UPV group of Lustrino *et al.*, 2000); b) Plio-Quaternary rocks (RPV group of Lustrino *et al.*, 2000); c) Oligo-Miocene rocks; d) fields of the three groups put together (very light grey : RPV group; light grey: UPV group; dark grey: OM rocks). Normalization factors after Sun and McDonough (1989).

Primitive mantle-normalized diagrams for the less evolved (MgO > 4.5 wt %) OM rocks (Fig. 6c) show patterns typical of magmas emplaced in collisional tectonic settings and/or magmas that experienced upper crustal contamination at shallow depths: a) troughs at Nb-Ta with values as low as 1.5 times primitive mantle (Capo Frasca); b) peaks for Pb (with values as high as 200 times primitive mantle). The OM rocks do not show the strong LILE enrichment seen in many other subduction-related igneous rocks, but share some geochemical similarities with Aeolian islands basic lavas (e.g., De Astis *et al.*, 2000).

Sr isotope data for OM igneous rocks have been available in literature sources since 1970s (e.g., Dupuy *et al.*, 1974), but Nd, O and, in particular, Pb isotope data are still scarce. Initial $^{87}Sr/^{86}Sr$ ranges from 0.70399 to 0.71127, with only 7 analyses out of 74 having $^{87}Sr/^{86}Sr < 0.705$ (Dupuy *et al.*, 1974; Dostal *et al.*, 1976; Morra *et al.*, 1994, 1997; Brotzu *et al.*, 1997a; Conte, 1997; Lonis *et al.*, 1997; Downes *et al.*, 2001; Franciosi *et al.*, 2003; authors' unpublished data). The first Nd and O isotope data on OM rocks were reported by Downes *et al.* (2001) on Arcuentu lavas, while Pb-isotope data were reported by Caron and Orgeval (1996) and Franciosi *et al.* (2003) on andesites and HMBs from various localities.

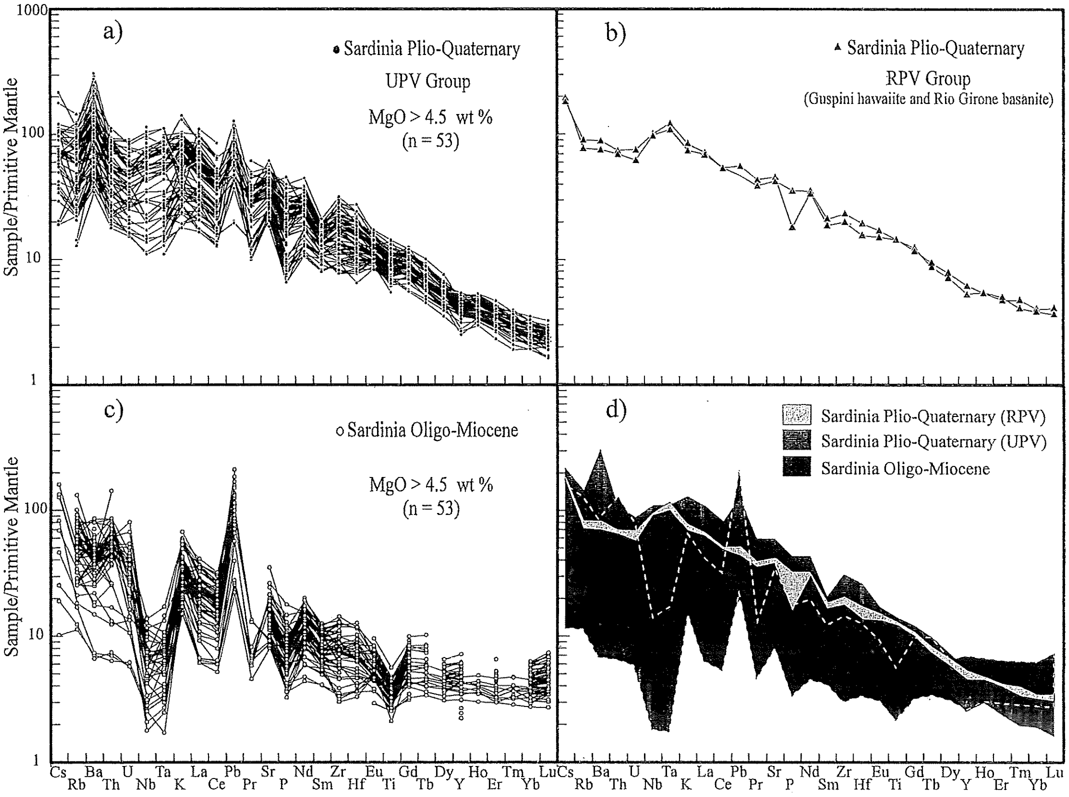

Fig. 6 – Primitive mantle-normalized diagrams for the most mafic (MgO > 4.5 wt %) samples of: a) Plio-Quaternary rocks (UPV group); b) Plio-Quaternary rocks (RPV); c) Oligo-Miocene rocks; d) fields of the three groups put together (very light grey : RPV group; light grey: UPV group; dark grey: OM rocks). Normalization factors after Sun and McDonough (1989).

The $^{143}Nd/^{144}Nd$ isotopic ratios of the Arcuentu volcanic rocks range from 0.51270 (HMB) to 0.51218 (andesite); Montresta HMBs have more radiogenic $^{143}Nd/^{144}Nd$, ranging from 0.51274 to 0.51271; OM rocks from Marmilla (central Sardinia) plot within the range defined by Arcuentu and Montresta samples (0.51268-0.51229; authors' unpublished data; Fig. 7a). The most mafic OM samples (Montresta and Arcuentu HMBs and HABs) cluster in a restricted area, partially overlapping the RPV compositions: $^{87}Sr/^{86}Sr$ ranges from 0.7040-0.7054 and $^{143}Nd/^{144}Nd$ cluster around ~0.5127. Also in this case, many Sr-Nd isotopic similarities between the mafic OM rocks and the mafic Aeolian Islands products do exist. For the remaining OM rocks, AFC (Assimilation and Fractional Crystallization) processes are invoked.

$^{87}Sr/^{86}Sr$ isotopic ratios of the less evolved PQ volcanic rocks (UPV group) range from 0.7031 to 0.7054, but most samples cluster near 0.7044±2 (Fig. 7a). The dacites and rhyolites of Mt. Arci are characterized by strongly radiogenic $^{87}Sr/^{86}Sr$ isotopic compositions (0.7052-0.7155; Montanini *et al.*, 1994; authors' unpublished data), suggesting a strong crustal involvement during their evolution. The few RPV samples (Rio Girone, Guspini and Capo Ferrato) plot towards lower $^{87}Sr/^{86}Sr$ ratios (0.7031-0.7044). The $^{143}Nd/^{144}Nd$ isotopic ratios show a much greater range for

