Geochemical Journal, Vol. 47, pp. 235 to 247, 2013

Evolution history of the crust underlying Cerro Pampa, Argentine Patagonia: Constraint from LA-ICPMS U–Pb ages for exotic zircons in the Mid-Miocene adakite

YUJI ORIHASHI,[1]* RYO ANMA,[2] AKIHISA MOTOKI,[3] MIGUEL J. HALLER,[4] DAIJI HIRATA,[5] HIDEKI IWANO,[6] HIROCHIKA SUMINO[7] and VICTOR A. RAMOS[8]

[1]Earthquake Research Institute, The University of Tokyo, Bunkyo-ku, Tokyo 113-0032, Japan
[2]Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba 305-8572, Japan
[3]Departamento de Mineralogia e Petrologia Ígnea, Rio de Janeiro State University, Maracanã, Rio de Janeiro, Brazil
[4]Universidad Nacional de la Patagonia San Juan Bosco & CONICET, Puerto Madryn, Argentina
[5]Kanagawa Prefecture Museum of Natural History, Odawara, Kanagawa 250-0031, Japan
[6]Kyoto Fission-Track Co., Ltd., Kyoto 603-8832, Japan
[7]Geochemical Research Center, Graduate School of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan
[8]Laboratorio de Tectónica Andina, FCEyN, Universidad de Buenos Aires, Buenos Aires, Argentina

(*Received April 14, 2012; Accepted December 25, 2012*)

This paper newly reports results of LA-ICPMS U–Pb dating for 282 zircon crystals separated from a Middle Miocene adakite in Cerro Pampa, southern Argentine Patagonia. With the exception of one spot age, 174 of the U–Pb concordia ages are markedly older (>94 Ma) than the cooling ages of the adakite magma (*ca.* 12 Ma). The presence of numerous exotic zircon crystals indicates that the adakitic magma carries up information related to the crustal components during its ascent through the entire crust underneath Cerro Pampa. The obtained concordia ages of exotic zircons, 94–1335 Ma, are divisible into five groups having distinctive peaks on a population diagram. The first (94–125 Ma) and second age groups (125–145 Ma) correspond to the age of plutonic activities that formed the main body of the South Patagonian Batholith. The third to fifth groups respectively correspond to activities of the El Qumado-Ibañez volcanic complex (145–170 Ma), plutonic rocks scarcely exposed in Central Patagonia (170–200 Ma), and the Eastern Andean metamorphic complex of Late Paleozoic to Early Mesozoic ages (200–380 Ma). Our data suggest that the crust underneath Cerro Pampa was formed mostly after 380 Ma, the majority forming during the Early Cretaceous to Middle Jurassic. The processes of crustal development ceased for *ca.* 80 m.y. until the activity of the Cerro Pampa adakite in *ca.* 12 Ma. In contrast to the existence of numerous Archaean–Palaeoproterozoic exotic zircons in Mesozoic plutonic rocks distributed in Andean Cordillera at around 46°S, no evidence was found for Archaean–Paleoproterozoic crust on the Cerro Pampa region at 48°S. This evidence suggests that two crusts must have aggregated along a boundary between 46°S and 48°S with the continental margin of Gondwana during Late Paleozoic times, as part of the amalgamation of Pangea.

Keywords: geochronological fingerprint, zircon, adakite, LA-ICPMS, crustal evolution, Cerro Pampa, Patagonia

INTRODUCTION

The episodic growth of the continental crust has been increasingly clarified through studies of zircon, an accessory mineral found commonly in the rocks of continental crust such as granites, gneisses, and sandstones. Zircon, which is fundamentally formed through granite magmatism, is resistant against chemical, physical, and thermal processes, and has suitable composition for U–Pb dating. Even after metamorphism or capture by magmas, the original crystallisation age can be preserved in a crystal core. A small domain of single zircon crystal can be dated *in-situ* using a sensitive high-resolution ion-microprobe (SHRIMP) (e.g., Compston *et al*., 1984; Black *et al*., 1986) or laser ablation—inductively coupled plasma mass spectrometry (LA-ICPMS) (e.g., Hirata and Nesbitt, 1995; Jackson *et al*., 2004; Kimura *et al*., 2011). The corresponding age distribution of zircons provides a fingerprint for the growth and recycling history of the continental crusts.

Goldstein *et al*. (1997) presented an age population histogram for detrital zircon grains collected from the outlet of the Orinoco River in South America, and demonstrated that 49 SHRIMP U–Pb age fingerprints reveals the evolutionary history of the crust exposed in the wa-

*Corresponding author (e-mail: oripachi@eri.u-tokyo.ac.jp)

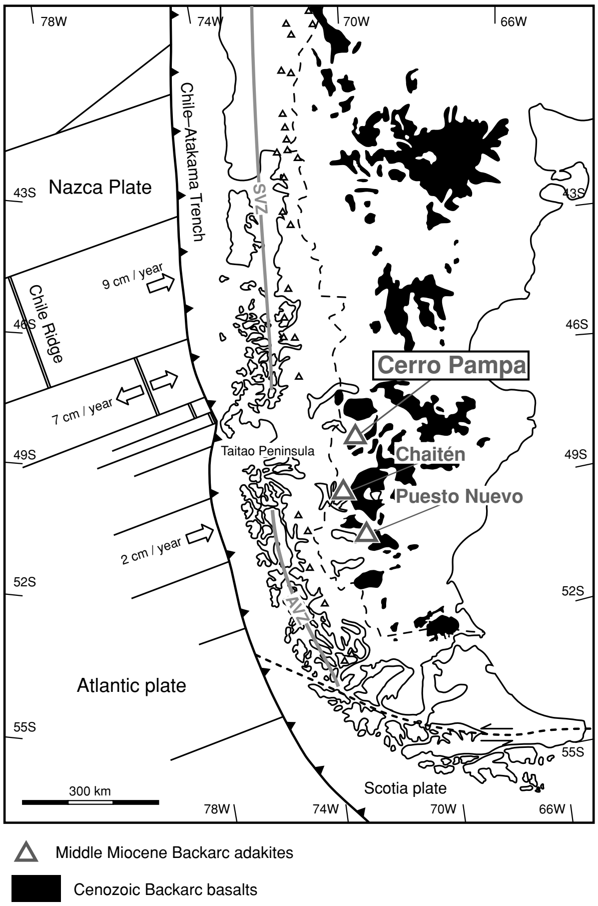

Fig. 1. Schematic map of Patagonia province showing distribution of Neogence back-arc volcanics and the location of active continental arc-volcanoes (modified from Stern et al., 1990). In addition, showing locations of three back-arc adakites (Cerro Pampa, Puesto Nuevo and Chaitén), southern Argentine Patagonia (Kay et al., 1993; Ramos et al., 1991, 2004). AVZ, Austral Volcanic Zone; SVZ, South Volcanic Zone; CTJ, Chile Triple Junction.

tershed. Using LA-ICPMS, Rino *et al*. (2004) demonstrated the episodic growth history of continental crust of North America based on 874 spot ages of zircons separated from sediments of the Mississippi River and the Mackenzie River, and of South America based on 368 spot ages from the Amazon River. Such detrital zircon studies provided fundamental views of the growth history of the continental crusts that have been exposed worldwide. Nevertheless, the growth history of the entire crust section has not been elucidated to date.

Adakitic magmas are presumably generated at depths of *ca*. 70 km by dehydration-induced melting of oceanic crust of young and hot subducted slab, leaving garnet-bearing restite behind (e.g., Kay, 1978; Defant and Drummond, 1990; Martin, 1999; Martin *et al*., 2005). Adakitic magma might also form by partial melting in a lower crust of garnet amphibolite to eclogite conditions under strong control of H_2O (Atherton and Petford, 1993). Such an origin is realistic in the Central Andes, which is up to 80 km thick in the Puna area, while the crust in southern Patagonia, particularly in the Cerro Pampa area examined in this study, is too thin to achieve garnet-in conditions (Kay *et al*., 1993). Although the genesis of adakitic magmas remains controversial, in broad terms, most of them must have formed in or under the lowermost continental crust and penetrated the entire crust. Consequently, U–Pb age distribution of exotic zircons included in adakite magmas might fingerprint the regional magmatic and metamorphic events involved in processes of crustal growth and recycling.

This paper reports new LA-ICPMS U–Pb age data for zircon xenocrysts included in the Middle-Miocene Cerro Pampa adakite, Argentine Patagonia (Fig. 1) and presents its U–Pb age distribution to discuss evolution of entire section of continental crust underlying the volcano.

