



THE RODEO BORDALESA TONALITE, SAN RAFAEL BLOCK (ARGENTINA): GEOCHEMICAL AND ISOTOPIC AGE CONSTRAINTS

CINGOLANI, C.A.¹, BASEI, M.A.S.², LLAMBÍAS, E.J.¹, VARELA, R.¹, CHEMALE JR., F.³,
SIGA JR., O.² AND ABRE, P.¹⁻⁴

¹Universidad Nacional de La Plata and Centro de Investigaciones Geológicas, Calle 1 N° 644, 1900 La Plata, Argentina. (ccingola@cig.museo.unlp.edu.ar)

²Universidade de Sao Paulo, Centro de Pesquisas Geocronológicas (CPGeo), Sao Paulo, Brasil (baseimas@spider.usp.br)

³Universidad Federal do Rio Grande do Sul, Laboratorio de Geología Isotópica, Porto Alegre, Brasil. (farid.chemale@ufrgs.br)

⁴Department of Geology, RAU University, Auckland Park 2006, Johannesburg, South Africa (paulinabre@yahoo.com.ar)

INTRODUCTION

The San Rafael Block (SRB) lies in west-central Mendoza province, Argentina (35°S-68°30'W), and has SSE-NNW structural Cenozoic trend in the pre-Andean region. To the North and South the Cuyo and Neuquen sedimentary basins bound it, respectively. To the East the SRB passes into the Pampean plains vanishing under the modern basaltic back arc volcanism and sedimentary cover; the boundary to the West is defined by the Andean foothill (Fig. 1a). Paleontological and geological evidences allow interpreting the SRB as a southern extension of the Precordillera Terrane (Keller, 1999 and therein references). Diverse igneous-metamorphic and sedimentary units of Precambrian-Middle Paleozoic age are present and are known as 'pre-Carboniferous units' (Fig.1b) due to their clear differentiation below a Carboniferous regional unconformity (Dessanti, 1956). One of these units is the metasedimentary La Horqueta Formation, which is distributed in a narrow belt from Seco de las Peñas creek to the North until El Nihuil town to the South. At the Rodeo Bordalesa Dessanti (1956) mapped two small intrusives in the La Horqueta Formation composed by tonalitic rocks, 'lamprophyre' and aplite dykes.

We present here, as a part of a research project on 'pre-Carboniferous units' from SRB, new geochemical and isotopic data from Rodeo Bordalesa intrusive rocks that contribute to characterize and constrain the emplacement of the tonalitic magmatism. Hence, these dates contribute to the knowledge of the correlation of the Late Famatinian magmatism in western Argentina. The sample location is shown in Fig. 1b.

