Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.

This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

Journal of South American Earth Sciences 27 (2009) 299–308

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Upper Carboniferous retroarc volcanism with submarine and subaerial facies at the western Gondwana margin of Argentina

M. Koukharsky[a,b,*], L. Kleiman[c], M. Etcheverría[d], S. Quenardelle[a,b], F. Bercowski[e]

[a] Universidad de Buenos Aires, Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Ciudad Universitaria, Pabellón 2, Piso 1 (C1428EHA), Buenos Aires, Argentina
[b] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
[c] U.A. de Geología, Comisión Nacional de Energía Atómica, Centro Atómico Ezeiza, Argentina
[d] Servicio Geológico Minero Argentino, Geología Regional, Julio A, Roca 651, Piso 10 (1322), Buenos Aires, Argentina
[e] Belgrano sn, Barreal (5405), Provincia de San Juan, Argentina

ARTICLE INFO

Keywords:
Retroarc volcanism
Upper Carboniferous
Argentine Precordillera
Subaerial and submarine volcanism

ABSTRACT

During Late Carboniferous times a continental magmatic arc developed at the western margin of Gondwana in South America, as several marine sedimentary basins were formed at the same time in the retroarc region. North of 33°S, at Cordón Agua del Jagüel, Precordillera of Mendoza, Argentina, a volcanic sequence crops out which was emplaced in a submarine environment with some subaerial exposures, and it is intercalated in marine sediments of Agua del Jagüel Formation, which fills of one of these retroarc basins. This paper presents, for the first time, a facies analyses together with geochemical and isotopic data of this volcanic suite, suggesting its deposition in an ensialic retroarc marine basin. The volcanic succession comprises debris flows with either sedimentary or volcanic fragments, base surge, resedimented massive and laminated dacitic–andesitic hyaloclastite, pillow lava, basic hyaloclastite and dacitic–andesitic lavas and hyaloclastite facies. Its composition is bimodal, either basaltic or dacitic–andesitic. The geochemistry data indicate a subalkaline, low K calk-alkaline and metaluminous affinity. The geochemistry of the basalts points to an origin of the magmas from a depleted mantle source with some crustal contamination. Conversely, the geochemistry of the dacites–andesites shows an important participation of both crustal components and subduction related fluids. A different magmatic source for the basalts than for the dacites–andesites is also supported by Sr and Nd isotopic initial ratios and Nd model ages. The characteristics of this magmatic suite suggest its emplacement in an extensional setting probably associated with the presence of a steepened subduction zone at this latitude during Upper Carboniferous times.

© 2009 Elsevier Ltd. All rights reserved.

ARTICLE INFO

Palabras clave:
Volcanismo de retroarco
Carbonífero superior
Precordillera argentina
Volcanismo subaéreo y submarino

RESUMEN

Durante el Carbonífero tardío se desarrolló un arco magmático continental en el margen oeste del Gondwana en Sudamérica y en el mismo tiempo se originaron varias cuencas sedimentarias marinas en la región del retroarco. Al norte de los 33°S, en el Cordón Agua del Jagüel, Precordillera de Mendoza, Argentina, aflora una secuencia volcánica emplazada en un ambiente submarino con algunas exposiciones subaéreas, intercalada en los sedimentos marinos de la Formación Agua del Jagüel que rellenan una de las mencionadas cuencas de retroarco. Este trabajo presenta, por primera vez, un análisis de las facies conjuntamente con los datos geoquímicos e isotópicos de dicha asociación volcánica los cuales sugieren la depositación en una cuenca marina ensiálica de retroarco. La secuencia volcánica está compuesta por facies de flujos de detritos con fragmentos de origen sedimentario o volcánico, oleadas piroclásticas basales, hialoclastitas dacíticas–andesíticas resedimentadas masivas y laminadas, lavas almohadilladas, hialoclastitas básicas y lavas y hialoclastitas dacíticas–andesíticas. La composición de estas rocas es bimodal, basáltica y dacítica–andesítica. La geoquímica indica una filiación subalcalina, calcoalcalina de bajo K y metaluminosa. Las características geoquímicas de los basaltos señalan un origen a

* Corresponding author. Address: Universidad de Buenos Aires, Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Ciudad Universitaria, Pabellón 2, Piso 1 (C1428EHA), Buenos Aires, Argentina. Fax: +54 11 47230273.
E-mail address: mkou@gl.fcen.uba.ar (M. Koukharsky).

0895-9811/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsames.2009.02.002

Author's personal copy

partir de un magma proveniente de un manto empobrecido con leve contaminación cortical. La geoquímica de las dacitas–andesitas, en cambio, muestra importante participación tanto de componentes corticales como de fluidos relacionados con la subducción. Estos hechos están sustentados por las diferentes relaciones iniciales de los isótopos de Sr y Nd y las edades modelo de Nd, que indican distintas fuentes magmáticas para ambos tipos de rocas. Las características de esta asociación volcánica sugiere, para los tiempos del Carbonífero tardío en esta latitud, un emplazamiento en un ambiente extensional, probablemente asociado a la presencia de una zona de subducción profunda.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

During Late Carboniferous times a subduction regime was active at the western margin of Gondwana in South America. Continental magmatic arc rocks of this age have been described, north of 33°S, in Chile and central western Argentina by Caminos (1972), Mpodozis and Kay (1992) and Llambías and Sato (1995), among others. Several marine sedimentary basins developed at the same time, eastwards, in the retroarc region (Azcuy et al., 1999). Some basaltic rocks occur in the foreland and some andesites in the retroarc regions farther north of the study area (Azcuy et al., 1999). Recent studies carried out in the Argentine Precordillera, (northern province of Mendoza, Fig. 1), revealed an Upper Paleozoic basic and intermediate volcanic sequence which deposited mostly in a submarine environment, with a reduced sector of undoubtedly subaerial characteristics (Koukharsky et al., 2005). These volcanic rocks crop out at Cordón Agua del Jagüel (32°26′38″–32°28′22″S and 69°14′53″–69°15′05″W, Fig. 1). This paper presents for the first time field observations and facies analyses as well as geochemical and isotopic data of the volcanic sequence which confirm their origin in a retroarc tectonic setting.

2. Geological setting

The stratigraphic column of the Precordillera geological unit at this latitude reflects a variable geologic story. The oldest units are Cambrian–Lower Ordovician low-grade metamorphosed, intensely folded, marine deep platform sediments and calcareous deposits which are interbedded with ophiolite complexes. The whole sequence is included in the Garganta del León Group (Cortés et al., 1999). This is followed, in tectonic contact, by a more than 1000 m thick succession of sandstones and pelites mostly deposited as turbidites and submarine fans of Middle Ordovician to Lower Devonian age (Villavicencio Formation, Padula et al., 1967; Gonzalez Bonorino, 1975). In the study area metasedimentary rocks of the Peñasco Formation (Cortés et al., 1999) are considered equivalent to the Villavicencio Formation. They are unconformably overlain by an about 800 m thick, Upper Carboniferous glacimarine and littoral sedimentary sequence, known as the Agua del Jagüel Formation (Amos and Roleri, 1965). The volcanic rocks of the Cordón Agua del Jagüel, which are the subject of the present paper, are considered the upper portion of this formation. The age of the Agua del Jagüel Formation was originally constrained between

