Revista de la Asociación Geológica Argentina, 59 (4): 671-684 (2004)

SHRIMP U-Pb zircon dates from igneous rocks from the Fontana Lake region, Patagonia: Implications for the age of magmatism, Mesozoic geological evolution and age of basement

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ABSTRACT. In the eastern margin of the Patagonian Andes and between 44° 30´S and 45° 30´S (Fontana Lake region), Middle Jurassic to Early Cretaceous volcanic and sedimentary rocks were intruded by granitic bodies during the Cretaceous. The reconstruction of the Jurassic-Cretaceous magmatic evolution in the Fontana Lake region and in the adjacent Patagonian Batholith was made possible by the consideration of the following characteristics: distribution in time and space of several intrusive bodies, retro-arc basin formation and volcanic intensity. U-Pb SHRIMP dating of zircon crystals from an ignimbrite, a dacitic porphyry and two granitoid rocks yielded dates of 148.7 ± 2.3, 144.5 ± 1.6, 117 ± 1.7 and 99.6 ± 2.8 Ma, respectively. The Cerro Bayo Ignimbrite (148.7 ± 2.3 Ma, Late Jurassic) was included in the Lago La Plata Formation; this unit hosts an epithermal ore deposit. The Laguna Escondida dacitic porphyry (144.5 ± 1.6 Ma, Jurassic-Cretaceous boundary) intruded metasedimentary rocks of the Lago La Plata Formation; this sub-volcanic body can chronologically be linked to the Patagonian Batholith. After the Jurassic volcanic events, a retro-arc basin formed in the eastern sector of the Patagonian Range at about 140-115 Ma (Late Berriasian-Barremian) and magmatism ceased during this event. The dating of granitoids (117 ± 1.7 and 99.6 ± 2.8 Ma) in the Fontana Lake region confirms a temporal magmatic continuity with the Patagonian Batholith. These dates also are in agreement with the volcanic rocks of the Divisadero Group and epithermal deposits in the region (La Ferrocarrilera deposit). One of the analyzed granitoids (Dedo Chico, 99.6 ± 2.8 Ma) has inherited zircon crystals of about 2,100 and 3,410 Ma, in agreement with other previous isotopic evidence for the occurrence of an underlying Precambrian basement in the region.

Key words: *Zircon, Magmatism, Lago Fontana, Cordillera Patagónica*

RESUMEN. *Datación de circón por U-Pb SHRIMP en rocas ígneas de la región del lago Fontana, Patagonia: Implicancia para la edad del magmatismo, la evolución geológica mesozoica y edad del basamento*. En la margen oriental de la cordillera Patagónica, entre los 44° 30´ L.S. y 45° 30´ L.S. (región del lago Fontana), rocas volcánicas y sedimentarias del Jurásico medio a Cretácico temprano fueron intruidas por cuerpos graníticos durante el Cretácico. La reconstrucción de la evolución magmática jurásico-cretácica en la región del lago Fontana y en el batolito patagónico adyacente fue posible considerando las siguientes características: distribución en el tiempo y el espacio de varios cuerpos intrusivos, la formación de una cuenca de retro-arco y la intensidad volcánica. Datación de cristales de circón (U-Pb SHRIMP) de una ignimbrita, un pórfido dacítico y dos rocas graníticas dieron edades de 148,7 ± 2,3, 144,5 ± 1,6, 117 ± 1,7 y 99,6 ± 2,8 Ma, respectivamente. La Ignimbrita Cerro Bayo (148,7 ± 2,3 Ma, Jurásico tardío) fue incluida en la Formación Lago La Plata; esta unidad hospeda un depósito del tipo epitermal. El pórfido dacítico de laguna Escondida (144,5 ± 1,6 Ma, límite jurásico-cretácico) intruyó rocas metasedimentarias de la Formación Lago La Plata; este cuerpo sub-volcánico puede vincularse cronológicamente al batolito patagónico. Después de los eventos volcánicos jurásicos, una cuenca de retroarco se formó en el sector oriental de la cordillera Patagónica aproximadamente a los 140-115 Ma (Berriasiano-Barremiano tardío) y el magmatismo cesó durante este evento. La datación de granitoides (117 ± 1,7 y 99,6 ± 2,8 Ma) en la región del lago Fontana confirma una continuidad magmática temporal con el batolito patagónico. Estas edades coinciden con la presencia en la región de rocas volcánicas del Grupo Divisadero y depósitos epitermales (yacimiento La Ferrocarrilera). Uno de los granitoides analizado (Dedo Chico, 99,6 ± 2,8 Ma) ha heredado cristales de circón de aproximadamente 2.100 y 3.410 Ma, confirmado otras evidencias isotópicas previas sobre la presencia de un basamento precámbrico subyacente en la región.

Palabras clave: *Circón, Magmatismo, Lago Fontana, Cordillera Patagónica*

Introduction

The Patagonian Andes extend between 39° latitudes to 53° S in the SW of Argentina and S of Chile; these mountains are limited by the Pacific Ocean to the west, and by the extra-Andean Patagonia plateau to the east (Fig. 1). The Patagonian Batholith crops out in the Andean region (Fig. 1) and is composed of calcalkaline granitic to gabbroic plutons with ages ranging from Middle Jurassic to Miocene. However, the peak of magmatic activity, as suggested by radiometric dates, is considered to have taken place in the Early Cretaceous, mainly in the Albian-Cenomanian period (Bruce *et al.* 1991; Townley 1997; Pankhurst *et al.* 1999; Rolando *et al.* 2002b). These rocks are undeformed, except near the Lifquiñe-Ofqui shear zone along the present active arc (Pankhurst *et al.* 1992; Hervé *et al.* 1993). Tertiary plutonic rocks occur in the center of the batholith, whereas Jurassic-Cretaceous rocks occur along the borders (Bruce *et al.* 1991; Parada *et al.* 1996; Pankhurst *et al.* 1999). Several epizonal granitic stocks crop out up to 100 km to the east of the Patagonian Batholith (pre-Andes region; Fig. 2), and possibly they have a same magma source (Rolando *et al.* 1999 and 2002b).

In the extra-Andean region, in the Deseado and North Patagonian Massifs (Fig. 1), occurs one of the world's largest of Phanerozoic volcanic province of silicic composition, that developed during the Jurassic (Kay *et al.* 1989). This volcanism is considered to be related to rifting that ultimately leads to the break-up of the Gondwana Supercontinent (Uliana *et al.* 1985). The Jurassic volcanic rocks from the Andean and extra-Andean Patagonia were considered as part of the same geological setting by Pankhurst *et al.* (1998 and 2000), but not for others authors (Kay *et al.* 1989; Ramos 2002). This volcanism constitute the basement in the study area (Fig. 2 and 3). The Jurassic volcanism is covered by Early Cretaceous (Neocomian) sedimentary rocks deposited in a basin known as Aysén basin in Chile (Bell *et al.* 1994; Suárez *et al.* 1996) and the Rio Mayo embayment in Argentina (Aguirre-Urrieta and Ramos 1981). In the Argentina sector this basin represents an embayment of the sea in a retro-arc setting, associated with the paleogeographic evolution of the arc system and connected with the Pacific Ocean (Aguirre-Urrieta and Ramos 1981). Extensive arc volcanism developed after the closure of the basin in the Middle Cretaceous. In the pre-Andes region some pollymetalic (Zn, Pb, Cu, Au, Ag) ore deposits are associated with the Jurassic-Cretaceous magmatism, such as Fachinal, El Toqui, La Ferrocarrilera and El Desquite (Rolando *et al.* 2000; Townley and Godwin 2001; Dejonghe *et al.* 2002; Sillitoe *et al.* 2002). The La Ferrocarilera deposit south of Fontana Lake (Fig. 2 and 4) is interpreted as formed by a Barremian-Aptian magmatic pulse and related to the intrusion of the Victoria Tonalite (Rolando *et al.* 1999 and 2000).

The main objectives of the present work are based on geochronologic studies, and supported by field work in the Fontana Lake region, near 45° S, is the understanding of the magmatic evolution of the epizonal granitic rocks and volcanosedimentary sequences and their relationship with the Patagonian Batholith. Paleontological ages are known from many sedimentary rocks, but magmatic ages are poorly constrained. Previous investigations in the Fontana Lake region are restricted to geological mapping and K-Ar dating of rocks (Ramos 1976 and 1981; Ramos *et al.* 1982). U-Pb zircon geochronology was recently undertaken in granitic rocks along a transect of the Patagonian Batholith and related apophyses near 45° S (Rolando *et al.* 2002b). These results are reviewed here, for a better understanding of the accurate timing of magmatic events. We used the sensitive high mass resolution ion microprobe (SHRIMP II) for U-Pb zircon geochronology to obtain the ages of magmatic crystallization, because the rocks have incipient to advanced hydrothermal alteration and, consequently other dating techniques may be misleading. This technique also allows identifying inherited zircon in the magmatic rocks.