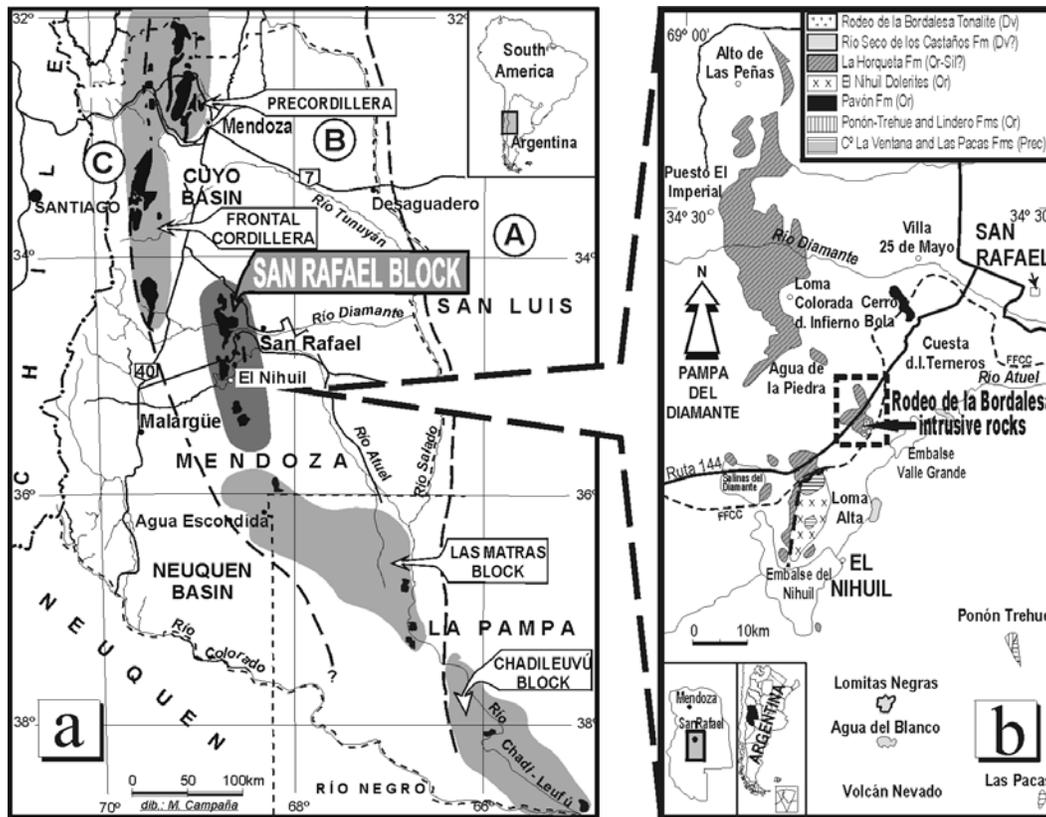


Figure 1 a: Regional location of the San Rafael Block. Pre-Carboniferous units are in black. A: Famatinian belt. B: Precordillera or Cuyania composite Terrane. C: Chilenia Terrane. B and C: Occidentalia Terrane **1b:** Location of the Rodeo Bordalesa study region.

GEOLOGICAL BACKGROUND

The Rodeo Bordalesa tonalitic bodies are clearly intrusive in the La Horqueta Formation (Dessanti, 1956 and González Díaz, 1981). Two main intrusive rock outcrops are present, dark grey porphyritic dykes characterize one and the other, near the old railroad, as a grey tonalitic body with abundant mafic enclaves (less than 30 cm) and thin late magmatic aplite veins. The La Horqueta Formation is a folded, cleaved and faulted meta-feldspathic sandstones, wackes and shales sequence. The main structural pattern is characterized by the NE vergence of the axial plane of folds. In addition to the *Nereites*-like trace fossils (Poiré, D.G., personal communication) Rubinstein (1997) described palynomorphs and acritarchs that suggest Silurian. Previous K-Ar geochronological data on the intrusive rocks exposed at Rodeo Bordalesa yielded biotite K-Ar ages of 475 ± 17 Ma and 452 ± 8 Ma (González, 1971; González Díaz, 1981), which are in disagreement with the intrusive character into the Silurian age country rocks.

PETROGRAPHY AND GEOCHEMISTRY ASPECTS

The Rodeo Bordalesa tonalite consists of two bodies with similar composition but different textures. The largest one is close to the old railroad and intrudes the feldspathic sandstones of the La Horqueta Formation. The contact aureole is characterized by recrystallized biotite and minor muscovite. The tonalite have medium grained equigranular texture composed of zoned plagioclase (average An_{40}), green amphibole, sometimes with a core of clinopyroxene, biotite and interstitial quartz. Zircon and apatite are present as accessory minerals. The second body consists

of dykes and small irregular bodies of porphyritic tonalite intruding La Horqueta Formation and crop out northward of the main body. Phenocrysts consist of zoned plagioclase (average An₅₀), scarce clinopyroxene surrounded by amphibole, green amphibole and biotite. The groundmass is plagioclase, scarce biotite and interstitial quartz.

