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Field Trip Guide Book - P69

32nd INTERNATIONAL GEOLOGICAL CONGRESS

EUROPEAN SUBCONTINENTAL MANTLE AS REVEALED BY NEOGENE VOLCANIC ROCKS AND MANTLE XENOLITHS OF SARDINIA

Leaders:
M. Lustrino, P. Brotzu, R. Lonis,
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Florence - Italy
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Post-Congress **P69**

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EUROPEAN SUBCONTINENTAL MANTLE AS REVEALED BY NEOGENE VOLCANIC ROCKS AND MANTLE XENOLITHS OF SARDINIA

AUTHORS:
M. Lustrino[1 2], P. Brotzu[3], L. Franciosi[3], R. Lonis[4], L. Melluso[3], V. Morra[3]

[1] Dipartimento di Scienze della Terra - Università degli Studi di Roma "La Sapienza" - Italy
[2] Istituto di Geologia Ambientale e Geoingegneria (IGAG) CNR, Roma - Italy
[3] Dipartimento di Scienze della Terra, Università degli Studi di Napoli "Federico II" - Italy
[4] Progemisa S.p.A., Cagliari - Italy

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Front Cover:
Pliocene hawaiitic neck of Guspini

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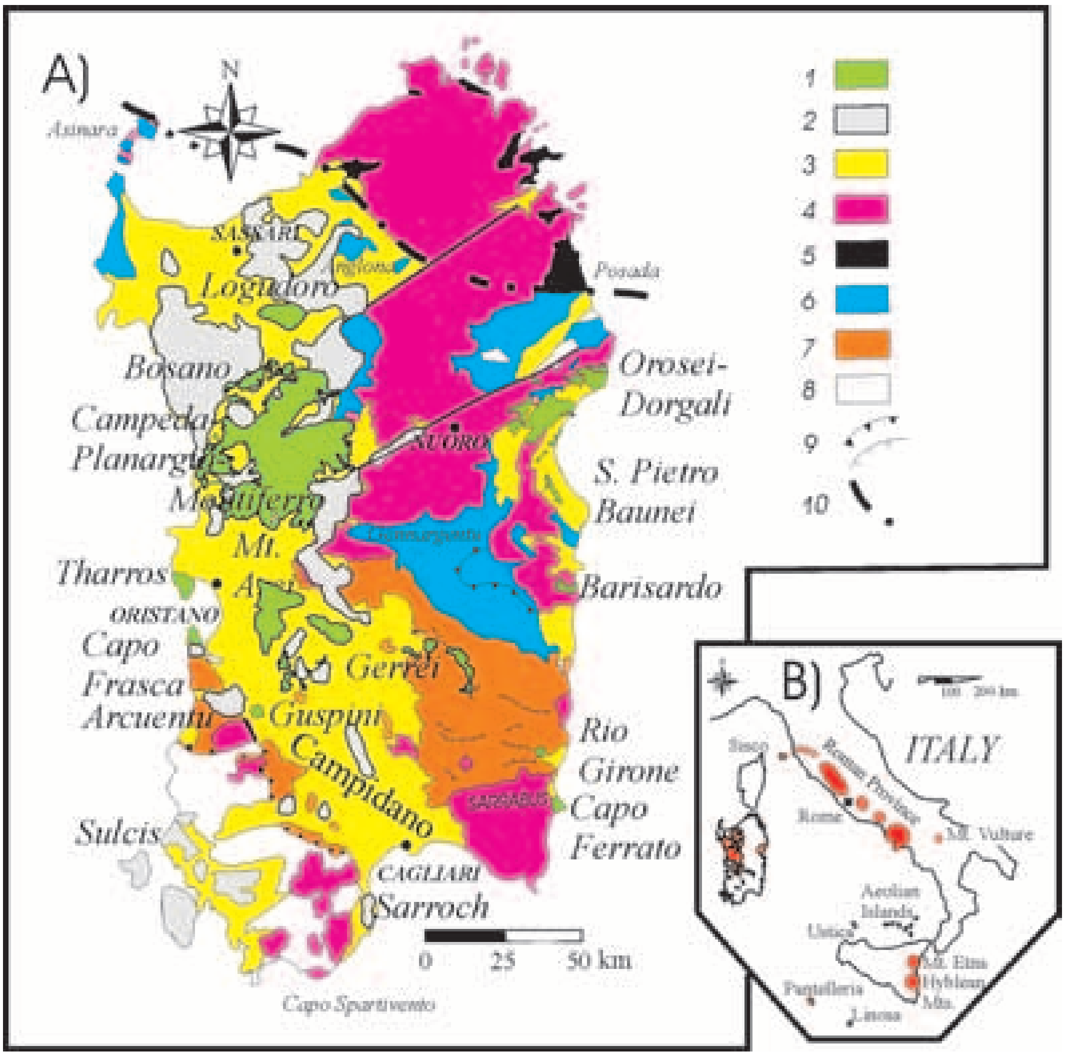
Introduction

The Neogene Italian magmatism is one of the Earth's most studied. It has attracted many researchers since XIX century because of the extremely complex geodynamic scenario in which it developed, as well as for the very wide chemical composition range of its igneous products (Lustrino, 2000a; Peccerillo, 2001; Conticelli et al., 2002).

Many non-specialistic researchers believe that Italian magmatism is concentrated only on the eastern border of the Tyrrhenian Sea (from southern Tuscany down to Sicily's Mt. Etna and the Aeolian islands). However, it should be stressed that other loci of intense igneous

Figure 1 - a) Simplified geological map of Sardinia. 1= Plio-Pleistocene volcanic rocks; 2 = Oligo-Miocene volcanic rocks; 3 = Cenozoic sedimentary cover; 4 = Hercynian granitoids; 5 = Paleozoic and Precambrian metamorphic rocks; 6 = Cambrian-Devonian metasandstones, metabasalts, metapelites (internal nappes); 7 = Cambrian-Carbonifeous metasandstones, slates, metabasalts and metarhyolites (external nappes); 8 = Precambrian-Carboniferous metasandstones, quartzites, metapelites, orthogneiss, metalimestones (external zone); 9 = Main thrusts; 10 = Posada-Asinara line. b) Schematic occurrences of the main igneous provinces of Italy.



activity during the Neogene are also: northern Italy (the Alps), the Tyrrhenian abyssal plain, the Sicilian Channel (in between Sicily and Tunisia) and Sardinia (the western border of the Tyrrhenian Sea) (Fig. 1). In order to propose a comprehensive magmatological model for the circum-Tyrrhenian area, Sardinia is thus a major study area.

With very few exceptions (e.g., Cioni et al., 1982; Di Battistini et al., 1990; Montanini et al., 1994), up to a few years ago the Sardinian magmatism (~ 32-0.1 Ma) was excluded from detailed geochemical-petrological investigations, the only scientific papers being mostly confined to the '70s. From the second half of the '90s an increasing number of data and interpretations of Sardinian volcanic rocks became available for the scientific community (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). From these studies, a complex petrological scenario became clear, and a large number of hypotheses have been proposed in order to explain two points: 1) the origin of the igneous activity in relation with the Alpine geodynamics, and 2) the origin of the modification that affected the mantle sources of these magmas.

The island of Sardinia (Figs. 1 and 2) records two distinct volcanic phases during Oligocene-Miocene and Plio-Pleistocene times. These phases produced magmas with completely different petrographic, volcanological and geochemical characteristics. The Oligocene-Miocene 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) are subalkaline, with serial affinity going from tholeiitic to calcalkaline, and subduction-related signatures (Morra et al., 1994, 1997; Brotzu et al., 1997a; Lonis et al., 1997; Downes et al., 2001; Franciosi et al., 2003). On the other hand, the Plio-Pleistocene volcanic rocks (~5-0.1 Ma) are mildly to strongly alkaline (mostly sodic) to subalkaline (with tholeiitic affinity), with peculiar within-plate geochemical signatures (Lustrino et al., 1996, 2000, 2002).

Studying the Neogene volcanic rocks of Sardinia is interesting for investigating the geochemical signature of this section of the European subcontinental mantle, as well as the magmatic evolution of the western Mediterranean area for several reasons: 1) the most mafic rocks of both volcanic cycles have compositions typical of mantle-derived melts; 2) the Plio-Pleistocene Sardinian volcanic rocks are often associated with mantle xenoliths that provide the only direct insights into the subcontinental mantle composition; 3) their geographic position is critical, as the region was involved in two major tectonic events that reworked the European subcontinental mantle (the Hercynian and Alpine orogenies); 4) the temporal 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 and the associated igneous activity is part of the Alpine Orogeny and related to the relative movements of Africa (Gondwana) towards Europe (Laurasia).

The circum-Mediterranean area is a geodynamically complex region which has been characterized during the last 30 Ma by a magmatic activity with a wide range of chemical compositions, from strongly alkaline (sodic to potassic and ultrapotassic) to subalkaline (tholeiitic and calc-alkaline) (Turner et al., 1999; Cebrià et al., 2000; Lustrino et al., 2000; Downes et al., 2001; Conticelli et al., 2002; Coulon et al., 2002; Trua et al., 2002).

Up to Oligocene times, the Sardinia-Corsica block was in crustal continuity with the southern European continental margin (Provence, France). This block first started to rotate counterclockwise and then moved eastwards in consequence of the opening of the Ligurian-Provençal as a back-arc basin. The formation of this basin is considered to be related to the subduction of the African oceanic crust (the Ionian Sea oceanic crust) under the European continental margin toward NNW (Beccaluva et al., 1994 and references therein). The Eocene-early Oligocene Alpine compression was followed by transtensive and extensional regimes (Hyppolite et al., 1993; Carmignani et al., 1994; Lecca et al., 1997) that caused, during the Oligocene, faulting and rifting processes in the southern European continental crust, including in Sardinia. These extensional stresses led to: 1) the counterclockwise rotation and, afterwards, the eastward translation of the Sardinia-Corsica continental microplate, together with the coeval opening of the Ligurian-Provençal and Balearic back-arc basins (Doglioni et al., 1999; Speranza et al., 1999 and references therein); 2) the formation of the Oligo-Miocene rift system (the so-called *Fossa Sarda;* Sardinian Trough) that crosses the whole island from north to south with a length of about 220

Figure 2 - Main outcrops of Plio-Pleistocene (dark grey) and Oligo-Miocene volcanic rocks (light grey)

km. The Fossa Sarda can be interpreted as an aborted rift system.

Orogenic magmatic activity associated with the opening of these back-arc basins went from the Valencia Trough to southern Sardinia in a time span ranging from ~32 to ~ 15 Ma (Beccaluva et al., 1985; Martì et al., 1992; Morra et al., 1994; Lecca et al., 1997). The Sardinian volcanism occurred along and within the Fossa Sarda and reached its climax of activity between 21 and 18 Ma (Beccaluva et al., 1985; Lecca et al., 1997; Morra et al., 1997). The products are subaerial and submarine, and mainly consist of andesite and dacite to rhyolite ignimbrites and, subordinately, of basalt. The explosive and the effusive products are interlayered and partially contemporaneous. On S. Pietro and S. Antioco islands, as well as on the Sulcis mainland (SW Sardinia) peralkaline rhyolites have also been erupted (Araña et al., 1974; Morra et al., 1994).

During the Langhian (~15 Ma) the eastward

Sample	Locality	Source	Type (TAS)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Mg#
KR 24	Montresta	M 97-F 03	Basalt (HMB)	47,51	0,79	15,24	10,46	0,19	11,06	11,89	2,15	0,45	0,26	0,70
KR14	Montresta	M 97	Basalt (HAB)	48,74	0,82	16,67	10,62	0,19	7,86	12,63	1,99	0,61	0,27	0,61
KR19	Montresta	M 97	Basaltic Andesite	53,69	1,10	18,01	9,78	0,14	3,20	8,90	3,22	1,70	0,35	0,42
KR29	Montresta	M 97	Andesite	56,99	0,99	17,57	8,48	0,18	3,12	7,48	3,78	1,32	0,35	0,45
SI01	Sindia	L 97	Basalt (HAB)	49,08	1,02	18,16	11,06	0,20	6,95	10,21	2,19	0,92	0,22	0,56
SIN22	Sindia	L 97	Basaltic Andesite	54,94	0,87	17,32	9,41	0,19	4,35	7,72	2,74	2,01	0,29	0,52
SIN43	Sindia	L 97	Andesite	60,61	0,69	16,78	6,99	0,12	2,08	6,10	2,75	2,91	0,17	0,44
FC136	Narcao	M 94	Basalt (HAB)	51,27	1,07	19,22	9,02	0,14	5,27	10,43	2,57	0,67	0,35	0,57
V 1228	Narcao	B 97b	Basaltic Andesite	53,99	0,95	18,62	9,89	0,15	2,91	8,89	2,84	1,45	0,29	0,40
V 1966	Narcao	B 97b	Andesite	59,31	0,75	18,73	7,11	0,10	2,12	7,47	2,64	1,47	0,30	0,40
ST46	Arcuentu	D 01	Basalt (HMB)	51,28	0,58	14,61	10,65	0,18	10,09	10,05	1,89	0,59	0,09	0,68
AR280	Arcuentu	B 97a-F 03	Basalt (HMB)	51,67	0,76	15,38	9,87	0,18	9,38	10,15	1,98	0,53	0,09	0,68
ST318	Arcuentu	D 01	Basaltic Andesite	54,45	0,68	15,86	8,74	0,15	8,06	9,78	2,16	1,20	0,11	0,64
RL92	Arcuentu	B 97a	Basaltic Andesite	55,77	0,63	15,76	9,26	0,17	7,30	10,31	2,01	0,71	0,08	0,64
ST134	Arcuentu	D 01	Andesite	63,32	0,79	16,24	5,56	0,08	2,62	5,70	2,86	2,01	0,13	0,52
AR164	Arcuentu	B 97a	Andesite	59,25	0,90	18,12	7,96	0,14	2,27	7,34	2,56	1,90	0,13	0,40
SH-14d	Sarroch	C 97	Gabbronorite	51,33	0,45	19,17	8,60	0,18	6,79	10,95	1,76	0,68	0,07	0,64
SH-22	Sarroch	C 97	Basalt (HAB)	52,18	0,80	17,18	9,97	0,18	6,09	10,45	2,28	0,75	0,14	0,58
SH-5	Sarroch	C 97	Basaltic Andesite	54,75	0,79	18,23	9,40	0,18	4,62	8,51	2,45	0,89	0,18	0,52
SH-49	Sarroch	C 97	Andesite	60,39	0,61	18,05	6,17	0,16	2,21	7,97	3,09	1,26	0,15	0,44
CM-37-603.5	Sulcis	M 94	Dacite	66,32	0,62	16,27	4,99	0,05	0,97	2,60	2,88	5,56	0,14	0,28
SE-370bis	Sulcis	M 94	Rhyolite	70,62	0,43	14,56	3,35	0,03	0,61	1,27	4,08	5,17	0,08	0,22
MS1-360	Sulcis	M 94	Comendite	73,37	0,28	13,06	2,95	0,08	0,17	0,16	4,89	5,03	0,02	0,11
1531	Logudoro-Bosano	D 76	Basalt (HAB)	45,12	1,25	18,41	13,08	0,28	6,76	12,08	2,22	0,67	0,19	0,54
1532	Logudoro-Bosano	D 76	Basalt (HAB)	49,67	1,00	18,94	11,79	0,20	5,38	9,94	2,90	1,00	0,19	0,50
1528	Logudoro-Bosano	D 76	Basaltic Andesite	54,00	0,75	18,47	8,50	0,15	4,37	8,39	2,74	2,13	0,26	0,55
2	Logudoro-Bosano	C 73	Basalt (HAB)	50,52	0,97	19,17	10,55	0,19	4,60	9,98	2,71	1,11	0,26	0,49
7	Logudoro-Bosano	C 73	Basaltic Andesite	54,10	0,71	18,02	8,71	0,16	4,80	8,82	2,76	1,68	0,25	0,55
3	Logudoro-Bosano	C 73	Andesite	57,15	0,81	18,00	7,59	0,14	3,14	7,52	3,02	1,85	0,18	0,48
9	Logudoro-Bosano	C 73	Dacite	66,27	0,59	16,07	4,72	0,09	1,26	4,47	3,63	2,89	0,21	0,37
19	Logudoro-Bosano	C 73	Rhyolite	71,85	0,25	14,84	2,68	0,07	0,29	2,43	1,47	4,01	0,11	0,20
MAL-28	Marmilla	TS	Basaltic Andesite	53,19	0,70	14,61	9,28	0,17	9,25	9,66	1,93	0,80	0,11	0,70

(Table 1) - 1-3. Representative analyses of Oligo-Miocene volcanic rocks of Sardinia. Sources:M 97 = Morra et al., 1997 ; L 97 = Lonis et al., 1997 ; M 94 = Morra et al., 1994 ; B 97b = Brotzu et al., 1997b ; D 01 = Downes et al., 2001 ; B 97a = Brotzu et al., 1997a ; F 03 = Franciosi et al., 2003 ; C 97 = Conte, 1997 ; D 76 = Dostal et al., 1976 ; C 73 = Coulon et al., 1973 ; TS = This study. HMB = High Mg Basalt ; HAB = High Al Basalt.

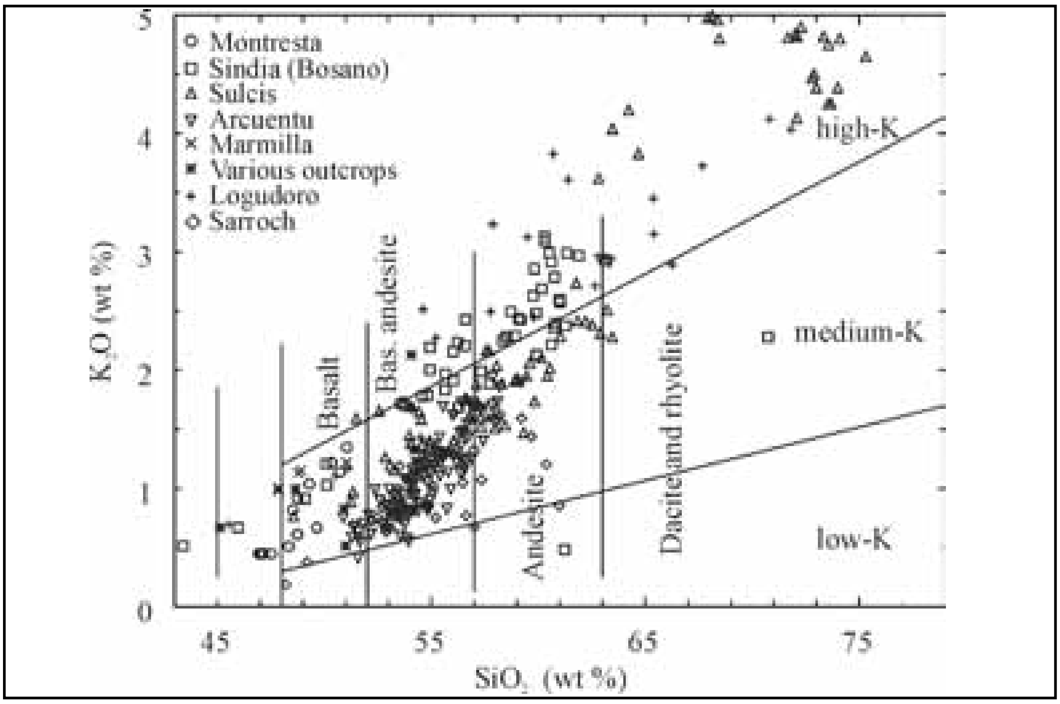


Figure 3 - SiO_2 vs. K_2O diagram (Le Maitre, 2002) of Oligo-Miocene volcanic rocks of Sardinia. References given in the text.

Sample	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$\delta^{18}O$	V	Cr	Co	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Cs
KR 24	0,70413	0,51274	18,70	15,63	38,41		333	793	33,7	229	93,4	93,5	7,12	450	15,3	38,1	1,97	0,0
KR14							318	186		54		89	16	392	20	40	4	
KR19	0,70573						261	10		0		101	48	338	31	109	10	
KR29	0,70592						170	6		7		78	64	332	31	135	12	
SD1	0,70519						324	19		16			16	313	20,11	67	6	
SN22	0,70615						166			7			64	414	27	147	9	
SN43	0,70592						119			7			95	395	25	178	10	
FC136	0,70480																	
V 1228	0,70610						390	10	23	16			35	469	22	132	6	
V 1666	0,70708						123	10	10	11			69	361	21	156	7	
ST46	0,70538	0,51269				6,4	265	268		148	106	75	18,1	193	15,4	37	1,8	
AR280	0,70625	0,51268	18,63	15,65	38,76		255	701	16,4	116	84,8	77	13,3	192	17,5	56,4	2,38	0,3
ST116	0,70910	0,512318				7,1	233	241		84	54	80	42,0	193	22,7	88,8	4,8	
RL92								402		101			26	201	16	78	2	
ST136	0,70971	0,512246				7,5	164	45		25	49	67	132	190	30,8	168	10,5	
AR164								30		7			56	256	32	188	10	
SH-14d	0,70632						156	41	22	18			24	357	30	66	3	
SH-27							251	140	26	17			17	369	10	100	4	
SH-5	0,70606						137	1	7	3			24	390	13	119	6	
SH-48	0,70744						125	1	13	13			54	315	21	105	4	
CM-37405,5	0,70735						30	8				80	167	193	44	544	25	
SE-37bris	0,70670						13	8				92	191	139	43	442	31	
MU-36d1	0,70609						5	7				66	210	21	54	635	77	
1531	0,7044												24	495				
1532	0,7047												26	469				
1528	0,7060												59	744				
2																		
7																		
3																		
9																		
10																		
MAL-28	0,70864						212	549	36	105		79	33,7	198	19,8	96	4,7	1,2

(Table 1) - 2-3.

