N. Jb. Geol. Paläont. Abh. 261/3, 309–320
published online June 2011

Article

Adakite-like signature in volcanic rocks associated with the Oro del Sur Au – (Cu) epithermal deposit, Southern Precordillera, Argentina

Silvia Irene Carrasquero, Nora Alicia Rubinstein and Denis Fontignie

With 7 figures and 4 tables

Carrasquero, S.I., Rubinstein, N.A. & Fontignie, D. (2011): Adakite-like signature in volcanic rocks associated with the Oro del Sur Au – (Cu) epithermal deposit, Southern Precordillera, Argentina. – N. Jb. Geol. Paläont. Abh., **261**: 309–320; Stuttgart.

Abstract: The Oro del Sur deposit is located in the southern part of the Precordillera of Mendoza Province, Argentina (32°30'S, 69°05'W) within the flat-slab subduction segment. It is a Cu-(Mo) porphyry type system with associated high sulfidation Au-(Cu) epithermal veins genetically linked to Miocene volcanic rocks which show geochemical characteristics (particularly low Y and low Yb values and high Sr/Y and La/Yb ratios) that indicate an adakite-like signature, and a Sr-Nd isotopic composition that suggests involvement of a depleted mantle source in their genesis. The age of this adakitic magmatism (~19 Ma) suggests a change in the geochemical signature of the magmatism linked to the onset of flattening of the subduction zone. The adakite-like signature of the Miocene volcanism of the Oro del Sur ore deposit supports a genetic relationship between adakitic magmatism, mineralization and slab shallowing in this part of the Andes.

Résumé: Le gisement Oro del Sur est situé au Sud de la Precordillera, Province de Mendoza, Argentine (32°30'S et 69°05'W) dans le segment de subduction nommé flat-slab. Il s'agit d'un gisement de type porphyre au Cu (Mo) associé aux veines épithermales (or) et génétiquement liés aux roches volcaniques du Miocène qui exhibent caractéristiques géochimiques (spécialement forts appauvrissements en Y et Yb et rapports Sr/Y et La/Yb exceptionnellement élevés) qui dénotent une tendance de type adakitique, pendant que leurs compositions isotopiques Sr-Nd proposent une participation du manteau dans sa genèse. L'âge du magmatisme adakitique (~19 Ma) suggère la modification de la signature géochimique du magmatisme lié au début de l'horizontalisation de la zone de subduction. La signature de type adakitique du volcanisme miocène au gisement Oro del Sur met en évidence une liaison privilégié entre le magmatisme adakitique, la minéralisation et l'horizontalisation de la plaque dans cette région andine.

Key words: High sulfidation, epithermal, Oro del Sur deposit, Miocene magmatism, adakite-like signature, Precordillera, Argentina.

Introduction

The Oro del Sur ore deposit (32°30'S, 69°05'W Argentina) is located in the Precordillera of the Mendoza Province (Fig. 1) and is part of the Paramillos de Uspallata mining district, where mining works started in the 17th century (Molina 1788; Ave Lallemant 1890). This district includes several ore deposits (Paramillos Norte, Paramillos Centro, Paramillos Sur, Oro del Norte and Oro del Sur) that were determined by Navarro (1972) to be epithermal and porphyry copper type deposits which are included in the Postcollisional

www.schweizerbart.de
DOI: 10.1127/0077-7749/2011/0172
0077-7749/2011/0172 $ 3.00

Neogene Arc Magmatism Metallogenic Belt (Zappettini 1999). The main characteristics of these deposits, which are genetically related to Miocene volcanism, are described in Table 1. All these deposits are located in the flat-slab segment (27-33°S) of the Chilean and Argentinean Andes, where recent volcanism is absent (Barazangi & Isacks 1976). According to Kay & Mpodosis (2002) this segment is linked to the shallowing of the subducted plate, a process that started during the latest Early Miocene due to a change in Nazca – South America plate convergence parameters and not to the subduction of the Juan Fernández Ridge (Yañez et al. 2001), which was far to the north at that time.

Genetic relationships between specific magma series and ore deposits have been documented worldwide and are also widely used as an exploration guide. A link between adakite-like rocks and epithermal and porphyry type deposits has been established by Thieblemont et al. (1997) and has been observed particularly in the Andes, for example, at Kori Kollo, Bolivia (Bray du et al. 1995), the Cordillera Blanca, Peru (Petford & Atherton 1996; Coldwell et al. 2005), Uspallata, Argentina (Carrasquero 1998), the Northern Chilean Andes (Oyarzun et al. 2001), the Central Chilean Andes (Maksaev 1990; Bissig et al. 2003; Reich et al. 2003), and in the Late Miocene to Recent (LMR) volcanics from Ecuador (Chiaradia et al. 2004).

The word adakite was introduced by Defant & Drummond (1990) for intermediate to acidic plutonic and volcanic rocks believed to be products of direct partial melting of subducted oceanic lithosphere at high pressure where garnet is a stable residual phase. The conditions under which the adakites are formed were detailed by Peacock et al. (1994). According to these authors, the necessary geodynamic conditions to allow the formation of adakitic magmas are the subduction of young, hot oceanic plate, although more recently other authors (Reich et al. 2003) invoked that adakitic rocks can be generated in a cold slab by melting a subducting oceanic ridge. However, key adakitic geochemical signatures (particularly low Y and Yb concentrations and high Sr/Y and La/Yb ratios) can be generated in normal asthenosphere-derived arc magmas by melting-assimilation-storage-homogenization (MASH) and assimilation-fractional-crystallization (AFC) processes which have been well documented particularly in the Southern Andes (Lopez 1982; Kay et al. 1987, 1991; Hildreth & Moorbath 1988) where later Petford & Atherton (1996) compared them with adakites considered to be a product of slab melting. In 2007, Richards & Kerrich reviewed the link between adakite-like rocks and epithermal and porphyry type deposits and concluded that in most Phanerozoic arc volcanic suites and porphyry-related intrusives the adakitic signature is due to MASH and AFC processes affecting normal tholeiitic to calc-alkaline arc magmas, predominantly sourced by partial melting of the asthenospheric mantle wedge.

The aim of this paper is to establish, based on geochemical and isotopic characteristics, the adakite-like signature of Miocene volcanic rocks genetically related to the Oro del Sur ore deposit in the Paramillos de Uspallata mining district, Mendoza Province.

Geological setting

The Oro del Sur ore deposit is located in the southern part of the Argentine Precordillera, 45 km NW from Mendoza city (Fig. 1). The Precordillera extends over

Table 1. Main mineral characteristics of the ore deposits from the Paramillos de Uspallata mining district (modified from Angelelli 1983). **Az** azurite; **bn** bornite; **cc** chalcocite; **cp** chalcopyrite; **chry** chrysocolla; **cup** cuprite; **gn** galena; **hm** hematite; **lm** limonite; **mal** malachite; **mob** molybdenite; **mrc** marcasite; **mt** magnetite; **pr** proustite; **py** pyrite; **pyrg** pyrargyrite; **sl** sphalerite; **td** tetrahedrite. **K** potassic; **Ph** phyllic; **A** argillic; **P** propilitic.

