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Mineral compositions and magmatic evolution of the calcalkaline rocks of northwestern Sardinia, Italy

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Abstract

During Early Miocene northwestern Sardinia was interested by widespread volcanic activity belonging to the calcalkaline to high-K calcalkaline “orogenic” Sardinian cycle. The peak of activity is recorded in the ~ 22-18 Ma time span and it is mostly concentrated along the *Fossa Sarda* graben, an Oligo-Miocene rift system cutting the western Sardinia from north to south. The northwestern Sardinia volcanic rocks crop out in the districts of Bosa-Alghero, Anglona, Logudoro, Mulargia-Macomer and Ottana graben, ranging in composition from rare high alumina basalt lavas to rhyolitic ignimbrites (welded and unwelded) and lava flows, through basaltic andesites, andesites and dacitic domes, with the most evolved rocks (dacites and rhyolites) being volumetrically predominant.

Here we report the chemical composition of the main rock-forming minerals (clinopyroxene, orthopyroxene, plagioclase, sanidine, magnetite, ilmenite, olivine, brown mica and amphibole) and whole-rock data covering the entire spectrum of occurring lithotypes.

The bulk-rock major and trace element variations are consistent with an evolution mainly driven by fractional crystallization of the observed mineral phases. This was confirmed by mass balance calculations and MELTS-based modelling, which allowed reconstructing liquid lines of descent for each district. Crystallization conditions took place at low pressures (1 kbar) and low H_2O contents (< 2 wt.%), with oxygen fugacities close to the QFM and Ni-NiO synthetic buffers and temperature values ranging from ~ 900 to ~ 1150 °C for mafic rocks and from ~ 800 to ~ 1000 °C for the silicic ones. Open-system processes may also have had a role in the petrogenesis of the silicic rocks.

Key words: ignimbrites; mineral chemistry; orogenic magmatism; Sardinia.

Introduction

During the Cenozoic an intense igneous activity with calcalkaline to high-K calcalkaline products took place in Sardinia (Coulon et al., 1974; Montigny et al., 1981; Beccaluva et al., 1985; Morra et al., 1994; 1997; Brotzu et al., 1997a; 1997b; Lustrino et al., 2004; 2009; 2011; Conte et al., 2010, and references therein). The volcanic products comprise pyroclastic flow deposits, lava flows and domes; their compositions are dominated by dacites and rhyolites, with subordinate andesites and very scarce basalts.

Despite the interest raised by the Sardinian igneous rocks in the last ~ 15-20 years, some key aspects remain to be investigated in detail. Indeed, most recent literature is focused on primitive magmatic compositions and their relationships with a subduction-modified mantle source (Brotzu et al., 1997a; 1997b; Morra et al., 1997; Mattioli et al., 2000; Downes et al., 2001; Franciosi et al., 2003; Conte et al., 2010), whereas the petrogenesis of the more widespread silicic products is basically that produced during ‘60s and ‘70s (e.g., Deriu, 1962; Coulon et al., 1973; 1978; Lonis et al., 1997). This study is intended to fill this gap by presenting a new set of data set for the calcalkaline volcanic rocks cropping out in the northwestern sector of Sardinia, where silicic lithologies are particularly abundant. This investigation is focused on the mineralogical characterization and on the evaluation of the physico-chemical environment of crystallization.

Geodynamic and geological background

Up to Early Oligocene times the Sardinia-Corsica micro-plate was contiguous with the southern European margin (Provence, France, and Catalonia, Spain; e.g., Cherchi et al., 2008; Dieni et al., 2008; Lustrino et al., 2009; Carminati et al., 2010, and references therein). During the Late Oligocene, with the opening of Ligurian-Provencal Basin, the Sardinia-Corsica micro-plate rifted toward SE and then drifted counter-clockwise away from the southern Europe paleo-margin, with a rotation pole located around the present gulf of Genoa (NW Italy; Carminati et al., 1998; 2010; Jolivet et al., 1998; Speranza et al., 2002; Gattacceca et al., 2007; Lustrino et al., 2009). The continental rifting phase started ~ 30 Ma, whereas the drifting phase started around ~ 22 Ma until ~ 15 Ma, after a counter clock-wise rotation of ~ 60 degrees (Gueguen et al., 1998; Speranza et al., 2002; Vigliotti and Langenheim, 1995; Schettino and Turco, 2006; Lustrino et al., 2009; Carminati et al., 2010). From Langhian (~ 15 Ma) the Sardinia-Corsica micro-plate reached its present position and the extensional tectonics shifted eastwards, leading to the development of Tyrrhenian Sea and the Apennine fold-and-thrust belt (Lustrino et al., 2009; Carminati et al., 2010, and references therein).

In this complex geodynamic scenario, the island of Sardinia experienced an intense magmatism (Lecca et al., 1997; Lustrino et al., 2004; 2009; 2011) which can be chronologically and geochemically divided into two distinct phases. The products of the oldest phase (Late Eocene-Middle Miocene activity, or LEMM; ~ 38-13 Ma; Lustrino et al., 2009, and references therein) show “orogenic” (i.e., subduction-related) geochemical signature, whereas the products of the youngest phase (Late Miocene-Quaternary, hereafter LMQ; ~ 12-0.1 Ma) show “anorogenic” (within plate) geochemical characteristics (e.g., Beccaluva et al., 1985; Lustrino et al., 2004; 2007a; 2007b; 2009; 2011; Lustrino and Wilson, 2007, and references therein).

The volume of the erupted magma amounts to ~ 1000-2500 km^3, excluding the volume of rocks deposited along the submerged margins of the island, hypothesizing an originally continuous pyroclastic flow cover in northern Sardinia (with an areal extent of ~ 4800 km^2 and an average thickness in the range of 200-500 m). Such a large amount of magma was produced, in a relatively short time span, and may have had significant effects on marine ecosystem of the area (e.g., Brandano et al., 2010; Brandano and Policicchio, 2011). As for the products emplaced in the northwestern sector, Deriu (1962) first proposed a stratigraphic and minero-petrographic subdivision taking into account four stratigraphic sequences: 1) the *andesitoide inferiore* (lower andesitic) series; 2) the *trachitoide inferiore* (lower trachytic) series, the first evidence of acid volcanism with ignimbritic facies; 3) the *andesitoide superiore* (upper andesitic) series, characterized by the intercalation of fluvial-lacustrine sediments and pyroclastic materials; 4) the *trachitoide superiore* (upper trachytic) series, characterized by erosive features and intercalations of fluvial-lacustrine sediments. Coulon (1977) provided a detailed volcano-stratigraphic, mineralogical and petrologic description (from base to top): 1) the *andesitica inferiore* (lower andesitic) series, characterized by products with basalt and basaltic andesite composition with minor dacites and rhyolites; 2) the *ignimbritica inferiore* (lower ignimbritic) series; 3) the *andesitica superiore* (upper andesitic) series; 4) the *dactic domes* and *rhyolitic lava flows*; 5) the *ignimbritica superiore* (upper ignimbritic) series and 6) the *andesitica terminale* (upper andesitic) series, with basaltic andesites, dacites and rhyolites. More recent studies (i.e., Lecca et al., 1997) still rely on this stratigraphic schemes.

The LEMM products range in composition from dacites to rhyolites, with subordinate basaltic andesites, andesites, high-Al basalts and rare high-Mg basalts and belong to the calcalkaline and high-K calcalkaline series (e.g., Brotzu et al., 1997a; 1997b; Lecca et al., 1997; Lonis et al., 1997; Morra et al., 1997; Downes et al., 2001; Lustrino et al., 2004; 2009; Conte et al., 2010). Rare peralkaline products (comendites) are found in southwestern Sardinia (Sulcis; Araña et al., 1974; Morra et al., 1994).

The mantle source of the mafic "orogenic" volcanic rocks is in the wedge above a west-directed oceanic lithosphere subducted below the southern European continental margin, enriched in large ion lithophile elements by fluids/melts derived from the subducted slab (Franciosi et al., 2003; Lustrino et al., 2004; 2009; 2011).

Analytical techniques

The samples were cut with a saw and crushed in a jaw crusher. The obtained chips were washed in distilled water and then ground in a low-blank agate mortar and analyzed for major and trace elements were obtained with XRF (X-Ray fluorescence) on pressed powder pellets at CISAG (Centro Interdipartimentale di Servizi per Analisi Geomineralogiche), University of Napoli Federico II (see Melluso et al., 2005 for details). Mineral compositions were obtained at IGAG-CNR, Rome, using a Cameca SX50 electron microprobe equipped with five spectrometers and at CISAG, with an Oxford Instruments Microanalysis Unit, equipped with an INCA X-act detector and a JEOL JSM-5310 microscope operating at 15 kV primary beam voltage, 50-100 μA filament current, variable spot size and 50 s net acquisition time (see Melluso et al., 2010 and Guarino et al., 2011 for full details).

Classification and geochemical features

The Early Miocene volcanic rocks subject of this study were collected in five districts in the northwestern sector of Sardinia (Figure 1a, b). The district, the number of samples, the lithologies and the absolute ages for each of them are summarized in Table 1.

Table 2 shows major and trace element composition of representative Early Miocene rocks from northwestern Sardinia. According to the TAS diagram (Figure 2a), the rocks are

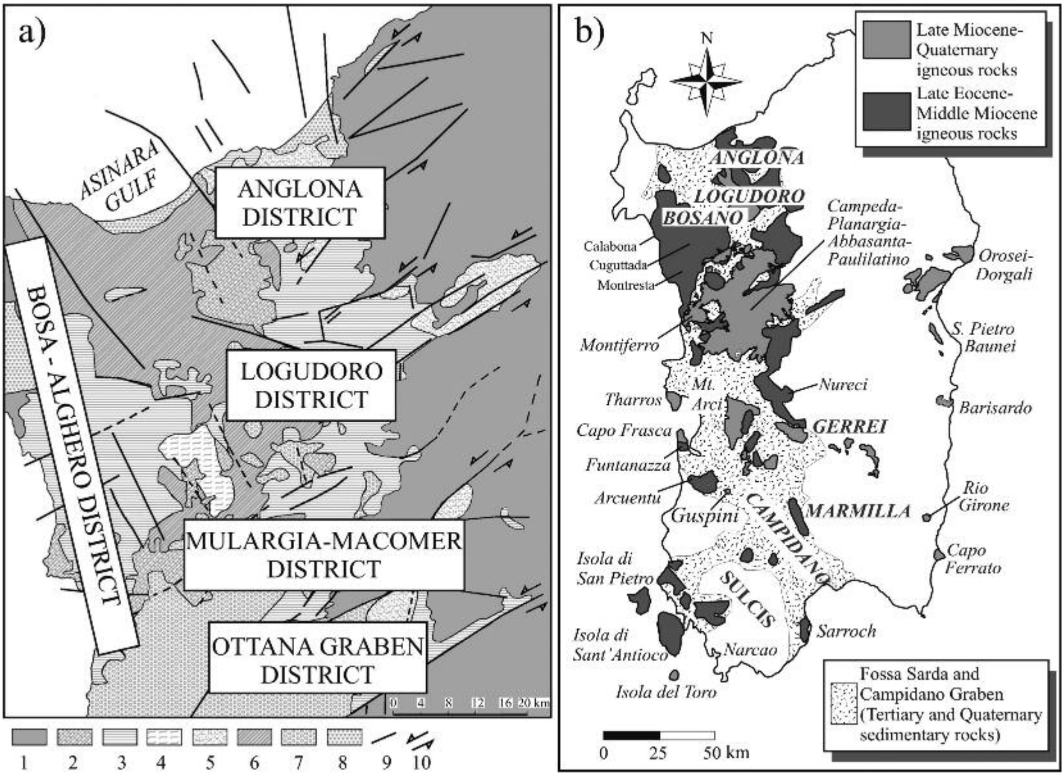

Figure 1. a) Geological sketch map (modified after Sau et al., 2005) for the studied districts of the Late Eocene-Middle Miocene Sardinia magmatic phase. 1 = Palaeozoic basement; 2 = Early Miocene andesites; 3 = Early Miocene ignimbrites; 4 = rhyodacitic lavas; 5 = fluvial-lacustrine and epiclastic complex of Miocene basins; 6 = marine sequences of Miocene basins; 7 = anorogenic volcanites of the Late Miocene-Quaternary cycle; 8 = Quaternary sedimentary deposits; 9 = fault zones; 10 = main transcurrent movements. b) Simplified geological sketch map of Sardinia (modified after Lustrino et al., 2009).

mainly dacites and rhyolites, with subordinate basalts, basaltic andesites and andesites. A bimodal composition is indicated by a Daly gap, with andesitic compositions (SiO_2 = 57-63 wt.%) being rare.