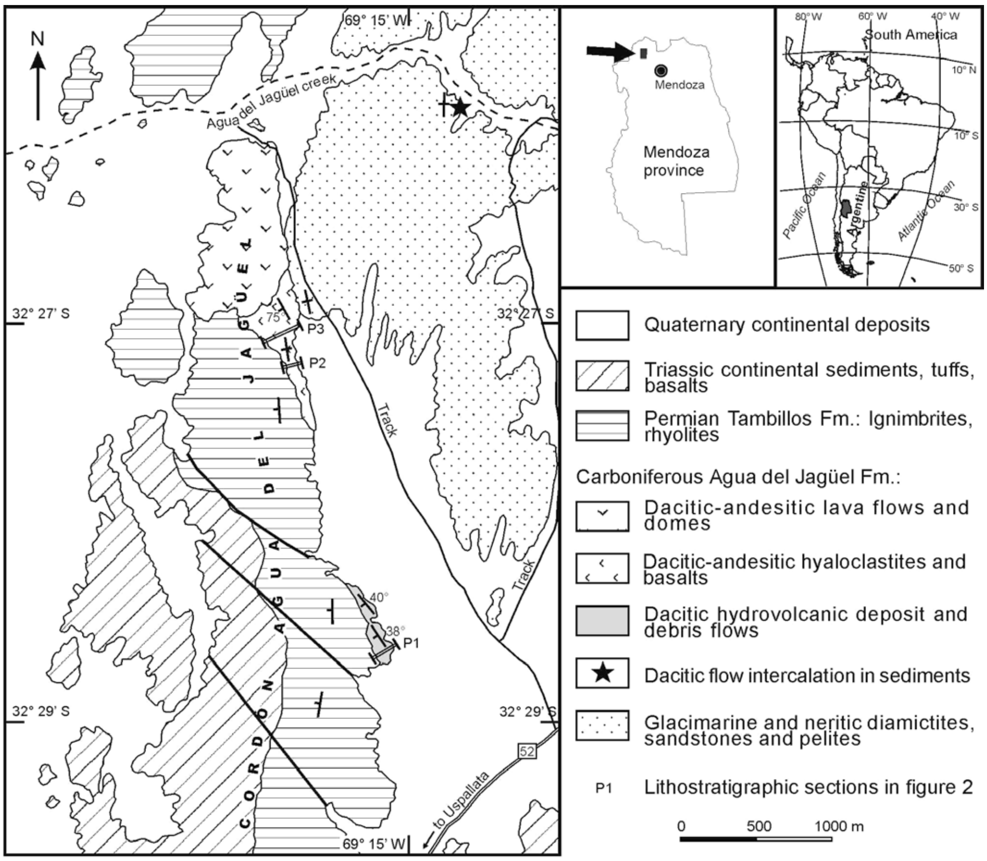

Fig. 1. Geological map of Cordon Agua del Jagüel. Locations of lithostratigraphical sections showed in Fig. 2 are indicated.

Author's personal copy

Upper Carboniferous and Lower Permian based on an invertebrate fauna (Amos, 1972; Gonzalez, 1982; Taboada, 1984, 1986; Lech, 1986, 1990, among others). An Upper Carboniferous K/Ar in biotite age of 307.2 ± 5.2 Ma was obtained in the Remane (2000) chart, from a 6 m thick intercalation of dacitic lava found in its middle section (Lech, 2002). Facies analyses and sedimentological studies indicated that the formation accumulated within a littoral marine environment where episodes of glacial retreat and advance were connected to sea level changes (Bercowski and Vallecillo, 1996). A retroarc setting for the regionally extensive Upper Paleozoic marine sedimentary formations of central western Argentina was proposed by Azcuy et al. (1999), who also suggested an extensional setting due to the presence of the previously mentioned basalt and andesite intercalations.

The Cordón Agua del Jagüel volcanic suite is overlain in high angle unconformity by welded tuffs, breccias and acidic lavas of the Tambillos Formation (Cortés, 1985), which forms part of the Choiyoi Group (Groeber et al., 1952; Stipanicic et al, 1968). They represent the magmatism associated with a generalized extensional episode occurring during Upper Permian to Triassic times, which followed the arc volcanism developed at the western Gondwana margin (Ramos, 1988).

The Tambillos Formation is followed in erosional unconformity by a Triassic sequence of continental siliciclastic sedimentary rocks and tuffs, in some places interbedded with basic lavas and sills, which accumulated in the Cuyo rift basin (Ramos and Kay, 1991).

The stratigraphic column culminates with Miocene volcanic and subvolcanic andesites and dacites associated with some terrestrial sedimentary rocks.

3. The Cordón Agua del Jagüel volcanic sequences

The volcanic rocks were poured out on sediments of the Agua del Jaguel Formation, which consist of greyish green, middle- to fine-grained sandstones with parallel lamination interbedded with massive pelitic beds, up to 20 cm thick, and some 50 cm thick levels of fine-grained calcareous sandstones. A dacitic lava intercalated in the middle section of the Agua del Jagüel Formation was also analyzed for comparison purposes. Stratigraphic sections in Fig. 2 illustrate the facies present in the volcanic sequence and their field relations. These facies consist of:

– *Debris flow (sedimentary source):* this facies was only observed at the base of section P1 (Fig. 2). Two levels of matrix supported, dark greenish grey breccias separated by a 10 cm thick tabular sabulitic deposit were recognized. The breccias contain only sedimentary detritus, mainly derived from the Agua del Jagüel Formation. Clasts include angular and subangular pelites and

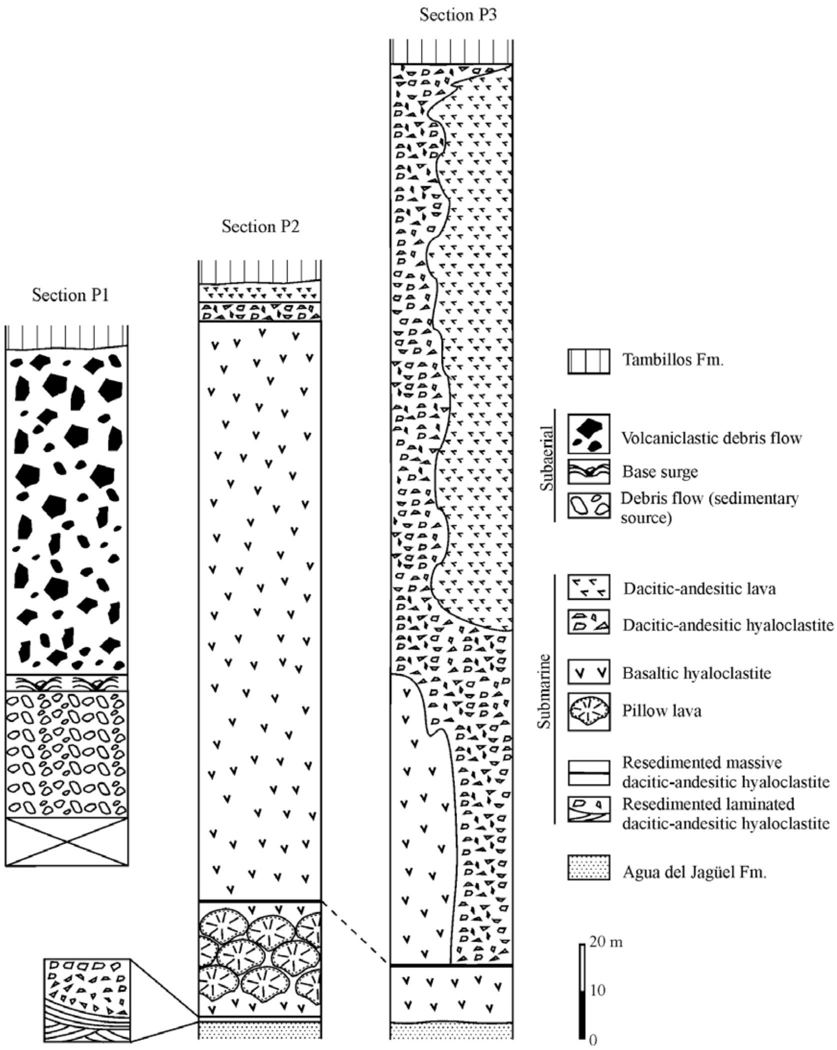

Fig. 2. Representative lithostratigraphical sections.

Author's personal copy

sandstones (3–4 cm in diameter) and rare, up to 60 cm long sandstone blocks. Long axes orientation of imbricated clasts suggest a southeastern provenance for the lower level and a southwestern for the upper one.

This facies is conformably covered by a base surge deposit.