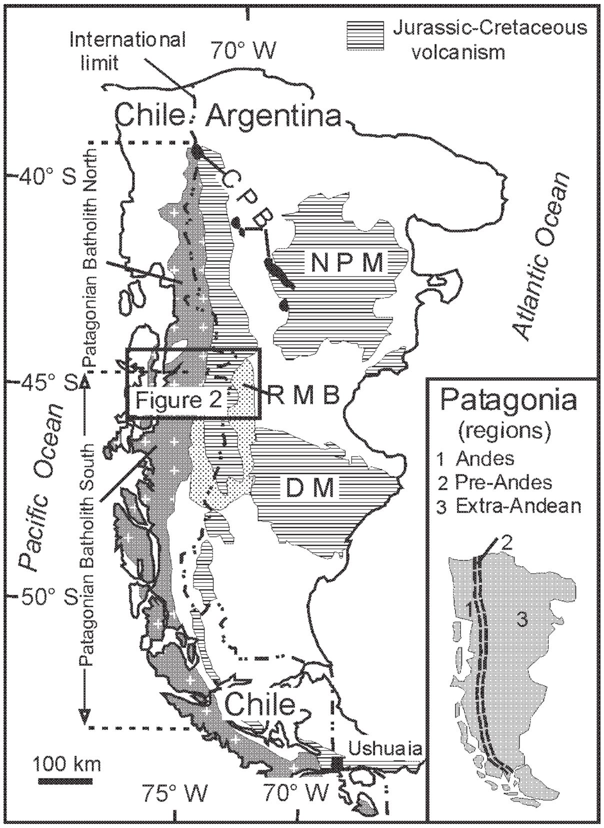

Figure 1: Location of Patagonia, showing the Patagonian Batholith (North and South), Central Patagonian Batholith (CPB), North Patagonian Massif (NPM), Deseado Massif (DM) and the Rio Mayo Basin (RMB).

Geological Setting

The Mesozoic stratigraphy in the Fontana Lake region is composed of volcanogenic rocks of Middle Jurassic to Early Cretaceous age alternating with marine and conti-

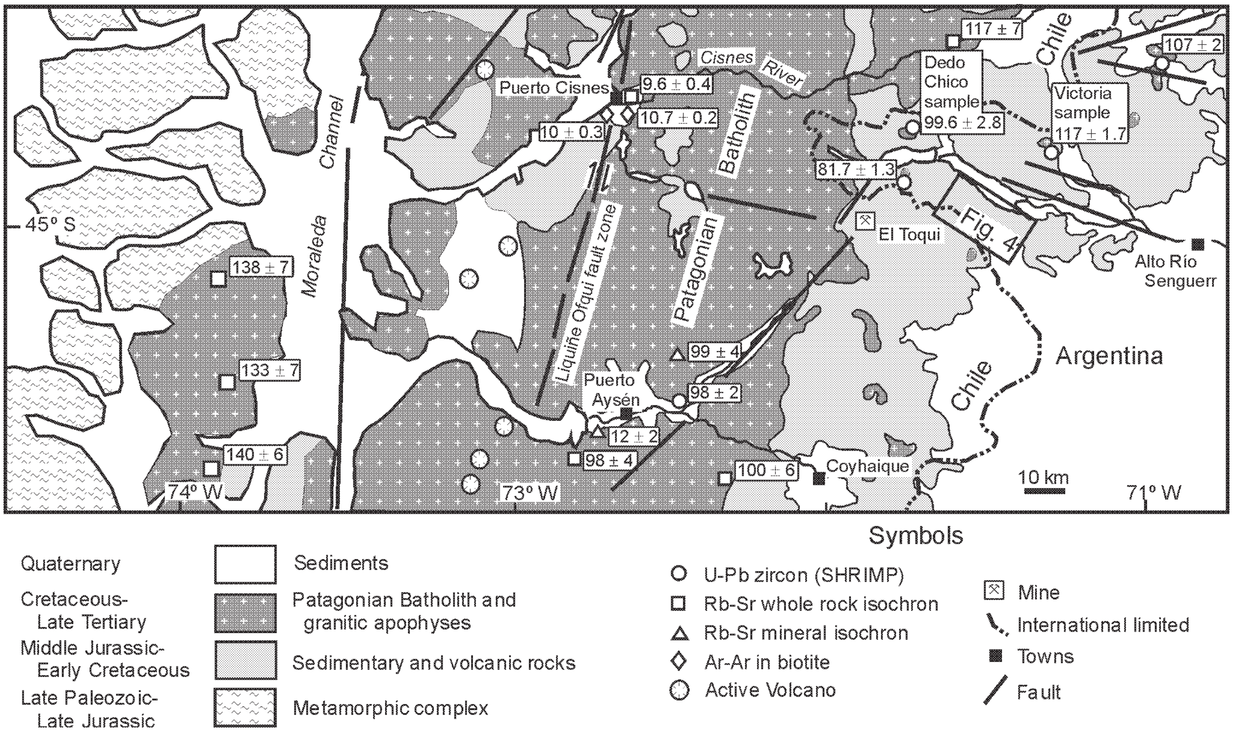

Figure 2: Geological map of the Patagonian Andes and pre-Andean region between 44° 30′ and 45° 30′ S. Based on geological map of Chile (Escobar, 1980) and geological map of Chubut (Lizuain *et al.* 1995). Selected reported ages from Halpern and Fuenzalida, 1978; Stanzione *et al.* 1991; Hervé *et al.* 1993; Pankhurst *et al.* 1999; Rolando *et al.* 2000 and 2002b.

nental sedimentary sequences (Ramos and Palma, 1983). Several granitic stocks in the region (Fig. 2) are thought to be apophyses of the Patagonian Batholith. Rolando *et al.* (2002b) identified Precambrian zircons in the magmatic rocks of this region and interpreted them as inherited from a deep Precambrian crust below this sector of the Patagonia.

The major structures in the study area are mostly NE and E trending (Ploszkiewicz and Ramos 1977; Marchionni and Lanfranchini 1998; Folguera *et al.* 2000). The region was uplifted during Cretaceous times along NE faults, with a basin and range topography (Folguera *et al.* 2000; Folguera and Iannizzotto 2004). The Senguerr River-Fontana Lake lineament corresponds to a fault; north of it several Cretaceous stocks are exposed (Fig. 2). This fault was characterized by Ramos (1981) and Folguera and Iannizzotto (2004), and may be responsible for exposing different erosion levels in the blocks limited by this structure. The region to the north has been eroded more deeply, exposing granitic rocks (for example, Victoria tonalite, Fig. 2) and thermal contact aureoles. Along the southern margin of Fontana lake, Early Cretaceous epithermal deposits were preserved (Rolando *et al.* 2000; Rolando 2001).

Stratigraphy

The Mesozoic, volcanic and sedimentary sequences in the Fontana Lake region belong to three major units: Lago La Plata Formation, Coyhaique and Divisadero Groups (Fig. 3). Since sedimentary rocks are recognized in the three units, their stratigraphic position may be determined by the paleontological content or reliable geochronology.

Andesitic to rhyolitic pyroclastic rocks and lavas from the Lago La Plata Formation (Ramos 1976), and related terrestrial clastic sedimentary rocks and marine limestones, are correlated with the nearby Ibañez Group in Chile (Heim 1940). Geochemical analyses of the volcanic rocks indicate calcalkaline composition (Suárez *et al.* 1996; Massaferro 1999). The base of Lago La Plata Fm. is not exposed in the Fontana lake region, but appears to have formed since the Middle Jurassic (Medina and Maisterrena 1981). The minimum age of the Lago La Plata Formation is defined by the position of the volcanic pile beneath the Tres Lagunas Formation deposited during the Late Berriasian (Olivero 1983; Covacevich *et al.* 1994). Based on Pankhurst *et al.* (2000), three episodes of silicic volcanism are defined during a 30 m.y. period in the Jurassic of the Patagonia, the peak activity in the study area is interpreted to have taken place between 157 and 153 Ma.