Among the mafic lithotypes, the few basalts, from the Bosa-Alghero and Logudoro districts, show high Al_2O_3 (17.8-19.4 wt.%) and relatively low MgO (3.4-7.2 wt.%), Mg# [0.41-0.60; Mg# = molar MgO/(MgO+FeO+MnO)], Cr (16-52.4 ppm) and Ni (9.0-19 ppm). These basalts are classified as high-Al basalts (HAB) according to Kersting and Arculus (1994). The basaltic rocks at Montresta (Figure 1b), are classified as high-Mg basalts (HMB; Morra et al., 1997; Franciosi et al., 2003), due to high MgO (up to 11 wt.%) and relatively low Al_2O_3 (< 16 wt.%).

Metaluminous [$Al_2O_3/(CaO+Na_2O+K_2O) < 1$] and peraluminous [$Al_2O_3/(CaO+Na_2O+K_2O) > 1$] dacites and rhyolites are present (Figure 2b); no peralkaline rhyolites or trachytes have been found in northern Sardinia.

Table 1. Synoptic table showing district, number of samples, main lithologies and absolute ages of the studied Early Miocene rocks from northwestern Sardinia.

District	*Number of samples*	*Lithology*	*Age*
Bosa-Alghero district	10	basalts, basaltic andesite lava flows	~ 28-16 Ma (Montigny et al.,1981; Beccaluva et al., 1985; Lecca et al., 1997; Deino et al., 2001; Gattacceca et al., 2007)
	1	andesitic lava flows	
	39	welded and unwelded ignimbrites	
Anglona district	2	andesitic lava flows	~ 21-18 Ma (Montigny et al., 1981; Lecca et al., 1997; Oudet et al., 2010)
	5	welded and unwelded ignimbrites	
Logudoro district	6	basalts and basaltic andesite lava flows	~ 25-17 Ma (Coulon et al., 1974; Beccaluva et al., 1985)
	1	andesitic lava flows	
	5	dacitic domes	
	1	rhyolitic lava flows	
	26	welded and unwelded ignimbrites	
Mulargia-Macomer district	1	rhyolitic lava flows	~ 21.8-21.6 Ma; (Lecca et al., 1997 and references therein)
	5	welded and unwelded ignimbrites	
Ottana graben district	3	welded and unwelded ignimbrites	~ 21-19.4 Ma (Lecca et al., 1997 and references therein)

The analyzed rocks display smooth and linear variation trends (Figure 3) characterized by decreasing TiO_2, Al_2O_3, Fe_2O_{3t}, MgO and CaO with increasing SiO_2. The trace elements Rb, Ba, Y and Zr, increase with silica, then their concentrations suddenly decrease at ~70% SiO_2. Sr decreases with increasing SiO_2 (Figure 4).

Petrographic features

The main petrographic features of Early Miocene rocks of northwestern Sardinia are reported in Figure 5 and are briefly summarized below.

Basalts. The rocks (from the Bosa-Alghero and Logudoro districts) are porphyritic. The main phenocrysts are subhedral to euhedral zoned plagioclase (sometimes with rounded rims), and clinopyroxene, generally showing rounded rims, only sporadically subhedral in shape. Olivine is quite common and shows euhedral shapes often corroded or iddingsitized. Opaque oxides mainly occur as inclusions or in the groundmass. The groundmass is microcrystalline and it is made of the same phases observed as phenocrysts (except olivine) plus rare orthopyroxene.

Basaltic Andesites. The rocks (Bosa-Alghero,

Table 2. Major (wt.%) and trace element (ppm) concentrations, and CIPW normative minerals for representative samples of Early Miocene rocks from northwestern Sardinia.

	Bosa - Alghero district													
Locality	M.te Ruju-M.te Majore	Montresta	Mt. Farre		P.ta Tripides	Mt. Farre	SW Mt. Mannu	Mt. Minerva	Mt. Farre	Mt. Ladu	Mt. Minerva	SE Miale Ispina	Bosa	Mt. Minerva
G.P.S. coordinates	N 40°25'25" E 08°25'02"	N 40°23'12" E 08°30'19"	N 40°21'39" E 08°25'54"	N 40°21'45" E 08°25'56"			N 40°21'58" E 08°24'17"	N 40°26'12" E 08°33'06"	N 40°21'48" E 08°25'52"	N 40°30'22" E 08°22'37"	N 40°26'36" E 08°32'35"	N 40°37'38" E 08°25'47"	N 40°22'5.4" E 08°24'27"	
Rock type	HAB	HAB	HAB	HAB	BA	BA	A	D	R	R	R	R	R	R
XRF (wt.%)	MA23	MARA21	MARA25	MARA23	MARA34	MARA33	MARA36	MARA13	MARA22	MA29B	MARA12	MA35	MARA38	MARA15
SiO_2	47.98	48.12	51.27	51.93	53.34	53.90	60.87	65.28	69.37	70.34	71.51	73.61	76.30	76.64
TiO_2	1.24	1.11	0.99	0.99	0.91	0.96	0.70	0.46	0.66	0.64	0.41	0.30	0.28	0.21
Al_2O_3	18.85	17.78	18.26	18.74	19.27	16.37	15.85	14.35	13.59	14.50	13.22	13.18	12.40	11.39
Fe_2O_{3t}	10.69	11.27	10.23	10.22	9.29	10.09	6.73	4.93	5.41	3.88	3.86	2.92	2.70	2.06
MnO	0.18	0.20	0.20	0.21	0.19	0.19	0.13	0.06	0.12	0.06	0.10	0.05	0.03	0.03
MgO	7.15	5.90	4.34	4.02	2.87	5.48	4.58	3.75	0.77	0.76	0.75	1.38	0.31	0.46
CaO	10.42	11.87	10.56	9.83	9.65	8.67	6.74	4.75	2.29	2.80	2.58	1.98	1.82	1.74
Na_2O	2.11	2.32	2.63	2.88	3.12	2.61	2.13	2.76	3.97	3.31	3.09	2.63	2.28	1.47
K_2O	1.14	1.22	1.26	1.01	1.12	1.51	2.11	3.49	3.66	3.56	4.36	3.89	3.78	5.95
P_2O_5	0.23	0.20	0.26	0.16	0.23	0.22	0.15	0.18	0.17	0.14	0.12	0.05	0.08	0.04
sum	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*
Mg#	0.60	0.53	0.48	0.46										
LOI	1.64	2.59	0.57	0.86	0.43	1.48	4.40	2.46	1.81	3.60	1.33	5.77	1.81	6.86
XRF (ppm)														
Sc	40	32	34	35	29	32	23	23	19	13	13	11	7	8
V	375	313	266	290	251	231	159	62	74	34	36	47	9	17
Cr	52	45	29	16	21	29	4	11		1				
Ni	9	19	9	11	11	11	9	5	3	7	3	5	1	1
Rb	33	35	30	31	29	39	45	127	117	135	161	152	125	255
Sr	492	366	329	318	327	300	291	286	202	187	194	144	186	153
Y	29	26	24	26	24	29	30	32	55	32	31	45	24	37
Zr	89	73	71	84	74	103	158	237	251	202	229	273	187	207
Nb	1.6	4.9	4.5	4.9	4.1	7.2	13.6	9.7	15.2	12.3	12.6	14.4	10.1	14.2
Ba	137	134	177	206	202	219	819	607	649	533	680	892	453	553
CIPW norms:														
quartz			0.56	1.64	3.75	3.95	16.88	19.14	24.17	28.71	28.95	35.62	42.92	40.18
corundum										0.43		1.16	1.43	
orthoclase	6.75	7.22	7.45	5.97	6.63	8.93	12.49	20.59	21.60	21.07	25.74	22.97	22.36	35.15
albite	17.88	19.65	22.27	24.39	26.43	22.11	18.05	23.39	33.55	28.05	26.18	22.29	19.31	12.45
anorthite	38.57	34.48	34.27	35.20	35.25	28.47	27.42	16.46	8.48	12.99	9.31	9.51	8.52	6.92
diopside	9.53	19.09	13.65	10.44	9.35	10.81	4.13	4.82	1.53		2.32			1.24
hypersthene	9.82	0.02	16.65	17.44	13.91	20.77	17.60	13.01	7.61	6.21	5.43	7.01	4.04	3.02
olivine	11.78	14.03												
magnetite	1.84	1.94	1.76	1.76	1.60	1.74	1.16	0.85	0.93	0.67	0.66	0.50	0.47	0.36
ilmenite	2.36	2.11	1.88	1.88	1.73	1.83	1.33	0.87	1.26	1.22	0.78	0.57	0.53	0.40
apatite	0.55	0.47	0.62	0.38	0.55	0.52	0.36	0.43	0.40	0.33	0.28	0.12	0.19	0.09
sum	*99.1*	*99.0*	*99.1*	*99.1*	*99.2*	*99.1*	*99.4*	*99.6*	*99.5*	*99.7*	*99.7*	*99.7*	*99.8*	*99.8*

The major oxide analyses are recalculated to 100 wt.% LOI-free. HAB = high alumina basalt; BA = basaltic andesite; A = andesite; D = dacite; R = rhyolite. Weight loss on ignition (LOI, in wt.%) was determined by standard thermo-gravimetric method.

Table 2. Continued...

Logudoro district

Locality	Thiesi		Ittiri	Thiesi	S. Mt. Frusciu					Ittireddu	M.te Traessu-Cossoine		Thiesi
G.P.S. coordinates	N 40°33'01" E 08° 39' 16"	N 40°23'49" E 08° 37' 38"		N 40°33'01" E 08° 39' 16"	N 40°28'09" E 08° 38' 13"	N 40°28'51" E 08° 37' 05"	N 40°29'53" E 08° 36' 09"	N 40°30'28" E 08° 36' 05"	N 40°30'28" E 08° 36' 05"	N 40°31'57" E 08° 54' 23"	N 40°28'35" E 08° 40' 48"	N 40°28'34" E 08°41' 41"	N 40°33'01" E 08° 39' 16"
Rock type	HAB	HAB	HAB	BA	BA	A	D	R	R	R	R	R	R
XRF (wt.%)	MA72C	MA38	MA19	MA72A	MA12	MA11	MARA7	MA13A	MA13B	MA50	MA37	MA36	MA71
SiO_2	49.93	51.54	51.81	54.79	55.70	61.23	69.73	70.06	72.42	73.28	75.93	76.66	77.42
TiO_2	0.93	1.01	0.83	1.04	0.81	0.77	0.46	0.42	0.36	0.26	0.18	0.17	0.17
Al_2O_3	19.43	17.82	18.78	19.09	16.51	16.55	14.05	14.10	13.20	13.30	12.09	11.75	11.82
Fe_2O_{3t}	10.72	10.76	10.32	9.74	8.46	7.25	3.56	3.42	2.71	2.70	2.16	2.05	2.04
MnO	0.13	0.19	0.20	0.06	0.15	0.09	0.07	0.08	0.04	0.02	0.07	0.05	0.04
MgO	3.39	4.49	4.66	0.86	4.48	1.10	1.48	1.44	0.86	0.25	0.53	0.22	1.16
CaO	11.15	9.40	9.58	9.73	8.28	6.31	3.47	3.34	3.04	0.98	1.33	0.97	1.86
Na_2O	2.77	3.02	2.65	2.30	2.74	3.03	2.93	3.09	3.02	2.14	2.92	3.18	1.61
K_2O	1.32	1.50	1.02	2.21	2.66	3.47	4.11	3.92	4.22	6.99	4.72	4.90	3.83
P_2O_5	0.21	0.26	0.15	0.16	0.20	0.19	0.14	0.12	0.12	0.07	0.06	0.05	0.04
sum	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*
Mg#	0.41	0.48	0.50										
LOI	1.89	1.86	1.84	1.34	1.27	1.74	2.56	2.45	0.72	0.80	3.45	0.56	6.20
XRF (ppm)													
Sc	30	27	32	29	25	25	11	7	9	9	2	4	4
V	317	266	239	415	195	190	37	38	25	25			16
Cr	33	24	15	23	30	24		4	5	5	1		3
Ni	18	16	13	6	13	12	0	3	2	2		1	
Rb	48	39	34	84	85	126	141	151	144	144	178	180	140
Sr	462	540	357	389	450	434	269	256	237	237	144	114	206
Y	24	24	21	18	24	31	30	30	29	29	29	27	13
Zr	72	91	66	82	150	205	234	227	210	210	186	180	111
Nb	1.1	0.6	1.8	2.4	4.4	6.2	12.1	11.6	11.1	11.1	14.8	14.6	8.2
Ba	155	243	184	235	288	388	633	601	647	647	484	509	569
CIPW norms:													
quartz			1.71	8.54	4.17	13.61	26.50	26.83	30.73	30.30	36.20	36.21	46.59
corundum										0.59			1.73
orthoclase	7.81	8.88	6.03	13.08	15.74	20.48	24.27	23.14	24.91	41.30	27.87	28.93	22.66
albite	23.46	25.59	22.44	19.49	23.21	25.68	24.83	26.18	25.59	18.13	24.74	26.94	13.64
anorthite	36.67	30.62	36.31	35.23	24.87	21.32	13.04	13.02	9.99	4.41	5.95	3.29	8.98
diopside	14.52	11.92	8.49	10.44	12.30	7.51	2.69	2.32	3.63		0.22	1.04	
hypersthene	6.90	15.23	20.40	8.34	15.50	7.63	6.55	6.54	3.49	3.90	3.98	2.61	5.46
olivine	5.59	2.44											
magnetite	1.85	1.86	1.78	1.68	1.46	1.25	0.61	0.59	0.47	0.47	0.37	0.35	0.35
ilmenite	1.77	1.92	1.58	1.98	1.54	1.46	0.88	0.80	0.68	0.49	0.34	0.32	0.32
apatite	0.50	0.62	0.36	0.38	0.47	0.45	0.33	0.28	0.28	0.17	0.14	0.12	0.09
sum	*99.1*	*99.1*	*99.1*	*99.2*	*99.3*	*99.4*	*99.7*	*99.7*	*99.8*	*99.8*	*99.8*	*99.8*	*99.8*