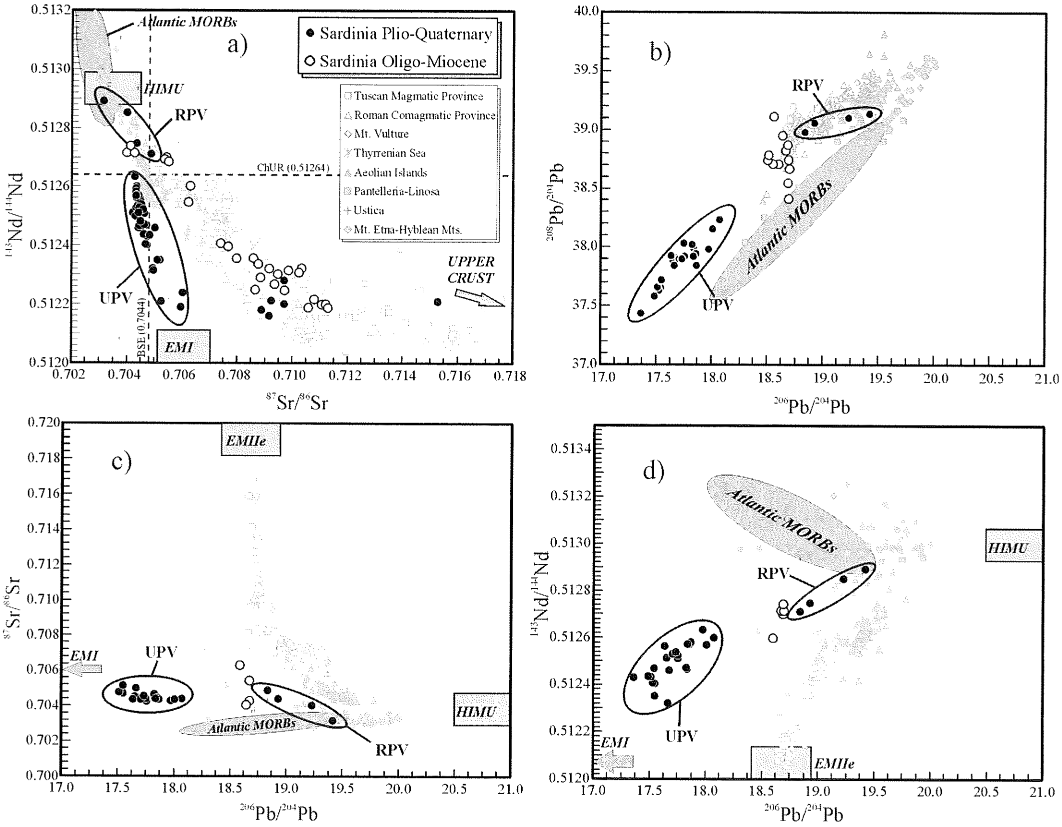

Fig. 7 – $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ (a), $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ (b), $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ (c), $^{143}Nd/^{144}Nd$ vs. $^{206}Pb/^{204}Pb$ (d) diagrams for Oligo-Miocene (orogenic s.l.) and Plio-Quaternary (anorogenic s.l.) igneous rocks of Sardinia. Fields of other Plio-Quaternary volcanic rocks from Circum-Tyrrhenian area are shown for comparison (references in Peccerillo and Lustrino, 2004). HIMU = HIgh MU (MU = μ = $^{238}U/^{204}Pb$) = Zindler and Hart (1986); EMI (Enriched Mantle type I) = Lustrino and Dallai (2004); EMIIe (Enriched Mantle type II enriched in Sr) = Peccerillo and Lustrino (2004); Atlantic MORBs field = petdb database (http://petdb.ldeo.columbia.edu/petdb/enterdatabase.htm).

the less differentiated products. In particular, the RPV samples are characterized by a much more radiogenic Nd isotopic composition ($^{143}Nd/^{144}Nd$ from 0.51289-0.51271) compared to the great majority of the PQ rocks (UPV group; $^{143}Nd/^{144}Nd$ from 0.51263-0.51219; Cioni *et al.*, 1982; Lustrino, 1999; Gasperini, 2000; Lustrino *et al.*, 2000, 2002; Petteruti-Lieberknecht *et al.*, 2003; authors' unpublished data; Fig. 7). The unradiogenic $^{143}Nd/^{144}Nd$ isotopic compositions (0.51228-0.51216) of the Mt. Arci dacites and rhyolites confirm upper crustal involvement in their genesis. The UPV and RPV groups define a nearly linear trend in Sr-Nd isotopic space from typical values of HIMU-OIB magmas (i.e., $^{87}Sr/^{86}Sr$ ~ 0.703, $^{143}Nd/^{144}Nd$ ~ 0.5129; RPV group) to typical values of EMI-type end-member (i.e., $^{87}Sr/^{86}Sr$ ~ 0.706, $^{143}Nd/^{144}Nd$ ~ 0.5122; UPV group) as also evidenced by Lustrino and Dallai (2004). Only the crustally contaminated dacites and the crustal anatectic rhyolites of Mt. Arci deviate from this trend, with more radiogenic Sr isotope values (up to 0.715) and $^{143}Nd/^{144}Nd$ buffered at ~ 0.5122.

Pb isotope ratios on Montresta and Arcuentu

HMBs (Franciosi *et al.*, 2003) range as follows: $^{206}Pb/^{204}Pb$ = 18.61-18.71; $^{207}Pb/^{206}Pb$ = 15.62-15.66; $^{208}Pb/^{204}Pb$ = 38.41-38.75. The results of Caron and Orgeval (1996) have roughly the same range ($^{206}Pb/^{204}Pb$ = 18.52-18.71; $^{207}Pb/^{206}Pb$ = 15.64-15.68; $^{208}Pb/^{204}Pb$ = 38.71-39.11; Fig. 7b). In contrast most of the PQ rocks (the UPV group) continue to share many isotopic similarities with the so-called EMI mantle end-member (Woodhead and Dewey, 1993; Hofmann, 1997; Lustrino and Dallai, 2004) showing $^{206}Pb/^{204}Pb$ down to 17.5 (Lustrino, 1999; Gasperini *et al.*, 2000; Lustrino *et al.*, 2000, 2002; authors' unpublished data; Fig. 7b). The RPV group deviate from the typical EMI character, resembling more closer the HIMU end-member (Lustrino *et al.*, 2000; authors' unpublished data) and the rocks belonging to this group are characterized by radiogenic $^{206}Pb/^{204}Pb$ (ranging from 18.84 to 19.42) and $^{208}Pb/^{204}Pb$ (38.97-39.13) ratios. Such features are common to most of the anorogenic products of the Cenozoic European Volcanic Province (CEVP) and also to the Cenozoic anorogenic igneous rocks of northern Africa (Tunisia, Algeria, Morocco, Libya) and the Middle East (Jordan, Syria, Israel, Turkey; e.g., Lustrino, 2003 and references therein).

In terms of Pb isotopic ratios, the OM rocks plot in an intermediate position between the UPV and RPV groups. The $^{206}Pb/^{204}Pb$ ratio of the OM rocks extends from the end of the RPV group towards the unradiogenic compositions of the UPV samples; the $^{207}Pb/^{204}Pb$ ratio (not reported) shows no systematic variation with $^{206}Pb/^{204}Pb$; the $^{208}Pb/^{204}Pb$ ratio of the OM samples show a great scatter of data (from 38.41 to 39.11) with a limited $^{206}Pb/^{204}Pb$ range (from 18.52 to 18.71), in strong contrast with the PQ rocks that show good correlation between $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ($R^2 = 0.96$).

The isotopic peculiarity of the UPV group is well evident in the $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ vs. $^{206}Pb/^{204}Pb$ diagrams (Fig. 7c,d). The UPV deviate from the typical trend of Plio-Quaternary igneous rocks of circum-Tyrrhenian area (with both anorogenic and orogenic geochemical features) pointing towards the EMI composition ($^{87}Sr/^{86}Sr$ ~ 0.706; $^{143}Nd/^{144}Nd$ ~ 0.5121; $^{206}Pb/^{204}Pb$ ~16.5; Lustrino and Dallai, 2004 and references therein).

Preliminary laser-fluorination oxygen isotopic results on the Cenozoic igneous rocks of Sardinia have been published and other studies are currently in progress. Two clinopyroxenes from OM andesitic basalt of Marmilla (southern Sardinia) show $\delta^{18}O_{SMOW}$ = +7.02‰ ± 0.03 (Lustrino *et al.*, 2003), consistent with the results obtained by Downes *et al.* (2001) on Arcuentu clinopyroxenes. Also olivine shows $\delta^{18}O_{SMOW}$ values (+6.07‰ ± 0.36; Lustrino *et al.*, 2003) relatively higher compared to typical MORB olivine values (5.16 ± 0.09‰; Eiler *et al.*, 1997).

Laser fluorination analyses on plagioclase of PQ rocks give a relatively wide range of $\delta^{18}O_{SMOW}$ from +6.46 to +7.56‰ (average 6.95 ± 0.36). Tholeiitic lavas show generally lower $\delta^{18}O_{SMOW}$ values (from +6.46 to +6.98‰) compared to the alkaline ones (from +7.04 to +7.56‰; Lustrino *et al.*, 2003). Calculated $\delta^{18}O_{SMOW}$ of the PQ lavas of Sardinia ranges from ~ +6 to ~+7‰. Two clinopyroxenes from the basaltic andesite of Capo Frasca (SW Sardinia) are characterized by relatively high $\delta^{18}O_{SMOW}$ (+6.74‰ ± 0.08). Duplicate analyses are within 0.2‰ of uncertainty.

Mantle sources features of the OM and PQ igneous rocks

The Sardinian OM basalts are mostly HABs, which are characteristic of subduction-related tectonic settings worldwide (e.g., Schiano *et al.*, 2003). The origin of HABs has been linked to two main processes: 1) high degree melting of subducted oceanic slabs (e.g., Myers, 1988) and 2) crustal level fractional crystallization of mafic phases such as olivine and clinopyroxene starting from liquids with HMB composition (e.g., Kersting and Arculus, 1994). In the latter hypothesis the delayed appearance of plagioclase as a liquidus phase reflects the effect of the high-H_2O (and high fO_2) of the metasomatized mantle wedge that was enriched in fluids released from a downgoing slab (see discussions in Schiano *et al.*, 2003).