Sample	Ba	Hf	Ta	Pb	Th	U	Sc	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
KR 24	491	1,13	0,14	1,8	0,54	0,13		4,2	10,5	1,69	7,93	2,26	0,775	2,34	0,394	2,44	0,504	1,42	0,200	1,41	0,23
KR14	89						31	1	12												
KR19	238						28	18	52												
KR29	330						22	21,23	40,19	5,36	21,85	5,11	1,4	4,5	0,76	4,82	1,09	2,89	0,43	2,97	0,47
SD1	196			6	4		11	15,17	32,74		18,34	4,51	1,19	3,72		3,56		1,82		1,90	0,29
SN22	315			11	7		19	25	52,61		23,98	5,55	1,46	4,65		4,41		2,48		2,67	0,42
SN43	493			14	15		18	30	59,67		26,66	5,84	1,33	4,49		3,99		2,31		2,46	0,42
FC136								12,7	27,2		17,9	4,93	1,34	4,41		3,98		1,79		1,90	0,26
V 1228	541							23	48												
V 1666	560							23	51												
ST46	129	1,1	0,07	2,9	2,2	0,22	16	4,6	11,4		6,6	1,79	0,61	1,84						1,44	0,27
AR280	153	1,42	0,17	4	1,11	0,22		6,55	14,1	1,92	7,91	2,2	0,784	2,58	0,437	2,91	0,596	1,59	0,239	1,76	0,26
ST116	293	2,1	0,52	8,5	5,6	0,56	10	19,4	29,8		15,1	3,67	0,88	3,77		3,26		2,17		2,04	0,31
RL92	260							11	22		10										
ST136	545	4,6	0,79	20	11,8	5,1	21	27,4	57		26,1	5,03	0,99	4,84		4,65		2,35		2,48	0,36
AR164	573							31	60		29										
SH-14d	248	1,22	0,12		2,13			11,20	23,00	10,80		2,81	0,65	3,13	0,61					2,09	0,35
SH-27	279	1,96	0,20		2,16			13,36	26,10		11,90	3,09	0,66	3,42	0,63					1,94	0,32
SH-5	394	3,01	0,41		4,56			20,20	39,30		19,50	4,61	1,20	5,02	0,93					3,79	0,54
SH-48	495	2,78	0,30		2,76			20,10	39,70		18,10	3,89	1,17	4,20	0,67					2,46	0,40
CM-37405,5	795			13				40,5	86,5		42,1	9,00	1,79	7,30		7,09		3,25		3,64	0,51
SE-37bris	872			20				51,7	94,6		45,1	8,55	1,90	7,66		7,04		3,50		3,84	0,55
MU-36d1	179			12				62,6	27,5		34,0	11,50	0,71	0,21		0,17		4,41		4,95	0,69
1531								7,5	17,7		12,5	3,15	1,04	3,71	0,63		0,74			1,98	0,30
1532								15	34,5		22,4	4,8	1,49	3,84	0,63		0,86			1,99	0,32
1528								16	71,9		31,7	5,89	1,59	4,23	0,63		0,80			2	0,32
2																					
7																					
3																					
9																					
10																					
MAL-28	297		0,51	5,4	5,6	0,79	41	34,5	28,7	3,6	14,5	3,19	0,78	3,13	0,54	3,21	0,67	1,66	0,27	1,76	0,27

(Table 1) -2-3.

translation of the Sardinia-Corsica block Stopped. As a consequence, also the opening of the Ligurian-Provençal and Balearic basins on the western side of Sardinia Stopped. The oceanization processes continued on the eastern side of Sardinia with the opening of the Tyrrhenian Sea. The Sardinia-Corsica block can be thus considered a continental lithospheric portion isolated during the extensional movements that produced a lithospheric boudinage (e.g., Carminati et al., 1998; Doglioni et al., 1998).

The igneous activity in the embrional western Mediterranean Sea did not Stop: the youngest igneous rocks of the Oligo-Miocene volcanic cycle of Sardinia (~ 15 Ma; south-west Sardinia; Araña et al., 1974; Morra et al., 1994) are contemporaneous with the Sisco lamproite in northwestern Corsica (~15 Ma; Civetta et al., 1978) that marks the first evidence of the Tyrrhenian Sea's opening.

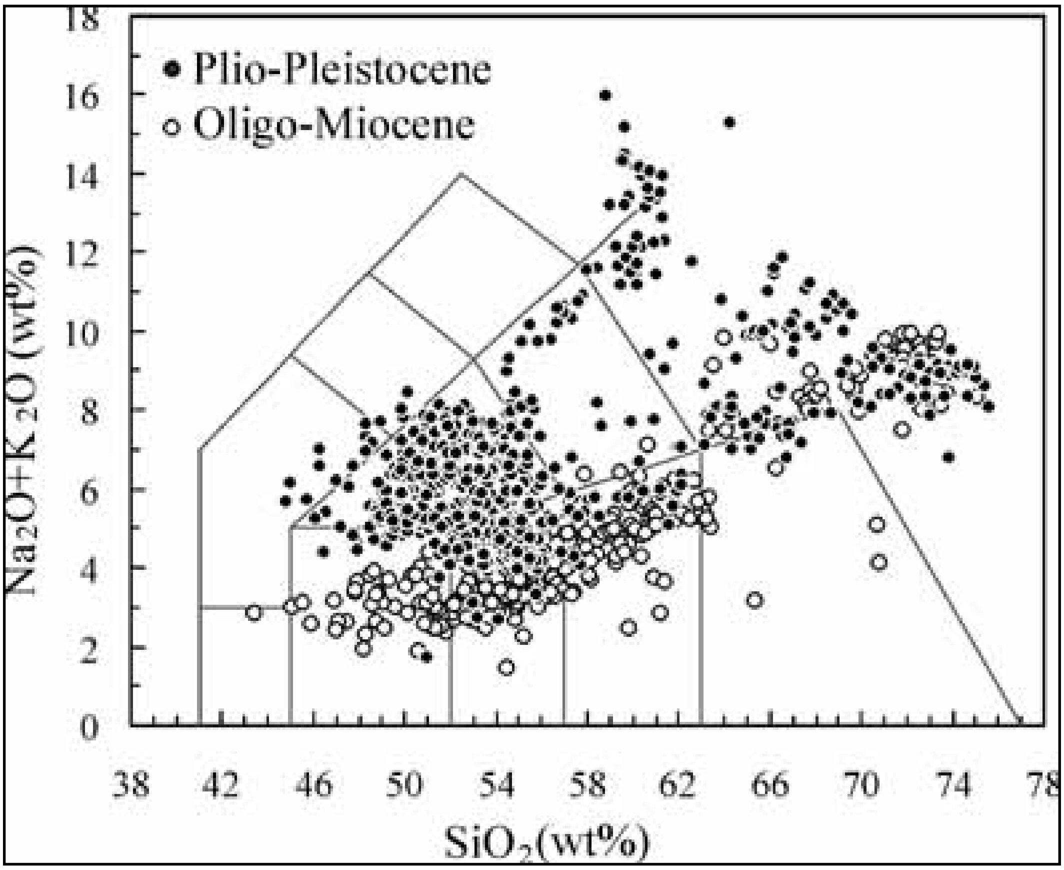


Figure 4 - SiO_2 vs. Na_2O+K_2O (TAS) diagram (Le Maitre, 2002) of Oligo-Miocene (white circles) and Plio-Pleistocene (black circles) volcanic rocks of Sardinia. References given in the text.

In the westernmost sector of the extending Tyrrhenian area, extensional movements resulted in the development of a rift system (Campidano graben in SW Sardinia, N-S oriented fault system in the Sarrabus area in the SW sector) as well as in within-plate magmatism. This magmatic activity developed in Sardinia about 10 Ma after the end of the "orogenic" Oligo-Miocene cycle, from ~ 5.3 Ma (Capo Ferrato; southwest Sardinia) to ~ 0.1 Ma (Logudoro, northern Sardinia), thus roughly contemporaneously with the potassic to ultrapotassic magmatic activity of the so-called Roman Comagmatic Province in central-southern Italy.

The Cenozoic-Quaternary magmatic evolution of Sardinia (the Oligo-Miocene orogenic volcanic cycle followed by Plio-Quaternary anorogenic volcanism) is a common feature throughout the entire circum-Mediterranean area and has its counterparts in many other circum-Mediterranean igneous provinces (Lustrino, 2003).

The Oligo-Miocene and the Plio-Pleistocene Sardinian volcanic rocks belong to the well-studied Cenozoic European Volcanic Province (hereafter CEVP) for which a large set of chemical data is currently available (e.g., Wilson and Downes, 1991; Pécskay et al., 1995; Liotard et al., 1999; Jung and Hoernes, 2000; Wedepohl, 2000; Bogaard and Wörner, 2003; Lustrino, 2003).

The Oligo-Miocene volcanic rocks of Sardinia

The Oligo-Miocene (32-15 Ma) volcanic activity of Sardinia occurred only in the western sector of the island along the *Fossa Sarda* (Figs 1 and 2) and is concentrated in the 23-17 Ma time interval (Savelli et al., 1979; Beccaluva et al., 1985).

The volcanic activity of Sardinia can be outlined as follows (Lecca et al., 1997):

1) Early sequences (~32-24 Ma) consisting of

small lava domes and subvolcanic intrusions, generally of andesitic composition;
2) From ~ 24 Ma, at the beginning of the Sardinian Rift system, the volcanic products were essentially dacitic to rhyolitic ignimbrites and subordinate lavas (Dostal et al., 1982);
3) The climax of effusive activity (21-18 Ma), during the maximum tectonic extension, was characterized by the effusion of more mafic magmas, some of which with primitive character (Arcuentu and Montresta; Brotzu et al., 1997a; Morra et al., 1997; Downes et al., 2001; Franciosi et al., 2003).
4) At ~ 15 Ma, the last activity was concentrated in the Sulcis area (southwestern Sardinia) where also potassic peralkaline rhyolitic magmas were erupted (Araña et al., 1974; Morra et al., 1994). Worth reminding is that in the Sulcis area (S. Pietro Island) is the comendite type-locality (mildly-peralkaline rhyolite, MacDonald, 1974).

All these volcanic products have subalkaline affinity (both tholeiitic and calcalkaline). The rocks show mainly medium-K serial character; the more evolved rocks (SiO_2 > 55 wt%) tend to have high-K affinity, in particular those from Logudoro-Bosano (northern Sardinia; Dostal et al., 1982; Lonis et al., 1997) and Sulcis (Araña et al., 1974; Morra et al., 1994); a few basaltic samples from the Arcuentu (Brotzu et al., 1997a) and Sarroch (Conte, 1997) districts (southern Sardinia) fall within the low-K field (Tab. 1; Fig. 3).

In summary, dacitic to rhyolitic ignimbrites are the prevailing products of the Oligo-Miocene volcanic activity, followed by andesitic, basaltic andesitic and, finally, basaltic lavas (Fig. 4). These rocks crop out in northern (the Anglona, Logudoro and Bosano areas), central (Marghine) and southern Sardinia (the Arcuentu, Marmilla, Sarroch and Sulcis areas)

Anglona. The volcanic products outcropping in the Anglona sector are andesitic lava domes with small, interbedded ignimbritic levels overlaid by volcaniclastic levels, pillow lavas and breccias of andesitic composition. More to the top are welded ignimbrites and, finally, small andesitic lava flows and pyroclastic levels of ash and pumice (Lecca et al., 1997).

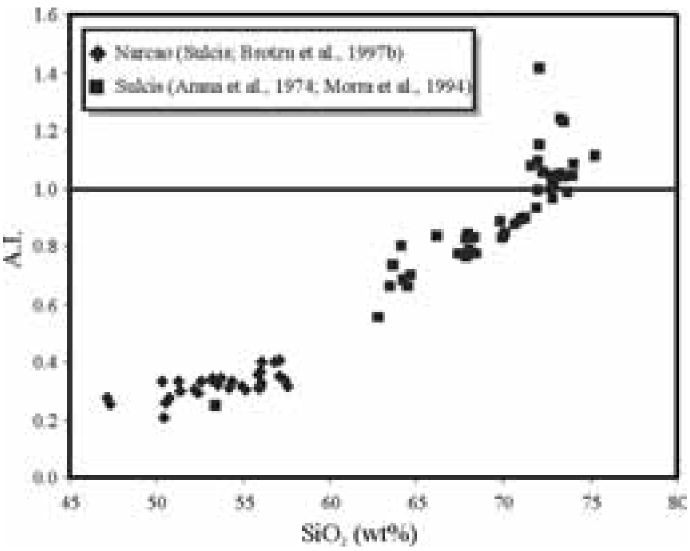


Figure 5 - SiO_2 vs. A.I. of the volcanic rocks of Sulcis.

Logudoro-Bosano. The Oligo-Miocene ignimbritic products outcrop mainly in northwestern Sardinia (the Logudoro-Bosano area), associated with subordinate calcalkaline andesitic rocks. In this area at least four volcanic phases have been identified (Coulon, 1977; Lecca et al., 1997). The oldest rocks consist of ash and pumice flow deposits, variably welded, with rhyolitic composition. These products are overlaid by dacitic to rhyolitic lava domes. The youngest products are again rhyolitic ignimbrites with variable degrees of welding. The total thickness of this succession is > 700 m. The origin of these ignimbrites has been related to partial melting of a crustal protolith with intermediate composition (Coulon et al., 1978). The extensive degree of partial melting in the crust could have been caused by the ascent and the heat release of andesitic magmas (the associated andesitic sequences, Coulon, 1977; Coulon et al., 1978). The least-evolved effusive rocks are found in erosion windows under the ignimbritic covers in the Sindia and Montresta areas (northwestwern Sardinia). The volcanic sequence of Sindia (Lonis et al., 1997) is made up of basaltic to andesitic lava domes and lava flows associated with local epiclastic breccias and ash flows. The evolution of the volcanic suite has been modeled with an open system fractional crystallization of plagioclase, clinopyroxene, olivine and Ti-magnetite, starting from different parental high alumina basalts (HABs ; MgO < 7 wt%; Al_2O_3 > 16 wt%). In the Montresta area the outcropping rocks are mainly HABs and high magnesia basalts (HMBs; MgO > 7 wt%; Al_2O_3

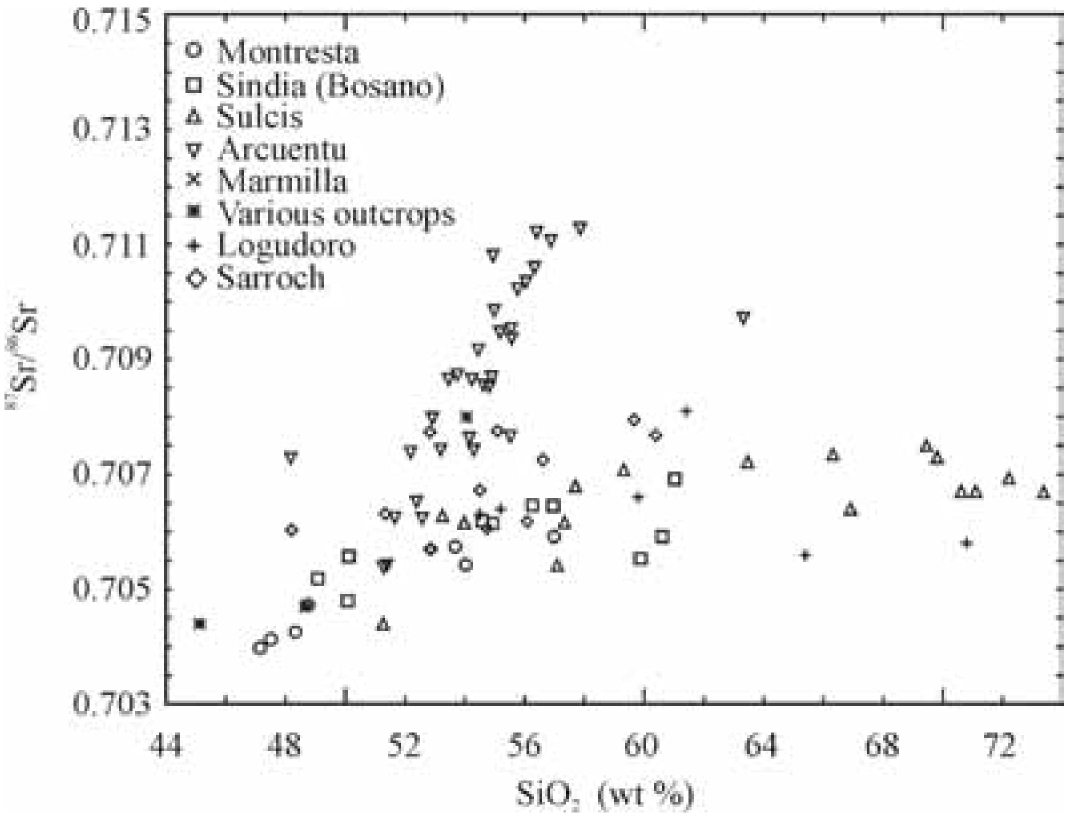


Figure 6 - SiO_2 vs. $^{87}Sr/^{86}Sr$ initial ratios of Oligo-Miocene volcanic rocks of Sardinia. References given in the text.

< 16 wt%), basaltic andesites and rare andesite with tholeiitic character (Morra et al., 1997). The HMBs, represent near-primitive compositions and are considered the parental magmas of the whole volcanic suite.

Marghine. The central section of Sardinia is characterized by sequences of andesitic lava flows followed by densely-welded ignimbrites and, finally, by pyroclastic flow levels (ash and pumice). Southward, the bottom of the sequence is represented by ash and pumice flow deposits followed by densely-welded ignimbrites, marine and continental sediments (Aquitanian-Burdigalian) and, finally, by the upper ash and pumice flow levels.

Arcuentu. The volcanic sequences of Arcuentu in southwestern Sardinia are intercalated with continental and marine sediments and were divided into four main units by Assorgia et al. (1984). From the bottom to the top: basaltic to andesitic domes and lava flows (30-24 Ma), effusive and explosive products emplaced in submarine settings (~23-21 Ma), effusive and pyroclastic andesites (~21-18 Ma), and, finally, basaltic dykes and sills (~18-17 Ma). On the basis of trace element variations in the Arcuentu rocks, Brotzu et al. (1997a) proposed an evolution of the magmas driven mainly by polybaric fractional crystallization in closed systems, without strong involvement of crustal assimilation.

Marmilla. The volcano-sedimentary succession (~ 300 m thick) is mainly made up by pyroclastic units (poorly-welded, strongly-porphyritic ash and pumice pyroclastic flows, in some cases covered by a thick pile of welded ignimbrites) occasionally interbedded on the top with andesitic flows (Lecca et al., 1997). In southern Sardinia, High-Mg near-primary basaltic pillow lavas have been recognized in the Lower Burdigalian volcano sedimentary succession of the Villanovaforru area (Mattioli et al., 2000).

