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Relationship between volcanism and marine sedimentation in northern Austral (Aisén) Basin, central Patagonia: Stratigraphic, U–Pb SHRIMP and paleontologic evidence

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ABSTRACT

The northernmost part of the oil-producing Austral Basin, known as Aisén Basin or Río Mayo Embayment (in central Patagonian Cordillera; 43–46°S), is a special area within the basin where the interplay between volcanism and the initial stages of its development can be established. Stratigraphic, paleontologic and five new U–Pb SHRIMP age determinations presented here indicate that the Aisén Basin was synchronous with the later phases of volcanism of the Ibáñez Formation for at least 11 m.yr. during the Tithonian to early Hauterivian. In this basin marine sedimentary rocks of the basal units of the Coihaique Group accumulated overlying and interfingering with the Ibáñez Formation, which represents the youngest episode of volcanism of a mainly Jurassic acid large igneous province (Chon Aike Province). Five new U–Pb SHRIMP magmatic ages ranging between 140.3 ± 1.0 and 136.1 ± 1.6 Ma (early Valanginian to early Hauterivian) were obtained from the Ibáñez Formation whilst ammonites from the overlying and interfingering Toqui Formation, the basal unit of the Coihaique Group, indicate Tithonian, early Berriasian and late Berriasian ages. The latter was a synvolcanic shallow marine facies accumulated in an intra-arc setting, subsequently developed into a retro-arc basin.

1. Introduction

The Austral Basin was a retro-arc ensialic marine basin developed in southwestern Gondwana during the late Mesozoic-Cenozoic and extending from the southern tip of the continent (e.g. Biddle et al., 1986) to at least latitude 43°S in the north (De La Cruz et al., 1996) (Fig. 1). It has been more thoroughly studied in its eastern region where it produces oil (e.g. Biddle et al., 1986), an area far-away from the volcanic arc. The northern part of the basin, known as Aisén Basin (Bell and Suárez, 1997) or Río Mayo Embayment (Aguirre-Urreta and Ramos, 1981; Ramos and Aguirre-Urreta, 1994), is a unique part of it where the relationship of volcanism and marine sedimentation during the initial stages of development of the basin can be established. Well exposed successions of interbedded volcanic rocks, mainly tuffs, and marine sedimentary beds, locally with guide fossils, allowed paleontologic and radiometric dating, which rendered a new and more precise understanding of the stratigraphy and evolution of this part of the basin. The main objective of this paper is the timing of the marine transgression of the Aisén Basin and the relationship between volcanism and marine sedimentation during that period.

The marine transgression started in the Late Jurassic and it was developed over a Middle-Upper Jurassic volcanic basement, represented by the Ibáñez and Tobífera formations and equivalent units, with a contact that in the southeastern part of the Austral Basin has been described as unconformable, whereas in the western and northern area (Aisén Basin) is conformable. Generally a sharp time-limit, approximately equivalent to the Jurassic-Cretaceous boundary, has been assigned to the contact of the marine beds of the Austral Basin and the underlying volcanic rocks (e.g. Niemeyer et al.,1984; Lizuaín, 1999; Rolando et al., 2004). The last authors even indicate that magmatism ceased after the Jurassic volcanic event when a retro-arc basin formed. In this article, we present zircon U–Pb SHRIMP ages that combined with stratigraphic work and paleontologic work, partly presented previously by the authors at geological congresses (Covacevich et al., 1994; De La Cruz et al.,1994, 1996; Suárez et al., 1996), indicates that the Jurassic volcanism continued into the early Hauterivian, synchronously with the transgressive phase of the basin.

The Aisén Basin was bounded to the southeast by the Deseado Massif and to the east by the San Jorge Basin, and extended from approximately Futaleufú (43°S) in the north and latitude

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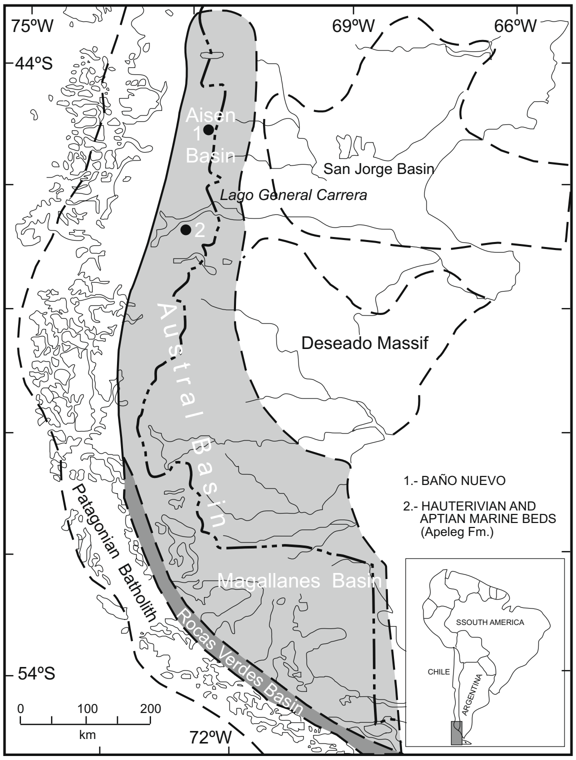
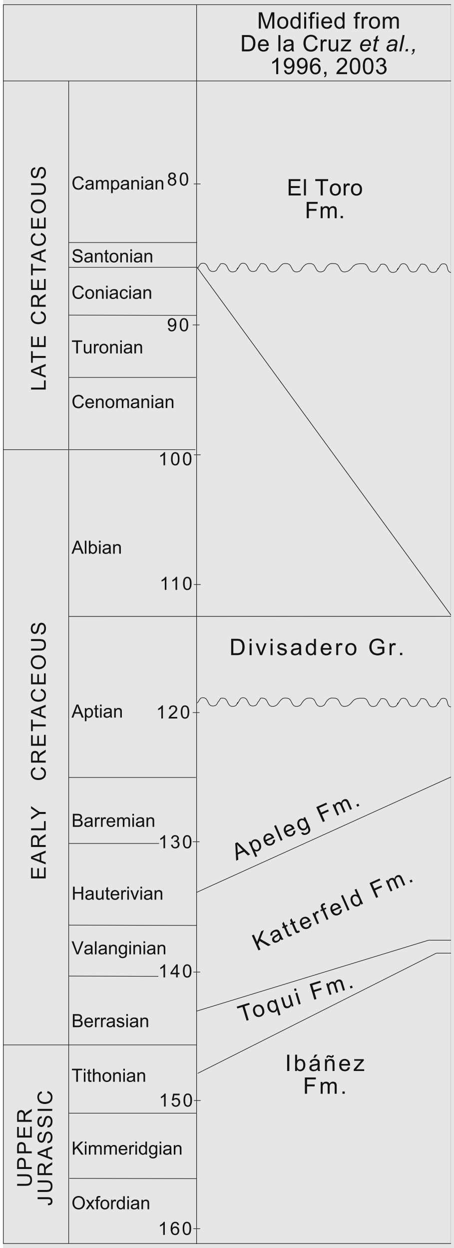


Fig. 1. Austral and Rocas Verdes Basin.

Table 1
Generalized Mesozoic stratigraphy of eastern Central Patagonian Cordillera, Chile.



			Modified from De la Cruz *et al.*, 1996, 2003
LATE CRETACEOUS	Campanian	80	El Toro Fm.
	Santonian		
	Coniacian		
	Turonian	90	
	Cenomanian		
EARLY CRETACEOUS		100	
	Albian	110	
			Divisadero Gr.
	Aptian	120	
	Barremian	130	Apeleg Fm.
	Hauterivian		Katterfeld Fm.
	Valanginian	140	
	Berrasian		Toqui Fm.
UPPER JURASSIC	Tithonian	150	Ibáñez Fm.
	Kimmeridgian		
	Oxfordian	160	

50–51°S, in the south (Fig. 1). The Coihaique Group represent the marine sediments accumulated in it and was overlain by Aptian-Albian subaerial volcanic deposits of the Divisadero Group (Table 1; Niemeyer et al., 1984; Suárez et al., 1996; Suárez et al., 2005a; Bell and Suárez 1997; De La Cruz et al., 2003; Pankhurst et al., 2003). We present a revised stratigraphic scheme for the Late Jurassic–Early Cretaceous of the Aysén Basin, between the area of Futaleufú (43°S) and Lago General Carrera (46°S) (Fig. 2). Within this framework, Neocomian volcanic associations form an important component of the main stratigraphic units in the region. Some of the volcanic rocks previously assigned to the Aptian-Albian Divisadero Group because they overlie marine sedimentary beds, are seen herein to be Neocomian volcanic associations representing the continuation of the Ibáñez volcanism into the Early Cretaceous.

Previous radiometric dating of the Ibáñez Formation was mainly carried out using the K–Ar method (Suárez and De La Cruz 1997a, b; Suárez et al., 1997; De La Cruz et al., 2003, 2004; De La Cruz and Suárez, 2006). However, the generalized alteration of the volcanic rocks allowed only local K–Ar dating. Scant Ar/Ar dates exist in the literature for these rocks (Parada et al., 1997, 2001) and only recently two U–Pb SHRIMP analyses in rocks of the Ibáñez Formation have been published (Pankhurst et al., 2000, 2003). In this work, we will use the geologic time scale of Gradstein et al. (2004).

2. Late Jurassic-Cretaceous geological setting

The overall Mesozoic stratigraphic record of the sedimentary and volcanic units of the region is represented in Table 1, and from base to top is formed by the Ibáñez Formation, a unit of calc-alkaline volcanic rocks (Baker et al., 1981; Suárez et al., 1999; Quiroz 2000; Bruce 2001), of Middle-Late Jurassic to Early Cretaceous age (Covacevich et al., 1994; Suárez and De La Cruz, 1996; Suárez et al., 1996, 1997, 2005; De La Cruz et al., 2003, 2004; Pankhurst et al., 2003; De La Cruz and Suárez, 2006). The Ibáñez Formation, equivalent to the Lago La Plata Formation in adjacent Argentina (Ramos, 1981), represents the youngest episode of volcanism of a mainly Jurassic acid large igneous province known as the Chon Aike province (Pankhurst et al., 1998, 2000; Riley and Leat, 1999; Riley et al., 2001) developed in Patagonia during rifting that preceded the dismembering of Gondwana (e.g. Gust et al., 1985). The Ibáñez Formation unconformably overlies Devonian-Carboniferous rocks of the Eastern Andean Metamorphic Complex (Hervé 1993; Hervé et al., 2000; De La Cruz et al., 2004; De La Cruz and Suárez, 2006). An angular unconformity between Toarcian limestones (ca. 180–190 Ma) of the Osta Arena Formation (Ploszkiewcz 1987) and overlying volcanic breccias assigned to the Lago La Plata Formation, has been observed in an outcrop near Aldea Apeleg in western Chubut Province, in Argentina (ca. 44°40'S; Fig. 2). This

