HORIZON - DON AU

Reprinted from

EARTH AND PLANETARY SCIENCE LETTERS

Earth and Planetary Science Letters 172 (1999) 83–96

$^{40}Ar/^{39}Ar$ dating of the Jurassic volcanic province of Patagonia: migrating magmatism related to Gondwana break-up and subduction

G. Féraud [a,*], V. Alric [a,b], M. Fornari [a], H. Bertrand [c], M. Haller [b]

[a] UMR 6526 Géoscience Azur, CNRS–IRD, Université de Nice–Sophia Antipolis, Parc Valrose, 06108 Nice Cedex 02, France
[b] Universidad Nacional de la Patagonia San Juan Bosco, Puerto Madryn, Chubut, Argentina
[c] Laboratoire de Géologie, UMR 5570 CNRS, Ecole Normale Supérieure de Lyon et UCBL, 46 Allée d'Italie, 69364 Lyon Cedex 07, France

Received 20 January 1999; revised version received 24 June 1999; accepted 29 July 1999

EARTH AND PLANETARY SCIENCE LETTERS

PUBLICATION INFORMATION

Earth and Planetary Science Letters (ISSN 0012-821X). For 1999 volumes 164–173 are scheduled for publication. Subscription prices are available upon request from the publisher. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, PR China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues must be made within six months of our publication (mailing) date.

Orders, claims, product enquiries: please contact the Customer Support Department at the Regional Sales Office nearest to you:

New York: Elsevier Science, PO Box 945, New York, NY 10159-0945, USA; phone: (+1) (212) 633 3730, [toll free number for North American customers: 1-8884ES-INFO (437-4636)]; fax: (+1) (212) 633 3680; e-mail: usinfo-f@elsevier.com
Amsterdam: Elsevier Science, PO Box 211, 1000 AE Amsterdam, The Netherlands; phone: (+31) 20 4853757; fax: (+31) 20 4853432; e-mail: nlinfo-f@elsevier.nl
Tokyo: Elsevier Science, 9-15 Higashi-Azabu 1-chome, Minato-ku, Tokyo 106-0044, Japan; phone: (+81) (3) 5561 5033; fax: (+81) (3) 5561 5047; e-mail: info@elsevier.co.jp
Singapore: Elsevier Science, No. 1 Temasek Avenue, #17-01 Millenia Tower, Singapore 039192; phone: (+65) 434 3727; fax: (+65) 337 2230; e-mail: asiainfo@elsevier.com.sg
Rio de Janeiro: Elsevier Science, Rua Sete de Setembro 111/16 Andar, 20050-002 Centro, Rio de Janeiro - RJ, Brazil; phone: (+55) (21) 509 5340; fax: (+55) (21) 509 1991; e-mail: elsevier@campus.com.br [Note (Latin America): for orders, claims and help desk information, please contact the Regional Sales Office in New York as listed above]

US mailing notice: *Earth and Planetary Science Letters* (ISSN 0012-821X) is published twice monthly by Elsevier Science B.V., Molenwerf 1, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. The annual subscription price in the USA is US $2490 (US$ price valid in North, Central and South America). Periodicals postage paid at Jamaica, NY 11431. **USA POSTMASTERS:** Send address changes to *Earth and Planetary Science Letters*, Publications Expediting Inc., 200 Meacham Avenue, Elmont, NY 11003. **AIRFREIGHT AND MAILING** in the USA by Publications Expediting Inc., 200 Meacham Avenue, Elmont, NY 11003.

ELSEVIER

Earth and Planetary Science Letters 172 (1999) 83–96

EPSL

www.elsevier.com/locate/epsl

$^{40}Ar/^{39}Ar$ dating of the Jurassic volcanic province of Patagonia: migrating magmatism related to Gondwana break-up and subduction

G. Féraud [a,*], V. Alric [a,b], M. Fornari [a], H. Bertrand [c], M. Haller [b]

[a] UMR 6526 Géoscience Azur, CNRS–IRD, Université de Nice–Sophia Antipolis, Parc Valrose, 06108 Nice Cedex 02, France
[b] Universidad Nacional de la Patagonia San Juan Bosco, Puerto Madryn, Chubut, Argentina
[c] Laboratoire de Géologie, UMR 5570 CNRS, Ecole Normale Supérieure de Lyon et UCBL, 46 Allée d'Italie, 69364 Lyon Cedex 07, France

Received 20 January 1999; revised version received 24 June 1999; accepted 29 July 1999

Abstract

The Mesozoic large igneous province (LIP) of Patagonia (southern South America), which is one of the largest silicic provinces on Earth has been investigated by the $^{40}Ar/^{39}Ar$ method. Twenty-seven ages considered as valid, including twenty plateau ages, show that the volcanic activity, ranging from 187 to 144 Ma, occurred between and contemporaneously with the initial break-up of Gondwana (starting with the Karoo–Antarctic–Tasmanian (KAT) flood basalt province) in the east, and a subduction in the west. The data display a regular decreasing of ages from the ENE (187 Ma) to the WSW (144 Ma) along about 650 km, apparently related to the tectonic structure in half-grabens oriented NNW–SSE. The good fitting of this trend with the opening of the Rocas Verdes–Sarmiento marginal basin favors a space–time evolution of this continental volcanism culminating towards the SSW in a continental disruption behind the magmatic arc. The observed age progression of volcanism may be the result of the variations of the physical characteristics of the subduction. The spreading and thermal effect of the KAT plume may have an additional effect and also could account for the unusually large volume of magma.

Keywords: geochronology; Jurassic; magmatism; Patagonia; acidic magmas

1. Introduction

Whereas flood basalt provinces were extensively studied in various aspects (petrology, geochemistry, geochronology, paleomagnetism, etc.), leading to numerous genetic models, the characteristics and the origin of the large-scale silicic igneous provinces remain largely unknown. Moreover, the flood basalt provinces are commonly considered as representing the large igneous provinces (LIP), whereas the silicic provinces are more generally seen as minor components of the Earth igneous provinces.

The Mesozoic volcanic province of Patagonia, in southern South America (Fig. 1), represents one of the largest silicic provinces in the world, at least three times as large as the more known Tertiary Sierra Madre Occidental province, in Mexico [1]. Its estimated volume (around 235,000 km^3 according to Pankhurst et al. [5]) is for instance higher than that of the Columbia River mafic LIP. The previous geochronological data performed on this