Sarroch. In the Sarroch district (southernmost Sardinia) the outcropping Oligo-Miocene volcanic

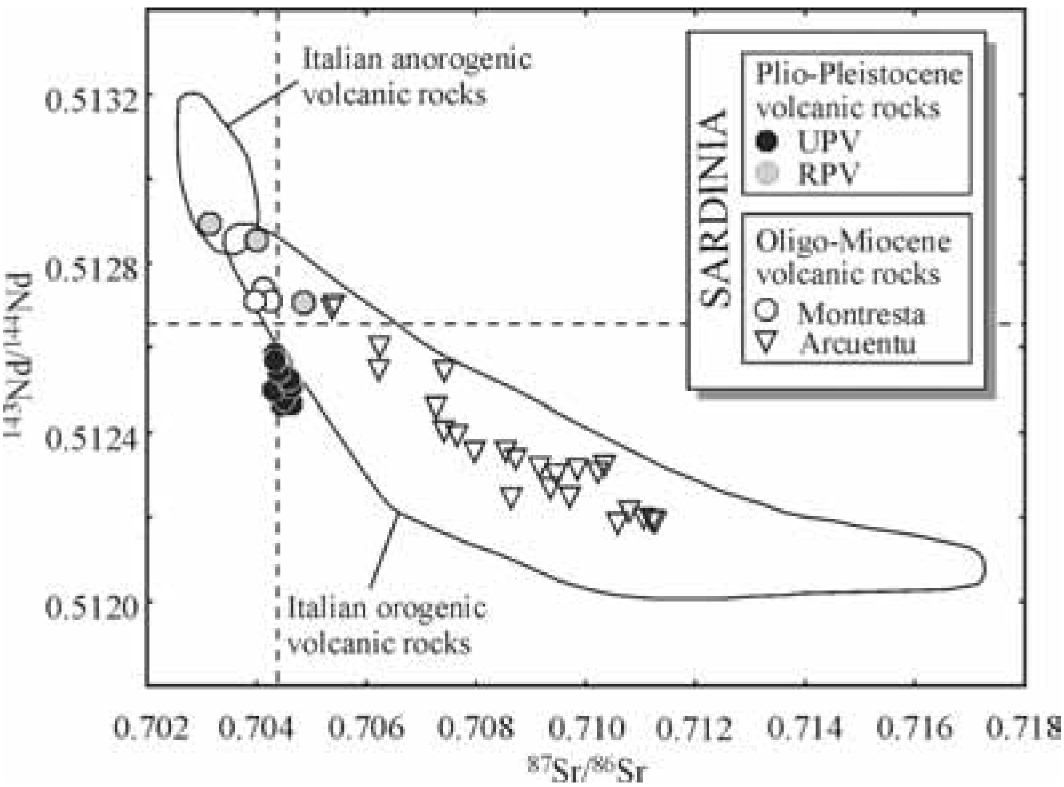


Figure 7 - $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ initial ratios of orogenic Oligo-Miocene and anorogenic Plio-Pleistocene volcanic rocks of Sardinia. References given in the text. UPV = Unradiogenic Pb Volcanics; RPV = Radiogenic Pb Volcanics (see below). For comparison, the fields of Neogene Italian anorogenic (Mt. Etna, Hyblean Mts.) and orogenic (Aeolian Islands, Roman Comagmatic Province) volcanic rocks) are also shown (References in Lustrino, 2000a and in the text).

rocks are prevailing pyroclastic and epiclastic andesitic breccias and conglomerates with subordinate basalts of calcalkaline affinity. Magmatic bodies with intrusive rocks (gabbronoritic to gabbrodioritic in composition) and late-stage dykes have also been found (Conte, 1997). Mineralogical, geochemical and Sr-isotope data indicate the presence of at least two rock groups evolved from different degrees of fractional crystallization and crustal contamination (at different depths) starting from different parental magmas.

Sulcis. The Sulcis area is located in southwestern Sardinia, outside the Sardinian Rift. The volcanic products can be schematized into a “lower” and “upper sequence”. The first sequence is made up by basaltic andesitic and andesitic lava domes and flows, with subordinate basalts, outcropping in the Cixerri graben, in the Narcao-Carbonia area and on S.Antioco Island. The effusive products are associated with subordinate pyroclastic and epiclastic breccias. The upper sequence consists of dacitic, rhyolitic and comenditic products, mainly in ignimbritic facies. The sequence, outcropping in the Nuraxi Figus – Seruci area and on S.Pietro and S.Antioco Islands, overlies Oligocene continental sediments in the northern Sulcis and the lower sequence in the Carbonia-Narcao area. All together, the Sulcis igneous rocks show an almost complete range of compositions from basalts to rhyolite (with a limited SiO_2 gap from ~58 to ~66 wt%), the most SiO_2-rich characterized by peralkaline affinity (Araña et al., 1974; Morra et al., 1994; Brotzu et al., 1997b) (Fig. 5).

Here calcalkaline basaltic andesites, andesites and minor basalts (~ 28 to 17 Ma; lava domes and lava flows with associated pyroclastic and epiclastic deposits; Brotzu et al., 1997b) are overlaid by Miocene (~18 to 15 Ma) felsic rock (dacite to calcalkaline rhyolites and comendites (Araña et al., 1974; Morra et al., 1994; Brotzu et al., 1997b). Many andesitic rocks contain abundant basaltic enclaves, indicating local mingling. The presence of xenocrystic assemblages in many lavas has been interpreted as the result of the recycling of settled crystals in zoned magmatic chambers (Brotzu et al., 1997b).

The rocks of the "upper sequence" (dacitic to rhyolitic in composition) have been divided into five groups (Morra et al., 1994):

G1) porphyritic to glomeroporphyritic (porphyritic index = 15-20%) dacites, with eutaxitic textures, made up of plagioclase + orthopyroxene + clinopyroxene ± olivine and locally plagioclase + biotite + amphibole ± orthopyroxene+clinopyroxene. In the G1 dacites gabbronoritic nodules and andesitic to leucoandesitic fragments are present. Accessory phases are Ti-magnetite, ilmenite and apatite.

G2) porphyritic to glomeroporphyritic rhyodacites with phenocrysts of plagioclase, clinopyroxene and orthopyroxene and microphenocrysts of sanidine. Gabbronoritic glomerules and andesitic lithics are also present with the latter being less abundant than in G1 dacites. Ti-magnetite and ilmenite are the accessory minerals.

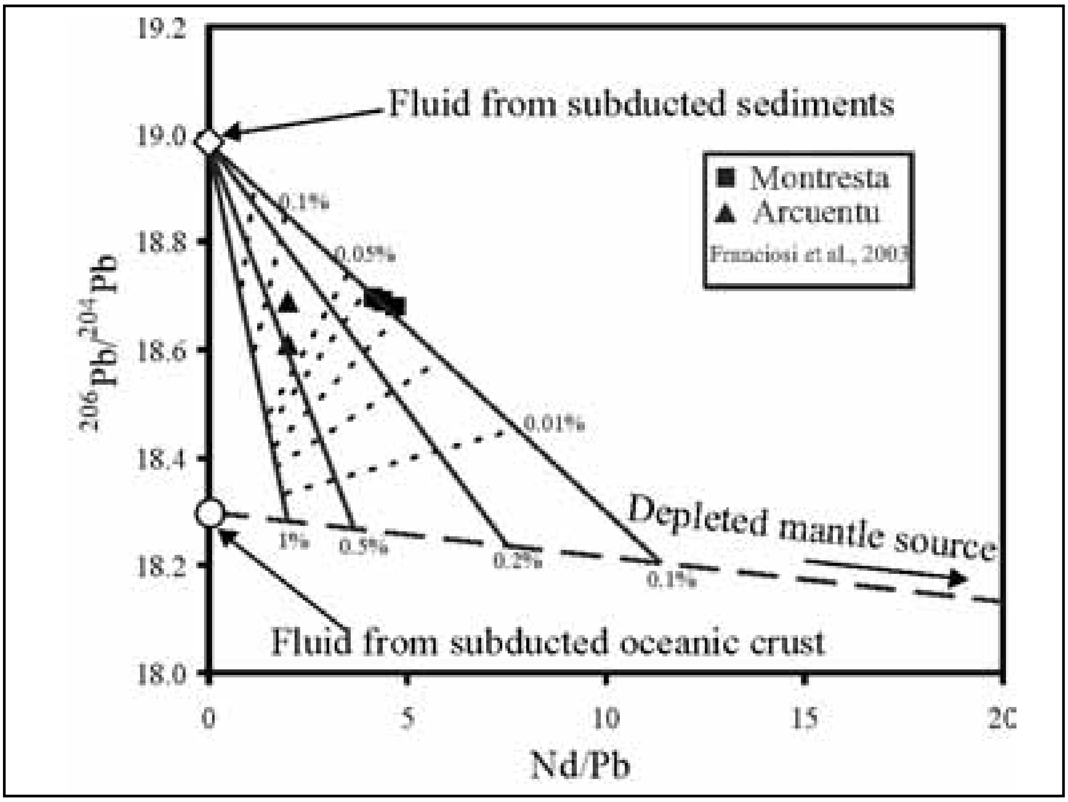
G3) hololeucocratic (colour index = 2%) transitional to peralkaline rhyolites with plagioclase (often mantled by anorthoclase) and sanidine as the main phenocrysts, as well as rare clinopyroxene and orthopyroxene. Accessory phases are Ti-magnetite and ilmenite. They occasionally contain leucoandesitic blobs.

G4) phenocryst-poor comendites made up of Na-sanidine, anorthoclase, quartz and microphenocrysts of Na-amphibole and aegirine. The accessory phases are: Ti-magnetite, ilmenite, fayalite and zircon.

G5) hololeucocratic rhyolites with glassy, partially devitrificated, groundmass and phenocrysts of Na-sanidine, plagioclase and subordinate anorthoclase.

Neighboring areas. High-K calcalkaline dacitic to rhyolitic ignimbrites of Burdigalian age (~19 Ma)

Figure 8 - Nd/Pb versus $^{206}Pb/^{204}Pb$ diagrams for the Mt. Arcuentu and Montresta samples. Dashed lines represent mixing between depleted mantle (S) and MORB fluid (MF). Solid lines represent different percentages of MORB fluid. Dotted lines represent different percentages of sediment fluid (SF). Fluid from Altered MORB is calculated assuming 2% by volume of fluid and, for eclogite/fluid, D_{Pb} = 0.01 and D_{Nd} = 3.26. Fluid from sediments is calculated assuming 1% by volume of fluid and sediment/fluid partition coefficients are D_{Pb} = 0.51 and D_{Nd} = 3.26. Modified from Franciosi et al. (2003)



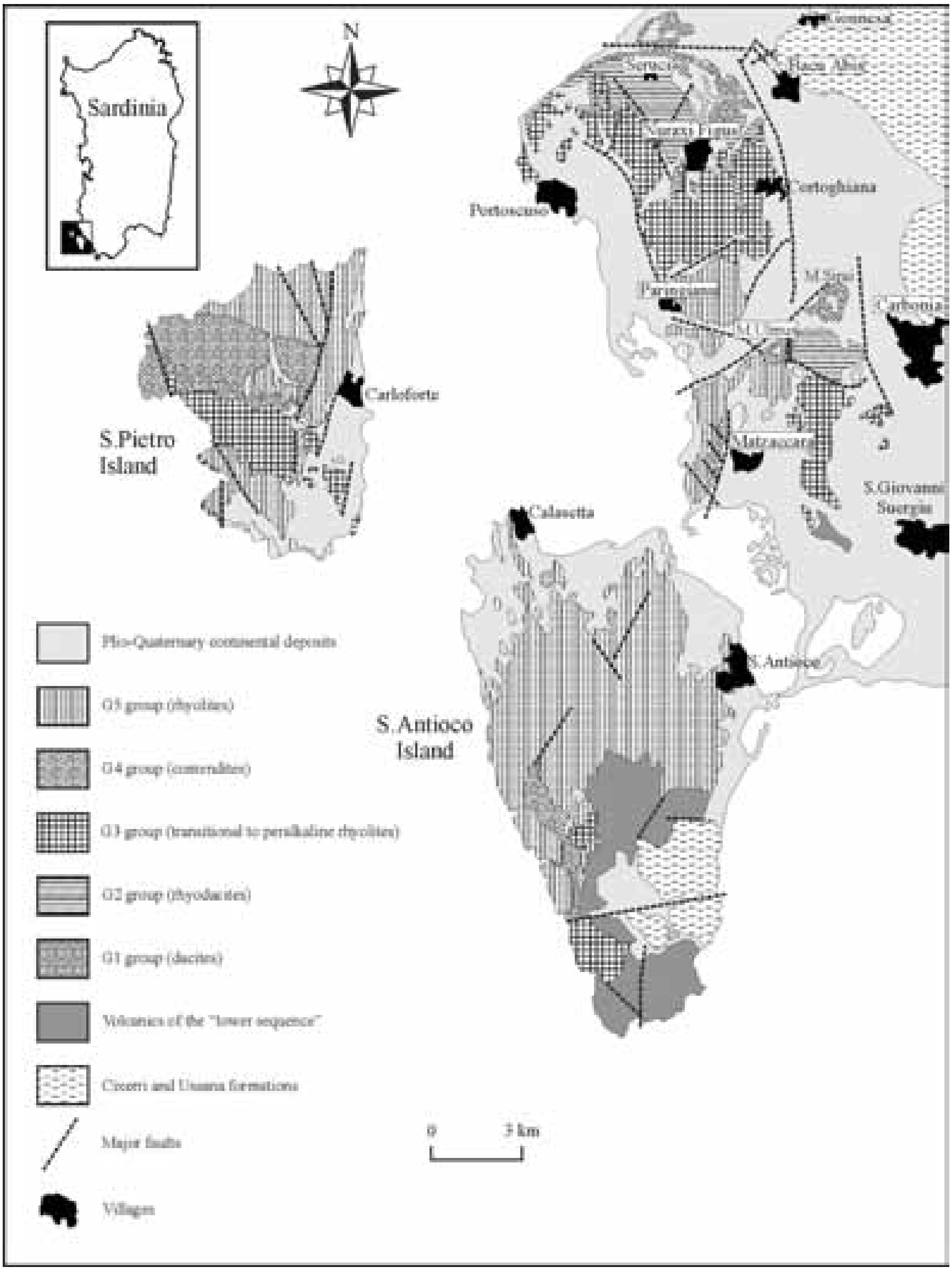


Figure 9 - Simplified geological sketch map of the "Upper sequence" of the Sulcis area. Modified from Morra et al. (1994).

have been reported in south Corsica (Balistra and Tre Paduli areas) by Ottaviani-Spella et al. (1996). These occurrences represent the northern equivalents of the Miocene Sardinian ignimbrites and demonstrate that the Oligo-Miocene Sardinian arc was extending northwards over the southern margin of Corsica.

More northeastward, Burdigalian (17.2-16 Ma) andesitic rocks dredged during the MARCO cruise along the western Corsican margin (Rossi et al., 1998) testify to an arc-type volcanism. Similarities in terms of trace-element abundance between these dredged samples and Sardinian Oligo-Miocene andesites allowed Rossi et al. (1998) to propose that the same subduction system linked these two regions.

Recently, Mascle et al. (2001) reported analyses of volcanic rocks dredged along a previously unknown 12 Ma old submerged volcano, named the Cornacya seamount, towards south-east Sardinia, in the Tyrrhenian Sea. These samples show shoshonitic to lamproitic geochemical and petrographical features, roughly similar to the 15-Ma-old Sisco lamproite in north-east Corsica. These two occurrences of Langhian shoshonitic to lamproitic melts are evidence of the first stages of opening of the Tyrrhenian Sea and have been related to post-collisional suites emplaced during the lithospheric extension of the Corsica-Sardinia block, just after its rotation.

The genesis of ignimbrites has been related to anatectic processes in the continental crust (Coulon et al., 1978), while the evolution of Tertiary Sardinian effusive rocks, starting from basaltic parental melts, seems to have been driven essentially by assimilation and fractional crystallization processes (AFC), as indicated by the variation of Sr isotopic ratios with the differentiation of the magmas (Dupuy et al., 1974; Morra et al., 1994, 1997; Brotzu et al., 1997b; Conte, 1997; Lonis et al., 1997). Initial $^{87}Sr/^{86}Sr$ ranges from 0.70399 to 0.71127 (Morra et al., 1997; Downes et al., 2001; Franciosi et al., 2003) (Fig. 6).

However, Downes et al. (2001), on the basis of Sr-, Nd- and O-isotope data, hold that the isotopic variation of rocks from Arcuentu was the effect of source contamination by subducted sediments.

The Sardinian basalts are mostly HABs, very abundant in subduction-related geodynamic settings worldwide. HMBs are found only in the Montresta (northern Sardinia; Morra et al., 1997; Franciosi et al., 2003), Arcuentu (southern Sardinia; Brotzu et al., 1997a; Downes et al., 2001; Franciosi et al., 2003) and Marmilla (central-southern Sardinia; Mattioli et al., 2000) districts.

On the basis of the flat HREE pattern in chondrite-normalized diagrams, Morra et al. (1997) proposed

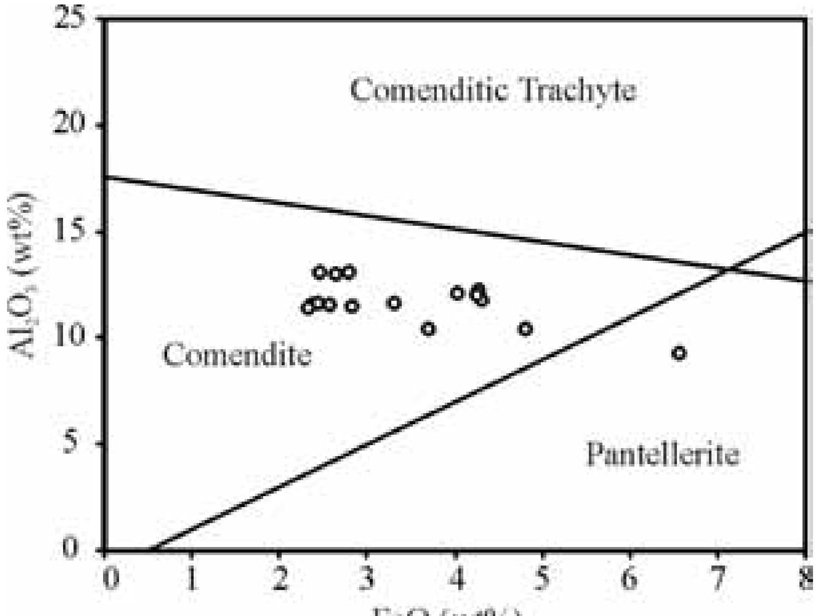


Figure 10 - FeO(tot) vs. Al_2O_3 discrimination diagram (MacDonald, 1974) for peralkaline rhyolites from Sulcis.

a N-MORB-like spinel-bearing lherzolite as the mantle source of the Montresta HMBs, variably metasomatized by fluids from subducted oceanic crust. Brotzu et al. (1997a) proposed for the Arcuentu HMBs spinel-bearing mantle sources more residual than those of the Montresta HMBs. The residual characters of the Arcuentu HMBs would be responsible for the higher SiO_2 and lower Al_2O_3, CaO,

FeO and TiO_2 contents compared to the Montresta primary melts.
Sr-isotope data for Oligo-Miocene volcanics have been available since the '70s (e.g., Dupuy et al., 1974), but Nd-, O- and, in particular, Pb-isotope data are still very scarce. The first Nd and O data were reported by Downes et al. (2001) on Arcuentu rocks, while Pb-isotope data were reported by Caron and Orgeval (1996) and Franciosi et al. (2003) on andesite and HMBs from Bosa (north-west Sardinia), San Martino (Logudoro), Portoscuso (Sulcis), Furtei (central-southern Sardinia), Arcuentu and Montresta. $^{143}Nd/^{144}Nd$ isotopic ratios of Arcuentu volcanic rocks range from 0.51270 (HMB) to 0.512185 (andesite); Montresta HMBs have more radiogenic $^{143}Nd/^{144}Nd$, ranging from 0.51274 to 0.51271 (Fig. 7).
Pb-isotope ratios on Montresta and Arcuentu HMBs range as follows: $^{206}Pb/^{204}Pb$ (18.609-18.707); $^{207}Pb/^{206}Pb$ (15.619-15.661); $^{208}Pb/^{204}Pb$ (38.408-38.747). Caron and Orgeval's (1996) results lie in the same isotopic range ($^{206}Pb/^{204}Pb$ (18.519-18.708); $^{207}Pb/^{206}Pb$ (15.640-15.679); $^{208}Pb/^{204}Pb$ (38.713-39.109). On the basis of such isotopic data, together with a detailed study of incompatible trace-element ratios, Franciosi et al. (2003) proposed a model to explain the components involved in the genesis of HMBs and HABs from Montresta and Arcuentu. The geochemical and isotopic compositions of these magmas require an approximate degree of partial melting of 15% of a MORB-like, and input of two subduction components in the mantle wedge: 1) fluids from subducted oceanic crust (altered MORB); 2) fluids from subducted sediments. 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 Sardinia magmas was enriched by less than 1% of both MORB fluid and sediment fluid released from a subducted slab (Fig. 8).
Geochemical and isotopic compositions of Montresta volcanic rocks are homogeneous, while samples from Arcuentu show quite heterogeneous traits, consistent with variations in mantle sources during the long time span (about 13 Ma) of volcanic activity in this district.
One of the most interesting aspects of the Oligo-Miocene volcanic rocks of Sardinia is the spatial and temporal relationships among calcalkaline mafic to intermediate rocks and the differentiated subalkaline to peralkaline rhyolites in the Sulcis area (south-west Sardinia) (Figs. 5 and 9).

The peralkaline types of the Sulcis area represent about 10-15% by mass of the entire succession of the area (basic to acid types) and ~30% by mass of the more evolved compositions (Morra et al., 1994). Among all the Oligo-Miocene products, the peralkaline types are <1%. The presence of such kind of lithologies in close spatial and stratigraphic relationships with calcalkaline basic to acid rocks is a relatively uncommon feature. Peralkaline compositions [igneous rocks with molar excess of (Na_2O+K_2O) over Al_2O_3] are almost exclusively confined to evolved compositions, both SiO_2 oversaturated and undersaturated (i.e., trachytes, rhyolites, phonolites; MacDonald, 1974; Scaillet and MacDonald, 2003). The SiO_2 oversaturated types are divided into comenditic trachyte, comendite (mildly peralkaline rhyolite), pantelleritic trachyte and pantellerite (strongly peralkaline rhyolite). A chemical distinction among these types is based mostly on FeO and Al_2O_3 content (MacDonald, 1974; Fig. 10).