Geological Setting

Adakite magmatism in Southern Patagonia and the Cerro Pampa adakite

Adakitic magmatism occurs in Southern Patagonia, forming a chain of active volcanoes of the Austral Volcanic Zone (AVZ: Kay *et al*., 1993; Stern and Killian, 1996) in the south of the Chile Triple Junction (CTJ), where the spreading Chile ridge separating the Nazca and Antarctic plates meets with and subducts underneath the South American plate at 46.5°S. The ridge subduction started at 14 Ma at *ca*. 50°S and continues to the present, migrating the triple junction position northward (Cande and Leslie, 1986; Ramos, 1989; Cahill and Isacks, 1992). Another chain of volcanoes in Southern Volcanic Zone (SVZ) extends to the north from the present CTJ, which has arc andesitic to basaltic compositions (e.g., Stern, 2004; Shinjoe *et al*., 2013) with intervals between each volcano closer than those of AVZ (Stern and Killian, 1996).

Close to the present CTJ, Late Miocene to Pliocene granitoids partly having adakitic signature are exposed on the Taitao Peninsula (e.g., Anma *et al*., 2006, 2009; Anma and Orihashi, 2013; Kon *et al*., 2013) but no active volcano is present along the mid-axis of the Andes Cordillera between Hudson volcano in the southernmost SVZ and Lautaro volcano in the northernmost AVZ (Orihashi *et al*., 2004; Stern, 2004). This *ca*. 350 km long volcanic gap is interpreted as a slab window linked to the collision of the Chile ridge (Ramos and Kay, 1992; Gorring *et al*., 1997). In the back-arc area of the volcanic gap, three adakite bodies of hornblende dacite exist in Santa Cruz Province, Argentina in the Middle Miocene, i.e., the Cerro Pampa, Puesto Nuevo, and Chaitén adakites (Fig. 1; Kay *et al.*, 1993; Orihashi *et al.*, 2003a; Ramos *et al.*, 2004). The occurrence of these adakites in the back-arc area is of a great interest for tectonic setting of adakite magmagenesis. Earlier reports suggest that an OIB-like asthenospheric upwelling induced by slab window opening caused slab heat-up, resulting in adakite magma generation (Ramos and Kay, 1992; Kay *et al.*, 1993; Gorring *et al.*, 1997).

The Cerro Pampa adakite occurs at 47°54′ S, 71°23′ W at Estancia Cerro Pampa, near southeastern Laguna del Asado in the northwest corner of Santa Cruz Province, Argentine Patagonia, as first reported by Ramos *et al.* (1991). The adakite body apparently forms a lava dome standing out from the table mountain covered with basaltic lava flows of Late Miocene ages (8.7 Ma: see Supplementary Table S1).

The Cerro Pampa adakite has high MgO, Ni, and Cr contents and N-MORB-like isotope compositions based on Sr–Nd–Pb isotope systematics in comparison with other adakitic rocks (Martin, 1999), and is regarded as being of "typical" slab melting origin (Kay *et al.*, 1993). To explain higher Ba, Th, and Cs concentrations as well as more radiogenic Pb isotopes in the adakitic rocks, however, Kay *et al.* (1993) also noted that the adakitic magma can be expected to experience a minor degree of upper crustal contamination.

Kay *et al.* (1993) and Ramos *et al.* (2004) respectively reported cooling ages of the Cerro Pampa adakite as 12.1 ± 0.7 Ma and 12.0 ± 0.7 Ma using K–Ar method, and 11.39 ± 0.61 Ma using Ar–Ar technique. A fission-track age was also obtained using zircon grains separated from the Cerro Pampa adakite, the same sample used for this study, to be yielding 11.9 ± 0.6 Ma (Motoki *et al.*, 2003: original data are shown in Supplementary Table S2). Orihashi *et al.* (2003a) reported 30 U–Pb ages of the same zircons. All were considerably older than the reported cooling ages of magmas, except for one age. Therefore, they concluded that the zircon grains are xenocrysts that originated from the host rocks of the continent crust. We use the same rock samples used by Motoki *et al.* (2003) and Orihashi *et al.* (2003a) to conduct the present study.

Basement rock

Because pre-Tertiary basement rocks of the Cerro Pampa's surroundings are covered with the Miocene continental sediments (Santa Cruz Formation/Zeballos Group) and the Neogene Patagonia Plateau lavas, and subsequently with the Pleistocene glacial deposit, it is difficult to observe the basement rocks on the field directly. Based on the regional geological maps (Kay *et al.*, 1993; Espinoza *et al.*, 2010), however, the Mesozoic volcanic rocks (El Quemado-Ibañez volcanic complex) are estimated to be distributed below the layers.

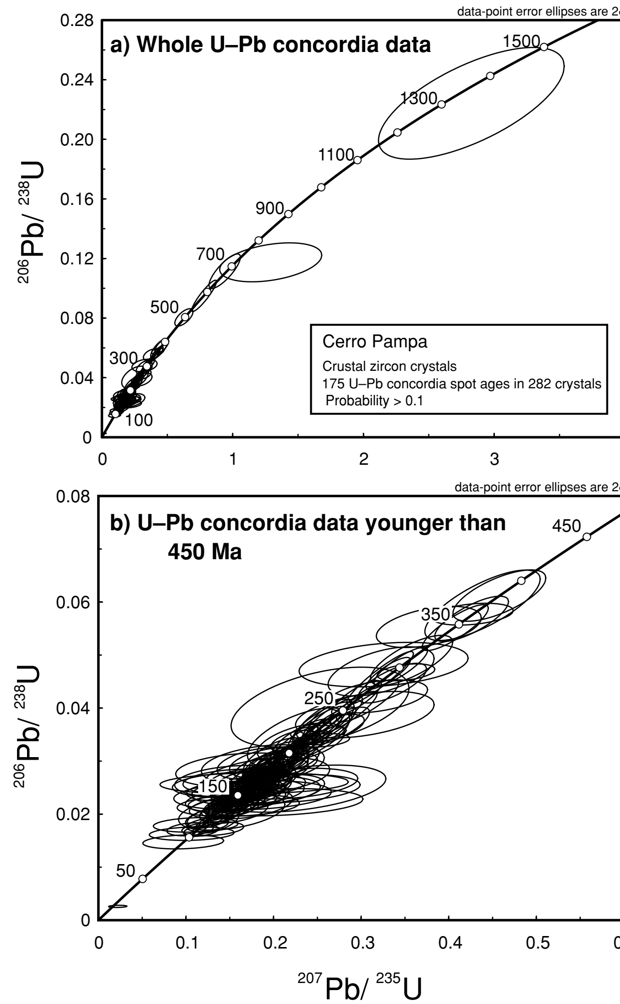

Fig. 2. $^{207}Pb/^{235}U$ vs. $^{206}Pb/^{238}U$ concordia diagram showing newly obtained from the zircon grains in the Cerro Pampa adakite: a) whole data having concordia probability larger than 0.1 on calculation of ISOPLOT program (Ludwig, 2001); b) the data younger than 450 Ma.

Dating Apparatus and Analytical Method

Zircons were extracted using the separation line of Kyoto Fission Track Co. Ltd., Japan. Zircons were scarce. A total of 282 grains were recovered from *ca.* 1.2 kg of three adakite samples. The separated grains were mounted in a Teflon sheet that was free of Pb, to allow dating of grains smaller than the laser beam diameter.

The ICPMS used for this study was a Thermo Elemental PlasmaQuad3 (PQ3) installed at ERI, The University of Tokyo. To obtain higher sensitivity, an S-option interface (Hirata and Nesbitt, 1995) and VG CHICANE ion lens (Hirata, 2000) were applied to the PQ3 instrument. We used a frequency-quadrupled Nd-YAG UV laser (266 nm wavelength) for laser ablation. In 25 s ablation time,

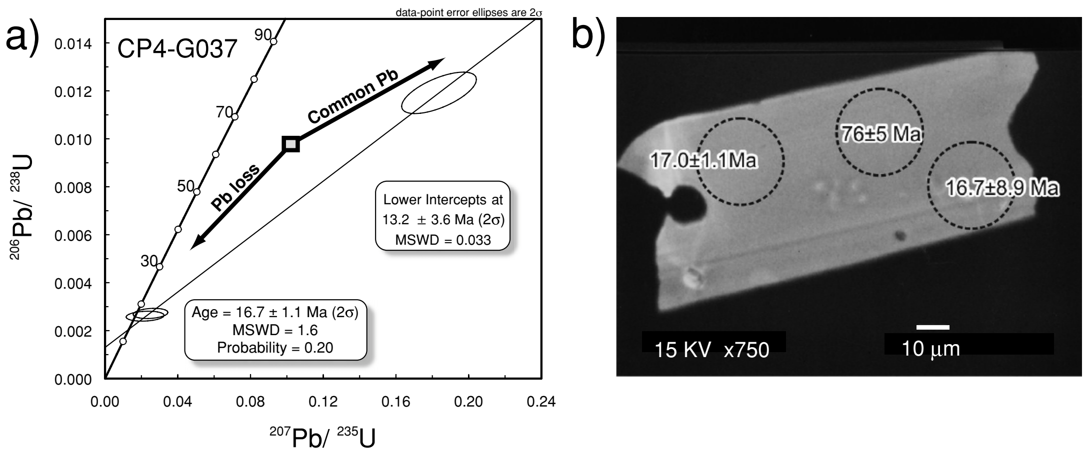

Fig. 3. a) $^{207}Pb/^{235}U$ vs. $^{206}Pb/^{238}U$ concordia plot and b) cathode luminescence image of CP4-G37 zircon grain showing Mid-Miocene age. The lower intercept age showed 13.2 ± 3.6 Ma (2 sigma, MSWD = 0.033), which overlapped the cooling ages determined by FT age within the range of analytical error (see, Table S1).

the system realized U–Pb dating with typical analytical error of less than 6% (SD). The instrumental sensitivities achieved by the present LA-ICPMS are 1.5–4.0 × 10^5 cps for Pb and U on SRM610 (NIST) from a diameter of 30 μm pit size ablated by 10 Hz repetition rate with source pulse energy of 0.2 mJ/spot. Details of the analytical procedure and age calculation were described in Orihashi *et al.* (2003b, 2008). We used an ISOPLOT program (Ludwig, 2001) for calculations of concordia and intercept ages, statistics, and plots. When a calculated U–Pb age has a concordia probability larger than 0.1, it is regarded as a concordia age and is regarded as representative of the age of the zircon crystallization.