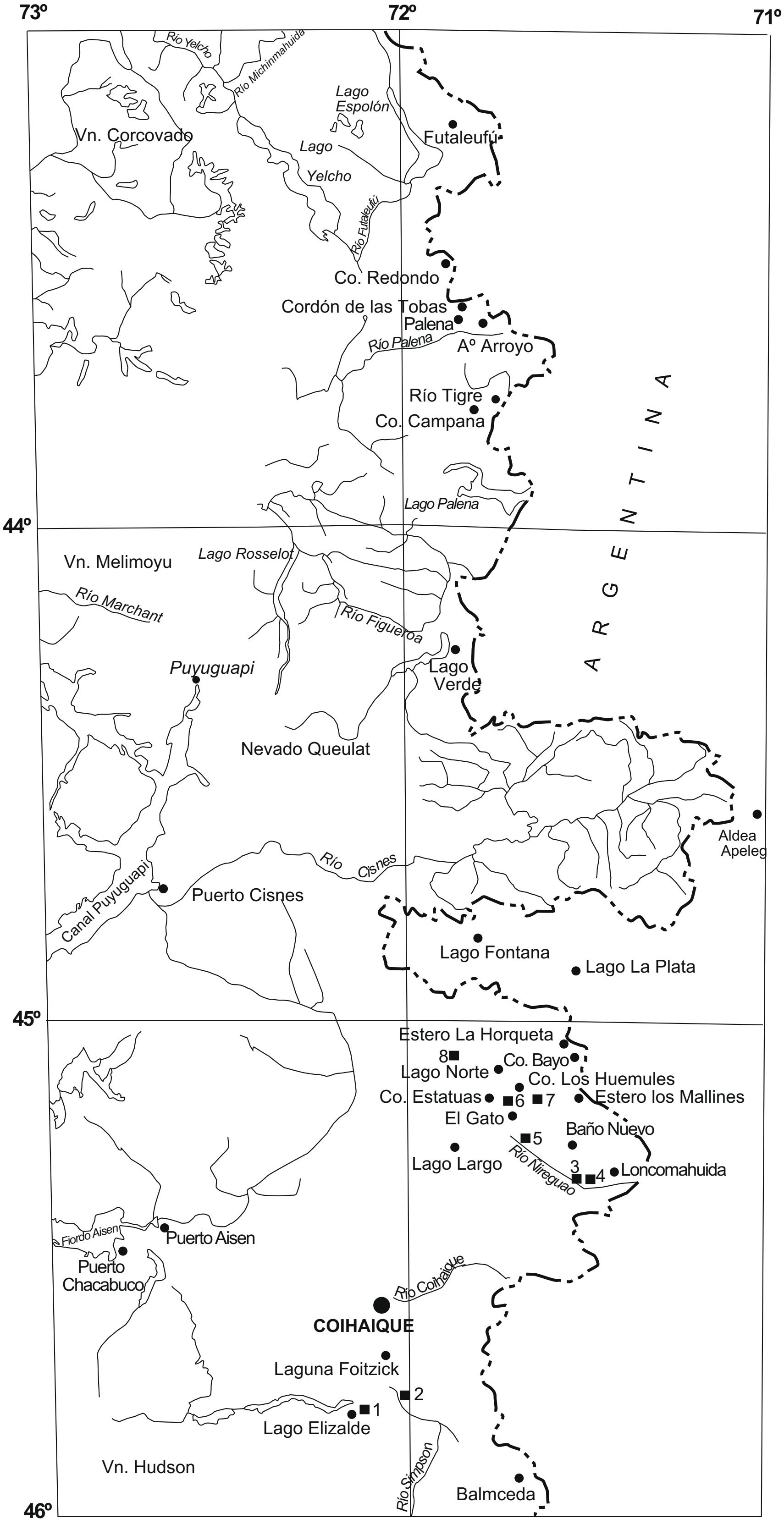


Fig. 2. Location map. Numbers are sampling sites for radiometric dates.

provides a maximum age for the Ibáñez Formation in that area (Suárez and Márquez, 2007). The Ibáñez Formation has an estimated thickness of 1900 m (Niemeyer et al., 1984) and along the chilean side of the central Patagonian Cordillera crops out from Futaleufú (43°S) to Lago O'Higgins (49°S), continuing to the south under the name of Tobífera Formation (Fig. 3).

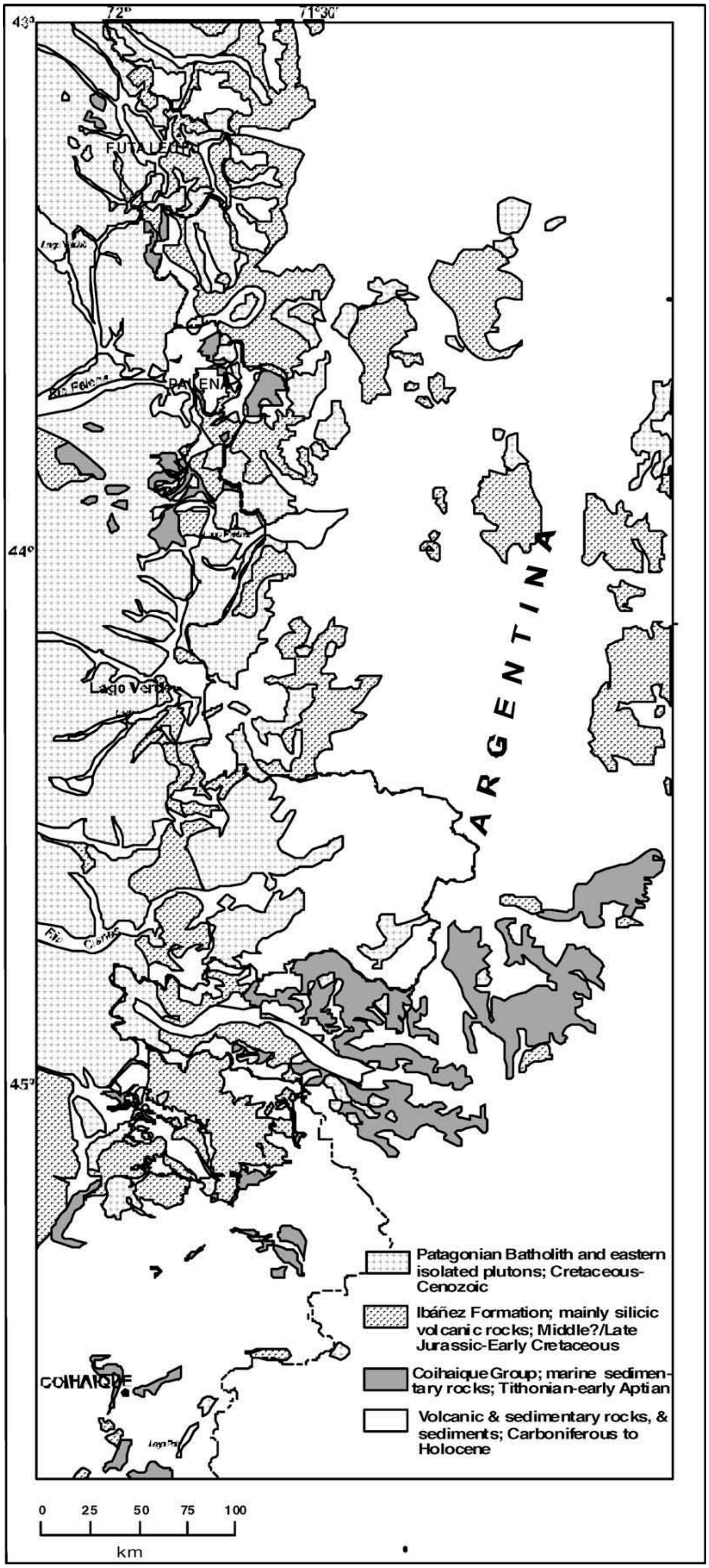
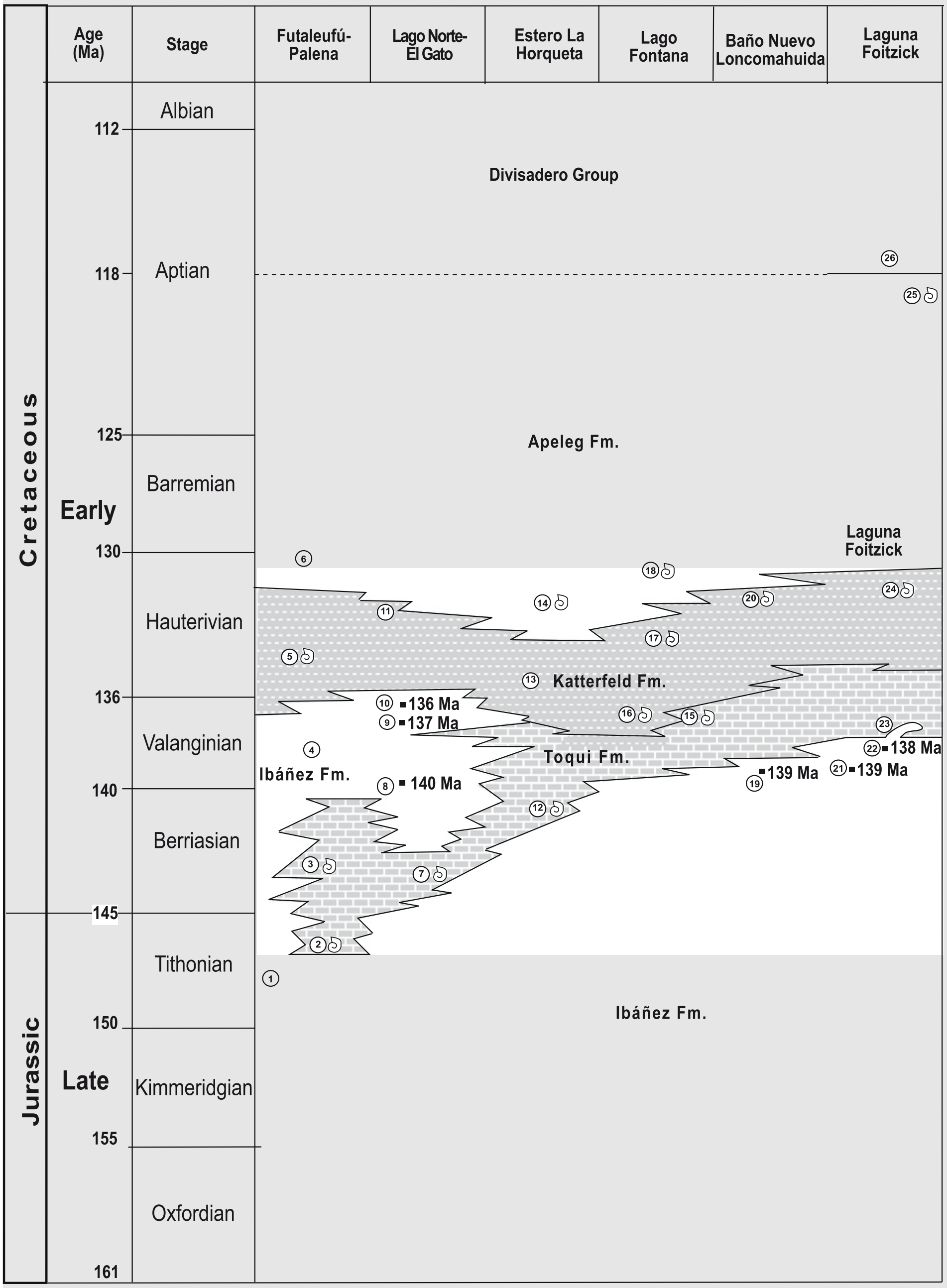


Fig. 3. Schematic geologic map (modified from De La Cruz et al., 1996, 2003; Suárez et al., 2007).