Compared to pantellerites, comendites are characterized by a lower Agpaitic Index [A.I. = (Na+K)/Al], generally lower FeO (< 7 wt%) and generally higher Al_2O_3 (> 9 wt%). Comendites are generally transitional between pantellerites and the non-peralkaline rhyolites in terms of FeO, MnO, Na_2O, TiO_2, Al_2O_3, CaO and MgO (MacDonald, 1974). Peralkaline rocks occur in both continental and oceanic settings (e.g., Civetta et al., 1998; Kar et al., 1998; Ayalew et al., 2002). When present as relatively low-volume products, these magmas are believed to represent end-products of protracted fractional crystallization of alkali basalt magmas, whereas when present in large volume and unrelated to mafic and intermediate rocks, their origin is related to partial melting of crustal rocks of basaltic to more silicic compositions (see Scaillet and MacDonald, 2003 for a summary). Recently, experimental evidences of genetic linkage between comendites and pantellerites have been highlighted by Scaillet and MacDonald (2003): strongly peralkaline pantelleritic melts can be produced by protracted crystallization of high-silica (anatectic) comendites.
The tectonic setting of peralkaline magmatism is generally associated with within-plate oceanic (e.g., hot-spot-related islands such as Ascension and the Azores, or large, plume-related igneous provinces such as Iceland) or continental settings (sometimes evolving into 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-peralkaline magmas, allowed many authors to consider comendites and pantellerites as typical products of tectonic settings unrelated to subduction systems. In this regard, the peralkaline magmatism of the Sulcis area can be considered an anomalous feature, its being associated with calcalkaline basic to acid volcanic rocks. At Sulcis, whole rock chemical variation of basic to acid roks, the continuous chemical shift of mineral phases (e.g., An content of plagioclase and Mg# of mafic minerals), the overall similarity in term of $^{87}Sr/^{86}Sr$ isotopic ratios between subalkaline and peralkaline rhyolites (0.70745 and 0.70667, respectively) and between acid and intermediate rocks (Sulcis andesite = 0.70711) suggest that the whole sequence is genetically linked (Morra et al., 1994). Depending on the mineralogical composition of the cumulate, basaltic melts can evolve up to subalkaline rhyolites or peralkaline types (comendites).

In this sense, no geodynamic meaning can be ascribed to the peralkaline character: A.I. values higher than 1 can be obtained from metaluminous or slightly-peralkaline melts after removal of mineral phases which are less peralkaline than coexisting liquids (e.g., the plagioclase and/or clinopyroxene effect; Brotzu et al., 1980; Scaillet and MacDonald, 2003, and references therein).

With the Oligo-Miocene volcanic rocks important mineralizations exploited for industrial purposes, such as gold, copper, manganese, kaoline and zeolite, are associated.

The most important gold mineralizations related to Oligo-Miocene volcanic rocks occur in the areas of Furtei, Osilo, Nulvi, Pozzomaggiore, Bosa,

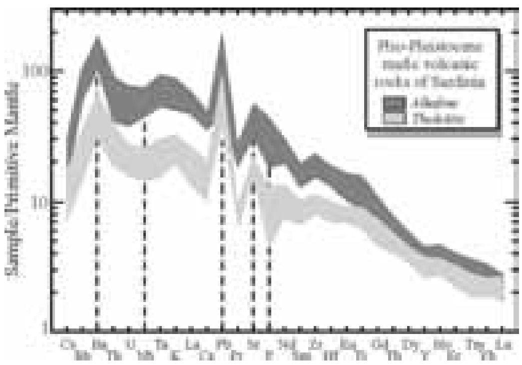


Figure 11 - Primitive mantle (Sun and McDonough, 1989) normalized diagram of mafic Plio-Quaternary volcanic rocks of Sardinia. References in the text.

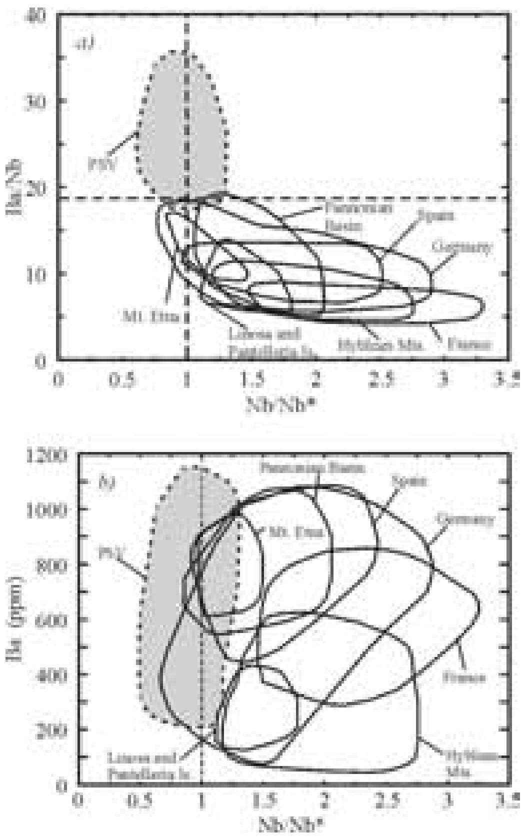


Figure 12 - Nb/Nb* vs. Ba/Nb and Nb/Nb* vs. Ba for Plio-Pleistocene volcanic rocks of Sardinia (PSV) compared to other European anorogenic volcanic rocks. Nb/Nb* = $Nb_R/Nb_{PM}/((K_R/K_{PM})*(La_R/La_{PM})^{0.5}$; where subscripts R and PM stand for rock and primitive mantle values. This parameter reflects the Nb anomaly in primitive mantle-normalized diagrams. The majority of Plio-Pleistocene volcanic rocks of Sardinia have low Nb/Nb* (<1), coupled with higher Ba/Nb (> 20), but roughly similar Ba, compared with mafic anorogenic volcanic rocks from Italy and Europe. Modified after Lustrino et al. (2002).

Montiferru and Sarroch. From an industrial point of view the most important localities are those of Furtei (central-southern Sardinia), Mt. Olesteddu (south-east Sardinia) and Osilo (north-east Sardinia) (e.g., Cidu et al., 1995; Dessi et al., 1996).

The Furtei Volcanic Complex (FVC) is a major Tertiary age sub-aerial calcalkaline volcanic center, 5 km in diameter. The earliest phase of gold mineralisation is hosted in sheeted microfractures developed in flat-lying sediments and ignimbrite sandwiched between andesite flows. Gold is associated with silica, pyrite and lesser sphalerite.

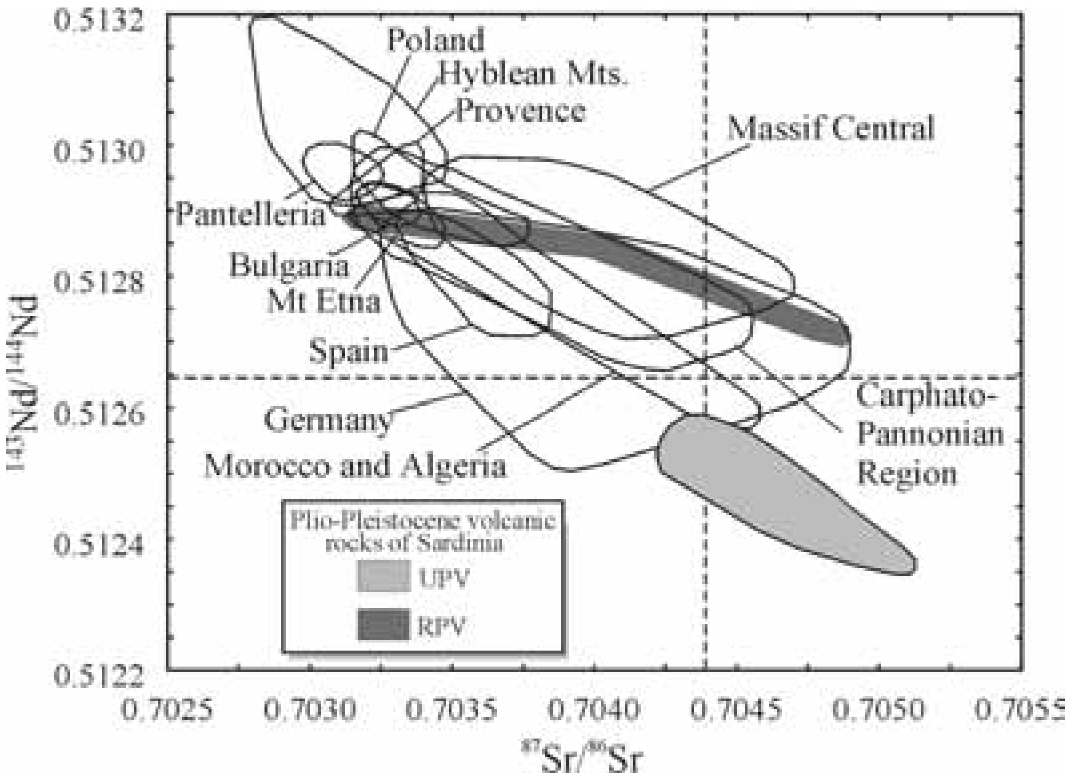


***Figure 13** - $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ isotopic ratios for anorogenic Plio-Pleistocene volcanic rocks of Sardinia. UPV = Unradiogenic Pb Volcanics; RPV = Radiogenic Pb Volcanics (Lustrino et al., 2000). For comparison the fields of Neogene circum-Mediterranean volcanic provinces are also shown. References in Lustrino et al. (2002) and in the text.*

This style of mineralisation is termed "stratabound" and represents a large tonnage, low-grade (2g/t) gold target. The average thickness of the mineralisation is 12-15 m, and average grades are 1.5-2.5 grams per ton of gold, up to 5.4 g/t Au in a diamond drill hole. The stratabound mineralisation is crosscut by the diatreme breccia, which is the predominant host to sub-vertical vuggy silica sulphide structures containing pyrite, enargite (copper sulphide) and gold mineralisation.
Resources and reserves at Furtei (the mine started operating in 1997) are 9.3 million tons (Mt) at 2.08 g/t Au (about 20 tons of Au) and 15,000 tons of Cu. At the moment Furtei consists of an open-pit operation with a production facility capable of processing 1,000,000 tons of ore annually. Currently the Furtei mine produces about 780 kg of gold a year.
The Monte Ollesteddu prospect was discovered in 2000 as an extensive gold-in-soil anomaly, identified as 3.5 kilometres long and up to 1 kilometre wide, with grades of up to 12 g/t gold in soils in the central area. Previous selective sampling of the individual quartz-sulphide veins returned values typically between 15 and 50 g/t, and as high as 220 g/t.
The Osilo epithermal vein district contains 1,600,000 tons, grading at 7.1g/t gold and 30g/t silver.
The kaolinitic deposits of Sardinia associated with Oligo-Miocene igneous rocks are developed on primary volcanic rocks or allumo-silicatic rocks. Volcanic rocks at Romana (the Bosano area) show a bimodal alteration. Mineral assemblage is made up of kaolinite and opal-calcedony-crystobalite; this assemblage replaces completely the original mineralogy of the rock. Incidence of kaolinite on one hand and of crystobalite on the other is extremely variable. Both components range between 0 and 80-95%, with complementary incidences. The scanty economic interest for Romana kaolinitic deposits is due to its great mineralogic variability (Novembre et al., 2003). Important kaoline deposits are found in various areas of Sardinia (Romana, Tresnuraghes and Furtei), but only a few of them are currently exploited. These deposits are mostly associated with pyroclastic facies and hydrothermal activity focused along faults

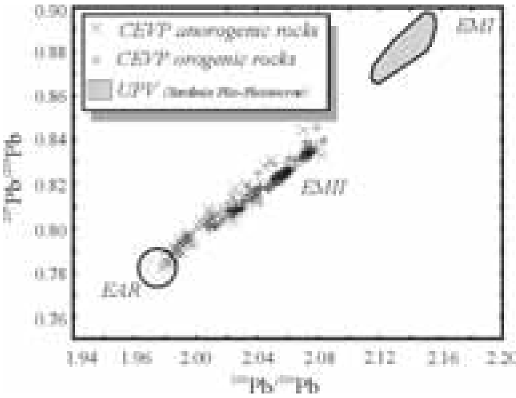


Figure 14 - $^{208}Pb/^{206}Pb$ vs. $^{207}Pb/^{206}Pb$ isotopic ratios for Plio-Pleistocene volcanic rocks of Sardinia. For comparison the values of anorogenic and orogenic igneous rocks of the Cenozoic European Volcanic Province (CEVP) are also shown. EAR = European Asthenospheric Reservoir. EMI and EMII = Enriched Mantle I and II. References in Lustrino et al. (2002) and in the text.

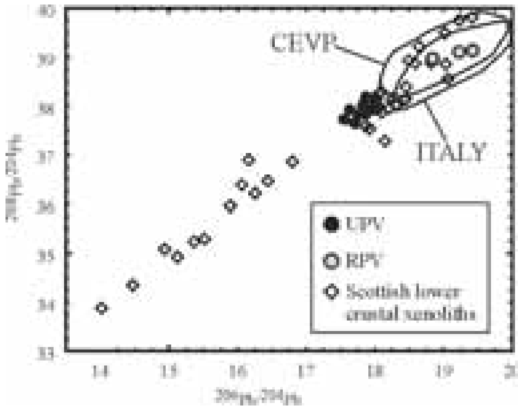


Figure 15 - $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ isotopic ratios for Plio-Pleistocene volcanic rocks of Sardinia. For comparison the values of anorogenic and orogenic igneous rocks of the Cenozoic European Volcanic Province (CEVP) and Italy are also shown. Scottish lower crustal xenoliths are from Halliday et al. (1993). Modified after Lustrino, 1999.

(Ligas et al., 1996).

Porphiry copper deposits are associated with microdioritic intrusions at Calabona (north-west Sardinia), whereas in the Siliqua-Decimoputzu area (southern Sardinia) Cu, Mo and Au mineralizations are associated with andesitic-dacitic sub-volcanic bodies. Mn mineralizations, related to hydrothermal activity in the Oligo-Miocene volcanic rocks in various sectors of the island, are found mostly in stockwork with abundant Mn and Fe oxides, associated with silicitization and argillification phenomena (e.g., San Pietro island).

Correlated to Oligo-Miocene volcanic rocks are also several zeolite occurrences (clinoptilolite) associated with riodacitic-rhyolitic ignimbrites (e.g., Cerri et al., 2001; Lonis et al., 2002). These localities (Logudoro and Bosano) represent the first Italian clinoptilolite/heulandite-rich occurrences with potential economic interest.

The Plio-Pleistocene volcanic rocks of Sardinia

Unlike the Oligo-Miocene orogenic volcanic rocks, which outcrop only along the western side of the island, the Plio-Pleistocene volcanic activity occurs both in the eastern and western sectors of Sardinia. This magmatism developed after a hiatus of about 10 Ma after the end of the previous orogenic magmatism. The activity is mainly located along normal faults related to the coeval opening of the back-arc Tyrrhenian Sea, interpreted as the middle-Miocene to recent-version of the Oligocene Provençal Basin. In some cases, the vents reactivated Oligo-Miocene magmatic conduits (e.g., at Mt. Arci). The Campidano Graben (Fig. 1), which crosscuts the island in its southwestern part and which partially overlaps the Oligo-Miocene Fossa Sarda, is the clearest structural evidence of such tensile stresses during the geodynamic evolution of the western Mediterranean Sea. The development of magmatic activity only after the rifting processes, and the lithospheric thickness of about 70 km (Panza, 1984), indicate a strong crustal control on the genesis of this magmatism, being unlikely a mantle plume involvement in the genesis of Plio-Pleistocene volcanic rocks of Sardinia (i.e., passive rifting processes) as, instead, has been proposed for many products of the CEVP (e.g., Wilson and Downes, 1991; Hoernle et al., 1995; Wilson and Patterson, 2001, and references therein).

From north to south, the volcanic areas in the eastern sector of Sardinia are (Fig 2):

Orosei-Dorgali (or Baronie area; 3.6-2.0 Ma). Volcanic rocks of this district rest on a Paleozoic crystalline basement, as well as on Mesozoic limestones and dolostones (Lauro, 1939; Savelli and Pasini, 1973; Lustrino, 1999; Lustrino et al., 2002). These rocks consist of mildly-alkaline lavas (mostly hawaiites plus rarer alkali basalts and mugearites) with a few tholeiitic counterparts (basaltic andesites). The relative proportion of the volcanic outcrops

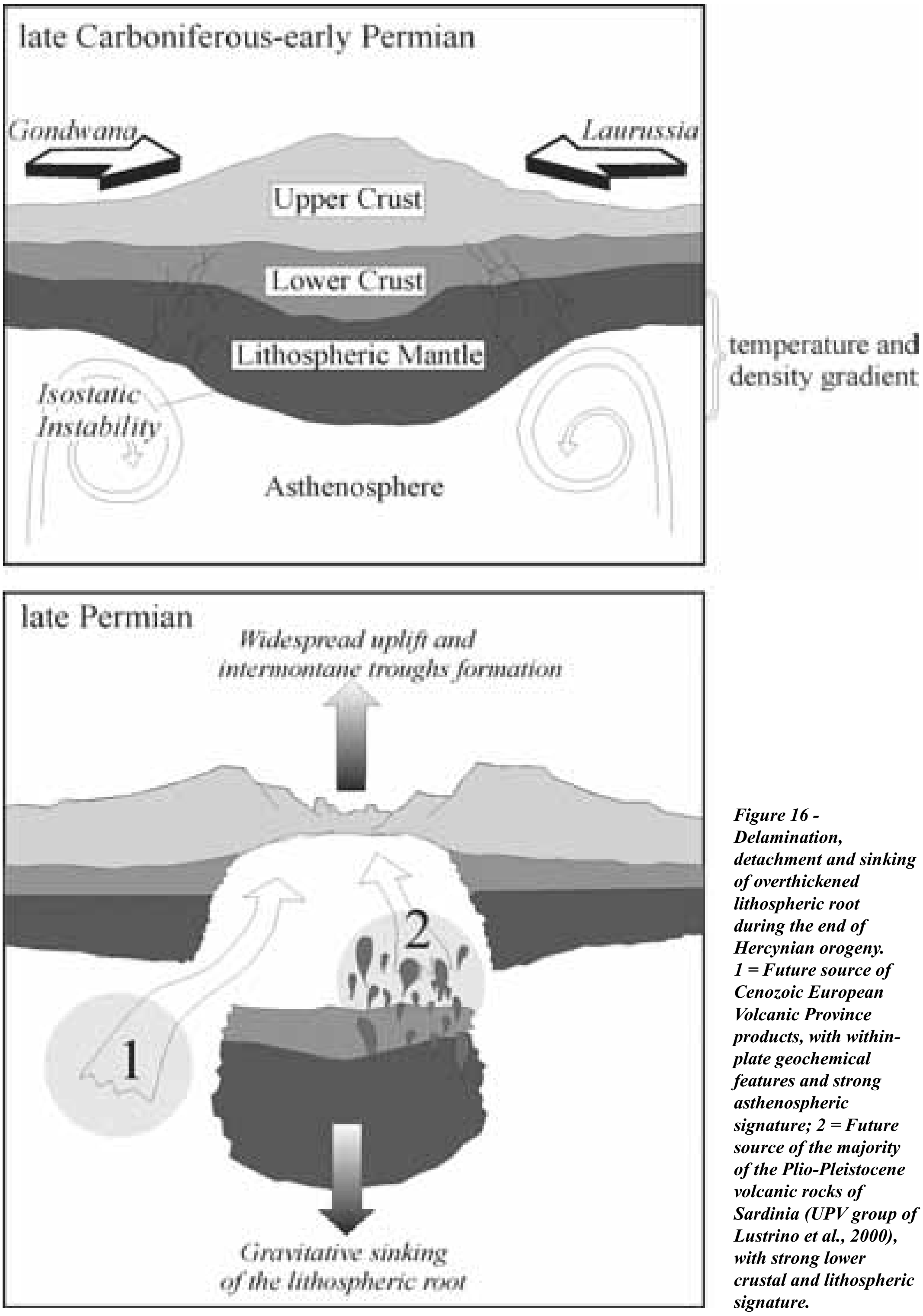
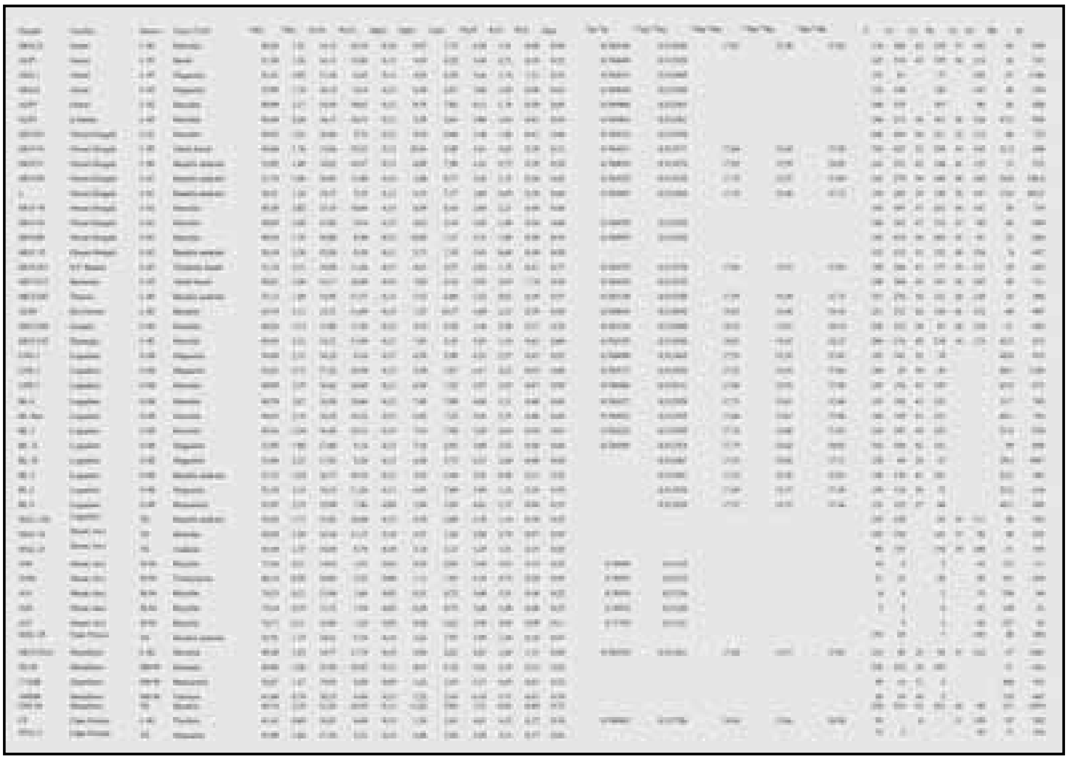


Figure 16 - Delamination, detachment and sinking of overthickened lithospheric root during the end of Hercynian orogeny. 1 = Future source of Cenozoic European Volcanic Province products, with within-plate geochemical features and strong asthenospheric signature; 2 = Future source of the majority of the Plio-Pleistocene volcanic rocks of Sardinia (UPV group of Lustrino et al., 2000), with strong lower crustal and lithospheric signature.