The major oxide analyses are recalculated to 100 wt.% LOI-free. HAB = high alumina basalt; BA = basaltic andesite; A = andesite; D = dacite; R = rhyolite. Weight loss on ignition (LOI, in wt.%) was determined by standard thermo-gravimetric method.

Table 2. Continued...

	Anglona district			Mulargia - Macomer district			Ottana graben district		
Locality	Sedini		Castelsardo	Mt. S. Padre	Ab. Mulargia	Mt. S. Padre	Ottana		
G.P.S. coordinates	N 40°50'54" E 08°44'06"	N 40°51'42" E 08°47'42"	N 40°54'47" E 08°41'58"	N 40°17'06" E 08°49'28"	N 40°17'53" E 08°48'36"	N 40°17'52" E 08°50'30"	N 40°17'20" E 09°02'46"	N 40°14'19" E 09°03'27"	N 40°13'34" E 09°01'54"
Rock type	A	D	R	R	R	R	D	R	R
XRF (wt.%)	MA82	MA84B	MA6A	MA65	MA61	MA62A	MA69	MA67	MA66
SiO_2	56.58	66.86	75.96	69.21	71.73	72.93	68.84	72.60	76.75
TiO_2	0.83	0.57	0.40	0.56	0.48	0.37	0.72	0.47	0.34
Al_2O_3	16.51	14.80	11.63	14.90	13.48	13.10	13.71	12.85	10.90
Fe_2O_{3t}	8.93	5.31	2.55	4.35	4.10	3.67	5.57	4.15	3.19
MnO	0.15	0.11	0.04	0.12	0.07	0.06	0.04	0.04	0.03
MgO	2.99	1.95	0.19	0.97	0.25	0.53	0.81	0.44	0.19
CaO	8.65	2.91	1.33	1.92	1.14	1.29	2.81	1.84	1.18
Na_2O	2.64	3.36	3.49	3.86	3.62	3.57	3.59	3.52	3.23
K_2O	2.51	3.98	4.32	4.00	5.06	4.38	3.73	3.98	4.09
P_2O_5	0.20	0.15	0.08	0.12	0.07	0.09	0.18	0.11	0.08
sum	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*
Mg#									
LOI	1.17	5.13	0.64	2.08	1.00	1.38	2.95	2.21	1.25
XRF (ppm)									
Sc	31	15	10	16	12	15	22	17	10
V	245	39	1	40	34	8	96	23	13
Cr	16			2		2			1
Ni	9	8	1	5	5		3		1
Rb	104	306	147	130	148	155	116	140	146
Sr	364	258	119	164	120	116	238	144	100
Y	25	52	38	41	34	47	43	37	43
Zr	119	283	243	221	244	279	229	260	254
Nb	4.7	14.4	16.1	13.5	15.1	17.5	13.8	16.5	16.2
Ba	372	604	502	496	515	571	1269	551	554
CIPW norms:									
quartz	7.55	20.45	35.50	23.91	26.45	30.05	24.59	30.56	38.41
corundum		0.04		1.03	0.13	0.35			
orthoclase	14.85	23.50	25.50	23.61	29.88	25.86	22.03	23.49	24.20
albite	22.36	28.39	29.56	32.62	30.67	30.25	30.35	29.82	27.36
anorthite	25.76	13.48	3.32	8.75	5.21	5.82	10.29	7.49	3.14
diopside	13.28		2.41				2.10	0.80	1.92
hypersthene	11.82	11.33	2.10	7.62	5.52	5.81	7.39	5.61	3.30
olivine									
magnetite	1.54	0.92	0.44	0.75	0.71	0.63	0.96	0.71	0.55
ilmenite	1.58	1.08	0.76	1.06	0.91	0.70	1.37	0.89	0.65
apatite	0.47	0.36	0.19	0.28	0.17	0.21	0.43	0.26	0.19
sum	*99.2*	*99.5*	*99.8*	*99.6*	*99.6*	*99.7*	*99.5*	*99.6*	*99.7*

The major oxide analyses are recalculated to 100 wt.% LOI-free. HAB = high alumina basalt; BA = basaltic andesite; A = andesite; D = dacite; R = rhyolite. Weight loss on ignition (LOI, in wt.%) was determined by standard thermo-gravimetric method.

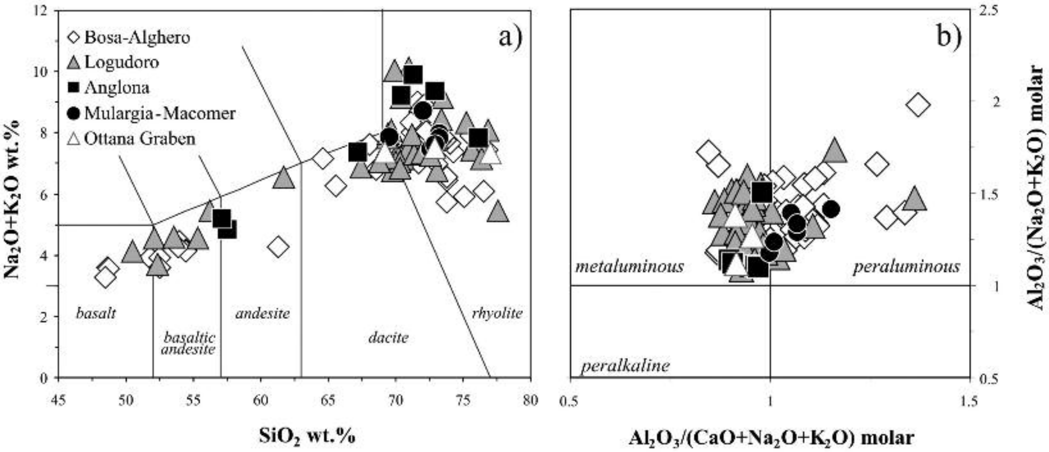

Figure 2. a) Total Alkali vs. Silica (TAS; Le Bas et al., 1986) classification diagram for the studied Early Miocene volcanic rocks from north western Sardinia. b) Molar $Al_2O_3/(Na_2O+K_2O)$ vs. $Al_2O_3/(CaO+Na_2O+K_2O)$ for the studied Early Miocene volcanic rocks from northwestern Sardinia.

Anglona and Logudoro districts) are porphyritic to glomeroporphyritic, with plagioclase being the predominant phenocryst. Clinopyroxene generally occurs as subhedral pheno- to microphenocrysts with rounded rims, sometimes completely altered. Olivine crystals are rare, often altered into haematite or iddingsite. Orthopyroxene is represented by rare euhedral and quite fractured crystals. Opaque oxides occur as inclusions within mafic minerals or in the groundmass. The groundmass is microcrystalline to intersertal, more rarely hypocrystalline, with microlites of plagioclase, clinopyroxene and opaque oxides.

Andesites. These rocks (Bosa-Alghero and Logudoro districts) are quite altered, with plagioclase and euhedral clinopyroxene phenocrysts. The groundmass is often argillified.

Dacitic domes. The dacites from Logudoro district are porphyritic for phenocrysts of plagioclase, clinopyroxene and occasionally opaque oxides. Clusters of plagioclase, clinopyroxene and oxides are sometimes noted. Brown mica (often altered), and euhedral green amphibole are common microlites. Orthopyroxene is a rare microlite. Accessory apatite is found in the groundmass.

Rhyolitic lavas. The Logudoro rhyolites are porphyritic, with euhedral to subhedral plagioclase with altered cores. Abundant alkali feldspar, oxidized brown mica and minor amphibole plus opaque oxide microcrysts are also observed, set into a completely glassy groundmass with no evidences of devitrification. The Mulargia-Macomer rhyolites are porphyritic with subhedral zoned phenocrysts of plagioclase, microcrysts of opaque oxides, quartz and deeply altered mafic phases set into a microcrystalline groundmass mainly made of alkali feldspar, quartz and rare apatite crystals.

Ignimbrites outcrop in the Bosa-Alghero, Anglona, Logudoro, Mulargia-Macomer and Ottana graben districts. These ignimbrites (dacitic to rhyolitic in composition) can be subdivided into two types: a) *unwelded ignimbrites* and b) *welded ignimbrites.*

a) Unwelded ignimbrites. These samples are made up of glassy shards, pumices and scoria fragments. The observed mineral assemblages comprise rounded and variably zoned