Deposit	Type	Hydrothermal alteration	Ore paragenesis
Oro del Sur	epithermal	K, Ph, A, P	cp, py (Au), lm (Au), mal
Oro del Norte	epithermal	K, Ph, A, P	cp, py (Au), gn (Ag), sl, lm (Au), mal
Paramillos Norte	Cu-Mo porphyry deposit	K, P, Ph, A, Q	
Paramillos Centro	Cu-Mo porphyry deposit	K, P, Ph, A, Q	py, cp, bn, mob, mt, hm
Paramillos Sur	Cu-Mo porphyry deposit	K, Ph, A, Q	

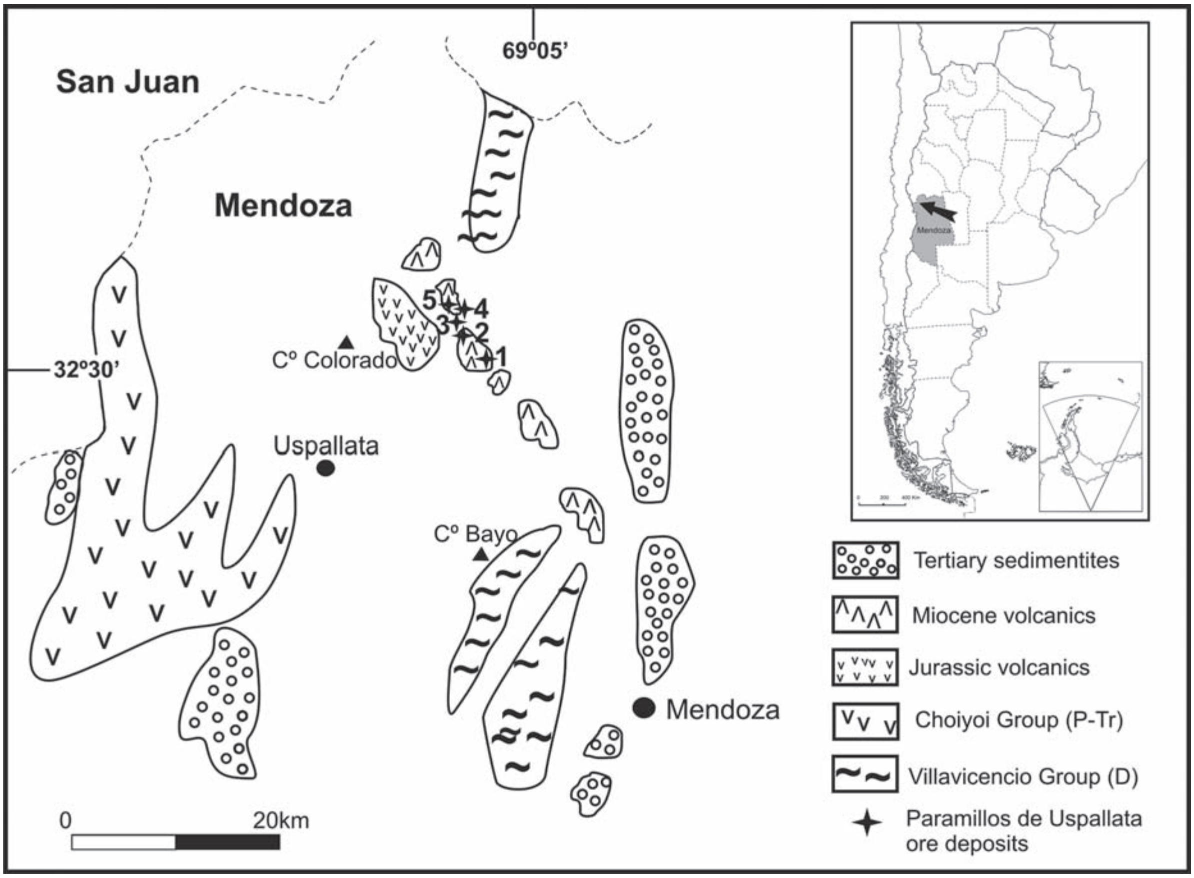

Fig. 1. Geological sketch of the Paramillos de Uspallata area showing the location of the Paramillos de Uspallata mining district ore deposits: **1** Oro del Sur; **2** Paramillos Sur; **3** Paramillos Centro; **4** Oro del Norte; **5** Paramillos Norte. The Pircas Conglomerate is not shown in the figure.

400 km, from La Rioja Province in the north to Mendoza Province in the south and has been described as a fold and thrust belt located to the east of the Andean Cordillera. It is composed predominantly of folded and flat-lying Paleozoic marine and non-marine sedimentary rocks, along with Cenozoic terrestrial sedimentary rocks related to the uplift of the Andes.

The basement that crops out in the area (Fig. 1) consists of Middle Devonian (?) metasedimentary rocks belonging to the Villavicencio Group which are unconformably overlain by sedimentary rocks of probable Upper Devonian age belonging to the Pircas Conglomerate (Harrington 1941, 1971). This sequence is overlain by the Upper Permian to Lower Triassic Choiyoi Group, which is composed of volcanic and pyroclastic rocks (Llambías et al.1993).

From the Middle to Upper Triassic the geological record shows a sequence of sandstones, slates and bituminous schists that comprise the Uspallata Group (Fig. 1). This sequence includes Jurassic sills and basaltic lavas (Massabie 1986; Ramos & Kay 1991) with a tholeiitic to slightly alkaline signature which have been linked to the early opening of the South Atlantic Ocean (Ramos & Kay 1991; Carrasquero 2001).

In early Miocene times, at around 19 Ma, flattening of the subduction zone occurred at this latitude and the igneous activity migrated from the Andean Cordillera eastward (Kay et al. 1987). During the middle Miocene (~19 to 16 Ma) the arc magmatism produced a large volume of volcanic rocks, including stocks, sills, magmatic breccias and dykes of andesitic to monzodioritic composition (Kay et al. 1991; Ramos & Nullo 1993). In the area of the Oro del Sur ore deposit, the Miocene volcanism is represented by hypa-