(Table 2) - 1-2. = Representative analyses of Plio-Pleistocene volcanic rocks of Sardinia. Sources: L 99 = Lustrino, 1999; L* 00 = Lustrino, 2000 ; L 00 = Lustrino et al., 2000; L 02 = Lustrino et al., 2002; G 00 = Gasperini et al., 2000; M 94 = Montanini et al., 1994; DB 90 = Di Battistini et al., 1990; TS = This Study.

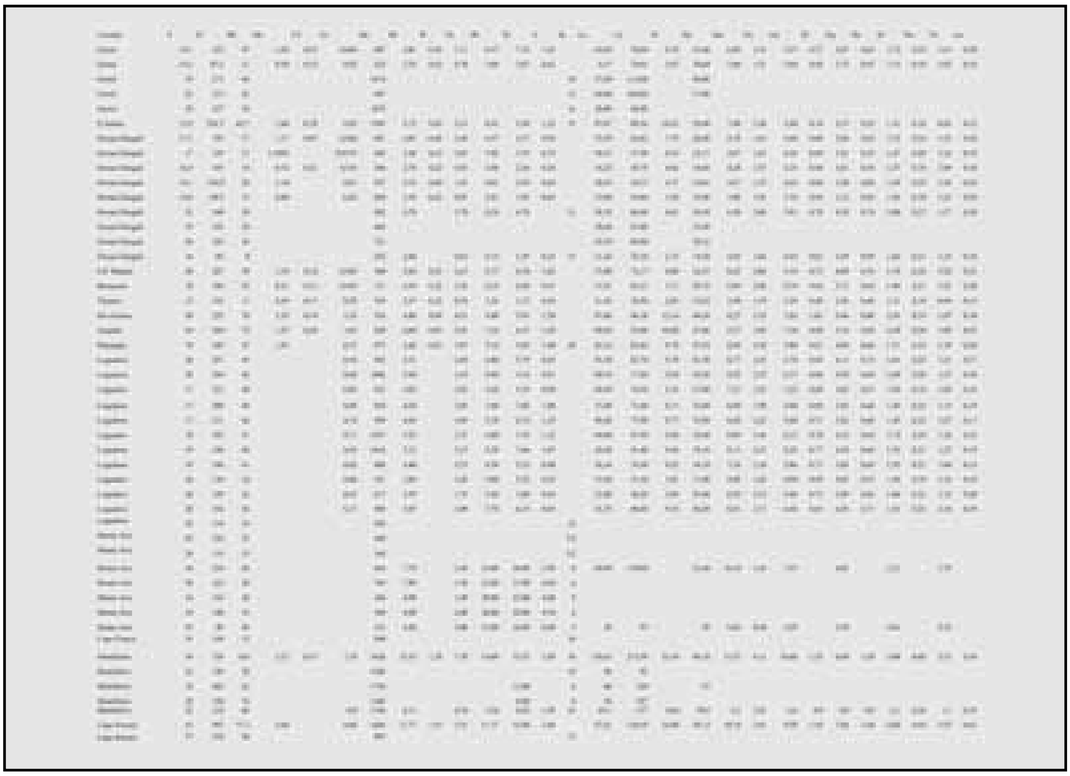
is ~80% alkaline and ~20 % tholeiitic. Many of the volcanic vents are located along NE-SW and NW-SE trending faults and their products form plateaus outcropping over ~150 Km^2. There is no correlation between time of emplacement, silica saturation character and geographic position of the products, with tholeiitic and alkaline K/Ar ages largely overlapping (Beccaluva and Macciotta, 1983). Finally, it is noteworthy that the beginning of the volcanic activity was almost contemporary to that on the continent and in the now-submerged area of the Orosei canyon in the Tyrrhenian Sea (Savelli and Pasini, 1973). Some localities are characterized by the abundant occurrence of mantle xenoliths (Beccaluva et al., 2001).

<u>S. Pietro Baunei</u>, (2.6 Ma). This is a 5.5 km long outcrop of alkaline lavas (alkali basalts, hawaiites, mugearites), whose width varies from several hundreds of meters to 1 km, lying on upper Malm limestones (Simboli, 1963; Lustrino, 1999; Lustrino et al., 2000). The thickness of the limestones is variable from a few meters up to ~20 m. The volcanic vent is not easily recognizable and the flow is canalized in a NW-SE fault system, parallel to the shoreline (Fig. 2). Chemical, mineralogical and structural similarities to the Orosei-Dorgali rocks favor the hypothesis of these volcanics being a dismembered portion of the larger Orosei-Dorgali volcanic area(Lustrino et al., 2002).

<u>Barisardo</u> (no age available). This small outcrop (~5 Km^2) is located south of S. Pietro Baunei in central-eastern Sardinia and rests on Hercynian granitoids. The main rock types are hawaiites/mugearites plus rarer transitional basaltic andesites (Fig.2; Lauro, 1937; Lustrino, 1999; Lustrino et al., 2000).

<u>Rio Girone</u> (no age available). This small outcrop is represented by a 50 m^2 neck of basanite which hosts small ultramafic xenoliths of mantle origin (Calvino, 1965; Lustrino et al., 1996, 1999, 2000). This neck intrudes Paleozoic phyllites and is located along a NS fault roughly parallel to the shore line (Fig. 2).

<u>Capo Ferrato</u> (5.3-2.3 Ma). This represents the first volcanic activity of the Plio-Pleistocene cycle in Sardinia. The main rock types are mainly intermediate-to-evolved alkaline rocks (mugearites and trachytes;



(Table 2) - 2-2.

Brotzu et al., 1975; Lustrino et al., 2000; Petteruti-Lieberknecht et al., 2003). The volcanic rocks are present as dikes and ellipsoidal domes which rest on Hercynian granitoids (Figs 1 and 2).

In the central-western sector, the scenario is more complicated, with the presence of large volcanic complexes (e.g., Montiferro and Mt. Arci) and widespread basaltic plains (Campeda-Planargia-Abbasanta). Starting from north to south these are:

Logudoro (2.4-0.1 Ma). The northernmost outcrops of the Plio-Pleistocene 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). This district is the best known site in Sardinia for finding mantle xenoliths (see below).

Campeda-Planargia-Abbasanta-Paulilatino basaltic plains (3.7-3.5 Ma). These basic-to-intermediate lava flows represent the widest Plio-Pleistocene volcanic plateau in Sardinia (~850 Km^2; Fig. 2). These volcanic rocks, partially covering other volcanic complexes (e.g., Montiferro to the west) and cinder cones (e.g., Logudoro, to the north) are tholeiitic (basaltic andesite) and alkaline lavas (hawaiites, mugearites) (Beccaluva et al., 1975; Lustrino, 1999; Lustrino et al., 2000).

Montiferro (3.9-2.8 Ma). This volcanic complex (~400 Km^2) is made up of mafic (basanites, hawaiites, and mugearites) and differentiated products (trachytes and phonolites) present mainly as flows up to 300 meters thick. The mafic alkaline rocks host mafic and ultramafic nodules (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 area (3.8-2.1 Ma). The volcanic rocks belonging to this district (central-southern Sardinia; Fig. 2) overlie Miocene marly-arenaceous or calcareous sediments (Lauro, 1937; Lustrino et al., 1996, 2000; Lustrino, 2000c). This area includes several outcrops: the lava plateau of about 50 Km^2 of Giara di Gesturi (2.76-2.05 Ma), Giara di Serri (2.27±0.09 Ma), Pitzu Mannu (2.11±0.09 Ma), Mt. Guzzini (2.62±0.11 Ma), Mt. Pizziogu (3.54±0.35 Ma), Corona Arrubia (2.2±0.11 Ma), Taccu Idda-Taccu Maiore (2.08±0.25 Ma), Taccu Piccinnu (2.62±0.24 Ma), and the Iras-Siddi-Pabillonis plateau

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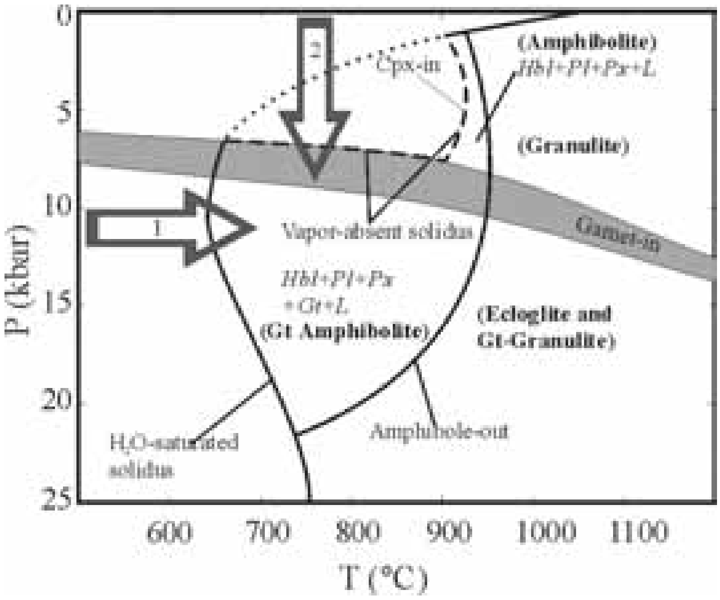

Figure 17 - Composite phase diagrams for amphibolitic assemblages as deduced from several sources (see Lustrino, 2001 for references). Continuous line, partly interrupted by dotted line: H_2O-saturated solidus. The garnet-in curve is represented by a shaded area because of contrasting results from experimental studies carried out on differing initial compositions. Above the garnet stability field, vapour-absent solidus coincides with H_2O-saturated solidus, because excess water provided by the breakdown of amphibole may form new garnet during dehydration partial melting. Below the garnet stability field, vapour-absent solidus, represented by dashed line, coincides with the appearance of clinopyroxene and garnet produced by reaction: amph + pl = melt ± gt ± cpx ± 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 substituting amphibole. Arrow "2": effect of tectonic piling following continent-continent collision and thickening of lower crust. Here too, lower crustal lithologies are forced to melt partially, with later 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. After Lustrino (2001).

(2.49-3.84 Ma; K/Ar ages from Assorgia et al., 1983). Almost all the alkaline lavas host variably-sized (up to 20 cm in diameter) ultramafic xenoliths, particularly abundant in the Zeppara Manna area (Lustrino et al., 1999; see below). The most common rock types are basaltic andesites and hawaiites.

Capo Frasca-Tharros (no age available). These are zone-limited outcrops at the southern and northern extremities of the Oristano Gulf, respectively (Fig. 2). The rocks are all basaltic andesites with tholeiitic affinity (Lustrino, 1999; Lustrino et al., 2000; Petteruti-Lieberknecht et al., 2003).

Mt. Arci (3.8-2.6 Ma). This is a volcanic complex located along the eastern side of the Campidano Graben (Fig. 2), 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 Plio-Pleistocene volcanic rocks of Sardinia, the Mt. Arci products show two peculiarities: 1) this is the only place where felsic SiO_2-oversaturated volcanic rocks (dacites and rhyolites) are present, and 2) this complex is made up of volcanic rocks belonging both to Oligo-Miocene and Plio-Pleistocene volcanic cycles.

Guspini. (no age available) This is a very small alkaline neck (about 20 m) of hawaiitic composition outcropping on the western branch of the Campidano Graben, intruding Ordovician metasandstones (Lustrino et al., 2000; Fig. 2). This outcrop is characterized by the presence of millimetric-to-centimetric, disrupted mantle fragments.

In summary, the Plio-Pleistocene volcanic rocks of Sardinia have mainly mafic to intermediate composition; differentiated products (both SiO_2-oversaturated and undersaturated) occur as well (Di Battistini et al., 1990; Montanini et al., 1994; Lustrino et al., 1996, 2000, 2002, 2003; Petteruti-Lieberknecht et al., 2003). Both alkaline (basanite, alkali basalt, basanite, hawaiite, mugearite, benmoreite, trachyte and phonolite) and subalkaline types (tholeiitic basalt to rhyolite) are present (Figs. 2, 4).

Representative analyses of Plio-Pleistocene volcanic rocks of Sardinia are reported in Table 2. 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).

(Table 2)

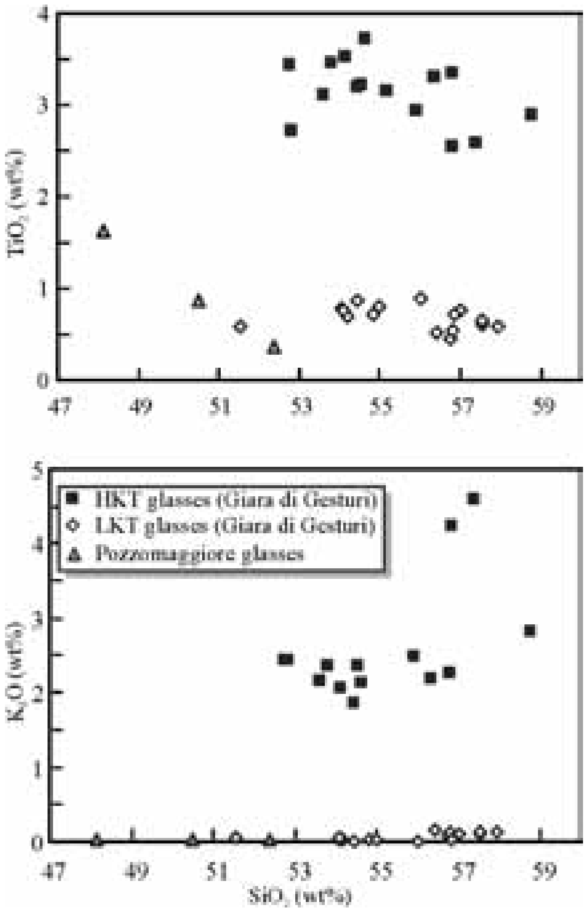

Figure 18 - SiO_2 vs. TiO_2 and SiO_2 vs. K_2O for glasses in the mantle xenoliths borne in Plio-Pleistocene volcanic rocks of Sardinia. HKT = High K_2O-TiO_2 glasses from the xenoliths of Zeppara Manna (Giara di Gesturi; Lustrino et al., 1999); LKT = Low K_2O-TiO_2 glasses from the xenoliths of Zeppara Manna (Giara di Gesturi; Lustrino et al., 1999); Pozzomaggiore glasses from Dostal and Capedri (1976).

The tholeiitic-alkaline association and its petrogenetic meaning was 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 lithologies, as well as similar incompatible trace-element ratios and overlapping Sr-Nd-Pb isotopic ratios have all 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. The tholeiitic group is characterized by a slightly higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ than alkaline rocks, probably linked to some limited degree of crustal contamination during stagnation in magma chambers.

Some of the most-evolved subalkaline volcanic rocks (e.g., rhyolites from Mt. Arci, in central Sardinia) appear to be mostly related to fractionation of tholeiitic magmas plus assimilation of crustal components via AFC processes (Montanini et al., 1994). Pure crustal anatectic partial melts with strongly Sr radiogenic compositions ($^{87}Sr/^{86}Sr$ = 0.7053 to 0.7155) are also reported (Cioni et al., 1982; Montanini et al., 1994). Processes of magma mixing between basaltic s.l. and rhyolitic melts produced intermediate dacitic compositions (Montanini et al., 1994).

The peculiarity of the great majority of Sardinian Plio-Pleistocene volcanic rocks (> 99% of outcrops) is their "transitional" character between typical 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; Figs. 11 and 12; Di Battistini et al., 1990; Lustrino et al., 1996, 2000, 2002).

Abundant mantle xenoliths (e.g., Dostal and Capedri, 1976; Albuquerque et al., 1977; Dupuy et al., 1987; Rutter, 1987; Beccaluva et al., 1989, 2001; Lustrino et al., 1999) are often associated with alkaline products at different stages of evolution (from basanite to trachyphonolite), testifying to the rapid ascent of magma and the existence of magma chambers at subcrustal depths (Di Battistini et al., 1990; Lustrino et al., 1996). $^{87}Sr/^{86}Sr$ isotopic ratios of the less evolved volcanic rocks range from 0.7031 to 0.7054, but most samples cluster near 0.7044 ± 2; ε_{Nd} show almost exclusively negative values clustering close to –5; only a few samples (Rio Girone basanite, Guspini hawaiite and Capo ferrato trachyte) reach more radiogenic values (up to +5; Cioni et al, 1982; Lustrino, 1999; Gasperini et al., 2000; Lustrino et al., 2000, 2002; Petteruti-Lieberknecht et al., 2003; Fig. 13).

The great majority of the Plio-Pleistocene volcanic rocks of Sardinia is characterized by the least-uranogenic Pb-isotopic composition of the entire circum-Mediterranean igneous province ($^{206}Pb/^{204}Pb$ down to 17.5; Lustrino, 1999; Gasperini et al., 2000; Lustrino et al., 2000, 2002; Authors' unpublished data; Fig. 14). Only a very few samples (Rio Girone basanite, Guspini hawaiite and Capo Ferrato trachyte) have relatively radiogenic $^{206}Pb/^{204}Pb$ ratios (18.84 to 19.42).

This peculiarity, coupled with trace element anomalies, has been related to ancient (Panafrican/Hercynian) modification of their mantle sources (Lustrino et al., 2000). Worth noting is that the Plio-Pleistocene volcanic rocks of Sardinia share many geochemical similarities with EMI-type basalts (Lustrino and Dallai, 2004).

Lustrino (1999, 2000a) and Lustrino et al. (2000) proposed an active role of continental lower crust in the genesis of the Plio-Pleistocene volcanic rocks of Sardinia (Fig. 15).

It has been proposed (Lustrino et al., in prep.) that the majority of Plio-Pleistocene Sardinian mafic volcanic rocks (the UPV; Unradiogenic Pb Volcanics; Lustrino et al., 2000) might derive from a DMM-like source (Depleted MORB Mantle), metasomatized by melts derived from partial melting of lower crustal lithologies: a melt derived from 12 % partial melting of lower crust, mixed with DMM in proportions of 2 and 98 %, respectively, could produce a heterogeneous source. Partial melts of this new source (DMM metasomatized by "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 a process of lower crustal contamination of magmas during the rising to the surface has been hypothesized for other CEVP rocks (e.g., Jung and Masberg, 1998) and other EM-I basalts in general (e.g., Baker et al., 1997), it should be noted that in this case, the lower crust signature is thought to represent source contamination. Interaction of the lithospheric mantle with lower crustal lithologies may have possibly taken place via post-collisional sinking of dense mafic lower crustal keel thickened during the collisional stage of the Hercynian Orogeny (Fig. 16; Lustrino, 2000a).