OM HMBs are found only in the Montresta (Morra *et al.*, 1997; Franciosi *et al.*, 2003), Arcuentu (Brotzu *et al.*, 1997b; Downes *et al.*, 2001; Franciosi *et al.*, 2003) and Marmilla (Mattioli *et al.*, 2000; authors' unpublished data) districts. The primitive characteristics of HMBs give a good opportunity to investigate their mantle sources. On the basis of the flat HREE pattern in chondrite-normalized diagrams, Morra *et al.* (1997) proposed a N-MORB-like spinel-bearing lherzolite, variably metasomatized by fluids from subducted oceanic crust, as the mantle source of the Montresta HMBs. Brotzu *et al.* (1997b) proposed for Arcuentu HMBs a spinel-bearing mantle source more residual than that of the Montresta HMBs. The residual character of this source leads to higher SiO_2 and lower Al_2O_3, CaO, Fe_2O_3 and TiO_2 content in Arcuentu HMBs compared to Montresta primary melts.

Franciosi *et al.* (2003) put constraints on the components involved in the genesis of HMBs and HABs of Montresta and Arcuentu. The geochemical and isotopic compositions of these magmas require an approximate degree of partial melting of 15% of a MORB-like mantle source, and input of two subduction components in the mantle wedge: *a)* fluids from subducted oceanic crust (altered MORB) and *b)* fluids from subducted sediments (Fig. 8). Ratios among trace elements variably compatible with fluid and melt phases (i.e., Th/Pb, Th/Nd and Sr/Nd) exclude the contribution of melts from subducted slab. Models based on isotopic ratios indicate that the pre-subduction depleted mantle source of the OM magmas was enriched by 0.1-0.5% fluid derived from altered MORB and less than 0.1% fluid derived from sediment (Franciosi *et al.*, 2003; Fig. 8). Geochemical and isotopic compositions of the Montresta rocks are homogeneous, while samples from Arcuentu are heterogeneous, consistent with variations in mantle source during the long time span (about 13 Ma) of volcanic activity in this district.

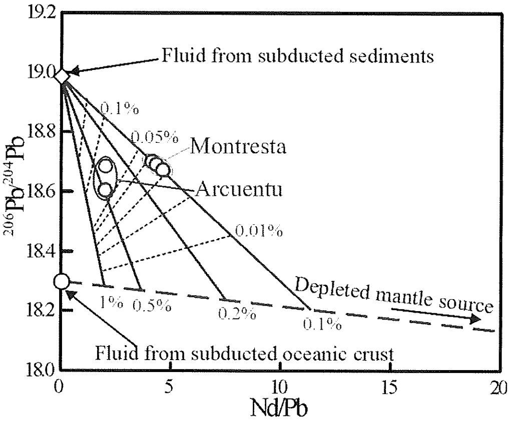

Fig. 8 – Nd/Pb vs. $^{206}Pb/^{204}Pb$ diagram for HMBs from Montresta and HABs from Arcuentu (Oligo-Miocene orogenic igneous cycle of Sardinia). The proposed model (Franciosi *et al.*, 2003) suggests that mantle sources of the magmas of the mentioned districts were modified by 0.1-0.5% MORB fluid and less than 0.1% sediment fluid.

In conclusion, it is proposed that the most primitive OM rocks originated from a MORB-like source only slightly modified by Oligo-Miocene subduction of (Mesogean?) oceanic lithosphere. Most of the «orogenic» geochemical features (e.g., high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$, high LILE/HFSE ratios, etc.) of the less primitive OM rocks (andesites to rhyolites) can be considered as «secondary effects» or «non primary characteristic» related to crustal contamination at shallow depths in magma chambers. Obviously, a clear distinction between the effects of crustal contaminations at mantle levels (source contamination) or shallower depth (melt contamination) is difficult to see in relatively evolved rocks such as the great majority of the OM types (e.g., Lustrino *et al.*, 2004).

Within the general problem of identifying the tectonic setting of the OM igneous rocks, the temporal relationship between calcalkaline basic-to-intermediate rocks and the peralkaline rhyolites (comendites) in the Sulcis area is a major issue (Morra *et al.*, 1994). The peralkaline rhyolites of Sulcis represent about 10-15% by mass of the entire succession of this district (basic to acid types) and ~30% by mass of the more evolved compositions (Morra *et al.*, 1994). Among the whole OM products, the peralkaline types are <<1%. The presence of such lithologies in close spatial and stratigraphic relationships with calcalkaline basic to acid rocks is a relatively uncommon feature.

The tectonic setting of peralkaline magmatism is generally within-plate oceanic (e.g., hot-spot-related islands such as Ascension and the Azores or plume-related large igneous provinces such as Iceland) and continental (sometimes evolving to continental rift systems such as the Afar). The relative scarcity of peralkaline magmatism in subduction-related settings and the extremely rare association of calcalkaline andesite with peralkaline magmas, has allowed some authors to suggest that comendites and pantellerites are products of tectonic settings unrelated to subduction systems (e.g., Maniar and Piccoli, 1989). In this context the peralkaline magmatism of the Sulcis area cannot be ascribed to a specific tectonic setting: agpaitic index values > 1 can be obtained from metaluminous or slightly peralkaline melts after removal of mineral phases less peralkaline than coexisting liquids (e.g., the plagioclase and/or the clinopyroxene effect; Scaillet and MacDonald, 2003 and references therein).

The petrogenesis of the PQ rocks is more complex than that of the OM products because of the existence of two distinct geochemical groups: the UPV and RPV groups (Lustrino *et al.*, 2000). The peculiarity of the UPV group is its «transitional» geochemical character between classical within-plate anorogenic products (e.g., «bell-shaped» incompatible trace element patterns in primitive mantle-normalized diagrams) and subduction-modified compositions (e.g., relatively low HFSE content and high LILE/HFSE ratios; Di Battistini *et al.*, 1990; Lustrino *et al.*, 1996, 2000, 2002).

Among the PQ rocks, the UPV group behaves as a coherent and uniform group. This is the reason why the UPV acronym (originally proposed on the basis of Pb isotopic composition of a limited set of representative rocks) is used here to group the great majority (> 99%) of the PQ volcanic rocks of Sardinia. Primitive mantle-normalized trace element patterns of the most primitive mafic magmas from the various PQ districts are virtually indistinguishable from each other (e.g., Lustrino, 1999, 2000a; Lustrino *et al.*, 2000, 2004). The only difference is the lower incompatible trace element content of the tholeiitic rocks compared to alkaline rocks.

The tholeiitic-alkaline association and its petrogenetic significance has been investigated in detail by Lustrino *et al.* (2002). As observed for other Italian (e.g., Hyblean Mts., Sicily; Beccaluva *et al.*, 1998; Trua *et al.*, 1998) and European volcanic rocks (e.g., Bas Languedoc, France; Dautria and Liotard, 1990; Liotard *et al.*, 1999), the close spatial and temporal association of these two different magma types, as well as similar incompatible trace element ratios and overlapping Sr-Nd-Pb isotopic ratios, have been related to a single mantle source which melted to different degrees: about 3 to 6 % for mafic alkaline rocks and about 8 to 12 % for tholeiitic rocks (Lustrino *et al.*, 2002).

The relatively low $^{206}Pb/^{204}Pb$ ratios of the UPV, coupled with distinctive trace element features (e.g., high Ba/Nb), have been related to ancient (Panafrican/Hercynian) modification of their mantle sources (Lustrino *et al.*, 2000). Lustrino (1999, 2000b) and Lustrino *et al.* (2000) proposed an active role of ancient continental lower crust in the genesis of the PQ volcanic rocks of Sardinia (Fig. 9).

Conversely, Gasperini *et al.* (2000) proposed for the Logudoro lavas recycling of subducted oceanic plateaux into the deep mantle and incorporation into a mantle plume. The absence of correlation between Eu/Eu* and Sr/Eu* (R^2 = 0.08) and the poor correlation of Eu/Eu* with Sr/Nd (R^2 = 0.45) seem inconsistent with the hypothesis of recycling plagioclase-rich assemblage as proposed by Gasperini *et al.* (2000). Moreover, a Sr-rich component (rich in plagioclase) with low Rb/Sr would be characterized by low time-integrated $^{87}Sr/^{86}Sr$ ratios, contrary to that noted for the EM-I component (relatively radiogenic Sr: $^{87}Sr/^{86}Sr$

