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The Bajo de la Alumbrera and Agua Rica Cu–Au (Mo) porphyry deposits of Argentina: Genetic constraints on ore formation and sources based on isotope signatures

Maurício Liska Borba [a,*], Farid Chemale Junior [b], Koji Kawashita [c], Lucy Takehara [d], Marly Babinski [c], Matheus Bruckman [a]

[a] Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Campus do Vale, Porto Alegre, RS 91501-970, Brazil
[b] Instituto de Geociências, Universidade de Brasília, Campus Universitário Darcy Ribeiro, Brasília, DF 70904-970, Brazil
[c] Centro de Pesquisas Geocronológicas, Universidade de São Paulo, Rua Lago 562, Cidade Universitária, São Paulo, SP 05508-080, Brazil
[d] Companhia de Pesquisas e Recursos Minerais, SGAN 603, Brasília, DF 70830-902, Brazil

A B S T R A C T

Important copper-gold ($\pm$ molybdenum) porphyry deposits occur in the northwest region of Argentina, part of the Central Andes. This paper provides new isotope information on two of these deposits, Bajo de la Alumbrera and Agua Rica, the latter having an epithermal overprint event. The two deposits are genetically associated with the Miocene Farallón Negro Volcanic Complex. Whole rock and sulfide samples were analyzed for Pb, Sr and Nd isotopes to characterize the sources of magma and mineralization of both deposits. Sr and εNd data made it possible to divide the samples into three distinct groups. Most samples are slightly differentiated, have OIB (Ocean Island Basalts) isotope characteristics, and show some Nd fractionation. Lead isotope also shows distinct groups with an enrichment trend in radiogenic lead. In both deposits, the sulfides are more radiogenic than the host rocks, but are clearly related to them because all plot on a single trend. A crustal contribution to the deposits is suggested on the basis of lead isotope signatures. The similarity on the Pb isotope signatures suggests the same magmatic fluid source, although at Agua Rica the crustal component is more evident than at Bajo de la Alumbrera, possibly because of the assimilation of Paleozoic country rocks at Agua Rica.

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1. Introduction

Isotope studies of rocks and ore from mineral deposits constitute a valuable tool for investigating the source of magma and mineralizing fluids. Lead isotopes from mineral deposits formed under the flat-slab subduction tectonic regime in the Central Andes are expected to have high radiogenic values and heterogeneous sources, as a result of continental crust contamination during magmatic processes preceding deposit formation (Macfarlane et al., 1990). The use of lead isotopes to characterize the source of rocks in the Andean Cordillera provided several information on crustal composition in this region (Tilton et al., 1981; Sillitoe and Hart, 1984; Kontak et al., 1990; Macfarlane et al., 1990) and Pb, combined with Nd and Sr isotopes are the key on this presented study.

The Central Andes, is an important metalliferous province, including two world-class porphyry Cu deposits, Bajo de la Alumbrera and Agua Rica, in northwestern Argentina (Fig. 1). Bajo de la Alumbrera is a classic porphyry Cu–Au deposit (Caelles et al., 1971; Sillitoe, 1973; Guilbert, 1995; Proffett et al., 1998), while Agua Rica is a breccia-hosted porphyry-epithermal Cu–Mo–Au deposit (Koukharsky and Mirré; Perelló et al., 1998). Both are related to the formation of the Farallón Negro Volcanic Complex (Llambías, 1970, 1972; Sasso, 1997; Sasso and Clark, 1998; Kay and Mpodozis, 2002; Ramos et al., 2002), in the Late Miocene. Bajo de la Alumbrera contains about 402 Mt (million metric tonnes) of ore with average grades of 0.54% Cu and 0.64 g/t Au and annual production of 180,000 tonnes of copper and 18.66 tonnes of gold (Minera Alumbrera, Institucional, December 2014, www.alumbrera.com.ar). Agua Rica is a at present being developed as a mine and the average ore grades are 0.49% Cu, 0.23 g/t Au, 3.5 g/t Ag and 0.031% Mo in an estimated resource of about 910 Mtof ore (Yamana Gold, News Release December 2014, www.yamana.com). Although these deposits are of different types and ages, both are associated with the same igneous events (Caelles et al., 1971; Sasso, 1997; Sasso and Clark, 1998; Halter et al., 2004; Harris et al., 2004, 2008; Von Quadt et al., 2011).

Previous studies have produced preliminary isotope data for the Farallón Negro rocks and region (Sasso, 1997; Sasso and Clark, 1998; Halter et al., 2004; Breitenmoser, 1999; Ulrich, 1999) and these data show that magma mixing has important role in these rocks formation and also that crustal contamination was somewhat relevant. Our new isotope study brings Pb–Pb, Sm–Nd and Sr isotope data to characterize the local isotope composition on rocks and sulfides, in order to