Table 2

Stratigraphic scheme of eastern Central Patagonian Cordillera, Chile. (1): Volcanic rocks inferred to exist but not demonstrated; (2): perisphinctids similar to *Aulacosphinctes* and *Himalayites* sp., Tithonian ammonites in Toqui Formation, Futaleufú-Palena area (De La Cruz et al., 1996); (3): *Blanfordiceras* (?) sp., Berriasian ammonite in Toqui Formation, Futaleufú-Palena area (De La Cruz et al., 1996); 4: volcanic rocks overlying Toqui Fm. and inferred to underlie Katterfeld Formation (De La Cruz et al., 1996); 5: *Favrella* sp., Hauterivian ammonite in Katterfeld Formation (De La Cruz et al., 1996); 6: sandstone hornfels assigned to the Apeleg Formation (De La Cruz et al., 1996); 7: *Groebericeras* Leanza and *Blandfordiceras* Cossman, Early Berriasian ammonites, Toqui Formation, W coast of río Ñireguao (Covacevich et al., 1994); 8: 140 Ma SHRIMP U–Pb zircon magmatic age, ignimbrite from W coast of río Ñireguao, Lago Norte Volcanic Complex; 9: 137 Ma SHRIMP U–Pb zircon magmatic age, Lago Norte Volcanic Complex, ignimbrite overlying Early Berriasian beds of Toqui Formation, 3 km NNW of Lago Norte; 10: 136 Ma SHRIMP U–Pb zircon magmatic age, andesite lava of Lago Norte Volcanic Complex underlying shales of Katterfeld Formation and Divisadero Group, southernwestern flank of cerro Los Huemules; 11: poorly exposed black shales (<5 m of outcrop) assigned to the Katterfeld Formation, and unconformably (?) underlying the Divisadero Group, southern flank of cerro Estatuas and western flank of cerro Los Huemules; 12: *Neocosmoceras sayni* (Simionescu) and *Neocosmoceras wichmanni* (Gerth), Late Berriasian ammonites in Toqui Formation (Covacevich et al., 1994); 13: Valanginian-Hauterivian age stratigraphically assigned to the Katterfeld Formation; 14: *Favrella* sp., Hauterivian ammonite in the Apeleg Formation in cerro Bayo (Bell and Suárez 1997); 15: $^{87}Sr/^{86}Sr$ of 0.707352 ± 0.000008 from *Gryphaea* sp. shells indicative of an early Late Valanginian age (Olivero and Aguirre-Urreta 2002); 16: *Kilianella* sp. aff. *K. superba* Sayn and *Thurmanniceras* sp. early late Valanginian, lower Katterfeld Formation (Olivero and Aguirre-Urreta 2002); 17: Crioceratitinae indet., late early Hauterivian-early late Hauterivian, upper Katterfeld Formation (Olivero and Aguirre-Urreta 2002); 18: Hauterivian-Barremian, base of Apeleg Formation (Archangelsky et al., 1981); 19: 139 Ma SHRIMP U–Pb zircon magmatic age (CC-350-3), tuff underlying andesitic lavas, Loncomahuida area, Ibáñez Formation; 20: *Favrella* sp., Hauterivian ammonite in Katterfeld Formation in the Baño Nuevo area; 21: 139 Ma SHRIMP U–Pb zircon magmatic age, Valanginian, ignimbrite exposed to the SE of Lago Elizalde, Ibáñez Formation; 22: 138 Ma SHRIMP U–Pb zircon magmatic age (Pankhurst et al., 2003), Valanginian, Foitzick Volcanic Complex; 23: peperite dacite sill emplaced along the contact between the Ibáñez-Toqui formations, Foitzick Volcanic Complex; 24: *Favrella* sp., Hauterivian ammonite in Katterfeld Formation; 25: Early Aptian ammonites, Apeleg Formation, south of Lago General Carrera (46°40'S); 26:118–116 Ma SHRIMP U–Pb zircon magmatic ages and K–Ar dates of Divisadero Group (De La Cruz et al., 2003; Pankhurst et al., 2003).



The Ibáñez Formation comprises different volcanic and sedimentary facies associations (Suárez et al., 1996; Bruce 2001; De La Cruz et al., 2003, 2004; De La Cruz and Suárez, 2006), and is mainly composed of silicic pyroclastic rocks, and subordinately rhyolitic, dacitic, andesitic and basaltic lava flows and domes. These mostly represent subaerial deposition, with local intercalations, usually of less than 50 m thick, of lacustrine black shales and debris flow deposits and fluvial sandstones. In places, the uppermost levels of the formation interfinger with marine sedimentary rocks. The rocks of the Ibáñez Formation experienced low-grade metamorphism (Aguirre et al., 1997) and, in many places, are hydrothermally altered (silicic, argillic, propilitic). South of lago General Carrera they host epithermal gold deposits (Laguna Verde-Cerro Bayo Mining District and El Furioso Mine). Clast-supported breccias and conglomerates, up to 30 m thick, and mainly composed of metasedimentary rock fragments, locally overlie with an unconformity the Eastern Andean Metamorphic Complex. They represent colluvial and alluvial deposits associated with the overlying volcanic rocks, and, at least in one locality, they are associated with acid peperites (De La Cruz et al., 2004). These basal breccias and conglomerates are equivalent to the Arroyo La Mina Formation on the eastern margin of Lago San Martin (Lago O'Higgins in Chile), in Argentina (Riccardi 1971), where the breccias have intercalated tuffs. Hechem et al. (1993) and more recently, De La Cruz et al. (2004) and De La Cruz and Suárez (2006) inferred that there were normal faults synchronous with the accumulation of the Ibáñez Formation. Normal faulting during this period, forming hemigrabens, have been identified in the subsurface of extra-Andean Patagonia (e.g. Gust et al., 1985; Robbiano et al., 1996). It may be tentatively suggested that the basal breccias may represent colluvial and alluvial deposition in the margins of these hemigrabens. This rifting was probably still active during the initial stages of deposition of the Coihaique Group, and the development of grabens and hemigrabens may explain the thickness variation observed in some of the formations of the Coihaique Group.

K–Ar (Suárez and De La Cruz 1997b, 2001; Suárez et al., 1997; De La Cruz and Suárez, 2006), Ar/Ar (Parada et al., 2001) and U–Pb (Parada et al., 1997; Pankhurst et al., 2000, 2003) dates on volcanic rocks of the Ibáñez Formation, and from plutons emplaced in this formation range between 158.9 ± 1.5 Ma (near the Callovian/Oxfordian boundary) and 138.4 ± 1.3 Ma (Valanginian), the latter from the uppermost beds of the Ibáñez Formation underlying the Toqui Formation in the area of Laguna Foitzick (Pankhurst et al., 2003). These dates coincide with the zircon U–Pb SHRIMP age of 148.7 ± 2.3 Ma and the K–Ar age of 145 ± 10 Ma obtained by Rolando et al. (2004) and Ramos (1981), respectively, in the equivalent Lago La Plata Formation. Geochemical analyses of rocks of the Ibáñez Formation have given a calc-alkaline trend (Baker et al., 1981; Suárez et al., 1999; Quiroz 2000; Bruce 2001). This, complemented by the presence of I-type late Jurassic coeval granitoids (Suárez and De La Cruz 2001), indicates subduction processes already operating at least since the early Oxfordian or even Callovian.

The Ibáñez Formation is overlain by the Coihaique Group, a succession of Tithonian to Lower Aptian marine beds accumulated in the Aisén Basin (Covacevich et al., 1994; De La Cruz et al., 1996; Suárez et al., 1996, 2005a, b). This group, is comprised from base to top by the Toqui, Katterfeld and Apeleg formations (Table 1), and represents a transgressive-regressive succession (e.g. De La Cruz et al., 2003). The Toqui Formation, composed of sandstones, tuffites, tuffs and calcareous beds and bearing marine fossils, represents shallow marine deposits. Shelf black shales of the Katterfeld Formation with Valanginian and Hauterivian marine fossils, which were deposited in the still-water anoxic conditions of a sheltered and partly enclosed marine embayment (Ramos 1976; Bell and Suárez 1997; Olivero and Aguirre-Urreta 2002; De La Cruz et al., 2003), overlie the Toqui Formation and, locally, rest directly on the Ibáñez Formation. Marine sandstones and shales, mainly of tidal deposition in an open marine shelf, but locally of delta accumulation of the Apeleg Formation conformably overlie the Katterfeld Formation (Table 1; Ploszkiewicz and Ramos, 1977; González-Bonorino and Suárez 1995; Bell and Suárez 1997). The latter, bears Hauterivian ammonites and south of lago General Carrera have Hauterivian to early Aptian ammonites (De La Cruz and Suárez, 2008).

The Coihaique Group is paraconformably overlain by the Divisadero Group, an association of Aptian-Albian subaerial volcanic rocks (Niemeyer et al., 1984; Suárez et al., 1996; De La Cruz et al., 2003), mainly composed of silicic pyroclastic rocks that have given Aptian K–Ar dates of 118 ± 4 to 113 ± 3 Ma (De La Cruz et al., 2003), and recently restricted to 118 ± 1.1 and 116.1 ± 1.0 Ma on the basis of SHRIMP U–Pb zircon ages (Pankhurst et al., 2003). The latter, in turn, underlie with a gentle angular unconformity, a calc-alkaline association of basalts, andesites and dacites of the El Toro Formation, that have given Campanian-Maastrichtian K–Ar dates of approximately 82–66 Ma (De La Cruz et al., 2003) (Table 1), and are synchronous with acid domes and basalts (Suárez et al., 1996; Demant et al., 2007).

Plutonic rocks form a substantial proportion of the Patagonian Cordillera, constituting a continuous belt between latitudes 41° and 56°S known as the Patagonian Batholith, and satellite plutons exposed to the east of the batholith. Chemical analyses show a calc-alkaline affinity for these rocks. Although most of these plutons are Cretaceous and Cenozoic in age (e.g. Halpern 1973; Halpern and Fuenzalida 1978; Hervé et al., 1984; Suárez et al., 1985; Pankhurst et al., 1999, 2000; Weaver et al., 1990; Bruce et al., 1991), Middle-Late Jurassic plutons have been locally identified mainly by K–Ar (Suárez and De La Cruz, 2001) and, locally by Ar–Ar and U–Pb SHRIMP dating (Parada et al., 1997; Pankhurst et al.,1999, 2000). The latter are probably genetically related to the Ibáñez Formation (Parada et al., 1997; Suárez and De La Cruz, 2001).

Five generalized stratigraphic columns, covering the area between Futaleufú (43°S) in the north, to Laguna Foitzick (45°30'S), 8 km SW of Coihaique (46°S), to the south (Fig. 2), will be briefly described herein from north to south (Table 2). A sixth column including data from the area of lago Fontana in Argentina (Olivero and Aguirre-Urreta, 2002) is also included.

3. Geochronology

3.1. Sample location and analytical techniques

Five samples of tuffaceous rocks have been sampled from the Ibáñez Formation in central Patagonian Cordillera, Chile (between 45° and 46°S). Mineral separations were carried out at the Geochronology Laboratory of the Servicio Nacional de Geología y Minería, Chile (SERNAGEOMIN) using standard crushing, heavy liquid and paramagnetic procedures. Zircon grains were hand picked from the heavy mineral concentrates, mounted in epoxy together with chips of the Temora reference zircon, sectioned approximately in half, and polished. Reflected and transmitted light photomicrographs were prepared for all zircons, as were cathodoluminescence (CL) scanning electron microscope (SEM) images. The CL images were used to decipher the internal structures of the sectioned grains and to ensure that the ~20 μm SHRIMP spot was wholly within a single age component.