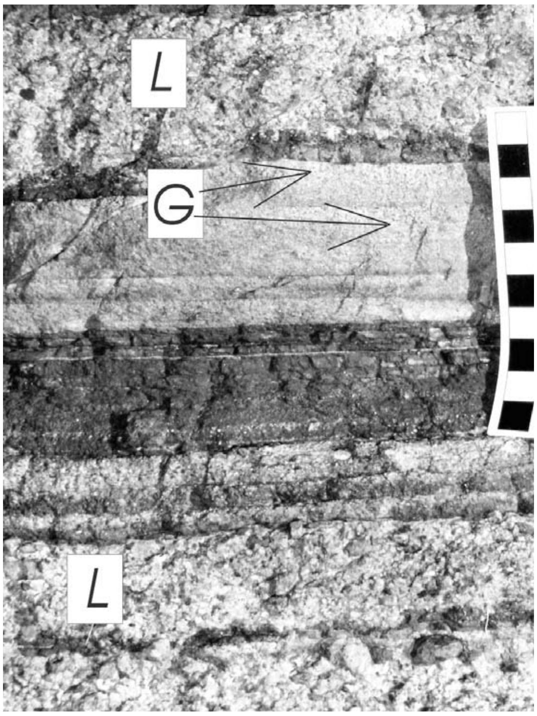

Fig. 3. Fine to coarse tuffs and lapillistone (*L*) levels in the surge deposit. Finest volcanic material appears in dark color. Arrows from G point to levels with inverse graded stratification. Scale is in centimetres.

Fig. 4. Compression over laminated tuffs levels caused by ballistic ejecta in the surge. As a reference there is a pen at the right of the ejecta.

– *Base surge:* this facies occurs in the southern part of Cordon Agua del Jagüel (section P1, Fig. 2). where it corresponds to a volcaniclastic laminated deposit with 1–13 cm thick levels of brownish grey, fine-grained tuff, pale yellowish brown medium- to coarse-grained tuff and greyish orange pink lapillistone. The fine and coarse tuffs contain blocky recrystallized shards in inverse and direct graded stratification (Fig. 3) and plagioclase crystal fragments up to 0.2 cm. The lapillistones include aphanitic and porphyritic equant fragments up to 1.5 cm. At the upper part of the sequence the volcanic rock fragments reach 8 cm in length, and there are some dacitic blocks up to 20 cm in size, which had strongly compressed the thin tuff lamination (bomb sags, Fig. 4). These blocks clearly constitute ballistic ejecta.

Under the microscope the clasts are hyalopilitic groundmasses devitrified either to felsitic aggregates or to alkaline feldspar mosaics with opaque granules. Besides these clasts there are porphyritic fragments having albitised plagioclase, oxidized amphibole and scarce expanded biotites. Vesicles are scarce and tiny. Among the crystal fragments, plagioclase is dominant and there is only few quartz.

This facies is covered by volcaniclastic debris flows which either bend down the top surface of the surge deposit, or disturb the thin laminated structures producing some mingling of materials, indicating that the surge deposit was still unconsolidated.

– *Volcaniclastic debris flow:* this facies was identified in section P1 (Fig. 2). It consists of a sequence of 1–3 m thick layers which show differences in matrix/clast ratios, textural types and average grain sizes. The rocks are brownish grey conglomerates and breccias with a few pebbly sandstone lenses. They are matrix supported and poorly sorted with inverse and normal graded bedding. Volcanic dacitic clasts are dominant; they contain plagioclase, green amphibole and biotite phenocrysts in a grey aphanitic groundmass. In minor proportion there are subangular to subrounded pelite and sandstone clasts. Isolated big dacitic blocks of about 60 cm in diameter are scattered in the matrix.

The flow had swept the base surge deposit in some places, and directly overlies the debris flow (sedimentary source) deposit.

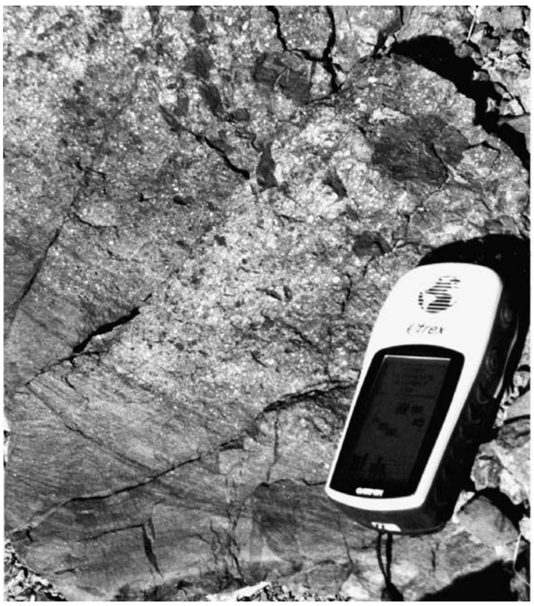

Fig. 5. Fine cross laminated resedimented hyaloclastite grading to fine breccia at the base of section P2 of Fig. 2.

Author's personal copy

Fig. 6. Pillow lava structures with quenched margins in basalt. As a reference there is a pen in the upper right corner.

– *Resedimented laminated dacitic–andesitic hyaloclastite:* in many places, this facies represents the onset of volcanism which followed the sedimentary deposition of the Agua del Jagüel Formation (section P2, Fig. 2). It consists of fine-grained, cross-bedded, epiclastites which gradually turn into fine-grained, matrix supported dacitic breccia (Fig. 5). The composition of the lithoclastic material is mostly phenoandesitic with scarce phenobasalts and pelites.
– *Resedimented massive dacitic–andesitic hyaloclastite:* this facies occurs as thin (10 cm), massive, tabular layers of brownish red sandstone containing angular fragments of phenoandesite, phenobasalt and fine volcanic material, similar to its interstitial matrix. Besides, there are fragments of plagioclase crystals and scarce sedimentary fine-grained rocks. It was observed in sections P2 and P3, and it probably constitutes a guide level (Fig. 2).
– *Pillow lava:* this facies is made up of dark grey basalt with clear pillow structures. Each pillow is a discrete unit up about 70 cm wide and 40 cm high, with conspicuous quenched margins (Fig. 6). Under the microscope they have a variolitic groundmass with abundant opaque minerals and altered plagioclase. Phenocrysts are colorless clinopyroxene and altered plagioclase.
– *Basaltic hyaloclastite:* this facies is represented by dark, massive, fine-grained and intensively fractured rocks. Under the microscope clinopyroxene is dominant, and it is severely fractured, showing a wide range of sizes from phenocrysts to groundmass (Fig. 7a). The plagioclase is fully fractured and exhibits light zonation. The glassy fragments are palagonitized and oxidized.
– *Dacitic–andesitic lavas:* this facies consists of porphyritic rocks containing plagioclase phenocrysts up to 0.5 cm, and smaller sized, altered amphibole and biotite (Fig. 7b). The groundmass is grey and reddish grey with pilotaxic to microgranular textures. Apatite, opaque minerals and very scarce idiomorphic zircon are the accessory phases.

In the northwestern portion of the Cordón Agua del Jagüel the dacitic–andesitic lavas are strongly altered and replaced by carbonates. They are recognized only by their textures because they were preserved and show abundant amphibole and scarce biotite as original phenocrysts. They were classified as andesites on the basis of their trace-element contents.

– *Dacitic lavas:* this facies constitute a very thin (6 m) intercalation within the sediments of the Agua del Jagüel Formation (Lech 2002, star in Fig. 1). These rocks correspond to an earlier volcanic episode than the one described in this paper. Their petrographic composition is similar to the dacitic lavas described above, but quartz phenocrysts are very common.