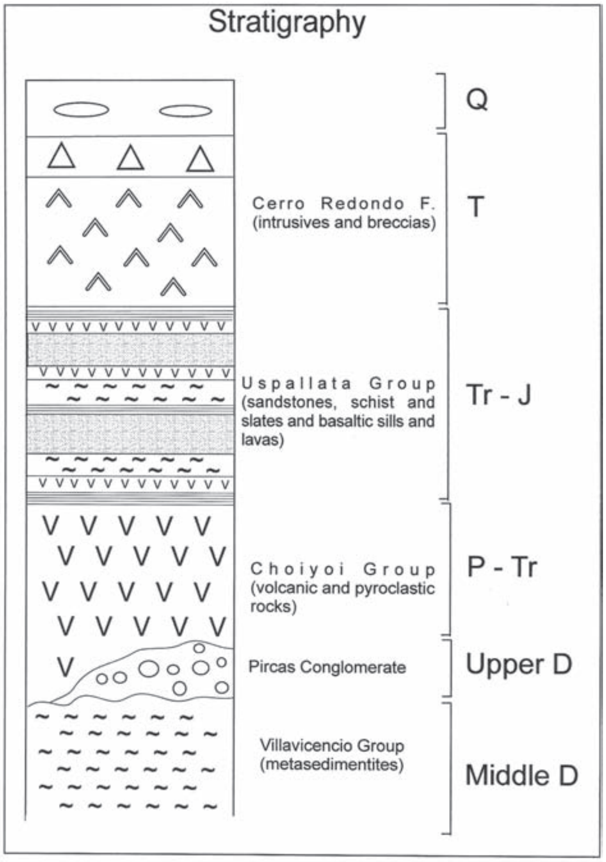

Fig. 2. Stratigraphy of the Paramillos de Uspallata area.

byssal and minor dykes of andesitic composition of the 19-16 Ma old Cerro Redondo Formation (Massabie et al. 1986; Linares & González 1990; Kay et al. 1991). They are porphyritic andesites composed of abundant plagioclase and minor biotite and hornblende phenocrysts in a fine groundmass of plagioclase and disseminated magnetite crystals. The stratigraphy of the area is presented in Fig. 2.

The Oro del Sur epithermal ore deposit

Exploration of the Oro del Sur ore deposit was undertaken between 1986 and 1993 and included regional geological mapping, surface geochemical sampling, and a preliminary drilling program (Fusari et al. 1993). The deposit was not studied any further until 2005 when Compañía Minera Tenke carried out new geochemical surface and drilling sampling but presently any new information remains confidential.

Oro del Sur is a high sulfidation (HS) epithermal deposit (Fusari et al. 1993) located in the western and central part of an alteration zone of about 4 km^2 developed in sedimentary rocks of the Uspallata Group and the Miocene volcanics of the Cerro Redondo Formation (Fig. 3). It is composed of veins and stockwork areas. The mineralized veins have a general strike of NNW-SSE with dips of 70-90°; their length ranging from tens of meters to 500 m and their mean thickness is about 1.20 m. The mineralized vein structures are developed in a ENE-WSW shear zone (Fig. 3). Close to the contact with the veins the host rocks show pervasive advanced argillic alteration with a paragenesis of sericite, clay, quartz and alunite. The veins consist of Fe-oxides with minor quartz; occasionally, pyrite and minor chalcopyrite, enargite and gold are present. Significant Ag and Au anomalies, up to 500 and 140 g/t respectively, have been detected by surface geochemical analyses.

To the east of the alteration zone, there is a small concentric halo surrounding a central potassic alteration area with a depth of up to 180 m which consists of pervasive biotitization, silicification and minor feldspathization with minor quartz-biotite veins; Fe-oxides with boxwork texture are locally recognized. Drill samples reveal disseminated and vein-hosted ore (the latter with quartz gangue) consisting of abundant pyrite (with chalcopyrite, pyrrhotite and gold inclusions) together with chalcopyrite, magnetite and minor pyrrhotite, gold (and electrum), molybdenite and sphalerite with chalcopyrite disease.

Supergenic enrichment is scarce and results in covellite with minor chalcocite recognized in the deeper part of the drills. Outwards from the potassic alteration zone there is an irregularly developed, advanced argillic alteration halo displaying intense bleaching down to 230 m depth with a paragenesis of sericite, clay, quartz and alunite and minor quartz-alunite veins (Fusari et al. 1993). It is extensively oxidized in its outer part with abundant Fe-oxides and jarosite in boxwork texture while in its inner part abundant pyrite disseminated and minor in veinlets with quartz gangue, is recognized.

The outer part of the alteration zone shows a pervasive propylitic alteration (mainly with chlorite and minor epidote) developed only in the volcanic rocks. Small spots of advanced argillic alteration are also found in the propylitic zone. In the south-western part of the alteration zone, and enclosed by propylitic alteration, small hydrothermal breccias with a tourmaline – quartz – chlorite cement and chalcopyrite mineralization are locally recognized (Fusari et al. 1993).

Table 2. Geochemistry of Cerro Redondo Formation samples from the Oro del Sur deposit area. (1) from Kay et al. 1991; (2) from Reich et al. 2003; (3) from Bissig et al. 2003; (4) Chiaradia et al. (2004).

	Oro del Sur					Uspallata (1)		Los Pelambres Chile (2)	El Indio Chile (3)	LEM Ecuador (4)
	Gn14	Gn15	UP19	UP67	UP75	ps2	cc1	F51	thb15b	E94007
SiO_2	59.95	60.07	66.53	62.21	64.09	58.17	57.26	63.7	64.88	56.69
TiO_2	1.09	1.19	0.34	0.69	0.41	0.72	0.94	0.67	0.59	0.63
Al_2O_3	20.62	20.56	18.48	19.82	17.89	19.09	18.65	17.7	16.32	17.71
Fe_2O_3	2.31	1.73	1.82	2.85	2.92	-	-	4.4	4.11	6
FeO	-	-	-	-	-	5.02	5.65	-	-	-
MnO	0	0.01	0.01	0.01	0	0.07	0.09	0.02	0.07	0.06
MgO	0.53	0.96	0.11	0.22	0.21	1.19	1.7	1.6	2.18	3.96
CaO	1	1.08	1.83	0.31	0.32	3.85	6.69	3.36	4.29	5.29
Na_2O	5.31	5.11	3.82	0.8	1.35	5.59	4.72	5.22	3.97	3.8
K_2O	4.33	4.92	5.41	8.35	7.51	5.44	4.29	1.58	2.88	1.89
P_2O_5	0.12	0.12	0.07	0.12	0.19	-	-	0.21	0.19	0.31
LOI	3.33	2.38	1.43	4.61	4.36	-	-	1.17	1.49	2.66
total	98.59	98.13	99.87	100	99.25	99.98	99.99	99.6	99.6	99.3
Nb	4.9	4.9	8	4	11	-	-	4	-	5
Zr	166	180	196	213	199	-	-	131	143	118
Y	6	12	21	13	4	-	-	6.42	6.2	10
Sr	740	884	1251	695	594	-	1152	750	609	1102
Rb	173	193	110	208	166	-	-	76.2	109	64
Th	0.9	0.9	2	1.4	1.9	7.76	7.35	-	11.2	3
Ga	19	20	5	19	22	-	-	-	23.3	-
Co	12	11	3	3	1.9	7	9	-	-	-
Cr	2.9	2.9	69	55	36	6	7	-	50.6	-
V	84	79	58	92	63	-	-	-	78.2	170
Ce	64	126	54	103	56	84.6	97.3	38.1	53.5	52.2
Nd	29	69	28	63	30	40.3	47.2	17	21.4	-
Ba	404	501	1461	1128	1079	1400	1147	461	643	594
La	39	65	32	58	33	43.1	48.4	19.5	25.9	25.1
Hf	3	3	8	5	2	5.95	4.98	4.45	6.5	-
Sc	4.9	13	3	1.8	1.9	4.2	7.5	-	9.9	23
Sm	6.4	7.5	5.3	5.9	2.7	7.77	9.12	2.95	3.7	4.6
Eu	1.6	1.7	1.7	1.3	0.6	2.09	2.47	0.96	0.91	1.19
Tb	0.9	0.9	0.9	0.9	0.2	0.88	1.04	0.257	0.33	0.5
Yb	1	1.9	1.9	1	0.6	2.86	3.05	0.529	0.84	1
Lu	0.2	0.3	0.3	0.2	0.1	0.397	0.405	-	0.12	0.16

Analytical techniques

Selected surface samples of Miocene volcanic rocks spatially associated with the Oro del Sur ore deposit (Table 2) were analyzed for major and trace elements (including LREE) using an XR Fluorescence PHILIPS PW 2400 spectrometer at the Centre d'Analyse Minérale (CAM), Lausanne University (Switzerland). HREE and Au were analyzed by INAA at the Actlabs and ITS Laboratories (Canada).