Five samples were analyzed for major, trace and rare earth elements (ACTLABS, Canada). They plot in the TAS diagram adapted to plutonic rocks by Bellieni et al. (1995) into the field of tonalites (Fig. 2c). They are characterized by high to medium potassium (after Peccerillo and Taylor, 1976) and metaluminous, with an A/CNK index ranging from 0.90 to 0.95. Modal composition indicates an I-type signature. In the AFM diagram (Irvine and Baragar, 1971) all the samples show a calc-alkaline trend. The extended multielement diagram normalized to primitive mantle (Taylor and McLennan, 1985) show depression of Nb and Ti and low enrichment of HFSE, typical of calc-alkaline series (Fig. 2a). The REE patterns show a slight LREE enrichment and flat HREE behavior, also characteristic of calc-alkaline rocks (Fig. 2b). In the granite discrimination diagram of Pearce et al. (1984) the samples confirm the magmatic arc signature (Fig. 2d) and in the Whalen et al. (1987) diagram plot into the I-type field (Fig. 2e).

According to the geological evolution of the SRB, a late orogenic character cannot be discarded because the Rodeo Bordalesa tonalite intruded previously folded Silurian sedimentary rocks. In agreement with this, the analyzed samples plot into the late and post-collision field in the discrimination diagram of Harris et al. (1986) (Fig.2f). All these characteristics allow us to differentiate the Rodeo Bordalesa tonalite from the tholeiitic basic rocks (mainly gabbros and porphyritic dolerites) exposed at the El Nihuil area (Cingolani et al., 2000).

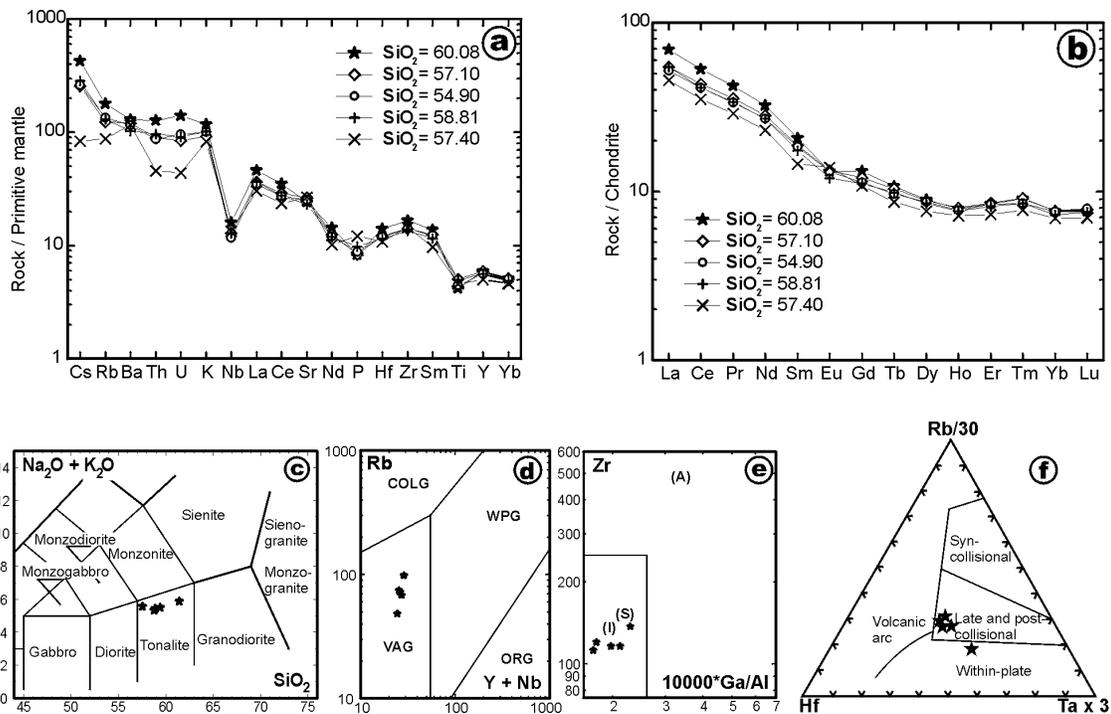


Figure 2: Rodeo Bordalesa geochemical diagrams. **2 a:** Multielements; **2 b:** REE; **2 c:** TAS diagram; **2 d:** Pearce et al (1984) diagram; **2 e:** Whalen et al (1987) diagram; **2 f:** Discrimination diagram after Harris et al (1986).-