* Corresponding author.
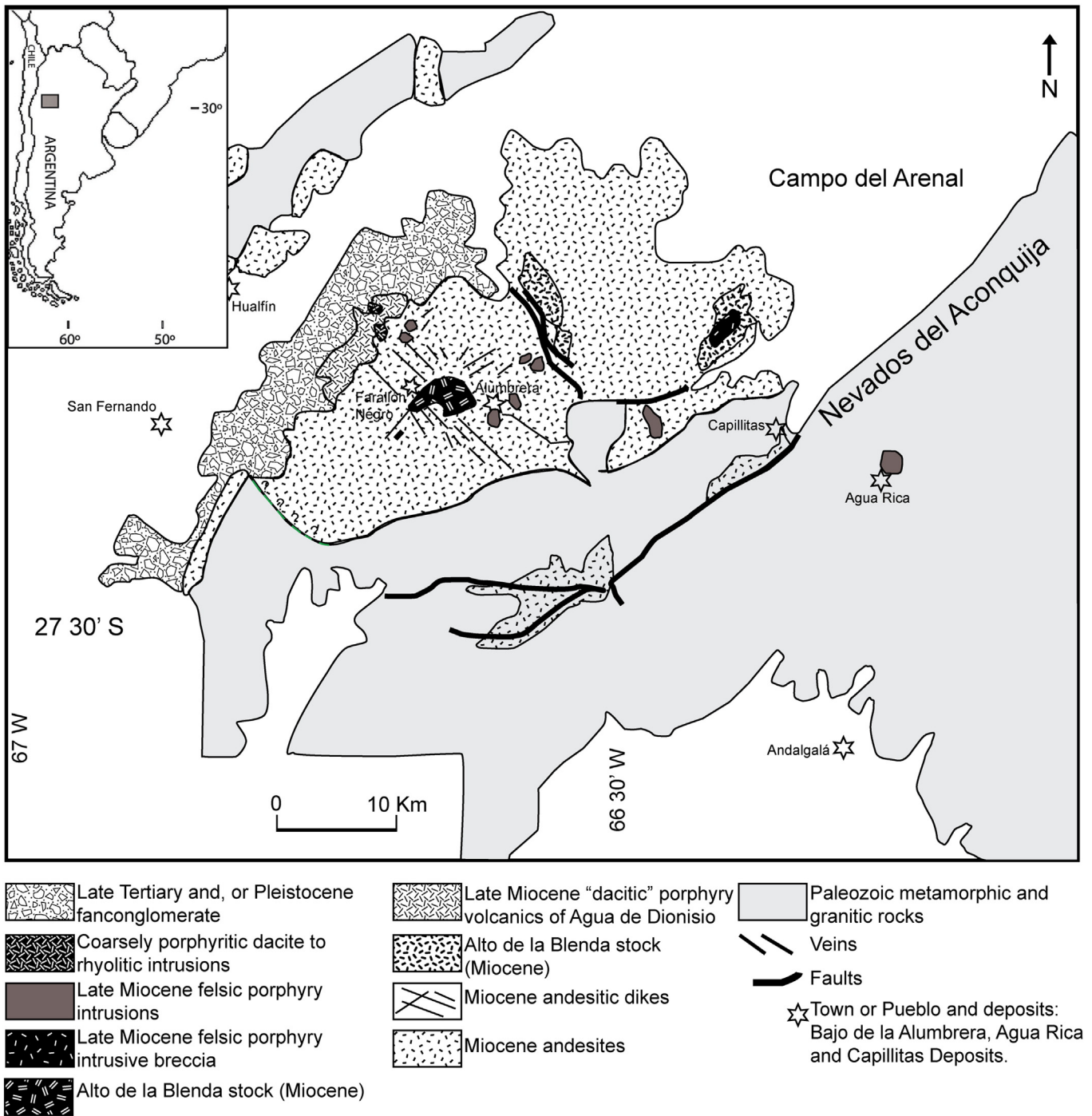 E-mail address: mauriciolborba@gmail.com (M.L. Borba).

Fig. 1. General geological map of the Farallón Negro Volcanic Complex. Modified from Proffett (2003), after Llambías (1970, 1972).

understand the source of the mineralization fluids. Herein we present isotope data from whole-rock samples and pyrites from both deposits and correlate our data with previous publications (Tilton et al., 1981; Macfarlane et al., 1990; Breitenmoser, 1999; Ulrich, 1999) in order to compare with other Andean ore deposits.

2. Geologic Setting

The Bajo de la Alumbrera and Agua Rica deposits are located in the Catamarca Province, Hualfín District, northwestern Argentina at latitudes 27° 10′ S and 27° 40′ S and longitudes 66° 50′ W and 66° 15′ W, respectively. The Sierras Pampeanas (González Bonorino, 1950), are one important geological feature as part of regional geology. These

group of mountains are the highest mountain ridge along the easternmost border of the Andes and genetically related to reverse fault movements during the Tertiary (Ramos, 1999). Basement rocks in the region consist of Paleozoic metamorphic rock sequences intruded by granitic bodies including the Capillitas Batholith of Ordovician age (Aceñolaza and Toselli, 1976). The Capillitas Batholith lies at the eastern limit of the Farallón Negro Volcanic Complex and also contains copper mineralization; itis currently exploited for gem-quality rhodochrosite. The El Morterito Formation, a Miocene continental sedimentary unit, overlies the basement and consists typically of red sandstone (fine- to medium-grained) and siltstone (Turner, 1962). The formation is overlain by the late Miocene Farallón Negro Volcanic Complex, consisting of basaltic-andesite to rhyolite extrusive rocks with dioritic and granodioritic

porphyritic intrusions (Caelles et al., 1971). In the Farallón Negro area, the predominant volcanic rocks are basaltic-andesite and andesite flows and pyroclastic breccias. Stocks and dikes are common and occur in diverse sizes. Numerous porphyry copper and epithermal deposits are recorded in this complex. A regional NE–SW lineament, known as Tucuman Transfer Zone (Urreiztieta et al., 1993), is considered to control the location of the Miocene magmatism. The Complex lies in the transition between the Sierras Pampeanas and the Puna Plateau, and is about 200 km from the Peru-Chile trench (Roy et al., 2006). Volcanic activity so far inland from the trench is consistent with the low subduction angle in this part of the Andean Ridge (Barazangi and Isacks, 1976; Kay et al., 1988; Kay and Abbruzzi, 1996; Kay and Mpodozis, 2002). The magmatic activity ceased by the time of the uplift of the Sierras Pampeanas in the Late Miocene (Sasso and Clark, 1998; Harris et al., 2004).

Geochronologic data for the Farallón Negro Volcanic Complex have been published by (Caelles et al., 1971; Sasso, 1997; Sasso and Clark, 1998; Halter et al., 2004; Harris et al., 2004, 2008; Von Quadt et al., 2011). Harris et al. (2008) compiled the available data and discussed the development of the volcanic complex with particular reference to the Bajo de la Alumbrera deposit. The previous $^{40}Ar/^{39}Ar$ data indicates that the most voluminous magmatism occurred over a period of at least 2.7 M.y between 9.5 and 6.8 Ma (Sasso, 1997; Sasso and Clark, 1998; Halter et al., 2004), whereas volcanic rocks dated by U–Pb zircon method yielded ages from 8.46 ± 0.14 to 6.92 ± 0.07 Ma (Harris et al., 2004). The Agua Rica intrusions and mineralization events are related to the final phase of activity of the volcanic complex, at the same time as low-temperature thermal activity occurred at Bajo de la Alumbrera between 6.3 and 5.0 Ma (Harris et al., 2008 and references therein).

2.1. Bajo de la Alumbrera geology

The Bajo de la Alumbrera deposit lies within the Farallón Negro Complex. The host rocks are high-potassium calc-alkaline andesites and the Cu–Au deposit is centered on a group of dacite porphyry stocks (Guilbert, 1995; Ulrich and Heinrich, 2001; Proffett, 2003; Halter et al., 2004; Harris et al., 2006). Dikes of felsic porphyry radiate outwards from the stocks. Previous studies have subdivided these intrusions into three phases (P1 to P3) according to field and chronological relations (Proffett, 2003; Harris et al., 2004). The term P1 is used in the previous publications about Bajo de la Alumbrera (Guilbert, 1995) and is

still used as a geographic location in the mine, but it has been abandoned, once this term was considered an invalid rock classification, because no porphyry is older than the P2 porphyry. For this reason, we considered only P2 and P3 for our isotope studies.