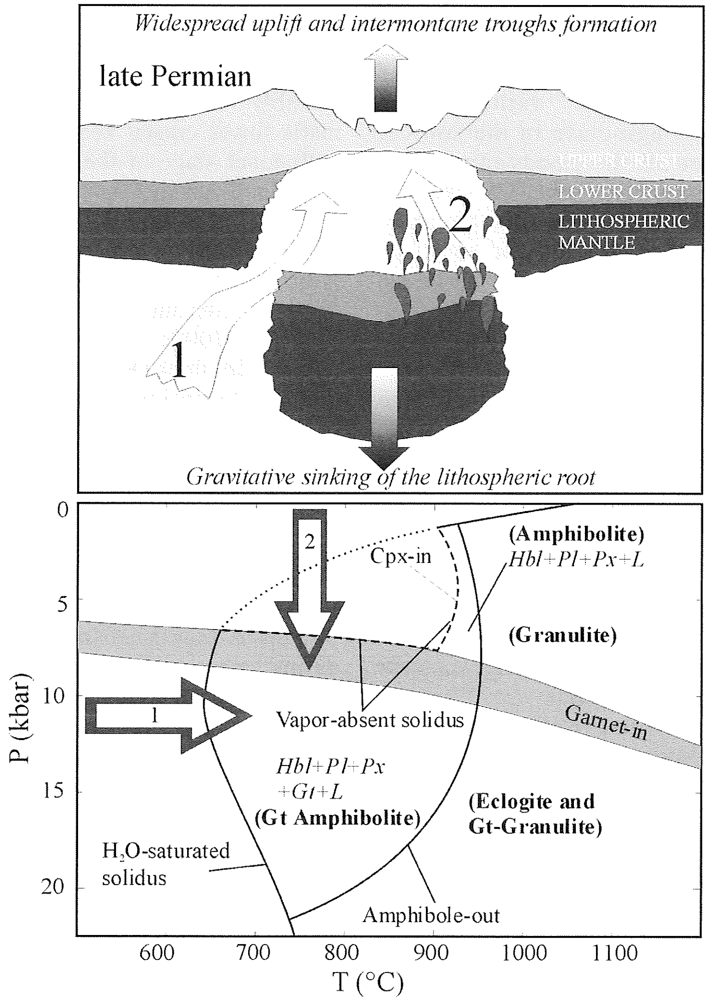

Fig. 9 – A) Delamination, detachment and sinking of overthickened lithospheric root during end of Hercynian orogeny. 1 = Future source of Cenozoic European Volcanic Province products, with within-plate geochemical features and strong asthenospheric signature; 2 = Future source of majority of Plio-Quaternary volcanic rocks of Sardinia (UPV group of Lustrino *et al.*, 2000), with strong lower crustal and lithospheric signature (Lustrino, 2000b); B) Composite phase diagrams for amphibolitic assemblages (whole-rock composition variable from alkali basalt to N-MORB) as deduced from several sources (references in Lustrino, 2001). Continuous line, partly interrupted by dotted line: H_2O-saturated *solidus*. Garnet-in curve represented by shaded area because of contrasting results from experimental studies carried out on differing starting compositions. Above garnet stability field (roughly P > 7 kbar), vapour-absent *solidus* coincides with H_2O-saturated *solidus*, because breakdown of amphibole (with the following formation of garnet) produces excess water (entering the melt) during dehydration partial melting. Below garnet stability field, vapour-absent *solidus* represented by dashed line, coincides with appearance of clinopyroxene (and garnet) produced by reaction: amph + pl = melt ± cpx ± gt ± other phases. Italics: stable mineralogical assemblages; bold type: rock types. Arrow «1»: effect of arrival of hot basaltic batches on amphibolitic lower crust, when system is forced to melt partially by dehydration, not requiring aqueous pore fluid. Assemblage increases in density, due to increasing volumes of garnet replacing amphibole. Arrow «2»: effect of tectonic thickening following continent-continent collision and thickening of lower crust. Here too, lower crustal lithologies are forced to melt partially, with an increase in density of restitic material. If density gradient reaches a critical value, restitic lower crust (represented by garnet amphibolite or eclogite/granulite) may delaminate, detach and sink into upper mantle (Lustrino 2001, 2004). See text for further explanations.

~0.706; Fig. 7). The positive correlation of CaO/Al_2O_3 with MgO in the Logudoro lavas ($R^2 = 0.68$) can be related to the effect of clinopyroxene removal rather than accumulation of plagioclase in the source. When considered in the geodynamic and geochemical context of the CEVP, the Logudoro volcanic rocks fall within the array defined by within-plate volcanic rocks of Spain, France, Germany and Italy, clustering toward the lower CaO/Al_2O_3 end. The low CaO/Al_2O_3 of the Logudoro volcanic rocks may be related to their relatively differentiated character (Mg# 0.64-0.46) and clinopyroxene fractionation. This latter aspect is confirmed by the relatively low Sc content of the Sardinian mafic PQ volcanic rocks compared to other within-plate products of the CEVP: the PQ Sardinian rocks show Sc contents of 15-21 ppm at MgO = 8-11 wt %, whereas volcanic rocks from French Massif Central, Germany and Spain show Sc ranges of 24-36, 18-36 and 16-26 ppm, respectively, at the same MgO content (references in Lustrino, 1999).

It is proposed (Lustrino *et al.*, in prep.) that the UPV group could derive from a cratonized DMM-like source metasomatized by melts derived from partial melting of lower crustal lithologies: a melt derived by 12 % partial melting of lower continental crust, mixed with DMM in proportion of 2 and 98 %, respectively, may produce a structure like the marble-cake mantle of Allegre and Turcotte (1986), even if these authors did not envisage continental lower crust involvement in their model. Partial melts of this new source (DMM plus pods or dykelets of «tonalitic s.l.» melts) are characterized by Ba and Sr positive anomaly with low, if any, Nb anomaly; the $(Ba/Nb)_N$ ratios of these calculated melts is >1.

While lower crustal contamination of magmas *en route* to the surface has been hypothesized for other CEVP rocks (e.g., Haase *et al.*, 2004) and other EMI basalts in general (e.g., Baker *et al.*, 1997), for the UPV the lower crust signature is interpreted as source contamination. In this case, interaction of lower crust-derived melts with the lithospheric mantle (with DMM-like geochemical features) may have taken place possibly via post-collisional sinking of dense mafic lower crustal keel thickened during the collisional stage of the Hercynian orogenesis (Fig. 9a; Lustrino, 2000b; 2004).

At the end of the Hercynian orogenesis (Carboniferous-Permian), the Sardinian lithosphere was probably affected by delamination and detachment processes (see Lustrino, 2000c, and references therein). In tectonically thickened crustal materials along a continent-continent collisional margin, the lowermost crust is metamorphosed to granulite/eclogite facies, with an attendant increase of density from ~ 2.8 up to ~ 3.8 g/cm^3 (e.g., Gao *et al.*, 1998; Tatsumi, 2000; Jull and Kelemen, 2001; Moore and Wiltschko, 2004), favouring sinking of the mafic keel. The density increase can be the result of two processes (see Lustrino, 2001; Fig. 9b): 1) during tectonic thickening following continent-continent collision, lower crustal lithologies (i.e., amphibolite) start to melt above the vapor-absent solidus, coincident with formation of garnet. During this process, amphibolite is metamorphosed to garnet-bearing amphibolite and eventually, with the total disappearance of amphibole, to eclogite and/or garnet-granulite; 2) arrival of hot basaltic magma in amphibolitic lower crust forces the system to melt partially by dehydration, producing a density increase with amphibole ± plagioclase melting and garnet ± pyroxene growth (Wolf and Wyllie, 1994; Rapp and Watson, 1995). Jull and Kelemen (2001) have demonstrated that for a wide range of crustal lithologies (such as gabbronorite, gabbro and granulite, all potential candidate to represent average lower crust composition) the density increase at pressures ~8-10 kb corresponds to the formation of garnet according to the reaction: plagioclase ($CaAl_2Si_2O_8$) + forsterite (Mg_2SiO_4) = pyrope-grossular ($CaMg_2Al_2Si_3O_{12}$).

These results evidence that: 1) delamination of lower crust is kinematically and thermodynamically possible (e.g., Jull and

Kelemen, 2001); 2) the driving force of lower crust delamination is its negative buoyancy as consequence of eclogitization (e.g., Moore and Wiltschko, 2004); 3) mantle lithosphere also may delaminate and can be decoupled from upper crust in correspondence of the lower crust (e.g., Morency and Doin, 2004).

Such a recycling of lower crust + lithospheric mantle in the asthenosphere has strong implications on the geochemical budget of the upper mantle. We relate the peculiar geochemical and isotopic characteristics of the UPV to such a delamination and detachment process.

Although high Ba/Nb is not a typical feature of late Hercynian post-collisional to anorogenic igneous rocks of Sardinia, some basic alkaline dykes from NE Sardinia (Concas-Alà dei Sardi area; ~ 240 Ma; Traversa *et al.*, 1997) show trace element abundances roughly similar to the UPV group. These Concas-Alà dei Sardi hawaiites show positive peaks at Ba and Sr, coupled with $(Ba/Nb)_N > 1$. These products can be considered as partial melts of a source made up of DMM contaminated by few percent of (tonalitic s.l.) crustal-derived partial melts. Therefore, they could represent the first expression of the Hercynian-age modification. Such a mantle could have been mobilized many Ma later, during the opening stages of the Tyrrhenian Sea and could have acted as source for the PQ rocks of Sardinia.