ISOTOPIC DATA

To constrain the age of the Rodeo Bordalesa intrusive rocks new U-Pb, K-Ar, Rb-Sr and Sm-Nd data have been obtained, in addition to the K-Ar dates reported by González (1971) and González Díaz (1981).

a. U-Pb: The procedure for U-Pb zircon analyses at Centro de Pesquisas Geocronológicas – IGcUSP is as follow: After 10 Kg of sample were crushed and reduced to 140 - 200-mesh grain-sizes the portion rich in heavy minerals was treated with bromoform ($d=2.89 \text{ g/cm}^3$) and methyl iodide ($d=3.3 \text{ g/cm}^3$), and the fraction containing the heavy minerals was processed in the Frantz separator at 1.5 Amp., and split in several zircon-rich magnetic fractions. The final purification of each fraction was by hand picking. The dissolution of the zircon crystals was carried out with HF and HNO₃ in Teflon micro bombs in which a mixed ²⁰⁵Pb/²³⁵U spike was added. A set of 15 micro bombs arranged in a metal jacket is left for three days in a stove at 200° C. Then, the HF is evaporated and HCl (6N) added to the micro bombs, replaced in the stove for 24 hours. After the evaporation of HCl 6N, the residue is dissolved in HCl (3N). U and Pb are concentrated and purified by passing the solution in an anionic exchange resin column. The solution enriched in U and Pb is, after addition of phosphoric acid, evaporated until the formation of a micro-drop. The sample is deposited in a rhenium filament and the isotopic composition is determined with Finnigan MAT 262 solid source mass spectrometer. After reduction of the data (PBDAT), the results (Table 1) are plotted in appropriate diagrams using the software ISOPLOT/EX (Ludwig, 1999, 2001). As we can see on Tera-Wasserburg diagram (Fig. 3) the U-Pb age obtained is 401 ± 3 Ma and that corresponds to Early Devonian time.

SPU	207/235#	Error (%)	206/238#	Error (%)	207/206#	Error	206/204 *	Pb (ppm)	U (ppm)	Weight (mg)	206/238 Age
1927	0,498825	0,81	0,064676	0,79	0,05594	0,160	882	17,1	251,5	0,0703	404
1928	0,497372	0,99	0,06454	0,97	0,05589	0,174	754	13,3	196,4	0,0672	403
1929	0,488365	0,55	0,064299	0,54	0,05509	0,109	2482	17,8	269,7	0,0727	402
1930	0,492999	1,03	0,064428	0,99	0,05550	0,245	886	12,2	183,2	0,0703	403
SPU: - laboratory number											
# - Radiogenic Pb corrected for blank and initial Pb; U corrected for blank											
* Not corrected for blank or non-radiogenic Pb											
Total U and Pb: - concentrations corrected for analytical blank											
Ages: - given in Ma using Ludwig Isoplot/Ex program (2000), decay constants by Steiger and Jäger (1977).											