The U–Th–Pb analyses were made using SHRIMP II at the Research School of Earth Sciences, The Australian National University, Canberra, Australia following procedures given in Williams (1998, and references therein). Each analysis consisted of six scans

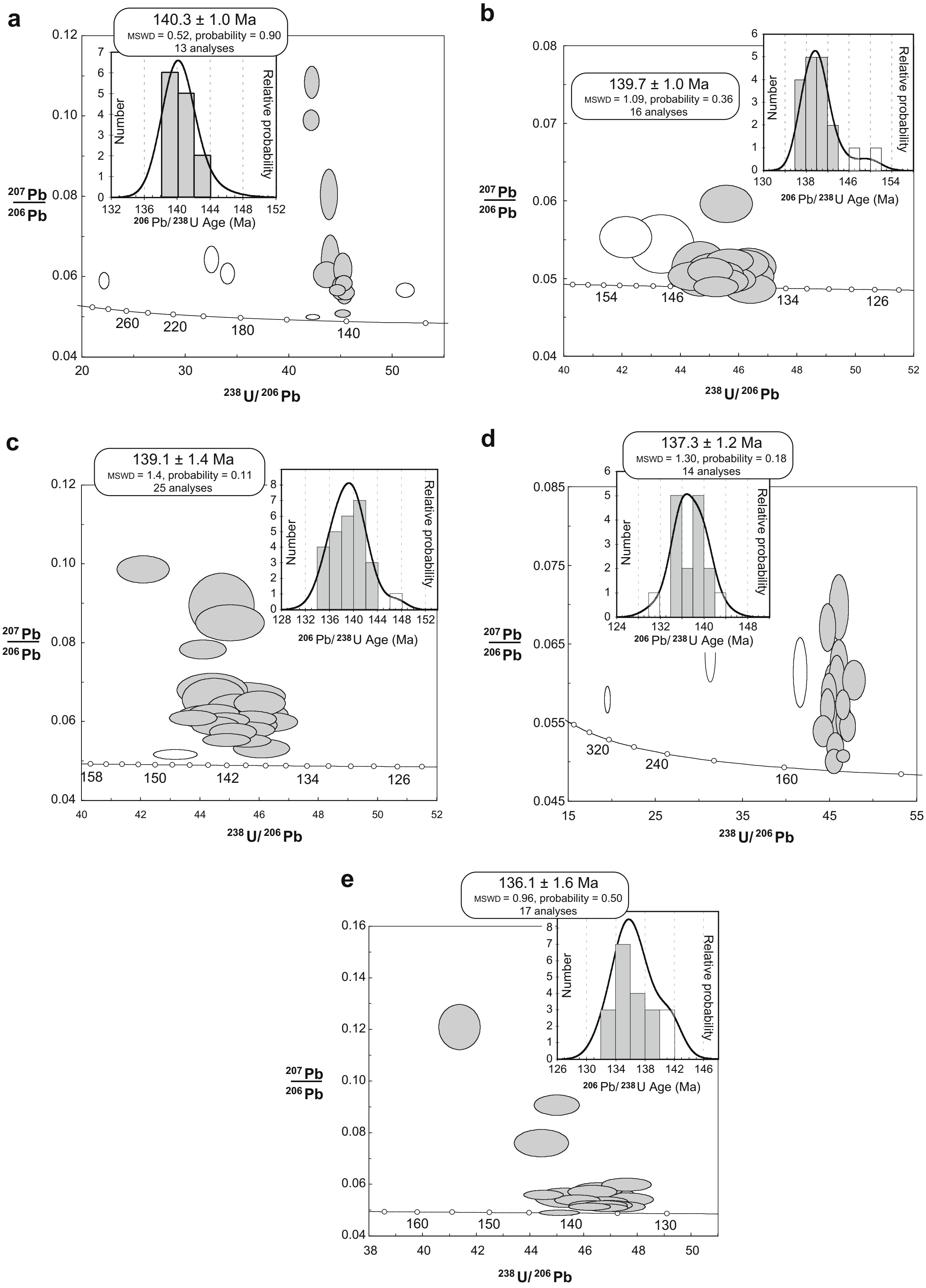


Fig. 4. SHRIMP U–Pb zircon results from samples of the Ibáñez Formation plotted on Tera & Wasserburg concordia plots of the total $^{207}Pb/^{206}Pb$ ratios versus the calibrated $^{206}Pb/^{238}U$ ratios. Inset shows a relative probability plot, with stacked histogram for the interpreted magmatic zircon analyses used for the weighted mean age calculation as shown: a, sample CH-6174 (Lago Norte Volcanic Complex); b, sample CC-650-3 (tuffite from Loncomahuida area); c, sample CH-6140 (ignimbrite from SE of Lago Elizalde); d, sample CH-6189 (Lago Norte Volcanic Complex); e, sample CH-6213 (Lago Norte Volcanic complex).

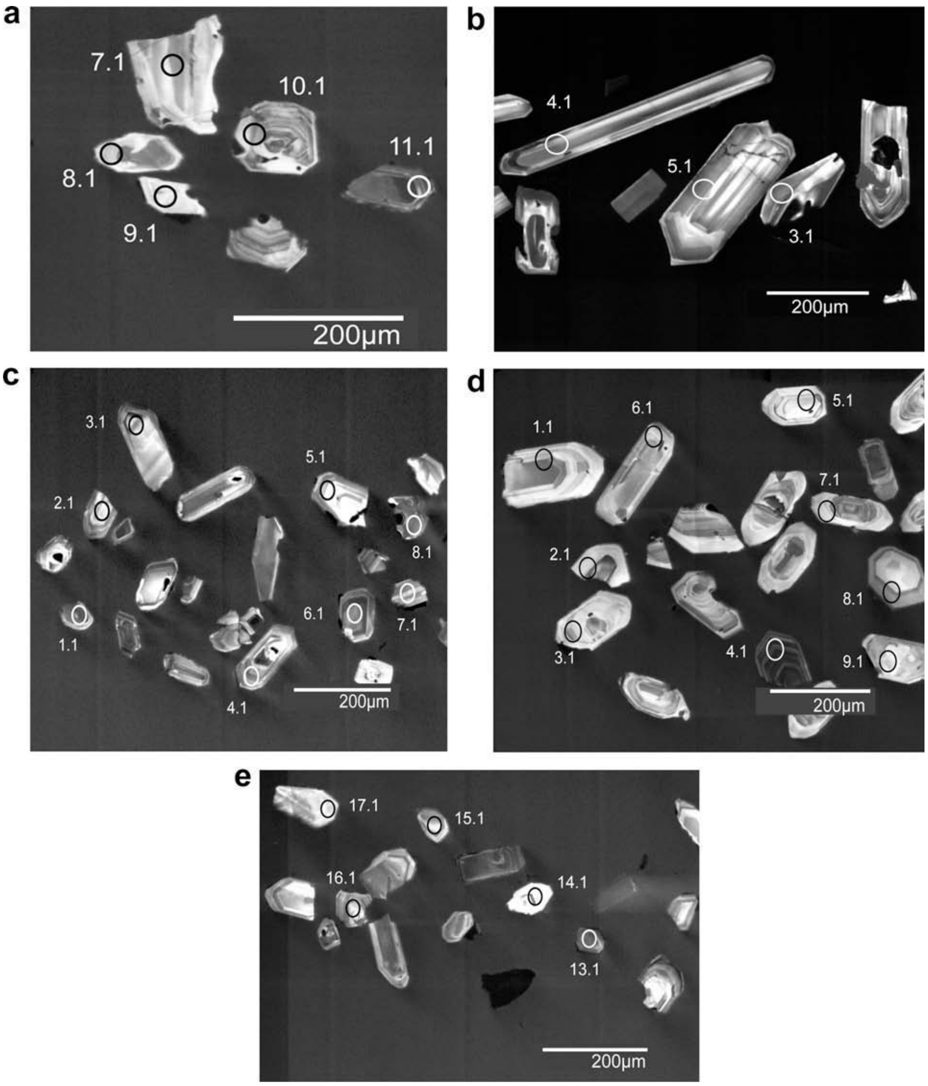


Fig. 5. Representative catholoduminescence images of the sectioned zircon grains analysed by SHRIMP. Samples are: a, sample CH-6174 (Lago Norte Volcanic Complex); b, sample CC-650-3 (Lago Norte Volcanic Complex); c, sample CH-140 (Lago Norte Volcanic Complex); d, sample CH-6189 (lava from Loncomahuida area); e, sample CH-6213 (ignimbrite from SE of Lago Elizalde).

through the mass range, with the Duluth Garbo (FC1) or Temora reference grains analyzed for every three unknown analyses. The data have been reduced using the SQUID Excel Macro of Ludwig (2001). The $^{206}Pb/^{238}U$ ratios have been normalised relative to a value of 0.0668 for the Temora reference zircon, equivalent to an age of 417 Ma (see Black et al., 2003) and 0.1859 for the FC1 reference zircons, equivalent to an age of 1099 Ma (see Paces and Miller, 1993). Uncertainty in the U–Pb calibrations are given in the data tabulations. Uncertainties given for individual analyses (ratios and ages) are at the one sigma level (Table 3). Tera and Wasserburg (1972) concordia plots, probability density plots with stacked histograms and weighted mean $^{206}Pb/^{238}U$ age calculations were carried out using ISOPLOT/EX (Ludwig, 2003). Weighted mean $^{206}Pb/^{238}U$ age uncertainties are reported as 95% confidence limits.

One sample from this region was collected for K–Ar dating at the Geochronology Laboratory of the Servicio Nacional de Geología y Minería, Chile. The K–Ar analytical procedures are described in De La Cruz et al. (2003). The Ar was purified in Pyrex extraction lines and the radiogenic ^{40}Ar volumes were determined using standard isotopic dilution techniques in a MS10S Mass Spectrometer, with a total accuracy of 1–2%. The potassium analyses were done in triplicate by atomic absorption techniques with an accuracy of 0.7–1.3%, depending on the K content. The errors are quoted at the 2 sigma level and the decay constants shown in Table 4 are those suggested by Steiger and Jäger (1977). Location of the samples is shown in Fig. 2.

3.2. Results

Five new SHRIMP U–Pb zircon dates are presented below and in Table 3 and Fig. 4. The samples are tuff rocks of the Ibáñez Formation and they range in age from 140.3 ± 1.0 Ma to 136.1 ± 1.6 Ma, representing an early Valanginian to early Hauterivian age range. The samples are discussed from oldest to youngest as follows:

1. Dacite ignimbrite south of río Ñireguao

Sample CH-6174 is of a dacitic ignimbrite of the Lago Norte Volcanic Complex of the Ibáñez Formation (see later). It has 10 m in thickness ans crops out adjacent to an exposure of marine beds with early Berriasian ammonites of the Toqui Formation (Covacevich et al., 1994) in the hills south of río Ñireguao in the area of El Gato. A fault probably separates the ignimbrite from the marine beds. The small number of zircons hand picked from this sample

Table 3a
SHRIMP U–Pb zircon data for sample CH-6174.

Grain. Spot	U (ppm)	Th (ppm)	Th/U	$^{206}Pb^{*}$ (ppm)	$^{204}Pb/^{206}Pb$	f_{206} %	Total				Radiogenic		Age (Ma)	
							$^{238}U/^{206}Pb$	±	$^{207}Pb/^{206}Pb$	±	$^{206}Pb/^{238}U$	±	$^{206}Pb/^{238}U$	±
1.1	137	176	1.28	3.5	–	1.36	34.08	0.45	0.0606	0.0017	0.0289	0.0004	183.9	2.4
2.1	174	80	0.46	3.3	0.000994	1.63	45.22	0.58	0.0618	0.0026	0.0218	0.0003	138.7	1.8
3.1	306	293	0.96	5.8	0.000578	0.88	45.48	0.55	0.0558	0.0012	0.0218	0.0003	139.0	1.7
4.1	122	83	0.68	2.4	0.001039	1.43	43.67	0.83	0.0603	0.0021	0.0226	0.0004	143.9	2.8
5.1	666	411	0.62	12.7	0.000683	1.11	44.97	0.49	0.0577	0.0015	0.0220	0.0002	140.2	1.5
6.1	114	114	1.00	3.0	0.001071	1.78	32.52	0.45	0.0641	0.0022	0.0302	0.0004	191.8	2.7
7.1	238	190	0.80	4.5	0.000356	0.98	44.99	0.56	0.0566	0.0017	0.0220	0.0003	140.3	1.8
8.1	207	135	0.65	4.0	0.000901	1.85	44.02	0.56	0.0636	0.0043	0.0223	0.0003	142.2	2.0
9.1	142	79	0.56	5.5	0.000810	0.87	22.14	0.32	0.0589	0.0014	0.0448	0.0007	282.4	4.1
10.1	272	243	0.90	5.1	0.001025	0.88	45.37	0.55	0.0558	0.0018	0.0218	0.0003	139.3	1.7
11.1	1145	738	0.64	21.8	0.000117	0.22	45.22	0.48	0.0506	0.0006	0.0221	0.0002	140.7	1.5
12.1	3769	234	0.06	76.5	0.000071	0.09	42.36	0.43	0.0498	0.0004	0.0236	0.0002	150.3	1.5
13.1	300	196	0.65	5.7	0.000837	1.18	45.33	0.54	0.0582	0.0013	0.0218	0.0003	139.0	1.7
14.1	1139	1284	1.13	23.2	0.004047	7.47	42.23	0.44	0.1083	0.0027	0.0219	0.0002	139.7	1.6
15.1	659	258	0.39	12.9	0.002646	3.96	43.88	0.55	0.0803	0.0042	0.0219	0.0003	139.6	1.9
15.2	600	185	0.31	10.1	0.000381	1.00	51.23	0.57	0.0565	0.0012	0.0193	0.0002	123.4	1.4
16.1	298	154	0.52	6.1	0.003069	6.28	42.14	0.51	0.0989	0.0017	0.0222	0.0003	141.8	1.7
16.2	514	375	0.73	9.9	0.000353	0.95	44.70	0.50	0.0565	0.0010	0.0222	0.0002	141.3	1.6

Notes:
1. Uncertainties given at the one a level.
2. Error in Temora reference zircon calibration was 0.25% for the analytical session (not included in above errors but required when comparing data from different mounts).
3. – denotes that no ^{204}Pb was detected.
4. f_{206} % denotes the percentage of ^{206}Pb that is common Pb.
5. Correction for common Pb made using the measured $^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios following Tera and Wasserburg (1972), as outlined in Williams (1998; the so called 207Pb correction method).