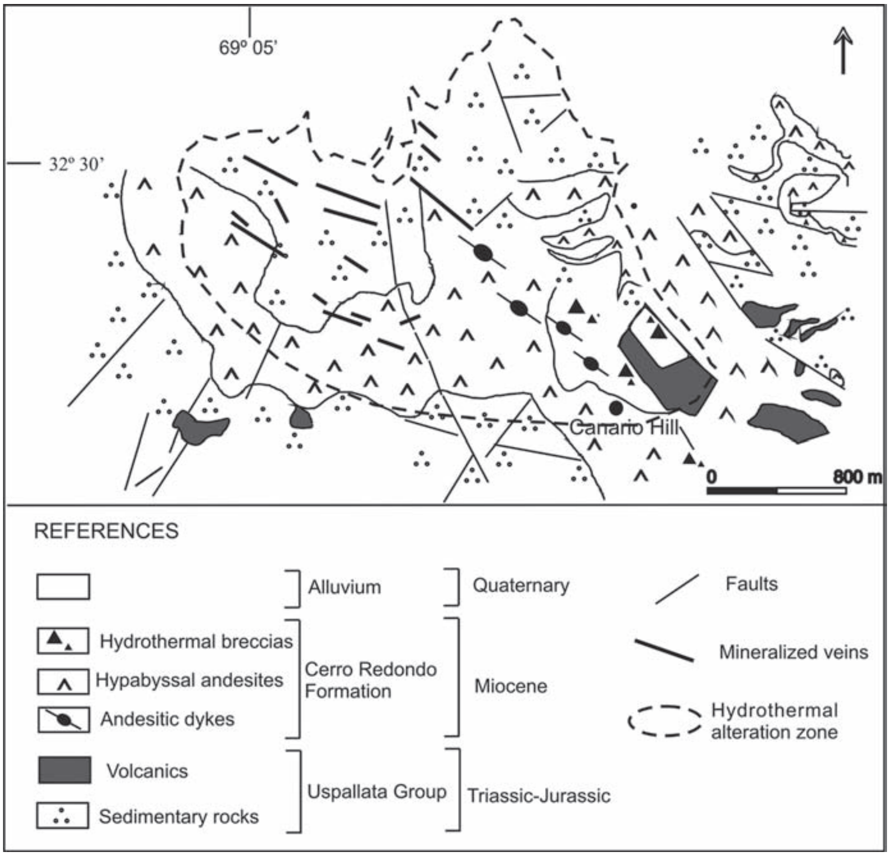

Fig. 3. Detailed map of the Oro del Sur deposit area (modified from Lavandaio & Fusari 1986).

Sr and Nd isotope compositions of four samples (Table 3) were obtained by a 7-collector thermal ionization mass spectrometer (Finnigan MAT 262) with extended geometry and stigmatic focusing at the University of Geneva. 500 mg of each sample were dissolved in 4 ml of concentrated HF and 0.5 ml of concentrated HNO3 and then evaporated to dryness. Dissolution was further assured, and HF was eliminated by evaporating twice with 1 ml 6M HCl at 130 ºC. The samples were then dissolved in 1 ml of 2.5 M HCl, centrifuged, and the solution was loaded on a column for separation of Sr.

Data were recalculated using the Eimer and Amend standard (mean value $^{87}Sr/^{86}Sr$ = 0.708001 ± 06). Sr isotopic ratios were corrected for mass fractionation assuming $^{86}Sr/^{88}Sr$ = 0.1194.

Geochemical characteristics

The analyzed samples (Table 2) show a calc-alkaline character with high SiO_2 (59.67-66.53 wt%) and Al_2O_3 (17.89-20.62 wt%), and low MnO (0-0.01 wt%) which are typical features of productive porphyritic intrusions (Baldwin & Pearce 1982). Low MgO (0.11-0.53 wt%) and CaO (0.31-1.83), low to moderate Na_2O (0.80-5.31) and high K_2O (4.33-8.35%) are due to hydrothermal alteration.

The multi-element 'spider' diagram (Fig. 4a) is strongly spiked and shows enrichment in incompatible elements (LILE and LREE), a Nb trough and negative anomalies in P and Ti, which are common features of convergent plate boundary magmas.

The overall chondrite normalized REE patterns (Fig. 4b) are similar to those of other middle Miocene volcanic rocks of the Uspallata area (Kay et al. 1991) and also of the adakite-like rocks from the Los Pelambres and El Indio ore deposits in Chile (Reich et al. 2003; Bissig et al. 2003) as well as from mineralized Eocene to Late Miocene (LEM) volcanics in Ecuador (Chiaradia et al. 2004), but with a higher Σ_{total} REE (Table 2). The most noticeable features are the low Y and Yb contents and particularly the high Sr/Y and