Early Cretaceous marine and continental sedimentary rocks of the Rio Mayo-Aysén basin are part of the Coyhaique Group (Haller and Lapido 1982). This group includes mainly siliciclastic rocks, containing intercalated limestones and minor volcanic rocks. From base to top, the group is divided into the Tres Lagunas, Katterfeld and Apeleg Formations, which show some interfingering

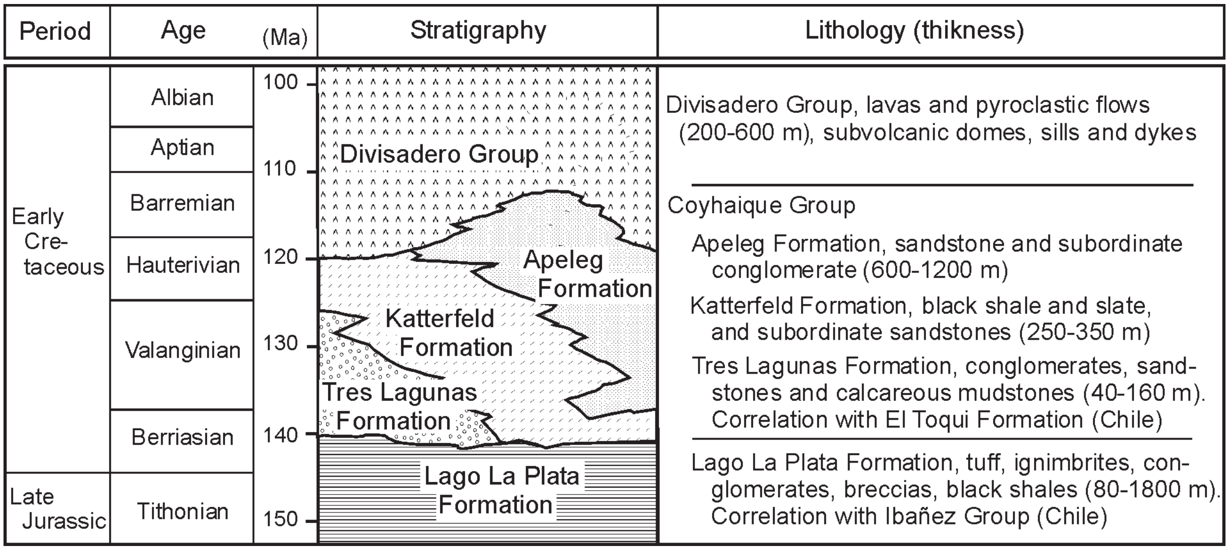

Figure 3: Mesozoic stratigraphic column in the Fontana Lake region and equivalent units in Aysén, Chile.

between them (Hechem *et al.* 1993). It seems that the base and top of the Coyhaique Group are diachronic and extend from the Late Berriasian to the Barremian (Fig. 3).

The Tres Lagunas Formation is correlated with the El Toqui Formation in Chile (Ramos 1981; Suárez *et al.* 1996). The Tres Lagunas Formation consists mostly of conglomerates, sandstone and limestones (Ramos 1981; Hechem *et al.* 1993). Based on the ammonite fossil contents, its age varies from the Late Berriasian to the Valanginian (Covacevich *et al.* 1994; Suarez *et al.* 1996). The Katterfeld Formation is made up of fossiliferous black shales, sandstones and minor carbonate facies (Ramos 1981; Ramos and Palma 1983) deposited during the Valanginian to Hauterivian age (Masiuk and Nakayama 1978; Riccardi 1988). The Apeleg Formation (Ploszkiewicz and Ramos 1977) contains fluvial and fan delta sandstones, of Valanginian to Barremian age (Masiuk and Nakayama 1978; Olivero 1987; González-Bonorino and Suárez 1995).

The volcanic rocks of the Divisadero Group (Haller and Lapido 1982) consist of pyroclastic successions, lavas and hypabissal intrusive bodies (Ramos 1981). These are rhyolitic and dacitic rocks with subordinate andesites, with an overall calcalkaline affinity (Ramos 1981; Ramos *et al.* 1982). Small volumes of continental sedimentary rocks and black shales are intercalated (Ramos and Palma 1983; Folguera and Iannizzotto 2004). A Barremian to Albian age is suggested for the Divisadero Group, based on K-Ar and Rb-Sr dates (Ramos 1981; Rolando *et al.* 1999).

Continental sediments containing vertebrate fossils and basaltic lava flows were deposited in the eastern portion of the area and north of the Fontana Lake during the Miocene-Pliocene (Ramos 1981). The youngest unit corresponds to glacial deposits of Pleistocene-Holocene age and includes debris flow, alluvial and colluvial deposits (Ramos 1981).

The eastern border of the Patagonian Batholith and related stocks

The eastern border of the Patagonian Batholith is exposed along the western margin of the La Plata Lake, and extends for 150 km west into Chile (Fig 2). Several granitic stocks intruded in the pre-Andes region in an extensional environment (Ramos 1981), and show a variety of compositions, textures and ages (Table 1). These stocks are interpreted to be cupolas of large Cretaceous epizonal plutonic bodies (Rolando *et al.* 2002b). An alternative hypothesis considers the stocks as independent bodies from the main batholith near 40° to 43° S and older in age (Gordon and Ort 1983; Pankhurst *et al.* 1999). If so, these stocks would be part of the NNW end portion of the Central Patagonian Batholith, near the Gastre shear zone (Fig. 1; Rapela and Pankhurst 1996).

Gabbroic intrusive bodies of the Muzzio Formation (Ramos 1981) occur south of the Fontana Lake and extend ward to the Chilean border (Fig. 4). These gabbros are of Early Jurassic age (Rolando *et al.* 2002b) and may be related to other basic bodies to the north (Gordon and Ort 1983) and in the extra-Andean region (Franchi and Page 1980). The presence of inherited zircons with Paleoproterozoic-Archean U-Pb dates and distinct isotopic composition of Pb, Nd and Sr indicate that these gabbros are more contaminated by crustal material than the granitoids (Rolando *et al.* 1999; 2002a and 2002b).

Field relationships and sample description

Four samples, an ignimbrite, a dacite and two granitoids from the vicinity of the Fontana Lake were dated. The access to the zone is by a dirt road from the town of Alto Rio Senguerr, Chubut province (Fig. 2).

Table 1: Location and description of dated samples from the Fontana Lake area.

Sample/location	Outcrop (km^2)	Host rock	Texture	Essential Minerals [a] (%)	Zircons Length:width (Size - μm)	Magmatic Age (Ma)	Inherited zircons Age (Ma)
Teta granodiorite 44° 52´S, 71° 46´W	0.03	Divisadero Group	Equigranular medium size	Pl(50), KF(15), Qz(30), Bt(5)		81.7 ± 1.3 [b]	100
Dedo Chico granodiorite 44° 49´S, 71° 50´W	0.5	Divisadero Group	Equigranular medium size	Pl(40), KF(25), Qz(30), M(5)	2:1 - 2.5:1 (150-200)	99.6 ± 2.8 [c]	2,100-3,400
Magdalena monzogranite 44° 37´S, 70° 57´W	42	Divisadero Group	Porphyritic graphic	KF(50), Qz(37), Pl(10), Bt(3)		107 ± 2 [b] 103 ± 10 [d]	2,000-3,200
Victoria tonalite 44° 51´S, 71° 20´W	6	Apeleg Formation	Equigranular medium size	Pl(60), Qz(25), Bt(15)	1.5:1 - 2.5:1 (100-300)	117 ± 1.7 [c] 126 ± 10 [d]	125 ± 2 180 ± 3
Laguna Escondida dacite 45° 00´S, 71° 32´W	0.02	Lago La Plata Formation	Microporphyic Equigranular	Pl(50), KF(5), Qz(40), M(2)	2:1 - 3:1 (220-350) 5:1 (375)	144.5 ± 1.6 [c]	151 ± 2
Muzzio gabbro 44° 59´S, 71° 28´W	0.9	Uncertain	Intergranular to subophitic	Pl(60), Px(30), Amp(10)		191 ± 3 Ma [b] 220 ± 10 [d]	1,950-3,300
Cerro Bayo ignimbrite 45° 01’ S, 71° 28´W	See description in the text		Flow tuff	Qz remnants; Se and Ca secondary	2:1 (150-200) 3.5:1 (450)	148.7 ± 2.3 [c]	-

[a] Amp: amphiboles; Bt: biotite; Ca: carbonates; KF: K-Feldspar; M: mafic minerals; Pl: plagioclase; Px: pyroxene; Qz: quartz; Se: sericite.
[b] Rolando et al. (2002b); [c] This paper; [d] Ramos (1981)

Cerro Bayo Ignimbrite

The section from Cerro Bayo (Fig. 4) was interpreted as Jurassic by Quartino (1952), but Ramos (1981) related these volcanic rocks to Early Cretaceous. Marshall *et al.* (1984) consider the base and top of this succession as interfingering with the Coyhaique Group. The stratigraphic position of the geological unit is re-evaluated in this work, based on isotopic dating of zircons from an ignimbrite south of Fontana Lake (Fig. 4).