RESULTS

Single crystal spot ages

In this study, a total of 437 spot ages were determined from 282 grains including 30 spot ages reported previously by Orihashi *et al.* (2003a). Among the 437 ^{238}U–^{206}Pb ages, only two yielded Middle Miocene ages, and plot onto the concordia curve (Fig. 2). Grain CP4-G037, a 130-μm-long and 60-μm-wide crystal, has 17 Ma-old rims (just one age plot on the concordia) and 76 Ma-old core that is a discordant pseudo-age (Fig. 3). The discordant age might be attributable to Pb loss because of multiple thermal events and/or contamination by common Pb. The cathode luminescence image for this grain shows no overgrowth structure. Therefore, the zircon grain CP4-G037 did not undergo severe multiple thermal events, and strong influence of common Pb was expected from some inclusions in the zircon grain (e.g., apatite, monazite, melt inclusion). Consequently, discordant ages are not useful to discuss the evolution history of the continental crust underneath the volcano. We neglect the discordant ages from further discussion.

Among the 437 data, 175 spot ages obtained from 282 grains were classified to concordia ages (Fig. 2). Supplementary Table S3 presents concordia ages obtained in the current study. Except for the one Miocene age, they are 94–1335 Ma. Consequently, 174 data out of 175 concordia ages were considerably older than the cooling ages of magma (*ca.* 12 Ma).

Among the 282 measured crystals, 22 grains show multiple concordant spot ages that differ between the core and rim (Supplementary Table S4; Figs. 4c–k; 5), corresponding respectively to igneous crystallisation and overgrowth during later thermal events. Nine grains achieving multiple spot analyses showed the same concordant ages between the core and rim within probability greater than 0.1 (Figs. 4a and 4b). Except for three grains, all core ages presented in Table S4 were older than 150 Ma. Actually, 18 out of 22 grains yielded dual concordia spot ages between the core and rim (Figs. 4c–4k) and seven out of 22 rim ages were 94–145 Ma. The grains CP1-G059 and CP4-G005 and G008 had similar ages of 104–119 Ma in rims whereas their core ages were 158–345 Ma (Figs. 4d and 4e). The grains CP1-G008, G021, G090, and CP4-G012 had a similar age of 130–139 Ma in rims, although their core ages were 144–187 Ma (Figs. 4f and 4g). The other 11 grains were older than 150 Ma both in the core and rim (Figs. 4h–k). Grains CP2-G027, and CP4-G015, G040 and G055 yielded three different concordia spot ages between the core and rim (Figs. 5a–e). The grain CP2-G027 is a 140 μm-long and 70 μm-wide crystal with two relic cores surrounded by rims with

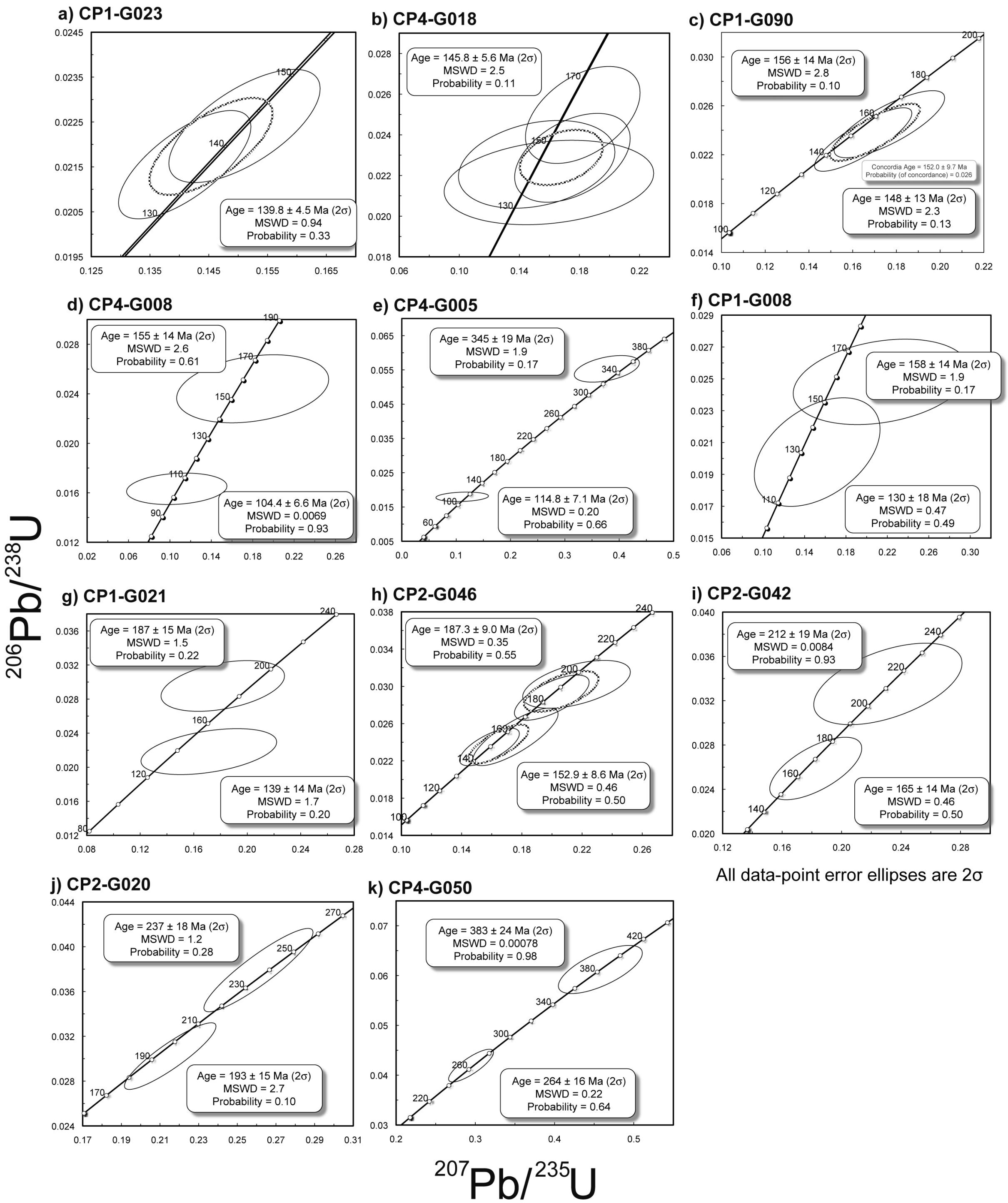

Fig. 4. $^{207}Pb/^{235}U$ vs. $^{206}Pb/^{238}U$ concordia plots for Cerro Pampa adakite zircon grains of a) CP1-G023 and b) CP4-G018, having single U–Pb concordia age on the same grain, and c) CP1-G090, d) CP4-G008, e) CP4-G005, f) CP1-G008, g) CP1-G021, h) CP2-G046, i) CP2-G042, j) CP2-G020 and k) CP4-G050, having dual U–Pb concordia ages on the same grain.