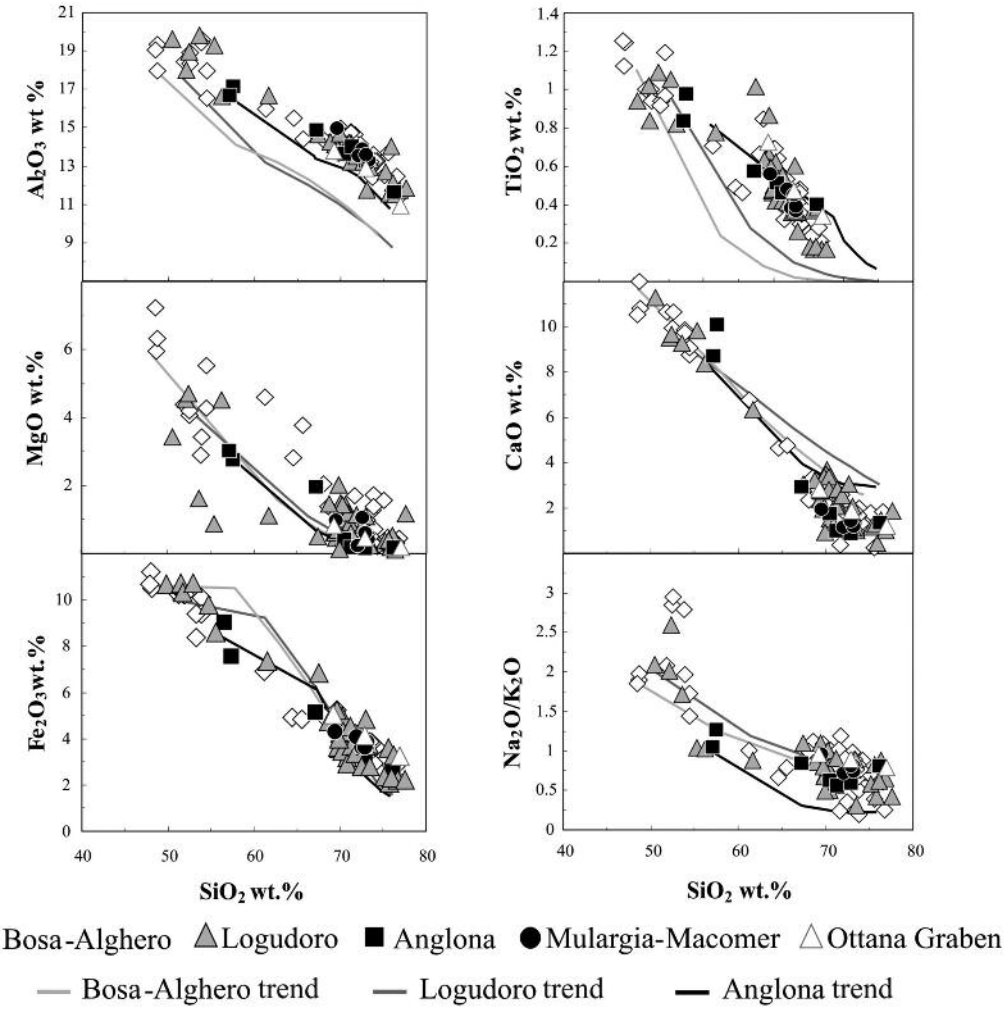

Figure 3. Selected major element variation diagrams for the studied Early Miocene volcanic rocks from northwestern Sardinia. The best-fit results of MELTS modelling for each volcanic district are also reported (see text for further explanations).

plagioclase, euhedral brown mica microcrysts, corroded clinopyroxene, quartz, rare subhedral green-brown amphibole and orthopyroxene, plus alkali feldspar and opaque oxides. Common accessories are zircon and apatite. Occasionally, secondary minerals such as zeolites, glauconite and chlorite are observed.

b) Welded ignimbrites. These rocks show textures varying from eutaxitic to spherulitic, more rarely vitrophyric. The observed mineral phases are euhedral to subhedral plagioclase, subhedral clinopyroxene, rare rounded

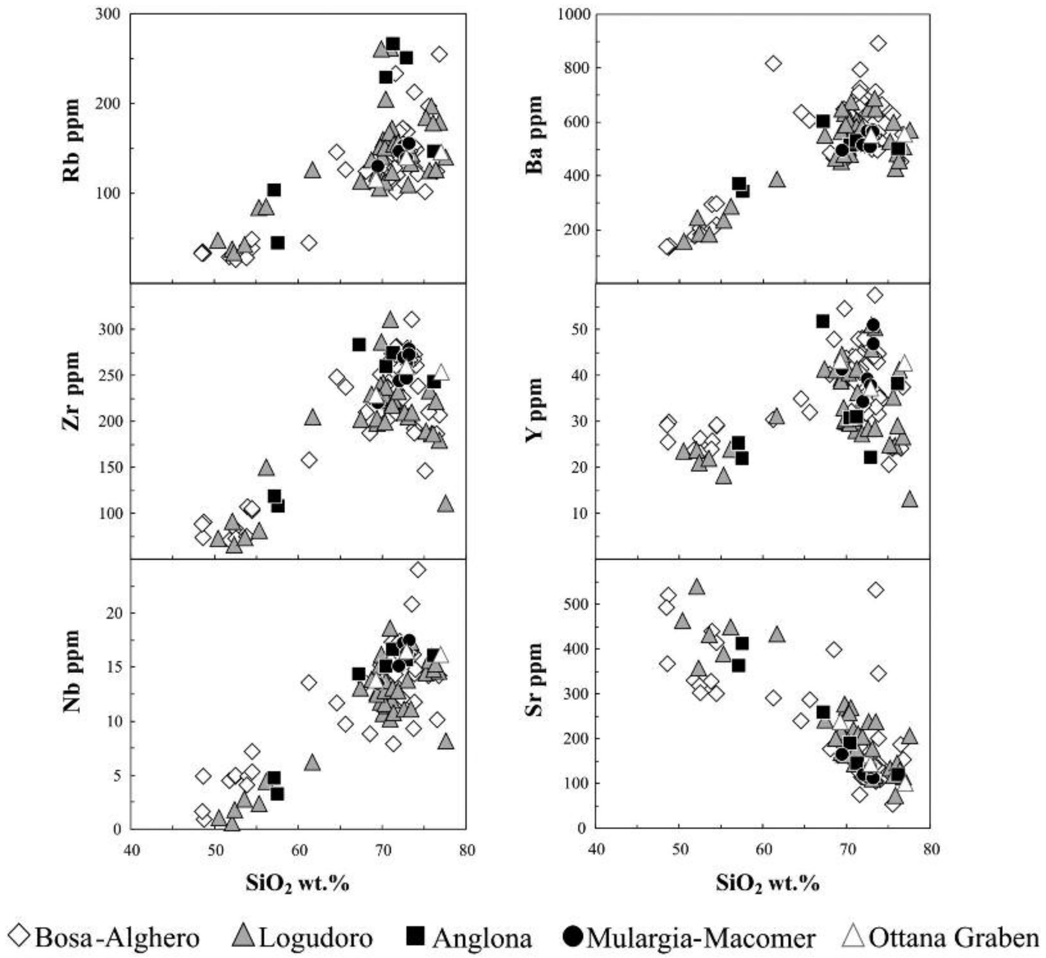

Figure 4. Selected trace element variation diagrams for the studied Early Miocene volcanic rocks from northwestern Sardinia.

orthopyroxene, apatite and opaque oxides included in mafic minerals or in isolated microcrysts. Subordinate microcrysts of alkali feldspar and quartz are also observed. The welded ignimbrites are characterized by the presence of volcanic fragments made principally of microcrystalline plagioclase, scorias and deeply altered subhedral minerals (probably mafic phases).

Mineral and glass chemistry

Pyroxenes. The composition of the pyroxenes are reported in Table 3 and Figure 6. Bosa-Alghero and Anglona clinopyroxenes are essentially augitic ($Ca_{36-46}Mg_{40-42}Fe_{14-22}$ and $Ca_{38-43}Mg_{30-43}Fe_{19-27}$, respectively) with no substantial chemical differences between basaltic andesites and dacitic-rhyolitic welded ignimbrites. Logudoro basaltic

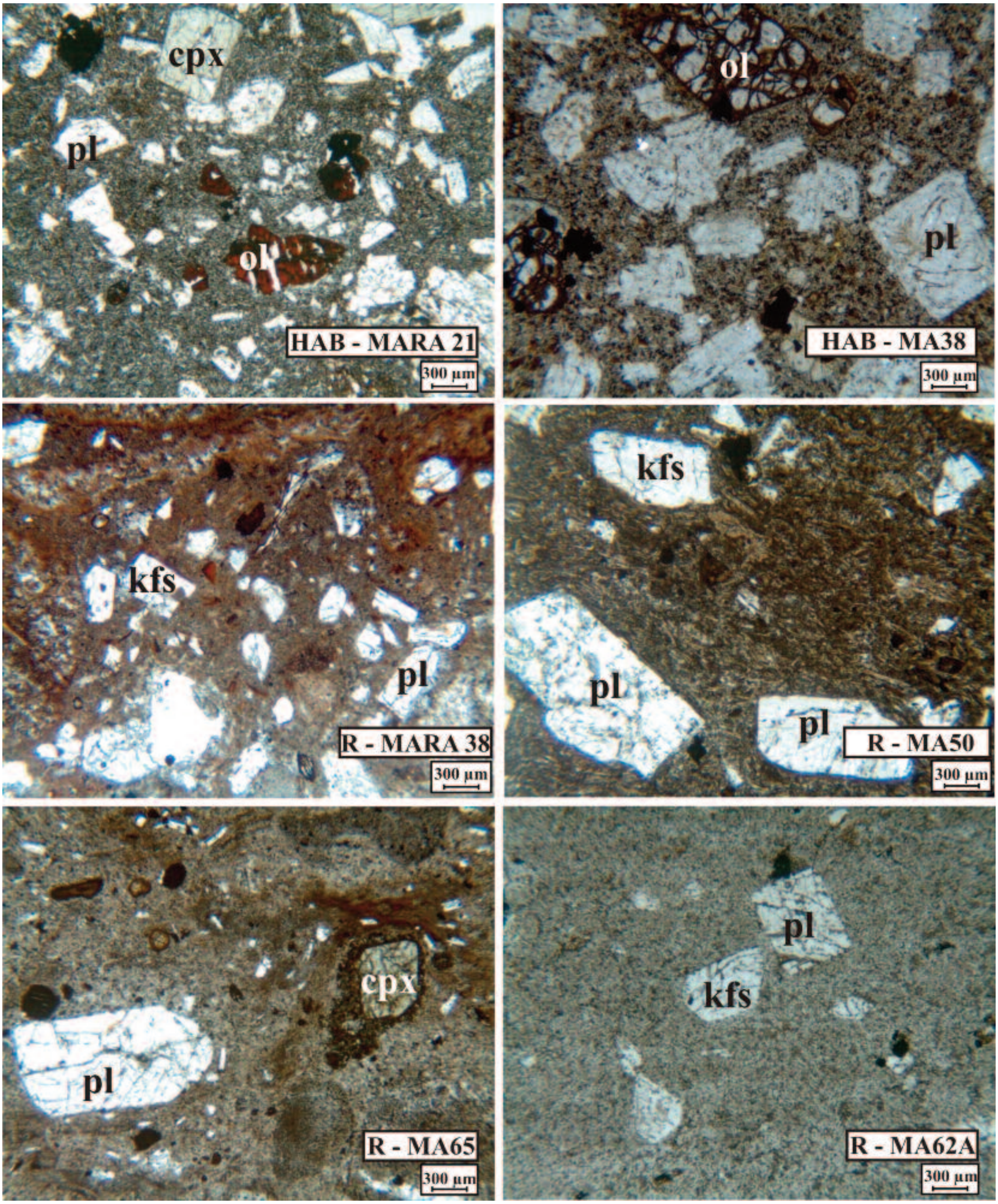

Figure 5. Thin section microphotographs for some representative samples of the studied Early Miocene volcanic rocks from northwestern Sardinia. ol = olivine; cpx = clinopyroxene; pl = plagioclase; kfs = alkali feldspar. HAB = high alumina basalt; R = rhyolite.

andesites have slightly Ca-richer and Fe-poorer clinopyroxenes ($Ca_{42-48}Mg_{37-41}Fe_{15-17}$). Mg# [Mg# = Mg/(Mg+Fe)] varies from 0.56 to 0.86. Orthopyroxene from the Bosa-Alghero dacites has variable Mg# (0.54 to 0.73; $Ca_3Mg_{53-70}Fe_{27-44}$), whereas orthopyroxene of the Anglona dacites have a narrower compositional spectrum and a generally Fe-richer composition (Mg# = 0.53-0.68; $Ca_{3-4}Mg_{50-64}Fe_{32-46}$). Orthopyroxenes of the Logudoro basaltic andesites and rhyolites have a rather homogeneous composition (Mg# = 0.59-0.65; $Ca_{2-3}Mg_{57-63}Fe_{34-41}$).

Feldspars. Plagioclase from the basalts and basaltic andesites of the Bosa-Alghero district show a wide compositional range from $An_{94}Ab_6Or_0$ to $An_{22}Ab_{74}Or_4$ (phenocrysts core and groundmass, respectively; Figure 7a; Table 4). Plagioclase of the Logudoro basaltic andesite shows a compositional range from $An_{88}Ab_{12}Or_0$ (phenocryst core) to $An_{52}Ab_{44}Or_3$ (groundmass). The andesites of the Anglona district are characterized by plagioclase with a moderate core-to-rim compositional variations ($An_{71-81}Ab_{19-29}Or_0$). Plagioclases from the more differentiated dacites and rhyolites show a wider compositional spectrum, ranging from labradorite to andesine and rare oligoclase ($An_{28-53}Ab_{45-67}Or_{2-5}$). Alkali feldspar occurs only in the most differentiated rocks (dacitic and rhyolitic) of the Bosa-Alghero, Anglona, Logudoro, Mulargia-Macomer and Ottana graben districts and range from K_2O-rich sanidine to anorthoclase ($Ab_{1-69}An_{1-16}Or_{15-97}$; Figure 7a).