The porphyry P2 is a dacite with evenly distributed potassic alteration, and is considered the primary mineralized porphyry and it is overprinted by the main mineralization event (Proffett, 2003). The latest intrusion event is represented by the P3 porphyry, which is a dacite with andesite fragments from the wall rocks, P3 also presents mineralized quartz veins (Proffett, 2003; Harris et al., 2004).

Step heating Ar–Ar and zircon U–Pb (LA-ICP-MS) geochronology (Halter et al., 2004; Harris et al., 2004, 2008) and zircon U–Pb ID-TIMS geochronology (Von Quadt et al., 2011) provide estimates of ages and duration of porphyry emplacement and mineralization at Bajo de la Alumbrera. These studies yielded ages of 7.216 ± 0.018 Ma for P2 and 7.126 ± 0.016 Ma for P3 (Von Quadt et al., 2011), indicating an interval between P2 and P3 intrusions of about 0.090 Ma, a little less time than presented by Harris et al. (2004, 2008) whose data indicate an interval of at least 1 Ma. This age bracket, obtained by U–Pb zircon ages with these different techniques (ID-TIMS and LA-ICP-MS)was interpreted as the record of the magma reservoir from which porphyry intrusions and fluids were extracted.

2.2. Agua Rica geology

The Agua Rica deposit is related to the final phase of activity in the Farallón Negro Volcanic Complex (Sasso, 1997; Sasso and Clark, 1998) and has a more complex succession of events than Bajo de la Alumbrera. High-sulfidation alteration overprinted the porphyry mineralization (Koukharsky and Mirré, 1976; Perelló et al., 1998; Landtwing et al., 2002). The host rocks are Precambrian gneiss and amphibolite, and Ordovician granites. These Precambrian and Paleozoic rocks were intruded by diorite stocks, and associated andesite porphyries and breccias (Koukharsky and Mirré, 1976). The diorite and andesite rocks are barren to weakly mineralized breccias (Perelló et al., 1998; Landtwing et al., 2002) and breccia-fragment-rich, where metasandstone are most of the clasts. Four main magmatic-hydrothermal stages are suggested for this deposit (Perelló et al., 1998; Landtwing et al., 2002): 1. The early emplacement of the Melcho intrusions was followed by potassic and propylitic alteration, presenting only a weak copper mineralization

Table 1
Lead isotopes data of whole-rock (WR) and sulfides (S). Samples from Agua Rica (AR), Bajo de la Alumbrera (BA) and Capillitas deposits.

Sample	Type	Lithology	Deposit	$^{206}Pb/^{204}Pb$	Error (%)	$^{207}Pb/^{204}Pb$	Error (%)	$^{208}Pb/^{204}Pb$	Error (%)
PAR-BA-010	WR	Diorite	AR	18.596	0.016	15.600	0.017	38.440	0.018
PAR-BA-010	S	Diorite	AR	18.675	0.014	15.640	0.016	38.677	0.018
PAR-BA-018	WR	Breccia	AR	18.816	0.008	15.623	0.009	38.640	0.008
PAR-BA-018	S	Breccia	AR	18.797	0.003	15.644	0.004	38.773	0.004
PAR-BA-020	WR	Breccia	AR	18.750	0.012	15.615	0.013	38.642	0.013
PAR-BA-020	S	Breccia	AR	18.817	0.014	15.655	0.017	38.819	0.021
PAR-BA-024	WR	Breccia	AR	18.811	0.013	15.634	0.013	38.747	0.012
PAR-BA-028	WR	Breccia	AR	18.864	0.013	15.693	0.014	38.954	0.016
PAR-BA-028	S	Breccia	AR	18.840	0.018	15.669	0.023	38.886	0.021
PAR-BA-031	WR	Andesite	BA	18.670	0.014	15.619	0.015	38.656	0.014
PAR-BA-032	WR	Dacite	BA	18.660	0.011	15.618	0.011	38.659	0.011
PAR-BA-033	WR	Andesite	BA	18.648	0.012	15.614	0.011	38.650	0.012
PAR-BA-033	S	Andesite	BA	18.710	0.005	15.634	0.005	38.762	0.006
PAR-BA-034	WR	Andesite	BA	18.631	0.009	15.612	0.010	38.630	0.009
PAR-BA-035	WR	Andesite	BA	18.655	0.014	15.622	0.014	38.674	0.015
PAR-BA-035	S	Andesite	BA	18.700	0.004	15.641	0.005	38.765	0.006
PAR-BA-036	WR	Dacite	BA	18.636	0.009	15.610	0.009	38.625	0.009
PAR-BA-037	WR	Dacite	BA	18.569	0.017	15.612	0.016	38.564	0.015
PAR-BA-038	WR	Dacite	BA	18.602	0.022	15.607	0.020	38.584	0.020
PAR-BA-039	WR	Dacite	BA	18.649	0.010	15.615	0.010	38.642	0.010
PAR-BA-040	WR	Andesite	BA	18.659	0.039	15.615	0.038	38.655	0.039
PAR-BA-041	WR	Andesite	BA	18.640	0.014	15.615	0.015	38.630	0.015
PAR-BA-042	WR	Andesite	BA	18.616	0.026	15.608	0.025	38.600	0.026
CAP-1 (Tilton et al., 1981)	S	Granite	Capillitas	18.825		15.664		38.884	
CAP-2 (Tilton et al., 1981)	S	Granite	Capillitas	18.835		15.668		38.920	

phase. This early porphyry phase was dated at 8.56 ± 0.48 Ma by the Ar–Ar method on hornblende (Sasso, 1997). 2. The emplacement of the Trampeadero and Seca Norte feldspar porphyries dated at 5.10 ± 0.05 Ma by K–Ar method on biotite (Perelló et al., 1998). This corresponds to the main mineralization phase, in which the porphyry intrusions developed potassic alteration and quartz stockwork veinlets rich in chalcopyrite, bornite and molybdenite. 3. Formation of igneous and hydrothermal breccias, with intense hydrothermal circulation in the zones of highest permeability, accompanied by advanced argillic and phyllic alteration at 4.88 ± 0.08 Ma (K–Ar age on alunite; Perelló et al., 1998). This phase appears to have brought about the sulfidation of stage 2 sulfides and the addition of arsenic, leading to the formation of a new assemblage consisting of covellite, pyrite, native sulfur and enargite. Pb, Zn and local high grade gold are related to this stage (Franchini et al., 2011). 4. Post-mineralization uplift and erosion at 3.94 ± 0.05 Ma (K–Ar ages on alunite;

Perelló et al., 1998) leading to supergene enrichment of copper as covellite (Franchini et al., 2011). (Perelló et al., 1998; Landtwing et al., 2002).