Table 3b
RIMP U–Pb zircon data for sample CC-650-3.

Grain. Spot	U (ppm)	Th (ppm)	Th/U	$^{206}Pb^{*}$ (ppm)	$^{204}Pb/^{206}Pb$	f_{206} %	Total				Radiogenic		Age (Ma)	
							$^{238}U/^{206}Pb$	±	$^{207}Pb/^{206}Pb$	±	$^{206}Pb/^{238}U$	±	$^{206}Pb/^{238}U$	±
1.1	177	121	0.68	3.4	–	0.29	44.68	0.64	0.0512	0.0023	0.0223	0.0003	142.3	2.1
2.1	366	277	0.76	6.8	0.000546	<0.01	46.41	0.58	0.0486	0.0216	0.0003	0.0003	137.5	1.7
3.1	242	208	0.86	4.6	0.000922	0.25	45..11	0.60	0.0508	0.0016	0.0221	0.0003	141.0	1.9
4.1	263	257	0.98	5.0	0.001185	1.35	45..59	0.60	0.0595	0.0016	0.0216	0.0003	138.0	1.8
5.1	99	68	0.69	2.0	0.001996	0.68	43..34	0.74	0.0544	0.0025	0.0229	0.0004	146.1	2.5
6.1	444	338	0.76	8.4	0.000173	0.28	45.28	0.54	0.0510	0.0011	0.0220	0.0003	140.4	1.7
7.1	347	283	0.81	6.5	0.000195	0.16	45.61	0.56	0.0501	0.0013	0.0219	0.0003	139.6	1.7
8.1	506	569	1.12	9.6	0.000090	0.09	45.54	0.53	0.0495	0.0011	0.0219	0.0003	139.9	1.6
9.1	473	380	0.80	9.0	0.000447	0.21	45.36	0.53	0.0505	0.0011	0.0220	0.0003	140.3	1.6
10.1	287	160	0.56	5.3	–	0.17	46.33	0.58	0.0502	0.0014	0.0215	0.0003	137.4	1.7
11.1	163	98	0.60	3.3	0.000345	0.78	42.12	0.59	0.0552	0.0018	0.0236	0.0003	150.1	2.1
12.1	441	298	0.68	8.3	–	0.12	45.77	0.54	0.0498	0.0011	0.0218	0.0003	139.2	1.6
13.1	659	517	0.78	12.6	0.000000	0.26	45.04	0.51	0.0509	0.0011	0.0221	0.0003	141.2	1.6
14.1	355	201	0.57	6.9	0.000300	0.17	44.40	0.54	0.0012	0.0225	0.0003	0.0003	143.3	1.8
15.1	721	557	0.77	13.7	0.000040	0.00	45.23	0.51	0.0488	0.0009	0.0221	0.0002	141.0	1.6
16.1	662	759	1.15	12.4	0.000318	0.43	45.68	0.54	0.0522	0.0010	0.0218	0.0003	139.0	1.6
17.1	270	150	0.55	5.0	–	0.33	46.35	0.62	0.0514	0.0016	0.0215	0.0003	137.1	1.8
18.1	285	280	0.98	5.3	0.000081	0.37	46.18	0.56	0.0517	0.0012	0.0216	0.0003	137.6	1.7

Notes:
1. Uncertainties given at the one a level.
2. Error in FC1 reference zircon calibration was 0.40% for the analytical session (not included in above errors but required when comparing data from different mounts).
3. – denotes that no ^{204}Pb was detected.
4. f_{206} % denotes the percentage of ^{206}Pb that is common Pb.
5. Correction for common Pb made using the measured $^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios following Tera and Wasserburg (1972), as outlined in Williams (1998; the so called 207Pb correction method).

are mostly equant grains, subhedral in shape, or fragments of larger grains. They have dark inclusions and some are cracked and altered. The CL images (Fig. 5a) show a dominantly oscillatory zoned interior, though some are structured with zoned inner areas overgrown by discordant zoned outer areas (for example grains 15 and 16).

Eighteen areas have been analysed on 16 zircon grains (Fig. 5a, Table 3a). A range of $^{206}Pb/^{238}U$ ages is recorded with a dominant grouping at about 140 Ma. The second analysis of grain 15 is interpreted to be of an area that has lost radiogenic Pb, whilst the analyses for grains 1, 9 and 12 are older and interpreted to inherited older zircon components of Early Jurassic (crystals 1 and 6) and Permian age (crystal 9; Table 3a). A weighted mean for the remaining 13 analyses has no excess scatter giving 140.3 ± 1.0 Ma (Fig. 4a). This is interpreted to date the time of zoned igneous zircon crystallisation in this felsic volcanic rock during the late Berriasian-early Valanginian.

2. Dacite tuff in the area of Loncomahuida

Sample CC-650-3 is an acid tuff from a ⩾30 m succession of tuffs and tuffites that is overlain by ⩾100 m thick succession of

Table 3c
SHRIMP U–Pb zircon data for sample CH-6140.

Grain. Spot	U (ppm)	Th (ppm)	Th/U	$^{206}Pb^{*}$ (ppm)	$^{204}Pb/^{206}Pb$	f_{206} %	Total				Radiogenic		Age (Ma)	
							$^{238}U/^{206}Pb$	±	$^{207}Pb/^{206}Pb$	±	$^{206}Pb/^{238}U$	±	$^{206}Pb/^{238}U$	±
1.1	1016	683	0.67	19.3	0.000848	1.05	45.12	0.52	0.0572	0.0015	0.0219	0.0003	139.8	1.6
2.1	413	194	0.47	7.7	0.001242	1.39	46.37	0.62	0.0598	0.0016	0.0213	0.0003	135.7	1.8
3.1	690	425	0.62	13.5	0.001041	1.49	43.78	0.53	0.0608	0.0012	0.0225	0.0003	143.4	1.8
4.1	602	323	0.54	11.2	0.001234	1.98	46.03	0.57	0.0645	0.0020	0.0213	0.0003	135.8	1.7
5.1	222	97	0.44	4.2	0.001442	1.49	45.26	0.70	0.0607	0.0022	0.0218	0.0003	138.8	2.2
6.1	675	462	0.68	12.9	0.001003	1.44	44.87	0.55	0.0603	0.0012	0.0220	0.0003	140.1	1.7
7.1	403	257	0.64	7.5	0.000825	0.53	46.09	0.63	0.0530	0.0016	0.0216	0.0003	137.6	1.9
8.1	831	443	0.53	16.2	0.002142	3.69	44.10	0.52	0.0782	0.0016	0.0218	0.0003	139.3	1.7
9.1	193	68	0.35	3.7	0.001943	4.55	45.02	0.76	0.0849	0.0031	0.0212	0.0004	135.2	2.3
10.1	218	146	0.67	4.2	0.003373	5.11	44.73	0.73	0.0894	0.0053	0.0212	0.0004	135.3	2.4
11.1	361	182	0.51	7.0	0.000665	1.53	44.18	0.63	0.0611	0.0018	0.0223	0.0003	142.1	2.0
12.1	627	289	0.46	12.0	0.001344	1.48	44.78	0.57	0.0606	0.0016	0.0220	0.0003	140.3	1.8
13.1	438	200	0.46	8.9	0.003560	6.24	42.08	0.58	0.0985	0.0023	0.0223	0.0003	142.1	2.0
14.1	917	579	0.63	17.7	0.000996	1.25	44.54	0.53	0.0588	0.0015	0.0222	0.0003	141.4	1.7
15.1	400	335	0.84	7.5	0.002417	1.61	45.94	0.69	0.0616	0.0021	0.0214	0.0003	136.6	2.1
16.1	356	155	0.44	6.7	0.001293	2.20	45.50	0.93	0.0663	0.0023	0.0215	0.0004	137.1	2.8
17.1	765	387	0.51	14.8	0.001427	2.10	44.48	0.71	0.0655	0.0035	0.0220	0.0004	140.4	2.3
18.1	671	356	0.53	12.6	0.000940	1.28	45.69	0.61	0.0589	0.0016	0.0216	0.0003	137.8	1.9
19.1	564	456	0.81	9.4	0.008337	12.93	51.35	0.74	0.1509	0.0044	0.0170	0.0003	108.4	1.7
20.1	258	134	0.52	5.0	0.000492	2.38	44.41	0.78	0.0678	0.0028	0.0220	0.0004	140.2	2.5
21.1	1147	715	0.62	22.8	0.000336	0.31	43.16	0.49	0.0515	0.0008	0.0231	0.0003	147.2	1.7
22.1	748	371	0.50	14.1	0.000877	0.78	45.60	0.54	0.0550	0.0011	0.0218	0.0003	138.8	1.7
23.1	591	273	0.46	11.1	0.000858	1.13	45.69	0.57	0.0578	0.0013	0.0216	0.0003	138.0	1.7
24.1	784	385	0.49	15.0	0.000638	0.79	44.91	0.53	0.0552	0.0011	0.0221	0.0003	140.9	1.7
25.1	319	147	0.46	6.1	0.001836	1.77	45.20	0.64	0.0629	0.0026	0.0217	0.0003	138.6	2.0
26.1	599	297	0.50	11.2	0.000986	1.47	45.73	0.57	0.0604	0.0013	0.0215	0.0003	137.4	1.7
27.1	548	228	0.42	10.6	0.001087	1.67	44.48	0.56	0.0622	0.0014	0.0221	0.0003	141.0	1.8

Notes:
1. Uncertainties given at the one a level.
2. Error in Temora reference zircon calibration was 0.75% for the analytical session (not included in above errors but required when comparing data from different mounts).
3. f206 % denotes the percentage of ^{206}Pb that is common Pb.
4. Correction for common Pb made using the measured $^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios following Tera and Wasserburg (1972), as outlined in Williams (1998; the so called 207Pb correction method).

Table 3d
SHRIMP U–Pb zircon data for sample CH-6189.