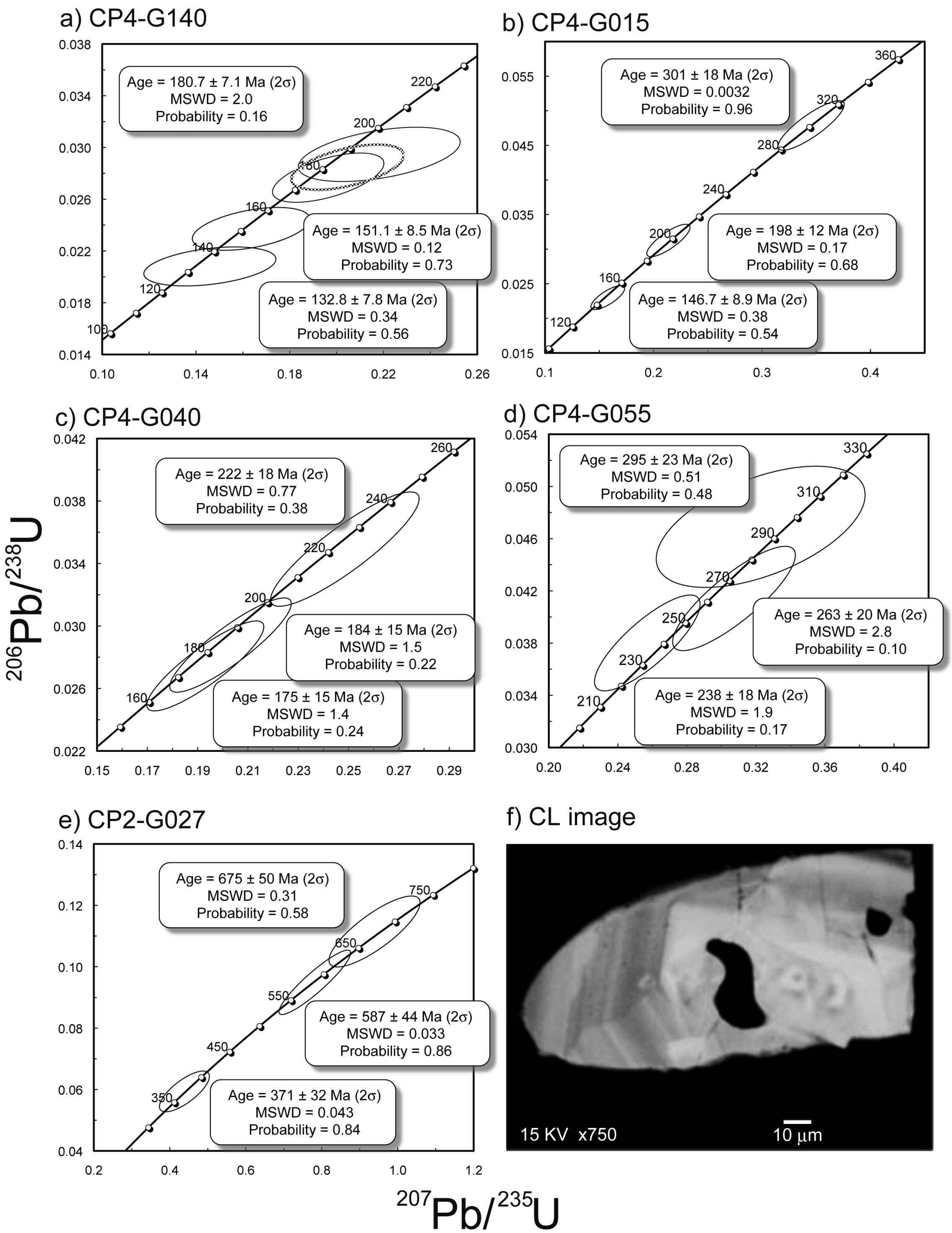

Fig. 5. $^{207}Pb/^{235}U$ *vs.* $^{206}Pb/^{238}U$ *concordia plots for Cerro Pampa adakite zircon grains of a) CP4-G140, b) CP4-G015, c) CP4-G040, d) CP4-G055 and e) CP2-G027, having triple U–Pb concordia ages on the same grain. f) Cathode luminescence image for CP2-G027.*

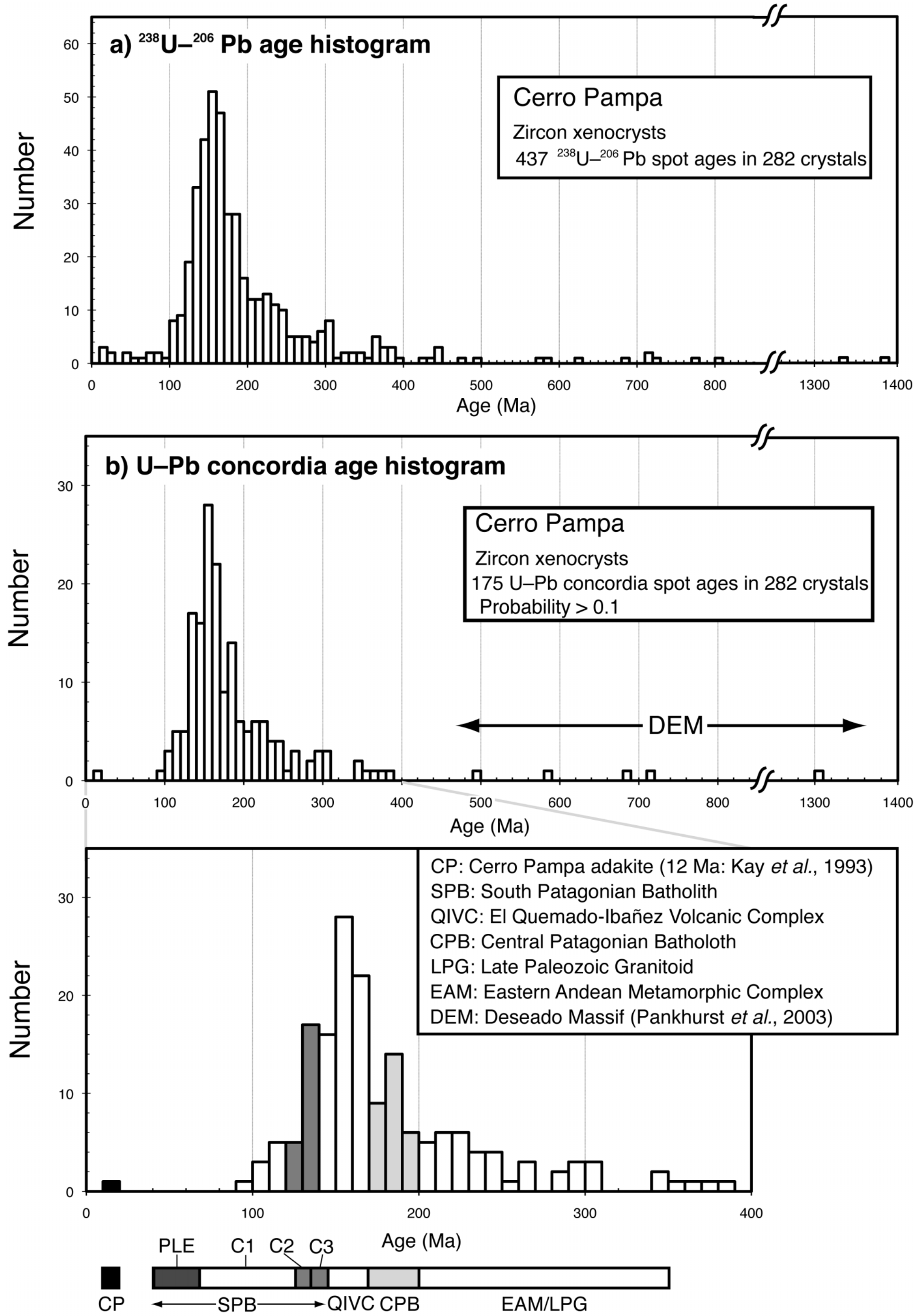

Fig. 6. Age population histogram showing A) $^{238}U–^{206}Pb$ ages and B) U–Pb concordia ages for spot analyses of the exotic zircons in the Cerro Pampa adakite. The obtained data in this study is divisible into five groups, i.e., the first age group: 94–125 Ma, the second age group; 125–145 Ma, the third age group: 145–170 Ma, the fourth age group: 170–200 Ma, fifth age group: 200–383 Ma. The divided five age groups are correlated to C3 of South Patagonian Batholith (SPB; Hervé et al., 2007) in the first age group, C2 and C1 of SPB in the second age group, El Quemado-Ibañez volcanic complex (QIVC; Bruhn et al., 1978; Hervé et al., 2007; Pankhurst et al., 2000) in the third age group, Central Patagonian Batholith (CPB; Roland et al., 2002) in the fourth age group, and Late Palaeozoic Granitoid (LPG) and the Eastern Andean metamorphic complex (EAM) (Bahlburg et al., 2009; Herve et al., 2003) in the fifth age group. The data obtained by Orihashi et al. (2003a) are also included in the histogram. Symbol bars in the bottom are as follows: Cerro Pampa adakite (CP), South Patagonian Batholith (SPG, subdivided into Palaeogene (PLE), Cretaceous 1 (C1), Cretaceous 2 (C2), Cretaceous 3 (C3)), El Qumado-Ibañez volcanic complex (QIVC), Central Patagonian Batholith (CPB), Late Palaeozoic Granitoid (LPG), Eastern Andean metamorphic complex (EAM) and Deseado Massif (DEM).