3. Analytical methods and results

Seventeen samples (whole-rock and sulfides) from drill cores from Bajo de la Alumbera and Agua Rica were analyzed. Petrographic descriptions were developed in order to identify mineral assemblages and to define petrogenetic relationships. Isotope data were obtained on whole rock samples and in sulfide minerals such as pyrite, chalcopyrite and covellite. Whole-rock powders were spiked with a ^{149}Sm–^{150}Nd tracer and dissolved in PFTE beakers using an HF-HNO$_3$ mixture and 6 M HCl. Sr and REE were separated on columns, with cationic AG-50 W-X8 resin (200–400 mesh), followed by separation Sm and Nd on anionic politeflon HDEHP LN-B50-A resin (100–200 μm) according to
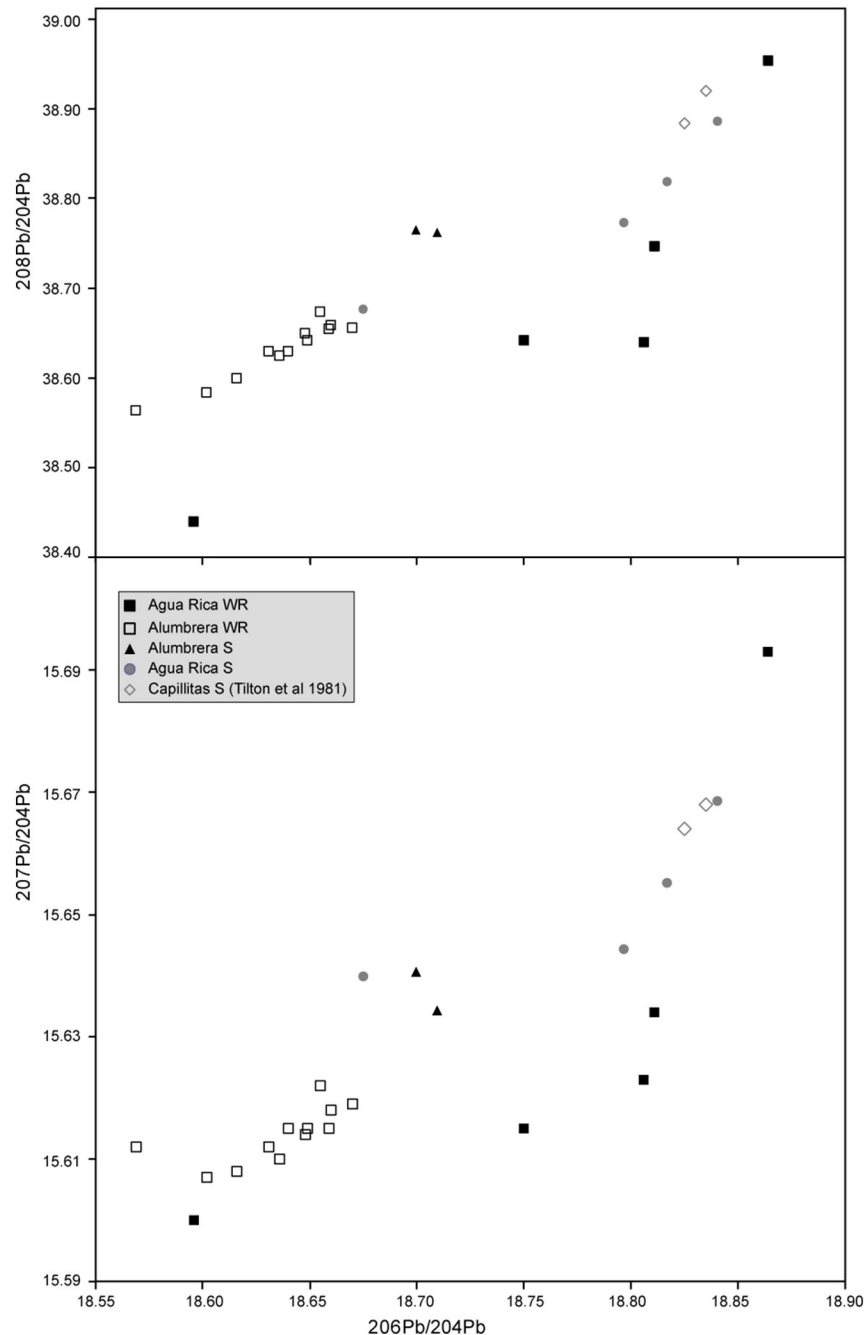

Fig. 2. Lead isotope diagrams comparing samples from Bajo de la Alumbrera, Agua Rica and Capillitas deposits.

Table 2
Sr and Sm–Nd isotope data from samples of the Agua Rica (AR) and Bajo de la Alumbrera (BA) deposits.

Sample	Lithology	Deposit	$^{87}Sr/^{86}Sr$*	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Sm$	$^{143}Nd/^{144}Nd$	εNd (0)**	εNd (t)***	TDM Ma****	fSm/Nd
PAR-BA-010	Diorite	AR	0.704105 ± 11	5.00	22.64	0.133	0.512883 ± 29	4.78	4.86	337	− 0.32
PAR-BA-018	Breccia	AR	0.712935 ± 5	–	–	–	–	–	–	–	–
PAR-BA-020	Breccia	AR	0.707190 ± 9	–	–	–	–	–	–	–	–
PAR-BA-024	Breccia	AR	0.710548 ± 9	6.72	34.1	0.119	0.512683 ± 9	0.87	0.97	596	− 0.40
PAR-BA-028	Breccia	AR	0.711293 ± 5	7.34	44.83	0.099	0.512610 ± 14	− 0.55	− 0.42	589	− 0,50
PAR-BA-031	Andesite	BA	0.706402 ± 10	–	–	–	–	–	–	–	–
PAR-BA-032	Dacite	BA	0.706485 ± 4	2.76	13.16	0.127	0.512634 ± 47	− 0.08	0.01	730	− 0.35
PAR-BA-033	Andesite	BA	0.707561 ± 12	5.26	26.14	0.122	0.512590 ± 34	− 0.94	− 0.84	760	− 0.38
PAR-BA-034	Andesite	BA	0.708190 ± 6	3.90	20.52	0.115	0.512578 ± 34	− 1.16	− 1.06	727	− 0.42
PAR-BA-035	Andesite	BA	0.706314 ± 12	4.17	20.95	0.120	0.512839 ± 41	3.93	4.03	360	− 0.39
PAR-BA-036	Dacite	BA	0.706457 ± 11	3.79	19.06	0.120	0.511962 ± 15	− 13.20	− 13.1	1754	− 0.39
PAR-BA-037	Dacite	BA	0.706247 ± 12	–	–	–	–	–	–	–	–
PAR-BA-038	Dacite	BA	0.706223 ± 7	4.51	21.32	0.128	0.512696 ± 28	1.14	1.22	632	− 0.35
PAR-BA-039	Dacite	BA	0.706298 ± 19	5.13	25.1	0.124	0.512674 ± 43	0.70	0.8	639	− 0.37
PAR-BA-040	Andesite	BA	0.705196 ± 8	4.23	20.12	0.127	0.512895 ± 67	5.01	5.09	295	− 0.35
PAR-BA-041	Andesite	BA	0.707330 ± 10	4.08	18.89	0.131	0.512958 ± 30	6.23	6.32	199	− 0.33
PAR-BA-042	Andesite	BA	0.706058 ± 10	4.87	22.46	0.131	0.512705 ± 30	1.30	1.38	641	− 0.33