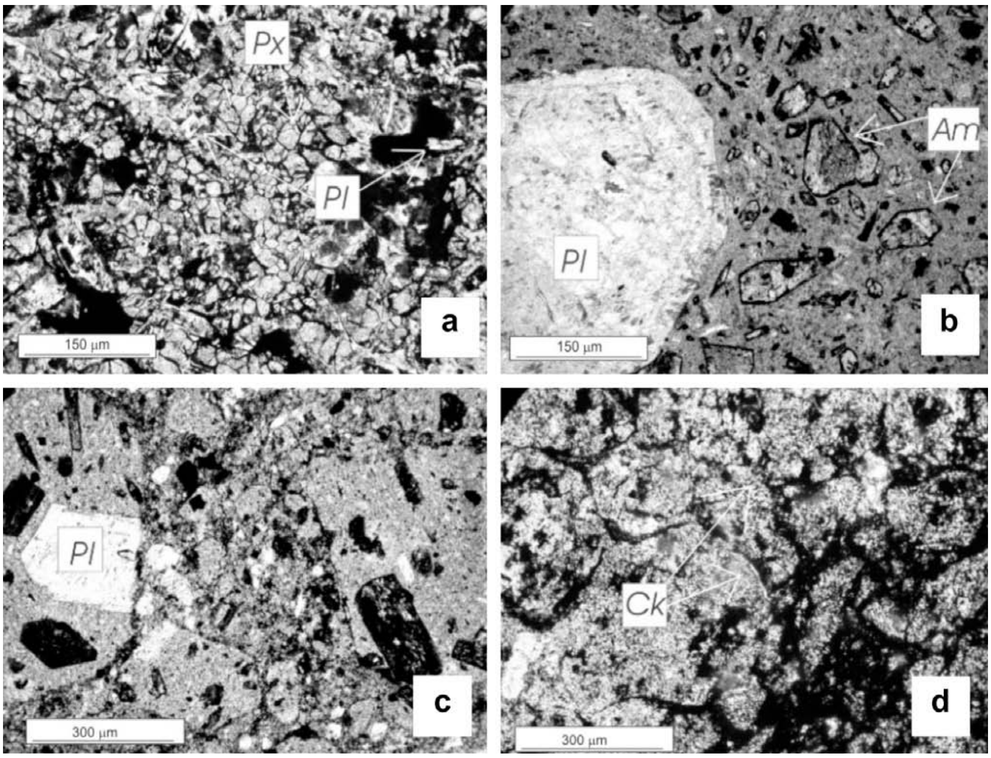

Fig. 7. Microphotographs of thin sections. (a) Basaltic hyaloclastite with oxidized glass dark fragments containing altered plagioclase phenocrystals (Pl) and abundant clinopiroxene fragments (Px). (b) Dacitic–andesitic lava with partially altered zoned plagioclase phenocrysts (Pl) and mafic pseudomorphous minor phenocrysts, where amphibole contours can be identified (Am). (c) Matrix of a dacitic hyaloclastite, composed by groundmass fragments similar to that of the sample illustrated in b. (d) Original glassy dacitic hyaloclastite, recrystallized and partly replaced by fine carbonate and opaque material. Fragments bordered by perlitic cracks are common (Cr).

Author's personal copy

Fig. 8. "Jig–saw" structures in dacitic hyaloclastite of section P3 of Fig. 2. As a reference there is a pen near the right border.

– *Dacitic–andesitic hyaloclastite:* this facies is related to the dacitic–andesitic lavas (section P3, Fig 2). It is represented by clast-supported autobreccias made up of porphyritic rocks in a dark grey groundmass. Their most conspicuous feature is the jig–saw structure (Fig. 8) indicating their *in situ* origin. The fragment size varies in different sectors of the outcrop, being larger near the massive lava. This change is not easy to observe because of the intense jointing of the rocks.

Under the microscope they are autobrecciated dacitic lavas, with abundant microgranular groundmass (Fig. 7c). Scarce altered basaltic fragments are present in thin sections from section P3 (Fig. 2). The tightly jointed dacitic hyaloclastite from the basal portion of section P3 (Fig. 2) shows different characteristics, as its texture is aphanitic and its color is greyish green. Under the microscope it is observed that devitrified vitroclasts are the main constituent, with fragments partially replaced by carbonates, bordered by imperfect perlitic cracks (Fig. 7d).

The facies sequence observed in section P1 (Fig. 2) indicates the erosion of Agua del Jagüel sediments related to the onset of volcanism (debris flow with sedimentary source), the subaerial deposition of some volcaniclastic rocks (base surge), and the presence of volcanic edifices, in order to generate flows of volcanic debris. Base surge deposits are typical of hydromagmatic explosive volcanism and would imply that this area was recently emerged as their delicate structures could only be preserved under subaerial conditions.

The pillow lavas and basaltic and dacitic–andesitic hyaloclastites in section P2 are evidence of submarine deposition, which is also supported by the marine fauna contained in Agua del Jagüel sediments. The presence of dacitic rocks at the base and at the top of the column implies the alternation of basic and intermediate magmatism which is even more apparent in section P3.

The recognition of subaerial and submarine facies within the Agua del Jagüel volcanic rocks has paleogeographic implications for the development of this sector of the Gondwana margin during upper Paleozoic times as it indicates the emergence of parts of the volcanic sequences originating small islands.

4. Geochemistry and Sr–Nd isotope data

4.1. Methodology

Major and trace elements of three basalt and seven andesite and dacite samples were analyzed at Actlabs (Canada) by inductively coupled plasma mass spectrometry (ICP–MS). Results are shown in Table 1.

Isotopic Sr and Nd determinations on two samples were also performed at Actlabs. Isotopic calculations were made applying the decay constant for ^{87}Rb reported by Steiger and Jager (1977) and for ^{147}Sm by Lugmair and Marti (1978). $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios of the present mantle are from Allègre et al. (1983), $^{143}Nd/^{144}Nd$ from Goldstein et al. (1984) and $^{147}Sm/^{144}Nd$ from Jacobsen and Wasserburg (1980). Present $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios for depleted mantle are from Michard et al. (1985). $^{147}Sm/^{144}Nd$ ratios of the samples as well as T_{DM} ages were calculated using, respectively, DePaolo's (1988) recommended coefficient and equation.

4.2. Major elements

On a SiO_2 vs. total alkalis ($Na_2O + K_2O$) plot (not shown), recalculated anhydrous data fall in the fields of basalt, dacite, and rhyolite with a gap between SiO_2 50 and 63 wt% which confirms hand-sample observations. Most samples are subalkaline (Irvine and Baragar, 1971). On a plot of SiO_2 vs. K_2O (Peccerillo and Taylor, 1976) most samples classified as low-potassium calk-alkaline rocks with the exception of the basalts and the early dacitic–rhyolitic lavas interbedded in Agua del Jagüel Formation (Fig. 10), which contain lower K and plot in the tholeiitic field. Both A/CNK and NK/A ratios are lower than one, implying that all the rocks are metaluminous and subalkaline.

Fe_2O_3(T), MgO, TiO_2, MnO, CaO decrease with increasing silica; no changes are observed in Al_2O_3 and P_2O_5, whereas Na_2O and K_2O increases with the exception of AJ lavas K_2O contents. The mg-# ranges from 30.15 for the dacites to 58.2 for the basalts.

4.3. Trace elements

Selected trace elements such as Cr and Y decrease with silica increment whereas Zr, Ba and Rb tend to increase. Nb contents show no variation and Sr increases with the exception of AJ samples. In Winchester and Floyd's (1977) diagrams the samples classify as subalkaline basalt, andesite and dacite (Fig. 9).

Leedy chondrite normalized REE patterns (after Kay and Hubbard, 1978) for basalts are almost flat (La/Yb = 2.26–2.35), ~10 times enriched with respect to chondrite (Fig. 11a) and show no Eu anomaly (Eu/Eu* = 0.92–1) denoting their primitive nature. Dacite and andesite show a considerable enrichment of LREE and an important HREE depletion (La/Yb = 7.8–22), suggesting the fractionation of amphibole also indicated by the increment of La/Yb ratios with increasing SiO_2 (Fig. 11b), and the presence of amphibole crystals in the rocks.