Minor phases. *Opaque oxides* are present as magnetite and Ti-magnetite groundmass microcrysts showing variable ulvöspinel contents (mol. ulvöspinel = 0.13-0.41), and low ilmenite (mol. ilmenite = 0.81-0.91; Table 5).

Olivine crystals were analyzed in basalts and basaltic andesites from the Bosa-Alghero district and in basalts from the Logudoro district (Table 5). The analyses show a moderate compositional variation (e.g., Fo_{54-71}), high FeO (26.4-39.1 wt.%) and very low CaO (0.2-0.4 wt.%) contents. More Mg-rich olivine compositions have been analyzed in the basalts of Montresta (Fo_{87}-Fo_{71}; Morra et al., 1997).

Mica belongs to the phlogopite-annite series (Figure 7b; Table 6) and have a relatively low Mg# (0.34-0.52). Micas show relatively high Fe^{2+} (2.44-3.39 apfu) and low Ti contents (0.42-0.66 apfu) resulting in a reddish-brown colour of the crystals. Most micas are characterized by Fe^{3+} in the tetrahedral site, with values up to 0.27 apfu, but several have Al excess in the tetrahedral site so the remaining Al filled the octahedral site, with values up to 0.33 apfu (Figure 7b; Guarino et al., 2011).

Amphiboles, analyzed in rhyolitic rocks of the Logudoro district (Table 6), are thus classified as tschermakite plus rarer ferrohornblende and magnesiohornblende (Leake et al., 1997; Figure 7c) showing high Ca (1.69-1.83 apfu) contents. The Fe^{2+} ranges from 1.62 to 2.91 apfu and is associated with low Ti (0.17-0.31 apfu) and variable Mg# values [$Mg/(Mg+Fe^{2+})$ = 0.38-0.65].

Glass. The analyzed glasses of rhyolites from the Bosa-Alghero and Logudoro are rhyoltic. The Anglona glasses are basaltic andesites (in andesitic rocks) and rhyolites (in dacites; Figure 7d; Table 7).

Discussion and Conclusions

The Early Miocene volcanic rocks of northwestern Sardinia have a bimodal chemical composition, with dacitic/rhyolitic rocks being definitely predominant over basalts and andesites. The high alumina basalts (HABs) are a common lithotype of "orogenic" magmatism worldwide, whose genesis has been variously ascribed to high-degree partial melting of the subducted oceanic slab or low-pressure fractional crystallization of a high magnesium basalt (HMB) primitive magma (e.g., Kuno, 1960; 1968; Crawford et al., 1987; Myers, 1988; Sisson and Grove, 1993; Kersting and Arculus,

Table 3. Representative analyses and site occupancies (structural formulas calculated on 6 oxygens) for orthopyroxene (opx) and clinopyroxene (cpx) crystals of Early Miocene rocks from northwestern Sardinia.

	Bosa-Alghero district						Anglona district							Logudoro district					
Rock type	BA	BA	BA	BA	R	R	A	D	D	D	D	A	D	BA	BA	R	BA	R	R
	MARA33	MARA33	MARA33	MARA34	MA29B	MA29B	MA82	MA84B	MA84B	MA84B	MA84B	MA82	MA84B	MA12	MA12	MA13A	MA12	MA13A	MA13A
	cpx	cpx	cpx	cpx	opx	opx	cpx	cpx	cpx	cpx	cpx	opx	opx	cpx	cpx	opx	opx	opx	opx
	rim	core	rim	gm	core	rim	rim	rim	core	gm	gm	rim	core	rim	rim	rim	core	core	gm
SiO_2	51.19	49.43	49.11	49.25	52.45	54.11	51.23	51.42	51.23	51.58	51.27	53.13	51.55	52.42	47.01	53.90	53.40	51.54	51.81
TiO_2	0.70	0.79	0.66	0.55	0.22	0.32	0.57			0.45	0.41			0.36		0.16	0.24	0.20	0.15
Al_2O_3	1.61	4.52	3.82	1.41	0.60	1.23	2.32	1.19	1.08	1.22	2.16	1.22	0.61	1.40	7.61	1.26	0.69	0.72	0.63
FeO	13.09	8.36	8.68	15.23	25.59	16.63	10.49	16.08	16.59	11.86	10.18	20.01	27.95	9.80	8.64	22.72	20.63	23.97	24.75
MnO	0.51	0.20	0.26	0.58	1.55	0.77		0.69	0.69			0.66	0.87	0.56	0.15	1.20	0.95	1.28	1.27
MgO	14.49	14.08	14.11	12.17	18.35	25.17	14.90	10.76	10.59	15.32	15.12	23.31	17.53	14.16	12.02	19.04	22.35	20.80	20.43
CaO	17.59	22.10	22.10	17.06	1.51	1.50	20.29	21.03	20.75	18.64	19.95	1.72	1.85	20.47	22.00	1.28	1.37	1.27	1.18
Na_2O	0.21	0.23	0.32	0.28	0.07	0.03								0.27	0.22	0.18	0.02	0.03	0.02
Cr_2O_3	0.03		0.06		0.04	0.05									0.05		0.02		
sum	*99.4*	*99.7*	*99.1*	*96.5*	*100.4*	*99.8*	*99.8*	*101.2*	*100.9*	*99.1*	*99.1*	*100.1*	*100.4*	*99.4*	*97.7*	*99.7*	*99.7*	*99.8*	*100.2*
Si	1.934	1.837	1.836	1.940	1.995	1.975	1.913	1.951	1.952	1.945	1.925	1.960	1.973	1.968	1.769	2.000	1.991	1.943	1.952
^{IV}Al	0.066	0.163	0.164	0.060	0.005	0.025	0.087	0.049	0.048	0.054	0.075	0.040	0.027	0.032	0.231		0.009	0.032	0.028
Fe^{3+}										0.001								0.025	0.021
Ti	0.020	0.022	0.019	0.016	0.006	0.009	0.016			0.013	0.012			0.010	0.038	0.005	0.007	0.006	0.004
^{VI}Al	0.006	0.035	0.005	0.006	0.022	0.028	0.015	0.004	0.000		0.020	0.013	0.001	0.029	0.107	0.056	0.021		
Fe^{2+}	0.378	0.159	0.128	0.460	0.814	0.508	0.288	0.465	0.481	0.345	0.288	0.589	0.869	0.305	0.209	0.719	0.643	0.731	0.759
Fe^{3+}	0.035	0.100	0.143	0.042			0.040	0.045	0.048	0.028	0.032	0.028	0.026	0.003	0.063				0.000
Mn	0.016	0.006	0.008	0.019	0.050	0.024		0.022	0.022			0.021	0.028	0.018	0.005	0.038	0.030	0.041	0.041
Mg	0.816	0.780	0.786	0.715	1.041	1.370	0.829	0.609	0.601	0.861	0.846	1.282	1.000	0.792	0.674	1.075	1.242	1.169	1.147
Ca	0.712	0.880	0.886	0.720	0.061	0.059	0.812	0.855	0.847	0.753	0.802	0.068	0.076	0.823	0.887	0.052	0.055	0.051	0.047
Na	0.016	0.017	0.023	0.021	0.005	0.002								0.020	0.016	0.013	0.001	0.002	0.001
Cr	0.001		0.002		0.001	0.001									0.002		0.001		
Ca	36	46	45	37	3	3	41	43	42	38	41	3	4	42	48	3	3	3	2
Mg	42	40	40	36	53	70	42	30	30	43	43	64	50	41	37	57	63	58	57
Fe	22	14	14	27	44	27	17	27	28	19	16	32	46	17	15	40	34	39	41
Mg#	0.68	0.83	0.86	0.61	0.56	0.73	0.74	0.57	0.56	0.71	0.75	0.69	0.54	0.72	0.76	0.60	0.66	0.62	0.59

Mg# = $Mg/Mg+Fe^{2+}$ gm = groundmass.

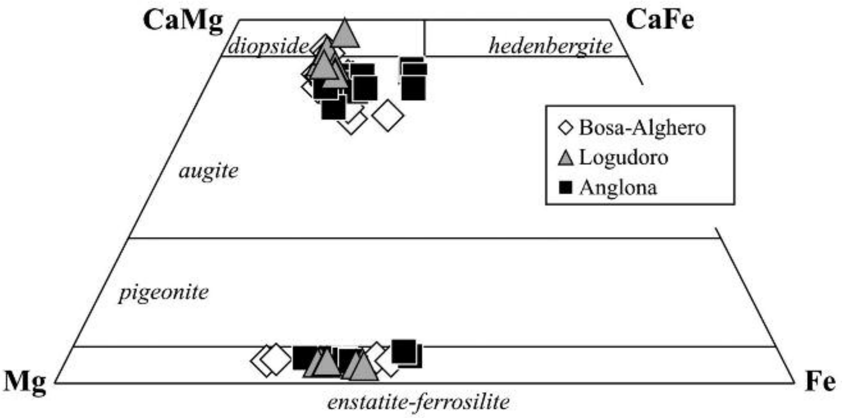

Figure 6. Classification of pyroxenes according to IMA rules (Morimoto et al., 1988).

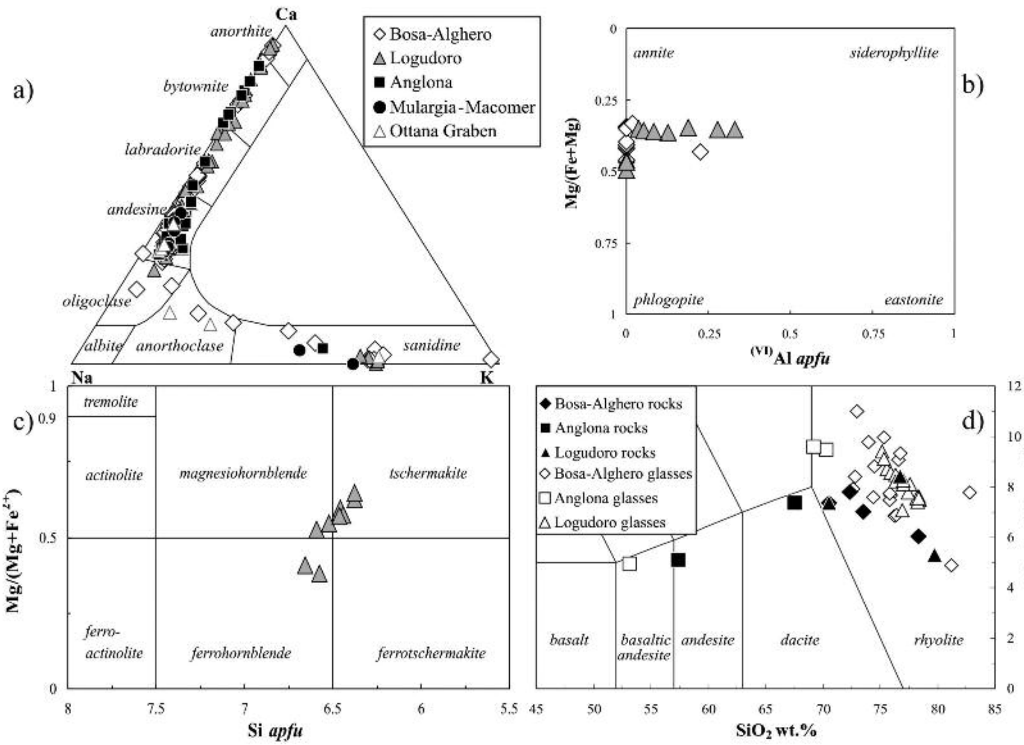

Figure 7. Classification diagrams for a) feldspar; b) brown mica (Deer et al., 1966); c) amphibole (Leake et al., 1997) and d) glasses (TAS, Le Bas et al., 1986) of the studied Early Miocene volcanic rocks from northwestern Sardinia.