Grain. Spot	U (ppm)	Th (ppm)	Th/U	$^{206}Pb^{*}$ (ppm)	$^{204}Pb/^{206}Pb$	f_{206} %	Total				Radiogenic		Age (Ma)	
							$^{238}U/^{206}Pb$	±	$^{207}Pb/^{206}Pb$	±	$^{206}Pb/^{238}U$	±	$^{206}Pb/^{238}U$	±
1.1	351	286	0.81	6.6	0.000337	0.80	45.79	0.55	0.0552	0.0016	0.0217	0.0003	138.2	1.7
2.1	150	59	0.39	4.1	0.000373	1.66	31.24	0.40	0.0634	0.0024	0.0315	0.0004	199.8	2.6
3.1	257	152	0.59	4.9	0.000855	1.00	44.85	0.56	0.0568	0.0016	0.0221	0.0003	140.8	1.8
4.1	1489	1101	0.74	27.4	0.000105	0.24	46.63	0.49	0.0506	0.0005	0.0214	0.0002	136.5	1.4
5.1	136	117	0.86	2.6	0.001498	2.29	44.82	0.61	0.0670	0.0020	0.0218	0.0003	139.0	1.9
6.1	205	159	0.78	3.7	0.001142	1.46	47.86	0.85	0.0603	0.0017	0.0206	0.0004	131.4	2.3
7.1	124	82	0.66	2.4	0.001225	1.33	45.37	0.64	0.0594	0.0020	0.0217	0.0003	138.7	2.0
8.1	176	69	0.39	7.7	0.000588	0.63	19.55	0.23	0.0579	0.0011	0.0508	0.0006	319.7	3.8
9.1	86	89	1.03	1.6	0.002629	2.63	46.11	0.72	0.0696	0.0027	0.0211	0.0003	134.7	2.1
10.1	121	80	0.66	2.2	0.001459	1.71	46.16	0.66	0.0623	0.0021	0.0213	0.0003	135.8	2.0
11.1	209	114	0.54	3.9	0.000771	1.48	45.90	0.60	0.0606	0.0019	0.0215	0.0003	136.9	1.8
12.1	339	271	0.80	6.2	0.001238	1.06	46.59	0.55	0.0572	0.0012	0.0212	0.0003	135.5	1.6
13.1	145	93	0.64	2.8	0.000729	1.21	44.99	0.59	0.0584	0.0019	0.0220	0.0003	140.0	1.9
14.1	186	111	0.60	3.6	0.000593	0.62	44.34	0.74	0.0538	0.0013	0.0224	0.0004	142.9	2.4
15.1	545	511	0.94	10.3	0.000270	0.14	45.57	0.66	0.0500	0.0010	0.0219	0.0003	139.7	2.0
16.1	234	157	0.67	4.3	–	0.72	47.13	0.58	0.0544	0.0013	0.0211	0.0003	134.4	1.7
16.2	264	162	0.61	5.0	0.000207	0.38	45.73	0.65	0.0518	0.0012	0.0218	0.0003	138.9	2.0
17.1	174	121	0.69	3.2	0.000630	0.80	46.71	0.61	0.0551	0.0015	0.0212	0.0003	135.5	1.8

Notes:
1. Uncertainties given at the one a level.
2. Error in Temora reference zircon calibration was 0.25% for the analytical session (not included in above errors but required when comparing data from different mounts).
3. – denotes that no ^{204}Pb was detected.
4. f206 % denotes the percentage of ^{206}Pb that is common Pb.
5. Correction for common Pb made using the measured $^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios following Tera and Wasserburg (1972), as outlined in Williams (1998; the so called 207Pb correction method).

andesitic lava flows exposed on the western bank of río Ñireguao, in the area of Loncomahuida. The tuffs are thinly bedded and have no base exposed, whilst the lava flows, of 5–10 m thick, have no top exposed. A whole rock K–Ar (whole rock) date of 135 ± 5 Ma has been obtained for the lavas (sample CC-647; Table 4).

The zircons from this sample range from elongate to slender grains with length to width ratios up to 10:1. The grains are mostly euhedral to subhedral, clear and with pyramidal terminations; or are fragments of such grains (Fig. 5b) Some more equant forms are also present. The CL images reveal a dominantly simple oscillatory

Table 3e
SHRIMP U–Pb zircon data for sample CH-6213.

Grain. Spot	U (ppm)	Th (ppm)	Th/U	^{206}Pb* (ppm)	^{204}Pb/^{206}Pb	f$_{206}$ %	Total				Radiogenic		Age (Ma)	
							^{238}U/^{206}Pb	±	^{207}Pb/^{206}Pb	±	^{206}Pb/^{238}U	±	^{206}Pb/^{238}U	±
1.1	661	659	1.00	12.0	0.000213	0.35	47.46	0.58	0.0515	0.0013	0.0210	0.0003	133.9	1.6
2.1	647	447	0.69	12.0	0.000433	0.39	46.31	0.56	0.0519	0.0012	0.0215	0.0003	137.2	1.7
3.1	749	627	0.84	13.7	0.000358	0.42	46.82	0.55	0.0521	0.0012	0.0213	0.0003	135.7	1.6
4.1	184	179	0.97	3.5	0.000349	0.76	45.33	0.73	0.0549	0.0024	0.0219	0.0004	139.6	2.3
5.1	601	434	0.72	12.5	0.003908	9.05	41.39	0.51	0.1209	0.0058	0.0220	0.0004	140.1	2.7
6.1	475	322	0.68	8.6	0.000667	1.42	47.63	0.61	0.0600	0.0016	0.0207	0.0003	132.1	1.7
7.1	1807	1591	0.88	34.4	0.000176	0.03	45.12	0.49	0.0491	0.0007	0.0222	0.0002	141.3	1.5
8.1	628	423	0.67	11.5	0.000448	0.40	46.98	0.57	0.0519	0.0013	0.0212	0.0003	135.2	1.7
9.1	557	500	0.90	10.6	0.003102	5.27	45.03	0.56	0.0907	0.0026	0.0210	0.0003	134.2	1.9
10.1	624	471	0.75	11.7	0.000633	0.65	45.80	0.56	0.0540	0.0013	0.0217	0.0003	138.4	1.7
11.1	463	340	0.73	8.4	0.001049	0.69	47.59	0.0542	0.0017	0.0209	0.0003	133.1	1	1.9
12.1	433	361	0.83	8.0	0.000641	0.61	46.34	0.82	0.0537	0.0016	0.0214	0.0004	136.8	2.4
13.1	1283	1148	0.89	23.8	0.000248	0.33	46.25	0.52	0.0514	0.0009	0.0216	0.0002	137.5	1.5
14.1	692	687	0.99	2.0	0.000246	1.75	296.54	5.45	0.0603	0.0036	0.0033	0.0001	21.3	0.4
15.1	435	330	0.76	8.0	0.000827	1.18	46.57	0.61	0.0581	0.0017	0.0212	0.0003	135.4	1.8
16.1	621	530	0.85	11.4	0.000585	0.56	46.82	0.58	0.0532	0.0014	0.0212	0.0003	135.5	1.7
17.1	302	180	0.60	5.5	0.000895	0.87	46.94	0.68	0.0557	0.0021	0.0211	0.0003	134.7	2.0
18.1	460	511	1.11	8.5	0.000897	1.07	46.35	0.61	0.0573	0.0016	0.0213	0.0003	136.1	1.8
19.1	200	258	1.29	3.9	0.002632	3.41	44.45	0.67	0.0760	0.0035	0.0217	0.0003	138.6	2.2
20.1	409	421	1.03	7.5	0.000281	0.29	46.89	0.53	0.0511	0.0010	0.0213	0.0002	135.7	1.5
21.1	559	618	1.10	10.8	0.000604	0.91	44.53	0.49	0.0561	0.0012	0.0223	0.0002	141.9	1.6

Notes:

1. Uncertainties given at the one a level.
2. Error in Temora reference zircon calibration was 0.96% for the analytical session (not included in above errors but required when comparing data from different mounts).
3. f206 % denotes the percentage of ^{206}Pb that is common Pb.
4. Correction for common Pb made using the measured ^{238}U/^{206}Pb and ^{207}Pb/^{206}Pb ratios following Tera and Wasserburg (1972), as outlined in Williams (1998; the so called 207Pb correction method).

Table 4
K–Ar data: andesite Loncomahuida area.

Sample no	Location UTM	Rock type	Material dated	% K	^{40}Ar Rad (nl/g)	Atm.Ar	Age and error (Ma)
CC-647	4 973823-303074	Andesite	Whole rock	0.77	4.185	20	135 ± 5

zoned internal structure, with some having broad zones, both indicating an igneous paragenesis.

Eighteen grains have been analysed (Fig. 5b, Table 3b). The areas analysed are all low in common Pb, plot close to the Tera-Wasserburg Concordia curve at about 140 Ma and mostly form a simple bell shaped age distribution. The analyses of grains 5 and 11 are slightly older than the dominant group with ^{206}Pb/^{238}U ages of about 145 and 150 Ma, respectively, interpreted to represent inherited zircon components. A weighted mean of the ^{206}Pb/^{238}U ages for the other 16 analyses has no excess scatter giving 139.7 ± 1.0 Ma (Fig. 4b). This constrains the time of zoned igneous zircon crystallisation during the early Valanginian.

3. Dacite ignimbrite southeast of Lago Elizalde

Sample CH-6140 is from an ignimbrite that has been thrusted above shales of the Katterfeld Formation southeast of Lago Elizalde (Fig. 1; De La Cruz et al., 2003). It therefore has an unknown stratigraphic position within the Ibáñez Formation but is inferred to be unconformably underlying the Divisadero Formation.

The zircons from this sample are generally equant in shape but range to elongate forms (Fig. 5c). Many grains have bipyramidal terminations, though some appear to be subrounded. The grains range form clear, with apatite inclusions to those that are less commonly dark and metiamict. The CL images show zoned igneous internal structure, with some broader zoned dark Cl grains.

Twenty seven zircon have been analysed (Table 3c). The analysis of grain 19 is enriched in common Pb, has a ^{206}Pb/^{238}U age of ~110 Ma and the area analysed interpreted to have lost radiogenic Pb. The analysis of grain 21 has a ^{206}Pb/^{238}U age of ~145 Ma; all other analyses have similar ^{206}Pb/^{238}U ages and form a simple bell shaped distribution on the relative probability plot (Fig. 4c). A weighted mean for 25 analyses gives 139.1 ± 1.4 Ma (MSWD = 1.4) and this dates the time of zoned igneous zircon crystallisation; that is Valanginian in age.

4. Rhyolite ignimbrite south of Lago Norte

Sample CH-6189 is from a 12 m thick rhyolitic ignimbrite of the Lago Norte Volcanic Complex. It overlies a 50 m thick fossiliferous marine succession assigned to the early Berriasian (Covacevich et al., 1994; Bruce, 2001) on the southern slope of Lago Norte (Fig. 1).

The zircons from this sample are equant to elongate grains with pyramidal terminations, or fragments thereof. The grains all have inclusions, ranging from opaque phases to needles of apatite, to cavities that are commonly seen in volcanic zircons. The CL images show a oscillatory zoned internal structure (Fig. 5d), though some grains have central areas that may reflect inherited zircon components.

Nineteen areas have been analysed on 18 grains (Table 3d). The majority of the analyses have similar ^{206}Pb/^{238}U ages of about 135–140 Ma. The analyses of grains 2 and 8 yield ^{206}Pb/^{238}U ages of about 200 Ma and 320 Ma, respectively, whilst that for grain 18 is about 150 Ma. The relative probability plot for the remaining 16 analyses is a bell shaped curve (Fig. 4d), however there is some dispersion and the analyses of grains 7 and 14 are slightly younger (~131 Ma) and older (~143 Ma) respectively than the main age grouping. A weighted mean for 14 areas give 137.3 ± 1.2 Ma (MSWD = 1.30) and this is interpreted to constrain the time of zoned igneous zircon crystallisation during the late Valanginian. This date is younger than the early Berriasian paleontologic age of for the underlying fossiliferous marine section, though the IGCP Time chart notes that the lower Valanginian boundary at 140.2 ± 3.0 Ma would be within analytical uncertainty. It is possible that there may be a hiatus between the marine succession and the volcanic dated.