MORB-normalized element plots (after Hoffman, 1988) for basalts (Fig. 12a) show an almost parallel pattern, although the enrichment of some LIL elements (K, Rb, Ba) indicate the contribution of a subduction zone component. Although no typical Nb–Ta depletion is apparent, the role of crustal contamination cannot completely be ruled out considering the relatively high Sr isotopic ratios (Table 3).

The dacites and andesites are LILE enriched, show a Nb–Ta trough and considerable depletion from Ti to Yb, suggesting the involvement of subduction fluids in the magma source region (Fig. 12b). However crustal contamination is indicated from the isotope data (Tables 2 and 3). High Ba/La, Ba/Th, and Rb/Nb ratios also suggest crustal contamination both for the basalts and the dacites–andesites.

Evidence for AFC or FC processes are not conclusive and contradictory. The lack of depletion of Al_2O_3 and Sr and the absence of Eu anomalies seem to rule out fractionation of plagioclase, even though the increase of Zr content at higher SiO_2 values and the

Author's personal copy

Table 1
Geochemical analyses. MK29* data from Cortés et al. (1999).

	CJ 04/04 Dacitic lava N of section P3	CJ 12/04 Volcanic debris flow section P1	CJ 16/04 Dacite dome? N of section P3	CJ 21B Pillow lava (rim) section P2	CJ 21 Pillow lava section P2	CJ 23 Basaltic hyaloclastite section P2	CJ27 Basaltic hyaloclastite section P2	MK29* Andesitic lava N of section P3	AJ1** Lava intercalated in A. del Jaguel Fm	AJ5** Lava intercalated in A. del Jaguel Fm	CJ57 Andesitic lava NW of section P3
SiO_2	61.99	64.75	66.38	47.21	46.8	46.22	44.91	61.68	66.4	69.1	
Al_2O_3	15.23	16.49	14.79	14.17	14.03	15.69	17.89	15.2	15.8	15.23	
Fe_2O_3(T)	4.57	1.9	2.96	10.72	12.66	10.49	9.17	5.17	2.07	2.48	
MnO	0.079	0.058	0.063	0.162	0.181	0.145	0.205	0.07	0.03	0.04	
MgO	1.91	0.41	1.08	6.75	6.69	7.3	7.94	1.74	0.55	0.65	
CaO	3.67	2.43	3.35	9.33	9.39	10.11	10.99	3.99	2.36	1.69	
Na_2O	4.97	7.51	4.78	3.82	3.42	2.47	1.92	4.75	6.59	6.71	
K_2O	2.28	2.04	2.44	0.29	0.15	0.63	0.13	2.04	0.94	0.43	
TiO_2	0.551	0.275	0.342	1.661	1.798	1.272	1.031	0.65	0.27	0.28	
P_2O_5	0.17	0.19	0.14	0.13	0.16	0.11	0.1	0.19	0.14	0.13	
LOI	3.77	2.96	2.96	4.5	4.51	5.18	5.59	3.73	3.63	3.12	
Total	99.18	99	99.28	98.73	99.78	99.61	99.88	99.22	98.7	99.76	
Sc	8	2	3	42	45	36	30	10			
Be	2	1	1	1	1	1	<1	2			
V	83	19	60	321	348	269	214	104		24	72
Cr	30	<20	<20	210	220	240	350	26.9		<20	40
Co	9	5	3	37	48	40	48	11.1		2	8
Ni	<20	<20	<20	70	80	80	160	6		<20	<20
Cu	<10	<10	40	30	120	90	100	18		<10	<10
Zn	50	80	40	50	100	70	90	83		50	60
Ga	22	17	17	17	19	17	18			16	16
Ge	1.2	0.7	0.7	1.5	1.6	1.2	2.1			0.7	0.8
As	<5	<5	<5	14	13	<5	<5	4		<5	<5
Rb	40	36	39	9	6	27	10	42		9	23
Sr	576	455	669	237	296	276	322	643		217	216
Y	17.6	14.3	9.3	29.9	32.4	20.6	16.8	17		8	16
Zr	154	192	149	80	91	63	61	144		166	193
Nb	5.3	6.3	4.9	6.6	7.4	4.3	4.2	5		4.9	4.6
Mo	<2	<2	<2	<2	<2	<2	<2	<2		<2	<2
Ag	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.4		<0.5	<0.5
In	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	<0.1			<0.1	<0.1
Sn	1	1	<1	<1	67	<1	5			<1	2
Sb	0.4	1.3	<0.2	<0.2	0.2	<0.2	6.3	0.8		1	1.5
Cs	1.6	0.9	1.7	7.3	1.4	5.2	7	3		0.6	1.2
Ba	1152	440	930	175	77	116	99	956		1420	409
La	15.4	11.3	13	6.07	6.4	4.2	4.15	14.3		12.7	15.1
Ce	34.7	29.9	29	15.5	16.8	10.8	10.3	32		28.7	33.6
Pr	4.74	4.33	4.04	2.39	2.53	1.71	1.53			3.8	4.53
Nd	20.3	19.6	16.5	12.6	13.3	8.69	7.77	19		15.9	19.3
Sm	4.52	4.93	3.61	3.81	4.03	2.66	2.32	3.89		3.32	4.4
Eu	1.31	1.31	1.04	1.38	1.42	1.03	0.907	1.23		0.867	1.28
Gd	3.75	4.15	2.89	4.36	4.88	3.19	2.96			2.47	3.93
Tb	0.55	0.57	0.37	0.78	0.86	0.56	0.48	0.5		0.32	0.58
Dy	2.89	2.59	1.75	4.94	5.19	3.46	2.86			1.46	3.08
Ho	0.56	0.44	0.3	1.02	1.06	0.71	0.57			0.26	0.57
Er	1.59	1.12	0.8	2.91	3.1	2.06	1.65			0.73	1.62
Tm	0.231	0.145	0.11	0.422	0.45	0.292	0.243			0.113	0.264
Yb	1.45	0.84	0.68	2.6	2.83	1.79	1.53	1.83		0.71	1.82
Lu	0.211	0.114	0.099	0.364	0.388	0.262	0.22	0.27		0.098	0.276
Hf	4.6	5.7	4	2.5	2.8	1.9	1.7	4.4		4.6	4.8
Ta	0.27	0.35	0.27	0.45	0.47	0.26	0.25	0.29		0.26	0.24
W	<0.5	<0.5	<0.5	<0.5	0.6	<0.5	<0.5	<1		0.8	4
Tl	0.12	0.3	0.09	<0.05	<0.05	0.08	0.09			<0.05	0.14
Pb	7	<5	<5	<5	56	<5	11	<5		8	25
Bi	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.6	<5		0.1	<0.1
Th	1.18	1.31	1.12	0.49	0.54	0.33	0.34	1.00		1	1.65
U	0.56	0.77	0.58	0.37	1.18	0.12	0.13	0.8		0.58	1.23

HREE depletion indicate the fractionation of mafic phases. The variation of trace-element ratios is not consistent with simple FC processes linking dacites and andesites to basalts (Table 1) as their REE patterns cross in the mid-REE (Sm to Tb). Tectonic discriminant diagrams are not conclusive for the basalts as they plot in different fields. For instance, in the Ta/Yb vs. Th/Yb diagram of Pearce (1983) they plot in MORB or WPB fields, whereas in Shervais's (1982) Ti vs. V diagram, they do in the MORB, BAB (back-arc) and calk-alkaline fields (Fig. 13). In Pearce and Gale's (1977) diagram of Ti/Y vs. Zr/Y, the samples plot in the field of plate margin basalts although they straddle into the field of WPB, and in Pearce and Norry's (1979) Zr vs. Zr/Y diagram, they plot in the MORB and VAB fields.

Most dacites and andesites plot in the WPVZ field of Gorton and Schandl's (2000) Th/Ta vs. Yb diagram. In the Ta–Hf/3-Th diagram (Wood, 1980) basalts plot in the E-type MORB and WPT fields, whereas dacites and andesites do in the primitive arc field, where Hf/Th > 3 (Fig. 14).