Table 4. Representative analyses for feldspars of Early Miocene rocks from northwestern Sardinia.

	Bosa - Alghero district								**Mulargia-Macomer**			**Ottana graben district**		
Rock type	HAB	HAB	BA	R	R	R	R	R	R	R	R	R	R	R
	MARA23	MARA23	MARA33	MA29B	MA35	MARA15	MARA27	MARA38	MA62A	MA62A	MA62A	MA67	MA67	MA67
	rim	gm	core	core	core	gm	mantle	core	core	mantle	gm	core	gm	gm
SiO_2	57.72	63.71	44.01	56.37	57.91	67.77	57.37	70.09	57.78	58.18	66.84	60.04	59.65	66.91
Al_2O_3	26.07	22.79	34.07	27.15	26.19	16.72	26.23	17.64	26.6	26.15	19.32	24.61	24.83	17.86
FeO	0.41	0.37	0.45	0.41	0.33	0.35	0.40	0.28					0.52	1.32
CaO	9.11	4.63	19.15	10.17	9.03	0.22	9.28	2.61	9.37	8.9	0.86	6.85	7.29	2.57
Na_2O	6.12	8.55	0.66	5.48	6.12	0.12	5.65	6.10	6.06	6.49	5.09	7.11	6.92	6.5
K_2O	0.47	0.74	0.00	0.38	0.35	14.19	0.40	3.26	0.58	0.57	8.89	0.65	0.69	2.2
sum	*99.9*	*100.8*	*98.3*	*99.9*	*99.9*	*99.4*	*99.3*	*99.9*	*100.4*	*100.3*	*101.0*	*99.3*	*99.9*	*97.4*
An%	44	22	94	50	44	1	46	15	45	42	4	33	35	15
Ab%	53	74	6	48	54	1	51	63	52	55	45	63	61	69
Or%	3	4	0	2	2	97	2	22	3	3	51	4	4	16

	Logudoro district								**Anglona district**					
Rock type	BA	BA	BA	BA	R	R	R	R	A	A	D	D	D	D
	MA12	MA12	MA12	MA12	MA13A	MA37	MA37	MA71	MA82	MA82	MA84B	MA84B	MA84B	MA84B
	rim	core	gm	gm	core	rim	rim	core	rim	rim	core	mantle	core	core
SiO_2	46.22	46.02	49.96	54.79	55.53	62.40	65.36	44.8	47.53	49.67	59.4	57.02	57.26	59.15
Al_2O_3	33.91	33.62	29.85	27.28	27.59	23.40	18.60	35.86	32.36	30.76	25.19	26.91	25.84	25.23
FeO	0.47	0.48	1.08	0.39	0.35	0.24	0.15	0.49	0.65	0.8			0.86	0.31
CaO	17.60	17.62	14.31	10.83	10.88	5.66	0.18	19.89	16.65	14.46	7.53	9.45	8.78	8.03
Na_2O	1.28	1.33	3.10	5.07	5.11	7.50	3.03	0.68	2.2	3.24	6.49	5.91	6.60	6.78
K_2O	0.05	0.07	0.22	0.57	0.40	0.93	11.78				1.24	0.81	0.37	0.61
sum	*99.5*	*99.1*	*98.5*	*98.9*	*99.9*	*100.1*	*99.1*	*101.7*	*99.4*	*98.9*	*99.9*	*100.1*	*99.7*	*100.1*
An%	88	88	71	52	53	28	1	94	81	71	36	45	41	38
Ab%	12	12	28	44	45	67	28	6	19	29	57	51	56	58
Or%	0	0	1	3	2	5	71	0	0	0	7	5	2	3

gm = groundmass An% = anorthite mol.% Ab% = albite mol.% Or% = orthoclase mol.%.

1994; Lopez-Escobar et al., 1997; Schiano et al., 2003). Dostal et al. (1982) were the first to deal with the genesis of northwestern Sardinia HABs, arguing for their non-primitive nature (mainly on the basis of their low Cr and Ni concentrations and Mg# values), but still considering them as a likely parental magma for the rocks of the calcalkaline suite. Morra et al. (1997) pointed that the Montresta HMBs represent the most primitive magma of northwestern Sardinia (i.e., Mg# between 0.64 and 0.71, Cr ~ 294-737 ppm and Ni ~ 47-205 ppm), and the neighbouring HABs are related to HMBs through closed-system fractional crystallization processes. The chemical composition of the Sardinia HABs (e.g., Al_2O_3 > 17.8 wt.%, MgO < 7.2 wt.%, Mg# < 0.60, low Cr and Ni) can be similarly interpreted as unlikely primary melt compositions, but, rather, as melts derived from a more primitive HMB-like magmas. As a consequence, the HABs cannot be used to obtain information on mantle source characteristics. On the other hand, their possible parental linkage with the evolved rocks should be investigated in order to shed light on the low-pressure evolution processes in the area.

On the whole, major- and trace-element compositional trends, as well as mineral compositions, are quite coherent among the various districts, suggesting, at least qualitatively, a cogenetic relationship. Fractional crystallization of the mineral phases observed in thin section can, indeed, explain the gross features observed in Figures 3 and 4. The decrease of Al_2O_3, MgO and CaO with increasing SiO_2 is compatible with removal of plagioclase and clinopyroxene plus olivine in the less evolved rocks. Orthopyroxene and alkali feldspar join the previous phases in the intermediate and evolved melts. This is particularly evident by the decrease of Rb and Ba at SiO_2 ~ 70 wt.%, a feature that suggests the onset of alkali feldspar fractionation roughly at the dacite-rhyolite transition. Similarly, the decrease of Zr and Y around SiO_2 ~ 70 wt.% marks the onset of zircon fractionation. Scatter of data can be due to local differences between the various districts, the porphyritic character and/or to post-emplacement processes that may have modified mobile element contents. In addition, some role should have been also played by open-system differentiation processes, which are known to have acted in many other LEMM Sardinian districts (e.g., Narcao, Brotzu et al., 1997b; Sarroch, Conte, 1997; Sindia, Lonis et al., 1997; Montresta, Morra et al., 1997; Sant'Antioco, Conte et al., 2010; Figure 1b).

Quantitative models of fractional crystallization processes were tested by means of mass balance calculations, performed using the Stormer and Nicholls (1978) method. The results are summarized in Table 8. The transition from a HMB-type primitive magma (sample KB13; Morra et al., 1997) to the HABs of the Bosa-Alghero (MARA21) and Logudoro districts (MA72C) was tested, yielding satisfactory results (ΣR^2 < 0.3 for both; ΣR^2 = sum of square residuals) involving ~ 30-36% removal of a gabbroic assemblage made of 64% clinopyroxene ($Ca_{35}Mg_{46}Fe_{19}$), 22.8% plagioclase ($An_{91}Ab_9O_0$) and 13.2% olivine (Fo_{87}) for the Bosa-Alghero district, and of 60% clinopyroxene ($Ca_{45}Mg_{42}Fe_{13}$), 13.2% plagioclase ($An_{91}Ab_9O_0$) and 26.5% olivine (Fo_{71}) for the Logudoro district.

In the Bosa-Alghero district, the transition from HAB to basaltic andesite is modelled assuming ~ 43% of removal of a cumulate made of ~ 45% plagioclase ($An_{90}Ab_9Or_1$), ~ 32% clinopyroxene ($Ca_{41}Mg_{43}Fe_{16}$), ~ 13% olivine (Fo_{74}) and ~ 9% magnetite (Table 8). The transition from basaltic andesite to andesite is obtained after removal of 59.4% of a cumulate made of ~ 78% plagioclase ($An_{54}Ab_{43}Or_3$), ~ 12% clinopyroxene ($Ca_{39}Mg_{45}Fe_{16}$) and ~ 10% magnetite. The evolution from andesite to dacite was obtained after the removal of ~ 33% of a cumulate made of ~ 62% plagioclase ($An_{68}Ab_{30}Or_2$), ~ 29% orthopyroxene ($Ca_4Mg_{50}Fe_{46}$) and ~ 9% clinopyroxene ($Ca_{43}Mg_{42}Fe_{15}$).

Table 5. Representative analyses for olivine (ol), magnetite (mt) and ilmenite (ilm) crystals of Early Miocene rocks from northwestern Sardinia.

	Bosa - Alghero district								Anglona district		
Rock type	HAB	HAB	BA	BA	BA	BA	R	R	A	D	D
	MARA25 ol core	MARA25 ol rim	MARA 33 ol core	MARA 33 ol rim	MARA34 ol	MARA34 ol	MARA22 mt	MA29B ilm	MA82 mt	MA84B mt	MA3 ilm
SiO_2	35.88	35.61	37.81	38.00	35.07	35.19		0.06			0.45
TiO_2							17.81	46.46	11.59	7.01	41.01
Al_2O_3							1.94	0.13	3.79	4.25	0.98
Fe_2O_3							30.06	9.93	41.77	50.47	16.99
FeO	38.08	39.06	26.39	26.52	37.46	37.68	42.81	37.63	38.54	36.13	32.92
MnO	0.80	0.56	0.70	0.47	0.96	0.96	4.07	0.76		0.54	1.91
MgO	26.17	25.24	36.29	35.96	24.38	24.59		1.95	2.12	0.92	1.44
CaO	0.32	0.34	0.16	0.38	0.24	0.16					
sum	*101.3*	*100.8*	*101.3*	*101.3*	*98.1*	*98.6*	*96.7*	*96.9*	*97.8*	*99.3*	*95.7*
Fo	55	54	71	71	54	54					
ulvöspinel							0.35		0.22	0.13	
ilmenite								0.90			0.81

Fo% = forsterite mol%

Finally, the transition from dacite to a rhyolite was modelled with removal 55.5% of a solid assemblage made of plagioclase (~ 35%, $An_{45}Ab_{52}Or_3$), alkali feldspar (~ 31%, $An_6Ab_{40}Or_{54}$), clinopyroxene (~ 17%, $Ca_{39}Mg_{43}Fe_{18}$), orthopyroxene (~ 15%, $Ca_3Mg_{70}Fe_{27}$) and magnetite (~ 2%) (Table 8).

As for the Logudoro district, the transition from HAB to basaltic andesite is modelled with removal of 50.7% of a cumulate made of ~ 63% plagioclase ($An_{67}Ab_{31}Or_2$), ~ 21% clinopyroxene ($Ca_{40}Mg_{43}Fe_{17}$), ~ 7% magnetite and ~ 8% olivine (Fo_{65}). The transition from basaltic andesite to rhyolite was modelled with removal of ~ 74% of solid assemblage made of ~ 62% plagioclase ($An_{69}Ab_{30}Or_1$), ~ 15% clinopyroxene ($Ca_{30}Mg_{43}Fe_{27}$), ~ 10% alkali feldspar ($An_4Ab_{27}Or_{69}$), ~ 11% magnetite and ~ 1% apatite.

The transition from andesite to dacite in the Anglona district was obtained after removal 61.2% of a solid assemblage made of ~ 52% plagioclase ($An_{58}Ab_{39}Or_3$), ~ 29% clinopyroxene ($Ca_{40}Mg_{39}Fe_{21}$), ~ 11% alkali feldspar ($An_4Ab_{27}Or_{69}$) and 8% magnetite. The evolution from dacite to rhyolite is obtained removing 44.7% of a solid assemblage made of ~ 54% plagioclase ($An_{43}Ab_{54}Or_3$), ~ 24% alkali feldspar ($An_2Ab_1Or_{97}$), ~ 17% orthopyroxene ($Ca_4Mg_{64}Fe_{32}$) and ~ 6% magnetite.

Finally, the evolution from the dacitic to rhyolitic compositions in the Ottana graben district is modelled by 20.3% removal of plagioclase (52%, $An_{33}Ab_{63}Or_4$), alkali feldspar (22%, $An_2Ab_{27}Or_{71}$), clinopyroxene (13.3%, $Ca_{43}Mg_{30}Fe_{27}$), magnetite (9.8%) and orthopyroxene (2.9%, $Ca_3Mg_{55}Fe_{42}$). The evolution from two slightly different rhyolitic composition in the Mulargia-Macomer district is obtained through 24.8% of a solid assemblage made of 55.5% plagioclase ($An_{35}Ab_{60}Or_5$),

Table 5. Continued...