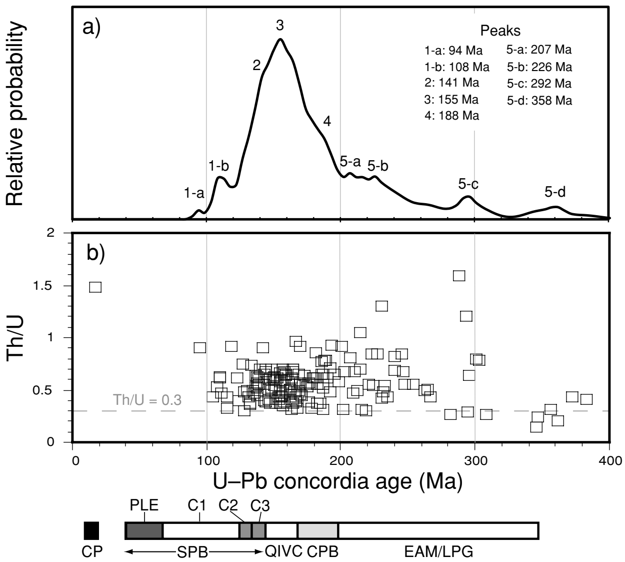

Fig. 7. a) Cumulative probability curve for U–Pb concordia ages of the entire zircon crystals included in the Cerro Pampa adakite, shown using the ISOPLOT program (Ludwig, 2001). The plot shows nine distinct peaks: 1-a (94 Ma) and 1-b (108 Ma) correlated to the first age group, 2 (141 Ma) correlated to the second age group, 3 (155 Ma) correlated to the third age group, 4 (188 Ma) correlated to the fourth age group, and 5-a (207 Ma), 5-b (226 Ma), 5-c (292 Ma) and 5-d (358 Ma) correlated to the fifth age group. b) Correlation of Th/U ratios and U–Pb concordia ages for zircon crystals of the Cerro Pampa adakite. Symbol bars shown at the bottom are the same as those in Fig. 6.

igneous overgrowth texture (Fig. 5f). The ages were 675–371 Ma. The grain CP4-G140 having four spot analyses showed one old concordia age (181 Ma) from two spot analyses, overlapping within probability larger than 0.1, and two different young ages (133 and 151 Ma) (Fig. 5a). From CP4-G015, G040 and G055 grains, three different concordia ages were obtained, ranging from 147 Ma to 301 Ma (Figs. 5b–d). Among them, three rim and mantle ages (175–198 Ma) and two core ages (295–301 Ma) overlapped respectively within analytical error. Consequently, at least four independent zircon age populations, i.e., 147 Ma, 175–198 Ma, 222–238 Ma, and 263–301 Ma, were identified with crystallization ages of 150–300 Ma.

With the exception of one Middle Miocene crystal, all U–Pb concordia ages were significantly greater (>94 Ma) than the cooling ages of the adakite magma (*ca*. 12 Ma), whereas the FT age for the zircon crystals obtained from the same studied sample yielded *ca*. 12 Ma. This result has indicated that exotic zircon crystals were once completely reset in the FT age system (the closure temperature of *ca*. 250°C in zircon; Hurford, 1986) but not reset in the U–Pb age system (the closure temperature of *ca*. 900°C in zircon; Cherniak and Watson, 2000) when the crystals were captured in the adakite magma. Consequently, presence of the enormous exotic zircon crystals was clearly incorporated during upwelling of the adakitic magma through the entire crust in Cerro Pampa.

Age population histogram

The obtained concordia ages of exotic zircons, 94–1335 Ma, are divisible into five groups having distinctive distributions on an age population histogram (Fig. 6): 1) 94–125 Ma, 2) 125–145 Ma, 3) 145–170 Ma, 4) 170–200 Ma, and 5) 200–383 Ma. The fifth age group has a broad distribution including the oldest age (1335 Ma). A calculation of relative probability (Fig. 7a) basically supports this classification, i.e., the first age group centred on 108 Ma, the second age group centred on 141 Ma, the third age group centred on 155 Ma and the fourth age group centred on 188 Ma. However, this diagram further suggests that the first and fifth age groups are divisible into two sub-groups centred on 94 Ma and 108 Ma, and four sub-groups centred respectively on 207 Ma, 226 Ma, 292 Ma, and 358 Ma. Zircon grains with ages older than 383 Ma are rare (5 out of 282 grains) and scattered in a wide range (498–1335 Ma). A distinctive gap exists in the age distribution of 498–383 Ma.

The third age group has the most remarkable and distinctive peak as well as distribution. The second and fourth age groups also define a clear distribution on the age population histogram, but are less significant than the third age group. Peaks of the first age group are more significant than those of the second and fourth age groups, but the population is less significant than those.

DISCUSSION

Correlations of exotic zircon ages and the exposed crust of Patagonia

As described above, we divided exotic zircon crystals into five age groups: 1) 94–125 Ma, 2) 125–145 Ma, 3) 145–170 Ma, 4) 170–200 Ma, and 5) 200–383 Ma. The first (94–125 Ma) and second age groups (125–145 Ma) correspond to the age of plutonic activity that formed the main body of the South Patagonian Batholith (SPB) that is exposed in the west of the Cerro Pampa adakite. Hervé *et al*. (2007) classified granitic rocks of the SPB into four groups using their age distribution: Cretaceous 1 (137–144 Ma), Cretaceous 2 (127–136 Ma), Cretaceous 3 (75–126 Ma), and Palaeogene (40–67Ma). The first age group of the Cerro Pampa zircon corresponds to the older part of the Cretaceous 3. The second age group of the Cerro Pampa zircon corresponds to the Cretaceous 1 and 2 igneous activities of Hervé *et al*. (2007). No exotic zircon with post-94 Ma concordia age was found from Cerro Pampa adakite.

The third age group (145–170 Ma), which is the most significant component of the Cerro Pampa zircons, corresponds to activities of El Quemado-Ibañez volcanic complex (Bruhn *et al*., 1978; Hervé *et al*., 2007; Pankhurst *et al*., 2000) that comprises the basement of the Cerro Pampa adakite dome. El Quemado-Ibañez volcanic complex can be correlated partly to the Chon Aike magmatism (Pankhurst *et al*., 1998; Suárez *et al*., 2009) and the Tobífera formation (Calderón *et al*., 2007), a voluminous rhyolitic ignimbritic sequence deposited partly over the Rocas Verdes Basin east of the SPB as well as the last of several southwestward-migrating silicic volcanic episodes in Patagonia that commenced in an Early Jurassic extensional tectonic regime over the Atlantic coast (Hervé *et al*., 2007). Hervé *et al*. (2007) also detected a voluminous Late Jurassic bimodal body mainly composed of leucogranite with some gabbro, emplaced along the eastern margin of present SPB at incipient stage of the formation of SPB (157–145 Ma). Recently, a range of ages similar to the third age group has also been found in the North Patagonian Batholith further north from the Cerro Pampa (Castro *et al*., 2011).

The fourth age group (170–200 Ma) might correspond to gabbroic rocks, scarcely distributed in Central Patagonia (e.g., Rolando *et al*., 2002) in the region to the north of Cerro Pampa body. In this study, we expediently define these plutonic rocks exposed in Central Patagonia as Central Patagonian Batholiths. In addition, the fourth age group was overlapped partly with eruption ages of Marifil volcanic formation near the Atlantic margin (e.g., Pankhurst *et al*., 2000) in the region to the northeast of Cerro Pampa body.

Focused on range of the above four age groups from 94 Ma to 200 Ma, each age group corresponds well to the frequency of detrital zircons in Cretaceous sediments of the Neuquén Basin, originating from the North Patagonian Batholith, i.e., 105–125 Ma, 125–135 Ma, 160–175 Ma and 175–200 Ma (Tunik *et al*., 2010). Moreover, the range of the four age groups is confirmed not only by recent data in different sections of the North Patagonian Batholith (Castro *et al*., 2011), but also by the exhumation of these granitic rocks in the South Patagonian Batholith, in the southernmost Patagonian Andes (Fildani *et al*., 2003). These results show that the major magmatic activity of the whole Patagonian Batholith occurs within the range of 94–200 Ma.

The fifth age group (200–380 Ma) might correspond to the Eastern Andean metamorphic complex of Late Paleozoic to Early Mesozoic ages. The fifth age group is divisble into four sub-groups centred on 207 Ma, 226 Ma, 292 Ma, and 358 Ma. The Eastern Andean metamorphic complex contains detrital zircon crystals with SHRIMP ages of 240–331 Ma (Hervé *et al*., 2003). Bahlburg *et al*. (2009) reported age distribution of detrital zircons from accretion complex in northern Chile (21°N–32°N) and found the concentration of the youngest age group in 250–350 Ma. In addition, this activity around 290 Ma was detected also by Fanning *et al*. (2011) and was confirmed as produced by a magmatic arc at these southern latitudes (Ramos, 2008), suggesting the presence of Late Paleozoic granite activity.

Zircons of detrital origin

Zircon grains with ages older than 383 Ma are rare (5 out of 282 grains) and scattered in a wide range (498–1335 Ma). The absence of clear age peaks in this range suggests that the zircon crystals originate from various sources.