* Corresponding author. Fax: +33 4 92 07 68 16; E-mail: feraud@unice.fr

0012-821X/99/$ – see front matter
PII: S0012-821X(99)00190-9

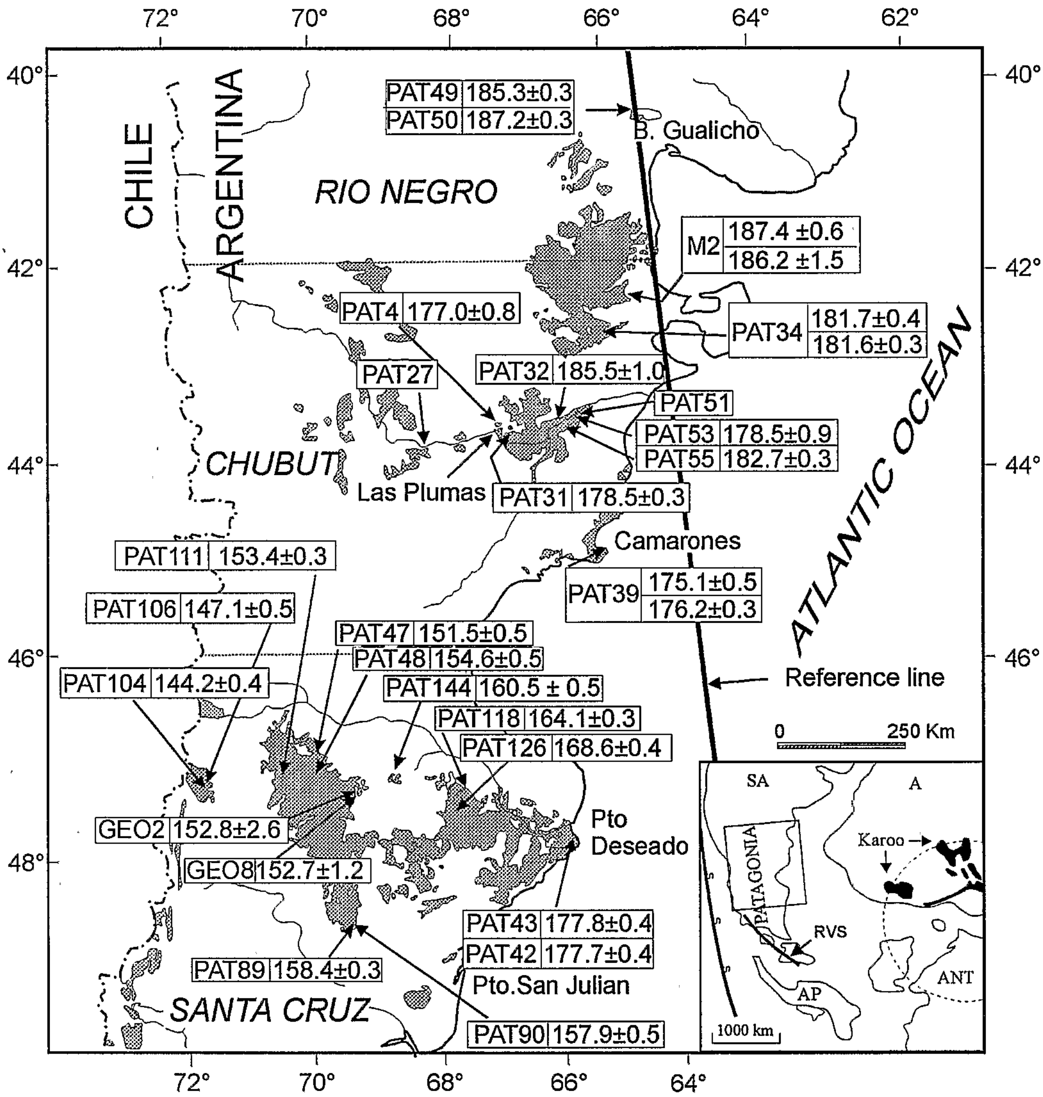

Fig. 1. Sketch map of the Jurassic volcanism of Patagonia, and location of analysed samples. The $^{40}Ar/^{39}Ar$ ages are in Ma with error bars at the 1σ level and represent either plateau ages or ages considered as valid (discussed in the text). The oblique line represents the reference line parallel to the grabens represented in Fig. 2, and used for distance calculations of rock samples on Fig. 7. In the insert is indicated the location of the studied region in a schematic early Middle Jurassic (about 183 Ma) reconstruction of Gondwana (after [7], modified). *SA* = South America, *A* = Africa, *AP* = Antarctica Peninsula, *ANT* = Antarctica, *RVS* = Rocas Verdes–Sarmiento basin. The assumed mantle plume head of Karoo (dashed circle) and subduction are also shown.

province [2–4] (see a review in [5]) show that this volcanism occurred between the initial break-up of Gondwana (marked in the east by the formation of the mantle plume-related Continental Flood Basalt province of Karoo–Antarctica–Tasmanian (KAT–CFB) about 180–184 Ma ago [6–10]) and the earliest true seafloor spreading in the Mozambique basin around 155 Ma [11]. At the western side, a subduction zone was acting during this time interval [12] (Fig. 1) but its location and geometry are uncertain. A marginal oceanic basin (Rocas Verdes–Sarmiento basin) related to this subduction, and in a back-arc position is supposed to be opened in the latest Jurassic [13,14] (Figs. 1 and 2). Moreover, it has been

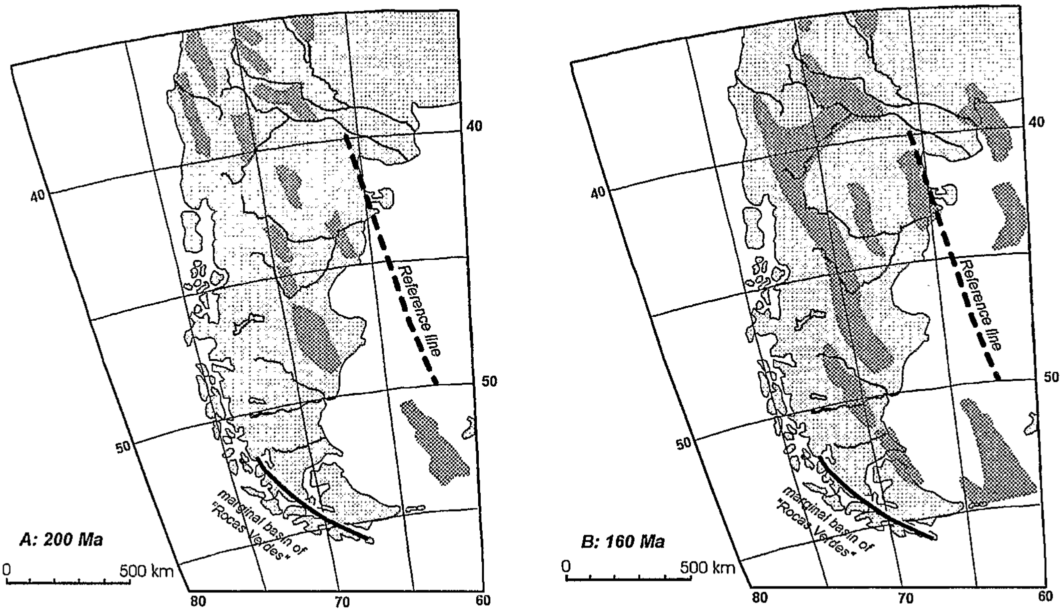

Fig. 2. Mid-Late Triassic (A) and Middle Jurassic (B) paleogeographic reconstructions of southern South America illustrating troughs and sags, after Uliana and Biddle [22]. These half-grabens defining the main Jurassic tectonic structure of the region, its direction is used as a reference line for the volcanism migration plotted in Fig. 7. The location of the future Rocas Verdes–Sarmiento marginal basin is indicated on both maps.

suggested that the Mesozoic Patagonian volcanism was related to large-scale half-grabens, mainly oriented NNW–SSE [15,16]. Hence, this volcanism corresponds to a broad extensional province (1) covering a large continental area stretching between a subduction plate boundary and plume-related CFBs, and (2) preceding the formation of the earliest South Atlantic seafloor (in the east) and a marginal basin (in the west).

Therefore, the Jurassic Patagonian volcanics represent a key-marker of the tectono-magmatic processes accompanying the initial break-up of Gondwana. The appraisal of its space–time evolution (and composition) will contribute to constrain (1) the genetic relationships between this extensional province and the initial fragmentation of Gondwana, e.g. whether it may have resulted in seafloor opening in South Atlantic, and (2) the relative contributions of the eastern mantle plume and the western subduction in the initiation and evolution of the investigated province, and therefore the interactions between these synchronous events.

By performing detailed $^{40}Ar/^{39}Ar$, it will be shown that this province is characterized by a regular and clear 650 km migration of the volcanism from ENE to WSW spanning 40 Ma, apparently related to the formation of the Rocas Verdes–Sarmiento marginal basin, at the end of this period. It will be proposed that this migration may be the result of the variations of the physical characteristics of the subduction. The contemporaneity of the initiation of the plume-related CFBs and the Patagonian province favors an additional thermal effect of the KAT plume.

2. Geological setting

The investigated Mesozoic volcanic province of Patagonia covers an area of around 10^6 km^2, in the Rio Negro, Chubut and Santa Cruz provinces of Argentina (Fig. 1), represented by huge outcrops and both onshore and offshore subsurface occurrences. The minimum thickness is more than 500 m in many places [4] and up to 2200 m in Santa Cruz (offshore and onshore), as deduced from seismic and drilling data [16]. These volcanics, described in more details by [15,17–21] among others, were locally named the Marifil, Lonco Trapial, Bahia Laura, Tobifera, El Quemado groups and the Chon Aike, La Matilde, Bajo Pobre, Lemaire, Ibanez formations.

Seismic evidence relates most of this volcanism to the NNW–SSE-trending large-scale half-grabens developed through Patagonia during Jurassic times, the thickest accumulations occurring within the grabens [15,16]. The paleogeographic reconstructions [22] suggest a ENE to WSW propagation of the grabens during Jurassic times (Fig. 2). Hence this volcanotectonic province may define a widespread back-arc extensional setting. The limit between arc and back-arc volcanics in the whole province remains to be clarified. For instance, it is not clear whether the westernmost El Quemado–Ibanez volcanics belong to this extensional system or are remnants of volcanic arc activity [17,23]. Moreover, it has been suggested that the Jurassic magmatic rocks of the Antarctic Peninsula represent the southwards extension of the Patagonian province presently studied [24], whereas they were also considered as mainly remnants of the magmatic arc [12,25,26], the back-arc volcanics being restricted to the SE margin of the Peninsula.

3. Field, petrographic and geochemical characteristics

In the Chubut and Rio Negro provinces, rhyolitic outcrops largely predominate east of 67°30 W longitude (Marifil group), whereas westwards they gradually change to andesites (Lonco Trapial group). In the transition zone, i.e. in the Rio Chubut valley near Las Plumas, the two groups interdigitate, the andesites being overlain by the rhyolites. However, in the eastern part of Rio Chubut, a dyke-in-dyke system, trending N120–130, composed of both rhyolites and andesites, intrudes rhyolitic pyroclastites. Hence andesitic and rhyolitic activity may have been coeval in places. In Santa Cruz, silicic outcrops largely predominate throughout the province with an exposed thickness ranging from 200 to 600 m [20]. They are mapped either as the Chon Aike lower formation and La Matilde upper formation or as the undifferentiated Bahia Laura group [21]. They overlay andesitic units (Bajo Pobre formation) which outcrop sporadically with a visible thickness averaging 150–200 m. All these formations are sub-horizontal. Seismic and drill data reveal higher thicknesses of 600–1200 m and 800–1600 m for rhyolitic and andesitic formations, respectively [16].