Average of ca. 100 isotopic values, 1,0 V of ionic intensity for ^{86}Sr and multicollector with ^{86}Sr in the axial collector, static mode.
Sr ratios normalized to $^{86}Sr/^{88}Sr = 0,1194$, fited to *bias with base on the SrCO₃ NBS-987, usin $^{87}Sr/^{86}Sr = 0.71025$* and correction in order of the presence of *spike*. NBS values during analyses were 0.710252 +/− 0.00002 (Sd abs).

  * Average of ca. 100 isotopic values, 1,0 V of ionic intensity for ^{86}Sr and multicollector with ^{86}Sr in the axial collector, static mode; Sr ratios normalized to $^{86}Sr/^{88}Sr = 0,1194$, fited to *bias with base on the SrCO₃ NBS-987, usin $^{87}Sr/^{86}Sr = 0.71025$* and correction in order of the presence of *spike*. NBS values during analyses were O.710252 +/− 0.00002 (Sd abs).
  ** Calculated assuming $^{143}Nd/^{144}Nd$ today = 0.512638 with data normalized to $^{146}Nd/^{144}Nd = 0.72190$. Epsilon Nd(0) = (($^{143}Nd/^{144}Nd$[sample, now]/0.512638) − I) × 10⁴.
  *** eNd(t) = (($^{143}Nd/^{144}Nd$[sample,590 Ma]/$^{143}Nd/^{144}Nd$[CHUR. 600 Ma])− II) × s10⁴.
  **** Calculated following model of DePaolo (1981).

the method of Patchett and Ruiz (1987). Each separated sample was dried and then loaded with 0.25 N H_3PO_4 on to an appropriate filament (single Ta for Sr and Sm and triple Ta–Re–Ta for Nd). Isotopic ratios were measured in static mode with a VG Sector 54 multi-collector mass spectrometer at the Laboratório de Geologia Isotópica of Universidade Federal do Rio Grande do Sul, UFRGS, in Brazil. We normally collected 100–105 ratios with a 1-V ^{88}Sr beam and a 0.5 to 1-V ^{144}Nd beam. Sr and Nd ratios were normalized to $^{87}Sr/^{86}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$, respectively. All analyses were adjusted for variations caused by instrumental bias due to periodic adjustment of collector positions as monitored by measurements of our internal standards. Measurements for the NBS-987 standard were $^{87}Sr/^{86}Sr = 0.710270 ± 0.000019$ (NBS 987 value for $^{87}Sr/^{86}Sr = 0.71025$). Measurements for the JNdi-1 standard were $^{143}Nd/^{144}Nd = 0.512110 ± 0.00007$ (literature value for $^{143}Nd/^{144}Nd = 0.512115 +/− 0.00007$; Tanaka et al., 2000). The average blanks were <100 pg for Sr and Sm and <500 pg for Nd. Corrections for blanks were negligible for Sr and Nd and were generally insignificant for Rb/Sr and Sm/Nd ratios. Neodymium crustal-residence ages (T_{DM}) were calculated following the depleted-mantle model of DePaolo (1981). The εNd(t) values were calculated using U–Pb zircon ages as references where available or using estimated ages based on regional geology and coherent results from nearby samples (Caelles et al., 1971; Perelló et al., 1998; Halter et al., 2004; Sasso and Clark, 1998; Harris et al., 2004, 2008; Von Quadt et al., 2011).

Lead isotope analyses were carried out on seventeen whole rock samples, twelve from Alumbrera and five for Agua Rica. Six sulfide samples were analyzed, two from Alumbrera and four from Agua Rica. For the whole rock (WR) Pb isotopic measurements, an aliquot of 1 ml from the dissolved WR samples was used. The sulfides were dissolved in PFTE beakers using a mixture of 6 M HCL and 7 M HNO_3. Pb was extracted by ion exchange in microcolumns (2 ml) using AG-1 X8, 200–400 mesh, anion resin and 0.6 M HBr and 6 M HCl acids. The purified Pb samples were dried and loaded on Re filaments with silica gel and H_3PO_4. The Pb isotope composition was measured in static mode with a VG Sector 54 multi-collector mass spectrometer at the UFRGS (WR) and at the Universidade de São Paulo, USP, (sulfides) laboratories; 50 ratios of Pb isotopes were collected, and the Pb ratios were corrected for a fractionation factor of 0.06% amu based on successive determinations of the NBS 981 Common Pb standard. Total Pb blanks for WR and sulfides were <200 picograms and <100 picograms, respectively.