Pankhurst *et al*. (2003) reported Paleozoic igneous activities (521–346 Ma) that formed the basement of the Deseado Massif in southern Patagonia. Provenance ages of detrital zircons in metasediments of the Deseado Massif were typical of materials available in the Gondwana margin, with prominent components at 1000–1100 and *ca*. 580 Ma (Pankhurst *et al*., 2003). A crust equivalent to the Deseado Massif might be responsible for zircons older than *ca*. 346 Ma of Cerro Pampa adakite.

Such old grains must be detrital grains that were transported and deposited in the sedimentary rocks of the Eastern Andes metamorphic complex (Hervé *et al*., 2003). For example, the grain CP2-G027 has a rounded shape and cores of 587 ± 44 and 675 ± 50 Ma old surrounded by an igneous rim of 371 ± 32 Ma. The grain must have once been captured by Paleozoic granitic magma that formed the basement of the Deseado massif. The rounded shape of the grain and ablated igneous zoning texture (Fig. 5f) reflect detrital processes that took place after igneous overgrowth.

Zircon crystallised from a granitic magma generally has high Th/U ratio, whereas a zircon formed by metamorphic process generally has a low Th/U ratio (e.g., Rubatto and Hermann, 2003; Whitehouse *et al*., 1999). The diagram of Th/U vs. U–Pb concordia age (Fig. 7b) shows that the presence of zircons having low Th/U ratio (lower than 0.3) in a range of 270–390 Ma. The data CP4-G051 have a low Th/U ratio (0.14) with age of 347 Ma. This observation suggests metamorphic overgrowth of old detrital zircons.

Evolution of the continental crust underneath the Cerro Pampa adakite body

Zircon ages older than 383 Ma are rare (5/282 grains), scattered in a wide range (498–1335 Ma) and extant in detrital grains. Rolando *et al*. (2002) reported that Mesozoic (191–82 Ma) plutonic rocks (gabbro and granitoids) distributed at 45°S contain numerous igneous zircons with Archaean to Paleoproterozoic ages (concentrated near 3.40–3.00, 2.75–2.50, and 2.15–1.95 Ga). They suggested the presence of Archaean to Paleoproterozoic middle crust underlying the upper crust that consists of the Ibañez volcanic complex and the Coyhaique group (Middle Jurassic to Early Cretaceous ages). During this study, no Paleoproterozoic or Archaean zircon was found. Therefore, we conclude that the Archaean to Paleoproterozoic middle crust extending from the north is not present at 48°S. The boundary between old South American crusts and newly formed Patagonian crust must lie between 45°S and 48°S. It is particularly interesting that Rolando *et al*. (2002) did not find Neoproterozoic and Paleozoic inherited zircons. In our study, all inherited/detrital zircon have ages younger than Neoproterozoic. The two crusts might have completely different tectonic histories and the crust to the south could be the result of the accretion of a younger age crust to the Gondwana margin, as proposed by Ramos (2008) and Hervé *et al*. (2010).

The age distribution of exotic zircons in the Cerro Pampa adakite indicates that the crust underneath the adakitic volcano was formed mostly after 383 Ma. Most zircons with age equivalent to or older than that of Deseado massif (down to 346 Ma) are detrital in origin. Consequently, the inception age could be even younger. Hervé *et al*. (2003) reported that the Eastern Andean metamorphic complex contains detrital zircon of 240–331 Ma. The inception of granitic plutonism (=zircon crystallization) that produced new crusts underneath the Cerro Pampa adakite could be as young as 240 Ma. Zircons younger than 240 Ma are evidently of igneous origin and reflect the evolution history of new continental crust (*ca*. granitic plutonism) underneath the Cerro Pampa adakite. The processes forming new continental crust of south Patagonia might have started with Jurassic gabbroic magmatism scarcely distributed in Central Patagonia (Rolando *et al*., 2002) in the region to the north of Cerro Pampa body. Subsequently to Gondwana break-up (*ca*. 184 Ma; Encarnacion *et al*., 1996), vast rhyolitic ignimbrites associated with melting of lower crust erupted in the back-arc region of south Patagonia during the Early to Late Jurassic (188–153 Ma) (Pankhurst *et al*., 2000). Then, the new continental crust should also be formed mainly along the Atlantic margin.

The third age group (145–170 Ma), the most important, corresponds to activities of the El Quemado-Ibañez volcanic complex (Hervé *et al*., 2007; Pankhurst *et al*., 2000; Rolando *et al*., 2002), which comprises the basement of the Cerro Pampa adakite. The El Quemado-Ibañez volcanic complex consists mainly of volcanic and volcaniclastic rocks of andesitic to dacitic compositions that rarely contain zircon crystals. The relative abundance of the third-age-group grains suggests the necessity of a large granitic batholith below the Cerro Pampa adakite that is contemporaneous to El Quemado-the Ibañez volcanic complex. Hervé *et al*. (2007) argued the presence of a voluminous Late Jurassic leucogranite, emplaced along the eastern margin of present SPB within a restricted time span (157–145 Ma). The third age group has a median at *ca*. 155 Ma (Fig. 7a) and might relate to the crust formed during the inception of SPB magmatism, i.e., Late Jurassic arc-volcanism near the Pacific margin. Pankhurst *et al*. (1998) also argued that subduction dynamics at the Pacific margin have played an important role in the formation of El Quemado-Ibañez volcanic complex based on arc-related geochemical characteristics.

To explain the wide distribution of Late to Middle Jurassic volcanic complexes in south Patagonia with multiple events over *ca*. 30 m.y., however, it is also necessary that decompression melting of immature lower crust accompanied with crustal extension and thinning in the tectonic region of Gondwana break-up (Pankhurst *et al*., 2000). Whatever magmatism of the El Quemado-Ibañez volcanic complex, such granitic batholith having similar age activities to those of the North Patagonian Batholith (Castro *et al*., 2011) reportedly underlie the present upper crust of the El Quemado-Ibañez volcanic complex beneath the Cerro Pampa because glassy volcanic rocks are well-known to include such large zircon crystals separated in this study only rarely.

Hervé *et al*. (2007) also argued that the granitic plutonic activity continued through the Cretaceous until the Palaeogene (40–67 Ma) at present SPB. Our results indicate that the processes forming the continental crust ceased by 94 Ma in the west of the SPB until the activity of the Cerro Pampa adakite in *ca*. 12 Ma. No evidence for Palaeogene igneous activity was found in this study, which means that the centre of Mesozoic to Palaeogene plutonic activities migrated westward through time. Thomson (2002) reported several Miocene plutonic intrusions along the western SPB. Consequently, regional volcano-plutonic activities covering a large area that includes the forearc to backarc regions started in Miocene times, perhaps associated with the collision of the Chile ridge (e.g., Ramos and Kay, 1992; Kay *et al*., 1993; Aragón *et al*., 2011).

CONCLUSIONS

This paper reports the results of U–Pb dating using LA-ICPMS for 282 zircon crystals separated from a Middle Miocene adakite in Cerro Pampa, southern Argentine Patagonia. Among 437 spot ages, 175 data fall onto the concordia curve. With the exception of one spot age, all U–Pb concordia ages are considerably older (>94 Ma) than the cooling ages of the adakite magma (*ca*. 12 Ma). Kay *et al*. (1993) attributed the origin of adakite magmas to partial melting of subducted slab induced by an OIB-like asthenospheric upwelling. Presence of exotic zircon crystals confirms the upper crustal contamination, which is also consistent with the geochemical characteristics of the adakites reported by Kay *et al*. (1993). The obtained U–Pb age distribution further indicates that the magma jumbled up the information related to crustal evolution during its ascension through the entire crust beneath the Cerro Pampa.

The obtained concordia ages of exotic zircons, 94–1335 Ma, are divisible into five groups having distinctive distributions and peaks on a population diagram and a relative probability diagram. The first (94–125 Ma centred on 94 and 108 Ma) and second age groups (125–145 Ma centred on 141 Ma) correspond to the age of plutonic activities that formed the main body of the South Patagonian Batholith. The third to fifth groups respectively correspond to the activity of El Quemado-Ibañez volcanic complex (145–170 Ma centred on 155 Ma), plutonic rocks are scarcely exposed mainly in Central Patagonia (170–200 Ma centred on 188 Ma) and the Eastern Andean metamorphic complex of Late Paleozoic to Early Mesozoic age (200–380 Ma centred on 207 Ma, 226 Ma, 292 Ma and 358 Ma).

Our data suggest that the crust underneath Cerro Pampa was formed mostly after 380 Ma and that the majority was formed during the Early Cretaceous to Middle Jurassic. The processes of crustal development ceased for *ca*. 80 m.y. until the activity of the Cerro Pampa adakite in *ca*. 12 Ma. No evidence was found for Archaean–Paleoproterozoic crust in the region, although existence of numerous Archaean–Paleoproterozoic exotic zircons in Mesozoic plutonic rocks distributed in Andean Cordillera at around 46°S was reported by Rolando *et al*. (2002). This speculation holds that two different crusts aggregated along a boundary between 46°S and 48°S. The timing must be on the growth of a hypothetical micro-continental mass that collided with the continental margin of the Gondwana during Late Paleozoic times, as part of the amalgamation of Pangaea (Hervé *et al*., 2010).