The Cerro Bayo section is composed by a thick sequence of volcanic, mostly pyroclastic rocks. A fault zone along the Mineros Creek marks the base of the succession, while the top is gradational into the sandstones of the Apeleg Formation (Fig. 4). The general structure is a homocline, striking N40° E and dipping 20° SE. The total measured thickness of 1800 m may be overestimated because many faults are present. The section begins with intercalated pelites and tuffs and evolves into breccias, tuffs and tuffites. Smaller volumes of rhyodacites, andesites and conglomerates also occur. The depositional environment was continental, as suggested by fossils (*Elatocladus, Otozamites*), but these do not define precise age for the sequence (Marshall *et al.* 1984). The rocks are strongly affected by hydrothermal alteration, mainly silicification and sericitization, dated in 126 ± 6 Ma for Rb-Sr isochron in hydrothermal minerals (Rolando *et al.* 2000). Field evidences suggest that a sinter, associated with Cerro Bayo deposit (Rolando *et al.* 2000), was formed before the sedimentary rocks of the Apeleg Formation.

The Cerro Bayo sample is an ignimbrite with abundant phenocrysts of quartz up to 2 mm in diameter, partly rounded and resorbed. Quartz is the only essential mineral preserved from alteration and forms about 25 % of the rock, which is intensely altered by sericitization and carbonatization, only the shapes of the original minerals are preserved (Fig. 5a). Small amounts of altered lithic fragments are present, marked by quartz remnants. The matrix also contains small crystals of quartz, sericite and carbonate.

Laguna Escondida Dacite

This sample was collected a few meters south of the Cerro Negro (Fig. 4), where two small bodies occur, both of approximately 1000 m^2 and partly covered by glacial drift. The country rock is thermally metamorphosed and is considered part of the Lago La Plata Formation. Aplitic veins cut this thermal aureole. The upper part of the intrusions shows radiating bundles of quartz and piedmontite.

The rock analyzed is a greenish pink dacite of sub-

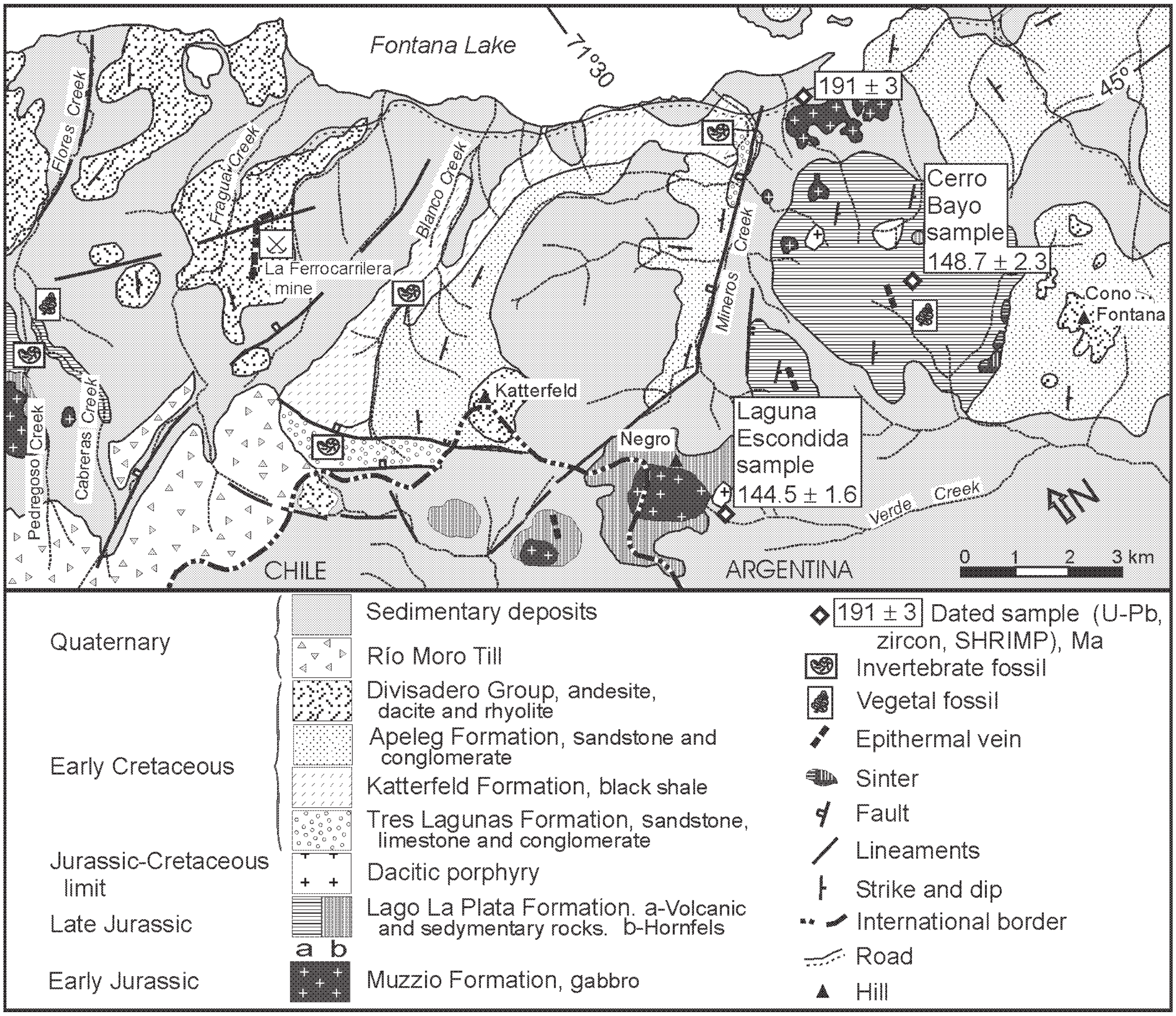

Figure 4: Geological map of the region south of Fontana Lake based on Ramos (1981).

volcanic origin with porphyritic texture; phenocrysts are about 3-5 mm in size and the matrix is very fine. Under the microscope, the phenocrysts (65%) are plagioclase (50%), K-feldspar (5%), mafic minerals (2%, chloritized biotite) and quartz (8%). The matrix is mostly quartz and epidote. Short, prismatic zircon (0.1-0.2 mm) is included in biotite or in the matrix (Fig. 5b). The rock was intensely altered by propilitization.

Victoria Tonalite

This stock covers about 6 km^2 north of Fontana Lake (Fig. 2), but based on the 1 km-wide thermal aureole on its bordering sandstones, it may be larger at depth. The granitic body varies in composition from diorite to granodiorite (Ramos 1981). The sampling site contains abundant sandstone xenoliths from the Apeleg Formation country rocks. Small aplitic veins also cut the surrounding metasediments.

The sample consists of coarse plagioclase (60%), which is zoned and has sericitic cores (Fig. 5c), quartz (25%) and biotite (15%). The biotite is partly chloritized and associated with opaque minerals. Zircon is abundant and 0.1-0.3 mm in size (Tab. 1).

Dedo Chico Granodiorite

This sample was collected 14 km WNW of the isthmus that separates La Plata Lake from Fontana Lake (Fig. 2). Hiking was required to reach an altitude of 1200 m, above the tree line where outcrops are extensive. The sample is a coarse-grained equigranular greenish-pink granodiorite with a graphic texture as seen in thin section and consists of plagioclase (40%), zoned K-feldspar (25%), quartz (30%), biotite (2%), amphibole (2%) and opaque minerals (1%). The biotites and some feldspars are partly chloritized and sericitized. Zircon crystals occur included in the amphiboles, biotites and opaque minerals (Fig. 5d).