3.1. Lead isotopes

The Pb isotope ratios are presented in the Table 1. The $^{206}Pb/^{204}Pb$ ratios range from 18.569 to 18.864, $^{206}Pb/^{204}Pb$ from 15.600 to 15,693, and $^{208}Pb/^{204}Pb$ from 38.440 to 38.954. The least radiogenic ratios were determined on the diorite (PAR-BA-010) and the most radiogenic sample is an igneous breccia, both from the Agua Rica deposit; the
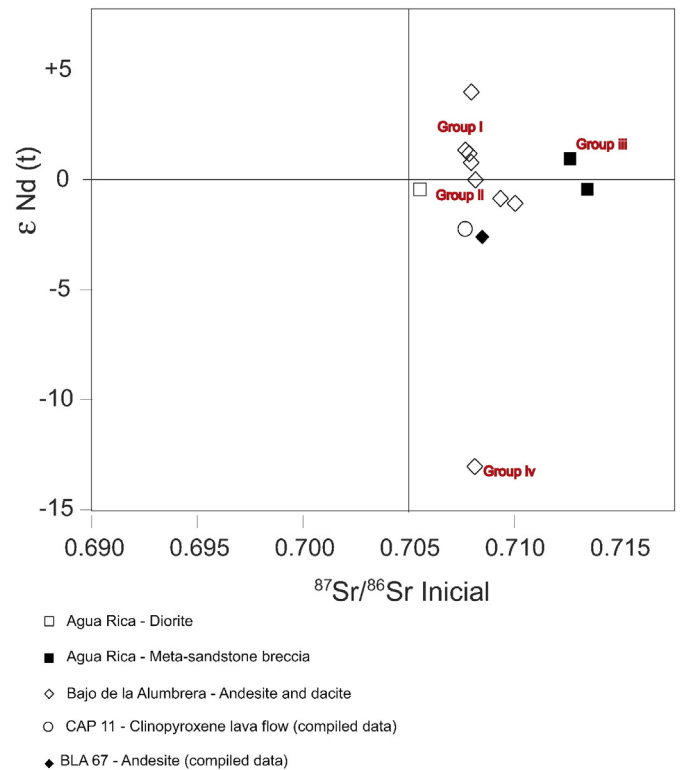

Fig. 3. Sr and epsilon Nd data from Agua Rica and Bajo de la Alumbrera deposits from this study and compiled data from Bajo de la Alumbrera (Ulrich, 1999) and Capillitas (Breitenmoser, 1999).

sulfides from this deposit show intermediate ratios. Whole rock samples from the Bajo de la Alumbrera show less radiogenic ratios compared to the breccias from Agua Rica, and the most radiogenic ratios from Bajo de la Alumbrera deposit were observed on the sulfide samples (Fig. 2). It is important to stress that the Pb isotope data from the Agua Rica diorite show non-radiogenic ratios like the ones from the whole rock samples of Bajo de la Alumbrera, which could suggest similar magma source. The analyzed sulfides present similar ratios for both Bajo de la Alumbrera and Agua Rica, although Agua Rica and Capillitas (compiled data from Tilton et al., 1981) have more radiogenic Pb ratios.

3.2. Samarium, neodymium and strontium isotopes

The $^{87}Sr/^{86}Sr$ ratios of igneous rocks from both deposits range between 0.7041 and 0.7081 (Table 2). Since both deposits are younger than 10 M.y. we consider the $^{87}Sr/^{86}S$ ratios to be the same as the initial ratios; no substantial radioactive decay would have occurred in this short period of time. The meta-sandstone-fragment-rich breccias from Agua Rica present ratios between 0.7071 and 0.7129, but these samples have strong hydrothermal alteration, which because the hydrothermal process could cause loss of strontium and change in the $^{87}Sr/^{86}Sr$ ratios. Compiled data from Breitenmoser (1999) and Ulrich (1999) indicate isotope ratios as follows: $^{87}Sr/^{86}Sr$ 0.7060 and $^{143}Nd/^{144}Nd$ 0.512521 for the Capillitas area (sample CAP 11, clinopyroxene lava flow sample) and 0.7067 and $^{143}Nd/^{144}Nd$ 0.512500 for Bajo de la Alumbrera (sample BLA 67, andesite) (Figs. 3 and 6).

Three groups can be recognized in the diagram εNd(t) versus $^{87}S/^{86}Sr_{initial}$ (Fig. 3). The first group is composed of those samples with lower $^{87}Sr/^{86}Sr$ ratios (0.7041–0.7051) and higher/positive εNd(t) values (+4.03 to +6.32). They comprise the Agua Rica Diorite and Bajo de la Alumbrera andesite and dacite. The second group is made up of the Bajo de la Alumbrera dacites and andesites of the potassic zone that display εNd (t) values that are slightly positive to negative (+1.22 to −1.0), and give T_{DM} model ages between 632 and 760 Ma. This group has $^{87}Sr/^{86}Sr$ values of 0.7052 to 0.7076 and includes the samples of Breitenmoser, 1999 and Ulrich, 1999. These data show an isotope signature with fractionation of the Sm–Nd isotopes. Breccia samples from Agua Rica deposit belong to a third group and have T_{DM} model ages close to 600 Ma and also higher radiogenic Sr ratios ($^{87}Sr/^{86}Sr_{initial} = 0.7105$ to 0.7112).
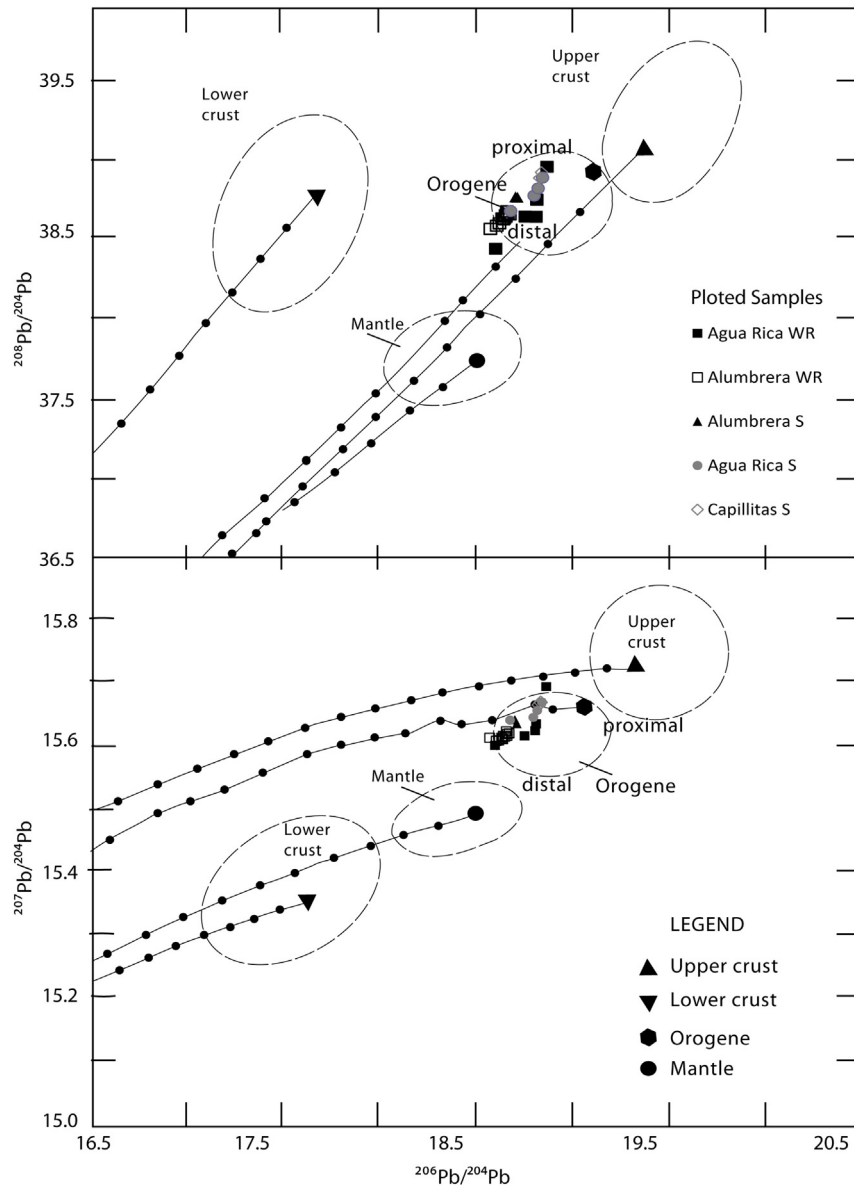