Table 1 : U-Pb analytical data

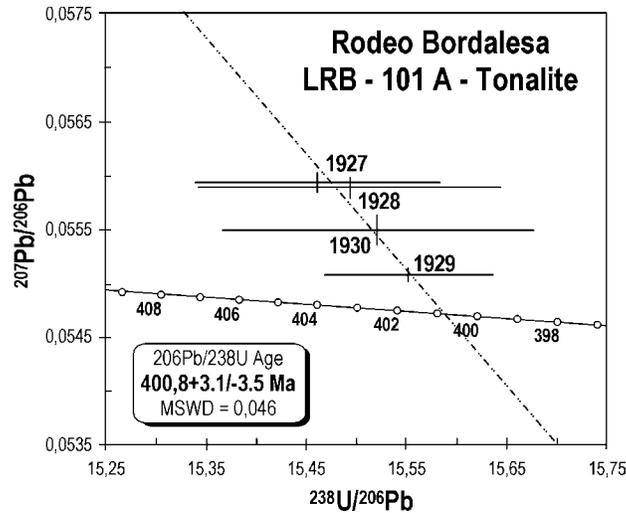


Fig.3: Tera-Wasserburg U-Pb diagram

b. K-Ar: Biotite fresh minerals separates from one tonalite sample (RB-04) were dated using the K-Ar technique at the Centro de Pesquisas Geocronológicas, USP and the data are presented in Table 2. The biotite gave an age of 401 ± 17 Ma. This value is very close to the zircon U-Pb age obtained in this work.

Lab N° SPK	Field N°	Mineral	Rock type	K (%)	Error (%)	Ar40Rad	Ar40Atm (%)	Age (Ma)	Error (Ma)
7731	RB-04 A21	Biotite	Tonalite	6,2488	3,0413	108,95	6,24	401,30	17,10

Table 2: K-Ar analytical data.

c. Rb-Sr: The Rb-Sr method was applied using five whole-rock samples from the main tonalite outcrop near de railroad. The biotite separate from one whole rock was also used. Rb and Sr XRF analyses for whole rocks as well as the mass spectrometry for Sr and isotope dilution in biotite, were carried out at the Laboratorio de Geología Isotópica, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil. The sample preparation and extraction of Rb and Sr through cation exchange columns was performed at the Centro de Investigaciones Geológicas, Universidad de La Plata. As we can see on the Table 3, the samples show low Rb (40-60 ppm) and high Sr content (300-500 ppm), with a low Rb/Sr ratio (0.10-0.20). Rb-Sr whole-rock diagram (Fig. 4) show an alignment of five samples within a very low range of $^{87}\text{Rb}/^{86}\text{Sr}$ (0.24 to 0.61), and define an 'age' of 600 ± 100 Ma and IR:0.7043. For this reason we utilized a biotite as an Rb rich mineral. For the biotite sample the Rb/Sr ratio is 26. The age obtained with the five whole-rocks and the biotite is 374 ± 4 Ma, with an IR:0.7056 \pm 0.0006 as we can see on the diagram (Fig. 4).

Field N°	Lab. N°	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	Error	$^{87}\text{Sr}/^{86}\text{Sr}$	Error
01LRB1	CIG 1248	52,9	506,6	0,3023	0,006	0,707074	0,000021
01LRB2	CIG 1249	40,8	488	0,242	0,0048	0,706387	0,000019
01LRB10	CIG 1251	54,7	464	0,3413	0,0068	0,70719	0,00002
01LRB16	CIG 1252	64,6	306,6	0,6101	0,0122	0,709615	0,000021
01LRB21	CIG 1253	52,3	415,5	0,3644	0,0073	0,707392	0,000023
Biotite (DI)	CIG 1268	313,07	19,49	47,64	0,24	0,959464	0,000294

Table 3: Rb-Sr analytical data

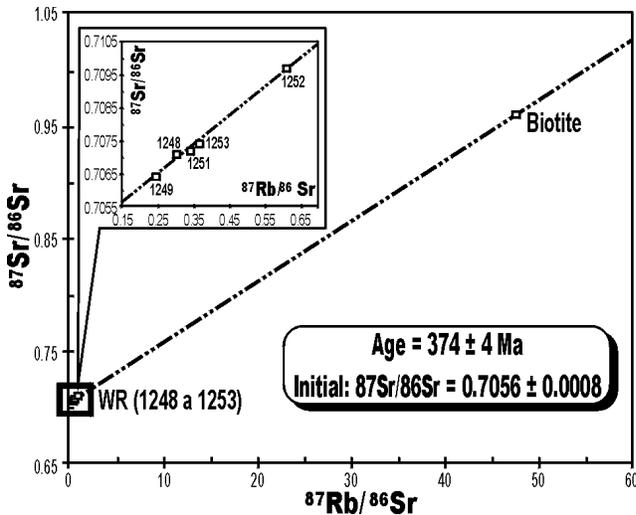


Figure 4: Rb–Sr isochronic diagram.