What emerges from these considerations is that both the OM and PQ rocks suffered variable extents of crustal contamination. For the PQ rocks (UPV group) such contamination is thought to have occurred at mantle depths after digestion of delaminated and detached lower crust. In particular, it is proposed that this is not a whole-rock contamination, but rather an ancient metasomatism of lower crust partial melts. Once delamination and detachment started, an asthenospheric flow replaced the volume formerly occupied by the lower crust and the lithospheric mantle. This new mantle volume (lithospheric mantle from a rheological point of view) is the locus where lower crust partial melts penetrated and froze. We propose that these metasomatized lithospheric portions of the Sardinian mantle were reactivated about 300 Ma later, in response to extension related to the Tyrrhenian Sea opening.

Only during the last stages of fractional crystallization evolution (e.g., with rocks with MgO < 3 wt %) did upper crust contamination at magma chamber levels (AFC processes) become the most important process in the petrogenesis of the PQ rocks. This model can be seen in the $^{87}Sr/^{86}Sr$ vs. MgO diagram of Fig. 10. Here the uniform $^{87}Sr/^{86}Sr$ isotopic ratio of the PQ rocks with MgO ranging from ~ 11 to ~ 3 wt % is surprising. This uniformity can be interpreted only as consequence of partial melting of a uniform mantle source and fractional crystallization in closed systems. In conclusion, it is possible to say that, with the exclusion of the most SiO_2-oversaturated products of Mt. Arci, the role of upper crustal contamination in the petrogenesis of the PQ rocks is considered unimportant. The PQ tholeiitic rocks (~20 % of the outcrops) show slightly more radiogenic $^{87}Sr/^{86}Sr$ ratios and less radiogenic $^{143}Nd/^{144}Nd$ ratios than the alkaline rocks, pointing to some degree of upper crustal contamination; however the relative similarity of incompatible trace element ratios among alkaline and tholeiitic PQ rocks limit upper crustal contamination processes to few percent (e.g., Lustrino *et al.*, 2002; authors' unpublished data).

The $^{87}Sr/^{86}Sr$ vs. MgO diagram for the OM rocks is much more complex (Fig. 10); in this case a single process of source contamination cannot be invoked. Rather, the $^{87}Sr/^{86}Sr$ isotopic variation of the OM rocks with MgO can be explained by multiple upper crustal assimilation events at varying stages of evolution. Different upper crustal contaminants and variable ratios of the «r» parameter (amount of assimilation/amount of fractional crystallization) are necessary. On the other hand, the weak $^{87}Sr/^{86}Sr$ vs. MgO correlation led Downes *et al.* (2001) to favour the hypothesis of «mantle source enrichment by subducted siliceous sediments». In conclusion,

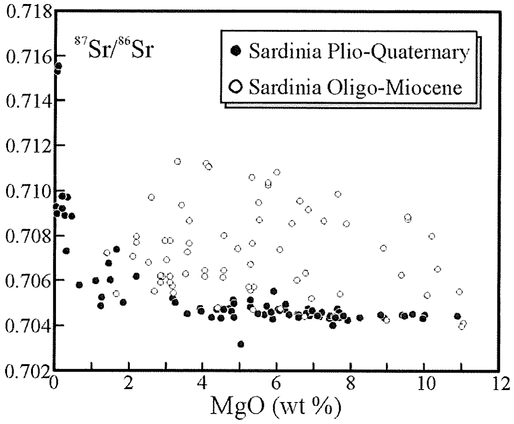

Fig. 10 – MgO vs. $^{87}Sr/^{86}Sr$ diagram for Oligo-Miocene (orogenic s.l.) and Plio-Quaternary (anorogenic s.l.) rocks of Sardinia.

it is possible to say that the evolution of the OM igneous rocks seems to be mostly governed by crustal contamination at shallow depths. The genesis of the OM ignimbrites (dacite and rhyolite) has been related to anatectic processes in the continental crust (e.g., Dupuy *et al.*, 1974), while other authors (Morra *et al.*, 1994, 1997; Brotzu *et al.*, 1997a; Conte, 1997; Lonis *et al.*, 1997) interpreted the positive correlation of $^{87}Sr/^{86}Sr$ ratios with the differentiation of the magmas as the result of fractional crystallization coupled with more or less intense crustal assimilation.

Here a petrogenetic model in the framework of the Alpine Orogenesis is presented. As evidenced before, the OM cycle of Sardinia is thought to have developed as consequence of a N-NW-directed subduction system below the southern European margin represented by the Provençal coast (SE France). Release of slab-derived fluids, together with decompression as consequence of back-arc opening would have triggered magmatic activity. We propose that the mantle sources of the OM magmas are part of the asthenospheric mantle, because of some geochemical similarities of the most primitive OM melts with DMM-like sources slightly modified by subduction-related fluids. The most extreme isotopic compositions among the OM rocks (e.g., the highest $^{87}Sr/^{86}Sr$ and lowest $^{143}Nd/^{144}Nd$ ratios) do not reflect «anomalous» mantle sources, but, rather, upper crustal contamination of mantle melts.

On the other hand, the trace element and isotopic peculiarities of the great majority of the PQ (the UPV group) are suggestive of «anomalous» mantle sources. The involvement of an active mantle plume to explain the PQ magmatism (hypothesis proposed for many others anorogenic products belonging to the CEVP; e.g., Wilson and Downes, 1991; Hoernle *et al.*, 1995; Wilson and Patterson, 2001) is considered very unlikely for the PQ volcanic rocks (e.g., Peccerillo and Lustrino, 2004) because of: 1) absence of crustal doming; 2) the magmatic activity postdates the rifting processes (passive rifting) and 3) the lithospheric thickness is about 70 km (Panza, 1984). This means that for the PQ rocks a shallow origin is preferred: lithospheric mantle (strongly metasomatized during Hercynian Orogenesis by lower crust-derived partial melts) for the UPV group and asthenospheric mantle (with HIMU-like geochemical features) for the RPV group.

The pre-metasomatism mantle sources of the OM rocks share some Sr-Nd-Pb isotopic similarities with the RPV group of the PQ rocks: in particular, the most primitive OM melts (Montresta and Arcuentu) analyzed for these systematics, show isotopic values similar or only slightly different from those of RPV. In Sr-Nd-Pb isotopic spaces (Fig. 7), the most primitive OM rocks tend to fill the gap existing between the RPV and the UPV. We propose that the original (pre-metasomatism) features of the OM mantle sources share many isotopic similarities with those of RPV, and therefore we identify them as the convecting asthenospheric mantle. On the other hand, the only place where the geochemical and isotopic anomalies seen in the UPV can be stored and evolve is the non-convecting lithospheric mantle. In order to produce low $^{206}Pb/^{204}Pb$ isotopic values such as those recorded by the UPV, a time-integrated growth of a source with very low μ ($^{238}U/^{204}Pb$) is required; the only place where this process is possible is a lithospheric mantle metasomatized by lower crust partial melts (e.g., Lustrino, 2004). In conclusion, we believe that the transition between orogenic (s.l.) to anorogenic (s.l.) magmatic cycles in Sardinia is the consequence of different depths of equilibration of melts: deeper for the OM rocks (asthenospheric mantle slightly modified by fluids released from subducted oceanic crust) and shallower for most of the PQ rocks (lithospheric mantle metasomatized by delaminated lower crust). In both cases, the last equilibration took place within the spinel stability field (Morra *et al.*, 1997; Lustrino *et al.*, 2002).

CONCLUSIONS

During the Cenozoic two magmatic episodes affected the island of Sardinia. The first, from Oligocene to Miocene (32-15 Ma), produced subalkaline rocks with tholeiitic to calcalkaline affinity and subduction-related geochemical signatures. Starting in the Pliocene, a second volcanic cycle developed and continued up to the Quaternary. This cycle (~5-0.1 Ma) is characterized by mildly to strongly alkaline (mostly with sodic character) volcanic rocks and fewer subalkaline (with tholeiitic affinity) lavas, with peculiar within-plate geochemical signatures.

To explain the geochemical features of primitive Oligo-Miocene orogenic basalts from Sardinia we propose that their genesis is related to the presence of three end-members: 1) depleted mantle wedge (with DMM-like Sr-Nd-Pb isotopic compositions); 2) a component from subducted altered oceanic crust; 3) a component from subducted oceanic sediments. The involvement of fluid phases from both oceanic crust and sediments, rather than melts released from the subducting plate input in the mantle wedge is favoured. Most of the intermediate to evolved compositions (andesite, dacite, rhyolite) reflect, in addition, crustal contamination at shallow depths.

