

New time constraints for the age of metamorphism at the ancestral Pacific Gondwana margin of southern Chile (42-52°S)

Stuart N. Thomson

Institut für Geologie, Mineralogie und Geophysik, Ruhr-Universität Bochum,
D-44780 Bochum, Germany
stuart.thomson@ruhr-uni-bochum.de

Francisco Hervé

Departamento de Geología, Universidad de Chile,
Casilla 13518 Correo 21, Santiago, Chile
fherve@cec.uchile.cl

ABSTRACT

Fission-track (FT) analysis was performed on ten samples of detrital zircons from several pre-Late Jurassic metamorphic accretionary complexes at the ancestral Pacific margin of Gondwana in southern Chile (42-52°S) previously dated by U-Pb SHRIMP. Post-metamorphic zircon FT cooling ages combined with published U-Pb provenance ages allow the estimation of the following maximum and minimum ages of deposition and metamorphism: the Eastern Andes metamorphic complex (EAMC), 364 to 250 Ma (Late Devonian to Permian/Triassic boundary); the Duque de York flysch of the Madre de Dios accretionary complex (MDAC), 234 to 195 Ma (Middle Triassic to Early Jurassic); and the Chonos/Chiloé metamorphic complex (CMC), 213 to 198 Ma (Late Triassic to Early Jurassic). The implications of these results are (1) they verify that deposition, accretion and metamorphism of most of the EAMC took place well before continentally derived flysch in the complexes west of the Patagonian batholith (MDAC and CMC) was deposited, accreted, and metamorphosed, supporting either a punctuated evolution of accretion along the ancestral Pacific Gondwana margin or the existence two distinct basement terranes and (2) that the continentally derived flysch of the CMC and MDAC share an equivalent depositional and metamorphic history indicative of widespread accretion in Late Triassic to Early Jurassic times. Mixed post-metamorphic zircon FT single grain ages and an apatite FT age from the island of Chiloé (43°S) reveal a previously unknown Late Cretaceous (109-60 Ma) phase of reheating in these rocks, most likely linked to plutonic activity of this age described in other parts of the CMC.

Key words: Fission-track dating, U-Pb SHRIMP ages, Metamorphic Complexes, Gondwana Margin, Southern Chile.

RESUMEN

Nuevas limitaciones temporales a la edad del metamorfismo, en el margen ancestral pacífico de Gondwana, sur de Chile (42-52°S). La datación por trazas de fisión (FT) fue realizada en circones detríticos previamente datados por U-Pb SHRIMP, pertenecientes a distintos complejos metamórficos del sur de Chile (42-52°S), de edad pre-Jurásico Inferior, ubicados en el margen pacífico ancestral de Gondwana. La combinación de edades de proveniencia U-Pb en circones, ya publicados, con sus historias de enfriamiento posmetamórfico permitieron establecer las siguientes edades máximas y mínimas de deposición y metamorfismo: para el complejo metamórfico andino oriental (EAMC) 364 a 250 Ma (Devónico Superior-Permiano/Triásico), para el flysch Duque de York perteneciente al complejo acrecionario Madre de Dios (MDAC) 234 a 195 Ma (Triásico Medio-Jurásico Inferior), y para el complejo metamórfico de Chonos/Chiloé (CMC) 213 a 198 Ma (Triásico Superior-Jurásico Inferior). Estos resultados implican: (1) que la deposición, acreción y metamorfismo de la mayor parte del EAMC tuvo lugar con anterioridad al flysch de derivación

continental en los complejos ubicados al oeste del Batolito Norpatagónico (MDAC y CMC), apoyando anteriores proposiciones sobre la existencia de dos terrenos de basamento de diferente edad; (2) que los depósitos de flysch de derivación continental en los CMC y MDAC comparten una historia equivalente de deposición y metamorfismo, indicativa de una amplia acreción a lo largo de esta parte del margen pacífico de Gondwana ocurrida entre el Triásico Superior y el Jurásico Inferior. Edades FT mixtas posmetamórficas en granos individuales de circón y una edad FT en apatita provenientes de la isla de Chiloé (43° S) revelan una fase cretácica de recalentamiento en estas rocas (entre 103 y 60 Ma), no documentada previamente, y de probable relación con actividad plutónica de esta edad en otras partes del CMC.

Palabras claves: Datación por Trazas de Fisión, Edades U-Pb SHRIMP, Complejos Metamórficos, Margen de Gondwana, Sur de Chile.

INTRODUCTION

In the southern Chilean Andes between ca. 40 and 52°S (Fig. 1) there are several discrete pre-Late Jurassic metamorphic accretionary complexes that were formerly part of the ancestral Pacific margin of Gondwana (Aguirre *et al.*, 1972; Forsythe, 1982; Davidson *et al.*, 1987). Their apparently common protolith and similar style of metamorphism and deformation has often led to them to being described simply as 'Palaeozoic basement' (*e.g.*, Servicio Nacional de Geología y Minería, 1982). However, several studies have questioned this general equivalence. For example, the geochemistry of pillow basalts from different complexes indicates eruption in contrasting tectonic environments (Hervé *et al.*, 1999a), while detailed studies of metamorphism and structural style (Bell and Suárez, 2000) reveal significant internal variation within the basement complexes. This has led to the proposal that the basement rocks of southern Chile comprise an accumulation of several microplates or suspect terranes with different metamorphic and structural histories (Hervé *et al.*, 1998; Hervé, 2000; Bell and Suárez, 2000). Unfortunately, later separation and disruption of the basement rocks by the Mesozoic to Cenozoic Patagonian batholith (Pankhurst *et al.*, 1999) has meant that this hypothesis is difficult to substantiate.

One way to approach this problem is to examine the detailed internal stratigraphy and geochronology of each of the complexes. Their domination by flysch lithologies with generally poor index fossil preservation means that few stratigraphic studies have been carried out (*e.g.*, Douglass and Nestell, 1976; Miller, 1979; Ramos, 1989; Fang *et al.*, 1998). A number of published geochronological results exist, including several Rb-Sr whole rock errorochrons and post-metamorphic K-Ar and Ar-Ar cooling ages

(Halpern, 1973; Forsythe, 1982; Davidson *et al.*, 1987; Hervé *et al.*, 1998; Duhart *et al.*, 2001). More recently, U-Pb detrital zircon dating using a Sensitive High-mass Resolution Ion Microprobe (SHRIMP) has been carried out on a number of samples from each of the metamorphic complexes (Hervé *et al.*, 1999c; Hervé and Fanning, 2001; Hervé *et al.*, in press). Such ages are retained even when subject to post-depositional high metamorphic temperatures (>900°C according to Lee *et al.*, 1997) meaning that they almost exclusively reflect the age of generation of the zircon in the sedimentary source of the rocks being analysed, either during volcanism, plutonism or zircon growth during metamorphism. They thus provide important information on the provenance of the sedimentary rocks being analysed, even if the zircons have been through several erosional and depositional cycles, but can only provide a maximum age of deposition, constrained by the youngest detrital zircon age or age component and say nothing about the age of post-depositional metamorphism. Also, if during deposition of the sediments the source area contained no young zircons (*e.g.* from volcanism), then the maximum apparent stratigraphic age constrained by U-Pb SHRIMP ages from individual zircons may be considerably older than the true stratigraphic age.