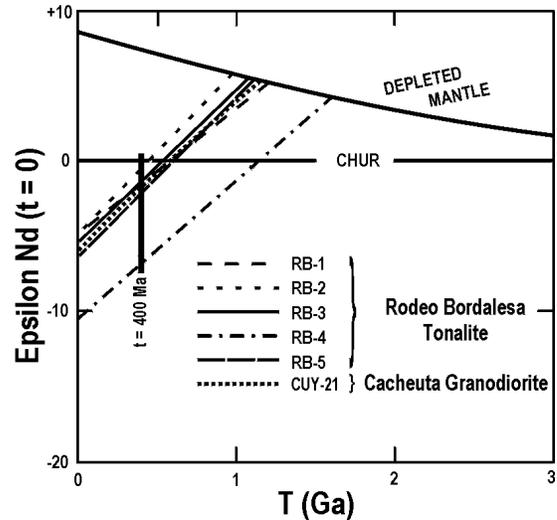


Figure 5: ϵ Nd evolution diagram

d. Sm-Nd: For Sm-Nd method five whole-rock tonalitic samples (RB1 to RB 5) were used (Table 4). The isotope dilution technique for Sm-Nd analyses (using a combined ^{149}Sm - ^{150}Nd spike) as well as the mass spectrometry for Sm and Nd, were carried out at the Laboratorio de Geología Isotópica, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil. The isotopic ratios were measured using the VG 354 mass spectrometer with multiple collector system. The samples not defined an acceptable alignment. The model ages (T_{DM}) calculated according to DePaolo (1981) for the whole-rock samples are in the range of 1 and 1.6 Ga. The ϵNd (400) for these samples is -0.10 to -1.12 , indicating crustal source (Fig. 5). For comparison we plot also a new Sm-Nd data from the Silurian-Devonian Cacheuta monzodiorite (Varela et al., 1993) obtained by Avila Nunes et al. (2003) that are very close to the Rodeo Bordalesa tonalite.

Field N°	Sm	Nd	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{147}\text{Nd}/^{144}\text{Nd}$	Error	End (0)	Age	End (t)	T_{DM} Ga
RB-1	4.02	18.66	0.130219	0.512406	10	- 4.52	400	-0.70	1.2
RB-2	2.93	15.06	0.117629	0.512410	25	-4.45	400	0.10	1.0
RB-3	3.79	19.15	0.119617	0.512354	15	-5.55	400	-1.12	1.1
RB-4	3.88	18.92	0.124118	0.512115	240	-10.20	400	-6.04	1.6
RB-5	3.78	18.78	0.121827	0.512381	20	-5.02	400	-0.72	1.1

Table 4: Sm-Nd analytical data.

CONCLUDING REMARKS

As a result of the present study, the following statements can be made:

1) The Rodeo Bordalesa tonalite at San Rafael Block is characterized by high to medium potassium contents, with metaluminous composition and I-type calc-alkaline signature. It forms part of a magmatic arc and could be related to a late to post-collision tectonic event.

2) We interpret the 400 Ma age U-Pb zircon data obtained within a Tera-Wasserburg diagram, as the crystallization age and that corresponds to the emplacement time. This data are in agreement with the new biotite K-Ar age of 400 ± 17 Ma. It is important to note that K-Ar ages greater than this value (González, 1971) are not supported by our new geochronological data and also are not

consistent with the new paleontological record.