Fig. 4. Lead isotope diagram comparing samples from the studied ore deposits with lead isotope evolution curves (version IV) for designated model reservoirs together with the fields containing their probable average modern composition. Dots along each curve indicate time in 0.1 Ga increments (Zartman and Haines, 1988)

4. Discussion

Different intrusive lithologies occur at the Bajo de la Alumbrera and Agua Rica deposits. The main intrusions at Bajo de la Alumbrera include andesite with high-K calc-alkaline composition (Guilbert, 1995; Ulrich and Heinrich, 2001; Proffett, 2003), whereas at Agua Rica, stocks within the deposit consist of diorite and andesite porphyry and breccia of several types (Koukharsky and Mirré, 1976; Perelló et al., 1998; Landtwing et al., 2002). The Agua Rica deposit presents an overprinted epithermal alteration event (Franchini et al., 2011), which could have contributed to an increase in the ore grades. Significant presence of covellite at the Agua Rica deposit suggests a sulfur-rich system or a high-sulfidation state (Barton, 1970) in an epithermal environment with post-mineralization intrusions. Besides the differences between both Bajo de la Alumbrera and Agua Rica deposits, some important similarities are shown by the isotope data.

The lead isotopes of diorite from the Água Rica deposit and dacites and andesites from the Bajo de la Alumbrera deposit show less radiogenic $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios and contrast with the data of the mineralized breccias from the Agua Rica deposit which are more radiogenic, and similar to sulfide samples from the Eopaleozoic Capillitas Granite (Tilton et al. (1981) (Fig. 2)). This suggests that some crustal Pb could have been incorporated into the hydrothermal fluid at Agua Rica. The mineralized breccias and their sulfide inclusions present similar behavior for lead isotopes and show a large contribution of radiogenic Pb, probably because of the meta-sandstone clasts present in the breccia. Part of the lead could therefore have been leached into hydrothermal fluid circulating in older crust, such as represented by Capillitas Granite, and was incorporated into mineralization during the hydrothermal process. The radiogenic lead is consistent with Province IIIa lead from Central Andes (Macfarlane et al., 1990), where lead is more radiogenic probably because magma in that region has assimilated of continental crust. The more radiogenic lead of the sulfides from Agua Rica and Capillitas Mine could indicate these mixed sources of fluids and contamination. In the plumbotectonic evolution diagram (Fig. 4, Zartman and Haines (1988)), the samples fall in the orogenic field, spanning the range from distal to proximal. In the diagram proposed by McDaniel et al. (1997) (Fig. 5), the analyzed data fall in two different groups, Nazca Plate sediments and Andean igneous rocks. Most of the igneous rocks and breccia samples belong to the Nazca Plate Sediments field and most of the sulfide samples belong to the Andean Igneous Rocks field. Based on the present results we suggest a mixing sources, which include the data presented by Macfarlane et al. (1990) and Halter et al. (2004).

The Sr and Nd isotopes can provide clues on the source of magma as suggested by our data compared with those from Halter et al. (2004). It is possible to suggest crustal material component and magma mixing in this magmatic system. The analyzed samples (Fig. 6) could be separated in four groups: (i) one shows a typical pattern of juvenile rocks incorporated during the Andean orogenesis, as those samples of the Bajo de la Alumbrera and one diorite of the Agua Rica, with low $^{87}Sr/^{86}Sr$ initial ratios and high positive εNd (t = 10 Ma) values (+4.03 to +6.32). They could be the source of Pb of magmatic rocks described for Agua Rica and Bajo de la Alumbrera. (ii) Another group of samples are dacite and andesite from Bajo de la Alumbrera that have slightly positive to negative εNd (t) values, T_DM model ages of between 632 and 760 Ma, $^{87}Sr/^{86}Sr$ initial values of 0.7052 to 0.7076, indicating some crustal contamination. The process of crustal contamination is not homogeneous, like suggested by the range from εNd (t) positive (+6.32) to negative values (−1.06) observed in our samples. (iii) A third group comprises breccias of the Agua Rica deposit with negative εNd (t) values (0.97 to −0.47) and radiogenic Sr samples ($^{87}Sr/^{86}Sr_{initial}$ = 0.7105 to 0.7129) that have a distinct isotope signature that also suggests a crustal component (Fig. 3). (iv) One dacite sample presents εNd (t) value of −13.51 and Nd model age of 1754 Ma, that can be interpreted as contribution of old crustal component (Paleoproterozoic). When plotted in the Pb–

Pb isotope plumbotectonic diagram (Fig. 4), the samples are close, or in the Orogen field, but with a trend to the mantle field, except one from Bajo de la Alumbrera that falls close to the crustal rocks field.

Sulfide samples in both deposits are more radiogenic than whole rock samples. This could be interpreted as caused by enrichment during mineralization processes that resulted from interaction with wall rocks and fluid circulation. Samples with higher levels of inherited clastic material (from Paleozoic wall-rocks) present an isotopic pattern that is enriched in radiogenic Pb, more radiogenic Sr and slightly negative εNd values.