To obtain information on the timing of metamorphism and the minimum age of deposition and possibly additional information on sediment provenance, the authors have taken several detrital zircon sample fractions previously dated using U-Pb SHRIMP by Hervé and Fanning (2001) and Hervé *et al.* (in press), and further analysed them using the more temperature sensitive fission track (FT) dating method. Information from deep boreholes, metamorphic contact aureoles, and experimental studies

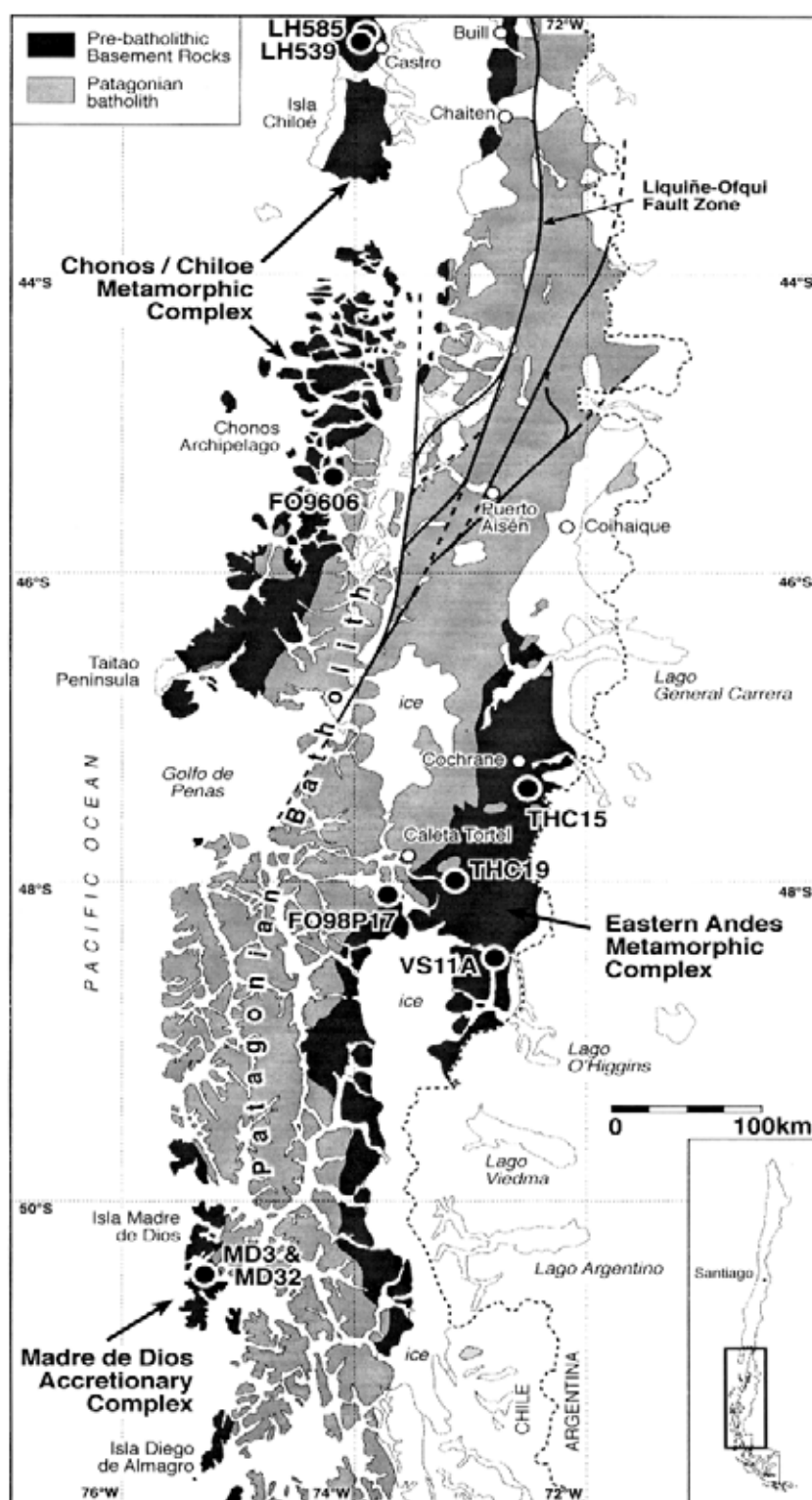


FIG. 1. Geological map of southern Chile between 42 and 52°S showing sample locations and approximate outcrop of the three basement complexes investigated in this study, and the nature of their separation by later intrusion of the extensive Mesozoic-Cenozoic Patagonian batholith.

(Tagami *et al.*, 1998 and references therein) demonstrate that over geological time ($>10^6$ years) partial resetting of zircon FT ages can be recognised at temperatures above ca. $240\pm 20^\circ\text{C}$, with total resetting occurring above ca. $310\pm 20^\circ\text{C}$. Therefore, where rocks have been subject to peak metamorphic temperatures above $310\pm 20^\circ\text{C}$, then the zircon FT age represents a post-metamorphic cooling age and thus provides a minimum age of both metamorphism and hence deposition prior to metamorphism (*i.e.*, the stratigraphic age). Consequently, if the maximum age of deposition is already constrained by the youngest detrital zircon U-Pb SHRIMP age component (where care has been taken not to have dated any possible zircon overgrowths grown during metamorphism), then the two techniques applied in tandem may provide key new stratigraphic age constraints, particularly in

poorly fossiliferous rock formations such as continentally derived flysch deposits. Alternatively, where rocks have not been subject to post-depositional temperatures above ca. $240\pm 20^\circ\text{C}$, then zircon FT detrital zircon ages can provide important new and complementary information on sediment provenance and the cooling history of the source region not achievable using just U-Pb SHRIMP data alone (*e.g.*, Carter and Moss, 1999; Carter and Bristow, 2000).

This study presents new FT data obtained from detrital zircon fractions of samples from three metamorphic basement complexes in southern Chile: the Chonos/Chiloé metamorphic complex (CMC), the Madre de Dios accretionary complex (MDAC), and the Eastern Andes metamorphic complex (EAMC). These are labelled in figure 1.

PRESENT KNOWLEDGE OF THE CHILEAN BASEMENT COMPLEXES BETWEEN 42 AND 52°S

EASTERN ANDES METAMORPHIC COMPLEX (EAMC)

The EAMC (Hervé, 1995) outcrops entirely to the east of the Patagonian batholith (Fig. 1). It can be divided into two distinct units. The main southern part is referred to, as either the Cochrane Formation (Miller, 1976) or the Bahía de la Lancha Formation (Riccardi, 1971). It is characterised by a thick sequence of clastic turbidites and isolated recrystallised limestones with large scale folding and low grade metamorphism. Peak P-T conditions of $380\pm 30^\circ\text{C}$ and 4.6 ± 1.3 kbar have been estimated from metaturbidites from the northern part of the Cochrane Formation (Ramírez, 1997; Sepúlveda, 2000). Similar values of 360°C and 2-4 kbar (Hervé *et al.*, 1999a) were obtained from metabasites further south near Lago O'Higgins (Fig. 1). The more restricted second unit of the EAMC, named either the Lago General Carrera Formation (Miller, 1976) or the Río Lácteo Formation (Leanza, 1972; Bell and Suárez, 2000), crops out around Lago General Carrera. It comprises a succession of quartzites, mica schists and phyllites, with some intercalations of marble and amygdaloidal basalts. This unit shows intense polyphase deformation and medium grade metamorphism that gradually becomes less intense

to the south. Although no P-T determinations have yet been published from these rocks, Bell and Suárez (2000) estimated greenschist to epidote-amphibolite facies peak metamorphic conditions.