Silicic outcrops mainly consist of ignimbritic units, each 10 to 100 m thick, associated locally with lava-flows and subvolcanic domes. The main petrographic types studied here are crystal-rich welded rhyolitic to rhyodacitic ignimbrites with felsitic to eutaxitic textures commonly displaying elongated fiammes. The glassy groundmass suffered various degrees of devitrification. Lithic fragments of ignimbrite, pumice and trachyte are included in some facies. The observed phenocrysts are (in decreasing amounts) embayed quartz, sanidine, sodic plagioclase, biotite more or less chloritized and opaque minerals. Discrete zircon grains can also occur. Samples from lava-flows or domes have the same mineralogy. Porphyritic trachytes containing phenocrysts of plagioclase, sanidine and hornblende were also recovered in the dyke system mentioned above.

Andesitic outcrops consist in superposed lava-flows and remnant domes. Petrographically, they range from andesitic basalts (containing augite and olivine phenocrysts in a groundmass made of plagioclase, alkali feldspar, augite and Ti-magnetite) to andesites, generally porphyritic and occasionally subaphyric, containing zoned plagioclase, augite, orthopyroxene and Fe–Ti oxides as phenocrysts and plagioclase, augite and glass as groundmass.

The samples selected for this study are not significantly affected by hydrothermal alteration and/or low-grade metamorphism, although these processes modified more or less severely the primary parageneses when approaching the cordillera (mostly in the Lonco Trapial and El Quemado formations).

Major element compositions display a strongly bimodal distribution mainly in Santa Cruz (Fig. 3): SiO_2 varies 51–61% for basaltic andesites–andesites and 71–82% for rhyolites with very few intermediate (dacite/trachydacite) lavas. The compositions define typical calc-alkaline trends, as illustrated by the $Na_2O + K_2O$–FeO–MgO (AFM) diagram and trace element patterns characterized by a strong enrichment in light rare earth elements (LREE) and large ion lithophile elements (LILE) and depletion in Nb–Ta. The detailed geochemistry and petrogenesis will be discussed elsewhere.

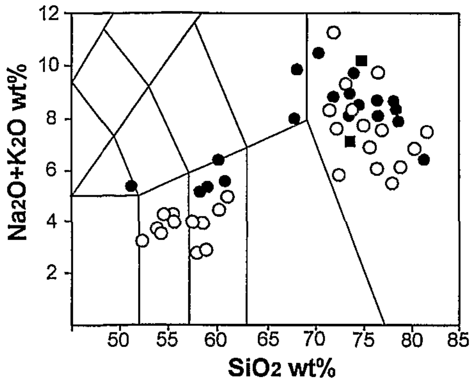

Fig. 3. Total alkali–silica diagram for the Mesozoic volcanics from Chubut (dots) and Santa Cruz (circles for Deseado formation and squares for El Quemado group) provinces (fields after Le Bas et al. [41]), data recalculated to volatile-free total of 100%.

4. Results

Twenty-seven samples of andesite, rhyolite and ignimbrites were analyzed by the $^{40}Ar/^{39}Ar$ step heating procedure on single grains and bulk samples of sanidine, biotite, plagioclase and amphibole, and whole rocks. Grain sizes for single grain analyses are on the order of 200–1000 μm. The grain sizes for the sanidine and plagioclase bulk samples are 160–250 μm, and the analyzed weight for plagioclases was 10–11 mg. The samples were irradiated in the nuclear reactor at the McMaster University in Hamilton, Canada, in position 5c. The total neutron flux density during irradiation is 8.8×10^{18} n cm^{-2}, with a maximum flux gradient estimated at ±0.2% in the volume where the samples were included. We used the Hb3gr hornblende as a flux monitor with an age of 1072 Ma [27]. The analytical procedures of single grains and bulk sample analyses are described in details in [28] and [29], respectively. The bulk sample analyses were performed with a mass spectrometer composed of a 120° M.A.S.S.E. tube, a Baur-Signer GS 98 source and a Balzers electron multiplier. The gas extraction of single grains and whole rocks was carried out by a Coherent Innova 70-4 continuous laser. It must be noticed that for the sanidine single grains, it was often necessary to interrupt the degassing before the usual heating time of 60 s in order to avoid a sudden unexpected fusing of the grain, for the last or 2 last steps before the fusion step. The mass spectrometer is a VG 3600 working with a Daly detector system. The typical blank values of the extraction and purification laser system are ranging from 9 to 5×10^{-13} ccSTP for ^{40}Ar, 8 to 1×10^{-14} ccSTP for ^{39}Ar, 2 to 1×10^{-13} ccSTP for ^{37}Ar, and 7 to 3×10^{-14} ccSTP for ^{36}Ar, measured every third step. The criteria for defining plateau ages were the following: (1) it should contain at least 70% of released ^{39}Ar, (2) there should be at least three successive steps in the plateau, and (3) the integrated age of the plateau should agree with each apparent age of the plateau within a 2 sigma (2σ) error confidence interval. All errors are quoted at the 1σ level and do not include the errors on the age of the monitor. The error on the $^{40}Ar^{*}/^{39}Ar_K$ ratio of the monitor is included in the plateau age error bar calculation. A summary of the geochronological data is given in Table 1. In Table 1 and Fig. 1, only the ages which are considered as valid (and discussed in the following section) are reported. The detailed table of data may be obtained upon request.

4.1. The Rio Negro and Chubut provinces

The investigated rocks from Rio Negro and the north of Chubut belong to the Marifil group. Plateau ages of 187.2 ± 0.3 Ma and 185.3 ± 0.3 Ma (except the seventh step, affected by an analytical problem) were respectively obtained on sanidine single grains from a rhyolitic lava (PAT50) and an ignimbrite (PAT49) from the Salina El Gualicho area (Rio Negro Province) (Fig. 4). A second grain of PAT49 displayed a more disturbed age spectrum with a weighted mean age of 186.3 ± 0.3 Ma concordant with the plateau age. An ignimbrite (M2) located about 400 km southwards in the Marifil massif gave a plateau age of 186.2 ± 1.5 Ma on one sanidine grain whereas a second grain gave a concordant fusion step age of $187.4 \pm 0.6_{Ma}$. Two concordant younger plateau ages of 181.6 ± 0.3 and 181.7 ± 0.4 Ma where obtained on sanidine single grains of an ignimbrite (PAT34) from the same massif (Fig. 4).

The analyzed rocks from central Chubut belong to the Marifil group except the samples PAT31 and PAT27 from the Lonco Trapial group, east of Las Plumas. A plateau age of 186.2 ± 1.5 Ma was displayed by the biotite PAT32 (on 91% of ^{39}Ar released), but because of the decreasing of the age

Table 1
Summary of geochronological data (error bars are given at the 1σ level)

Formation	Province	Sample	Mineral	Rock	^{39}Ar (%)	Accepted age (Ma)	Plateau age	Comment
Marifil	Rio Negro	PAT49	Sanidine	Rhyolite (ignimbrite)	100	185.3 ± 0.3	yes	
						186.3 ± 0.3	no	
Marifil	Rio Negro	PAT50	Sanidine	Rhyolite (lava)	100	187.2 ± 0.3	yes	
Marifil	NE Chubut	M2	Sanidine	Rhyolite (ignimbrite)	96.1	186.2 ± 1.5	yes	
					88.9	187.4 ± 0.6	no	one step
Marifil	NE Chubut	PAT34	Sanidine	Rhyolite (ignimbrite)	100	181.6 ± 0.3	yes	
					100	181.7 ± 0.4	yes	
Marifil	E. Chubut	PAT51	Whole rock	Andesite (dyke)	–	–	no	
Lonco Trapial	Central Chubut	PAT27	Whole rock	Andesite (lava)	–	–	no	
Marifil	E. Chubut	PAT55	Sanidine	Rhyolite (ignimbrite)	96.3	182.7 ± 0.3	yes	
Marifil	E. Chubut	PAT53	Amphibole	Trachyte (dyke)	100	178.5 ± 0.9	yes	
Marifil	E. Chubut	PAT31	Biotite	Rhyolite (ignimbrite)	95.6	178.5 ± 0.3	yes	
Marifil	E. Chubut	PAT4	Biotite	Trachy-basalt (lava)	91.7	177.0 ± 0.8	yes	
Marifil	SE Chubut	PAT39	Sanidine	Trachyte (ignimbrite)	100	175.1 ± 0.5	yes	
						176.2 ± 0.3	no	w.m. fusions
Marifil	E. Chubut	PAT32	Biotite	Rhyolite (ignimbrite)	61.9	185.5 ± 1.0	no	may be affected by chloritization
Bajo Pobre	Santa Cruz	PAT118	Whole rock	Basaltic andesite (lava)	74.7	164.1 ± 0.3	yes	
Bajo Pobre	Santa Cruz	PAT144	Whole rock	Basaltic andesite (lava)	51.3	160.5 ± 0.5	no	w.m. high temperature
Bajo Pobre	Santa Cruz	GEO8	Plagioclase	Andesite (lava)	85.0	152.7 ± 1.2	yes	
Bajo Pobre	Santa Cruz	GEO2	Plagioclase	Andesite (lava)	79.3	152.8 ± 2.6	yes	
Chon Aike	Santa Cruz	PAT126	Sanidine	Rhyolite (ignimbrite)	93.4	168.6 ± 0.4	yes	
Chon Aike	Santa Cruz	PAT111	Sanidine	Rhyolite (ignimbrite)	92.2	153.4 ± 0.3	yes	
Chon Aike	E. Santa Cruz	PAT42	Sanidine	Rhyolite (ignimbrite)		177.7 ± 0.4	no	w.m. high temperature
Chon Aike	E. Santa Cruz	PAT43	Sanidine	Rhyolite (ignimbrite)	82.5	177.8 ± 0.4	yes	one step lacking
Chon Aike	Santa Cruz	PAT48	Sanidine	Rhyolite (ignimbrite)	87.3	154.6 ± 0.5	yes	
Chon Aike	Santa cruz	PAT47	Sanidine	Rhyolite (ignimbrite)	95.4	151.5 ± 0.5	yes	
Chon Aike	Santa Cruz	PAT89	Sanidine	Rhyolite (ignimbrite)	100	158.4 ± 0.3	yes	
Chon Aike	Santa Cruz	PAT90	Sanidine	Rhyolite (ignimbrite)	100	157.9 ± 0.5	yes	
El Quemado	W. Santa Cruz	PAT104	Sanidine	Rhyolite (ignimbrite)	87.8	144.2 ± 0.4	yes	
El Quemado	W. Santa Cruz	PAT106	Biotite	Rhyolite (ignimbrite)	97.0	147.1 ± 0.5	yes	