At the end of the Hercynian Orogeny (Carboniferous-Permian), the Sardinian lithosphere probably was affected by delamination and detachment processes; these processes were facilitated by: 1) the increasing of thickness of the lithosphere due to crustal stacking following continent-continent collision, and 2) weakness zones in the lithosphere, following the consumption of water-rich altered oceanic crust before the closure of the Rheic and Massif Central-Moldanubian Oceans (see Lustrino, 2000b, and references therein). In tectonically-piled crustal materials along a continent-continent collisional margin, the lowermost crust is metamorphosed into granulite/eclogite facies, with a subsequent increase of density from ~ 2.8 up to ~ 3.8 g/cm^3 (e.g., Gao et al., 1998; Tatsumi, 2000) This increase in density favored the sinking of the mafic keel which was detached from the uppermost portion (made up mainly of intermediate-to-upper crust) and recycled into the mantle. The density increase can be the result of two processes (see Lustrino, 2001; Fig. 17): 1) during tectonic piling following continent-continent collision, lower crustal lithologies (i.e., amphibolite) start to melt as they pass the vapor-absent solidus, coinciding with the garnet-in line. During this process, amphibolite is metamorphosed into garnet-bearing amphibolite and eventually, with the total disappearence of amphibole, to eclogite and/or garnet-granulite; 2) the arrival of hot basaltic batches on amphibolitic lower crust forces the system to partially melt by dehydration, producing the same density increase with amphibole ± plagioclase melting and garnet ± pyroxene growth (Wolf and Wyllie, 1994; Rapp and Watson, 1995).

Notwithstanding the fact that high Ba/Nb is not a typical feature of late Hercynian post-collisional to anorogenic igneous rocks of Sardinia, some basic alkaline dykes from north-east Sardinia (the Concas-Alà dei Sardi zone) show trace element abundances roughly similar to the Orosei-Dorgali rocks. Traversa et al. (1997) report hawaiitic dykes of Permian-Triassic age (~ 240 Ma) whose trace element abundance is closely similar to that one of the Plio-Pleistocene Sardinian volcanic rocks. The Concas-Alà dei Sardi hawaiites show positive anomaly at Ba and Sr, coupled with $(Ba/Nb)_N$ >1. These products can be considered as partial melts of a source made up by DMM contaminated by a few percents of (tonalitic s.l.) crustal-derived partial melts. Therefore, they could represent an expression of the Hercynian-age modification. Such a mantle could have been mobilized also many Ma after, during the opening stages of the Tyrrhenian Sea and could have acted as source for Plio-Pleistocene volcanic rocks of Sardinia (Fig. 16).

An oxygen isotopic study on mineral separates of Plio-Pleistocene volcanic rocks of Sardinia is currently in progress. Preliminary results (Lustrino et al., 2003) obtained on plagioclase, clinopyroxene

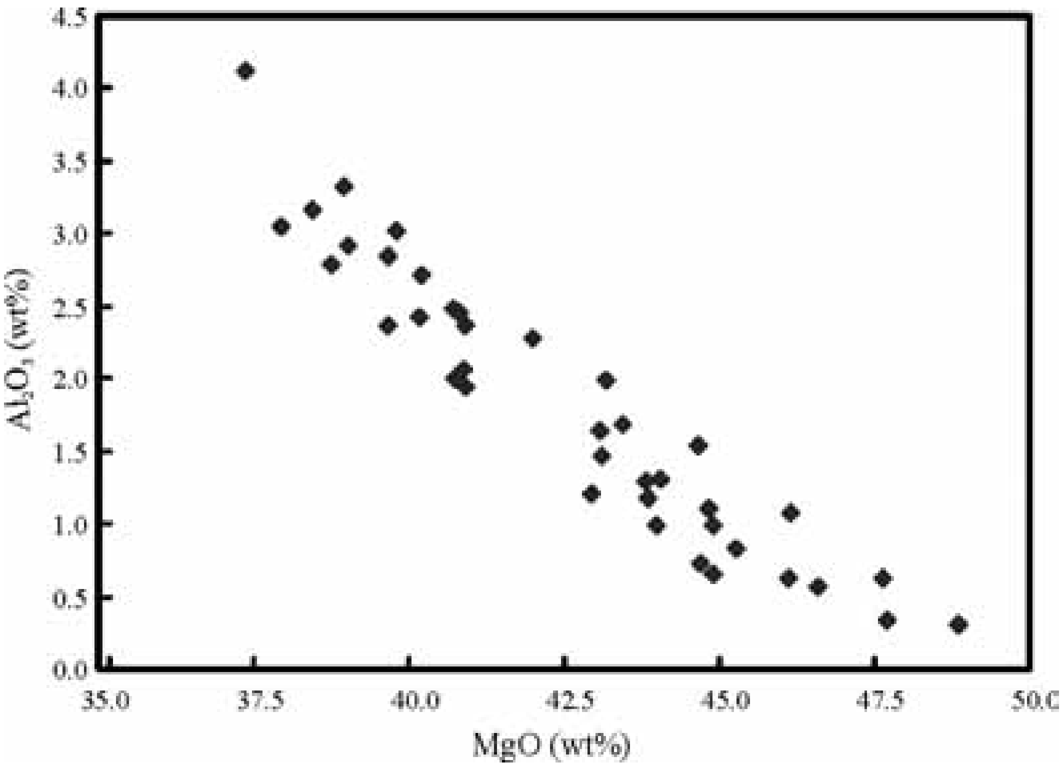

Figure 19 - MgO vs. Al_2O_3 for whole rock xenoliths from Pozzomaggiore (Dupuy et al., 1987; Rutter, 1987; Beccaluva et al., 1989; 2001) and Giara di Gesturi (Lustrino et al., 1999).

and olivine separates (analyzed via laser fluorination technique) limit their possible mantle sources.

Nine analyses on plagioclase separates from alkaline (alkali basalt, mugearite and trachyte) and tholeiitic (basaltic andesite) lavas gave a relatively large range of $\delta^{18}O_{SMOW}$ from 6.46 to 7.56‰ (average 6.95 ± 0.36). Tholeiitic lavas show generally lower values (6.46-6.98‰; n = 4) compared to the alkaline ones (7.04-7.56‰; n = 5); no difference has been noted among plagioclase of alkali basalts and trachytes.

Two clinopyroxenes from the tholeiitic basaltic andesite of Capo Frasca (south-west Sardinia) are characterized by relatively high $\delta^{18}O_{SMOW}$ (6.74‰ ± 0.08). Two clinopyroxenes from Oligo-Miocene andesitic basalt of Marmilla (southern Sardinia) show $\delta^{18}O_{SMOW}$ = 7.02‰ ± 0.03, consistent with the results obtained by Downes et al. (2001) on other clinopyroxene of Sardinian Oligo-Miocene volcanic rocks. Liquidus olivine of Plio-Pleistocene volcanic rocks from Orosei-Dorgali and Planargia are characterized by $\delta^{18}O_{SMOW}$ = 5.55‰ ± 0.25.

These preliminary results (the anomalously high $\delta^{18}O_{SMOW}$ values) find a sort of similarity in the anomalous Sr-Nd-Pb ratios of the same volcanic rocks (Gasperini et al., 2000; Lustrino et al., 2000, 2002). The high values of $\delta^{18}O_{SMOW}$ of Plio-Quaternary Sardinian plagioclase, therefore, could be related to the presence of crustal material in their mantle sources (Lustrino et al., 2003).

The Lithospheric mantle of Sardinia as revealed by mantle xenoliths

Ultramafic inclusions are relatively common in Plio-Pleistocene alkaline rocks (basanite, alkali basalt, hawaiite) of Sardinia. These xenoliths span, in composition, from harzburgites/cpx-poor lherzolites to lherzolite and rare wehrlites and pyroxenites (Rutter, 1987; Beccaluva et al., 1989, 2001; Lustrino et al., 1999). The origin of the two latter types (wehrlites and pyroxenites) has been related to cumulus processes, whereas the first two types (harzburgites to lherzolites) have been interpreted as upper mantle residues variably affected by metasomatic processes.

The typical mantle xenoliths localities in Sardinia are: Pozzomaggiore and Logudoro area (northern Sardinia; Dostal and Capedri, 1976; Albuquerque et al., 1977; Dupuy et al., 1987; Rutter, 1987; Beccaluva et al., 1989; Lustrino, 1999), Orosei-Dorgali area (central-eastern Sardinia; Brotzu et al., 1970; Beccaluva et al., 1989, 2001; Lustrino, 1999), Montiferro (central-western Sardinia; Beccaluva et al., 1989, 2001), Mt. Arci (central-southern Sardinia; Beccaluva et al., 1989) and Giara di Gesturi (Gerrei, central-southern Sardinia; Lustrino et al., 1999). Other small occurrences are at Rio Girone (south-eastern Sardinia; Lustrino et al., 1999) and Guspini (central-western Sardinia; Lustrino, 1999). No systematic differences in modal and chemical composition, as well as in texture have been reported among the different localities.

The overall size of the xenoliths ranges from a few centimeters (e.g., Rio Girone and Guspini; Lustrino, 1999; Lustrino et al., 1999) to about 20 cm in diameter (e.g., Pozzomaggiore; Dupuy et al., 1987; Beccaluva et al., 1989, 2001).

The xenoliths show exclusively a spinel equilibration facies, and the whole-rock composition varies from values close to model fertile lherzolite (Niu, 1997) (cpx-rich lherzolite) to relatively depleted harzburgite (Dupuy et al., 1987; Rutter, 1987; Beccaluva et al., 1989, 2001; Lustrino et al., 1999).

Especially in the Logudoro area, the xenoliths are often associated with black augite megacrysts (up to 4 cm long), usually corroded and with evidence of incipient partial melting (marginal sieve texture) (Rutter, 1987; Beccaluva et al., 1989), together with pyroxenites and gabbroic nodules.

Three are the most common textures observed:

1) *Protogranular*, with grains of olivine and orthopyroxene (the latter often with exolution lamellae of clinopyroxene) up to 8 mm in size, with smaller clinopyroxene and spinel (~1 mm).

2) *Porphyroclastic*, with large olivine (and, more rarely, orthopyroxene) grains (2-5 mm in size) set in a fine-grained recrystallized matrix (< 2 mm) of strained clinopyroxene and spinel, as well as unstrained olivine and orthopyroxene (Beccaluva et al., 1989).

2) *Pyrometamorphic* with spongy clinopyroxene and melt pockets. The latter are made up by a glassy matrix including clinopyroxene and spinel relicts, skeletal olivine and tiny quench microlites of clinopyroxene and, more rarely, plagioclase.

Only in rare cases (< 1% of studied xenoliths from the Giara di Gesturi and Orosei-Dorgali outcrops) is the anhydrous four-phase assemblage iassociated with the presence of hydrous phases like phlogopite (Lustrino et al., 1999; Beccaluva et al., 2001). Interstitial glass pools unrelated to host lava are reported from Pozzomaggiore (Logudoro; Albuquerque et al., 1977; Beccaluva et al., 1989), Giara di Gesturi (Lustrino et al., 1999) and Orosei-Dorgali (Beccaluva et al., 2001).

The contacts between xenoliths and host lava are generally sharp, but in some cases resorption of enstatite grains (most likely reacting with the silica-undersaturated host lava and developing a rim of fine-grained rounded olivine) produced an irregular shape of the xenolith. Sometimes, particularly in the Rio Girone xenoliths, growth of hourglass-zoned titaniferous clinopyroxene (probably due to crystallization near the cooler surface of the xenolith) has been observed (Lustrino et al., 1999). Reddish oxidation rims around the xenoliths are relatively common. Green Cr-diopside veins, of about 0.5 to 1 cm in width, sometimes cross-cut the xenoliths.

<u>Olivine</u>: Primary olivine has a quite constant composition ($Fo_{91.5-89.3}$), with high NiO (0.26-0.66 wt%) and low CaO (0.02-0.16 wt%) and MnO (0.01-0.24 wt%). Olivine is mostly coarse and often exhibits curved boundaries, as well as, sometimes, kink banding. At the contact with the host lava, the forsterite content (Fo_{80-74}) overlaps with the values of olivine in the groundmass, suggesting Mg/Fe reaction exchange. Rare relicts of olivine, partially enclosed in glass (Lustrino et al., 1999), are compositionally similar to the uncorroded olivine. The crystallites of olivine included in pyrometamorphic glass (secondary olivine) differ from primary olivine in their being euhedral and for their higher forsterite (Fo_{93-91}) and CaO (0.1.-0.30 wt%) and lower FeO (6.71-8.61 wt%), as generally reported for worldwide glass-related olivine (e.g., Girod et al., 1981; Yaxley et al., 1997). The higher CaO could be related to a shallower depth of equilibration where these microlites possibly nucleated. Disrupted mantle olivine grains are very commonly found in host lavas and can be easily distinguished from liquidus olivine on the basis of: 1) higher Fo content (~ 91 versus ~ 80); 2) larger size; 3) anhedral shape; 4) common presence of kink banding.

<u>Orthopyroxene</u>: Orthopyroxene is enstatite, often showing exsolution lamellae of clinopyroxene. The range in Mg# is narrow (91.6-89.5), overlapping the values of coexisting primary olivine, with variable Cr# ranging from 22.6 to 4.5. Orthopyroxene is never found as a quench phase in the pyrometamorphic glass, and only very rarely as a partially corroded relict phase in the melt pockets. Enstatite is always

		SiO_2	TiO_2	Al_2O_3	MnO	FeO	MgO	CaO	Na_2O	K_2O	Sum	Na+K	Na/K	Mg#
LKT GLASSES														
Nod1 8-4	L 99	51,55	0,59	19,19	0,06	7,66	5,70	13,55	0,88	0,06	99,2	0,94	14,72	0,57
Nod1 10-12	L 99	57,94	0,58	19,31		5,41	4,11	8,74	2,87	0,13	99,1	3,00	22,62	0,58
ZM1 6-9	L 99	55,00	0,80	18,12	0,11	4,24	5,00	12,13	2,16	0,01	97,6	2,17	154,3	0,68
ZM1	L 99	56,85	0,72	23,09	0,01	2,21	0,91	11,04	2,07	0,03	96,9	2,10	69,00	0,42
ZM1	L 99	56,01	0,90	20,42	0,06	4,24	3,31	10,68	2,01	0,01	97,6	2,02	201,0	0,58
ZM1	L 99	54,07	0,76	18,20	0,07	5,53	6,83	12,64	1,49	0,04	99,6	1,53	37,3	0,69
HKT GLASSES														
ZM2 7-6	L 99	55,91	2,94	19,09	0,11	3,36	3,19	7,92	4,00	2,48	99,0	6,48	1,61	0,63
ZM2 5-8	L 99	53,80	3,47	19,26		4,27	3,38	8,61	3,95	2,37	99,1	6,32	1,66	0,59
ZM2 3-8	L 99	52,75	3,44	19,88	0,07	4,07	3,07	8,29	4,40	2,43	98,4	6,83	1,82	0,57
ZM1 3-9	L 99	57,40	2,59	18,45	0,17	2,85	2,32	6,69	2,66	4,59	97,7	7,25	0,58	0,59
ZM1	L 99	54,64	3,72	20,17	0,09	4,10	3,46	7,96	3,41	2,13	99,7	5,54	1,60	0,60
ZM1	L 99	58,75	2,89	19,19	0,13	2,75	2,97	6,82	2,61	2,81	98,9	5,42	0,93	0,66
94-1	DC 76	48,13	1,62	8,30	0,06	2,75	14,02	22,22	0,77	0,03	97,9	0,80	25,7	0,90
94-1	DC 76	50,50	0,88	5,12	0,05	2,90	15,26	23,10	0,60	0,02	98,4	0,62	30,0	0,90
94-3	DC 76	52,38	0,36	2,95	0,11	2,54	16,08	23,60	0,57	0,03	98,6	0,60	19,0	0,92

CIPW Norm calculated assuming a Fe_2O_3/FeO ratio = 0.15

		Q	or	ab	an	ne	lc	di	hy	ol	mt	il	hm	or+ab+an
LKT GLASSES														
Nod1 8-4	L 99	7,96	0,36	7,53	48,59	0,00	0,00	15,70	17,35	0,00	1,48	1,13	0,00	56,5
Nod1 10-12	L 99	13,59	0,76	24,53	39,78	0,00	0,00	3,26	16,00	0,00	1,04	1,11	0,00	65,1
ZM1 6-9	L 99	11,23	0,08	18,73	40,70	0,00	0,00	16,91	10,02	0,00	0,83	1,55	0,00	59,5
ZM1	L 99	19,55	0,18	18,07	55,32	0,00	0,00	0,98	4,08	0,00	0,44	1,41	0,00	73,6
ZM1	L 99	15,92	0,06	17,42	47,79	0,00	0,00	5,27	11,01	0,00	0,83	1,75	0,00	65,3
ZM1	L 99	9,03	0,24	12,65	43,01	0,00	0,00	16,06	16,57	0,00	1,06	1,45	0,00	55,9
HKT GLASSES														
ZM2 7-6	L 99	4,00	14,81	34,16	27,10	0,00	0,00	9,83	3,85	0,00	0,65	5,64	0,00	76,1
ZM2 5-8	L 99	1,20	14,13	33,69	28,09	0,00	0,00	11,80	3,68	0,00	0,82	6,64	0,00	75,9
ZM1 3-9	L 99	8,42	27,75	23,02	25,43	0,00	0,00	6,68	3,14	0,00	0,56	5,03	0,00	76,2
ZM1	L 99	5,68	12,63	28,95	33,55	0,00	0,00	4,74	6,65	0,00	0,79	7,09	0,00	75,1
ZM1	L 99	14,25	16,79	22,32	32,70	0,00	0,00	1,03	7,00	0,00	0,00	5,45	0,37	71,8
94-1	DC 76	0,00	0,00	0,00	19,51	3,61	0,14	65,34	0,00	4,80	0,54	3,14	0,00	19,5
94-1	DC 76	0,00	0,00	0,00	11,40	2,79	0,09	78,35	0,00	3,53	0,56	1,70	0,00	11,4
94-3	DC 76	0,00	0,00	0,00	5,48	2,65	0,14	88,65	0,00	1,82	0,49	0,69	0,00	5,5

(Table 3) = EMP analyses of glasses in the mantle xenoliths from Giara di Gesturi (Lustrino et al., 1999; L 99) and Pozzomaggiore (Dostal and Capedri, 1976; DC 76).

in reaction with SiO_2-undersaturated host lava. The result of this reaction process is: orthopyroxene + SiO_2-undersaturated melt = olivine ± clinopyroxene ± spinel ± glass (e.g., Arai and Abe, 1995). If orthopyroxene is Cr-rich (enstatite in harzburgite), its instability produces typical podiform chromitite zones.

Clinopyroxene: Clinopyroxene can be found as: 1) small interstitial grains between larger olivine and orthopyroxene; 2) clouded by opaque grains and minute green spinel inclusions; 3) spongy-textured crystals; 4) relict and quenched microlite in pyrometamorphic glass; 5) exsolved lamellae in larger orthopyroxene. Spongy-textured and relict clinopyroxene have been interpreted as incipient partial melting of the xenoliths, probably a consequence of the thermal shock after incorporation into host lava and the pressure release en route to the surface (e.g., Albuquerque et al., 1977; Lustrino et al., 1999). Clinopyroxene straddles the field of diopside and endiopside, with only a small variation in FeO (Wo_{42-49} En_{43-53} Fs_{4-8}). Compared to the coexisting olivine and orthopyroxene, wider Mg# and Cr# variations (92.8-88.2 and 20.6-3.7, respectively) were observed. As noted for olivine, euhedral microlites in glasses show higher Mg# up to 93.3; clinopyroxene in glass also shows higher TiO_2 (0.3-2 wt%) and lower Na_2O (down to 0.3 wt%; Beccaluva et al., 2001). The spongy pyroxene shows low TiO_2 (0.26-0.32 wt%) and Al_2O_3 (2.9-3.8 wt%), and the highest Cr_2O_3 (1.15-1.34 wt%). Clinopyroxene from the Cr-diopside veins has low CaO and the highest Na_2O. Chondrite-normalized REE patterns of Cr-diopside are spoon-like, with a depletion of MREE (Eu, Gd) compared to LREE and HREE; LREE abundance ranges from 3 to 7 times chondrite, whereas HREE are less enriched (2-3 times chondrite; Rutter, 1987). Clinopyroxene REE patterns range from nearly flat in cpx-rich lherzolite [$(La/Yb)_N$ = ~0.25-10] to LREE-enriched in cpx-poor lherzolite [$(La/Yb)_N$ = ~4.5-5.0] and harzburgite [$(La/Yb)_N$ = ~7-18] (Beccaluva et al., 2001). The $^{87}Sr/^{86}Sr$ isotopic ratios measured on separates of Cr-diopside from lherzolite range from 0.70263 to 0.70455; clinopyroxene from harzburgite are confined to the more radiogenic end ($^{87}Sr/^{86}Sr$ from 0.70418 to 0.70431; Beccaluva et al., 2001; Lustrino et al., unpublished data). Also $^{143}Nd/^{144}Nd$ show a relatively wide range for clinopyroxene from lherzolite (0.51323 to 0.51253) whereas these ratios are much more uniform and less radiogenic for clinopyroxene from harzburgite (0.51259 to 0.51252; Beccaluva et al., 2001; Lustrino et al., unpublished data). Low-$^{87}Sr/^{86}Sr$, high-$^{143}Nd/^{144}Nd$ clinopyroxenes plot close to the RPV field of Plio-Pleistocene volcanic rocks of Sardinia defined by Lustrino et al. (2000), whereas the high-$^{87}Sr/^{86}Sr$, low-$^{143}Nd/^{144}Nd$ clinopyroxenes plot close to the UPV field of Plio-Pleistocene volcanic rocks of Sardinia defined by Lustrino et al. (2000).