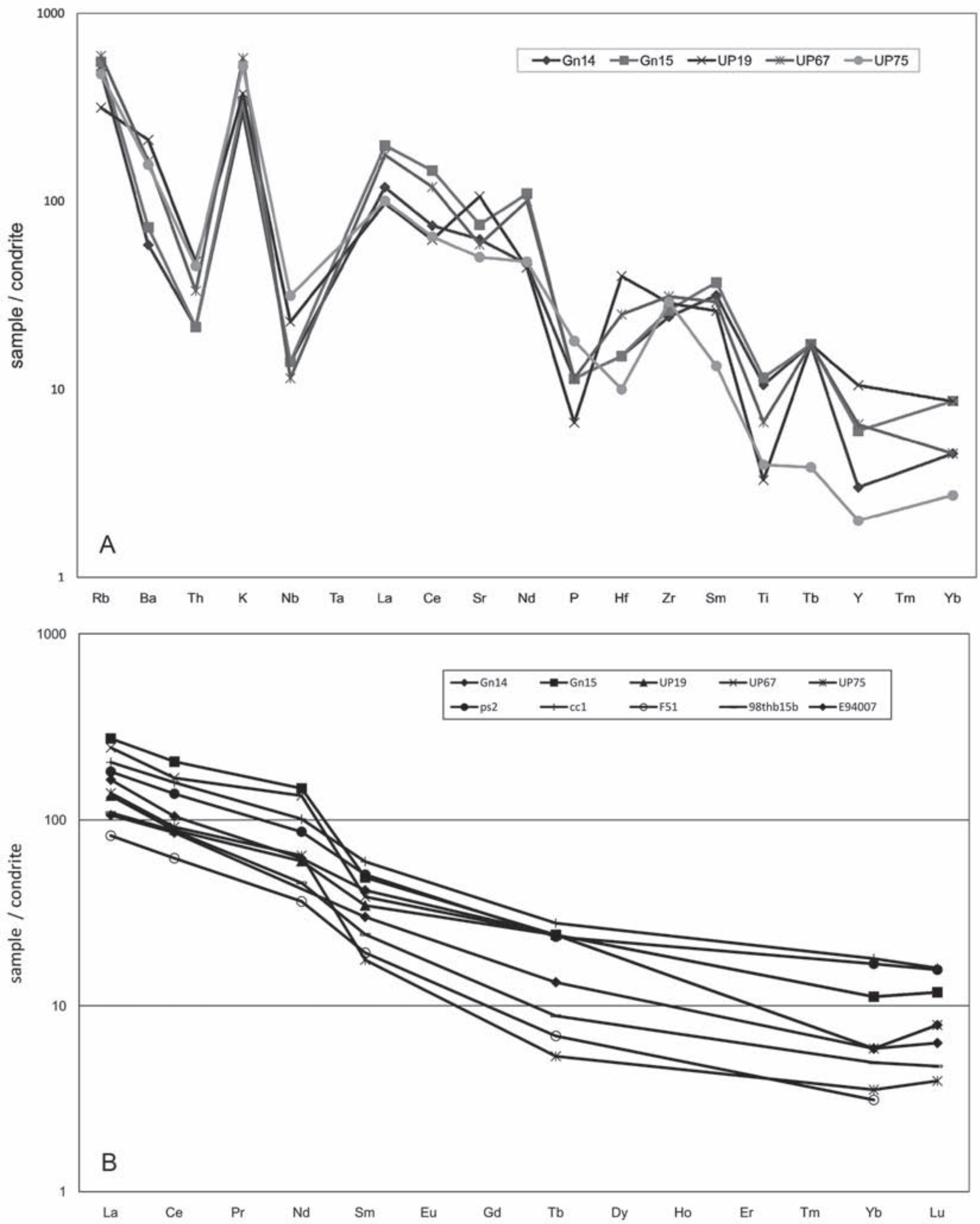

Fig. 4. a. Chondrite-normalized (SUN & MCDONOUGH 1989) multi-element 'spider' diagram of volcanic rocks from Oro del Sur. **b.** Chondrite-normalized (SUN & MCDONOUGH 1989) REE diagram of samples from the Oro del Sur, Los Pelambres and El Indio ore deposits (BISSIG et al. 2003; REICH et al. 2003) and mineralized LEM volcanics from Ecuador (CHIARADIA et al. 2004).

La/Yb ratios, which are characteristics of rocks with an adakitic signature. In the Y vs. Sr/Y diagram (Fig. 5), they plot in the adakitic field, which is similar to adakite-like rocks genetically linked to porphyry copper deposits from Ecuador (CHIARADIA et al. 2004) and from the 27-33° S flat-slab segment in Chile (REICH et al. 2003; BISSIG et al. 2003).

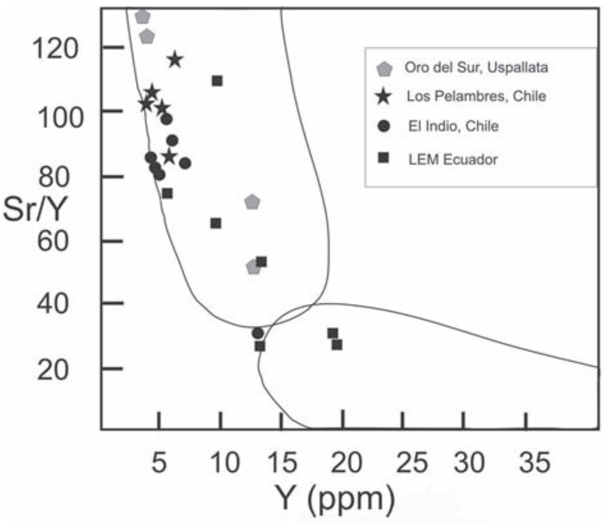

Fig. 5. Y vs. Sr/Y diagram discriminating normal calc-alkaline rocks from adakite-like rocks (modified from Defant & Drummond 1990) including adakite-like rocks genetically linked to the porphyry copper deposits Los Pelambres (Reich et al. 2003) and El Indio (Bissig et al. 2003), and mineralized LEM volcanics from Ecuador (Chiaradia et al. 2004).

Sr-Nd isotope ratios

Sr-Nd isotope ratios of the Miocene volcanics from the Oro del Sur ore deposit area display a wide range of $(^{87}Sr/^{86}Sr)_i$ (0.703617 to 0.705615) and $^{143}Nd/^{144}Nd$ (0.512546 to 0.512813) ratios (Table 3), encompassing those from the Uspallata Miocene volcanic rocks (Kay et al. 1991) and the Los Pelambres ore deposit (Table 4). In the $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ correlation diagram (Fig. 6), the Oro del Sur samples plot in the Mantle Array area as do the samples from Los Pelambres and the Uspallata area.

Discussion

The Oro del Sur alteration area displays in its eastern part a consistent alteration zoning pattern similar to that of porphyry copper type deposits. It comprises a central potassic alteration zone with biotite, quartz and feldspar and EB veins (Gustafson & Quiroga 1995) passing outwards into an advanced argillic alteration halo with sericite, quartz and alunite and quartz-alunite veins which in its inner part has abundant disseminated pyrite and D veins, typical of the phyllic zone (Gustafson & Quiroga 1995). Propylitic alteration developed distally with a paragenesis of chlorite and minor epidote and enclosed magmatic – hydrothermal breccia bodies with a tourmaline, quartz, chlorite and chalcopyrite cement genetically linked to the phyllic stage (Sillitoe 2010). Moreover, the ore paragenesis (chalcopyrite–magnetite–pyrrhotite–gold (electrum)–molybdenite–sphalerite) is also characteristic of this type of deposit. The Oro del Sur Au-(Cu) HS epithermal deposit could be preliminarily linked to this probably telescoped (Sillitoe 2010) Cu-(Mo) porphyry hydrothermal system.

The Oro del Sur hydrothermal system is genetically linked to the Miocene volcanism of the area which has a geochemistry typical of productive porphyritic

Table 3. Sr-Nd isotopic compositions of Miocene volcanic rocks from the Oro del Sur deposit area. The $(^{87}Sr/^{86}Sr)T$ was corrected for T-18 Ma.