w.m. = weighted mean.

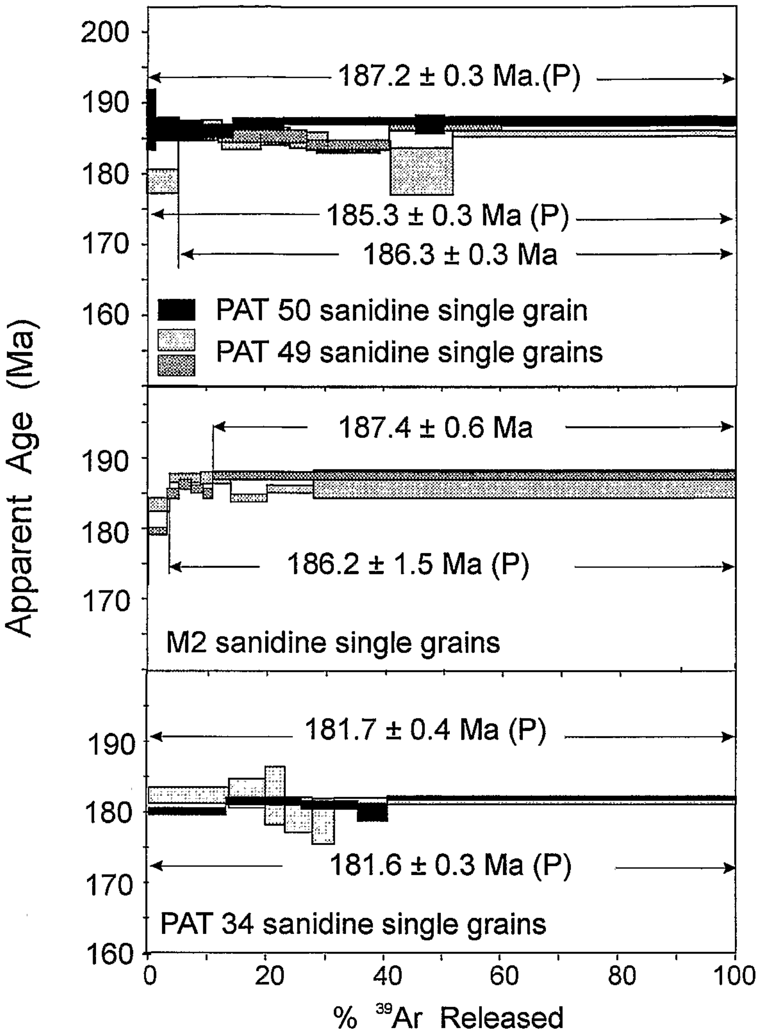

Fig. 4. $^{40}Ar/^{39}Ar$ age spectra obtained on single grains of sanidine from ignimbrites and rhyolites from the Rio Negro province and the north Chubut province (Patagonia). Plateau ages are indicated by *(P)*.

spectrum which probably indicates a chloritization of the mineral (as observed on thin sections), we prefer to retain the high-temperature weighted mean of 185.5 ± 1.0 Ma calculated on the three concordant high-temperature steps (Fig. 5). Nevertheless, although we shall consider this age in the following discussion, it must be taken cautiously. In the same region, lower plateau ages ranging from 177.0 ± 0.8 to 182.7 ± 0.3 Ma (PAT4, 31, 53, 55), were obtained on amphibole, sanidine and biotite single grains from rocks varying from andesitic basalt (PAT4) to rhyolite and ignimbrite. On one of the two analyzed biotites of PAT4, a disturbed age spectrum, which may be the result of a chloritization and subsequent ^{39}Ar recoil effect, shows a high-temperature apparent age concordant with the plateau age obtained on the other grain.

The andesitic whole rocks PAT51 and PAT 27 displayed complex age spectra probably due (at least partly) to a recoil of ^{39}Ar during the irradiation, but the apparent ages at intermediate temperature (before the degasing of low-K minerals, as shown by the higher $^{37}Ar/^{39}Ar$ ratio, enriched in ^{39}Ar by recoil (Fig. 5), are around 174 Ma for PAT51 (similar

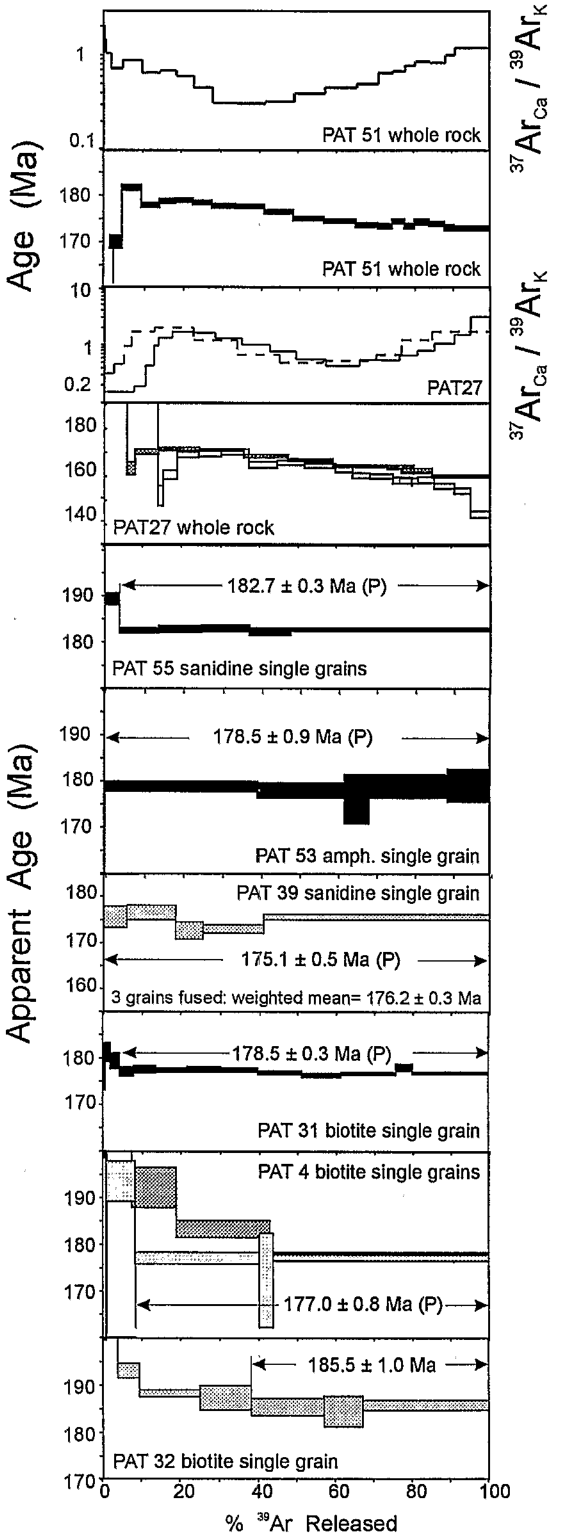

Fig. 5. $^{40}Ar/^{39}Ar$ age and $^{37}Ar/^{39}Ar$ ratio spectra obtained on amphibole, sanidine, biotite single grains and whole rocks from andesites, rhyolite and ignimbrites of the central Chubut province (Patagonia). Plateau ages are indicated by *(P)*.

to previously mentioned plateau ages from the same region), and 165 Ma for PAT 27 (located more westwards in the Chubut valley). These ages will not be considered as valid ages. Nevertheless, because of its crucial location (see below), the intermediate temperature age of PAT27, which must be taken cautiously, is reported in Fig. 7.