5. Dacite tuff area El Cerrito

Sample CH-6213 is from a tuff interbedded in a succession of alternating andesitic lava flows and dacitic tuffs, including ignimbrites, of the Lago Norte Volcanic Complex. The sample underlies the Divisadero Formation in the area of El Cerrito, on the southern flank of cerro Estatuas (Fig. 2). From the local contact relationships of the overlying Divisadero Formation it can be inferred that this unit is, at least in parts laterally equivalent with the Coihaique Group. The Divisadero Formation unconformably overlies, in one area, the Hauterivian volcanic succession (south of Cerro Estatuas and west of Cerro Huemules) and, in another area, the Apeleg Formation (on the northern and eastern slopes of Cerro Huemules).

The zircons from this sample range from small equant grains, 30–50 μm in diameter to relatively large, clear crystals up to 200 μm in diameter. The grains are mostly euhedral with bipyramidal terminations; some elongate forms are present. The CL images show a zoned igneous internal structure, mostly oscillatory zoned, but broad zoning is also seen (Fig. 5e).

Twenty one grains have been analysed (Table 3e). For some grains the ~20 μm SHRIMP spot encompasses the majority of the grain. The analysis of grain 14 is anomalously young and the grain has a brighter Cl character, though no difference in U concentration relative to the others analysed. This grain is thought to be a contaminant and so not considered further in this discussion. Most of the analyses are close to the Tera-Wasserburg Concordia, ie low in total common Pb, though three range to higher common Pb. The relative probability plots shows a bell shaped age distribution with a shoulder on the older age side (Fig. 4e). This reflects inherited zircon components and a weighted mean of the ^{206}Pb/^{238}U ages for 17 analyses has no excess scatter giving 136.1 ± 1.6 Ma (MSWD = 0.96, Fig. 4e). This date constrains the time of zoned igneous zircon crystallisation to be during the early Hauterivian.

4. The marine transgression at Futaleufú-Palena area

Description: Pelitic hornfels overlying the Ibáñez Formation in Cerro Redondo (43°19'S), approximately 25 km to the south-southwest of the town of Futaleufú (Figs. 2 and 3), represent the northernmost exposure so far identified of the Coihaique Group in the Chilean part of the Patagonian Cordillera (De La Cruz et al., 1996). Further south, the Toqui Formation exposed in the area of Arroyo Culebra, few km SE of the town of Palena (Fig. 2), crops out without base or top exposed. It is mainly formed by fossiliferous volcanic sandstones, locally pebbly, oyster beds and with an intercalation of an ignimbrite 15 m thick, stratigraphically bounded below and above by sandstones with marine fossils. Black shales of the Katterfeld Formation, with occasional *Favrella* sp. and a minimum thickness of 200–250 m thick, crop out in areas adjacent to the town of Palena, and sandstone hornfels exposed to the west of Palena have been assigned to the Apeleg Formation (De La Cruz et al., 1996). These successions are overlain by the Cordón de las Tobas Formation (Thiele et al., 1979), that forms part of the Divisadero Group. This group appears to be unconformably on top of the earlier formations, as it is apparent when the mountain chain named as the Cordón de las Tobas is observed at a distance from the south. Further south, in the area of Cerro Campana (43°43'S), on the northern flank of the valley of Río El Tigre, in the headland of Río Palena, the Toqui Formation is exposed in contact with an intrusive dacite dome forming Cerro Campana: one outcrop is to the north and the other to the south of the dacite. In both localities it overlies the Ibáñez Formation and has no top exposed. In the northern outcrop the Toqui Formation has a minimum thickness of 20 m and in the southern outcrops of 70 m. These rocks are composed of ash-fall deposits, volcanic breccias representing debris flow and pyroclastic flow deposits, pebbly sandstones, tuffaceous siltstones and sandstones, finely laminated chert, and limestones, all capped by ten meters of black shales with no top exposed.

Paleontology and age: Fossils in the Coihaique Group exposed in this area are scarce and include ammonites, oysters and other bivalves and were firstly described by Fuenzalida (1968). The pelitic hornfels exposed in Cerro Redondo include flattened ammonites identified as perisphinctids that would indicate a Tithonian age (Covacevich in De La Cruz et al., 1996). Few ammonites were collected from the Toqui Formation exposed north and south of Cerro Campana. Covacevich (in De La Cruz et al., 1996) identified ammonites resembling perisphinctids similar to *Aulacosphinctes* in the northern exposures, and in the southern outcrops several indetermined perisphinctids and *Himalayites* sp. were identified. This author assigned these ammonites to the Tithonian (De La Cruz et al., 1996). In the area of Arroyo Culebra the Toqui Formation bears abundant marine fossils including *Blanfordiceras* (?) sp., an ammonite indicative of the Berriasian (Covacevich in De La Cruz et al., 1996). *Favrella* sp., a Hauterivian ammonite has been identified in the Katterfeld Formation in this area. Consequently, the marine environment in these localities can be bracketed between the Tithonian and, at least, the Hauterivian (Table 2).

5. The marine transgression at Lago Norte-El Gato area

Description: A 40 m thick marine succession of bioclastic tuffites, shales, sandstones and limestone oyster-beds with early Berriasian fossils intercalated in volcanic rocks, exposed in the hill bordering the southern coast of Lago Norte, represents a thin succession of the Toqui Formation intercalated in the Ibáñez Formation (Figs. 2 and 3; Table 2). These beds conformably overlie a 10 m thick succession composed of two dacitic ignimbrites, with no base exposed, of the Ibáñez Formation, that conform the southern margin of the lake. In turn, the Toqui Formation conformably underlie volcanic rocks herein named the Lago Norte Volcanic Complex (Fig. 6), and also grouped in the Ibáñez Formation. This

Fig. 6. Ignimbrites overlying marine beds of the Toqui Formation (assigned to the Berriasian) with an intercalation of marine sedimentary beds. Lago Norte Volcanic Complex, south of Lago Norte.

complex has an exposed thickness of approximately 350 m on the southern coast of Lago Norte. A marine intercalation of less than 5 m thick, of volcaniclastic sandstones with marine fossils, mainly oysters, occurs above a succession of ignimbrites 20–30 m at the base of this volcanic complex.

The beds of the Toqui Formation just north of a lake to the northwest of Lago Norte are represented by a section of 16 m thick overlying ca. 40 m of ignimbrites 1–9 m thick, some highly silicified. These beds include oyster-rich strata with fragments of corals and pumice, calcareous sandstones, tuffites that may represent reworked ignimbrites, bioclastic limestones and a 2.5 m thick ignimbrite emplaced in shallow marine waters. Ammonites and poorly preserved belemnites were collected from these beds.

The exposures of the Toqui Formation south of the locality of El Gato, to the south of Río Ñireguao, overlie and underlie ignimbrites, the latter of the Lago Norte Volcanic Complex. This volcanic complex, south of Río Ñireguao includes a unit of ignimbrites and andesitic lava flows, of over 500 m thick. The Lago Norte Volcanic Complex, underlies badly exposed black shales assigned to the Katterfeld Formation (<5 m thick exposures and probably of the order of 50 m thick), in turn underlying the Divisadero Group in the northwestern flank of Cerro Los Huemules and southern flank of Cerro Estatuas. A peculiar stratigraphic relationship occurs in the Cerro Los Huemules: in this area, the Divisadero Group overlies the Lago Norte Volcanic Complex on the north-western flank of the hill, whereas on its north-eastern flank overlies the Apeleg Formation, apparently with an erosional unconformity. Consequently, the uppermost layers of the Lago Norte Volcanic Complex either interfingers with the Apeleg Formation or, the latter originally covered the Lago Norte Volcanic Complex and was later partially eroded away prior to the deposition of the Divisadero Group.

Paleontology and age: The Toqui Formation south of Río Ñireguao and south of the locality of El Gato includes *Groebericeras* Leanza and *Blanfordiceras* Cossman (Covacevich et al., 1994). These authors indicate that the degree of coiling and the ornament of the former are near that of *Groebericeras bifrons* Leanza, of the early Berriasian of the Neuquén Basin (Leanza 1945). The presence of both ammonites in these beds suggest an early Berriasian age (Covacevich et al., 1994). The Toqui Formation includes a comparable calcareous and tuffaceous marine intercalation, containing *Blanfordiceras* sp. indicative of a Berriasian age, three kilometers north-west of Lago Norte. In turn, ammonite fragments from the beds exposed immediately south of Lago Norte match the description of *Blanfordiceras* sp. given by Covacevich et al. (1994) according to Bruce (2001). This marine succession exposed south of Lago Norte and of Río Ñireguao include *Anditrigonia* aff. *A. eximia*, *Pterotigonia* sp. and *Steinmanella* sp. (Covacevich et al., 1994), in accordance with an early Neocomian age (Perez, E., personal communication, 2002). Other fossils included in these beds are other bivalves, bryozoa, corals, gastropods, serpulids, trace fossils and fossil plant debris with no age information (Covacevich et al., 1994).

Three Early Cretaceous U–Pb SHRIMP dates obtained from this complex and interpreted as representing the time of zoned igneous zircon crystallization, range from ca. 140 to 136 Ma, indicating volcanism during the late Berriasian to early Hauterivian. The Lago Norte Volcanic Complex is intruded by the Lago Largo Pluton, an altered pink granite that rendered a K–Ar (biotite) age of 119 ± 4 Ma (mid-Aptian; Suárez and De La Cruz, 2001). Considering the altered state of the pluton, this date cannot be interpreted with confidence. Hence this volcanic complex has an early Berriasian age in its lower levels, as inferred from the intercalation of a marine horizon in these lower beds, and an early Hauterivian age in its upper levels, with the possibility of hiatuses in the stratigraphic record.

6. The marine transgression at Estero La Horqueta

Description: The Toqui Formation exposed in Estero La Horqueta and Cerro Bayo (Figs. 2 and 3; Table 2) overlies an ignimbrite of the Ibáñez Formation and has a thickness of approximately 45 m. It underlies black shales of the Katterfeld Formation, thinly represented in this locality with not more than 40–50 m of thickness. The latter unit is overlain, in turn, by at least 200 m thick sandstones of the Apeleg Formation covered by Plio-Pleistocene glacigenic sediments. The Toqui Formation is composed of an oyster lenticular bank, 9–10 m thick, separated from the base of the formation by a 10 m thick sandstones succession, and overlain by approximately 35 m of volcanic sandstones with ammonites. Usually the oysters are intact, frequently articulated and in occasions in life position. These beds include coral fragments and traces of bivalve borers (*Mytiloida lithophaga*). It suggests a restricted depositional environment near the coast and adjacent to a volcanic edifice. The black shales of the Katterfeld Formation at this locality, represented by a succession 40–50 m thick, can be interpreted as prodelta facies considering that the overlying strata of the Apeleg Formation exposed in Cerro Bayo, has been interpreted as deposits from an easterly-derived delta system (González-Bonorino and Suárez, 1995). In turn, the facies of the Apeleg Formation exposed tens of kilometers to the SW of Cerro Bayo (on the southern flank of the valley of Estero Los Mallines), have been interpreted to represent offshore tidal sandbars or sand ridges on a shallow marine shelf (Bell and Suárez, 1997). It is important to mention that the thicknesses of the Katterfeld Formation varies greatly. Approximately 15 km north of cerro Bayo, in Argentina, Olivero and Aguirre-Urreta (2002) measured a succession of approximately 325 m thick of black shales of the Katterfeld Formation. This thickness variation suggests deposition in tectonically controlled basins, probably hemigrabens.