3) The Rb-Sr whole-rocks and biotite age of 374 ± 4 Ma, could be related with a metamorphic event in agreement with others geochronological data constrain the deformational event of the La Horqueta Formation (K-Ar whole rock ages of 320 ± 20 Ma, 390 ± 15 Ma and 395 ± 15 Ma after Toubes and Spikermann, 1976; 1979). It is important to note that Tickyj et al. (2002) based on Rb-Sr isotopic studies found the isochronic whole rock ages from 371 ± 62 and 379 ± 15 Ma, and they interpreted that the low metamorphism of La Horqueta Formation is Devonian. Similar data were obtained in metasedimentary rocks from Precordillera (Cucchi, 1971; Buggish et al., 1994; Ramos et al., 1998 and Davis et al., 1999) that strongly suggests an Early to Middle Devonian age for the syn-metamorphic ductile deformation in the western side of Precordillera terrane.

4) Nd model ages (T_{DM}) show an interval between 1 to 1.6 Ga. and negative ϵ_{Nd} is characteristics from crustal sources.

5) The crystallization age for the Rodeo Bordalesa tonalite corresponds to a Lower Devonian time (Pragian-Emsian boundary) according to IUGS time scale and suggest that the Late Famatinian magmatic arc is present in the SRB. The tonalite has a similar age respect to the Cacheuta monzodiorites in Precordillera and is contemporaneous with the large peraluminous batholiths in Pampeanas Range (Rapela et al. 1992), and with the transpressional shear belts during "Achalian" event (Sims et al., 1998).

6) The new geochemical and geochronological data allow us to differentiate the Rodeo Bordalesa tonalite from the tholeiitic basic rocks (mainly gabbros and porphyritic dolerites with tholeiitic signature) exposed at the El Nihuil area.

ACKNOWLEDGMENTS

Field and laboratory work was financed partially by CONICET-CNPq agreement. We thank H. Tickyj for his assistance during fieldwork. The students D. Licitra and N. Hernandez, helped us in mineralogical and petrographical descriptions. To M. Campaña and C. Pereyra for helpful technical assistance. Satellite images were obtained from CONAE, Argentina. This is a contribution to IGCP Project N° 436 'Tectonic Evolution of the Pacific Gondwana Margin'.

REFERENCES

- Avila Nunes, J., Chemale Jr., F., Weissheimer de Borba, A. and Cingolani, C.A. 2003. Sequence stratigraphy and U/Pb SHRIMP geochronology of the active margin deposits of the Cacheuta sub-basin, Cuyo Basin, Northwestern Argentina. 2° Congresso Brasileiro de P&D em Petróleo & Gás.
- Bellieni, G., Visentin, J. and Zanettin, B. 1995. Use of the chemical TAS diagram (total alkali silica) for classification of plutonic rocks: problems and suggestions. *PLINIUS* (Supplemento italiano all'European Journal of Mineralogy), n. 14:49-52.
- Buggish, W., von Gosen, W., Henjes-Kunst, E., and Krumm, S. 1994. the age of early Paleozoic deformation and metamorphism in the Argentine Precordillera-Evidence from K-Ar data. *Zentralblatt Geologische un Palaontologie*, Teil I:275-286.
- Cingolani, C.A., Llambías, E.J. and Ortiz, L.R. 2000. Magmatismo básico pre-Carbónico del Nihuil, Bloque de San Rafael, Provincia de Mendoza, Argentina. 9° Congreso Geológico Chileno, 2:717-721, Puerto Varas.
- Cucchi, R.J., 1971. Edades radimétricas y correlación de metamorfitas de la Precordillera, San Juan-Mendoza, Rep. Argentina. *Revista Asociación Geológica Argentina*, 28(3):241-267.
- Davis, J., Roeske, S., McClelland, W., and Snee, L. 1999. Crossing the ocean between the Precordillera terrane and Chilena: Early Devonian ophiolite emplacement and deformation in the Southwest Precordillera. In Ramos V.A. and