Author's personal copy

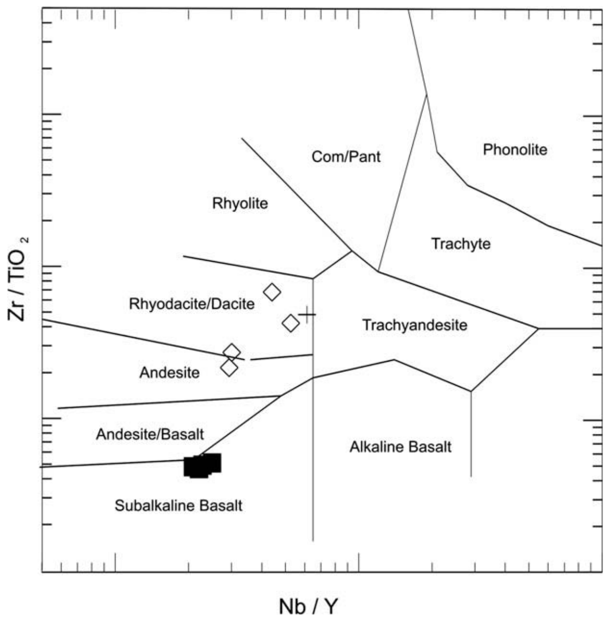

Fig. 9. Zr/TiO_2 vs. Nb/TiO_2 classification of volcanic rocks (Winchester and Floyd, 1977). Filled squares: basalts; diamonds: dacite–andesites from Cordon del Jagüel; cross: dacite flow intercalated in Agua del Jaguel Fm.

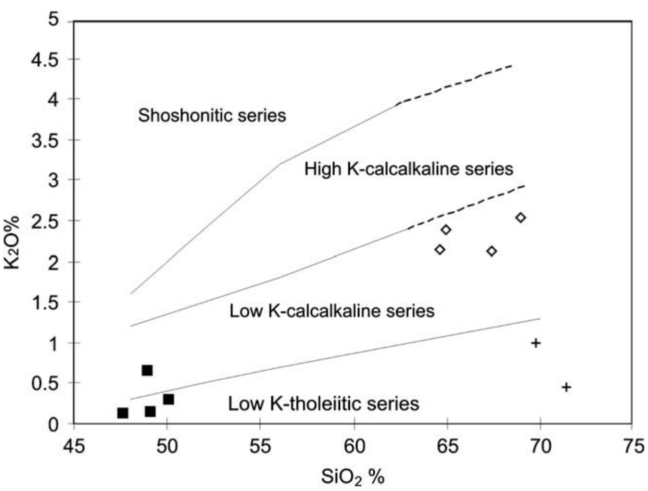

Fig. 10. K vs. silica classification of subalkaline rocks from Peccerillo and Taylor (1976). Symbols as in Fig. 9.

4.4. Sr and Nd isotopes

Sr and Nd isotopic ratios were determined in selected samples of basalt (CJ21) and of dacite (CJ16). Different magma sources are inferred for these rocks as they show different initial (300 Ma) isotopic ratios (Tables 2 and 3). For the basalt, the εNd value suggests a source in a moderately depleted mantle whereas the εSr points to some crustal contamination. Possible sources of contamination are abundant pre-Carboniferous rocks exposed in the region. Among these, the thick, low-grade, Ordovician–Devonian (?) metasedimentary sequence of the Villavicencio Formation contains pelitic levels with barite nodules and lenses which showed εSr_{300Ma} values as high as +94.3 (Brodtkorb et al., 1988). The dacite shows lower εNd and higher εSr values than the basalt, indicating a higher participation of crustal material in its genesis. An origin involving abundant melting of either sediments or older crustal rocks is supported by its relatively high $T_{(DM)}$ value (Table 2). The source for

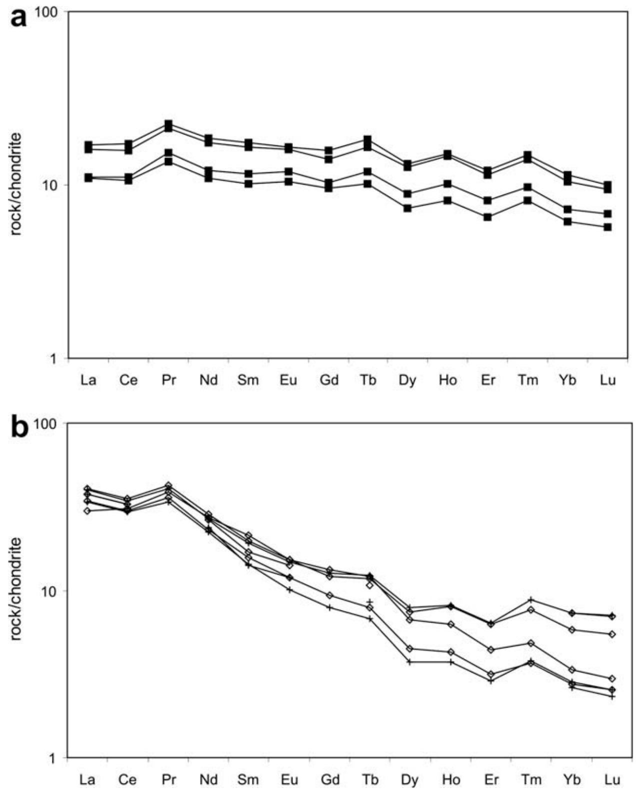

Fig. 11. Chondrite normalized REE diagrams.

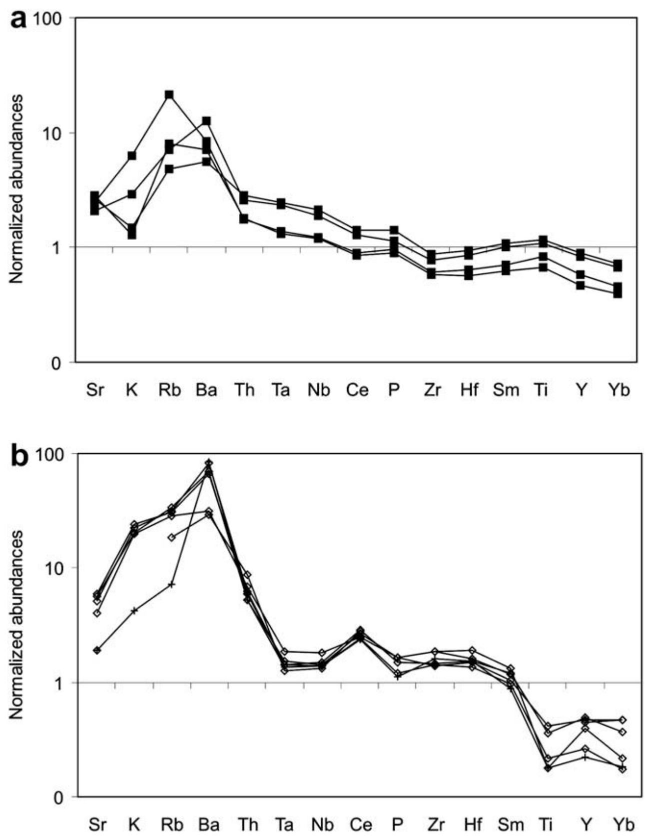

Fig. 12. MORB-normalized trace diagrams. (a) Basaltic rocks. (b) Acid rocks. Symbols as in Fig. 9.

Author's personal copy

Table 2
Analytic data and initial $^{143}Nd/^{144}Nd$ isotopic and εNd values calculated to 300 Ma.

Sample	$^{143}Nd/^{144}Nd$	2σ	$(^{143}Nd/^{144}Nd)i$	εNd	T_{DM} Ma
CJ16	0.512433	4	0.512003	−4.8	1156
CJ21	0.512887	5	0.512527	+5.3	894

Table 3
Analytic data and initial $^{87}Sr/^{86}Sr$ isotopic and εSr values calculated to 300 Ma. Shale samples of Villavicencio Fm. Data are from Brodtkorb et al. (1988).