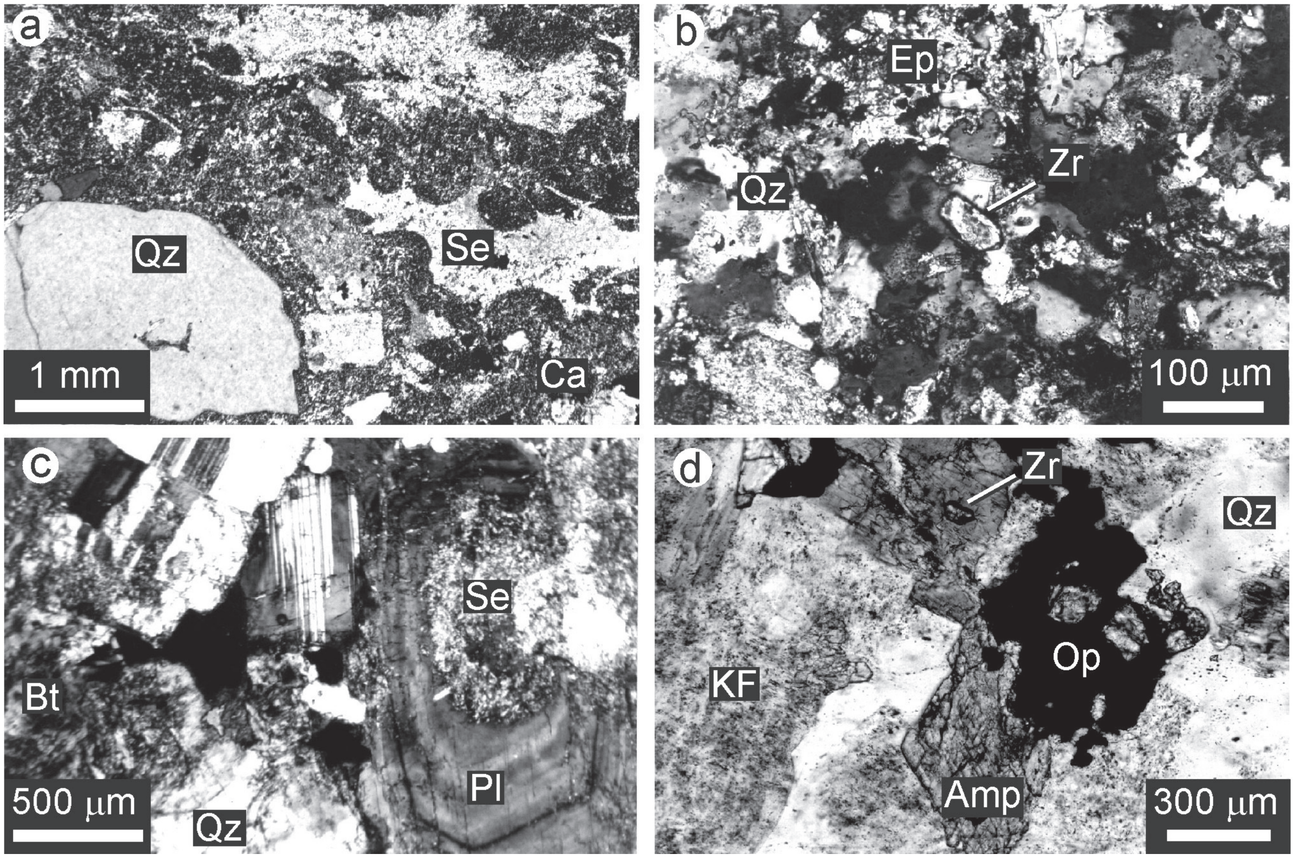

Figure 5: Photomicrographs (crossed polars) of the four studied samples. **a)** Sample Cerro Bayo ignimbrite with quartz relicts and secondary sericite-carbonate. **b)** Sample Laguna Escondida; dacite matrix with quartz and subordinated epidote. **c)** Victoria tonalite sample showing crystals of zoned plagioclase with cores altered to sericite. **d)** Dedo Chico granodiorite sample showing a crystal of zircon included in amphibole. Amp: amphibole, Bt: biotite, Ca: carbonates, Ep: epidote, KF: K-feldspar, Op: opaque minerals, Pl: plagioclase, Qz: quartz, Se: sericite, Zr: zircon.

U-Pb geochronology

Analytical Techniques

Zircon analyses were carried out on the SHRIMP II at Curtin University of Technology in Perth, Western Australia. For each sample, 3 kg of rock were collected for zircon separation. Samples were powdered and mineral fractions were obtained by density pre-concentration with use of turbulent water flux, followed by heavy liquids. The non-magnetic fraction was separated with a Frantz isodynamic magnet. After passing through a 115 and 250 mesh sieve, final mineral fractions for analyses were hand-picked under a binocular microscope.

Analytical methods are described by Smith *et al.* (1998) and the established isotopic constants given by Jaffey *et al.* (1971) are used. The CZ3 zircon standard was used as reference (564 Ma: $^{206}Pb/^{238}U=0.0914$). The initial Pb correction for the total Pb in each analysis was done by removing initial ^{206}Pb, ^{207}Pb, and ^{208}Pb, using the observed ^{204}Pb and assuming Pb of Broken Hill isotopic composition. Uncertainties in the data are given at one standard deviation, and those for ages cited in the text are at the 95 % confidence level. Ages in Ma are marked on the concordia curves; $^{206}Pb/^{238}U$ ratios were used to estimate the age of each sample. The $^{207}Pb/^{235}U$ ratios were used to estimate the Precambrian ages. Scanning electron microscopy (SEM) and cathodoluminescense (CL) microscopy were performed to produce backscattered electron (BSE) and CL images before and after SHRIMP analyses to aid in interpretation of the analytical data. These images also provide important information on zircon morphology and internal structure which cannot be obtained from conventional optical microscopy.

Results

Zircon morphology and sizes of crystals analyzed in this investigation are summarized in Table 1. The SHRIMP zircon U-Pb isotopic results are shown in Tables 2 and 3.

Cerro Bayo Ignimbrite: Fourteen spots were analyzed on eleven zircon crystals. The crystals are euhedral, short prismatic (2:1), and show typical magmatic zoning with no signs of alteration (Figs. 6a and 6b). The date obtained from thirteen spots is concordant at 148.7 ± 2.3 Ma (c^2=

Table 2: U-Pb SHRIMP data for zircons from the Fontana Lake.

Sample	Concentration (ppm)				f^{206} Pb	Isotopic ratios [b,c]				Apparent ages (Ma)				Conc.
Mount/ spot	U	Th	Pb	Th/U	(%) [a]	^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	(%) [d]
Cerro Bayo Ignimbrite														
A.a1.1	265	239	7	0.90	0.790	0.0238	0.43	0.1510	16	152	3	143	15	106
A.a1.2	102	174	3	1.71	3.380	0.0225	0.60	0.0684	50	144	4	67	48	214
A.a3.1	1290	734	32	0.57	0.058	0.0231	0.37	0.1610	5	147	2	152	4	97
A.a3.2	1103	395	26	0.36	0.000	0.0232	0.38	0.1601	4	148	2	151	4	98
A.a4.1	159	112	4	0.70	1.213	0.0237	0.50	0.1357	33	151	3	129	29	117
A.a5.1	157	132	4	0.84	0.000	0.0239	0.46	0.1541	10	152	3	146	8	104
A.a6.1	99	157	3	1.60	0.000	0.0223	0.48	0.1582	13	142	3	149	11	95
A.a7.1	83	59	2	0.71	0.213	0.0239	0.64	0.1606	54	152	4	151	47	101
A.a8.1	156	50	3	0.32	0.856	0.0218	0.37	0.1285	22	139	2	119	20	117
A.a10.1	481	383	10	0.80	0.000	0.0182	0.31	0.1185	5	116	2	114	5	102
A.a12.1	166	520	7	3.14	1.095	0.0235	0.37	0.1522	28	150	2	139	24	108
A.a13.1	240	250	7	1.04	2.089	0.0233	0.47	0.1401	30	148	3	133	27	111
A.a17.1	960	988	27	1.03	0.080	0.0237	0.39	0.1693	6	151	2	159	6	95
A.a17.2	186	95	5	0.51	1.238	0.0239	0.46	0.1460	22	152	3	138	19	110
Laguna Escondida Dacite														
A.d21.1	771	240	17	0.31	0.917	0.0225	0.31	0.1447	10	143	2	137	9	104
A.d21.2	301	230	8	0.77	0.667	0.0232	0.36	0.1413	15	148	2	134	13	110
A.d22.1	400	196	11	0.49	4.539	0.0230	0.36	0.1540	23	147	2	145	21	101
A.d22.2	485	166	12	0.34	2.543	0.0226	0.33	0.1479	15	144	2	140	13	103
A.d23.1	236	151	11	0.64	19.200	0.0229	0.52	0.1271	54	146	3	121	49	121
A.d23.2	126	69	3	0.55	0.130	0.0229	0.44	0.1500	31	146	3	142	28	103
A.d24.1	334	135	8	0.40	0.056	0.0227	0.34	0.1569	12	145	2	148	11	98
A.d25.1	178	101	4	0.57	1.354	0.0226	0.38	0.1316	22	144	2	126	20	114
A.d25.2	355	382	10	1.08	0.588	0.0228	0.34	0.1453	11	145	2	138	10	105
A.d29.1	4901	11241	158	2.29	0.505	0.0238	0.31	0.1598	3	151	2	150	3	101
A.d29.2	1000	413	25	0.41	1.701	0.0229	0.31	0.1599	9	146	2	151	8	97
A.d37.1	239	245	6	1.03	0.954	0.0220	0.34	0.1280	14	140	2	122	13	115
A.d40.1	356	263	9	0.74	0.000	0.0227	0.33	0.1560	6	145	2	147	5	99
A.d43.1	121	71	3	0.59	2.622	0.0225	0.43	0.0773	29	144	3	76	27	189
A.d47.1	153	111	4	0.72	0.554	0.0221	0.41	0.1513	27	141	3	143	24	99
Victoria Tonalite														
A.c77.1	722	871	19	1.208	1.965	0.0195	0.30	0.1563	12	125	2	147	11	85
A.c78.1	124	70	2	0.565	1.574	0.0181	0.40	0.1008	30	115	3	97	28	118
A.c79.1	233	175	5	0.751	0.924	0.0183	0.30	0.1199	18	117	2	115	16	102
A.c81.1	1250	93	22	0.074	0.000	0.0187	0.30	0.1235	3	119	2	118	3	101
A.c81.2	210	112	4	0.533	0.334	0.0186	0.30	0.1205	21	119	2	116	19	102
A.c82.1	267	167	5	0.625	0.499	0.0184	0.30	0.1182	14	118	2	114	12	103
A.c85.1	238	125	4	0.525	0.445	0.0180	0.30	0.1095	21	115	2	106	19	108

Table 2: Continuation.