Paleontology and age: The volcanic sandstones of the Toqui Formation in Estero La Horqueta (Table 2), include *Neocosmoceras*, with one specimen similar to *Neocosmoceras sayni* (Simionescu) and *Neocosmoceras wichmanni* (Gerth), that indicate a late Berriasian age (Covacevich et al., 1994). Approximately 25 km to the north, at the type locality of the Katterfeld Formation, in Argentina, Olivero and Aguirre-Urreta (2002) identified three horizons with distinctive ammonite associations in the Katterfeld Formation that, from base to top include (i) an interval with Kilianella sp. aff. *K. superba* Sayn and *Thurmanniceras* sp. that could be assigned to the base of the late Valanginian, (ii) an interval with crioceratids, assigned to the late Valanginian by its stratigraphic position, and (iii) an interval with *Favrella americana* (Favre) indicative of an Hauterivian age (column of Lago Fontana in Table 2). Although the oldest ammonites from the Katterfeld Formation in the area indicate a Valanginian age as described above, the age of the basal beds of the Katterfeld Formation exposed in the area of Estero La Horqueta may have been of latest Berriasian-early Valanginian age, considering that overlies late Berriasian sandstones of the Toqui Formation. In the Apeleg Formation exposed in Cerro Bayo, just south of Estero La Horqueta, *Favrella* sp. was identified, indicating an Hauterivian age (Suárez et al., 1996). *Favrella americana*, of Hauterivian age (early Hauterivian according to Aguirre-Urreta et al. (2000)), has been reported from this formation exposed SE of the locality of Ñireguao, approximately 50 km SW of Cerro Bayo, where they have been interpreted as tidal sandbars or sand ridges (Bell and Suárez 1997). Hence, the transgression at this locality occurred during the late Berriasian, and the field relationships and ammonite chronology suggests a lateral interfingering of, at least the upper levels of the Katterfeld Formation with the basal layers of the Apeleg Formation during the Hauterivian.

In the area of the lakes La Plata and Fontana, in neighboring Argentina, the Divisadero Group has been subdivided in two units separated by and angular unconformity (Iannizzotto et al., 2004). The lower unit, has been named as Catedral Formation, and the upper unit, as Don Rueda Formation. However, the Catedral Formation has comparable stratigraphic boundaries to the Lago Norte Volcanic Complex and we reinterpret it as representing the waning volcanic stages of the Ibáñez Formation or Lago La Plata Formation, and separated from the Divisadero Group by a large hiatus due to the mid-Cretaceous tectonism already recognized in the region (e.g. Suárez and De La Cruz, 2000).

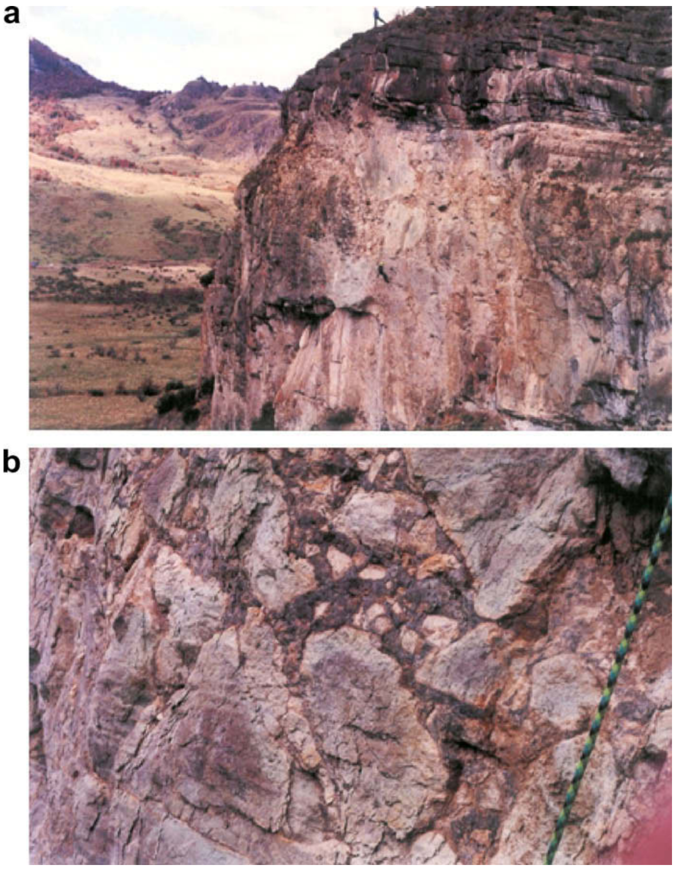


Fig. 7. Peperite sill along contact between Foitzick Volcanic Complex and Toqui Formation. See jig saw fit of dacite; matrix of fossiliferous calcareous sandstones of the overlyng marine beds.

7. The marine transgression at Laguna Foitzick-Lago Elizalde area

Description: Two km to the SE of Laguna Foitzick, and approximately 8 km south-southwest of the city of Coihaique, volcanic rocks grouped in the Foitzick Volcanic Complex of the Ibáñez Formation, crop out (De La Cruz et al., 2003). It is composed of pyroclastic flow deposits, including ignimbrites and block and ash deposits, dacitic lava flows and domes, and andesitic lava flows cut by paleochannels filled by ignimbrites, suggestive of volcanic slopes disected by stream flows (De La Cruz et al., 2003). It is overlain by calcareous and tuffitic marine strata of the Toqui Formation, locally with a peperitic dacite sill along the contact. This volcanic complex represent the products of a system of stratovolcanoes and volcanic domes, emplaced near the coast of the marine Aisén Basin. Two main areas of exposures of this complex, separated by the main road from Coihaique to the south and approximately 1 km apart, will be described:

- In the southern part of the western outcrops a gentle-dipping volcanic succession of approximately 60 m thick is composed, from base to top, of clast-supported monomyctic dacite breccia, poorly sorted (1 mm to 30 cm diameter), locally with resemblance of in situ brecciation, and of 20 m thick. It may represent a distal fragmented dacite lava flow, capped by a dacite with flow banding subparallel to the layering and approximately 30 m thick. This flow-banded dacite is directly overlain by calcareous beds ot the Toqui Formation, and locally its upper part, in direct contact with the marine beds, is brecciated (Fig. 7). The matrix of the breccia is composed of fossiliferous calcareous rock that merge into the overlying calcareous beds of the Toqui Formation and in many places the dacite fragments show a "jig-saw texture". This dacite is interpreted as a peperite sill, intruded into the basal sediments of the Toqui Formation while they were still wet. Consequently, it indicates contemporaneity of the waning stages of volcanism of the Ibáñez Formation with

Fig. 8. Onlapping beds of the Toqui Formation over monolithologic dacitic breccias of the Foitzick Volcanic Complex, and interpreted as disrupted lava flows on a steep slope of a volcano.

the beginning of the marine transgression represented by the Toqui Formation. This supports the interpretation that the contact between these two formations does not represent an important time gap. Another peperite, this time rhyolitic, was identified along part of the contact between these formations to the southwest of Chile Chico (ca. 46°S).

- The eastern outcrop, conformed by monolithologic dacitic breccias, in beds of 1–4 m thick, and relatively steeply dipping, underlies with an angular unconformity onlapping subhorizontal beds of the Toqui Formation (Fig. 8). These breccias have no internal organization, are badly sorted, have almost no matrix and exhibit fragments from 1 to 150 cm in diameter, and no juveniles. They have been interpreted as distal and gravitationally broken facies of a colapsed dacitic lava flow accumulated on a steep slope of a volcanic edifice and thus, the steeper dipping attitude of the breccias may represent the original depositional surface (De La Cruz et al., 2003). Hence, the unconformable contact may represent the truncation of a volcanic cone during transgression of the sea of the Aisén Basin and not an evidence of tectonism as it can easily be supposed. A U–Pb SHRIMP zircon date of 138.4 ± 1.3 Ma was obtained from these rocks (Pankhurst et al., 2003). The absence of a major tectonic event separating the Ibáñez and Toqui formations is well demonstrated in the area by the interfingering nature of their contact (Table 2).

A new U–Pb SHRIMP zircon date of 139.1 ± 1.4 Ma, representing a Valanginian age, was obtained from an ignimbrite exposed southeast of Lago Elizalde and approximately 15 km southwest of the Foitzick exposures (Fig. 2). The overlying Toqui Formation includes neocomitid ammonites, *Entolium* sp., grypheid bivalves, *Serpula* sp. and indeterminate plant debris (Covacevich in De La Cruz et al., 2003).

8. Discussion and conclusions

The Austral Basin, developed in southernmost Chile and Argentina (Biddle et al., 1986), identified as far north as latitude 43°S, near the town of Futaleufú, in Chile (De La Cruz et al., 1996; Suárez et al., 1996), was a back–arc ensialic basin known as the Aisén Basin or Río Mayo Embayment in its northwestern part, where the Coihaique Group accumulated. It was initially developed synchronously with the later phases of calc-alkaline volcanism represented by the Ibáñez Formation and equivalent units, that also forms their basement in this region. This formation was previously thought to have been restricted to the Middle-Late Jurassic, but the stratigraphic, paleontologic, and radiometric data presented here indicates that it continued up to the early Hauterivian. This means active volcanism during a time span of at least 22 million years.

The transgression of the Aisén Basin, mainly represented by the Toqui Formation, was diachronous during the Tithonian, Berriasian, Valanginian and early Hauterivian (Table 2) and was synchronous with volcanism of the Ibáñez Formation. In places the ammonite-bearing marine beds of the Toqui Formation are of Tithonian age (Cerro Campana and Cerro Redondo, near Palena and Futaleufú, respectively) and in others are Berriasian (El Gato-Lago Norte, Arroyo Culebra, near Palena, and Estero La Horqueta). A younger age has been reported from the area of Lago Fontana, in Argentina, where the transgression has been paleontologically dated as Valanginian in age (Olivero and Aguirre-Urreta 2002). A date of 140.3 ± 1.0 Ma (sample CH-6174; Fig. 4a), representing a late Berriasian-early Valanginian age, was obtained from a dacitic ignimbrite 10 m thick, exposed adjacent to marine beds with early Berriasian ammonites in the hills south of río Ñireguao in the area of El Gato. The contact between these two exposures is a fault. A date of 137.3 ± 1.2 Ma (sample CH-6189; Fig. 4d), representing a late Valanginian age, was obtained from a rhyolitic ignimbrite, 12 m thick, overlying the Toqui Formation with fossils assigned to the early Berriasian (Covacevich et al., 1994; Bruce 2001) on an outcrop 3 km to the north-northwest of the exposures of Lago Norte (Fig. 2). In this case there is a discrepancy between the paleontologic and radiometric ages that may indicate a hiatus in the stratigraphic record. A Valanginian or younger age for the base of the Toqui Formation is indicated by the 139.1 ± 1.4 Ma SHRIMP U–Pb date (sample CH-6140; Fig. 4c) from a sample from the underlying ignimbrite exposed to the SE of Lago Elizalde, which is concordant with the 139.7 ± 1.0 Ma SHRIMP U–Pb for the Loncomahuida tuffs (of unknown stratigraphic position within the Ibáñez Formation; sample CC-650; Fig. 4b) and with the 138.4 ± 1.3 Ma SHRIMP U–Pb age (Pankhurst et al., 2003) for the Foitzick Volcanic Complex. The younger SHRIMP U–Pb zircon age obtained for the Ibáñez Formation is that of 136.1 ± 1.6 Ma, obtained from a tuff intercalated in the Lago Norte Volcanic Complex (sample CH-6123; Fig. 4e), and indicative of an early Hauterivian age for the succeeding marine succession at that locality.

Active volcanism during the initial stages of the Aysén Basin is also shown by the presence of submarine tuffs, including ignimbrites and ash-fall deposits in the ammonite-bearing Tithonian and Berriasian beds of the Toqui Formation (De La Cruz et al., 1996; Suárez et al., 2007), and by the presence of silicic peperites emplaced in the basal beds of the Toqui Formation south of Coihaique (Foitzick Volcanic Complex; Fig. 7), which indicate volcanic activity coeval with marine sedimentation. Therefore, the Foitzick Volcanic Complex, the volcanic rocks SE of Lago Elizalde, the Loncomahuida volcanic rocks and the Lago Norte Volcanic Complex are partly coeval (Table 2) and, represent the waning volcanic stages of the Ibáñez Formation into the Early Cretaceous. Considering that only the uppermost levels of the Foitzick Volcanic Complex and Loncomahuida volcanic rocks are exposed, the possibility exists that Tithonian-Early Berriasian marine intercalations could be present in subsurface underlying these units.

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