Fossil plant remains and tetrapod tracks indicate deposition of the EAMC during Late Devonian to Early Carboniferous times (Ramos, 1989). The minimum age of this complex is constrained by unconformably overlying Late Jurassic acidic volcanic rocks of the Ibáñez and Tobifera formations. These vary in age between 153 and 172 Ma where they directly overlie the EAMC (Pankhurst *et al.*, 2000). Radiometric data from the EAMC are few. Bell and Suárez (2000) reported a muscovite K-Ar age of 307 ± 10 Ma from a granitoid emplaced in greenschists on the south shore of Lago General Carrera. Ramos (1989) referred to an unpublished Late Carboniferous-Early Permian K-Ar amphibole age of 283 ± 10 Ma from a tonalite emplaced in the Lago General Carrera Formation. A Rb-Sr whole rock errorchron of 333 ± 33 Ma with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7104 ± 0.0024 and $\text{MSWD} = 38$ (R.J. Pankhurst, oral communication, 2001) has also been obtained from the EAMC metasedimentary rocks close to Cochrane (Fig. 1). This age most probably represents a minimum age of deposition and could be related to the initial stages of

metamorphism. Comparisons of the geochemistry and metamorphism of pillow basalts from both the EAMC and CMC have been made by Hervé *et al.* (1999a). Their different geochemical characteristics, enriched MORB from the CMC and continental alkaline from the EAMC, and the contrasting metamorphic evolution of both basalts supports the idea that the coastal CMC and inland EAMC evolved independently of one another prior to being unconformably overlain by Late Jurassic acidic volcanic rocks.

MADRE DE DIOS ACCRETIONARY COMPLEX (MDAC)

South of ca. 50°S, rocks of a fore-arc accretionary complex form an isolated, but semi-continuous basement terrane on a number of remote islands along the Pacific margin of southern Chile (Fig. 1). The younger age limit of this complex is constrained by cross-cutting Early Cretaceous granitoid intrusions of the South Patagonian batholith (Halpern, 1973). Three main stratigraphic assemblages are recognised (Mpodozis and Forsythe, 1983): the Tarlton limestone, a sequence of Late Carboniferous to Early Permian limestones (Douglass and Nestell, 1976); the Denaro complex, a number of discontinuous bodies of oceanic affinity comprising enriched MORB affinity pillow basalts grading up into bedded cherts and silicified calcarenites; and the Duque de York complex, a widespread and very thick sequence of continentally derived flysch that unconformably overlies both other units. Subsequent accretion of all these units at the ancestral Pacific continental margin of Gondwana has resulted in complex tectonic interweaving, with large scale intensive folding particularly evident in the Duque de York complex. Little is known about the grade and timing of metamorphism of the MDAC, although abundant pumpellyite in many of the rocks implies that the maximum P-T conditions reached during accretion were largely sub-greenschist facies.

On Isla Diego de Almagro (Fig. 1) an isolated outcrop of highly deformed blueschist and greenschist facies rocks were discovered by Forsythe *et al.* (1981), separated from rocks of the MDAC proper by a major shear zone. They have a similar oceanic protolith to the MDAC, including some local marble blocks. Geochronological results from these rocks have been summarised elsewhere by Hervé *et al.* (1999b). U-Pb detrital zircon ages as young as 157 ± 2 constrain the maximum age of deposition to

the Late Jurassic. K-Ar glaucophane ages of 122 ± 21 and 117 ± 11 Ma imply post-metamorphic cooling in mid-Cretaceous times. An age of 89 ± 8 Ma from a recrystallised white mica aggregate within the major shear zone led Hervé *et al.* (1999b) to speculate that the final significant exhumation of the Isla Diego de Almagro HP-LT rocks occurred at this time.

CHONOS/CHILOE METAMORPHIC COMPLEX (CMC)

The existence of metamorphic rocks in the Chonos Archipelago of southern Chile was first recognised by Darwin (1846) during the voyage of the *Beagle*. More recent studies (Stiefel, 1970; Miller, 1979; Hervé *et al.*, 1981; Davidson *et al.*, 1987; Hervé *et al.*, 1994; Willner *et al.*, 2000) have since demonstrated that these rocks form part of a Palaeozoic-Mesozoic subduction accretionary complex that can be broadly subdivided into an eastern and a western belt each with contrasting structural and metamorphic histories.

The eastern belt consists predominantly of submarine fan turbidites with local pelagic cherts and rare metabasites metamorphosed to pumpellyite-actinolite facies (Hervé *et al.*, 1994). Willner *et al.* (2000) have estimated maximum P-T conditions of around 5.5 kbar and 250–280°C. This is in agreement with chlorite geothermometry mean maximum temperature estimates of ca. 300°C (Hervé *et al.*, 1999a) and anchizone-epizone boundary illite crystallinity values (Hormazábal, 1991). The eastern belt is characterised by a low degree of deformation and the preservation of primary igneous and sedimentary structures (Davidson *et al.*, 1987). Locally Late Triassic (Norian) fossil bivalves have been described (Fang *et al.*, 1998). These fossils were previously misidentified as early Devonian brachiopods by Miller and Sprechmann (1978).

The western belt consists primarily of strongly foliated mica schists and greenschists, with local metacherts. A pronounced metamorphic fabric and pervasive deformation has destroyed most primary sedimentary features (Aguirre *et al.*, 1972; Davidson *et al.*, 1987). The presence of very rare glaucophane schists (Davidson *et al.*, 1987) is indicative of local HP-LT metamorphism. However, most rocks of this belt are characterised by greenschist and albite-epidote-amphibolite facies metamorphism with maximum P-T conditions varying around 8–10 kbar and 380–500°C (Willner *et al.*, 2000).

Published geochronological results from the CMC are sparse. Davidson *et al.* (1987) reported some poorly defined Rb-Sr whole rock errorchrons from rocks of the western belt. Two ages (262 ± 15 Ma and 263 ± 53 Ma) were suggested to represent the minimum age for the onset of accretionary growth and metamorphism, while three younger errorchron ages (125–140 Ma) imply thermal resetting during emplacement of granitoids of the Patagonian batholith. The oldest granitoid cross-cutting the rocks of the eastern belt of the CMC gives an Early Cretaceous Rb-Sr whole rock isochron age of 140 ± 6 Ma (Pankhurst *et al.*, 1999). In the western belt, post-metamorphic granitoids are rare; the only dated body yields a Late Cretaceous U-Pb SHRIMP age of 76 ± 1 Ma (Pankhurst *et al.*, 1999). Low pressure mineral assemblages within contact aureoles of the batholith means that post-metamorphic exhumation of the rocks of the CMC was nearly complete by the time of early Cretaceous plutonic intrusion (Willner *et al.*, 2000). A significant population of Late Triassic U-Pb SHRIMP ages from detrital volcanic zircons in several metasandstone samples of the CMC (Hervé and Fanning, 2001) are consistent with Late Triassic fossils described from the same rocks (Fang *et al.*, 1998), but provide no further information on the timing of metamorphism of these rocks.

Metamorphic basement rocks on the Island of Chiloé (Fig. 1) are less well studied than those of the Chonos Archipelago because of the frustrating lack of outcrop, except along the remote Pacific facing

coast. Nevertheless, studies by Saliot (1969) and Aguirre *et al.* (1972) and more recently by Massonne *et al.* (1999) reveal that the petrology, HP-LT metamorphism and deformation is similar to the western belt rocks of the Chonos Archipelago. Conventional U-Pb detrital zircon ages from metapelites at the northwestern extremity of Chiloé (Duhart *et al.*, 2001) indicate a maximum age of deposition of 388 Ma, while the time of post-metamorphic cooling to below ca. 350°C is indicated by K-Ar and Ar-Ar muscovite ages of 220 ± 6 Ma and 233 ± 3 Ma respectively.