The Plio-Quaternary mafic volcanic rocks of Sardinia are divided geochemically into two groups: (1) the most abundant (> 99 %) volcanic rocks (UPV; Unradiogenic Pb Volcanics) group, characterized by unradiogenic Pb isotopic ratios and (2) rare volcanic rocks (RPV; Radiogenic Pb Volcanics) with radiogenic Pb isotopic ratios. These two rock groups occur in distinct areas, and define a significant geochemical discontinuity, roughly running E-W, across the southern part of the island, where the RPV rocks are concentrated. The isotopic signature of the UPV is not observed in any of the Italian orogenic and anorogenic rocks, nor in any other Cenozoic circum-Mediterranean igneous province.

The UPV rocks closely resemble the EMI mantle end-member composition, and their geochemical signature is believed to be a source feature related to mixing of depleted mantle and partial melts from ancient lower crust that have relatively low $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ and very low $^{206}Pb/^{204}Pb$. The rarer RPV group matches the HIMU-like geochemical characteristics found in other Italian and circum-Mediterranean Na-alkaline and tholeiitic anorogenic volcanic rocks, and their origin is not well constrained.

The temporal transition from orogenic (s.l.) to anorogenic (s.l.) igneous cycles is relatively common in the circum-Mediterranean area and has been explained elsewhere by delamination and detachment processes of subducting slabs whose volume is replaced by new asthenospheric mantle. This mantle volume did not experienced subduction-related metasomatism and therefore shows «anorogenic» geochemical features.

The chemical and isotopic characteristics of the Sardinian Plio-Quaternary rocks and those of the roughly coeval Roman Magmatic Province imply that completely different mantle processes occurred in the central-western Mediterranean area, and that there are no genetic or tectonic relationships between these two provinces.

ACKNOWLEDGMENTS

The authors whish to thank all the Sardinian people, for their hospitality and warmth demonstrated during all the field trips in the island. In particular we want to thank Colonel Murru for the permission to sample rocks within the Air Base of Capo Frasca. Special thanks also to Antonio Assorgia for having introduced RL, LM, VM and (indirectly) ML to the magic igneous world of Sardinia. Thanks to Yongjun Su and Charles H. Langmuir for the petrological software Petroplot. ML, VM and LM thank Enrica Mascia, Gisella Majorano and Donatella Insinga, respectively, for their patience during the numerous field trips in Sardinia and the writing of this manuscript. This paper benefited of thorough reviews of Fred Frey (Cambridge, USA), Robert Ellam (Glasgow, UK) and Marjorie Wilson (Leeds, UK) and of excellent editorial handling of Sandro Conticelli (Florence, Italy) to whom all we send our sincere thanks. This does not imply that all the referees totally agree with the conclusions drawn by the authors of this paper. CNR-Agenzia 2000, PRIN-MIUR (2001) and FIRB-MIUR grants to VM, as well as Giovani Ricercatori (CNR and University of Rome La Sapienza) and FIRB-MIUR grants to ML are acknowledged.

REFERENCES

ALLEGRE J.-C. and TURCOTTE D.L. (1986) — *Implications of a two-component marble-cake mantle.* Nature, **323**, 123-127.

ARAÑA V., BARBERI F. and SANTACROCE R. (1974) — *Some data on the comendite type area of S. Pietro and S. Antioco islands, Sardinia.* Bull. Volcanol., **38**, 725-736.

ASSORGIA A., BROTZU P., MORBIDELLI L., NICOLETTI M. and TRAVERSA G. (1984) — *Successione e cronologia (K/Ar) degli eventi vulcanici del complesso calco-alcalino Oligo-Miocenico dell'Arcuentu (Sardegna centro-occidentale).* Per. Mineral., **53**, 89-102.

BAKER J.A., MENZIES M.A., THIRLWALL M.F. and MACPHERSON C.G. (1997) — *Petrogenesis of Quaternary intraplate volcanism, Sana'a, Yemen: implications for plume-lithosphere interaction and polybaric melt hybridization.* J. Petrol., **36**, 1359-1390.

BECCALUVA L., BIANCHINI G., COLTORTI M., PERKINS W.T., SIENA F., VACCARO C. and WILSON M. (2001) — *Multistage evolution of the European lithospheric mantle: new evidence from Sardinian peridotite xenoliths.* Contrib. Mineral. Petrol., **142**, 284-297.

BECCALUVA L., CIVETTA L., MACCIOTTA G. and RICCI C.A. (1985) — *Geochronology in Sardinia: results and problems.* Rend. Soc. It. Min. Petr., **40**, 57-72.

BECCALUVA L., COLTORTI M. GALASSI B., MACCIOTTA G. and SIENA F. (1994) — *The Cainozoic calcalkaline magmatism of the western Mediterranean and its geodynamic significance.* Boll. Geofis. Teor. Appl., **36**, 293-308.

BECCALUVA L., DERIU M., MACCIONI L., MACCIOTTA G. and VENTURELLI G. (1974) — *Il massiccio vulcanico di M.te Arci (Sardegna centro-occidentale).* Rend. Soc. It. Min. Petr., **30**, 1069-1080.

BECCALUVA L., MACCIOTTA G. and VENTURELLI G. (1975) — *Dati geochimici e petrografici sulle vulcaniti Plio-Quaternarie della Sardegna centro-occidentale.* Boll. Soc. Geol. It., **94**, 1437-1457.

BECCALUVA L., MACCIOTTA G. and VENTURELLI G. (1976) — *Le vulcaniti Plio-Quaternarie del Logudoro.* Boll. Soc. Geol. It., **95**, 339-350.

BECCALUVA L., SIENA F., COLTORTI M., DI GRANDE A., LO GIUDICE A., MACCIOTTA G., TASSINARI R. and VACCARO C. (1998) — *Nephelinitic to tholeiitic magma generation in a transtensional tectonic setting: an integrated model for the Iblean volcanism, Sicily.* J. Petrol., **39**, 1547-1576.

BROTZU P. (Ed.) (1997) — *The Tertiary calcalkaline volcanism of Sardinia.* Per. Mineral., Spec. Issue, vol. **66**.

BROTZU P., FERRINI V., MORBIDELLI L. and TRAVERSA G. (1975) — *Il distretto vulcanico di Capo Ferrato.* Rend. Semin. Fac. Sci. Univ. Cagliari, **45**, 1-26.

BROTZU P., CALLEGARI E., MORRA V. and RUFFINI R. (1997a) — *The orogenic basalt-andesite suites from the Tertiary volcanic complex of Narcao, SW-Sardinia (Italy): petrology, geochemistry and Sr-isotope characteristics.* Per. Mineral., **66**, 101-150.

BROTZU P., LONIS R., MELLUSO L., MORBIDELLI L., TRAVERSA G. and FRANCIOSI L. (1997b) — *Petrology and evolution of calcalkaline magmas from the Arcuentu volcanic complex (SW Sardinia, Italy).* Per. Mineral., **66**, 151-184.

CARMIGNANI L., BARCA S., DISPERATI L., FANTOZZI P., FUNEDDA A., OGGIANO G. and PASCI S. (1994) — *Tertiary compression and extension in the Sardinian basement.* Boll. Geof. Teor. Appl., **36**, 5-62.

CARMINATI E., WORTEL M.J.R., MEIJER P.TH. and SABADINI R. (1998) — *The two-stage opening of the western-central Mediterranean basins: a forward modeling test to a new evolutionary model.* Earth Planet. Sci. Lett., **160**, 667-679.

CARON C. and ORGEVAL J.J. (1996) — *Origine du* *plomb des minéralisations à métaux de base et métaux précieux de Sardaigne occidentale et de leur encaissant volcanique tertiaire*. C. Rend. Acad. Sci. Paris., **323**, 41-47.

Catalano R., Doglioni C. and Merlini S. (2001) — *On the Mesozoic Ionian basin*. Geophys. J. Int., **144**, 49-64.

Cavazza W., Zattin M., Ventura B. and Zuffa G.G. (2001) — *Apatite fission-track analysis of Neogene exhumation in northern Corsica (France)*. Terra Nova, **13**, 51-57.

Cioni R., Clocchiatti R., Di Paola G.M., Santacroce R. and Tonarini S. (1982) — *Miocene calc-alkaline heritage in the Pliocene post-collisional volcanism of Monte Arci (Sardinia, Italy)*. J. Volcanol. Geotherm. Res., **14**, 133-167.

Civetta L., Orsi G., Scandone P. and Pece R. (1978) — *Eastwards migration of the Tuscan anatectic magmatism due to anticlockwise rotation of the Apennines*. Nature, **276**, 604-606.

Conte A.M. (1997) — *Petrology and geochemistry of tertiary calcalkaline magmatic rocks from the Sarroch district (Sardinia, Italy)*. Per. Mineral., **66**, 63-100.

Coulon C. (1977) — *Le volcanisme calco-alcaline cénozoique de Sardaigne (Italie): pétrographie, géochimie et genèse des laves andesitiques et des ignimbrites. Signification geodinamique*. Thèse Univ. Marseille.