At last, sanidine single grains of the ignimbrite PAT39 from the Camarones region (southeast Chubut) displayed one plateau age at 175.1 ± 0.5 Ma concordant (at the 2σ level) with the weighted mean of 176.2 ± 0.3 Ma calculated from total fusion ages measured on three other sanidine single grains (Fig. 5).

4.2. The Santa Cruz province

Most of the dated ignimbrites belong either to the Chon Aike formation or to the undifferentiated Bahia Laura group, and the investigated andesites are from the Bajo Pobre formation. The westernmost samples PAT104 and PAT106 belong to the El Quemado group [18].

At the furthest east of the province, near Puerto Deseado (Fig. 1), the sanidine bulk sample from the ignimbrite PAT43 displays a plateau age (despite an analytical problem on one step) of 177.8 ± 0.4 Ma (calculated on 21 steps) (Fig. 6b). An other sample from the same area (ignimbrite PAT42) did not show plateau ages on each of the three analyzed single grains, but the last or two last steps, representing more than 73% of the ^{39}Ar, released display concordant ages ranging from 177.5 ± 0.5 Ma to 178.5 ± 0.9 Ma, with a weighted mean of 177.7 ± 0.4 Ma. This age, indistinguishable from the accepted age for the previous sample, is considered as a valid age.

Further to the west, a sanidine from the ignimbrite PAT126 displays a plateau age of 168.5 ± 0.4 Ma (Fig. 6a). The two andesite whole rocks PAT118 and PAT144 displayed disturbed age spectra probably due to alteration phases released at low temperature, but a plateau age of 164.1 ± 0.3 Ma could be obtained

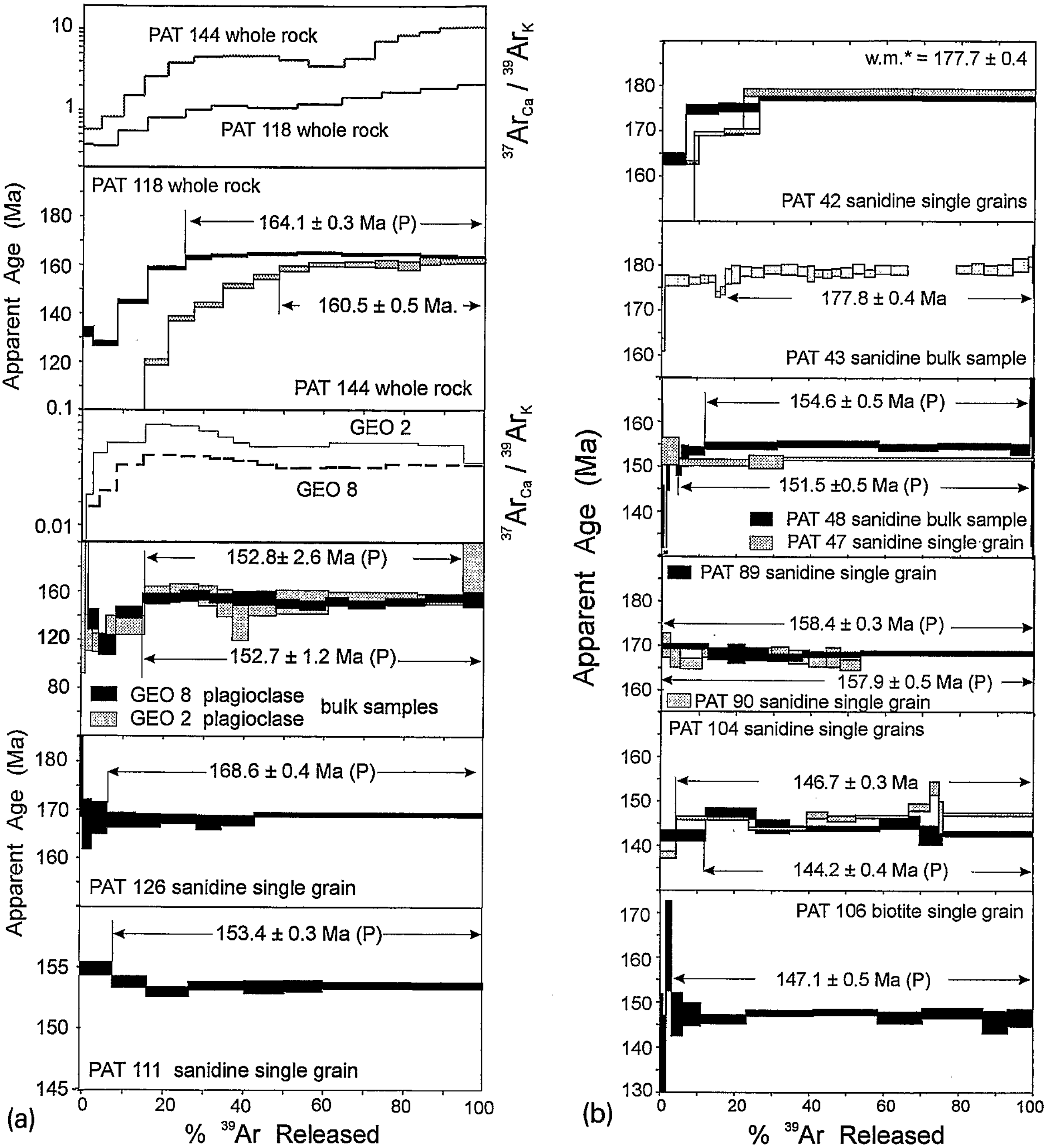

Fig. 6. $^{40}Ar/^{39}Ar$ age and $^{37}Ar/^{39}Ar$ ratio spectra obtained on plagioclase and sanidine bulk samples, sanidine and biotite single grains and whole rocks from andesites, rhyolites and ignimbrites of the Deseado and El Quemado formations from Santa Cruz Province (Patagonia). Plateau ages are indicated by *(P)*; *w.m.(*)* = weighted mean ages calculated on high-temperature steps (see text).

on PAT118. The weighted mean of 160.5 ± 0.5 Ma, calculated on the seven last steps of PAT144, does not represent a plateau age and must be cautiously considered, but because of the concordance of its apparent high-temperature ages with the PAT118 plateau age, this age is probably not far from the true age. We shall retain this age in the discussion because of the crucial location of this sample (Fig. 1).

Two plagioclase bulk samples separated from the andesites GEO2 and GEO8, displayed concordant plateau ages of 152.8 ± 2.6 and 152.7 ± 1.2 Ma, respectively (Fig. 6a). Single grains (PAT111, Fig. 6a; PAT47, Fig. 6b) and bulk sample (PAT48, Fig. 6b) of sanidine gave plateau ages of 153.4±0.3, 151.5±0.5, and 154.6 ± 0.5 Ma.

The sanidine single grains from the southernmost investigated ignimbrites PAT89 and PAT90 displayed two concordant plateau ages of 158.4 ± 0.3 Ma and 157.9 ± 0.5 Ma, respectively (Fig. 6b).

At the furthest west of the province (El Quemado group), one biotite single grain displayed a plateau age of 147.1 ± 0.5 Ma (ignimbrite PAT106, Fig. 6b), whereas sanidine single grains (four analyses, two of them are shown on Fig. 6b) gave disturbed age spectra (ignimbrite PAT104). Nevertheless one plateau age at 144.2 ± 0.4 Ma could be obtained on one of the sanidines.

5. Comparison with previous age data

Previous geochronological data are reviewed in detail by Pankhurst et al. [5]. In the Chubut province, when compared to the Rb/Sr whole rock data [4, 19], several results are in reasonable agreement. For instance, we observe a good concordance of data in the Marifil complex (188 ± 1 Ma, compared to our 187.4 ± 0.6 and 186.2 ± 1.5 Ma obtained on the M2 sample), and in the center of the Chubut Province (location of PAT27), where the Rb/Sr age of 169 ± 2 Ma fits well with our general time–distance trend (see Fig. 7 and below), despite a lack of good quality $^{40}Ar/^{39}Ar$ data in this area. Nevertheless, on the same complex, our ages are older than the 174 ± 2 Ma Rb/Sr isochron [4], and showing an unusually high initial $^{87}Sr/^{86}Sr$ ratio of 0.7127. They are more in agreement with the 183 ± 2 Ma obtained on two of their Marifil samples, corresponding to a more usual initial Sr ratio.