North of Chiloé basement rocks of the Bahía Mansa metamorphic Complex (BMMC-Duhart *et al.*, 2001) form the northward extension of the CMC. Here two poorly defined Rb-Sr whole rock errorchrons of 309 ± 88 Ma and 280 ± 46 Ma from micaschists (Munizaga *et al.*, 1988) possibly relate to resetting during metamorphism. The same authors reported a post-metamorphic K-Ar muscovite cooling age of 231 ± 4 Ma and K-Ar biotite ages of 103 ± 2 Ma and 86 ± 3 Ma from two small granitoid stocks that intrude the BMMC. Triassic post-metamorphic K-Ar and Ar-Ar muscovite ages of between 260 and 220 Ma were obtained by Duhart *et al.* (2001) from the BMMC, with the Ar-Ar age indicating evidence of partial, but important post-metamorphic resetting. The youngest conventional U-Pb detrital zircon age obtained by the same authors constrains the maximum age of deposition of the sedimentary rocks of the BMMC as 275 Ma.

ANALYTICAL METHODS AND RESULTS

Mounting, polishing and etching of zircon and apatite heavy mineral fractions for fission track analysis was carried out using the methods outlined in Hurford *et al.* (1991). Multiple etching of different detrital zircon fractions from the same sample, often required owing to the different etching characteristics of multiple component zircons with varied chemistry, radiation damage, and age (Garver *et al.*, 1999), was not necessary for the samples investigated in this study, as most contain only a single zircon grain age component or a sufficient spread in grain ages using only one mount. The samples were analysed using the external detector method and irradiated with Corning dosimeter glasses (CN2 for zircon and

CN5 for apatite) at the Riso National Laboratory at Roskilde, Denmark and at the Oregon State University Triga Reactor, Corvallis, USA. Central ages (Galbraith and Laslett, 1993) quoted with 1σ errors were calculated using the IUGS approved zeta-calibration approach of Hurford and Green (1983). Zeta calibration factors of 130.7 ± 2.8 for CN2 (zircon) and 358.8 ± 12.7 for CN5 (apatite) were obtained by repeated calibration against a number of internationally agreed age standards according to the recommendations of Hurford (1990). Ten zircon FT ages including one repeat analysis (sample VS11A) from the metamorphic basement rocks of southern Chile are presented in table 1 according to

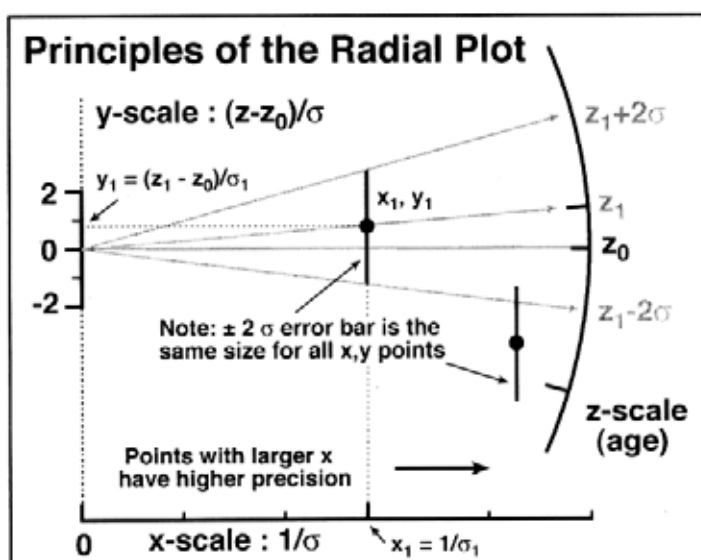


FIG. 2. Principles and features of the radial plot (after Galbraith, 1988; 1990). This diagram is referred to in the Analytical Methods and Results section of the text.

IUGS recommendations (Hurford, 1990). Two ages (THC15 and THC19) were previously published in Thomson *et al.* (2001). One unpublished apatite FT age with length analysis from the basement of Chiloé (LH539) is also included. The FT individual grain age data are graphically presented using the radial plot representation proposed by Galbraith (1988; 1990). The radial plot isolates individual grain age precision from the variation between individual grain ages, making it easier to interpret the data correctly. The basic principles behind the

radial plot are illustrated in figure 2 (after Galbraith, 1990). Each point or age has a unit standard error that can be read off the y-scale, and a precision (increasing to the right) represented on the x-scale. The formula used to plot the (x, y) data points (see Fig. 4c) allows the age of each point to be represented on a circular z-scale, whereby the age is simply read by extrapolating a line from (0,0) or 0 on the y-scale through (x, y) and on to the circular z-scale. The plot is usually drawn so that the central fission track age of the sample (z_0) plots as horizontal line.

FISSION TRACK RESULTS AND COMPARISON TO U-Pb SHRIMP DATA

THE EASTERN ANDES METAMORPHIC COMPLEX (EAMC)

The zircon FT individual grain age data from four samples of the EAMC are shown in figure 3. The individual zircon FT grain age data of sample VS11A (Fig. 3, a), a low grade psammite from the Cochrane Formation, are from a sample close to where Ramírez (1997) and Sepúlveda (2000) estimated peak metamorphic P-T conditions of $380 \pm 30^\circ\text{C}$ and 4.6 ± 1.3 kbar and very low epizone illite crystallinity values of 0.14°D20. Such conditions are well above the

temperatures required for total annealing of fission tracks in zircon ($>310 \pm 20^\circ\text{C}$; Tagami *et al.*, 1998). This and the high chi-squared values and low age dispersions (Table 1) indicative of a single age component, are clear evidence that the zircon FT central age of sample VS11A (267 ± 17 Ma) represents a post-metamorphic cooling age. This constrains the minimum age of metamorphism and hence the minimum stratigraphic age of this sample to 250 Ma. Similar single component zircon FT central ages were obtained from other parts of the Cochrane Formation of the EAMC. Samples THC15

TABLE 1. FISSION-TRACK DATA FROM THE METAMORPHIC BASEMENT COMPLEXES OF THE GONDWANA MARGIN OF SOUTHERN CHILE (BETWEEN 42 AND 51°S).

Sample No.	Location	Mineral	No. of crystals	P_s (N)	Track density ($\times 10^6 \text{ tr cm}^{-2}$)	P_t (N)	P_a (N)	Age dispersion (P_{χ^2})	Central age Ma ($\pm 1\sigma$)	Apatite mean track length ($\mu\text{m} \pm 1\sigma$ error)	Standard deviation (μm)
THC15	Valle Chacabuco 47°29'S-72°23'W	Zircon	20	15.58 (4152)	1.516 (404)	0.3836 (2648)	0.7% (75%)	252.6 $\pm$ 15.1**	-	-	-
THC 19	Rio Bravo 47°59'S-73°11'W	Zircon	20	18.01 (5968)	1.675 (555)	0.3837 (2650)	0% (98%)	264.2 $\pm$ 14.0**	-	-	-
VS11A	Villa O'Higgins 48°25'S-72°45'W	Zircon	20	17.38 (3888)	1.444 (323)	0.3460 (4756)	0% (>99%)	266.6 $\pm$ 16.9	-	-	-
VS11A (b)	Villa O'Higgins 48°25'S-72°45'W	Zircon	10	19.72 (3778)	1.766 (249)	0.3781 (5221)	0% (99%)	269.9 $\pm$ 19.1	-	-	-
FO98P17	Canal Baker 48°10'S-73°35'W	Zircon	20	9.506 (4096)	1.490 (542)	0.3462 (4763)	0% (99%)	142.8 $\pm$ 7.1	-	-	-
MD3	Isla Madre de Dios 50°30'S-75°16'W	Zircon	20	12.08 (2769)	1.287 (295)	0.3461 (4761)	0% (99%)	208.8 $\pm$ 13.9	-	-	-
MD32	Isla Madre de Dios 50°30'S-75°16'W	Zircon	20	19.43 (4159)	2.055 (442)	0.3461 (4758)	0% (97%)	209.4 $\pm$ 11.8	-	-	-
FO6606	Isla Pofranca 45°25'S-74°09'W	Zircon	20	10.82 (4406)	1.146 (467)	0.3463 (4765)	0% (97%)	210.1 $\pm$ 11.6	-	-	-
LH585	Chiloé 42°23'S-73°55'W	Zircon	30	16.68 (9330)	2.596 (1452)	0.3804 (5253)	11% (2%)*	155.4 $\pm$ 6.9	-	-	-
LH539	Chiloé 42°19'S-73°50'W	Zircon	30	17.03 (11052)	2.912 (1890)	0.3792 (5237)	17% (0%)*	142.3 $\pm$ 6.8	-	-	-
		Apatite	8	1.017 (118)	3.758 (436)	1.400 (9566)	0% (76%)	67.6 $\pm$ 7.5	13.82 $\pm$ 0.17 (77)	-	1.46