	GN 14	**GN 21**	**UP 67**	**UP 75**
Sm ppm	6.4	5.5	5.9	2.7
Nd ppm	29	12	63	30
$[^{143}Sm/^{144}Nd]$	$2.598.10^{-5}$	0.275824	0.052537	0.05416
$(^{143}Nd/^{144}Nd)_m$	0.512562	0.512846	0.5126704	0.512693
2σ	0.000009	0.000006	0.000006	0.000022
$(^{143}Nd/^{144}Nd)_T$	**0.512546**	**0.512813**	**0.512697**	**0.512687**
$(Nd/Nd)_{CHUR\ 0}$	0.512615	0.512615	0.512615	0.512615
ε_{Nd}	-1.0	4.5	1.7	1.5
Rb ppm	173	427	208	166
Sr ppm	740	229	695	594
$[^{87}Rb/^{86}Sr]$	0.676	5.393	0.866	0.808
$(^{87}Sr/^{86}Sr)_m$	0.705788	0.704995	0.704212	0.704364
2σ	0.000002	0.000006	0.000002	0.000003
$(^{87}Sr/^{86}Sr)_T$	**0.705615**	**0.703617**	**0.703991**	**0.704157**

Table 4. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic compositions of Miocene volcanic rocks from the Oro del Sur ore deposit area. (1) from Kay et al. 1991; (2) from Reich et al. 2003; (3) from Bissig et al. 2003. * $(^{87}Sr/^{86}Sr)T$ corrected data; ** (87Sr/86Sr)T non-corrected data.

Sector	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$
Oro del Sur	0.703617 0.705615 (*)	0.512546 0.512813 (*)
Uspallata (1)	0.704167 (**)	0.512627 (**)
Los Pelambres, Chile (2)	0.70439 0.70465 (*)	0.512619 0.512635
El Indio Chile (3)	0.706106 0.707159 (**)	0.512369

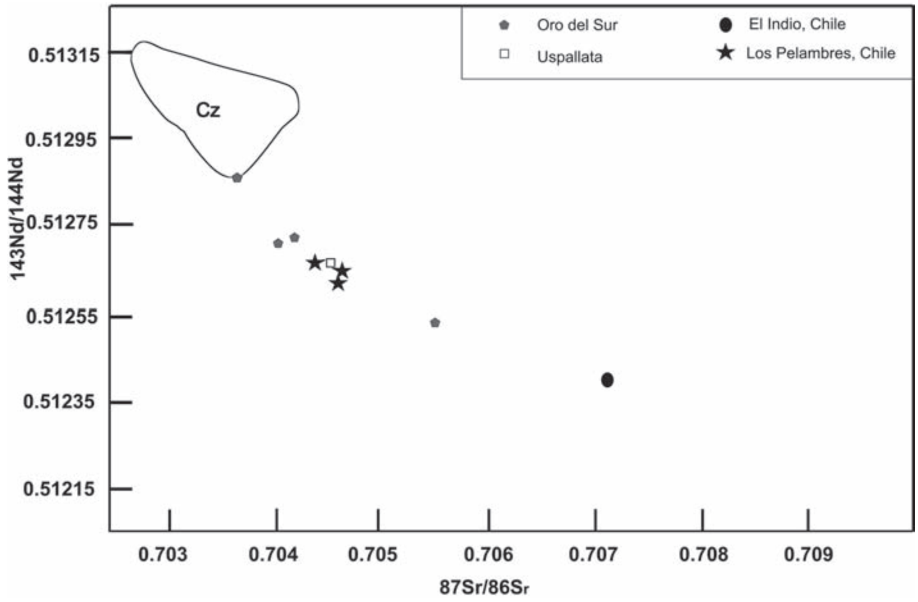

Fig. 6. $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ diagram plotting samples from the Oro del Sur deposit area, Uspallata area (KAY et al. 1991), Los Pelambres (REICH et al. 2003) and El Indio (BISSIG et al. 2003). **CzA** Cenozoic adakites from Adak and Cook Island, Baja California and Central America (CASTILLO 2006).

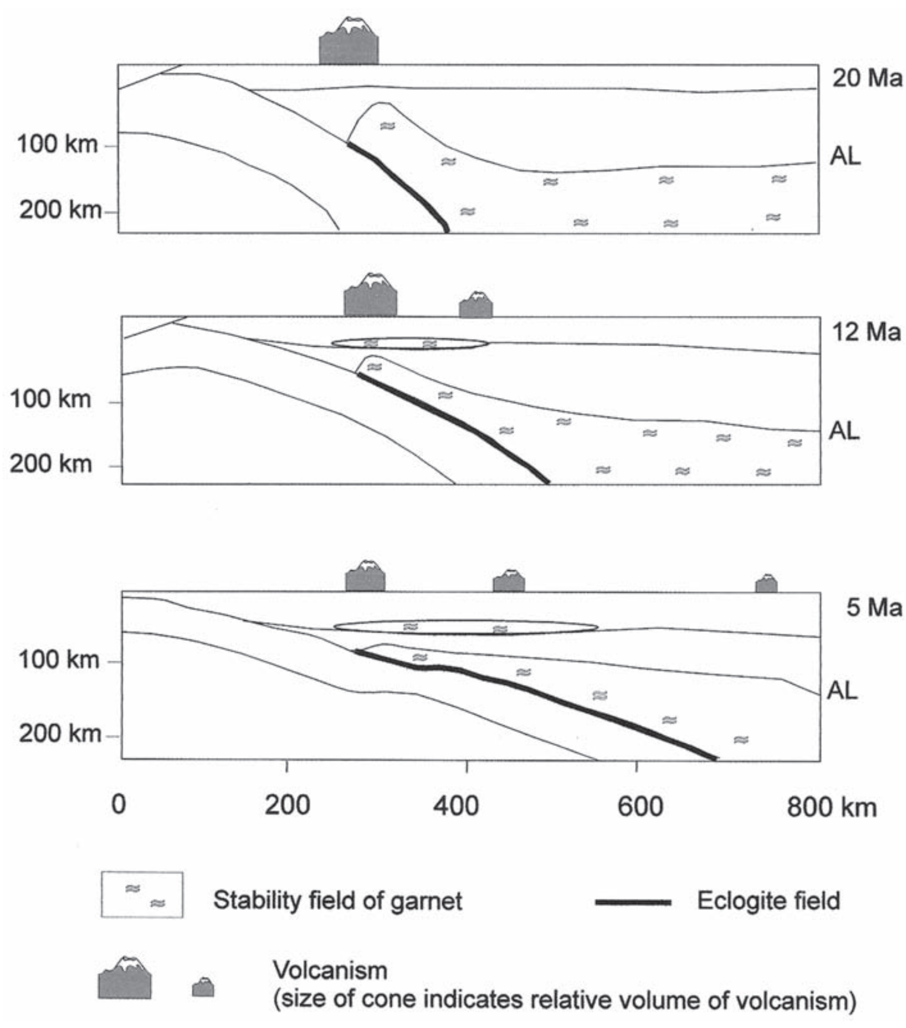

Fig. 7. Schematic cross sections at 31ºS which shows changes through time in the depth of the asthenosphere - lithosphere boundary line (**AL**), crustal thickness and volcanism (modified from KAY et al. 1987).

intrusions (Baldwin & Pearce 1982). It shows geochemical characteristics (particularly low Y and low Yb contents and high Sr/Y and La/Yb ratios) that indicate an adakite-like signature.