Spinel: Spinel shows wide textural and chemical variations even in the same xenolith. It occurs as: 1) black to reddish brown grains (up to 4 mm) with holly leaf or vermicular crystal habit at grain boundaries (often in triple point junctions) or included in pyroxene crystals; 2) small octhaedra associated with spongy clinopyroxene; 3) small round grains within or between olivine grains; 4) in vermicular symplectitic intergrowths with orthopyroxene, mostly at contact with host lava; 5) associated with glass both as relict phase and euhedral crystallite. In contact with the host lava, Cr-rich spinel tends to react to form a more Fe-rich black oxide rim, up to 0.5 mm thick (Rutter, 1987). Spinel ranges from chromiferous (Cr_2O_3 45.5 wt%; Al_2O_3 18.8 wt%), FeO-rich, to aluminous (Cr_2O_3 11.1 wt%; Al_2O_3 54.9 wt%), MgO-rich. Cr# ranges from 9.3 to 62.4, while Mg# vary from 63.2 to 82.4. Spinel octhaedra associated with spongy clinopyroxene are interpreted as a newly formed phase, subsequent to the incongruent melting of clinopyroxene into Cr-poor liquid and Cr-rich phase (spinel). Both "molten phase" and spinel octhaedra in the spongy clinopyroxene relict are too small to be analyzed.

Phlogopite: High-Ti phlogopite (TiO_2 3.22-4.72 wt%; Lustrino et al., 1999) occurs in or between orthopyroxene and olivine in some Zeppara Manna xenoliths. It was never found close to the pyrometamorphic glass. Texturally, two types of phlogopite occur: 1) euhedral deformed stringers (0.5 mm long) in larger orthopyroxene crystals having equilibrium grain boundaries, and 2) anhedral grains (~1 mm) along the contact with orthopyroxene and olivine and as veinlets cutting orthopyroxene (Lustrino et al., 1999). Their Mg# (89.5-88.3) are roughly similar to coexisting olivine and pyroxenes, suggesting possible equilibrium with the other silicate phases. The composition falls in the field of phlogopite from sp-bearing mantle, being characterized by higher TiO_2 and Al_2O_3 as well as by lower SiO_2 compared to the garnet-peridotite mica from kimberlites.

Glass: excluding "jacket glass" (e.g., Edgar et al., 1989) along the contact between xenolith and host lava, the glass in mantle xenoliths of Sardinia occurs mostly as crosscutting veinlets and/or as interstitial pods and in melt pockets (pyrometamorphic glass). In the latter case it may be devoid of crystals or may contain clinopyroxene and spinel relicts, together with euhedral microlites of olivine, clinopyroxene and spinel (Lustrino et al., 1999). Worth noting is that glass unrelated to the host basalt is always associated with clinopyroxene and spinel (Albuquerque et al., 1977; Lustrino et al., 1999). In some cases, alkali feldspar (An lower than 5%, Or up to 57%) and plagioclase microlites (An up to 77%, Or lower than 3%) are associated with small interstitial glassy blebs (Lustrino, 1999; Beccaluva et al., 2001).

The glass in the mantle xenoliths from Giara di Gesturi is quartz-normative with 47.8 to 71.1 CIPW normative feldspars, and two of them are also corundum-normative (Lustrino et al., 1999). The glass compositions of Pozzomaggiore are nepheline-leucite normative (2.5-3.7 ne-norm; 0.09-0.14 lc-norm; Dostal and Capedri, 1976) The Giara di Gesturi glasses show SiO_2 ranging from 51.55 wt% to 58.75 wt%, high Al_2O_3 (18.0-23.1 wt%) and CaO (5.9-13.6 wt%), variable TiO_2 (0.76-3.72 wt%), alkalies

(0.94-7.25 wt %), and extremely variable Na_2O/K_2O. Glasses from the Pozzomaggiore xenoliths have generally lower SiO_2 (48.13-52.38 wt%), Al_2O_3 (2.95-8.30 wt%), FeO (2.54-2.90 wt%) and Na_2O (0.57-0.77 wt%), coupled with higher MgO (14.02-16.08 wt%) and CaO (22.22-23.60 wt%) than the glasses from Giara di Gesturi. The most striking aspect of the latter glasses is their bimodal distribution of K_2O and TiO_2. Indeed, glasses can be divided into (Lustrino et al., 1999): *(a)* low K_2O-TiO_2 (LKT) type [average K_2O and TiO_2 = 0.07 wt% and 0.68 wt%, respectively, CaO (av. 11.36 wt%), MgO (av. 4.88 wt%) and FeO (av. 5.06 wt%)], and *(b)* high K_2O-TiO_2 (HKT) type [average K_2O and TiO_2 = 2.51 wt% and 3.14 wt%, respectively, CaO (av. 7.91 wt%), MgO (av. 3.00 wt%) and FeO (3.71 wt%)] (Tab. 3; Fig. 18).

(Table 3)

The LKT glasses show a subalkaline character and basaltic-andesite-to-andesite composition, whereas the HKT group is more alkali-rich and straddle the field of mugearite and trachyandesite.

In terms of Mg# (assuming a Fe_2O_3/FeO ratio = 0.15) these glasses range from a primitive liquid composition (Mg# = 71.1) to relatively evolved types (Mg# = 41.9), with the LKT glasses having generally higher Mg# than the HKT ones. Mg# of Pozzomaggiore glasses are very high (90.1-92.3).

The existence of glasses with approximately the same chemical composition as plagioclase has been related to the incipient partial melting of the xenolith at pressure-temperature conditions overlapping those of the field of stability of plagioclase-lherzolite (5-10 kbar; < 1000 °C; Albuquerque et al., 1977). On the other hand, glass patches with compositions approaching that of clinopyroxene seem to confirm the hypothesis that this phase was affected by melting processes together with spinel, as originally hypothesized by Dostal and Capedri (1976) and Albuquerque et al. (1977). The high Ti content of some glasses has been alternatively related to the involvement in the melting processes of a Ti-rich phase like rutile (Albuquerque et al., 1977) or phlogopite (Lustrino et al., 1999).

Dupuy et al. (1987) proposed for the glass in the mantle xenoliths from Pozzomaggiore an origin by the breakdown of amphibole during the ascent of the xenoliths, even if this phase has never been found in Sardinian mantle xenoliths.

Basically, the glasses in mantle xenoliths may have derived from: 1) infiltration of material, external to the peridotitic assemblage, which variably reacted with the preexisting phases, or 2) *in situ* partial melting of peridotitic phases due to decompression after incorporation within the host lava. In the first case the glass formation may have predated, or been coeval with, magmatic activity, while, in the second case, it is necessarily contemporaneous with magmatic activity.

Both LKT- and HKT-type glasses show fractional crystallization-type paths in Harker-type diagrams, considered by Lustrino et al. (1999) evidence of crystallization of the microlites (olivine ± clinopyroxene ± spinel) from a parental melt.

The presence of spongy pyroxene, glassy blebs almost exclusively associated with diopside and spinel, and the high CaO and Al_2O_3 and low Na_2O and K_2O of the LKT glasses, have all been considered evidence of non-modal partial melting of peridotite (Lustrino et al., 1999), with diopside and spinel being the first phases to be consumed, as evidenced by several experiments (e.g., Baker and Stolper, 1994).

These observations agree with the experiments performed by Doukhan et al. (1993) and Raterron et al. (1997) on early partial melting (EPM) in pyroxenes.

Incongruent melting of diopside and spinel cannot explain the high K_2O (up to 4.6 wt%) and TiO_2 (up to 3.7 wt%) of HKT glasses, nor the high TiO_2 both of the enclosed diopside and spinel (up to 5.32 and 0.8 wt%, respectively). The high TiO_2-K_2O phlogopite is likely to be involved in the genesis at least of the HKT glasses.

In conclusion, the presence of glassy patches in the Giara di Gesturi xenoliths is not consistent with metasomatic processes, but only with thermo-baric disequilibrium of the phases. On the other hand, the presence of phlogopite laths requires processes which metasomatized the Sardinian subcontinental mantle.

The relatively high SiO_2 of the glasses (higher than SiO_2 of diopside) was related to the incongruent melting of clinopyroxene and spinel, with crystallization of a virtually SiO_2-free phase (new spinel) according to the reaction cpx + sp ± phl ⇒ ol + sp + cpx + glass (Lustrino et al., 1999).

Whole rock composition: More that 75 % of inclusions in Plio-Pleistocene alkaline volcanic rocks of Sardinia are harzburgite-lherzolite, therefore these compositions have the greatest relevance. On the basis of their mineralogy, modal proportions, mineral compositions, textures and chemical compositions, the Sardinian xenoliths belong to Frey and Prinz's (1978) group I (or Cr-diopside series). The Mg# of

Locality	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm	Pm
Source	R87	R87	R87	R87	R87	R87	R87	R87	R87	R87	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
SiO2	40,86	42,93	42,54	43,81	41,20	43,90	43,34	45,15	44,90	45,95	40,63	44,18	42,93	42,54	43,81	41,20	43,90	43,34	44,95
TiO2	0,01	0,05	0,01	0,04	0,01	0,01	0,01	0,07	0,08	0,10	0,01	0,01	0,05	0,05	0,04	0,07	0,02	0,03	0,02
Al2O3	0,50	0,99	1,07	1,11	1,29	1,31	1,54	2,00	2,40	2,79	0,5	0,65	0,99	1,07	1,11	1,29	1,31	1,54	1,95
Fe2O3tot	9,05	8,50	9,39	8,39	9,22	9,14	8,55	8,72	8,69	8,79	9,05	8,14	8,5	9,39	8,39	9,22	9,14	8,55	8,64
MnO	0,12	0,12	0,13	0,13	0,14	0,15	0,12	0,14	0,13	0,14	0,12	0,12	0,12	0,13	0,13	0,14	0,15	0,12	0,13
MgO	48,96	44,00	46,15	44,84	43,81	44,06	44,65	40,74	40,70	38,74	48,96	44,91	44,9	46,15	44,84	43,81	44,06	44,65	40,9
CaO	0,25	1,47	0,50	0,86	3,18	0,94	1,16	1,40	2,09	2,54	0,25	0,44	1,47	0,5	0,86	3,18	0,94	1,16	2,2
Na2O	0,05	0,10	0,06	0,08	0,22	0,10	0,05	0,15	0,21	0,17	0,05	0,02	0,1	0,06	0,08	0,22	0,1	0,05	0,16
K2O	0,01	0,05	0,03	0,04	0,07	0,02	0,03	0,04	0,05	0,11	0,01	0,01	0,05	0,01	0,04	0,01	0,01	0,01	0,01
P2O5	0,02	0,06	0,03	0,02	0,06	0,04	0,01	0,03	0,02	0,02	0,02	0,02	0,06	0,03	0,02	0,06	0,04	0,03	0,03
Sum	99,5	99,3	99,9	99,3	99,2	99,7	99,5	98,4	99,4	99,4	99,3	99,5	99,2	99,9	99,3	99,2	99,7	99,5	99,8
Ni	2820	2400	2500	2320	2100	2330	2340	2140	2085	1870	2820	2440	2400	2500	2320	2100	2330	2340	2100
Co	127	112	120	111	113	112	114	109	105	104	127	114	112	120	111	113	112	114	108
Cr	1240	1940	1210	3350	3600	2355	3410	2130	2190	2665	1240	3400	1940	1210	3350	2600	2355	3410	2900
V	15	39	32	52	62	36	58	51	64	82	15	32	39	32	52	62	36	58	54
Ba																			
Sr																			
Nb																			
Zr																			
Y																			
La	0,32	1,26	0,17	1,52	5,79	0,83	0,54	0,418	1,07	0,49	0,32	0,072	1,26	0,27	1,52	5,79	0,83	0,54	0,227
Ce	0,58	2,08	0,495	2,75	12,63	2,22	1,02	0,59	2,05	1,09	0,58	0,145	2,08	0,495	2,75	12,64	2,22	1,02	0,932
Pr																			
Nd		0,94	0,24	1	5,94	1,4	0,38	0,32	0,9	0,67			0,94	0,24	1	5,94	1,4	0,38	
Sm	0,045	0,198	0,057	0,171	1,15	0,339	0,064	0,083	0,164	0,194	0,045	0,009	0,198	0,057	0,0171	1,15	0,339	0,068	0,058
Eu											0,012	0,003	0,040	0,018	0,040	0,265	0,089	0,021	0,025
Gd																			
Tb											0,006		0,023	0,015	0,017	0,11	0,04	0,016	0,021
Dy																			
Ho																			
Er																			
Tm																			
Yb											0,021	0,009	0,087	0,086	0,06	0,273	0,149	0,07	0,19
Lu											0,003	0,002	0,017	0,016	0,011	0,045	0,027	0,027	0,033
Th																			
U																			
Sc	3,7	6,9	5,9	9,1	11,1	8,4	9,3	9,3	11,2	13,8	3,7	6,8	6,9	5,9	9,1	11,1	8,4	9,3	11,5
Cu	2	6	7	0,3	12	3	3	10	8	8	2	9	6	7	0,3	12	3	3	11
Zn	67	67	74	68	76	81	67	65	56	59	67	68	67	74	68	76	81	67	67

(Table 4) - 1-2. =Whole rock analyses of mantle xenoliths borne in Plio-Pleistocene alkaline lavas of Sardinia. Sources = R87 = Rutter, 1987; L)) = Lustrino et al., 1999 ; B 01 = Beccaluva et al., 2001. Pm = Pozzomaggiore ; GdG = Giara di Gesturi ; OD = Orosei-Dorgali; M = Montiferro.

(Table 4) - 2-2.

the xenoliths (calculated assuming a Fe^{3+}/Fe^{2+} ratio = 0.15) range from 88.3 to 92.8).

Compared to the primitive mantle estimate by Sun and McDonough (1989), these xenoliths are slightly-to-strongly depleted in basalt components (Ti, Al, Ca, and alkalies). MgO ranges from 37.4 to 47.7 wt% and is negatively correlated with SiO_2 (42.5-46.5 wt%), TiO_2 (0.02-0.15 wt%), Al_2O_3 (0.34-4.12 wt%) and CaO (0.54-3.62 wt%) (Dupuy et al., 1987; Lustrino et al., 1999; Beccaluva et al., 2001) (Tab. 4; Fig. 19).

(Table 4)

REE whole rock content (Dupuy et al., 1987; Beccaluva et al., 2001) displays large variations, with a general enrichment in LREE relative to HREE [$(La/Yb)_N$ ratio ~ 4-18]. Some samples display spoon-like patterns, with relative depletion in the middle REE and $(Tb/Yb)_N$ <1 that mimic the REE content of clinopyroxene to lower absolute abundance. The highest ΣREE is found in the most depleted xenoliths (Montiferro harzburgites; Beccaluva et al., 2001). This aspect, relatively common in many other worldwide mantle xenoliths (e.g., Downes, 1990) is evidence of a two-stage process: 1) depletion by varying degrees of partial melting and extraction of basaltic components from the peridotitic matrix, with the formation of harzburgite; 2) interaction with metasomatizing agents REE- and incompatible elements-rich.

Whole rock isotopic composition mimics the clinopyroxene isotopic data: lherzolites are generally characterized by lower $^{87}Sr/^{86}Sr$ (0.70308-0.70423) and higher $^{143}Nd/^{144}Nd$ (0.51302; analyses available only for one sample) than harzburgites (0.70385-0.70460 and 0.51256-0.51252, respectively; Beccaluva et al., 2001).

Megacrysts: Clinopyroxene megacrysts have been studied by Rutter (1987) and Beccaluva et al. (1989). These megacrysts are Al-augites, with a chemical composition different from that of the host lava clinopyroxene (mostly titaniferous salite) and that of mantle xenoliths (diopside to endiopside). Their relatively high Al and Na content indicates a high pressure (~ 9-15 kbar) and temperature of formation (e.g., Irving and Frey, 1984; Nimis, 1999). Lower-pressure disequilibrium is mirrored by incipient melting and exsolution lamellae with perthite-like mesostructures (Beccaluva et al., 1989; Authors' unpublished data).

Field Trip Itinerary

DAY 1

Departure from Rome and arrival at Cagliari after about 1.5 hours of flying.

Go on to Carloforte (San Pietro Island, south-west Sardinia), about 100 km west of Cagliari. Night spent on San Pietro Island. During dinner, presentation of the field trip itinerary and an ice-breaker party.

San Pietro Island is situated at the south-eastern tip of Sardinia and is half an hour away from Sulcis. Its coastline is a series of ragged and sandy areas. The island has a very long history and has had many names: the Phoenicians called it "Inosim", the Greeks "Hioera" or "Nesos"; the Romans "Accipitrum Insula". Its present name is derived from a legend which narrates how the apostle Peter once landed on its shores during his journey to Rome. Its recent history is just as rich and unique. This island remained uninhabited for centuries until 1736. Charles Emmanuel III of Savoy then bestowed it upon the descendants of the Ligurian families that had been forced to settle in Tunisia during the XVI century. That is why San Pietro has Ligurian and Arab tastes and characteristics which can still be seen in the colours of the houses in Carloforte (named after the sovereign) and in its flavours (such as cascà, derived from the Tunisian cuscus, side by side with such Ligurian specialities as panisse, farinate and buridde) as well as in its sounds (the inhabitants still speak with a strong Ligurian accent).

DAY 2

(Miocene metaluminous to peralkaline felsic volcanic rocks)

Departure from Carloforte at h. 9.00

Stop 2.1:

h. 9.15-9.45. (N39°08'46"; E8°15'45")

Open quarry of comenditic lavas at km 7.4. This Stop is at a site called Commenda, which is the type locality of comendites (mildly peralkaline rhyolites). Well-evident are big columnar joints. Discussion on the origin of peralkaline magmas and the possible geodynamic implications of this type of magmatism.

Stop 2.2a:

h. 10.30-14.00

Trip around San Pietro Island with a rented boat. General overview of many lithologies and outcrops.

Stop 2.2b:

(in case of bad weather) - h. 10.00-11.00 (N39°09'23"; E8°13'44") at km 11.0.

Stratified comenditic lava flows of Cala Fico with columnar joints. Visit to the LIPU (Italian League for the Protection of Birds) oasis.

Stop 2.2c:

(in case of bad weather) - h. 11.15-11.45

Capo Sandalo with a swim and box lunch.
(Stops 2.2b and 2.2c are alternatives to Stop 2.2a).

Stop 2.3:

h. 15.30-15.45 (N39°11'20"; E8°25'20").

Basal contact of comenditic rhyolites on the road to Portovesme (Nuraxi or Conca-is-Angius); possibility of seeing the retinitic level of the ignimbrite.

Stop 2.4:

16.10-17.30 (N39°10'52"; E8°29'21")

Locality: Mt. Sirai. Overview of San Pietro and Sant'Antioco Islands and of the Sulcis area from the top of the Seruci ignimbrite. Discussion on peralkaline magmatism. Visit to the Archaeological Museum at Villa Sulcis of Carbonia.

The museum, situated in a park which also includes botanical gardens, houses archaeological material dating back to 6,000 BC, which documents the pre-nuraghic, nuraghic, and Phoenicio-Punic periods, up to the Roman and post-classical ages. On display are a number of grave furnishings from the Phoenician and Punic necropoli on Mt. Sirai; the reconstruction of a "trophet", a cemetery-sanctuary devoted to children, with cinerary urns and original carved steles. The museum also offers visitors a "touchscreen" system for a virtual tour of Mount Sirai, the famous Punic archaeological site, founded around 720 BC by the Phoenicians and conquered in the 6th century by the Carthaginians. Stay the night at Iglesias.

Iglesias is a little town in south-west Sardinia. It is a town full of art, traditions and hospitality; the mines are the most important testimony of a glorious and rich history. The city centre is magical: you feel like you're living in the Middle ages, so walk and see the castle, the Cathedral, the walls, but also look up at the balconies, the windows and the people. For more than three thousand years this land has given life and prosperity to its inhabitants through its mining activities.