Notes: (i)=, analyses by external detector method using 0.5 for the $2\pi/4\pi$ geometry correction factor; (ii)= ages calculated using dosimeter glasses; CN2 (zircon) with $\zeta_{\text{CN2}} = 130.7 \pm 2.8$; CN5 (apatite) with $\zeta_{\text{CN5}} = 358.8 \pm 12.7$; (iii)= P_{χ^2} is the probability of obtaining a χ^2 value for v degrees of freedom where $v = \text{no. of crystals} - 1$. * Represents a mixed fission-track age (see Galbraith and Laslett, 1993); ** Previously published age (Thomson *et al.*, 2001).

and THC19 (Fig. 3, c and d) give ages of 253 ± 15 Ma and 264 ± 14 Ma respectively (Thomson *et al.*, 2001).

The zircon FT age of sample FO98P17 (143 ± 7 Ma; Fig. 3, b) has clearly been reset by a nearby 149 ± 1 Ma (U-Pb zircon age; Bruce *et al.*, 1991) granitoid of the Patagonian batholith. Thus no constraint on the minimum age of non-contact metamorphism and deposition of this sample can be made other than it was sometime before 148 Ma (latest Jurassic).

U-Pb SHRIMP detrital zircon grain ages younger than 600 Ma from sample VS11A (Hervé *et al.*, in

press) are illustrated graphically in figure 3, e and f as simple frequency histograms binned into age groups of 10 Ma overlain by composite probability distribution plots that sum the Gaussian distributions of each detrital grain age and its error (Brandon, 1992; Sircombe, 1999). The youngest U-Pb SHRIMP detrital zircon age obtained from sample VS11A is 354 ± 10 Ma (quoted with 1σ error) and is represented on the radial plots of samples VS11A, THC15, THC19 in figure 3. This limits the maximum stratigraphic age of the part of the EAMC from where this sample was collected to 364 Ma. The stratigraphic age and

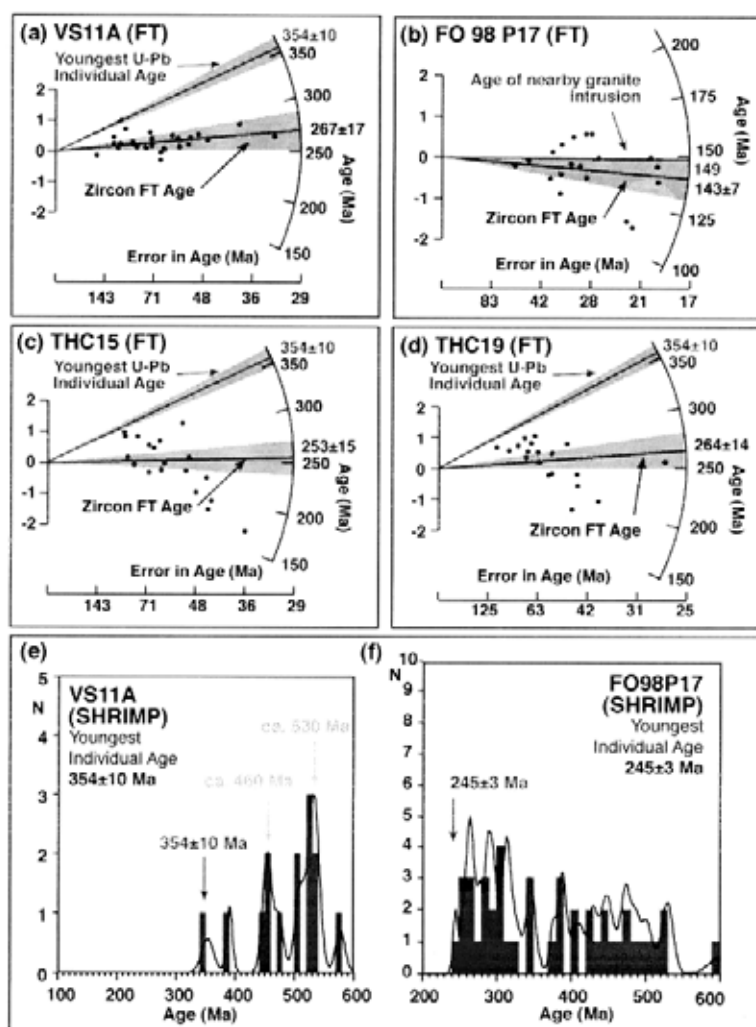


FIG. 3. Age data from the Eastern Andes metamorphic complex. (a to d) Radial plot representation of the zircon single grain fission-track age data from four samples of the EAMC. The low dispersion of the single grain ages around the calculated central age is indicative of a single grain age component. The grey region around the extrapolated youngest U-Pb individual and zircon FT age lines represent the 1σ age error. The youngest U-Pb individual age refers to that from sample VS11A. (e) Graphical representations of the U-Pb SHRIMP single grain ages <600 Ma from sample VS11A, as a simple binned age frequency histogram overlain by a composite probability distribution (f) U-Pb SHRIMP single grain age data <600 Ma from sample FO98P17.

timing of metamorphism of the Cochrane Formation of the EAMC close to Villa O'Higgins is thus bracketed by the U-Pb SHRIMP and FT zircon ages to between 364 Ma and 250 Ma (Late Devonian to the Permian/Triassic boundary according to the IUGS International Stratigraphic Chart, 2002). If 2σ errors are considered for both the FT and U-Pb SHRIMP ages, then the time interval when these rocks could have been deposited increases slightly to between 374 Ma and 233 Ma. This is consistent the Late Devonian to Early Carboniferous fossils described by Ramos (1989) and with the few radiometric data from the EAMC, including a 307 ± 10 Ma K-Ar age from a granitoid (Bell and Suárez, 2000) and a 283 ± 10 Ma K-Ar amphibole age from a post metamorphic tonalite reported by Ramos (1989).