Dautria J.M. and Liotard J.M. (1990) — *Les basaltes d'affinité tholeiitique de la marge Mediterraneenne Francaise*. C. R. Acad. Sci. Paris., **311**, 821-827.

De Astis G., Peccerillo A., Kempton P.D., La Volpe L. and Wu T.W. (2000) — *Transition from calcalkaline to potassium-rich magmatism in subduction environments: geochemical and Sr, Nd, Pb isotopic constraints from the island of Vulcano (Aeolian arc)*. Contrib. Mineral. Petrol., **139**, 684-703.

Deino A., Gattacceca J., Rizzo R. and Montanari A. (2001) — *$^{40}Ar/^{39}Ar$ dating and paleomagnetism of the Miocene volcanic succession of Monte Furru (western Sardinia): Implications for the rotation history of the Corsica-Sardinia microplate*. Geophys. Res. Letters., **28**, 3373-3376.

Di Battistini G., Montanini A. and Zerbi M. (1990) — *Geochemistry of volcanic rocks from southeastern Montiferro*. Neues. Jahrb. Miner. Abh., **162**, 35-67.

Doglioni C., Carminati E. and Bonatti E. (2003) — *Rift asymmetry and continental uplift*. Tectonics, **22**, 1024, doi:10.1029/2002TC001459.

Doglioni C., Innocenti F., Morellato C., Procaccianti D. and Scrocca D. (2004) — *On the Tyrrhenian Sea opening*. Mem. Soc. Geol. It., (in press).

Doglioni C., Mongelli F. and Pialli G. (1998) — *Boudinage of the Alpine belt in the Apenninic back-arc*. Mem. Soc. Geol. It., **52**, 457-468.

Dostal J., Dupuy C. and Coulon C. (1976) — *Rare-Earth elements in high-alumina basaltic rocks from Sardinia*. Chem. Geol., **18**, 251-262.

Downes H., Thirlwall M.F. and Trayhorn S.C. (2001) — *Miocene subduction-related magmatism in southern Sardinia: Sr-Nd and oxygen isotopic evidence for mantle source enrichment*. J. Volcanol. Geotherm. Res., **106**, 1-21.

Dupuy C., McNutt R.H. and Coulon C. (1974) — *Determination de $^{87}Sr/^{86}Sr$ dans les andesites Cenozoiques et les laves associees de Sardaigne nord occidentale (Italie)*.

Eiler J.M., Farley K.A., Valley J.W., Hauri E., Craig H., Hart S.R. and Stolper E.M. (1997) — *Oxygen isotope variations in ocean island basalt phenocrysts*. Geochim. Cosmochim. Acta, **61**, 2281-2293.

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

Gao S., Luo T.C., Zhang B.R., Hang H.F., Han Y.W., Zhao Z.D. and Hu Y.K. (1998) — *Chemical composition of the continental crust as revealed by studies in east China*. Geochim. Cosmochim. Acta. **62**, 1959-1975.

Gasperini D., Blichert-Toft J., Bosch D., Del Moro A., Macera P., Télouk P. and Albarede F. (2000) — *Evidence from Sardinian basalt geochemistry for recycling of plume heads into the Earth's mantle*. Nature, **408**, 701-704.

Giraud J., Bellon H. and Turco G. (1979) — *L'intrusion microdioritique tertiaire d'Alghero (Sardigne). Age K/Ar et relation avec le magmatisme calco-alcalin sarde. Analogies avec les esterellites de l'Esterel (var)*. C.R. Acad. Sc. Paris, **288**, 9-12.

Gueguen E., Doglioni C., Fernandez M. (1998) — *On the post-25 Ma geodynamic evolution of the western Mediterranean*. Tectonophysics, **298**, 259-269.

Haase K.M., Goldschmidt B. and Garbe-Schonberg C.-D. (2004) — *Petrogenesis of Tertiary continental intra-plate lavas from the Westerwald region, Germany*. J. Petrol., **45**, 883-905.

Hoernle K., Zhang Y.S. and Graham D. (1995) — *Seismic and geochemical evidence for large-scale mantle upwelling beneath the eastern Atlantic and* *western and central Europe.* Nature, **374**, 34-39.

Hofmann A.W. (1997) — *Mantle geochemistry: the message from oceanic volcanism.* Nature, **385**, 219-229.

Hyppolite J.C., Angelier J., Bergerat F., Nury D. and Guieu G. (1993) — *Tectonic-stratigraphic record of paleostresses time changes in the Oligocene basins of the Provence, southern France.* Tectonophysics, **226**, 15-35.

Jolivet L., Frizon de Lamotte D., Mascle A. and Séranne M. (1999) — *The Mediterranean basin: Tertiary extension within the Alpine Orogen - an introduction.* In Durand B., Jolivet L., Horvath F. and Séranne M (Eds.) *The Mediterranean basins: Tertiary extension within the Alpine Orogen.* Geol. Soc. London., **156**, 1-14.

Jull M. and Kelemen P.B. (2001) — *On the conditions for lower crustal convective instability.* J. Geophys. Res., **106**, 6423-6446.

Kersting A.B. and Arculus R.J. (1994) — *Klyuchevskoy volcano, Kamchatka, Russia: the role of high-flux recharged, tapped and fractionated magma chamber(s) in the genesis of high-Al_2O_3 from high-MgO basalt.* J. Petrol., **35**, 1-41.

Le Bas M.J., Le Maitre R.W., Streckeisen A. and Zanettin B. (1986) — *A chemical classification of volcanic rocks based on the total alkali-silica diagram.* J. Petrol., **27**, 745-750.

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

Liotard J.M., Briqueu L., Dautria J.M. and Jakni B. (1999) — *Basanites et néphélinites du Bas-Languedoc (France): contamination crustale et hétérogénéité de la source mantellique.* Bull. Soc. Geol. France, **170**, 423-433.

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

Lustrino M. (1999) — *Petrogenesis of Plio-Quaternary volcanic rocks from Sardinia: possible implications on the evolution of the European subcontinental mantle.* PhD Thesis, Università di Napoli Federico II 188 pp.

Lustrino M. (2000a) — *Petrogenesis of tholeiitic volcanic rocks from central-southern Sardinia.* Miner. Petrogr. Acta, **43**, 1-16.

Lustrino M. (2000b) — *Volcanic activity during the Neogene to Present evolution of the western Mediterranean area: a review.* Ofioliti, **25**, 87-101.

Lustrino M. (2000c) — *Phanerozoic geodynamic evolution of the circum-Italian Realm.* Int. Geol. Rev., **42**, 724-757.

Lustrino M. (2001) — *Debated topics of modern igneous petrology.* Per. Mineral., **70**, 1-26.

Lustrino M. (2003) — *Spatial and temporal evolution of Cenozoic igneous activity in the circum-Mediterranean realm.* Inst. Geophys. Polish Acad. Sci., M-28 (363), 143-144.

Lustrino M. (2004) — *Lithospheric control on basaltic magmatism.* Earth Sci. Rev. (submitted).

Lustrino M. and Dallai L. (2004) — *On the origin of EM-I end-member.* N. Jahrb. Miner. Abh., **179**, 85-100.

Lustrino M., Brotzu P., Lonis R., Melluso L. and Morra V. (2004) — *European subcontinental mantle as revealed by Neogene volcanic rocks and mantle xenoliths of Sardinia.* Field trip guide, IGC Florence 2004.

Lustrino M., Melluso L. and Morra V. (1999) — *Origin of glass and its relationships with phlogopite in mantle xenoliths from central Sardinia (Italy).* Per. Mineral., **68**, 13-42.

Lustrino M., Melluso L. and Morra V. (2000) — *The role of lower continental crust and lithospheric mantle in the genesis of Plio-Pleistocene volcanic rocks from Sardinia (Italy).* Earth Planet. Sci. Lett., **180**, 259-270.

Lustrino M., Melluso L. and Morra V. (2002) — *The transition from alkaline to tholeiitic magmas: a case study from the Orosei-Dorgali Pliocene volcanic district (NE Sardinia, Italy).* Lithos **63**, 83-113.

Lustrino M., Melluso L., Morra V., Dallai L., d'Amelio F. and Petteruti Lieberknecht A.M. (2003) — *Oxygen isotope composition of Plio-Quaternary volcanic rocks of Sardinia.* Proc. 4° forum FIST - Geoitalia, Bellaria, 231-232.

Lustrino M., Melluso L., Morra V. and Secchi F. (1996) — *Petrology of Plio-Quaternary volcanic rocks from central Sardinia.* Per. Mineral., **65**, 275-287.

Maniar P.D. and Piccoli P.M. (1989) — *Tectonic discrimination of granitoids.* Geol. Soc. Am. Bull., **101**, 635-643.