	Logudoro districts							**Mulargia-Macomer district**		**Ottana graben district**	
Rock type	HAB	BA	BA	R	R	R	R	R	R	R	R
	MA38	MA72A	MA72A	MA13A	MA13A	MA13A	MA50	MA62A	MA62A	MA67	MA67
	ol	mt	ilm	mt	ilm	ilm	mt	ilm	mt	mt	mt
SiO_2	36.88	0.32		0.67	0.19	0.3		0.56			
TiO_2		8.52	40.69	10.59	48.29	47.15	9.35	44.87	6.93	21.09	19.71
Al_2O_3		1.49	1.76	1.94	0.17	0.17	1.43	0.87	1.35	1.2	1.44
Fe_2O_3		46.99	16.49	44.73	8.20	10.60	47.18	6.90	53.93	24.89	24.61
FeO	29.28	36.62	30.77	40.49	38.71	36.79	37.53	39.95	37.68	48.89	46.65
MnO	0.46	0.01		0.77	1.13	3.29	0.7	1.07		1.08	0.89
MgO	31.91	0.93	3.27	0.49	2.14	1.49	0.46				
CaO	0.37										
sum	*98.9*	*94.9*	*93.0*	*99.7*	*98.8*	*99.8*	*96.6*	*94.2*	*99.9*	*97.2*	*93.3*
Fo	66										
ulvöspinel		0.17		0.20			0.18		0.13	0.41	0.40
ilmenite			0.81		0.91	0.89		0.90			

Fo% = forsterite mol%

30.1% alkali feldspar ($An_4Ab_{45}Or_{51}$), 8.5% orthopyroxene ($Ca_3Mg_{70}Fe_{27}$) and 5.9% magnetite.

Further informations on the evolutionary processes of Early Miocene rocks from northwestern Sardinia can be obtained from the estimation of T and fO_2 based on the mineral chemistry data (Table 9). The olivine-liquid geothermometer (Putirka, 2008) applied to olivine in the basalts and basaltic andesites from the Bosa-Alghero district gave temperatures in the range of 1071-1140 °C and of 1114 °C for the olivine in the basalts from the Logudoro district. The clinopyroxene-orthopyroxene geothermometer (Putirka, 2008) applied for pairs in equilibrium with the host rocks (i.e., ${}^{Fe/Mg}K_d{}^{cpx\text{-}liq} = 0.27 \pm 0.03$; Putirka, 2008; Figure 8a), yielded temperatures between 931 and 964 °C for the Bosa-Alghero rhyolites, between 958 and 979 °C for the Anglona andesites and between 934 and 1010 °C for the Anglona dacites.

Temperature and oxygen fugacity values for the Logudoro rhyolites were estimated on amphibole minerals following the method of Ridolfi et al. (2010). Temperature and oxygen fugacity ($\log fO_2$) range from 821 to 923 °C and from -10.7 to -13.6 log units, respectively. Similar T-fO_2 estimates were obtained by using coexisting magnetite-ilmenite pairs for samples from the Bosa-Alghero, Logudoro and Mulargia-Macomer districts. The Bosa-Alghero rhyolites gave temperature estimates spanning from 872 to 1035 °C and oxygen fugacity values ranging from -12.8 to -10.4 log units. As for the Logudoro rocks, basaltic andesites gave T values of 853-918 °C and oxygen fugacity of -12 to -11.1 log units, whereas rhyolites yielded temperature estimates spanning from 777 to 841.3 °C and oxygen fugacity from -14.8 to

Table 6. Representative analyses for mica and amphibole (amph) crystals of Early Miocene rocks from northwestern Sardinia. Also reported are site occupancies (structural formulas calculated on 22 oxygens for mica, 23 for amphiboles).

	Bosa-Alghero district				Logudoro district									
Rock type	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	MARA15 mica	MARA38 mica	MARA38 mica	MARA38 mica	MA37 mica	MA37 mica	MA13A mica	MA50 mica	MA48B mica	MA71 mica	MA13A amph	MA13B amph	MA37 amph	MA37 amph
SiO_2	36.53	36.96	35.45	36.48	34.84	34.47	35.72	36.20	37.11	35.21	42.18	43.65	42.9	43.38
TiO_2	4.95	3.91	4.269	5.27	4.15	3.76	4.52	5.70	3.55	3.53	2.73	2.44	1.45	2.35
Al_2O_3	12.38	15.10	13.583	13.89	13.43	12.64	13.13	13.41	13.15	13.76	9.94	9.56	9.46	10.78
FeO	22.41	20.82	23.3	20.71	24.99	24.44	20.25	21.15	23.29	25.88	13.82	16.87	22.74	13.22
MnO	0.26	0.24	0.31	0.22	0.58	0.47	0.35		0.57	0.50	0.48	0.31	1.17	0.43
MgO	9.24	9.00	8.663	10.35	7.55	7.03	11.37	10.17	7.40	8.23	13	11.39	7.81	13.57
BaO	0.76	0.43	0.348	0.54	0.35	0.38	0.41							
CaO	0.07	0.16	0.098	0.01	0.09	0.09	0.05				11.15	11.46	10.27	11.15
Na_2O	0.47	0.46	0.416	0.68	0.42	0.44	0.52	0.55		0.58	1.95	1.89	1.79	2.3
K_2O	8.17	7.76	7.966	8.60	8.41	7.88	8.73	8.78	8.07	8.71	0.96	1.05	0.85	0.73
F	0.55	1.01	2.12	0.75	0.37	0.47	0.53				0.22		0.3	0.52
sum	*95.8*	*95.9*	*96.5*	*97.5*	*95.2*	*92.1*	*95.6*	*96.0*	*93.1*	*96.4*	*96.4*	*98.6*	*98.7*	*98.4*
Mg#	0.43	0.44	0.42	0.48	0.35	0.34	0.52	0.46	0.36	0.36	0.63	0.55	0.38	0.65
Si	5.624	5.552	5.327	5.457	5.496	5.600	5.473	5.544	5.876	5.513	6.375	6.519	6.573	6.377
^{IV}Al	2.246	2.448	2.406	2.448	2.496	2.400	2.371	2.420	2.124	2.487	1.625	1.481	1.427	1.623
Fe^{3+}	0.130		0.268	0.094	0.008		0.156	0.036						
^{VI}Al		0.225				0.020			0.330	0.052	0.146	0.202	0.282	0.244
Ti	0.573	0.442	0.482	0.593	0.492	0.460	0.521	0.656	0.423	0.416	0.310	0.274	0.167	0.260
Fe^{3+}														
Fe^{2+}	2.755	2.616	2.658	2.496	3.288	3.320	2.438	2.673	3.084	3.389	1.747	2.107	2.914	1.625
Mn	0.034	0.030	0.039	0.027	0.077	0.065	0.045		0.076	0.066	0.061	0.039	0.152	0.054
Mg	2.119	2.015	1.940	2.307	1.775	1.702	2.596	2.321	1.746	1.921	2.929	2.536	1.784	2.974
Ba	0.045	0.025	0.020	0.031	0.022	0.024	0.025							
Ca	0.012	0.026	0.016	0.001	0.016	0.015	0.008				1.805	1.834	1.686	1.756
Na	0.140	0.135	0.121	0.197	0.130	0.139	0.154	0.163		0.176	0.571	0.547	0.532	0.655
K	1.605	1.486	1.527	1.641	1.691	1.633	1.706	1.715	1.630	1.740	0.185	0.200	0.166	0.137
OH	3.732	3.519	2.993	3.648	3.816	3.761	3.743	4	4	4	1.895	2	1.855	1.758
F	0.268	0.481	1.007	0.352	0.184	0.239	0.257				0.105		0.145	0.242

Mg# = Mg/(Mg+Fe^{2+}).

Table 7. Representative glass analyses for Early Miocene rocks from northwestern Sardinia.

	Bosa - Alghero district													
Rock type	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	MA35	MA35	MA35	MA35	MA29B	MA29B	MA29B	MA29B	MARA38	MARA38	MARA12	MARA12	MARA12	MARA12
SiO_2	76.24	76.42	74.38	75.82	74.50	75.34	72.65	73.01	81.21	82.83	76.61	76.78	72.81	75.82
TiO_2	0.15	0.15	0.04	0.13	0.35	0.09	0.41	0.09	0.13	0.00	0.19	0.16	0.31	0.20
Al_2O_3	13.60	13.68	14.21	13.54	14.38	13.57	14.15	14.80	9.25	8.83	12.94	12.61	15.60	13.79
FeO	1.65	1.44	2.11	1.58	0.83	0.27	2.41	0.49	3.08	0.16	0.43	0.39	0.82	0.78
MnO	0.07	0.06	0.00	0.08	0.00	0.07	0.10	0.00	0.02	0.00	0.00	0.00	0.00	0.00
MgO	0.17	0.14	0.24	0.18	0.01	0.00	0.44	0.03	0.05	0.00	0.00	0.00	0.01	0.03
CaO	1.29	1.21	1.42	1.15	1.10	0.64	1.93	0.56	1.35	0.42	0.72	0.62	2.03	1.41
Na_2O	2.45	2.41	2.60	2.37	3.25	3.37	3.63	3.34	2.93	1.95	3.02	2.79	4.27	3.90
K_2O	4.39	4.49	4.98	5.10	5.58	6.59	4.28	7.65	1.97	5.82	6.06	6.53	4.14	3.86
P_2O_5	0.00	0.00	0.02	0.04	0.00	0.06	0.00	0.03	0.00	0.00	0.03	0.12	0.02	0.22
sum	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*

	Anglona district			Logudoro district										
Rock type	A	D	D	R	R	R	R	R	R	R	R	R	R	R
	MA82	MA84B	MA84B	MA13A	MA13A	MA13A	MA13A	MA13A	MA71	MA71	MA71	MA37	MA37	MA37
SiO_2	53.15	70.31	69.18	75.17	75.93	76.33	76.35	75.33	78.47	78.38	78.35	77.48	77.63	77.06
TiO_2	0.00	0.47	0.54	0.12	0.14	0.00	0.14	0.20	0.00	0.00	0.00	0.04	0.00	0.18
Al_2O_3	28.53	16.03	15.62	13.33	13.66	13.85	13.63	13.77	12.68	12.37	12.59	12.62	12.57	12.80
FeO	1.10	2.30	3.04	1.10	0.74	0.60	0.79	0.71	0.54	0.65	0.42	1.06	0.85	0.96
MnO	0.00	0.19	0.05	0.07	0.07	0.00	0.07	0.06	0.00	0.00	0.00	0.16	0.00	0.03
MgO	0.00	0.10	0.46	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.02	0.03
CaO	12.25	1.11	1.45	0.71	0.78	0.75	0.79	0.75	0.83	0.96	0.89	0.70	0.66	0.77
Na_2O	4.56	4.43	3.91	2.99	2.86	2.76	2.49	2.84	2.44	2.58	2.43	2.71	2.99	2.91
K_2O	0.42	5.06	5.68	6.41	5.68	5.71	5.73	6.28	5.04	5.06	5.15	5.05	5.11	5.18
P_2O_5	0.00	0.00	0.07	0.00	0.15	0.00	0.00	0.05	0.00	0.00	0.16	0.12	0.18	0.07
sum	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*100*

Table 8. Results of mass balance calculations for Early Miocene districts from northwestern Sardinia.

			subtracted solidus							residual liquid	
	from	*to*	**ol**	**pl**	**cpx**	**opx**	**mt**	**kfs**	**ap**	*%f*	$\sum R^2$
Bosa-Alghero district	KB13 (HMB, Morra et al., 1997)	MARA21 (HAB)	13.2	22.8	64.0					71.2	0.29
Logudoro district		MA72C (HAB)	26.5	13.2	60.3					64.0	0.30
Bosa-Alghero district	MARA21 (HAB)	MARA34 (BA)	13.2	45.4	32.4		9.0			56.7	0.49
	MARA34 (BA)	MARA36 (A)		77.9	12.3		9.8			40.6	0.32
	MARA36 (A)	MARA13 (D)		62.1	8.6	29.3				67.5	0.49
	MARA13 (D)	MARA38 (R)		34.7	17.0	14.8	1.9	31.5		44.5	0.18
Anglona district	MA82 (A)	MA84B (D)		51.9	28.8		8.0	11.3		38.8	0.35
	MA84B (D)	MA6A (R)		54.2		16.7	5.6	23.6		55.3	0.47
Logudoro district	MA72C (HAB)	MA72A (BA)	8.3	63.3	21.1		7.3			49.3	0.35
	MA72A (BA)	MA36 (R)		61.9	15.5		10.2	11.1	1.3	25.8	0.38
Mulargia-Macomer district	MA65 (R)	MA62A (R)		55.5		8.5	5.9	30.1		75.2	0.10
Ottana graben district	MA69 (D)	MA67 (R)		52.0	13.3	2.9	9.8	22.0		79.7	0.05

HMB = high magnesium basalt HAB = high alumina basalt BA = basaltic andesite A = andesite D = dacite R = rhyolite %f = wt.% of residual liquid ΣR^2 = sum of squared residuals ol = wt.% of subtracted olivine pl = wt.% of subtracted plagioclase cpx = wt.% of subtracted clinopyroxene mt = wt.% of subtracted magnetite ilm = wt.% of subtracted ilmenite opx = wt.% of subtracted orthopyroxene kfs wt.% of subtracted alkali feldspar ap = wt.% of subtracted apatite. See text for further explanations.