In the Peninsula Camarones, our ages of 176.2 ±

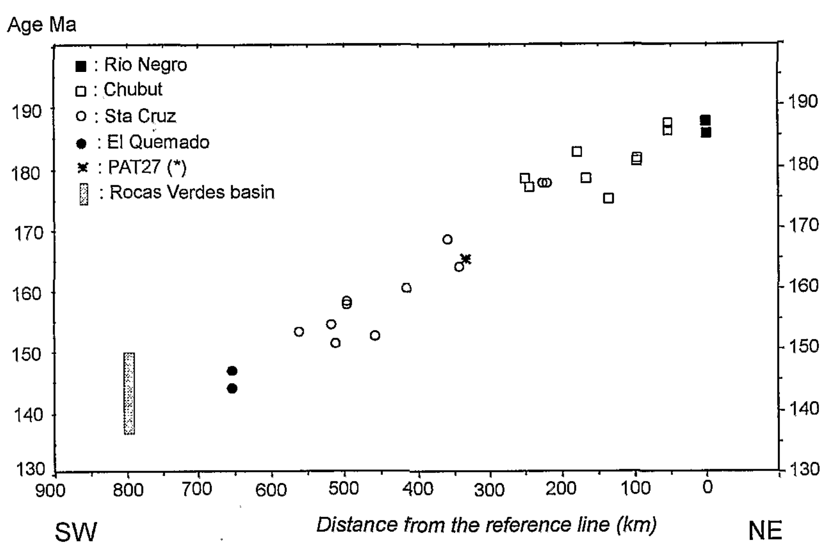

Fig. 7. Twenty-seven $^{40}Ar/^{39}Ar$ plateau ages and ages considered as valid (indicated also in Fig. 1, see text) versus the distance to an arbitrary line (shown in Fig. 1) parallel to the NNW–SSE-oriented grabens defined by Gust et al. [15] and Uliana and Biddle [22]. (*) Despite the poor quality results obtained on the whole rock PAT27 from Chubut, its estimated age has been plotted because this sample is located at the west of the other samples from the Province, and therefore it contributes to showing the continuity between the Chubut and Santa Cruz provinces data on this diagram. The approximate location and age (after [13,14,38,39]) of the Rocas Verdes marginal basin are shown.

0.3 and 175.1 ± 0.5 Ma are slightly younger than the 178 ± 1 Ma Rb/Sr age [19], whereas previous K–Ar conventional ages were scattered between 157 ± 3 Ma and 173 ± 3 Ma [2].

In the Santa Cruz province, our results differ significantly from previous Rb–Sr isochrons. In the region of Puerto Deseado, the Rb/Sr age of 168±2 Ma [18] is distinctly younger than the two concordant ^{40}Ar/^{39}Ar plateau ages of 177.7 and 177.8 (±0.4) Ma (PAT42, 43), whereas the Rb/Sr age of 162 ± 11 Ma [23] measured at the northwest of the Deseado massif is significantly higher than the three plateau ages of 151.5 ± 0.5, 154.6 ± 0.5 and 153.4 ± 0.2 Ma (PAT47, 48, 111) obtained in the same region. For the Bajo Pobre formation, ^{40}Ar/^{39}Ar plateau ages at 164 ± 2 Ma were previously obtained on plagioclase from basaltic andesites [30], of which the location is unknown, they are significantly higher than our ages of 152.7 and 152.8 Ma (GEO2-8) but in agreement with that obtained on PAT118 (164.1 ± 0.3 Ma. Our data from El Quemado group are partly in agreement with K/Ar ages measured on biotites, ranging from 142 ± 4 and 159 ± 4 Ma [31] and from 144 ± 3 and 150 ± 4 Ma [32].

6. Time–space evolution

The present data set displays a regular decrease of ages from the ENE towards the WSW of the studied region, with ages varying from around 187 to 144 Ma. It was previously suggested a southward migration over 20 Ma, from 188 to 169 Ma [4]. Our data rather suggest a migration of volcanic activity with larger age brackets (our youngest ages are partly in agreement with recent K/Ar ages measured at the southwest of the investigated area [31]), and which seems related to the NNW–SSE-oriented half-graben structure [15,22]. This is clearly demonstrated by a plot of the 25 ages considered as valid (including 20 plateau ages: see the previous section), versus the distance to a NNW–SSE straight reference line (shown in Fig. 1) parallel to the half-grabens and located arbitrarily at the sites of the samples PAT49 and 50 in the Rio Negro province. A very regular migration of volcanism appears over 650 km and during 43 Ma without showing any significant gap in the volcanic activity. Note the overlapping of the westernmost data from Chubut and the easternmost data from Santa Cruz, precluding a simple N–S migration. This strong time–space correlation argues for a control of the volcanic activity by an extensional system propagating across the whole of Patagonia during part of the Jurassic. This interpretation is consistent with the successive paleogeographic reconstructions of the graben system through the Jurassic in southern South America [22].

When they are both present in the same area, rhyolites and andesites do not show systematic age difference. This suggests a broad contemporaneity of felsic and mafic magmas in a given place, rather than significantly younger ages for the former as assumed by Panza et al. [20] in Santa Cruz. This is consistent with the bimodal andesitic–rhyolitic dyke-in-dyke system observed in eastern Chubut: the age of igneous activity is clearly controlled by the distance to the reference line and not by the stratigraphic position within the lava pile.

7. Geodynamic implications

During the period of 187–144 Ma of volcanic activity in the studied area of Patagonia, the geodynamic environment of southernmost South America is characterized as follows.

(1) To the east, extensional features related to the initial stages of break-up of Gondwana, and the emplacement of the large KAT–CFB province (Fig. 1). The Ferrar group (Antarctica) was dated mostly between 176 and 184 Ma (see the review of [9]), and based on precise U/Pb data around 184 Ma, the emplacement of the Karoo basalts is supposed to be synchronous [7,10]. The first phases of seafloor spreading between Africa and Antarctica occurred about 155 Ma ago (anomaly M22) near the Mozambique basin [11] and probably shortly later in the Weddell Sea [33].

(2) To the west, a subduction was supposed to be continuous from Southern America to Antarctica [34] (Fig. 1). In the Antarctic Peninsula, a magmatic arc is documented by plutons dated at 175–181 Ma [35]. By Middle to Late Jurassic times the magmatic focus migrated westwards as documented by volcanic rocks from Antarctica dated at 156 Ma [36]. In Patagonia, a magmatic arc is also documented

by the volcanics from the Lago de La Plata group (western Chubut), which are stratigraphically considered as Toarcian to Tithonian [37], but accurate dating and constraints on the evolution of the subduction geometry through Jurassic times are lacking. In the latest Jurassic–earliest Cretaceous, a marginal oceanic basin (Rocas Verdes–Sarmiento) opened in back-arc setting behind this magmatic arc from 51°S to 56°S [13,14,38,39] (Fig. 2).

Therefore, the study area in Patagonia represents a transition zone between continental rifting associated to abundant flood basalt volcanism, and a subduction. Ultimately continental break-up occurred, forming an oceanic domain on both sides.

Without sufficient precise data on the silicic volcanism, particularly in geochronology, it was difficult to evaluate the relative contributions of the eastern mantle plume and the western subduction in the initiation and evolution of the silicic province. In this respect, the discovery of a widespread ENE to WSW migration related to extensional structures does represent a strong constraint to any model on both the mechanisms of Gondwana break-up, and the variation of the characteristics of the western subduction, and also to evaluate the interactions between them.

The KAT–CFBs and the oldest investigated silicic volcanism were nearly synchronous (184 and 187 Ma, respectively), and therefore both may appear as precursors of the same rifting event leading to the break-up between east and west Gondwana. Nevertheless, the Jurassic volcanic activity in Patagonia clearly migrated to the WSW, i.e. in the opposite direction with respect to this break-up, some 155 Ma ago, precluding a direct relationship between the two processes. On the other hand, we observe that the marginal basin of Rocas Verdes–Sarmiento is aligned on our space–time volcanic trend (Fig. 7). These observations more satisfactorily support that this migration was related to extension propagating across Patagonia (towards the WSW), culminating in a distinct continental disruption and formation of oceanic crust in the Rocas Verdes–Sarmiento basin, near the subduction zone.

This apparent relationship between the Patagonian Jurassic volcanism and the Rocas Verdes–Sarmiento marginal basin allows to relate this volcanism propagation to the evolution of the subduction of the Pacific margin. It has been previously suggested that "a change from Gondwanide compression to lithospheric extension in the Jurassic is linked to a change from flat [40] to steeply dipping subduction, or to slowing of subduction rates" [12]. The corresponding modifications of the physical characteristics of the subduction (dip angle, rollback, age and density of the subducting plate, relative direction, etc.) may induce a migration of tensile stress in the overriding lithosphere, and therefore a progressive formation or reactivation of the half-grabens. The regular migration of volcanism may result from such a tectonic evolution.

A remaining question is the unusually large volume of dominantly silicic magma in such a context which cannot be easily explained without an additional thermal supply. The nearby mantle plume head, which produced the KAT–CFBs (Fig. 1) contemporaneously with the oldest Patagonian lava, is a potential candidate. The plume could generate convective heat in the mantle wedge which would widen consequently to the deepening and rollback of the subducted slab previously suggested. The observed volcanic age progression towards the WSW would therefore be the result of the combined effect of both displacement of the front of the convective heat and the progressive half-graben reactivation. This would require a persistent thermal effect of the plume head over at least 40 Ma. Although unusual, such an hypothesis was recently proposed beneath Africa [42].

8. Conclusion

(1) Twenty-seven ages considered as reliable (as discussed in the text), including twenty plateau ages, were obtained on sanidine and biotite single grains, sanidine bulk samples and whole rocks from rhyolitic ignimbrites and andesitic lavas from the Jurassic silicic LIP of Patagonia, investigated over a region of more than 10^6 km^2 from the Rio Negro to the Santa Cruz provinces of Argentina, and from the vicinity of the first Andean relieves to the eastern coast (Fig. 1). The data are in agreement with some previous Rb/Sr isochron data obtained on some common investigated formations [4,18,19] although some significant differences were observed.