Martí J., Mitjavila J., Roca E. and Aparicio A. (1992) — *Cenozoic magmatism of the Valencia trough (western Mediterranean): relationship between structural evolution and volcanism.* Tectonophysics, **203**, 145-165.

Mascle G.H., Tricart P., Torelli L., Bouillin J-P., Rolfo F., Lapierre H., Monié P., Depardon S., Mascle J. and Peis D. (2001) — *Evolution of the Sardinia channel (western Mediterranean): new constraints from a diving survey on Cornacya seamount off SE Sardinia.* Mar. Geol., **179**, 179-202.

Mattioli M., Guerrera F., Tramontana M., Raffaelli G. and D'Atri M. (2000) — *High-Mg Tertiary basalts in southern Sardinia (Italy).* Earth Planet. Sci. Lett., **179**, 1-7.

Montanini A., Barbieri M. and Castorina F. (1994) — *The role of fractional crystallization, crustal melting and magma mixing in the petrogenesis of rhyolites and mafic inclusion-bearing dacites from the Monte Arci volcanic complex (Sardinia, Italy).* J. Volcanol. Geotherm. Res., **61**, 95-120.

Montigny R., Edel J.B. and Thuizat R. (1981) — *Oligo-Miocene rotation of Sardinia: K-Ar ages and paleomagnetic data of Tertiary volcanics.* Earth Planet. Sci. Lett., **54**, 261-271.

Morency C. and Doin M.P. (2004) — *Numerical simulations of the mantle lithosphere delamination.* J. Geophys. Res., **109**, b03410, doi:10.1029/2003jb002414, 2004.

Morra V., Secchi F.A. and Assorgia A. (1994) — *Petrogenetic significance of peralkaline rocks from Cenozoic calcalkaline volcanism from SW Sardinia, Italy.* Chem. Geol., **118**, 109-142.

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

Moore V.M. and Wiltschko D.V. (2004) — *Syncollisional delamination and tectonic wedge development in convergent orogens.* Tectonics, **23**, tc2005, doi:10.1029/2002tc001430.

Myers J.D. (1988) — *Possible petrogenetic relations between low- and high-MgO Aleutian basalts.* Geol. Soc. Am. Bull., **100**, 1040-1053.

Ottaviani-Spella M.M., Girard M. and Cheilletz A. (1996) — *Les ignimbrites Burdigaliennes du sud de la Corse. Pétrologie et datation K-Ar.* C.R. Acad. Sci. Paris, **323**, 771-778.

Panza G.F. (1984) — *Structure of the Lithosphere Asthenosphere system in the Mediterranean region.* Ann. Geophys., **2**, 137-138.

Peccerillo A. and Lustrino M. (2004) — *Compositional variations of the Plio-Quaternary magmatism in the circum-Tyrrhenian area: deep- vs. shallow-mantle processes.* Geol. Soc. Am., Bull., in press.

Petteruti Lieberknecht A.M., Fedele L., d'Amelio F., Lustrino M., Melluso L. and Morra V. (2003) — *Plio-Pleistocene igneous activity in Sardinia (Italy).* Geophys. Res. Abstr., **5**, 7260.

Rapp R.P. and Watson E.B. (1995) — *Dehydration melting of metabasalt at 8-32 kbar: implications for continental growth and crust-mantle recycling.* J. Petrol., **36**, 891-931.

Rollet N., Deverchere J., Beslier M.O., Buennoc P., Rehault J.P., Sosson M. and Truffert C. (2002) — *Back arc extension, tectonic inheritance, and volcanism in the Ligurian sea, western Mediterranean.* Tectonics, **21**, 1015, doi:10.1029/2001tc900027.

Rosenbaum G., Lister G.S. and Duboz C. (2002a) — *Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene.* J. Virtual Expl., **8**, 107-126.

Rosenbaum G., Lister G.S. and Duboz C. (2002b) — *Relative motions of Africa, Iberia and Europe during Alpine Orogeny.* Tectonophysics, **359**, 117-129.

Rossi P., Guennoc P., Réhault J.P., Arnaud N., Jakni B., Poupeau G., Tegyey M., Ferrandini J., Sosson M., Beslier M.O., Rollet N. and Gloaguen R. (1998) — *Importance du volcanisme calco-alcalin Miocène sur la marge sud-ouest de la Corse (campagne MARCO).* C. R. Acad. Sci. Paris., **327**, 369-376.

Savelli C., Beccaluva L., Deriu M., Macciotta G. and Maccioni L. (1979) — *K/Ar geochronology and evolution of the Tertiary «calc-alkalic» volcanism of Sardinia (Italy).* J. Volcanol. Geotherm. Res., **5**, 257-269.

Scaillet B. and MacDonald (2003) — *Experimental constraints on the relationships between peralkaline rhyolites of the Kenya Rift Valley.* J. Petrol., **44**, 1867-1894.

Schiano P., Clocchiatti R., Boivin P. and Medard E. (2003) — *The nature of melt inclusions inside minerals in an ultramafic cumulate from Adak volcanic center, Aleutian arc: implications for the origin of high-Al basalts.* Chem. Geol., **203**, 169-179.

Séranne M. (1999) — *The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: an overview.* In: Durand B., Jolivet L., Horvath F. and Séranne M (Eds.) *The Mediterranean basins: Tertiary extension within the Alpine Orogen.* Geol. Soc. London Spec. Publ., **156**, 15-36.

Speranza F., Villa I.M., Sagnotti L., Florindo F., Cosentino D., Cipollari P. and Mattei M. (2002) — *Age of the Corsica-Sardinia rotation and Liguro-Provençal basin spreading: new paleomagnetic and Ar/Ar evidence.* Tectonophysics, **347**, 231-251.

Sun S.S. and McDonough W.F. (1989) — *Chemical and isotopic systematics of oceanic basalts: implications for mantle compositions and processes.* In «Magmatism in the ocean basins», Saunders A.D. and Norry M.J. (Eds.), Geol. Soc. Long. Spec. Publ., **42**, 313-345.

Tatsumi Y. (2000) — *Continental crust formation by crustal delamination in subduction zones and complementary accumulation of the Enriched Mantle I component in the mantle.*

Geochem. Geophys. Geosyst., 1 (12), doi:10.1029/2000gc000094, 2000.

TRAVERSA G., RONCA S. and PASQUALI C. (1997) — *Post-Hercynian basic dyke magmatism of the Concas-Alà dei Sardi alignment (northern Sardinia - Italy).* Per. Mineral., **66**, 233-262.

TRUA T., ESPERANÇA S. and MAZZUOLI R. (1998) — *The evolution of the lithospheric mantle along the N. African plate: geochemical and isotopic evidence from the tholeiitic and alkaline volcanic rocks of the Hyblean Plateau, Italy.* Contrib. Mineral. Petrol., **131**, 307-322.

VIGLIOTTI L. and LANGENHEIM V.E. (1995) — *When did Sardinia stop rotating?*, Terra Nova, **7**, 424-435.

WILSON M. and BIANCHINI G. (1999) — *Tertiary-Quaternary magmatism within the Mediterranean and surrounding regions.* In: Durand B., Jolivet L., Horvath F. and Séranne M (Eds.) The Mediterranean basins: Tertiary extension within the Alpine Orogen. Geol. Soc. London Spec. Publ., **156**, 141-168.

WILSON M. and PATTERSON R. (2001) — *Intraplate magmatism related to short-wavelength convective instabilities in the upper mantle: evidence from the Tertiary-Quaternary volcanic province of western and central Europe.* In: Ernst R.E. and Buchan K.L. (Eds.) Mantle plumes: their identification through time. Geol. Soc. Am. Spec. Paper, **352**, 37-58.

WILSON M. and DOWNES H. (1991) — *Tertiary-Quaternary extension-related alkaline magmatism in western and central Europe.* J. Petrol., **32**, 811-849.

WOLF M.B. and WYLLIE P.J. (1994) — *Dehydration-melting of amphibolite at 10 kbar: the effects of temperature and time.* Contrib. Mineral. Petrol., **115**, 369-383.

WOODHEAD J.D. and DEVEY C.W. (1993) — *Geochemistry of the Pitcairn seamounts, I: source character and temporal trends.* Earth Planet. Sci. Lett., **116**, 81-99.

ZARKI-JAKNI B., VAN DER BEEK P., POUPEAU G., SOSSON M., LABRIN E., ROSSI P. and FERRANDINI J. (2004) — *Cenozoic denudation of Corsica in response to Ligurian and Tyrrhenian extension: results from apatite fission track thermochronology.* Tectonics. 23, tc1003, doi:10.1029/2003tc001535.

ZINDLER A. and HART S. (1986) — *Chemical Geodynamics.* Ann. Rev. Earth Planet. Sci., **14**, 493-571.