-12.9 log units. The rhyolites from the Mulargia-Macomer district gave temperature estimates in the range of 717-902 °C and oxygen fugacity values between -16.2 and -13 log units. Some magnetite-ilmenite pairs giving lower temperatures (< 800 °C), coupled with low oxygen fugacity values (up to -16.2 log units), probably represent re-equilibration effects, rather than original crystallization conditions. The same can be held as true for the temperature estimates obtained for the basaltic andesites from the Logudoro district, which seem to be too low for such relatively SiO_2-poor magmas.

The results of the temperature and oxygen fugacity calculations presented above show that most of the data for the Bosa-Alghero and Mulargia-Macomer districts plot close to or slightly above the Quartz-Fayalite-Magnetite (QFM) buffer, whereas the Logudoro rocks plot close to the Nickel-Nickel Oxide (Ni-NiO) buffer (Figure 8b).

The estimated temperatures are consistent with a genetic linkage among the various rocks. A negative correlation between temperature and SiO_2 can be observed, a feature compatible with the interpretation as a coherent liquid line of descent for each district. Some spread of values is present, and this can be due to different causes, including the use of T and fO_2 estimates based on different minerals or mineral pairs. However, we are confident that this does not significantly affect the reliability of the proposed model for magma evolution.

The oxygen fugacity and temperature data obtained on minerals were then used to fix the starting conditions for the application of the MELTS algorithm (Ghiorso and Sack, 1995) to the evolution of the studied Early Miocene rocks. The best-fit results of MELTS simulations are reported in Figure 3. The starting conditions are characterized by 1 kbar pressure, 0.2 wt.% of H_2O and QFM oxygen buffer for the Bosa-Alghero rocks, Ni-NiO oxygen buffer for the Logudoro and Anglona rocks. Such pressure values, approximately correspond to a depth of 3 km, MELTS simulations performed using higher pressure values (2-5 kbar) resulted in the fractionation of a mineral assemblage which did not match the observed parageneses (e.g., no olivine). It is also to note that the the strongly evolved composition of the ignimbritic products may have been reached only after polybaric evolution.

The obtained best-fit trends (Figure 3) assume the following fractionating assemblages:

- Bosa-Alghero district: 79.3% removal of olivine (0.6% $Fo_{75}Fa_{25}$), clinopyroxene (22% $Di_{81}Hd_{19}$ to $Di_{50}Hd_{50}$), plagioclase (40.8% $An_{77}Ab_{23}$ to $An_{24}Ab_{76}$), alkali feldspar (1.5% Or), spinel (14.3%) and apatite (0.2%) for the transition from HAB to "rhyolitic" composition (~ 74 SiO_2 wt.%);

- Logudoro district: 73% removal of olivine (2.9% $Fo_{67}Fa_{33}$), clinopyroxene (11.9% $Di_{78}Hd_{22}$ to $Di_{50}Hd_{50}$), plagioclase (44.8% $An_{67}Ab_{33}$ to $An_{26}Ab_{74}$), alkali feldspar (0.9% Or), spinel (12.5%) and apatite (0.1%) for the transition from HAB to "rhyolitic" composition (~ 76 SiO_2 wt.%);

- Anglona district: 69.5% removal of clinopyroxene (13.5% $Di_{63}Hd_{37}$ to $Di_{51}Hd_{49}$), orthopyroxene (4.1% $En_{51}Fs_{49}$ to $En_{47}Fs_{53}$), plagioclase (40.1% $An_{54}Ab_{46}$ to $An_{40}Ab_{60}$), alkali feldspar (4.4% Or) and spinel (7.4%) for the transition from andesite to "rhyolitic" composition (~ 76 SiO_2 wt.%).

In summary, the fractionating assemblage obtained through MELTS (olivine ± clinopyroxene ± orthopyroxene ± plagioclase ± alkali feldspar ± spinel ± apatite) are generally consistent with petrography and mass balance calculations reported above, even though the difficulties in defining the exact starting conditions suggest that some parameters (e.g., P and H_2O contents) needs to be better constrained. The estimated evolutionary trends obtained by MELTS simulations are in quite good agreement with those shown by the studied Sardinian rocks

Table 9. Temperature (T, in °C) and oxygen fugacity ($\log fO_2$) estimates obtained from different methods for the studied Early Miocene volcanic rocks from northwestern Sardinia.

	District	*Rock type*	*Sample*	**T (°C)**	**$\log fO_2$**
magnetite-ilmenite pairs (IL-MAT Lepage, 2003)	Bosa-Alghero district	R	MA29B	872.3	-12.8
		R	MA29B	1035.1	-10.4
	Logudoro district	BA	MA72A	918.4	-11.1
		BA	MA72A	853.0	-12.0
		R	MA13A	828.7	-13.3
		R	MA13A	816.9	-13.5
		R	MA13A	786.8	-14.6
		R	MA13A	776.7	-14.8
		R	MA13A	841.3	-12.9
		R	MA13A	828.9	-13.1
	Mulargia-Macomer district	R	MA62A	866.2	-13.6
		R	MA62A	839.4	-14.0
		R	MA62A	901.9	-13.0
		R	MA62A	716.9	-16.2
Amphibole (Ridolfi et al., 2010)	Logudoro district	R	MA13A	856.3	-12.3
		R	MA13A	896.6	-11.4
		R	MA13A	919.0	-10.9
		R	MA13A	894.8	-11.6
		R	MA13B	883.2	-12.0
		R	MA37	832.5	-13.5
		R	MA37	922.7	-10.7
		R	MA37	821.2	-13.6
		R	MA37	890.0	-11.8
olivine-liquid geothermometer (Putirka, 2008)	Bosa-Alghero district	HAB	MARA25	1109.8	
		HAB	MARA25	1109.8	
		BA	MARA33	1139.9	
		BA	MARA33	1139.9	
		BA	MARA33	1139.9	
		BA	MARA33	1139.9	
		BA	MARA34	1070.7	
		BA	MARA34	1070.7	
	Logudoro district	HAB	MA38	1113.7	
		HAB	MA38	1113.7	
clinopyroxene-orthopyroxene geothermometer (Putirka, 2008)	Bosa-Alghero district	R	MA29B	931.0	
		R	MA29B	953.1	
		R	MA29B	941.8	
		R	MA29B	964.3	
	Anglona district	A	MA82	979.5	
		A	MA82	957.9	
		D	MA84B	967.2	
		D	MA84B	967.7	
		D	MA84B	983.2	
		D	MA84B	951.0	
		D	MA84B	963.3	
		D	MA84B	1010.1	
		D	MA84B	934.3	
		D	MA84B	949.3	
		D	MA84B	949.8	
		D	MA84B	964.6	
		D	MA84B	933.8	
		D	MA84B	945.6	
		D	MA84B	990.3	

HAB = high alumina basalt BA = basaltic andesite D = dacite R = rhyolite.

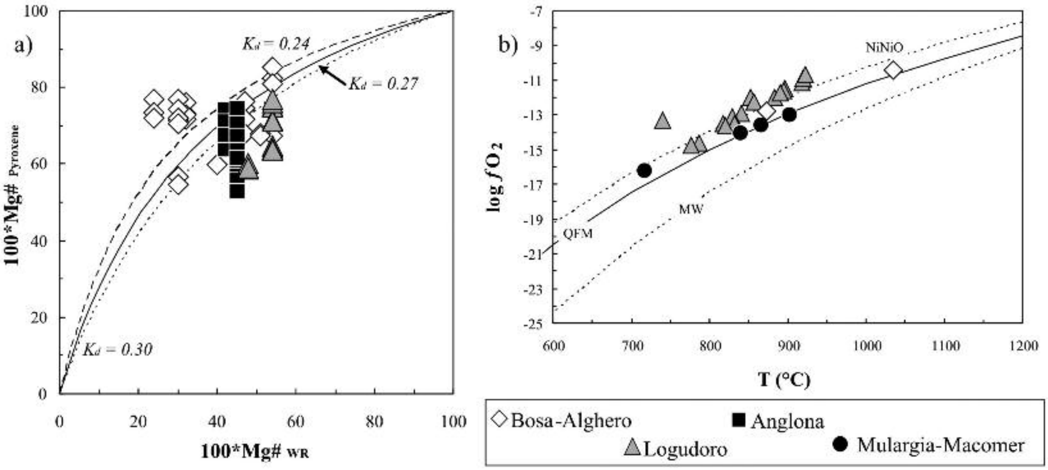

Figure 8. a) 100*Mg#$_{Pyroxene}$ vs. 100*Mg#$_{WR}$ diagram for Fe-Mg partitioning [Kd = $^{(Fe/Mg)}$px/$^{(Fe/Mg)}$$_{WR}$] between pyroxene and whole rock of the studied Early Miocene rocks from northwestern Sardinia. b) logfO_2 vs. T (in °C) diagram for magnetite-ilmenite equilibrium pairs and amphiboles of the studied Early Miocene rocks from northwestern Sardinia.

for MgO, K_2O, Al_2O_3 (less evidently for the Bosa-Alghero district) and partly for the Fe_2O_{3t} (except for an anomalous peak at ~ 58-61 wt.% SiO_2 for the Bosa-Alghero and Logudoro districts; Figure 3). On the other hand, the very steep trend obtained for TiO_2 is likely due to the fact that MELTS assumes spinel crystallization in the initial evolutionary steps. The trends for CaO are remarkably good for the compositions up to 60 wt.% SiO_2, whereas discrepancy exists for the most evolved rocks (which show CaO values close to zero, while MELTS simulations never reach concentrations below 2 wt.%).

In conclusion, the postulated genetic linkage between mafic and silicic rocks apparently rules out the early hypothesis of a crustal anatectic origin for the silicic Early Miocene rocks of Sardinia (e.g., Coulon et al., 1978; Beccaluva et al., 1987). Indeed, as previously observed by Morra et al. (1994) for the Sulcis area rocks, the widespread occurrence of the evolved rocks would have required unrealistically high degrees of partial melting. Such considerations, along with the overall reliability of the above modelling, make the crustal anatexis model unlikely, even though a more detailed treatment of the matter (with isotopic data, geochemical modelling of partial melting of a crustal materials, and so on) will possibly give much stronger constraints. At the same time, the high amount of solid required to fractionate an original basaltic melt to reach rhyolitic compositions (~ 95%) remains hard to explain. Indeed, the huge amounts of dacitic and rhyolitic melts, if interpreted as the results of fractional crystallization would require huge amounts of cumulates (20,000 to 50,000 km^3) at shallow depths, not easy to be detected by geophysical studies. Also, open-system AFC-type processes must be appropriately taken into account, as their interplay seems likely given the local recognition of evidences of textural (e.g., crystals with corroded rims) and chemical (e.g., high Ca plagioclase in dacites and rhyolites) disequilibrium features.

The obtained results are preliminary basis for further mineralogical, petrographic, chemical and isotopic investigations, which could help to shed new light on the petrogenesis of the silicic rocks in northwestern Sardinia , as well as on the whole LEMM magmatic cycle of Sardinia.

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