Consequently, U–Pb ages for exotic zircons in the Cerro Pampa adakite provided insightful crustal information even if granitic batholiths lie beneath the region. The geochronological fingerprint based on numerous U–Pb ages of exotic zircon crystals can clarify the entire evolutional history of the crust underlying the adakite.

Acknowledgments—The authors are thankful to Profs. S. Maruyama, K. Nagao, F. Hervé and other colleagues of the Chile Ridge Subduction To Magma Supply System (CHRISTMASSY) Project Group for their discussions and supports, and to Drs. M. Schilling, Y. Watanabe and Mr. M. Haller for their field assistance. The authors are also grateful to Drs. A. Folguera and M. Calderon for their kind reviews and Dr. K. R. Ludwig for generously supplying the ISOPLOT program. The present studies were supported by JSPS KAKENHI Grant Numbers 13373004 and 21403012 awarded respectively to RA and YO.

REFERENCES

Anma, R. and Orihashi, Y. (2013) Shallow-depth melt eduction due to ridge subduction: LA-ICPMS U–Pb igneous and detrital zircon ages from the Chile Triple Junction and the Taitao Peninsula, Chilean Patagonia. *Geochem. J.* **47**, this issue, 149–165.

Anma, R., Armstrong, R., Danhara, T., Orihashi, Y. and Iwano, H. (2006) Zircon sensitive high mass-revolution ion microprobe U–Pb and fission-track ages for gabbros and sheeted dykes of the Taitao ophiolite, Southern Chile, and their tectonic implications. *Island Arc* **15**, 130–142.

Anma, R., Armstrong, R., Orihashi, Y., Ike, S., Shin, K.-C., Kon, Y., Komiya, T., Ota, T., Kagashima, S., Shibuya, T., Yamamoto, S., Veloso, E. E., Fannin, M. and Herve, F. (2009) Are the Taitao granites formed due to subduction of the Chile ridge? *Lithos* **113**, 246–258.

Aragón, E., Castro, A., Díaz-Alvarado, J. and Liu, D.-Y. (2011) The North Patagonian batholith at Paso Puyehue (Argentina–Chile). SHRIMP ages and compositional features. *J. S. Am. Earth Sci.* **32**, 547–554.

Atherton, M. P. and Petford, N. (1993) Generation of sodium-rich magmas from newly underplated basaltic crust. *Nature* **362**, 144–146.

Bahlburg, H., Vervoort, J. D., Du Frane, S. A., Bock, B., Augustsson, C. and Reimann, C. (2009) Timing of crust formation and recycling in accretionary orogens: Insights learned from the western margin of South America. *Earth-Sci. Rev.* **97**, 215–241.

Black, L. P., Williams, E. S. and Compston, W. (1986) Four zircon ages from one rock: the history of a 3,900 Ma-old granulite from Mount Scones, Enderby Land, Antarctica. *Contrib. Mineral. Petrol.* **94**, 427–437.

Bruhn, R. L., Stern, C. R. and de Wit, M. J. (1978) Field and geochemical data bearing on the development of a Mesozoic volcano-tectonic rift zone and back-arc basin in southernmost South America. *Earth Planet. Sci. Lett.* **41**, 32–46.

Cahill, T. and Isacks, B. L. (1992) Seismicity and shape of subducted Nazca Plate. *J. Geophys. Res.* **97**, 17503–17529.

Calderón, M., Fildani, A., Herve, F., Fanning, C. M., Weislogel, A. and Cordani, U. (2007) Late Jurassic bimodal magmatism in the northern sea-floor remnant of the Rocas Verdes basin, southern Patagonian Andes. *J. Geophys. Res.* **164**, 1011–1022.

Cande, S. C. and Leslie, R. B. (1986) Late Cenozoic tectonic of the southern Chile trench. *J. Geophys. Res.* **91**, B1, 471–496.

Castro, A., Moreno-Ventas, I., Fernández, C., Vujovich, G., Gallastegui, G., Heredia, N., Martino, R. D., Becchio, R., Corretgé, L. G., Díaz-Alvarado, J., Such, P., García-Arias, M. and Liu, D.-Y. (2011) Petrology and SHRIMP U–Pb zircon geochronology of Cordilleran granitoids of the Bariloche area, Argentina. *J. S. Am. Earth Sci.* **32**, 508–530.

Cherniak, D. J. and Watson, E. B. (2000) Pb diffusion in zircon. *Chem. Geol.* **172**, 5–24.

Compston, W., Williams, I. S. and Meyer, C. (1984) U–Pb geochronology of zircon from lunar breccia 73217 using a sensitive high mass-resolution ion microprobe. *J. Geophys. Res.* **89**, 525–534.

Danhara, T., Iwano, H., Yoshioka, T. and Tsuruta, T. (2003) Zeta calibration values for fission track dating with a diallyl phthalate detector. *J. Geol. Soc. Japan* **109**, 665–668.

Defant, M. J. and Drummond, M. J. (1990) Derivation of some modern arc magmas by melting of young subducted lithosphere. *Nature* **347**, 662–665.

Encarnacion, J., Fleming, T. H., Elliot, D. H. and Eales, H. V. (1996) Synchronous emplacement of Ferrar and Karoo dolerited and the early breakup of Gondwana. *Geology* **24**, 535–538.

Espinoza, F., Morata, D., Polvé, M., Lagabrielle, Y., Maury, R. C., de la Rupelle, A., Guivel, C., Cotton, J., Bellon, H. and Suárez, M. (2010) Middle Miocene calc-alkaline volcanism in Central Patagonia (47°S): petrogenesis and implications for slab dynamics. *Andean Geol.* **37**, 300–328.

Fanning, C. M., Hervé, F., Pankhurst, R. J., Rapela, C. W., Kleiman, L. E., Yaxley, G. M. and Castillo, P. (2011) Lu–Hf isotope evidence for the provenance of Permian detritus in accretionary complexes of western Patagonia and the northern Antarctic Peninsula region. *J. S. Am. Earth Sci.* **32**, 485–496.

Fildani, A., Cope, T. D., Graham, S. A. and Wooden, J. L. (2003) Initiation of the Magallanes foreland basin: Timing of the southernmost Patagonian Andes orogeny revised by detrital zircon provenance analysis. *Geology* **31**, 1081–1084.

Galbraith, R. F. (1981) On statistical model for fission track counts. *J. Mathemat. Geol.* **13**, 471–488.

Goldstein, S. L., Arndt, N. T. and Stallard, R. F. (1997) The history of a continent from U–Pb ages of zircons from Orinoco River sand and Sm–Nd isotopes in Orinoco basin river sediment. *Chem. Geol.* **139**, 271–286.

Gorring, M. L., Kay, S. M., Zeitler, P. K., Ramos, V. A., Rubiolo, D., Fernandez, M. I. and Panza, J. L. (1997) Neogene Patagonian plateau lavas: continental magmas associated with ridge collision at the Chile Triple Junction. *Tectonics* **16**, 1–17.

Hervé, F., Fanning, C. M. and Pankhurst, R. J. (2003) Detrital zircon age patterns and provenance of the metamorphic complexes of southern Chile. *J. S. Am. Earth Sci.* **16**, 107–123.

Hervé, F., Pankhust, R. J., Fanning, C. M., Calderón, M. and Yaxley, G. M. (2007) The South Patagonian batholith: 150 my of granite magmatism on a plate margin. *Lithos* **97**, 373–394.

Hervé, F., Calderón, M., Fanning, C. M., Kraus, S. and Pankhust, R. J. (2010) SHRIMP chronology of the Magallanes Basin basement, Tierra del Fuego: Cambrian plutonism and Permian high-grade metamorphism. *Andean Geol.* **37**, 253–275.

Hirata, T. (2000) Development of a flushing spray chamber for inductively coupled plasma-mass spectrometry. *J. Anal. At. Spectrom.* **15**, 1447–1450.

Hirata, T. and Nesbitt, R. W. (1995) U–Pb isotope geochemistry of zircon: Evaluation of laser prove-inductively coupled plasma mass spectrometer technique. *Geochim. Cosmochim. Acta* **59**, 2491–2500.

Hurford, A. J. (1986) Cooling and uplift patterns in the Lepontine Alps South Central Switzerland and an age of vertical movement on the Insbric fault line. *Contrib. Mineral. Petrol.* **92**, 413–427.

Jackson, S. E., Pearson, N. J., Griffin, W. I. and Belousova, E. A. (2004) The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. *Chem. Geol.* **211**, 47–69.

Kay, R. W. (1978) Aleutian magnesian andesites: melts from subducted Pacific Ocean crust. *J. Volcanol. Geoth. Res.* **4**, 497–522.