In addition, these rocks display REE patterns similar to those of the adakite-like rocks genetically linked to the flat-slab porphyry copper deposits in Chile (Bissig et al. 2003; Reich et al. 2003). Their Sr-Nd isotopic compositions enclose that of the Los Pelambres ore deposit (Reich et al. 2003), and in the $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ correlation diagram (Fig. 6) they plot in the Mantle Array area, suggesting the involvement of a source with a depleted mantle isotopic signature in their genesis.

The adakitic signature of the magmas is linked to the shallowing of the subducting Nazca Plate which was induced by changes in convergence parameters in middle Miocene times (~ 20 Ma). The shallowing resulted in an important decrease in the asthenospheric wedge thickness, migration of the volcanic arc to the east (Fig. 7), a crustal thickening, and the transition from a transpressional to a compressional regime (Kay et al. 1987, 1991; Kay & Mpodozis 2002). It has been suggested that partial melting of overthickened mafic lower crust equilibrated with a garnet-amphibole residual mineralogy may result in adakite-type melts (Petford & Atherton 1996; Kay & Mpodozis 2002). In this scenario, melts entering the thickening lower crust from the asthenospheric wedge become increasingly hydrous as fluids are progressively concentrated in the cooling mantle leading to amphibole crystallization.

As the thickening progresses, the breakdown of amphibole into a higher pressure garnet-bearing residual mineral assemblage can release a significant amount of fluid that promotes mineralization processes under oxidizing conditions, allowing metals to be concentrated in the residual fluids of the crystallizing magmas (Kay & Mpodozis 2001). This mechanism is considered to be of significant importance in the genesis of the large Central Andean porphyry deposits (Kay & Mpodozis 2001; Richards & Kerrich 2007) and allows to establish a genetic link between mineralization and adakite-like magmatic rocks.

Conclusions

Based on the distribution and paragenesis of the hydrothermal alteration and mineralization, the Oro del Sur ore deposit can be preliminary classified as a Cu-(Mo) porphyry type system with associated HS Cu-Au epithermal veins. It is genetically linked to the Miocene volcanism of the area which shows geochemical characteristics that indicate an adakite-like signature with the involvement of a depleted mantle source in their genesis. The age of these adakite-like rocks (~19 Ma) suggests a change in the geochemical signature of the magmatism linked to initiation of the subduction zone flattening. In this way, the adakite-like signature of the Miocene volcanism of the Oro del Sur ore deposit supports a genetic relationship between adakitic magmas, mineralization and slab shallowing in this part of the Andes.

Because of the metallogenic significance of rocks with an adakite-like signature, geochemical characterization of such magmatism could result in a powerful tool in the initial stages of ore deposit exploration.

Acknowledgements

We thank Dr. Massimo Chiaradia, Geneva, Switzerland, for his support in the Sr-Nd isotopic analyses, and Lic. Anabel Gomez (UBA-CONICET) who helped with the figures. We are grateful to Prof. Dr. Lluís Fontboté and Fabio Capponi (Geneva, Switzerland) for providing geochemical analyses, as well as to Dr. Richard Bevins, Cardiff, UK, for reviewing the manuscript. Reviews by Prof. Dr. Miguel A. Parada, Santiago de Chile, Chile, and an anonymous referee led to considerable improvement of the manuscript. This contribution is part of S. Carrasquero's PhD. research investigation (UNLP).

References

Angelelli, V. (1983): Yacimientos metalíferos de la República Argentina. I. – Comision de Investigaciones Científicas de la Provincia de Buenos Aires: 109-202.

Ave Lallemant, G. (1890): El Paramillo de Uspallata. – 136 pp.; Sociedad Científica Argentina; Buenos Aires.

Baldwin, J.A & Pearce, J.A. (1982): Discrimination of productive and nonproductive porphyritic intrusions in the Chilean Andes. – Economic Geology, **77**: 664-674.

Barazangi, M. & Isacks, B.L. (1976): Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America. – Geology, **4**: 686-692.

Bissig, T., Clark, A., Lee, K.W. & von Quadt, A. (2003): Petrogenetic and metallogenetic responses to Miocene slab flattening: new constraints from the El Indio-Pascua Au-Ag-Cu belt, Chile/Argentina. – Mineralium Deposita, **38**: 844-862.

Carrasquero, S.I. (1998): Volcanismo de arco en el área del pórfido cuprífero Paramillos Sur, Uspallata, Mendoza, Argentina. – X Congreso Latinoamericano de Geología y VI Congreso Nacional de Geología Económica, **1**: 95-100. Buenos Aires.

Carrasquero, S.I. (2001): Nuevos aportes a la geoquímica del volcanismo de intraplaca en la región de Paramillos de Uspallata, Mendoza, Argentina. – CD without pagination; XI Congreso Latinoamericano de Geología y III Congreso Uruguayo.

Castillo, P.R. (2006): An overview of adakite petrogenesis. – Chinese Science Bulletin, **51** (3): 257-268.

Chiaradia, M., Fontboté, L. & Beate, B. (2004): Cenozoic continental arc magmatism and associated mineralization in Ecuador. – Mineralium Deposita, **39**: 204-222

Coldwell, B., Petford, N., Murphy, P. & Smith, M. (2005): "Adakitic" rocks of the Yungay Formation, Peru: problems with tectonic setting and origin. – 1 p.; European Geosciences Union General Assembly, file EGU05-A-02656.

Defant, M.J. & Drummond, M.S. (1990): Derivation of some modern arc magmas by melting of young subducted oceanic lithosphere. – Nature, **347**: 662-665.

du Bray, E.A., Ludington, S., Brooks, W.E., Gamble, B.M., Ratte, J.C., Richter, D.H. & Soria Escalante, E. (1995): Compositional characteristics of Middle to Upper Tertiary volcanic rocks of the Bolivian Altiplano. – U.S. Geological Survey Bulletin, **2119**: 1-41.

Fusari, C., Lapido, O. & Kross, G. (1993): Proyecto "Oro del Sur" (de investigación y exploración geológico-minera), Departamento Las Heras, Provincia de Mendoza, República Argentina. – 35 pp.; Dirección General de Minería, Centro de Exploración Mendoza; unpublished.

Gustafson, L. & Quiroga, J. (1995): Patterns of mineralization and alteration below the porphyry copper orebody at El Salvador. – Economic Geology, **90** (6): 2-16.

Harrington, H.J. (1941): Investigaciones geológicas en las sierras de Villavicencio y Mal País, Provincia de Mendoza. – 54 pp.; Dirección de Minas y Geología, Boletín, **49**.

Harrington, H.J. (1971): Descripción geológica de la Hoja 22c, "Ramblón", provincias de Mendoza y San Juan. – 81 pp.; Dirección Naciónal de Geología y Minería, Boletín, **114**.