A.c88.1	295	133	5	0.452	0.000	0.0180	0.30	0.1190	6	115	2	114	6	101
A.c91.1	173	158	4	0.915	1.279	0.0182	0.40	0.0987	21	116	2	96	20	121
A.c92.1	316	169	6	0.533	0.070	0.0189	0.30	0.1220	13	121	2	117	12	104
A.c93.1	309	210	6	0.678	0.617	0.0188	0.30	0.1173	11	120	2	113	10	106
A.c96.1	139	110	3	0.787	1.589	0.0183	0.40	0.1137	25	117	2	109	23	107
A.c98.1	271	455	10	1.679	0.372	0.0283	0.50	0.1999	16	180	3	184	13	98
A.c100.1	192	119	4	0.619	0.341	0.0184	0.40	0.1104	21	118	2	106	19	111
A.c103.1	569	460	12	0.808	0.745	0.0185	0.30	0.1192	9	118	2	114	9	103
Dedo Chico Granodiorite														
B.c25.1	115	61	2	0.53	0.071	0.0163	0.58	0.0613	60	104	4	60	58	173
B.c26.1	207	141	3	0.68	2.432	0.0148	0.33	0.0689	22	94	2	68	21	138
B.c26.2	193	131	3	0.68	0.084	0.0153	0.31	0.1114	16	98	2	107	15	91
B.c27.1	102	79	2	0.77	8.719	0.0141	0.51	0.0527	52	90	3	91	15	99
B.c29.1	113	82	2	0.72	1.632	0.0155	0.66	0.0390	73	99	4	39	69	254
B.c33.1	209	109	4	0.52	4.393	0.0157	0.38	0.0228	32	100	2	23	31	435
B.c36.1	253	218	5	0.86	3.271	0.0160	0.36	0.0637	34	102	2	63	33	162
B.c39.1	157	124	3	0.79	0.139	0.0161	0.43	0.1081	35	103	3	104	32	99
B.c40.1	106	68	2	0.65	6.126	0.0130	0.97	0.1022	124	83	6	81	28	103
B.c41.1	143	131	3	0.92	2.790	0.0158	0.41	0.0659	33	101	3	65	32	155
B.c42.1	92	74	2	0.80	3.985	0.0160	0.49	0.0381	45	102	3	38	43	268

[a] Percentage of common ^{206}Pb relative to total ^{206}Pb, based on measured ^{204}Pb ~^{208}Pb (B.c27.1 and B.c40.1). [b] All Pb in ratios are radiogenic component. Standart deviation (1s level). [C] Errors are x 1000. [d] Concordance: 100t (^{206}Pb/^{238}U)/t(^{207}Pb/^{206}Pb). Mounts: A- UWA 98-40; B- UWA 98-47

Table 3: U-Pb SHRIMP data for inherited zircons from the Dedo Chico

Sample	Concentration (ppm)				f^{206} Pb	Isotope ratios[b, c]								Apparent ages (Ma)				Conc.
Mount/ spot	U	Th	Pb	Th/U	(%)[a]	^{206}Pb[d]/^{238}U	±	^{207}Pb[d]/^{235}U	±	^{207}Pb[e]/^{206}Pb	±	^{208}Pb[e]/^{206}Pb	±	^{206}Pb/^{238}U	±	^{207}Pb/^{206}Pb	±	(%)[d]
Dedo Chico granodiorite																		
B.c24.1	165	20	106	0.12	0.064	0.5825	9.889	20.278	38	0.2525	15	0.0321	10	2959	40	3200	10	92
B.c30.1	250	41	188	0.16	0.081	0.6569	10.872	26.189	46	0.2892	12	0.0418	8	3255	42	3413	7	95
B.c43.1	238	117	93	0.49	0.133	0.3538	5.866	6.346	13	0.1301	13	0.1416	19	1953	28	2099	17	93
B.c43.2	250	88	102	0.35	0.272	0.3821	6.937	6.853	15	0.1301	12	0.0968	18	2086	32	2099	16	99

[a] Common ^{206}Pb/total ^{206}Pb, based on measured ^{204}Pb. [b] All Pb in ratios are radiogenic component. [c] Uncertainties are 1 ð. Errors are x 100 (d) and x 1000 (e). [d] Concordance: 100t (^{206}Pb/^{238}U)/t(^{207}Pb/^{206}Pb). Mounts: B- UWA 98-47

2.07). In three crystals from this population, both the center and edge were analyzed and yielded similar dates. This result is interpreted as the crystallization age of the zircon (Fig. 7a). A date of 116 ± 2 Ma was obtained in crystal A.a10.1, but its significance is unknown. This crystal has no evidence of alteration of internal structure; it may be a contamination during sample handling. The hydrothermal minerals from the Cerro Bayo region yielded a Rb-Sr date of 126 ± 6 Ma (Rolando *et al.* 2000) which is older than that of crystal A.a10.1.

Laguna Escondida Dacite: The analyses of 15 spots in 10 zircon crystals yielded a date of 144.5 ± 1.6 Ma (c^2= 0.78), which is interpreted as the crystallization age of the stock (Fig. 7b). In five crystals, a new spot was analyzed to investigate the presence of inherited cores (Figs. 6c

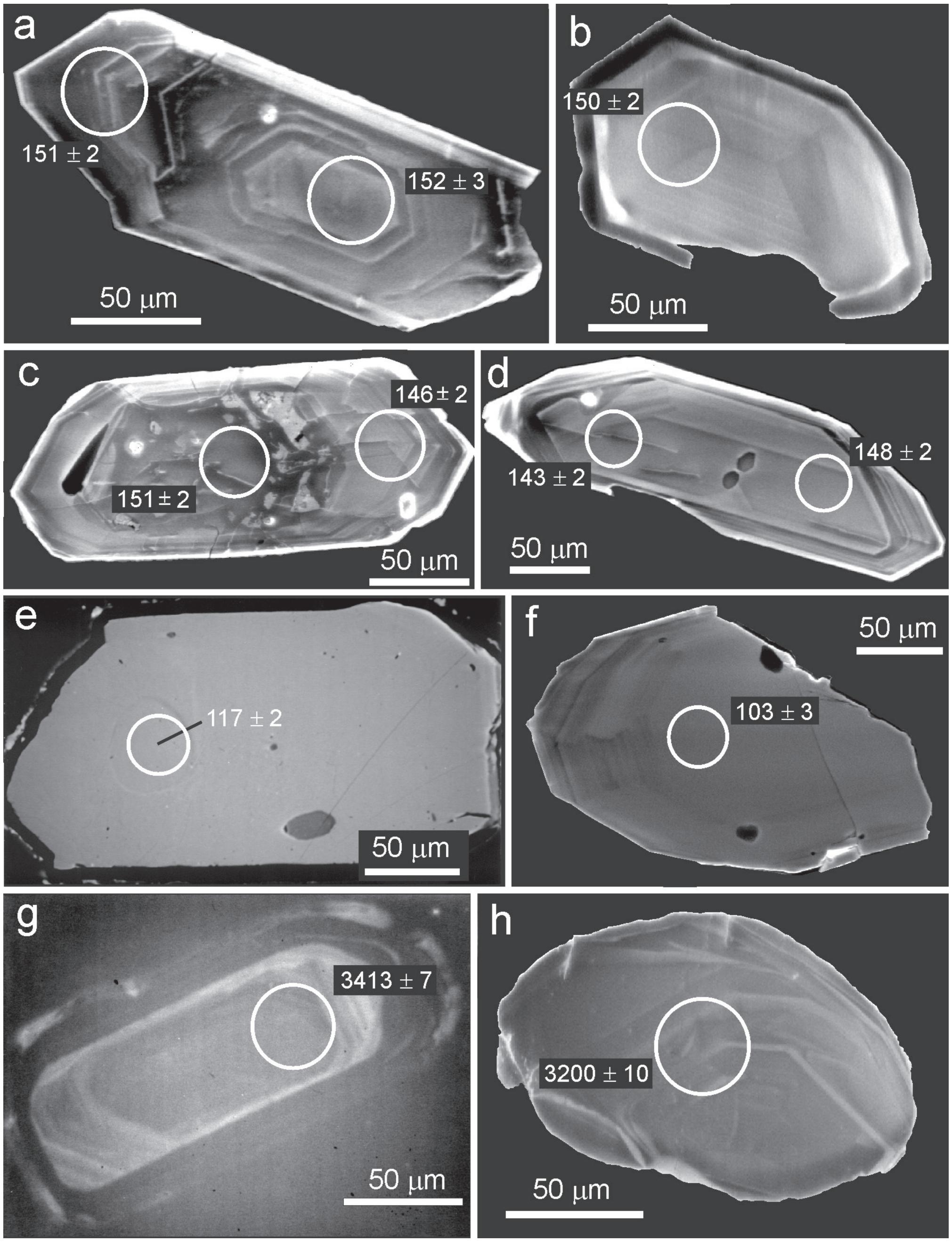

Figure 6: Backscattered electron (BSE) and cathodoluminescence (CL) images of zircon crystals. Numbers indicate ages in Ma. **a , b)** CL of zoned prismatic zircon crystals from Cerro Bayo ignimbrite. **c, d)** Images from Laguna Escondida dacite; note specially in c. the slightly older core from A.d29 crystal. **e)** BSE image of Mesozoic zircon crystal from sample Victoria tonalite. **f)** CL image of crystal from granodiorite, sample Dedo Chico. **g, h)** CL images of xenocryst zircons from Dedo Chico.