(2) The similar ages obtained on rhyolitic and andesitic rocks from the same areas suggest a broad

contemporaneity of felsic and more mafic magmas, supporting a bimodal character of the Patagonian Jurassic volcanism.

(3) The space–time evolution of this dominantly silicic LIP strongly contrasts with the brevity of most basaltic LIPs. The data display a regular decrease of ages from the ENE (around 187 Ma) to the WSW (144 Ma) along about 650 km, which is probably correlated to the main tectonic structure in half-grabens oriented perpendicularly to the observed migration direction.

(4) This trend fits with the opening of a latest Jurassic–earliest Cretaceous back-arc marginal oceanic basin (named Rocas Verdes–Sarmiento), behind the magmatic arc. This suggests that the Patagonian Jurassic LIP is related to a propagating extensional feature (towards the WSW), and culminating in continental disruption near the subduction zone, 10 Ma later and reversely to the eastern Atlantic side. Therefore this dominantly silicic LIP would not be genetically a precursor of the Atlantic Ocean opening.

(5) The observed age progression of volcanism would be the result of the variations of the physical characteristics of the subduction. The spreading and thermal effect of the KAT plume may have an additional effect and also could account for the unusually large volume of magma.

Acknowledgements

We are grateful to C. Meister for his assistance during field work. We acknowledge M. Zubia and C. Labudia who gave some of the investigated rocks. The manuscript was sensibly improved by positive criticisms from P. Layer and J.P. Encarnacion who reviewed the paper. This work was financially partially supported by the cooperation project CNRS–CONICET, and the INSU–CNRS program 'Intérieur de la Terre'. Géosciences Azur contribution nb. 248. *[AC]*

References

[1] M. Cameron, W.J. Rea, R. Skarmeta, R. Carminos, D.C. Rex, Petrogenesis and voluminous mid-Tertiary ignimbrites of the Sierra Madre Occidental, Chihuahua, Mexico, Contrib. Mineral. Petrol. 74 (1980) 271–284.

[2] K.M. Creer, J.G. Mitchell, J. Abou Deeb, Paleomagnetism and radiometric age of the Jurassic Chon Aike formation from Santa Cruz Province, Argentina: implications for the opening of the South Atlantic, Earth Planet. Sci. Lett. 14 (1972) 131–138.

[3] E. Linares, R.R. Gonzales, Catalogo de edades radiometricas de la Republica Argentina 1957–1987, Publ. Especiales Asoc. Geol. Argent., Ser. B 19 (1990) 628 pp.

[4] R.J. Pankhurst, C.R. Rapela, Production of Jurassic rhyolite by anatexis of the lower crust of Patagonia, Earth Planet. Sci. Lett. 134 (1995) 23–36.

[5] R.J. Pankhurst, P.T. Leat, P. Sruoga, C.W. Rapela, M. Marquez, B.C. Storey, T.R. Riley, The Chon Aike Province of Patagonia and related rocks in West Antarctica: a silicic large igneous province, J. Volcanol. Geotherm. Res. 81 (1998) 113–136.

[6] A. Heimann, T.H. Fleming, D.H. Elliot, K.A. Foland, A short interval of Jurassic continental flood basalt volcanism in Antarctica as demonstrated by Ar-40/Ar-39 geochronology, Earth Planet. Sci. Lett. 12 (1994) 19–41.

[7] J. Encarnacion, T.H. Fleming, D.H. Elliot, H.V. Eales, Synchronous emplacement of Ferrar and Karoo dolerites and the early break-up of Gondwana, Geology. 24 (1996) 535–538.

[8] D.R. Minor, S.B. Mukasa, Zircon U–Pb and hornblende Ar-40–Ar-39 ages for the Dufek layered mafic intrusion, Antarctica: implications for the age of the Ferrar large igneous province, Geochim. Cosmochim. Acta 61 (1997) 2497–2504.

[9] T.H. Fleming, A. Heimann, K.A. Foland, D.H. Elliot, Ar-40/Ar-39 geochronology of Ferrar Dolerite sills from the Transantarctic Mountains, Antarctica: implications for the age and origin of the Ferrar magmatic province, Geol. Soc. Am. Bull. 109 (1997) 533–546.

[10] J.S. Marsh, P.R. Hooper, J. Rehacek, R.A. Duncan, A.R. Duncan, Stratigraphy and age of Karoo basalts of Lesotho and implications for correlations within the Karoo igneous province, in: J. Mahoney, M.F. Coffin (Eds.), Large Igneous Provinces, 1997, pp. 247–272.

[11] A.K. Martin, C.J.H. Hartnady, Plate tectonic development of the South Indian Ocean: a revised reconstruction of East Antarctica and Africa, J. Geophys. Res. 91 (1986) 4767–4786.

[12] B.C. Storey, T. Alabaster, M.J. Hole, R.J. Pankhurst, H.E. Wever, Role of subduction-plate forces during the initial stages of Gondwana break-up: evidence from the proto-Pacific margin of Antarctica, in: B.C. Storey, T. Alabaster, R.J. Pankhurst (Eds.), Magmatism and the Causes of Continental Break-Up, Geol. Soc. Spec. Publ. 68 (1992) 149–163.

[13] I.W.D. Dalziel, M.J. de Wit, K.F. Palmer, Fossil marginal basin in the Southern Andes, Nature 250 (1974) 291–294.

[14] I.W.D. Dalziel, Back-arc extension in the southern Andes: a review and critical reappraisal, Philos. Trans. R. Soc. London A 300 (1981) 319–335.

[15] D.A. Gust, K.T. Biddle, D.W. Phelps, M.A. Uliana, Associated Middle to Late Jurassic volcanism and extension in southern South America, Tectonophysics 116 (1985) 223–253.

[16] J. Homovc, L. Constantini, A. Pellon de Miranda, R. Ferreira, Evolution of the Deseado massif in Argentina, and its relationship with the San Julian offshore area in the South Atlantic Ocean. YPF S.A. Argentina, Petrobras Internacional Brazil, 1996.

[17] P.E. Baker, W.J. Rea, J. Skarmeta, R. Caminos, D.C. Rex, Igneous history of the Andean cordillera and Patagonian plateau around latitude 46°S, Philos. Trans. R. Soc. London 303 (1981) 105–149.

[18] R.J. Pankhurst, P. Sruoga, C.W. Rapela, Estudio geocronologico de los complejos Chon-Aike y EL Quemado a los 47°30′ S, Actas XII Congr. Geol. Argent. 4 (1993) 171–178.

[19] C.W. Rapela, R.J. Pankhurst, El volcanismo riolitico del noroeste de la Patagonia: un evento meso-jurasico de corta duracion y origen profundo, Actas XII Congr. Geol. Argent. 4 (1993) 179–188.

[20] J.L. Panza, M. Marquez, M. Godeas Hoja geológica, 4966-KI y II, Bahía Laura, 1:250 000, Dir. Nacl. Serv. Geol. Bol. Buenos Aires 214 (1994) 1–83.

[21] J.L. Panza, F.E. Nullo (Coord.). Mapa geológico de la provincia de Santa Cruz, 1:750 000. Dirección Nacional del Servicio Geológico, Buenos Aires, 1994.

[22] M.A. Uliana, K.T. Biddle, Mesozoic–Cenozoic paleogeographic and geodynamic evolution of southern South America, Rev. Bras. de Geocienc. 18 (1988) 172–190.

[23] R.E. De Barrio, El volcanismo acido jurasico en el noroeste de Santa Cruz, Argentina, Actas XII Congr. Geol. Argent., Mendoza 4 (1993) 189–198.

[24] S.M. Kay, V.A. Ramos, C. Mpodozis, P. Sruoga, Late Paleozoic to Jurassic silicic magmatism at the Gondwana margin: analogy to the middle Proterozoic in North America, Geology 17 (1989) 324–328.

[25] B.C. Storey, T. Alabaster, Tectonomagmatic controls on Gondwana break-up models; evidence from the protopacific margin of Antarctica, Tectonics 10 (1991) 1274–1288.

[26] H.E. Wever, B.C. Storey, Bimodal magmatism in northeast Palmer Land, Antarctica Peninsula: geochemical evidence for a Jurassic ensialic back-arc basin, Tectonophysics 205 (1992) 239–259.

[27] G. Turner, J.C. Huneke, F.A. Podosek, G.J. Wasserburg, ^{40}Ar–^{39}Ar ages and cosmic ray exposure ages of Apollo 14 samples, Earth Planet. Sci. Lett. 12 (1971) 19–35.

[28] G. Ruffet, G. Féraud, M. Ballèvre, J.R. Kienast, Plateau ages and excess argon in phengites: an ^{40}Ar–^{39}Ar laser probe study of Alpine micas (Sesia Zone, Western Alps, northern Italy), Chem. Geol. (Isot. Geosci. Sect.) 121 (1995) 327–343.