DAY 3

(Plio-Pleistocene volcanic rocks and mantle xenoliths)

Departure from Iglesias at h. 9.00.

Stop 3.1:

h. 10.00-10.30 (N39°32'22"; E8°38'09")

Visit to the Guspini neck (hawaiite) with spectacular columnar jointing.

Stop 3.2:

h. 11.00-12.00 (N39°43'15"; E8°43'53")

Abandoned obsidian quarry (rhyolites of Mt. Arci) in between the towns of Uras and Siris/Morgongiori. Short walk (10-15 minutes).

Stop 3.3:

h. 12.30-12.45 (N39°41'45"; E8°48'27")

On the road between Masullas and Gonnostramatza. Spectacular example of a cooling structure in basalt.

Stop 3.4:

h. 13.30-15.30

Arrival at the village of Barumini near the tholeiitic plateau of Giara di Gesturi (central Sardinia). Box lunch. Guided visit to the Su Nuraxi Nuragic Complex.

Around 1500 BC, a group of settlers arrived in Sardinia from a still-unknown place and spread rapidly throughout the island, taking with them advanced building techniques, beautiful Hellenistic pottery and what appears to be a fairly well-developed religion. Obsessed, as Sardinians have always been, with protecting themselves from invasion, the Nuragic people built roughly 30,000 circular fortified dwellings, strategically located so that each could easily see its neighbor. Today, 7000 of these megalithic structures survive, and they are unlike any other ruins in the world. The most important complex is *Nuraghe Su Nuraxi*, in Barumini, centered around a three-story tower built 3500 years ago. This site was recently added to UNESCO's World Heritage List. The complex consists of circular defensive towers in the form of truncated cones built of dressed stone, with corbel-vaulted internal chambers. Extended and strengthened in the first half of the 1st millennium under Carthaginian pressure, it is the finest and most complete example of this remarkable form of prehistoric architecture. According to others these ruins represent palaces or temples around which were villages, primarily made up of huts. The Nuraghes were built with superimposed blocks of stone (often Plio-Pleistocene tholeiitic basalt). Their age is not well constrained, but they should be more or less from around 3500 years ago. “Su Nuraxi” is a “polilobato” nuraghe, placed on a plateau situated 230 meters above the surrounding land. This nuraghe has a central tower surrounded by a bastion with 4 towers. This bastion is within a large hexagonal barbican which has 7 towers, with just as many rectilinear raised embankments connecting them, and two entrances. The central tower is currently 14 meters high (originally it was over 18 meters), with a diameter at the base of 10 meters; it consists of two superimposed rooms (originally 3) going back again to the Middle Bronze Age (~ 1450 b.C.). Around the fortress was the village, made up of circular huts. (more information can be found at: http://www.sardi.it/indexuk.htm; http://www.sardegna.com/code/archeologia/LINGUA/EN).

Stop 3.5:

h. 17.30-18.00 (N40°23’21”; E8°40’49”)

Pozzomaggiore (Logudoro, northern Sardinia) alkaline sodic lavas with abundant mantle xenoliths and clinopyroxene megacrysts. Spending the night at Bosa Marina (north-west Sardinia).

A small marine town, Bosa is one of the ancient capitals of Sardinia and still preserves signs of its splendid past throughout the main streets and historical downtown, rich in churches and monuments. Bosa is situated at the mouth of the Temo River; it is the only riverside town in Sardinia, and it is of ancient Carthaginian origin. The medieval castle of Serravalle, built in 1112, overlooks its orderly streets and squares and is a fascinating example of civil and military architecture.

DAY 4

(Oligo-Miocene ignimbrites, Pliocene alkaline rocks and mantle xenoliths)

Departure from Bosa Marina at h. 9.00

Stop 4.1:

h. 9.15-9.45

Visit to the giant ignimbritic deposits of Bosa and of north-western Sardinia up to Capo Marangiu.

Stop 4.2:

h. 11.30-12.15 (N40°13’22”; E8°36’33”)

Visit to an abandoned quarry of Montiferro (hawaiite with abundant mantle xenoliths). Observation of the contact between Pliocene lava and Miocene sandstone. Box lunch at the town of San Leonardo.

Stop 4.3 - h. 14.15-14.45 (N40°09’30’’; E8°37’48’’) Montiferro igneous complex at Badde Urbara. Visit to an abandoned quarry of phonolite.

Stop 4.4 - h. 15.00-15.30 (N40°12’06’’; E8°35’28’’) Moving towards the town of Cuglieri, visit phonolitic domes and basanitic lavas.

Stop 4.5 - h. 16.00-17.00 Abandoned quarry of Punta Teprera (Montiferro) with abundant mantle xenoliths and gabbroic nodules.

Staying the night at Bosa Marina.

DAY 5

(Plio-Pleistocene volcanic rocks and mantle xenoliths)

Departure from Bosa Marina at h. 9.00

Stop 5.:

h. 10.30-11.30 (N40°32’41”; E8°54’31”)

Exploited spatter cone of Ittireddu (Logudoro) with mantle xenoliths.

Stop 5.2:

h. 13.30-14.30 (N40°19’54”; E9°33’07”)

Basaltic lava flows near the Cedrino River in central-northern Sardinia with spectacular columnar joints.

Stop 5.3:

h. 15.00-16.00 (N40°17”12”; E9°38’29”)

Box lunch at Cala Gonone (Orosei-Dorgali igneous district, north-eastern Sardinia). Basaltic lava flows with columnar joints and mantle xenoliths. Free time in the afternoon for swimming. Staying the night at Oliena (Su Gologone, central Sardinia).

DAY 6

Departure from Oliena at 9.00.

Arrival at Cagliari after about 3-4 hours. End of the trip.

Cagliari, the capital city of Sardinia, is a very old city founded by the ancient Phoenicians. The city is located on the southern end of the island. It is an aesthetically pleasing city, often referred to as the “City of the Sun”, with some interesting medieval architecture and a marvelous beach nearby. There are various interesting tourist sights and attractions in and around Cagliari. Here are some of them: Poetto Beach, located on the outskirts of Cagliari, has more than 6 miles of fine white sand facing the Gulf of the Angels. It is regarded by many as one of the world's top beaches. Lined with kiosks and cafés, the beach attracts sun worshippers by day, and serves as a vibrant meeting place for young people at night. Archaeological Sights/Medieval Architecture. A 2nd century Roman amphitheater and the 13th-century Cathedral of Santa Cecilia are here. Cagliari also hosts Sardinia's National Archaeological Museum. San Michele, an impressive medieval castle perched on top of a hill, enables you take in a magnificent view of the city in its entirety. The *Marina* and *Stampace* areas of the city - two of the four quarters into which the town was divided in the Middle Ages - have some wonderful examples of medieval architecture, including several churches. Also, there are extensive ruins of the ancient Phoenician city of Nora just outside Cagliari.

General information on Sardinia

Though it has been inhabited since prehistory (the first human settlements date back to 6.000 - 5.000 B.C.), Sardinia never developed a unified population. Traces of settlement are therefore extremely fragmentary, as lots of little villages throughout the island even today attest.

Villages, which are an expression of the civil-social order, were organized into communities and according to tribal groups of modest size.

The age of the nuragic civilization was a period of independence, but also of relative isolation from the larger cultural movements in the Mediterranean area. The Nuraghi, with their peculiar architectural structure, are the most representative sign of that past.

A typical trait of Sardinian archaeology is the lay out of the monuments and architectural works: they are spread out all over the countryside, in harmony with the natural environment.

The Nuraghi, as well as other evidence from the past, such as Domus de Janas, holy wells and temples, the giants' tombs, the big stones fixed in the ground (betili or megalithic menhirs) make Sardinia a kind of "open-air museum".

These signs are very frequent. On the whole island there are, in fact, about 7000 Nuraghi and hundreds of archaeological monuments.

Prehistory

Sardinia is one of the most ancient lands in Europe, visited way back from the Palaeolithic period, though inhabited permanently by man only much later, in the Neolithic age, around 6000 B.C.

The first men to settle in Gallura and Northern Sardinia probably came from the Italian mainland and, in particular, from Etruria. Those who populated the central region of the island around the salt lakes of Cabras and S. Giusta, arrived, it seems, from the Iberian Peninsula by way of the Balearic Islands. Those who founded their settlements around the gulf of Cagliari were never one single people, but actually several peoples.

As time passed, the Sardinian peoples became united in their language and customs, yet remained politically divided into various smaller tribal states. Sometimes they banded together, while other times they were at war with one another. Tribes lived in villages made up of thatched, round, stone huts, similar to the present day "pinnate" of shepherds.

From about 1500 B.C. onwards the villages were built at the foot of mighty truncated-cone fortresses (often reinforced and enlarged with battlement towers) called "nuraghi".

The boundaries of tribal territories were guarded by smaller, lookout nuraghi erected on strategic hills commanding a view of the enemy. Today some 7000 nuraghi dot the Sardinian landscape.

Ancient history

Around 1000 B.C. the Phoenicians began to land on the shores of Sardinia with increasing frequency. Setting sail from Lebanon, on their trade routes as far afield as Britain they needed safe anchorages for the night or to weather a storm.

With the local chieftain's consent the more common ports of call were those later named as: Caralis, Nora, Bithia, Sulcis, Tharros, Bosa, Torres and Olbia. They soon became important markets, and after a while real towns were established, inhabited by Phoenician families who traded on the open sea and with the Nuragic Sardinians inland.

In 509 B.C., in view of the Phoenician expansion inland becoming ever more menacing and penetrating, the native Sardinians attacked the coastal cities held by the enemy who, in order to defend themselves, called upon Carthage for help.

The Carthaginians, after a number of military campaigns, overcame the Sardinians and conquered the most mountainous region, later referred to as Barbarian or Barbagia.

For 271 years, the splendid Carthaginian or Punic civilization flourished alongside the fascinating local Nuragic culture.

In 238 B.C. the Carthaginians, defeated by the Romans in the first Punic War, surrendered Sardinia, which then became a province of Rome. The Romans enlarged and embellished the coastal cities and, with their armies, even penetrated the Barbagia region, thereby bringing down the Nuragic civilization. The Roman domination in Sardinia lasted 694 long years and was often opposed by the Sardinians from the mountains who, netherless, adopted the Latin language and civilization.

Medieval History

In 456 A.D., when the Roman Empire was sinking fast, the Vandals of Africa, on their return from a raid on Latium on the mainland, occupied Caralis, along with other coastal cities of Sardinia.

In 534 the Vandals were defeated at Tricamari - a place some 30 km from Carthage - by the troops of the Eastern Emperor Justinian, and Sardinia thus became Byzantine. The island was divided into districts called "merèie", governed by a magistrate residing in Caralis (Cagliari) and controlled by an army stationed in Forum Traiani (nowadays Fordongeanus) under the command of a "dux". Along with the Byzantines and the Eastern monastivism of the followers of St. Basil, Christianity spread throughout the island, except in the Barbagia regions. Here, towards the end of the sixth century, a short-lived independent domain re-established itself, with Sardinian –heathen, lay, and religious traditions; one of its kings was Ospitone.

From 640 to 732 the Arabs occupied North Africa, Spain and part of France. In 827 they began their occupation of Sicily. Sardinia remained isolated and was forced to defend herself; thus, the provincial magistrate assumed overall command, with both civil and military powers.

The continual raids and attacks by the Islamic Berbers on the Sardinian shores began in 710 and grew ever more ruinous with time. Their inhabitants abandoned one by the coastal towns and cities. The provincial magistrate, in order to provide a better defence of the island, assigned his civil and military powers to his four lieutenants in the meréie of Cagliari, Torres or Logudoro, Arborea and Gallura. Around 900, the lieutenants gained their independence, in turn becoming "judices" (in Sardinian "judikes" means "king") of their own "logo" or state.

Each one of these four Sardinian states, called "judicative", constituted a sovereign kingdom, not patrimonial, but independent since it was not the property of the monarch. But they were at the same time democratic, since all the most important issues of national interest were not for the king (or "judice") himself to decide but were a matter for the representatives of the people gathered in assembly called "corona de logu". Each kingdom manned its own fortified boundaries to protect its own political and trading affairs; each had its own parliament, its own laws (cartas de logu), its own national languages, own chancelleries, own state emblems and symbols, etc.

The kingdom or "giudicato" of Cagliari was politically pro-Genoese. It was brought to an end in 1258 when its capital, S. Igia, was stormed and destroyed by an alliance of Sardinian-Pisan forces. The territory then became a colony of Pisa.

The kingdom of Torres, too, was pro-Genoese, and came to an end in 1259, on the death of the "giudicessa" Adel Asia. The territory was divided up between the Dorian family of Genoa and the Bas-Serra family of Arborea, while the city of Sassari became an autonomous city-republic.

The kingdom of Gallura ended in the year 1288, when the last "giudice" Nino Visconti a friend of Dante's, was driven out by the Pisans who occupied the territory.

The kingdom of Arborea was almost always under the political and cultural influence of the powerful marine republic of Pisa. It lasted some 520 years, with Oristano as its capital.

In 1297, Pope Boniface VIII in order to settle diplomatically the War of the Vespers, which broke out in 1282 between the Angevins and the Aragons over the possession of Sicily, established propriety a hypothetical "regnum Sarduniae et Corsicae". The Pope enfeoffed it to the Catalan Jaume II the Just, king of the Crown of Aragon (a confederation made up of the kingdoms of Aragon and Valencia, plus the peasants of Catalonia), promising him support should he wish to conquer Pisan Sardinia in exchange for Sicily.

In 1323 Jaume II of Aragon formed an alliance with the kings of Arborea and, following a military campaign which lasted a year or so, occupied the Pisan territories of Cagliari and Gallura, along with the city of Sassari, naming them "the kingdom of Sardinia and Corsica".

In 1353, for reasons of state survival, war broke out between the kingdom of Arborea and the kingdom of "Sardinia and Corsica", part of the Crown of Aragon.

In 1354 the Aragons seized Alghero and reshaped it into an entirely Catalan city, which still today displays its Iberian origins.

In 1353 Pere IV of Aragon, called "the Cerimonious", granted legislative autonomy (a parliament) to the kingdom of "Sardinia and Corsica", which was followed in due course by self-government (Viceroy)

and judicial independence (Royal Hearing).
From 1365 to 1409 the kings or "giudici" of Arborea, Mariano IV, Ugone III, Mariano V (assisted by his mother Eleonora, the famous giudicessa regent) and Guglielmo III (Eleonora's French grandson) succeeded in occupying very nearly all of Sardinia except the Castle of Cagliari (today Cagliari and Alghero).
In 1409 Marti the Younger, king of Sicily and heir to Aragon, defeated the judicable Sardinians at Sanluri and conquered once and for all the entire land. Shortly afterwards he died in Cagliari of malaria, without an heir, and consequently the Crown of Aragon passed into the hands of the Trastàmara Castilians - and in particular Ferran I of Antequera and his descendants --with the Compromise of Caspe in 1412.

Modern History
In 1479, as a result of the unification enacted by Ferran II of Aragon and Isabel of Castile (the so-called "Catholic king and queen"), married ten years earlier, the Crown of Spain was born. Even the "kingdom of Sardinia" (which in the new title was separated from Corsica since that island had never been conquered) became Spanish; with the state symbol that of the Four Moors. Following the failure of the military ventures against the Muslims of Tunis (1535) and Algiers (1541) Carlos V of Spain, in order to defend his Mediterranean territories from the pirate raids of the African Berbers, fortified the Sardinian shores with a system of coastal lookout towers.
The kingdom of Sardinia remained Iberian for approximately four hundred years, from 1323 to 1720, assimilating a number of Spanish traditions, customs, linguistic expressions and lifestyles, nowadays vividly portrayed in the folklore parades of S. Efisio in Cagliari (May 1st), by the Cavalcade on Sassari (next to last Sunday in May) and by the Holiday of the Redeemer in Nuoro (August 28th).
In 1708, as a consequence of the Spanish War of Succession, the rule of the kingdom of Sardinia passed into the hands of the Austrians, who had landed on the island.
In 1717, cardinal Alberoni, minister of Felipe V of Spain, reoccupied Sardinia.
In 1718, with the Treaty of London, the kingdom of Sardinia was handed over to the Dukes of Savoy, princes of Piedmont, who rendered it perfect from imperfect bestowing upon itthe "summa potestas", that is the authority to stipulate international treaties. The kingdom was then Italianised.
In 1799, as a consequence of the Napoleonic wars in Italy, the Dukes of Savoy left Turin and took refuge in Cagliari for some fifteen years.
In 1847 the Sardinians spontaneously renounced their state autonomy and "melded" with Piedmont in order to have a single parliament, a single magistracy and a single government in Turin.
In 1848 the Wars of Independence broke out for the Unification of Italy and were led by the kings of Sardinia for thirteen years.
In 1861 the kingdom of Sardinia was made part of the newly-founded Italian nation .
Contemporary Era
In 1946, by popular referendum, Italy became a Republic. Sardinia - administered since 1948 by special Statute - is today one of the twenty Italian regions, with 1,700,000 inhabitants spread out over the provinces of Cagliari, Sassari, Oristano and Nuoro, retracing more or less the territories of the four ancient and glorious judicable states.

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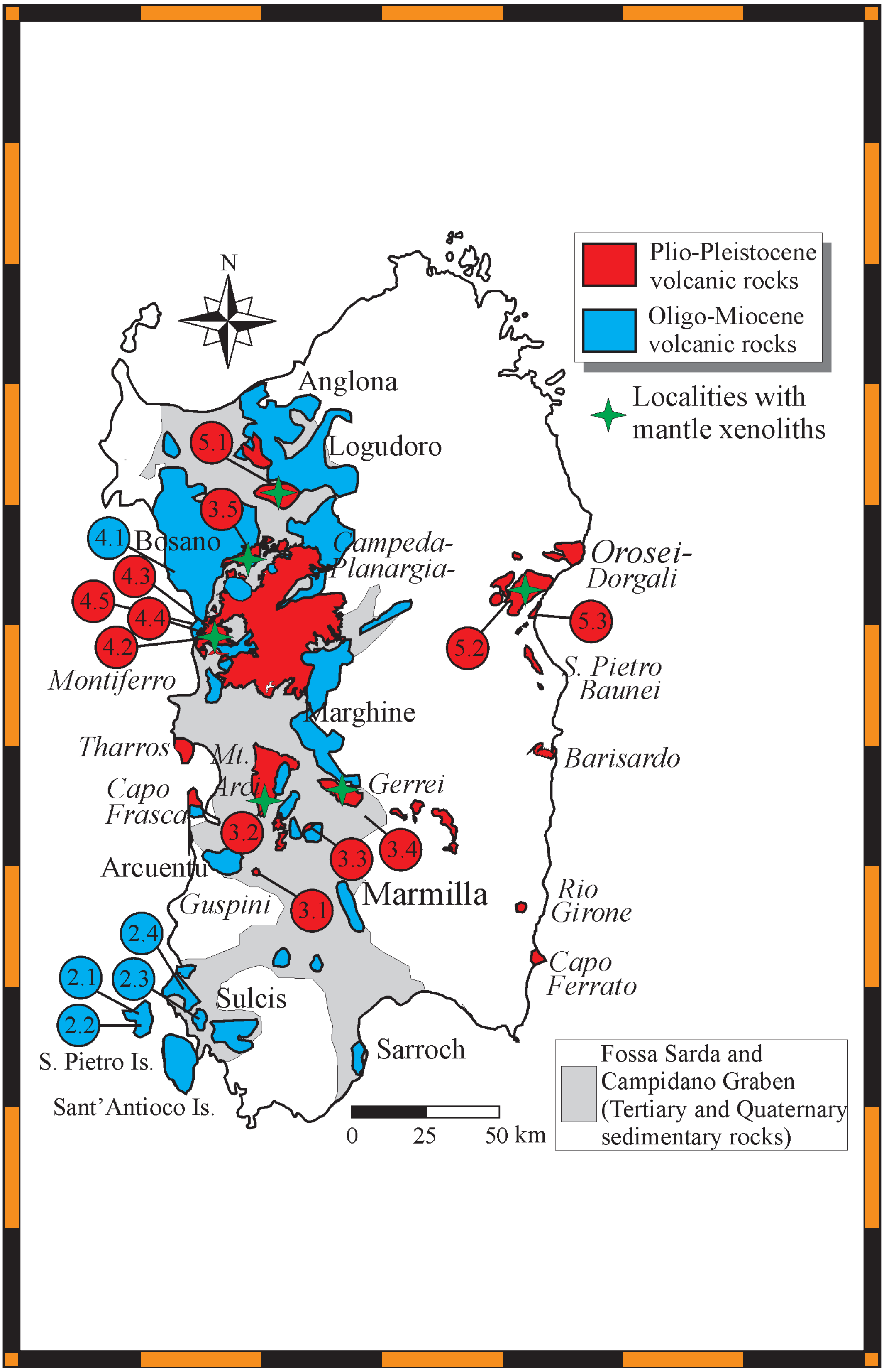

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