and 6d), but the dates obtained were similar to the previous one, except for spot A.d29.1 (Fig. 6c), which yielded 151 ± 2 Ma and had a Th/U ratio of about 2.29 and U, Th and Pb concentrations higher than the other spots (Table 2). This spot is slightly older than the others and may belong to an assimilated country rock from Lago La Plata Formation.

Victoria Tonalite: A large number of zircons, unaltered short stubby prisms, was separated from this rock (Fig. 6e). Thirteen crystals were selected for dating; the date obtained from a cluster of thirteen spots is 117 ± 1.7 Ma (c^2= 0.80), which is interpreted as the crystallization age of the zircons (Fig. 7c). Two spots were analyzed on crystal A.c81, one in the cores and one in the rim, but the same date was obtained. However crystals A.c77 and A.c98 have dates of 125 ± 2 Ma and 179.6 ± 2.9 Ma, respectively, and higher Th/U ratio than the remaining spots. These two crystals are inherited, probably from xenoliths.

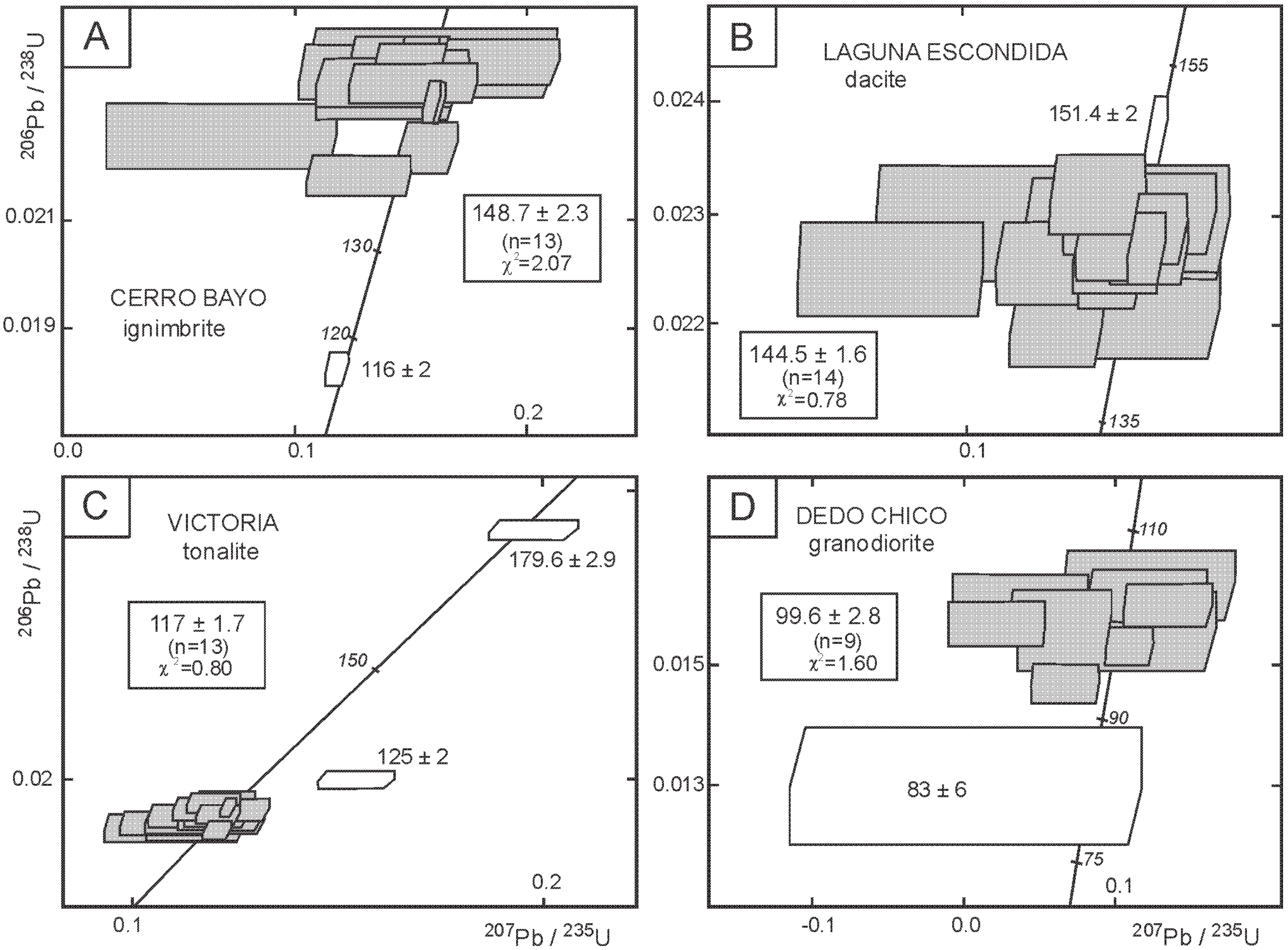

Figure 7: Concordia diagram showing the SHRIMP U-Pb isotopic systematics of zircons from: **a)** ignimbrite, sample Cerro Bayo; **b)** dacite, sample Laguna Escondida; **c)** tonalite from Victoria; **d)** granodiorite, sample Dedo Chico.

Dedo Chico Granodiorite: Fourteen crystals were selected for analyses and ten Mesozoic dates and four Precambrian dates were obtained. The Mesozoic crystals are euhedral and short prismatic (Fig. 6f). The date obtained from ten spots is 99.6 ± 2.8 Ma (c^2= 1.60), which is interpreted as the crystallization age of the stock (Fig. 7d). Spot B.c27.1 and B.c40.1 are not included in the date calculation, because of high concentration of ^{206}Pb.

The analytical results for the four Precambrian crystals are included in Table 3. These xenocrysts are rounded and corroded (Fig. 6g and 6h) and partly altered in the center. Two yielded dates near 2,100 Ma, and the others yielded Archean ages (Fig. 8). Spot B.c30.1 has a date of 3,413 ± 7 Ma, which is the oldest age determined for a single crystal in Patagonia.

Discussion

We report of U-Pb SHRIMP dates of zircons from Mesozoic rocks intending to determine the chronology and evolution of the magmatic activity Patagonian Andes at about 45° S. U-Pb zircon ages were determined from one ignimbrite 148.7 ± 2.3 Ma, one dacitic porphyry 144.5 ± 1.6 Ma and two granitoids 117 ± 1.7 and 99.6 ± 2.8 Ma. Although the alteration observed in the rocks ranges from incipient to extensive, the isotopic results were sharp and precise in all cases, allowing the determination of magmatic pulses during the Jurassic-Cretaceous in an area of 5,000 km^2.

Gabbros from the Muzzio Formation (Ramos 1981) are placed in the Early Jurassic (Toarcian), based on Rolando *et al.* (2002b). This magmatic event is restricted to the south area of Fontana Lake, but volcanic and sedimentary covers make the determination of its regional extent difficult.