Hildreth, W. & Moorbath, S. (1988): Crustal contributions to arc magmatism in the Andes of central Chile. – Contributions to Mineralogy and Petrology, **98**: 455-489.

Kay, S.M. & Mpodozis, C. (2001): Central Andean ore deposits linked to evolving shallow subduction systems and thickening crust. – Geological Society of America Today, **11**: 4-9.

Kay, S.M. & Mpodozis, C. (2002): Magmatism as a probe to the Neogene shallowing of the Nazca plate beneath the modern Chilean flat-slab. – Journal of South American Earth Sciences, **15**: 39-57.

Kay, S.M., Maksaev, V., Moscoso, R. & Nasi, C. (1987): Probing the evolving Andean lithosphere: Mid-Late Tertiary magmatism in Chile (29º-30º30'S) over the modern zone of subhorizontal subduction. – Journal of Geophysical Research, **92** B7: 6173-6189.

Kay, S.M., Mpodozis, C., Ramos, V. & Munizaga, F. (1991): Magma source variations for mid-late Tertiary magmatic rocks associated with a shallowing subduction zone and a thickening crust in the central Andes (28º to 33ºS). – In: Harmon, R. & Rapela, C.W. (Eds.): Andean magmatism and its tectonic setting. – Geological Society of America Special Paper, **265**: 113-137.

Lavandaio, E. & Fusar, I.C. (1986): Informe preliminar sobre el reconocimiento expeditivo del Distrito Polimetálico Mendoza Norte. – 80 pp.; Dirección Nacional de Geología y Minería. Centro Exploración Mendoza; unpublished.

Linares, E. & González, R. (1990): Catálogo de edades radimétricas de la República Argentina 1957-1987. – Asociación Geológica Argentina, Serie B (Didáctica y Complementaria), **19**: 1-628.

Llambías, E., Kleiman, L.E. & Salvarredi, J. (1993): El magmatismo Gondwánico. – In: Ramos, V. (Ed.): Geología y recursos naturales de Mendoza. – XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos. – Relatorio, **I** (6): 53-64.

López, L. (1982): Características geoquímicas de rocas ígneas asociadas con pórfidos cupríferos chilenos – Revista Geológica de Chile, **17**: 3-19.

Maksaev, V. (1990): Metallogeny, geological evolution and thermochronology of the Chilean Andes between latitudes 21º and 26º South and the origin of major porphyry copper deposits. – 554 pp.; unpublished doctoral thesis; Halifax (Dalhousie University).

Massabie, A.H. (1986): Filón-capa Paramillos de Uspallata, su caracterización geológica y edad, Paramillos de Uspallata, Mendoza. – 1ras Jornadas sobre Geología de Precordillera, San Juan, **I**: 325-330.

Massabie, A.H., Rapalini, A.E. & Soto, J.L. (1986): Estratigrafía del Cerro Los Colorados, Paramillos de Uspallata, Mendoza. – 1^{ras} Jornadas sobre Geología de Precordillera, San Juan, **I**: 71-76.

Molina, A.J.I. (1788): Compendio de la historia geográfica, natural y civil del Reyno de Chile: Primera parte, que abraza la historia geográfica y natural. – Madrid (Imprenta de Sancha): 86-125.

Navarro, H. (1972): Area de reserva N° 3. Zona "Paramillos Norte", provincia de Mendoza. – IV Jornadas Geológicas Argentinas (Mendoza, 1969), **3**: 105-125.

Oyarzún, R., Márquez, A., Lillo, J., López, I. & Rivera, S. (2001): Giant versus small porphyry copper deposits of Cenozoic age in northern Chile: adakitic versus normal calc-alkaline magmatism. – Mineralium Deposita, **36**: 794-798.

Peacock, S., Rushmer, T. & Thompson, A.B. (1994): Partial melting of subducting oceanic crust. – Earth and Planetary Sciences Letters, **121**: 227-244.

Petford, N. & Atherton, M. (1996): Na-rich partial melts from newly underplated basaltic crust: The Cordillera Blanca Batholith, Peru. – Journal of Petrology, **37**: 1491-1521.

Ramos, V. & Nullo, F. (1993): El volcanismo de arco Cenozoico. – In: Ramos, V. (Ed.): Geología y Recursos Naturales de Mendoza. – XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos, Relatorio, **I** (12): 149-160.

Ramos, V. & Kay, S.M. (1991): Triassic rifting and associated basalts in the Cuyo bassin, central Argentina. – Geological Society of America, Special Paper, **265**: 79-91.

Reich, M., Parada, M.A., Palacios, C., Dietrich, A., Schultz, F. & Lehmann, B. (2003): Adakite-like signature of Late Miocene intrusions at the Los Pelambres giant porphyry copper deposit in the Andes of central Chile: metallogenic implications. – Mineralium Deposita, **38**: 876-885.

Richards, J.P. & Kerrich, R. (2007): Adakite-like rocks: Their diverse origins and questionable role in metallogenesis. – Economic Geology, **102**: 537-576.

Sillitoe, R.H. (2010): Porphyry copper systems. – Economic Geology, **105** (1): 3-41.

Sun, S.S. & McDonough, W.F. (1989): Chemical and isotopic systematics of oceanic basalts: Implication for mantle composition and processes. – In: Saunders, A.D. & Norry, M.J. (Eds.): Magmatism in ocean basins. – Geological Society of London, Special Publication, **42**: 313-345.

Thiéblemont, D., Stein, G. & Lescuyer, J.L. (1997): Gisements épithermaux et porphyriques: la conexion adakite. – Comptes Rendus Académie de Sciences, Sciences de la Terre et des planètes, **325**: 103-109.

Yañez, G.A., Ranero, C.R., von Huene, R. & Díaz, J. (2001): Magnetic anomaly interpretation across the southern central Andes (32°-34°S): The role of the Juan Fernández Ridge in the late Tertiary evolution of the margin. – Journal of Geophysical Research, **106 B4**: 6325-6345.

Zappettini, E. (1999): Evolución geotectónica y metalogénesis de la Argentina. – In: Zappettini, E. (Ed.): Recursos Minerales de la República Argentina. – Servicio Geológico Minero Argentino (SEGEMAR), Anales, **35**: 51-73.

Manuscript received: December 30th, 2009.
Revised version accepted by the Greifswald editor: January 03rd, 2011.

Addresses of the authors:

Silvia I. Carrasquero, Instituto de Recursos Minerales (INREMI), FCNyM, Universidad Nacional de La Plata, 64 Nº 3, entre 119 y 120; (1900) La Plata, Argentina;
E-mail: silviacarrasquero@yahoo.com.ar

Nora A. Rubinstein, CONICET-Departamento de Geología, FCEN, Universidad Buenos Aires, Pabellón 2, Ciudad Universitaria, (1428) Ciudad Autónoma de Buenos Aires, Argentina;
E-mail: narubinstein@gmail.com

Denis Fontignie, Department of Mineralogy, University of Geneva, Switzerland;
E-mail: Denis.Fontignie@unige.ch