THE MADRE DE DIOS ACCRETIONARY COMPLEX, (MDAC)

Matching Late Triassic single component zircon FT central ages are obtained from two metasandstone samples of the Duque de York Complex of the MDAC (Fig. 4, a and b): MD3 (209 ± 14 Ma) and MD 32 (209 ± 12 Ma). Unfortunately no independent peak metamorphic temperature constraints have been obtained from these rocks. The presence of pumpellyite only constrains peak conditions to somewhere between 160 and 320°C and 2 to 8 kbar (Frey *et al.*, 1991). However, the authigenic nature of the metamorphic minerals, the very low single grain age dispersion in each sample, and the lack of evidence for a source of older detrital zircons favour inter-

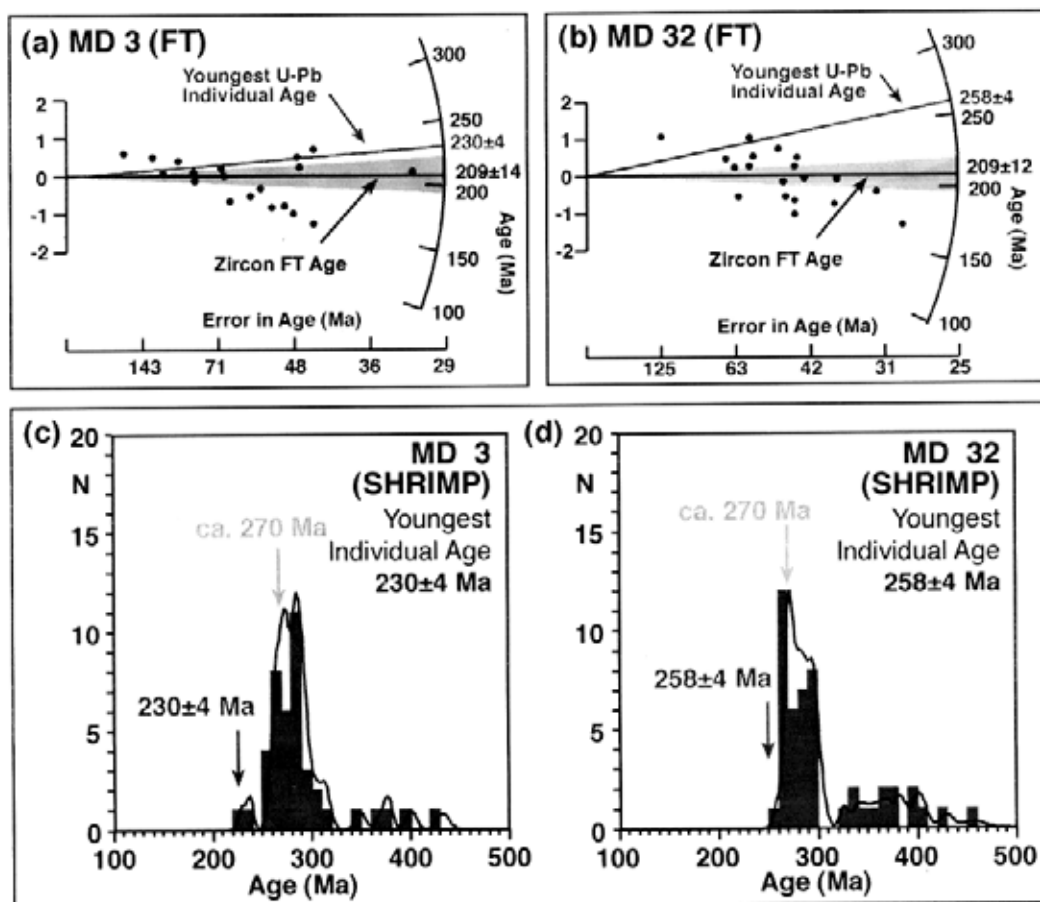


FIG. 4. Age data from metamorphosed sandstones of the Duque de York complex of the Madre de Dios accretionary complex. (a and b) Radial plots of the zircon FT single grain ages. (c and d) Graphical representation of the U-Pb SHRIMP single grain age data <500 Ma. The major peaks of U-Pb detrital zircon ages in both samples at ca. 270 Ma (mid Permian) are also indicated.

pretation of the zircon FT central ages as post-metamorphic and hence post-depositional cooling ages. If this assumption is correct, then the minimum age of deposition and metamorphism of these rocks is 195 Ma.

Detrital zircon U-Pb SHRIMP ages <500 Ma from samples MD3 and MD32 (Hervé *et al.*, in press) are shown in the histogram and composite probability distribution plots in figure 4, c and d. The youngest individual detrital U-Pb zircon age is 230 ± 4 Ma in sample MD3. This limits the maximum stratigraphic age of this sample to 234 Ma (Middle Triassic). The U-Pb SHRIMP data from sample MD32 imply a slightly older maximum age of deposition of 262 Ma (mid to late Permian). The timing of metamorphism and stratigraphic age of the Duque de York Complex rocks of this part of the MDAC is thus constrained to within ca. 40 Ma between 234 Ma and 195 Ma (Middle Triassic to Early Jurassic).

THE CHONOS/CHILOE METAMORPHIC COMPLEX (CMC)

From the eastern belt of the CMC sample FO9606, a low grade flysch sandstone from Isla Potranca in the Chonos Archipelago containing Late Triassic fossils (Fang *et al.*, 1998), yields zircon FT single grain ages which define a single component age of 210 ± 12 Ma (Fig. 5, a). Maximum temperatures during peak metamorphism of the eastern belt of the CMC (250–300°C, Hervé *et al.*, 1999a; Willner *et al.*, 2000) are close to the temperatures of total resetting of fission tracks in zircon ($310 \pm 20^\circ\text{C}$, Tagami *et al.*, 1998). As no evidence for partially reset detrital zircon FT ages were found in this sample, the zircon FT central age obtained is taken to represent a post-metamorphic cooling age, constraining the timing of metamorphism and deposition for this part of the eastern belt of the CMC to sometime before 198 Ma. U-Pb SHRIMP detrital zircons with ages <500 Ma from the same sample (Hervé and Fanning, 2001) are represented graphically in figure 5, b. The youngest single grain age obtained is 207 ± 6 Ma, indicative of a maximum stratigraphic age of 213 Ma. The combination of both dating methods thus allows the stratigraphic age and timing of metamorphism of this part of the CMC to be extremely well constrained between 213 and 198 Ma (latest Triassic to earliest Jurassic) or between 219 Ma and 186 Ma when 2σ errors are considered. This

agrees well with the Late Triassic stratigraphic age determined from fossil bivalves at the same locality by Fang *et al.* (1998) and the supports a Late Triassic volcanic source for the significant population of zircons of this age dated by U-Pb SHRIMP from the same sample by Hervé and Fanning (2001).

Two zircons and one apatite FT age (Table 1) were also determined from two quartz-phylite samples of the western belt metamorphic basement rocks of the CMC on the Island of Chiloé, ca. 20 NW of the town of Castro (Fig. 1). The zircon FT ages are remarkable as they represent a mixed population of single grain ages. This is in contrast to the single

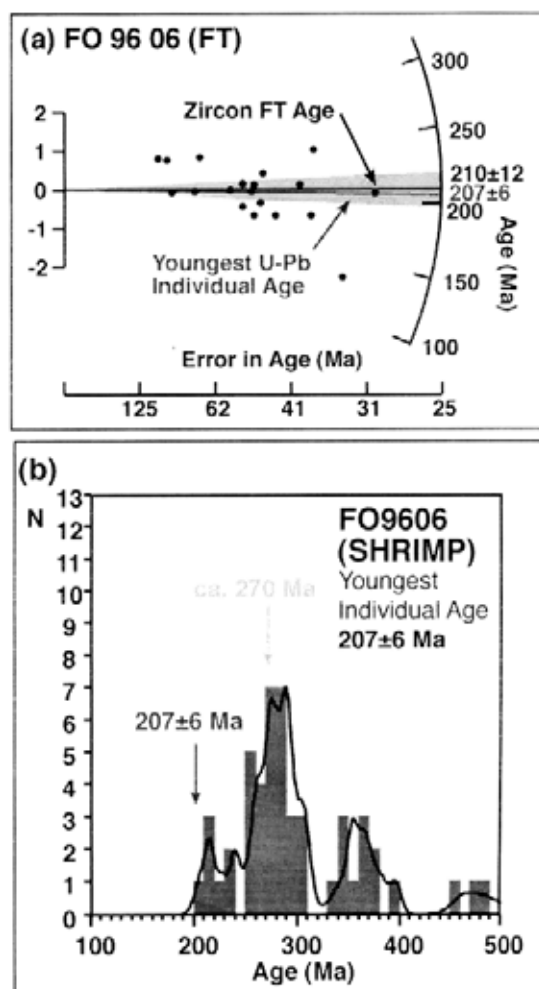


FIG. 5. Age data from a metamorphosed sandstone of the eastern belt of the Chonos metamorphic complex. (a) Radial plot of the zircon FT single grain ages. (b) Graphical representation of the U-Pb SHRIMP single grain age data <500 Ma.