[29] G. Féraud, J. Gastaud, J.M. Auzende, J.L. Olivet, G. Cornen, ^{40}Ar–^{39}Ar ages for the alkaline volcanism and the basement of Gorringe Bank, North Atlantic Ocean, Earth Planet. Sci. Lett. 57 (1982) 211–226.

[30] D.F. Mertz, P.R. Bitschene, P.R. Renne, J.F. Homovc, C.W. Dewey, Age, source, and tectonic setting of Patagonian Bajo Pobre volcanic rocks, Lateinamerika-Kolloquium, Hamburg, Terra Nostra, 8, 1998.

[31] M. Suarez, M. Marquez, R. de la Cruz, Nuevas edades del complejo El Quemado a los 47°13′–47°22′ LS, Actas VIII Congr. Geol. Chil., Antofagasta 2 (1997) 1552–1555.

[32] M. Suarez, R. de la Cruz, Edades K–Ar del Grupo Ibanez en la parte oriental del Lago general Carrera (46°–47° LS), Aysen, Chile, Actas VIII Congr. Geol. Chil., Antofagasta 2 (1997) 1548–1551.

[33] Y. Kristofferson, K. Hinz, Evolution of the Gondwana plate boundary in the Weddell Sea area, in: M.R.A. Thomson, J.A. Crame, J.W. Thomson (Eds.), Geological Evolution of Antarctica, Cambridge University Press, Cambridge, 1991, pp. 225–230.

[34] A.M. Grunow, I.W.D. Dalziel, T.M. Harrison, M.T. Heizler, Structural geology and geochronology of subduction complexes along the margin of Gondwanaland: new data from the Antarctic Peninsula and southernmost Andes, Geol. Soc. Am. Bull. 104 (1992) 1497–1514.

[35] M.J. Hole, R.J. Pankhurst, A.D. Saunders, Geochemical evolution of the Antarctic Peninsula magmatic arc: the importance of mantle–crust interaction during granitoid genesis, in: M.R.A. Thomson, J.A. Crame, J.W. Thomson (Eds.), Geological Evolution of Antarctica, Cambridge University Press, Cambridge, 1991, pp. 369–374.

[36] I.L. Millar, A.J. Milnen, A.G. Whitham, Implications for Sm–Nd garnet ages for the stratigraphy of northern Graham Land, Antarctica Peninsula, Zentr. Geol. Paläontol. 1 (1990) 97–104.

[37] M.J. Haller, O.R. Lapido, El Mesozoico de la Cordillera Patagonica Central, Asoc. Geol. Argent. Rev. 35 (1980) 230–247.

[38] S.B. Mukasa, I.W.D. Dalziel, Southernmost Andes and South Georgia Island, North Scotia Ridge: zircon U–Pb and muscovite $^{40}Ar/^{39}Ar$ age constraints on tectonic evolution of southwestern Gondwanaland, J. S. Am. Earth Sci. 9 (1996) 349–365.

[39] C.R. Stern, S.B. Mukasa, R. Fuenzalida, Age and petrogenesis of the Sarmiento ophiolite complex of southern Chile, J. S. Am. Earth Sci. 6 (1992) 97–104.

[40] B.E. Lock, Flat-plate subduction and the Cape Fold Belt of South Africa, Geology 8 (1980) 35–39.

[41] M.J. Le Bas, R.W. Le Maitre, A. Streckeisen, B. Zanettin, A chemical classification of volcanic rocks based on the total alkali–silica diagram, J. Petrol. 27 (1986) 745–750.

[42] C.J. Ebinger, N.H. Sleep, Cenozoic magmatism throughout east Africa resulting from impact of a single plume, Nature 395 (1998) 788–791.

REVISED NOTE TO CONTRIBUTORS 1 April 1997

1. Submission of manuscripts

Contributions should be sent to one of the editors. Four copies of the manuscript including photographs, line-drawings and tables should be submitted initially. Original line-drawings should *not* be sent until the final revised manuscript is submitted to the editor. Submission of an article is understood to imply that the article is original and unpublished and is not being considered for publication elsewhere. **Only the title page and abstract should be provided on diskette with the original submission; this will be used when e-mailing potential referees.** With the submitted manuscript, authors should enclose the names and addresses and fax, phone and e-mail numbers of five suggested reviewers. The editors will keep the identity of the reviewers anonymous but the reviewers may feel tree to correspond directly with the authors if they so desire. The responsibility for direct communication between the reviewer and the author must lie with the reviewer. **With a view to increasing the speed of publication authors are encouraged to revise within 6 weeks after receiving their reviews. At the editors' discretion, any revision received after this time limit may be regarded as a new submission that is subject to handling as a new paper.** Upon acceptance of an article by the journal, the author(s) will be asked to transfer the copyright of the article to the publisher. This transfer will ensure the widest possible dissemination of information. **There is an "Express Letter Section" for short, topical papers. The maximum permissible length is 5 journal pages and the total time from submission to publication will be ca. 3 months.** (a) *Submission of electronic text.* In order to publish the paper as quickly as possible, after acceptance authors are encouraged to submit the final text also on diskette. Please see the full instructions in the last issue of this volume. **Authors are encouraged to ensure that the diskette version and the hardcopy are identical — discrepancies can lead to publication of the wrong version.** (b) Authors are requested to provide details of a full corresponding address, telephone/fax and **e-mail numbers.**

2. Length of papers

THE MAXIMUM PERMISSIBLE LENGTH OF PAPERS IS 15 PRINTED JOURNAL PAGES. The average number of words on a (full) EPSL page = 580. Figures on a ratio of 1:1 (based on size). A WORD COUNT MUST BE PROVIDED ON THE TITLE PAGE OF MANUSCRIPTS. THERE ARE NO PAGE CHARGES.

3. Language

Manuscripts should be written in English only, and except for very short papers they should include a brief abstract.

4. Preparation of the text

(a) The manuscript should be prepared on a word processor and printed with double spacing and wide margins and include an abstract of not more than 500 words.

(b) Authors should use JUGS terminology. The use of S.I. units is also recommended.

(c) The title page should include the names of the authors, and their affiliation addresses and fax and e-mail numbers. In the case of more than one author please indicate to whom the correspondence should be addressed.

5. References

References should be limited to the minimum number necessary for citation of pertinent material. As a guide an average of 4 references per printed page can be used, **with a maximum of 50 references per article.** References to internal reports, etc., are to be avoided. (The statement "personal communication" with publication date in the text is preferable.)

References to the literature should strictly follow the journal's format: the references should be numbered in the order in which they are cited, and given in numerical sequence in the reference list at the end of the manuscript. The numbers should appear in the text in the appropriate places using numerals in square brackets on the line. In the reference list, periodicals [1], books [2], multi-author books [3] and proceedings [4], should be cited in accordance with the following examples:

1 I.M. Villa, J.C. Huneke, G.J. Wasserburg, ^{39}Ar recoil losses and presolar ages in Allende inclusions, Earth Planet. Sci. Lett. 63 (1983) 1–12.
2 I.S.E. Carmichael, F.J. Turner, J. Verhoogen, Igneous Petrology, McGraw-Hill, New York, NY, 1974, 739 pp.
3 S.R. Taylor, Chemical composition and evolution of the continental crust: the rare earth element evidence, in: M.W. McElhinney (Ed.), The Earth, its Origin, Structure and Evolution, Academic Press, London, 1978, pp. 2–44.
4 V.T. Bowen, H.D. Livingston, J.C. Burke, Distribution of transuranium nuclides in sediment and biota of the North Atlantic Ocean, in: Transuranium Elements in the Environment, IAEA Symp. Proc., 1976, pp. 107–120.

Abbreviations for titles of journals should follow the system used in the "Bibliographic Guide for Editors and Authors" published in 1974 by the American Chemical Society, Washington, DC.

6. Tables and illustrations

Tables should be compiled on separate sheets. A title should be provided for each table and they should be referred to in the text. Tables can also be sent as camera-ready versions to avoid errors in type-setting; a normal page-size reproduction of such tables should also be included in the manuscript. Efforts should be made to make the size of the tables correspond to the format of the journal (max. 15 × 20 cm).

(a) All illustrations should be numbered consecutively and referred to in the text.

(b) Each illustration should be lettered throughout, the size of the lettering being appropriate to that of the illustrations, but taking into account the possible need for reduction in size. The page format of the journal should be considered in designing the illustrations. All illustrations must be originals, in the form of glossy figures or laser prints. Each illustration must be accompanied by a photocopy

(c) Photographs must be of good quality, printed on glossy paper.

(d) Figure captions should be supplied on a separate sheet.

(e) Colour figures can be accepted providing the reproduction costs are met by the author. Please consult the publisher for further information.

7. Proofs

To achieve the high speed of publication, no proofs are sent to the authors. Manuscripts should therefore be prepared with the greatest possible care, and the submission of negatives for tabular materials in encouraged. Galley proofs may occasionally be obtained by making a special request to the editor, with the understanding that this implies delay in publication.

8. Fifty free reprints

Fifty reprints of each article published are supplied free of charge. A form for ordering extra reprints will be sent to the corresponding author on receipt of the accepted manuscript by the publisher.