Sample	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ	$(^{87}Sr/^{86}Sr)i$	εSr
CJ16	0.1952	0.706043	11	0.705209	+37.8
CJ21	0.0561	0.705008	11	0.704768	+31.6
Shale1	0.20	0.70999	3	0.709136	+93.7
Shale2	0.19	0.70999	5	0.709178	+94.3

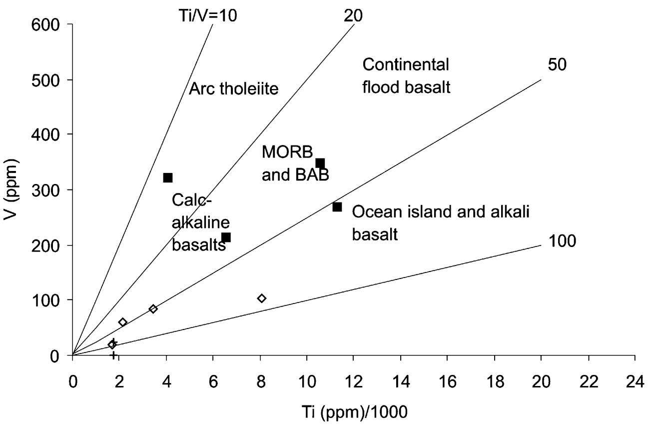

Fig. 13. V vs. Ti diagram of Shervais (1982). Symbols as in Fig. 9.

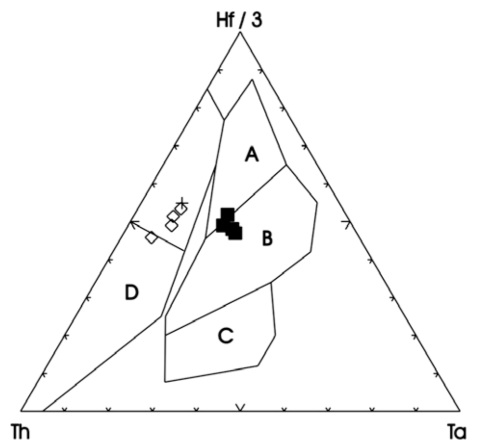

Fig. 14. Th–Hf–Ta diagram after Wood (1980). Symbols as in Fig. 9.

the metasedimentary Villavicencio Formation has been established in an older igneous-metamorphic basement and in a metasedimentary cover (Kury, 1993). A larger contamination of the dacitic magma with these sediments could be the reason for its higher T_{DM} age.

If εSr and εNd values of the Cordón Agua del Jagüel rocks are plotted together and compared with those of classical volcanic associations, it can be seen that the dacite is similar to Andean arc rocks, for which an origin in a parental basalt from the mantle which interacted with crust was invoked (DePaolo, 1988). The basalt, having a relatively primitive signature due to its low εNd, is displaced from the current arc fields to an unusually high Sr isotopic ratio, suggesting the above-mentioned continental crust contamination.

5. Discussion and conclusions

In the southern area of the Cordón Agua del Jagüel (section P1 in Fig. 2) the facies association indicates a subaerial depositional environment. Well preserved volcaniclastic flow structures with “bomb sags” are the main evidence. In the northern section the presence of pillow lavas and hyaloclastites with jig–saw structures, in close spatial relationship to marine fosiliferous sediments (sections P2 and P3), imply a submarine origin for the volcanic rocks.

Dacitic–andesitic volcanic facies which interfinger with the basalts (P2 in Fig. 2) demonstrate the concurrence of basic and acidic magmatism, a typical feature of extensional settings. A lateral contact between basaltic and dacitic facies is seen in section P3 (Fig. 2). The identification under the microscope of basaltic fragments in the dacitic hyaloclastite and the absence of dacitic fragments in the basaltic hyaloclastite, show that at least locally, the acidic rocks were the last emplaced.

In most tectonic discriminant diagrams the basalts classify as MORB and VAB. The transitional nature between N-MORB and calk-alkaline of the Cordón Agua del Jagüel basalts are typical of back-arc settings (Saunders and Tarney, 1984). Dacites plot in WPZ and/or IAT (primitive arcs) fields while trace-element contents reveal the participation of subduction derived fluids in their origin.

Chemical compositions of the basalts can be compared with those of the Japan Sea back-arc basin (Group 2A of Pouclet et al., 1994), which are tholeiites with mineralogy and chemical compositions similar to continental tholeiites, and show slight enrichment of LREE, low abundance of LILE and no negative Nb anomaly, although εSr and εNd from Cordón Agua del Jagüel basalts show higher values. These two last characteristics suggest an origin in a depleted mantle with crustal contamination for the Cordón Agua del Jagüel basalts and participation of subduction related fluids which imprinted the distinctive trace-element signatures mainly on the dacitic–andesitic rocks.

The interpretation of a back-arc volcanism is coherent with the existence, at the same latitude, of arc-related plutonic and volcanic Neopaleozoic rocks in Chile and in western Argentina. The coeval emplacement of the Cordon del Jagüel basalts and dacites in a marine sedimentary basin together with their relatively primitive nature points to an extensional environment. This extension in the retroarc would point to a steepened subduction zone at this latitude during Late Carboniferous times.

The ensialic location of this marine volcanism is supported by both the regional stratigraphy and the Nd model ages of the volcanic rocks, and it is the main reason for considering a retroarc rather than a back-arc basin environment.

Acknowledgements

We thank Héctor Ostera for the revision of isotopic calculations and Eduardo Llambías, Víctor Ramos and an anonymous reviewer for their comments that helped to improve the original version of the manuscript. This research was supported by funds to UBA-CYT-X270 and to PIP CONICET 2379/00 projects.

References

Allègre, C.J., Hart, S.R., Minster, J.R., 1983. Chemical structure and evolution of the mantle and continents determined by inversion of Nd and Sr isotopic data, I. Theoretical models. Earth and Planetary Science Letters 66, 177–190.

Author's personal copy

Amos, A.J., 1972. La cuencas carbónicas y pérmicas de Argentina. Anais Academia Brasileira de Ciências 44 (Suplemento), 21–26.

Amos, A.J., Roleri, E.O., 1965. El Carbónico marino en el valle de Calingasta–Uspallata (San Juan–Mendoza). Boletín de Informaciones Petroleras 368, 50–71.

Azcuy, C.L., Carrizo, H. A., Caminos, R., 1999. Carbonífero y Pérmico de las Sierras Pampeanas, Famatina, Precordillera, Cordillera Frontal y Bloque de San Rafael. Instituto de Geología y Recursos Minerales, Geología Argentina, Anales, vol. 29 (12), pp. 261–318.

Bercowski, F., Vallecillo, G., 1996. Facies glacimarinas de plataforma: Reinterpretación de la Formación Agua del Jagüel (Neopaleozoico), Precordillera, provincia de Mendoza. 13° Congreso Geológico Argentino y 3° Congreso de Exploración de Hidrocarburos, Actas 2, 77–86.

Brodtkorb, M.K.de, Schalamuk, I.B.A., Barbieri, M., Puchelt, H., Ametrano, S., Etcheverry, R., 1988. Nodular barite deposits of Canota, Argentina. In: Proceedings of the Seventh quadrannial IAGGOD Symposium, pp. 275–286.

Caminos, R., 1972. Perfil geológico de la Cordillera entre los 28°00′ y 28°30′ de latitud Sur, provincia de La Rioja, República Argentina. Revista de la Asociación Geológica Argentina 27 (1), 71–83.

Cortés, J.M., 1985. Vulcanitas y sedimentitas lacustres en la base del Grupo Choiyoi al sur de la Estancia Tambillos, Mendoza. Argentina. 4° Congreso Geológico Chileno, Actas 1, 89–108.