component zircon FT ages obtained from all the other basement rocks analysed in this study. Note that to allow better analysis of the variation in single grain zircon FT ages, 30 zircon grains were dated from each sample (LH539 and LH 585). The nature of the spread in ages is illustrated as a histogram, probability distribution plot, and radial plot in figure 6. Sample LH539 yields ages with an apparent continuous variation between 220 ± 34 and 95 ± 14 Ma, while sample LH585 has single grain ages from 247 ± 53 to a youngest age of 108 ± 18 Ma. Such a mix of single grain ages means that the quoted central ages (Table 1) have no geological meaning. The spread in ages cannot represent a mixed provenance, as these rocks experienced post-depositional peak metamorphic conditions well in excess of those required to totally reset the zircon FT age (Massonne *et al.*, 1999). The variation in zircon FT

ages must thus reflect post-peak metamorphism heating to temperatures high enough to cause partial annealing of fission tracks in zircon (above ca. $240 \pm 20^\circ\text{C}$; Tagami *et al.*, 1998). Why fission track annealing was more pronounced in some zircon grains than others is open to several possible interpretations. The detrital nature of the zircons signifies that the main causes are likely to be due to either differing zircon trace element chemistries, and/or variation in radiation damage in different grains. How these factors effect the annealing of fission tracks in zircon is an area of ongoing research (*e.g.*, Yamada *et al.*, 1995; Tagami *et al.*, 1998; Rahn *et al.*, 2000) and is not dealt with further here, except to say that further investigation of the Chiloé zircon samples may offer the chance to qualitatively assess which of the above named factors has the most pronounced effect on the kinetics of annealing

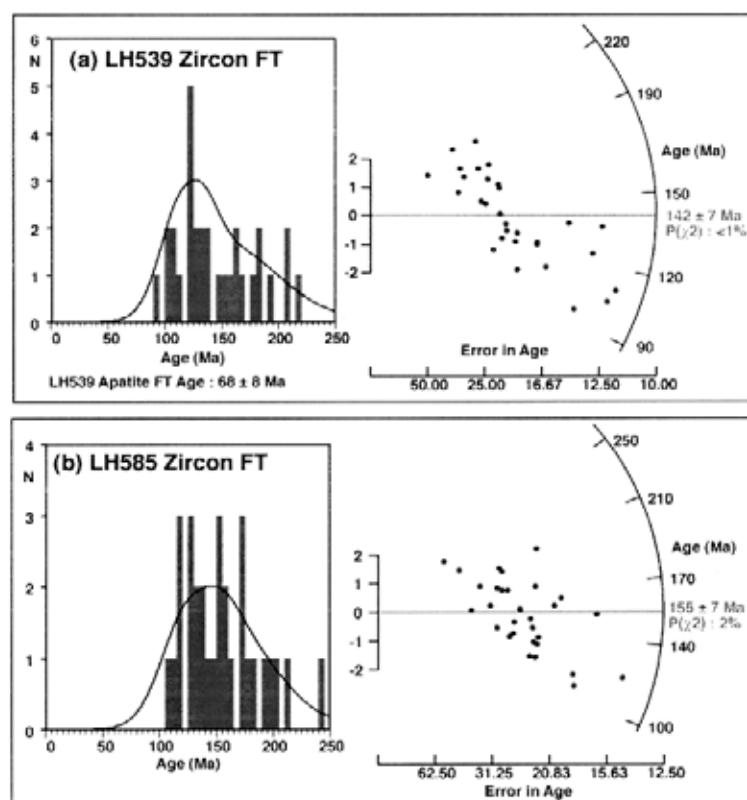


FIG. 6. Graphical representation of the zircon FT single grain age data from two quartzite samples of the metamorphic basement rocks of Chiloé. Note the large dispersion of single grain ages in both samples indicative of a mix of different single grain age components, in this case caused by differential partial resetting of each of the grains following a reheating event constrained to sometime between the youngest single grain age ($<95 \pm 14$ Ma) and post-reheating cooling indicated by lower temperature sensitive apatite FT age of 68 ± 8 Ma.

of fission tracks in zircon in a natural geological environment.

The oldest single grain zircon FT ages from both Chiloé samples are the same within 1σ error as the post-metamorphic zircon FT cooling age of 210 ± 12 Ma obtained from sample FO9606 from the CMC in the Chonos Archipelago ca. 300 km further south. This implies that the CMC basement rocks of Chiloé and those of the Chonos Archipelago have a common pre-Late Triassic metamorphic history. This is in good agreement with the K-Ar and Ar-Ar muscovite cooling ages of 220 ± 6 and 233 ± 3 Ma obtained from basement rocks in northern Chiloé by Duhart *et al.* (2001). The youngest partially reset grain ages must define the maximum age for post-peak metamorphism heating as having occurred since 95 ± 14 Myr (mid-Cretaceous). As these samples were heated to temperatures sufficient to partially reset the zircon FT age ($>240 \pm 20^\circ\text{C}$), then the lower temperature sensitive apatite fission track age (total resetting at ca. $110 \pm 10^\circ\text{C}$; Green *et al.*, 1986; 1989; Laslett *et al.*, 1987), must have been totally reset by this later heating event. The apatite FT age of sample LH539 (68 ± 8 Ma) thus represents a cooling age following this later heating event, and defines a minimum age for heating. Apatite track length data from this sample (Table 1) are consistent with this interpretation. The long unimodal mean track length and smallish standard deviation ($13.82 \pm 1.46 \mu\text{m}$) are typical for a sample that had undergone steady cooling from temperatures of $>110 \pm 10^\circ\text{C}$ to $<60^\circ\text{C}$ at the time indicated by the apatite FT age (e.g.,

Green *et al.*, 1989). In summary, these FT data require that the CMC rocks in Chiloé in the vicinity of the two samples analysed were affected by post-metamorphic heating to temperatures of between $240 \pm 20^\circ\text{C}$ and $310 \pm 20^\circ\text{C}$ sometime in the Late Cretaceous (or more exactly between the Late Early Cretaceous (Albian) to earliest Cenozoic between 109 and 60 Ma). Interestingly, Duhart *et al.* (2001) described a Late Triassic post metamorphic Ar-Ar cooling age from the Bahía Mansa Metamorphic Complex, the northward continuation of the CMC on mainland Chile, that also shows evidence of a partial, but important post-metamorphic resetting.

The Late Cretaceous heating of the basement rocks on Chiloé can most readily be related to plutonic activity recorded in other parts of the western belt of the CMC at this time. Although presently no Late Cretaceous plutons have been described from Chiloé, in the Chonos Archipelago to the south, a large granitoid was emplaced in the western belt of the CMC in the Late Cretaceous at 76 ± 1 Ma (Pankhurst *et al.*, 1999), while two small granitoid stocks with ages of 103 ± 2 and 86 ± 3 Ma intrude the basement rocks that form the northward extension of the CMC of Chiloé on the Chilean mainland (Munizaga *et al.*, 1988). The implied existence of a magmatic activity in the basement rocks of Chiloé during the Late Cretaceous, with the possibility of a buried pluton, may have important implications regarding hydrothermal fluid circulation and the presence of mineralisation in the generally poorly exposed basement rocks of the island.