Kay, S. M., Ramos, V. A. and Márquez, M. (1993) Dominant slab-melt component in Cerro Pampa adakitic lavas erupted prior to the collision of the Chile rise in Southern Patagonia. *J. Geol.* **101**, 703–714.

Kimura, J., Chang, Q. and Tani, K. (2011) Optimization of ablation protocol for 200 nm UV femtosecond laser in precise U–Pb age dating coupled to multi-collector ICP mass spectrometry. *Geochem. J.* **45**, 283–296.

Kon, Y., Komiya, T., Anma, R., Hirata, T., Shibuya, T., Yamamoto, S. and Maruyama, S. (2013) Petrogenesis of the ridge subduction-related granitoids from the Taitao Peninsula, Chile Triple Junction Area. *Geochem. J.* **47**, this issue, 167–183.

Ludwig, R. K. (2001) User Manual for Isoplot/Ex rev. 2.49. *Berkeley Geochronology Center Special Publication* **1a**, Berkeley Geochronology Center, Berkeley, CA.

Martin, H. (1999) Adakitic magmas: modern analogues of Archaean granitoids. *Lithos* **46**, 411–429.

Martin, H., Smithies, R. H., Rapp, R., Moyen, J. F. and Champion, D. (2005) An overview of adakite, tonalite–trondhjemite–granodiorite (TTG), and sanukitoid: relationship and some implications for crustal evolution. *Lithos* **79**(1–2), 1–24.

Motoki, A., Orihashi, Y., Hirata, D., Haller, M. J., Ramos, V. A., Schilling, M., Iwano, H., Cario, F. D. and Anma, R. (2003) U–Pb dating for single grain zircon using laser ablation ICP mass spectrometer and fission track ages of zircon for back-arc adakitic bodies, the Cerro Pampa and the Puesto Nuevo, Argentine Patagonia. *Short Papers of VI South American Symposium on Isotopic Geology* **1**, 108–110.

Nagao, K., Ogata, A., Miura, Y. N. and Yamaguchi, K. (1996) Ar isotope analysis for K–Ar dating using two modified—VG5400 mass spectrometers—I: Isotope dilution method. *J. Mass Spectrom. Soc. Japan* **44**, 36–61.

Orihashi, Y., Hirata, T., Tani, K. and Yoshida, H. (2003a) Rapid and simultaneous determination of multi-element abundance and U–Pb age for zircon crystal using UV laser ablation ICP-MS technique: critical evaluation of the technique with 91500 zircon standard. *J. Miner. Petrol. Sci.* **98**, 109–117.

Orihashi, Y., Motoki, A., Hirata, D., Haller, M. J., Ramos, V. A., Ota, T., Yoshida, H. and Anma, R. (2003b) Zircon geochemistry of Mid-Miocene adakites in the southern Patagonian province (abstract). *Geochim. Cosmochim. Acta* **67**, A364.

Orihashi, Y., Naranjo, J. A., Motoki, A., Sumino, H., Hirata, D., Anma, R. and Nagao, K. (2004) The Quaternary volcanic activities of Hudson and Lautaro volcanoes, Chilean Patagonia: new constraints from K–Ar ages. *Rev. Geol.*

Chile **31**, 207–224.
Orihashi, Y., Nakai, S. and Hirata, T. (2008) U–Pb age determinations for seven standard zircons using inductively coupled plasma-mass spectrometry coupled with frequency quintupled Nd-YAG (λ = 213 nm) laser ablation system: comparison with LA-ICP-MS zircon analyses with a NIST glass reference material. *Resour. Geol*. **58**, 101–123.
Pankhurst, R. J., Leat, P. T., Sruoga, P., Rapela, C. W., Márquez, M., Storey, B. C. and Riley, T. R. (1998) The Chon Aike province of Patagonia and related rocks in West Antarctica: A silicic large igneous province. *J. Volcanol. Geoth. Res*. **81**, 113–136.
Pankhurst, R. J., Riley, T. R., Fanning, C. M. and Kelley, S. P. (2000) Episodic silicic volcanism in Patagonia and the Antarctic Peninsula: chronology of magmatism associated with the breakup of Gondwana. *J. Petrol*. **41**, 605–625.
Pankhurst, R. J., Rapela, C. W., Loske, W. P., Márquez, M. and Fanning, C. M. (2003) Furthermore, chronological study of the pre-Permian basement rocks of southern Patagonia. *J. S. Am. Earth Sci*. **16**, 27–44.
Ramos, V. A. (1989) Foothills structure in northern Magallanes basin, Argentina. *Amr. Assoc. Petrol. Geol. Bull*. **73**, 887–903.
Ramos, V. A. (2008) Patagonia: A Paleozoic continent adrift? *J. S. Am. Earth Sci*. **26**, 235–251.
Ramos, V. A. and Kay, S. M. (1992) Southern Patagonian plateau basalts and deformation: Back-arc testimony of ridge collisions. *Tectonophysics* **205**, 325–394.
Ramos, V. A., Kay, S. M. and Márquez, M. (1991) La Dacita Cerro Pampa (Mioceno - provincia de Santa Cruz): evidencias de la colisión de una dorsal oceánica (abstract). *4° Congreso Geológico Chileno Acta* **1**, 747–751.
Ramos, V. A., Kay, S. M. and Singer, B. S. (2004) Las adakitas de la Cordillera Patagónica: Nuevas evidencias geoquímicas y geocronológicas. *Rev. Assoc. Geol. Argentina* **59**, 693–706.
Rino, S., Komiya, T., Windley, B. F., Katayama, I., Motoki, A. and Hirata, T. (2004) Major episodic increases of continental crustal growth determined from zircon ages of river sands; implications for mantle overturns in the Early Precambrian. *Phys. Earth Planet. Inter*. **146**(1–2), 369–394.
Rolando, A. P., Hartmann, L. A., Santos, J. O. S., Fernandez, R. R., Etcheverry, R. O., Schalamuk, L. A. and McNaughton, N. J. (2002) SHRIMP zircon U–Pb evidence for extended Mesozoic magmatism in the Patagonian Batholith and assimilation of Archean crustal components. *J. S. Am. Earth Sci*. **15**, 267–283.
Rubatto, D. and Hermann, J. (2003) Zircon formation during fluid circulation in eclogites (Monviso, Western Alps): Implications for Zr and Hf budget in subduction zones. *Geochim. Cosmochim. Acta* **67**, 2173–2187.
Shinjoe, H., Orihashi, Y., Naranjo, J. A., Hirata, D., Hasenaka, T., Fukuoka, T., Sano, T. and Anma, R. (2013) Boron and other trace element constraints on the slab-derived component in Quaternary volcanic rocks from the Southern Volcanic Zone of the Andes. *Geochem. J*. **47**, this issue, 185–199.
Stern, C. R. (2004) Acitive Andean volcanism: its geologic and tectonic setting. *Rev. Geol. Chile* **31**, 161–206.
Stern, C. R. and Killian, R. (1996) Role of the subducted slab, mantle wedge and continental crust in the generation of adakite from the Andean Austral Volcanic Zone. *Contrib. Mineral. Petrol*. **123**, 263–281.
Stern, C. R., Frey, F. A., Futa, K., Zartman, R. E., Peng, Z. and Kyser, T. K. (1990) Trace element and Sr, Nd, Pb and O isotopic composition of Pliocene to Quaternary alkali basalts of the Patagonian Plateau Lavas of southernmost South America. *Contrib. Mineral. Petrol*. **104**, 294–308.
Suárez, M., De La Cruz, R., Aguirre-Urreta, B. and Fanning, M. (2009) Relationship between volcanism and marine dedimentation in northern Austral (Aisén) Basin, central Patagonia: Stratigraphic, U–Pb SHRIMP and paleontologic evidence. *J. S. Am. Earth Sci*. **27**, 309–325.
Thomson, S. N. (2002) Late Cenozoic geomorphic and tectonic evolution of the Patagonian Andes between latitudes 42 degrees S and 46 degrees S: An appraisal based on fission-track results from the transpressional intra-arc Liquine–Ofqui fault zone. *Geol. Soc. Am. Bull*. **114**, 1159–1173.
Tunik, M., Folguera, A., Naipauer, M., Pimentel, M. M. and Ramos, V. A. (2010) Early uplift and orogenic deformation in the Neuquén basin: constraints on the Andean uplift from U–Pb and Hf isotopic data of detrital zircons. *Tectonophysics* **489**, 258–273.
Whitehouse, M. J., Kamber, B. S. and Moorbath, S. (1999) Age significance of U–Th–Pb zircon data from early Archean rocks of west Greenland—a reassessment based on combined ion-microprobe and imaging studies. *Chem. Geol*. **160**, 201–224.

SUPPLEMENTARY MATERIALS

URL (http://www.terrapub.co.jp/journals/GJ/archives/data/47/MS242.pdf)
Tables S1 to S4