- Keppie, J.D. (eds.). *Laurentia-Gondwana connections before Pangea*. Geological Society of America, Special Paper 336:115-138. Boulder, Co. USA.
- Dessanti, R.N. 1956. Descripción geológica de la Hoja 27c-cerro Diamante (Provincia de Mendoza). Dirección Nacional de Geología y Minería. Boletín 85, 79 p. Buenos Aires
- González, R.N. 1971. Edades radimétricas de algunos cuerpos eruptivos de Argentina. *Revista Asociación Geológica Argentina*, 26(3):411-412.
- González Díaz, E.F. 1981. Nuevos argumentos a favor del desdoblamiento de la denominada "Serie de la Horqueta" del Bloque de San Rafael, Provincia de Mendoza. 8° Congreso Geológico Argentino, Actas 3:241-256. San Luis.
- Harris, N.B.W., Pearce, J.A. and Tindle, A.G. 1986. Geochemical characteristics of collision-zone magmatism. In: *Collision Tectonics*. Coward M.P. and Rios, A.C. (Eds.) Geological Society of London, Special Bulletin 19:67-81.
- Irvine, T.N. and Baragar, W.R.A. 1971. A guide to the chemical classification of the common rocks. *Canadian Journal Earth Sciences*, 8: 523-548.
- Keller, M. 1999. The Argentine Precordillera-sedimentary and plate tectonic history of a Laurentian crustal fragment in South America. Geological Society of America, Special Publication 341, 239 p.
- Ludwig, K.R. 1999. Using Isoplot/Ex, version 2. A geochronological toolkit for Microsoft excel. Berkeley Geochronological Center, Special Publication 1a, 47 p.
- Ludwig, K.R. 2000. Squid 1.02: A user manual. Berkeley Geochronological Center, Special Publicacion, 2, 19p.
- Pearce, J.A., Harris, N.B.W. and Tindle, A.G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology*, 25:956-983.
- Peccerillo, A. and Taylor, S.R. 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. *Contributions to Mineralogy and Petrology*, 58:63-81.
- Ramos, V.A., Dallmeyer, R., and Vujovich, G.I. 1998. Time constrains on the Early Paleozoic docking of the Precordillera central Argentina. In: *The Proto-Andean Margin of Gondwana* (Eds. R.J. Pankhurst and C.W. Rapela). Geological Society of London, Special Publication, 142:143-158-
- Rapela, C.W., Coira, B., Toselli, A. and Saavedra, J. 1992. The lower Paleozoic magmatism of south-western Gondwana and the evolution of the Famatinian orogene. *International Geology Review*, 34:1081-1142.
- Rubinstein, C. 1997. Primer registro de palinomorfos silúricos en la Formación La Horqueta, Bloque de San Rafael, provincia de Mendoza, Argentina. *Ameghiniana*, 34(2):163-167.
- Sims, J.P., Ireland, T.R., Camacho, A., Lyons, P., Pieters, P.E., Skirrow, R.G., and Stuart-Smith, P.G. 1998. U-Pb, Th-Pb and Ar-Ar geochronology from the southern Sierras Pampeanas, Argentina: Implications for the Palaeozoic tectonic evolution of the western Gondwana margin, In: Pankhurst, R.J. and Rapela, C.W. (eds.) *The Proto-Andean Margin of Gondwana*. Geological Society of London, Special Publication 142:259-282.
- Taylor, S.R. and McLennan, S.M. 1985. *The continental crust: its composition and evolution*. Blackwell, 312 p., Oxford.
- Toubes, R.O. and Spikermann, J.P. 1976. Algunas edades K-Ar para la Sierra Pintada, provincia de Mendoza. *Revista Asociación Geológica Argentina*, 31(2):118-126.
- Toubes, R.O. and Spikermann, J.P. 1979. Nuevas edades K-Ar para la Sierra Pintada, provincia de Mendoza. *Revista Asociación Geológica Argentina*, 34(1):73-79.
- Varela, R. Cingolani, C.A., Dalla Salda, L.H., Aragón, E. and Teixeira, W. 1993. Las monzodioritas y monzogabros de Cacheuta, Mendoza: edad, petrología e implicancias tectónicas. 12° Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos, 4:75-80.
- Whalen, J.B., Currie, K.L. and Chappel, B.W. 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology*, 95: 407-419.