Cortés, J.M., González Bonorino, G., Koukharsky, M., Pereyra, F., Brodtkorb, A., 1999. Memoria de la Hoja Geológica 3369-09, Uspallata, provincia de Mendoza. Servicio Geológico Minero Argentino, Boletín N° 281, 1–163.

DePaolo, D., 1988. Neodymium Isotope Geochemistry. An Introduction. Springer Verlag. 187p.

Goldstein, S.L., ÓNions, R.K., Hamilton, P.J., 1984. A Sm–Nd study of atmospheric dusts and particulates from major river systems. Earth and Planetary Science Letters 70, 221–236.

Gonzalez, C.R., 1982. Bivalvos de la Formación Agua del Jagüel. Pérmico inferior de Mendoza (Argentina). Ameghiniana 19 (3–4), 367–376.

Gonzalez Bonorino, G., 1975. Sedimentología de la Formación Punta Negra y algunas consideraciones sobre la geología regional de la Precordillera de San Juan y Mendoza. Revista de la Asociación Geológica Argentina 30 (3), 223–246.

Gorton, M.P., Schandl, E.S., 2000. From continents to island arcs: A geochemical index of tectonic setting for arc-related and within-plate felsic to intermediate volcanic rocks. The Canadian Mineralogist 38, 1065–1073.

Groeber, P., Stipanicic, P.N., Mingramm, A.R.G., 1952. Mesozoico. Geografía de la República Argentina. Sociedad argentina de Estudios Geográficos GAEA 2, 1–541.

Hoffman, A.W., 1988. Chemical differentiation of the earth: the relationship between mantle, continental crust, and oceanic crust. Earth and Planetary Science Letters 90, 297–314.

Irvine, T.N., Baragar, W.R.A., 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences 8, 523–548.

Jacobsen, S.B., Wasserburg, G.J., 1980. Sm–Nd isotopic evoutin of condrites. Earth and Planetary Science Letters 50, 139–155.

Kay, R.W., Hubbard, N.J., 1978. Trace elements in ocean ridge basalts. Earth and Planetary Science Letters 38, 95–116.

Koukharsky, M., Kleiman, L., Etcheverría, M., Quenardelle, S., Litvak, V., 2005. Transición entre un ambiente marino y uno subaéreo en volcanitas del Paleozoico superior, Cordón Agua del Jagüel, provincia de Mendoza. 16° Congreso Geológico Argentino, Actas 1, 821–828.

Kury, W., 1993. Características composicionales de la Formación Villavicencio, Devónico, Precordillera de Mendoza. 12° Congreso Geológico Argentino y 2° Congreso de Exploración de Hidrocarburos, Actas 1, 321–328.

Lech, R.R., 1986. *Septosyringothyris Jagüelensis* sp. nov. (Brachipoda) del Pérmico inferior de Mendoza, Argentina. Ameghiniana 23 (1–2), 57–60.

Lech, R.R., 1990. Distribución de la fauna de braquiópodos de la Formación Agua del Jagüel (Carbonífero superior–Pérmico inferior). Provincia de Mendoza. Argentina. 11° Congreso Geológico Argentino, Actas 2, 15–18.

Lech, R.R., 2002. Consideraciones sobre la edad de la Formación Agua del Jagüel (Carbonífero superior), provincia de Mendoza, Argentina. 15° Congreso Geológico Argentino, Actas 3, 142–146.

Llambías, E.J., Sato, A.M., 1995. El batolito de Colangüil: transición entre orogénesis y anorogénesis. Revista de la Asociación Geológica Argentina 50 (1–4), 111–131.

Lugmair, G.W., Marti, K., 1978. Lunar initial $^{143}Nd/^{144}Nd$: differential evolution of the lunar crust and mantle. Earth and Planetary Science Letters 39, 349–357.

Michard, A., Gurriet, P., Soudant, M., Albarede, F., 1985. Nd isotopes in French Phanerozoic shales: external vs. internal aspects of crustal evolution. Geochemical and Cosmochimical Acta 49, 601–610.

Mpodozis, C., Kay, S.M., 1992. Late Paleozoic to Triassic evolution of the Gondwana margin: Evidence from Chilean Frontal Cordilleran batholiths (28°S to 31°S). Geological Society of America Bulletin 104 (8), 999–1014.

Padula E.L., Rolleri, E.O., Mingramm, A., Criado Roque, P., Flores, M., Baldis, B., 1967. Devonian of Argentina. In: International Symposium on the Devonian System Proceedings, vol. 2, pp.165–199.

Pearce, J.A., 1983. Role of the sub-continental lithosfere in magma genesis at active continental margins. In: Hawkesworth, C.J., Norry, M.J. (Eds.), Continental Basalts and Mantle Xenoliths. Shiva Press, Nantwich, UK, pp. 230–249.

Pearce, J.A., Gale, G.H., 1977. Identification of ore-deposition environment from trace element geochemistry of associated igneous host rocks. Geological Society of London Special Publication 7, 14–24.

Pearce, J.A., Norry, M.J., 1979. Petrogenetic implications of Ti, Zr, and Nb variations in volcanic rocks. Contributions to Mineralogy and Petrology 69, 33–47.

Peccerillo, R., Taylor, S.R., 1976. Geochemsitry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. Contributions to Mineralogy and Petrology 58, 63–81.

Pouclet, A., Lee, J.S., Vidal, P., Cousens, B., Bellon, H., 1994. Cretaceous to Cenozoic volcanism in South Korea and in the Sea of Japan: magmatic constraints on the opening of the back-arc basin. In: Smellie J.L. (Ed.), Volcanism Associated with Extension at Consuming Plate Margins. Geological Society Special Publication, vol. 81, pp 169–191.

Ramos, V.A., 1988. The tectonics of the Central Andes: 30° to 33° S latitude. In: Clark, S. and Burchfiel, D. (Eds.) Processes in Continental Lithospheric Deformation. Geological Society of America, Special Paper, vol. 218, pp. 31–54.

Ramos, V.A., Kay, S.M., 1991.Triassic rifting and associated basalts in the Cuyo basin, central Argentina. In: Harmon, R.S. Rapela, C.W. (Eds.) Andean magmatism and its tectonic setting. Geological Society of America, Special Paper, vol. 265, pp. 79–91.

Remane, J., 2000. International Stratigraphic Chart. Division of Earth Sciences, UNESCO and International Union of Geological Sciences.

Saunders, A.D., Tarney, J., 1984. Geochemical characteristics of basaltic volcanism within back-arc basins. In: Kokelaar, B.P., Howells, M.F. (Eds.), Marginal Basin Geology: Volcanic and Associated Sedimentary and Tectonic Processes in Modern and Ancient Marginal Basins. Geological Society Special Publication, London, vol. 16, pp. 59–76.

Shervais, J.W., 1982. Ti–V plots and the petrogenesis of modern and ophiolitic lavas. Earth and Planetary Science Letters 59, 101–118.

Steiger, R.H., Jager, E., 1977. Subcommission on geochronology: convention of the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters 36, 359–362.

Stipanicic, P.N., Rodrigo, F., Baulíes, O.L., Martínez, C.G., 1968. Las formaciones presenonianas en el denominado Macizo Nordpatagónico. Revista de la Asociación Geológica Argentina 32 (2), 67–98.

Taboada, A.C., 1984. Formación Agua del Jagüel, Paleozoico superior de Precordillera, Uspallata – Mendoza, Argentina. Annual Meeting of Working Group Project 211 IUGS-UNESCO, Boletin 41.

Taboada, A.C., 1986. Estratigrafía y contenido paleontológico de la Formación Agua del Jagüel, Pérmico inferior de la Precordillera Mendocina. Primeras Jornadas Geológicas de la Precordillera (San Juan 1985), Actas 1, 181–186.

Winchester, J.A., Floyd, P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using inmobile elements. Chemical Geology 20, 325–343.

Wood, D.A., 1980. The application of a Th–Hf–Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary province. Earth and Planetary Science Letters 50, 11–30.