5. Conclusions

The Farralón Negro volcanic Complex lies within a flat slab setting where two types of copper-gold (± molybdenum) porphyry deposits are exposed, the Bajo de la Alumbrera, formed around a complex of dacite porphyry stocks, and more complex Água Rica deposit that contains high-sulfidation alteration overprinting the porphyry mineralization. The lead isotopic signature of igneous rocks of both deposits and the breccias of the Agua Rica deposit are clearly distinct, suggesting that the igneous rocks have a similar Pb source. However, the sulfides of Bajo de la Alumbera are somewhat more radiogenic when compared with the Miocene igneous rocks, indicating that some crustal Paleoproterozoic Pb could have been incorporated during the mineralization process. The sulfides, hydrothermal breccias and breccia-s containing meta-sandstone fragments show Pb isotope signatures similar and more radiogenic than Cenozoic igneous rocks of both deposits. They are therefore indicative of interaction between the magmatic fluid and the wall rocks represented by the Eopaleozoic basement rocks in the Agua Rica deposit, as suggested by the Pb isotope ratios obtained by the sulfides from the Eopaleozoic Capillitas Granite. Sr- and Nd isotopes from Agua Rica diorite and volcanic rocks of Bajo de la Alumbrera show typical pattern of juvenile rocks incorporated during the Andean orogenesis (low $^{87}Sr/^{86}Sr$ initial ratios and high positive εNd values) towards to samples with low degree of crustal contamination with slightly positive to negative εNd (t) values and $^{87}Sr/^{86}Sr$ ratios of 0.7052 to 0.7076. The meta-sandstone breccias show higher initial $^{87}Sr/^{86}Sr$ ratios and slightly positive and negative εNd values suggesting also an Eopaleozoic crustal incorporation in the mineralizing fluids of the hydrothermal Agua Rica deposit. Although more isotopic studies are needed (e.g. Re-Os, U–Pb dating at Agua Rica), our data support the genetic relation between Bajo de la Alumbrera and Agua Rica deposits, that they are distinguished mainly by the mineralization process
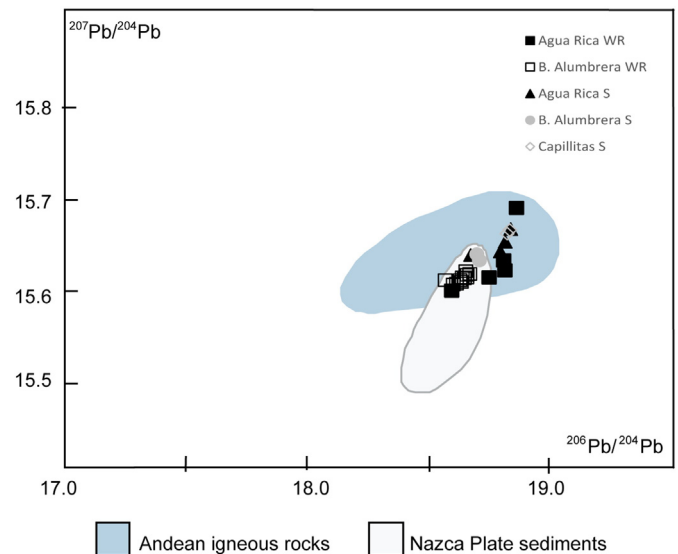

Fig. 5. Lead isotope diagram comparing samples from the studied ore deposits and Pb signatures modified from McDaniel et al., 1997.
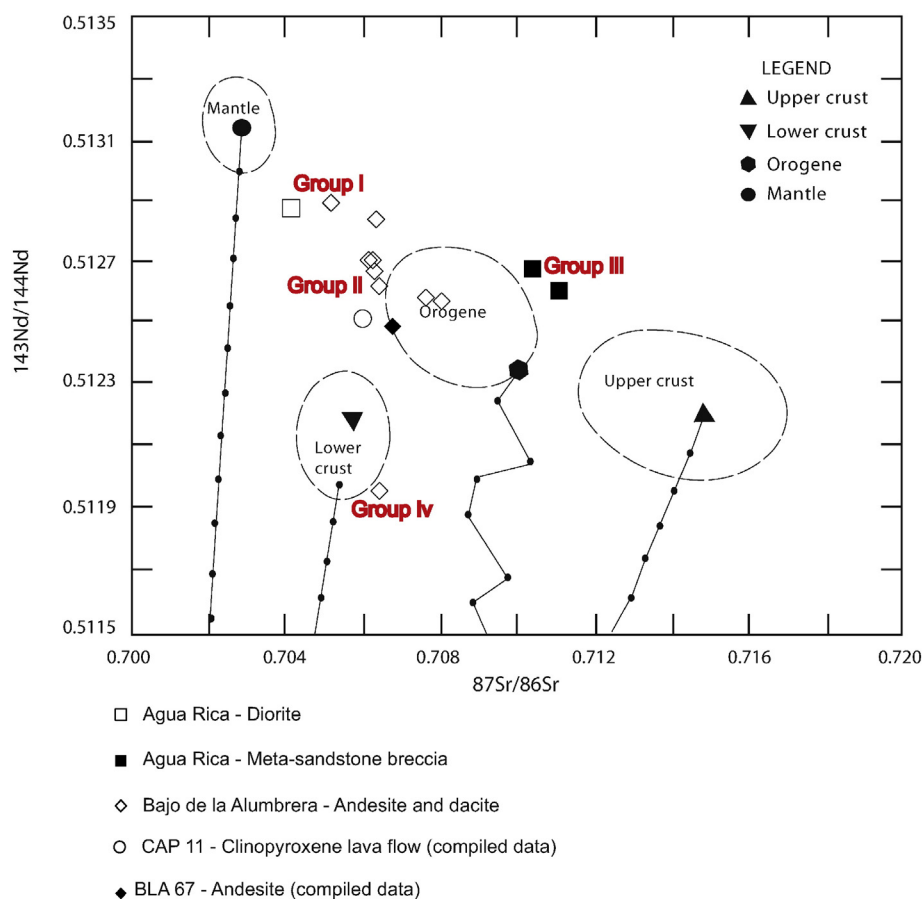
Fig. 6. Strontium-neodymium diagram comparing data from this study with strontiumneodymium isotope evolution curves (version IV) for designated model reservoirs together with the fields containing their probable average modern composition. Dots along each curve indicate time in 0.1 Ga increments (Zartman and Haines, 1988).

and different degree of crustal component in the mineralization. This statement is also supported by previous studies done in these ore deposits (Tilton et al., 1981; Macfarlane et al., 1990; Halter et al., 2004; Harris et al., 2008).

Conflict of interest

Anthony Harris, University of Tazmania, email: anthony.harris@ newcrest.com.au

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