The geological environment during the Middle and Late Jurassic was dominated by acid to intermediate volcanism along with continental and marine sedimentation. The Cerro Bayo ignimbrite could be dated by U-Pb zircon, but other techniques would face difficulties due to very strong hydrothermal alteration. This was even more significant because the field relations with other formations are not clear and the fossils are of no biostratigraphic value (Marshall *et al.* 1984). In this way, the Cerro Bayo (148.7 ± 2.3 Ma) section was positioned

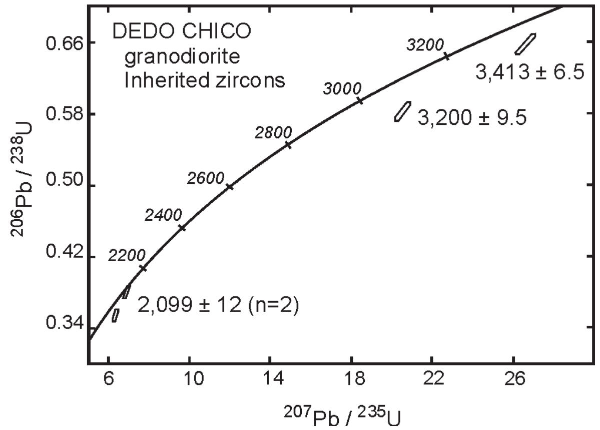

Figure 8: Concordia diagram showing the SHRIMP U-Pb isotopic systematics of inherited zircons from Dedo Chico granodiorite.

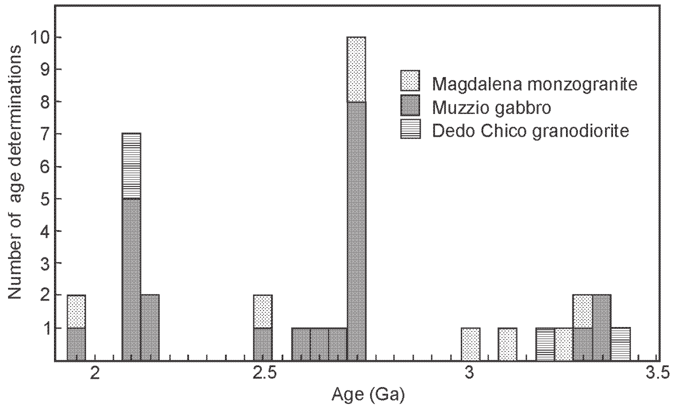

Figure 9: Inherited zircons from Fontana Lake region; includes on sample dated by Rolando *et al.* (2002b).

in Lago La Plata Formation (Late Jurassic) and hosted the hydrothermal alteration of the Cerro Bayo prospect that was dated at 126 ± 6 Ma (Rolando *et al.* 2000).

Near Cerro Negro (Fig. 2), metasedimentary rocks intruded by the Laguna Escondida dacite porphyry. This dacite yielded an U-Pb zircon date of 144.5 ± 1.6 Ma (Jurassic-Cretaceous boundary), which is the minimum age for that stratigraphic unit, now included in the Lago La Plata Formation.

No plutonic rocks are recorded during the Rio Mayo basin fill (Late Berriasian to Barremian, 140-115 Ma) in the Fontana Lake region, but coeval plutonic rocks do occur in the western part of the Patagonian Batholith at the same latitude (Fig. 2; Pankhurst *et al.* 1999).

The crystallization age of the Victoria Tonalite is given by its U-Pb date of 117 ± 1.7 Ma. A previous whole rock K-Ar date yielded 126 ± 10 Ma (Ramos 1981), which implies that the incipient sericitic alteration of the tonalite did not affect much the Ar isotopic composition. Metasedimentary rocks of the Apeleg Formation intruded by the Victoria Tonalite define the minimum age for the stratigraphic unit in this sector limited take Hauterivian-Barremian.

The granitoids stocks of the area cannot be correlated, because the Dedo Chico Granodiorite yielded an U-Pb date of 99.6 ± 2.8 Ma, whereas another granodiorite 10 km to the south (Fig. 2) was dated at 81.7 ± 1.3 Ma (Rolando *et al.* 2002b). This shows that differences in ages exist between stocks at a local scale, because the granodiorite to the south and north of Fontana-La Plata Lakes have yield differences between 14 and 22 m.y. However, two whole rock Rb-Sr isochrons were obtained from the Rio Cisnes region, 20 km to the north, and yielded 95.6 ± 2.4 Ma (Pankhurst *et al.* 1999) and 117 ± 7 Ma (Stanzione *et al.* 1991). These Rb-Sr ages are close to the age of the Dedo Chico granodiorite (99.6 ± 2.8 Ma) and the Victoria tonalite (117 ± 1.7 Ma), respectively.

The geochronological determinations of the two granitoids presented in this work, together with previous dating (Rolando *et al.* 2002b) confirm a temporal agreement of the Patagonian Batholith between 44° 30´ and 45° 30´ S and its epizonal stocks of the eastern area. The granitic bodies, dated by U-Pb in zircon, intruded within a time period of around 40 million years between Barremian-Campanian ages (Tab. 1, Fig. 2). This time period is in agreement with the extrusion of the volcanic rocks of the Divisadero Group. Epithermal deposits (i.e., La Ferrocarrilera deposit) were formed at 112 ± 6 Ma and are associated with an intrusion at depth (Rolando *et al.* 1999 and 2000). The Patagonian Batholith, epizonal granitic stocks, subvolcanic and volcanic rocks of the Divisadero Group, and the occurrence of epithermal deposits represent the magmatic arc developed between Barremian and Campanian. Those geological manifestations represent different erosion levels for the same Andean magmatic arc.

The Precambrian xenocryst zircons from the Dedo Chico Granodiorite have corroded and rounded rims. These xenocrysts were probably partly dissolved in the magma (Watson 1996) or eroded by erosion during transport. The Dedo Chico zircon xenocrysts, together with the other samples (Rolando *et al.* 2002b), have dates concentrated near 1.95-2.15, 2.50-2.75 and 3.00-3.41 Ga (Fig. 9). This suggests the presence of a hypothetical Archean-Paleoproterozoic basement underlying the Fontana Lake region, a new concept for the basement of the Patagonian Andes (Rolando *et al.* 2002b).

Conclusions

The age of the Cerro Bayo Ignimbrite (148.7 ± 2.3 Ma; Middle Jurassic) helps to reconstruct the stratigraphy of the region to the south of Fontana Lake. The Cerro Bayo Ignimbrite is coeval with the extensive volcanic deposits present in the Andes and in the extra-Andean region of Patagonia (Pankhurst *et al.* 2000).

Some Jurassic plutons are known in the Patagonian Batholith near 47° S (Parada *et al.* 1996), but these are yet to be discovered in the portion of the Patagonian Andes at 45° S. In this section of the Andes plutonic equivalents of the volcanic rocks of the La Plata Formation were not found. A possibility is that the Laguna Escondida dacitic porphyry can be linked to the batholith since it is 145 Ma old and it was intruded in the Jurassic-Cretaceous boundary, during the final stages of extrusion of the volcanic rocks of the Lago La Plata Formation.

The Rio Mayo basin was formed during the Late Berriasian-Barremian (140-115 Ma; Aguirre-Urrieta and Ramos 1981) in a retro-arc extensional strain setting. This basin may have formed because of an increase in the angle of subduction of the oceanic plate beneath South America (Rolando 2001, Folguera *et al.* 2002; Folguera and Iannizzotto, 2004). At the same time, the magmatic arc migrated to the west, where granitic rocks were dated at 146-126 Ma along the western border of the Patagonian Batholith (Fig. 2; Pankhurst *et al.* 1999). Also, granitic rocks of this age are not at the eastern border of the batholith and the Fontana Lake region, and only minor volcanic activity was recognized (Ramos and Palma 1983).

A normal subduction angle was established in the Barremian, causing the closure of the retro-arc basin and the formation of a single magmatic arc, which constitute the present-day, part of the eastern border of the batholith and the pre-Andes region. Several isotopic ages from this region confirm this temporal and spatial relationship (Rolando *et al.* 2002b) and indicate that the major plutonic activity occurred around 100 Ma (Ramos *et al.* 1982; Townley 1997; Pankhurst *et al.* 1999; Rolando *et al.* 2002b). Also, typical arc-related volcanism (Divisadero Group) dated at about 120-80 Ma is widely distributed in the pre-Andes region.

The xenocryst zircons in the Dedo Chico Granodiorite (99.6 ± 2.8 Ma) are about 2,100, 3,200 and 3,410 Ma in age, suggesting the presence of a underlying unexposed crust of Archean-Paleoproterozoic age, as previously proposed by Rolando *et al.* (2002b).

Acknowledgements

This paper is part of a PhD thesis by Ariel Pablo Rolando on “Metallogeny and Hydrothermal Alteration in the Lago Fontana Region, Patagonia”, funded by CAPES/SPU and submitted to Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil. The authors wish to thank Mabel Lafranchini and Matias Pierri for field assistance. Moacir Macambira is thanked for his help with zircon separation at UFPA. The laboratory expenses were covered by FAPERGS and field support in Argentina by the “Metalogenia of Lago Fontana” Project - BID 802/OC.AR PID N°0337. Paul Potter, Leandro Etchavarria, Friederich Lucassen, Francisco Hervé, Andrés Folguera and Victor Ramos are acknowledged for very helpful advice on the manuscript.

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Recibido: 9 de junio, 2004
Aceptado: 10 de octubre, 2004