CONCLUSIONS AND GEOLOGICAL IMPLICATIONS

This study demonstrates that constraints on the stratigraphic age of fossil poor metamorphosed terrigenous sedimentary rocks, such as those commonly found within accretionary complexes, can be vastly improved by applying and integrating two independent dating methods to a common detrital zircon fraction. Zircon FT ages provide a minimum age of metamorphism and hence deposition if the rock being analysed has seen post-depositional metamorphic temperatures sufficient for total resetting of this system ($>310 \pm 20^\circ\text{C}$), while the acquisition of U-Pb SHRIMP detrital zircon grain ages allows the maximum age of deposition to be established. This

has allowed the following stratigraphic age constraints to be obtained from the metamorphic basement rocks of southern Chile (using 1σ error):

(i) Eastern Andes Metamorphic Complex: 364 to 250 Ma (Late Devonian to the Permian/Triassic boundary); (ii) Duque de York flysch of the Madre de Dios Accretionary Complex: 234 to 195 Ma (Middle Triassic to Early Jurassic); (iii) Chonos Metamorphic Complex: 213 to 198 Ma (latest Triassic to earliest Jurassic).

When 2σ errors are taken, then the time constraints increase slightly to between 374 Ma and 233 Ma for the EAMC, 238 and 181 Ma for the MDAC, and

219 Ma and 186 Ma for the CMC. Of course these constraints also only apply to the actual samples analysed. Variation may occur outside these limits within other parts of each of the studied complexes. Indeed, this seems to be the case for sample FO98P17 from the westernmost part of the EAMC. Here the maximum stratigraphic age (248 Ma - earliest Triassic) is apparently younger than the age of cooling below $ca. 240 \pm 20^\circ\text{C}$ following metamorphism indicated by the samples of the EAMC $ca. 50$ km further to the east. Another anomaly is the presence of Early Devonian fossil trilobites in basement rocks of continental Chiloé at Buill ($ca. 42^\circ\text{S}$ - Fig. 1), $ca. 50$ km east of the CMC rocks of the island of Chiloé (Fortey *et al.*, 1992). The maximum stratigraphic age of the metamorphic rocks from Isla Diego de Almagro, as constrained solely by U-Pb SHRIMP detrital zircon ages (159 Ma - Late Jurassic), is also considerably younger than the minimum age of metamorphism (195 Ma) of the rocks of the Duque de York Complex of the MDAC $ca. 50$ km to the north.

The new post-metamorphic cooling and stratigraphic age constraints from the various basement complexes of southern Chile obtained in this study have several important implications regarding the nature of the geological and tectonic evolution of this part of the former Pacific margin of Gondwana before it was disrupted by intrusion of the Patagonian batholith in the Early Cretaceous. First, the new FT data verify that most of the EAMC was deposited, metamorphosed and cooled to below $240 \pm 20^\circ\text{C}$, before deposition, accretion, and metamorphism of the investigated continentally derived flysch that comprise the Chonos and Madre de Dios basement complexes further west. This significant difference in metamorphic histories and the likely regional extent of this metamorphism reinforces arguments originally made by Hervé *et al.* (1999a), that no direct correlation can be made between the basement rocks east and west of the Patagonian batholith at these latitudes. This would apparently favour the interpretation of the basement rocks of southern Chile as representing separate microplates or terranes accreted at different times to the Pacific Gondwana margin during the Late Palaeozoic and early Mesozoic (*e.g.*, Bell and Suárez, 2000). The independent stratigraphic ages that fall outside the age limits obtained from the samples analysed in this study could also imply the presence of several additional microplates, as similarly proposed by Bell

and Suárez (2000). However, given the seemingly eastern 'Gondwana' continental source of many of the terrigenous basement rocks (*e.g.*, Hervé and Fanning, 2001), the presence of several anomalous ages, and the difference in ages east and west of the Patagonian batholith could simply reflect a complex and punctuated evolution of fore-arc accretion at the former Pacific Gondwana margin during the Late Palaeozoic to Early Mesozoic. In this case the only rocks that may truly represent an exotic terrane are the accreted remnants of former oceanic seamounts, such as the Tarlton limestones and Denaro complex oceanic rocks of the MDAC. Indeed, the Late Triassic to Early Jurassic Duque de York complex sedimentary rocks of the MDAC are considerably younger than the Carboniferous to Permian Tarlton limestones onto which they are unconformably deposited, implying that the two units are not genetically related. This is consistent with the idea of Mpodozis and Forsythe (1983), who proposed that the Tarlton limestone and related Denaro complex were part of an earlier formed exotic oceanic terrane or seamount that was later accreted to the Gondwana margin concomitant with being overlain by and tectonically interleaved with the continentally derived terrigenous sedimentary rocks of the Duque de York complex.

A common stratigraphic age, sedimentary provenance, and similar metamorphic history is recorded by the analysed samples from the eastern belt of the CMC and the Duque de York complex of the MDAC some 300 km further south, both now situated west of the Patagonian batholith. This apparent shared history implies that these two basement complexes were formed together during a widespread phase of increased accretion during the Late Triassic to Early Jurassic that extended for at least 500 km along the former Pacific Gondwana subduction margin at this time. The reason why increased accretion and related metamorphism occurred only at certain times with the formation of apparently distinct metamorphic basement complexes can presently only be speculated upon. One possibility is a change in the plate tectonic regime at this time at this part of the former Pacific Gondwana margin Chile, such as a variation in plate convergence rates, the obliquity of plate convergence, the angle of subduction, the age of the subducting oceanic crust or other interactions between the subducting and overriding lithosphere.

ACKNOWLEDGEMENTS

This work has been supported by a German Science Foundation (DFG) Stipendium (Th 573/2-1) granted to SNT. Fieldwork in southern Chile was funded from DFG grants Sto 196/11-1 and Sto 196/11-2 awarded to Bernhard Stöckhert, Manfred Brix and SNT at the Ruhr-Universität Bochum. Preparation of the samples for fission-track analysis was carried out by F. Hansen (Ruhr Universität Bochum). Collection of the samples for U-Pb SHRIMP analysis at the The Australian National University, Canberra, Australia under the supervision of M. Fanning (ANU), was funded by Fondecyt Projects 1980741/1010412 and the Cátedra Presidencial de Ciencias granted

to FH. L. Hufmann (Universität Stuttgart) is thanked for collecting and donating samples LH539 and LH585 from Chiloé. Also thanks to A. Adriasola (Ruhr-Universität Bochum) for translating the abstract. The comments and suggestions of reviewers R.J. Pankhurst (British Antarctic Survey, U.K.), A. Carter (Research School of Geological Sciences, Birkbeck and University Colleges, London), J. Cembrano (Universidad Católica del Norte), M. Zentilli (Dalhousie University, Canada) and E. Godoy (Sernageomin) are greatly appreciated. This work forms a contribution to IGCP Project 436 'Pacific Gondwana Margin'.

REFERENCES

- Aguirre, L.; Hervé, F.; Godoy, E. 1972. Distribution of metamorphic facies in Chile - an outline. *Krystallinikum*, Vol. 9, p. 7-19.
- Bell, C.M.; Suárez, M. 2000. The Río Lácteo Formation of Southern Chile. Late Paleozoic orogeny in the Andes of southernmost South America. *Journal of South American Earth Sciences*, Vol. 12, p. 133-145.
- Brandon, M.T. 1992. Decomposition of fission-track grain age distributions. *American Journal of Science*, Vol. 292, p. 535-564.
- Bruce, R.M.; Nelson, E.P.; Weaver, S.G.; Lux, D.R. 1991. Temporal and spatial variation in the southern Patagonian batholith: constraints on magmatic arc development. In Andean magmatism and its tectonic setting (Harmon, R.S.; Rapela, C.W.; editors). *Geological Society of America, Special Paper*, Vol. 265, p. 1-12.
- Carter, A.; Moss, S.J. 1999. Combined detrital-zircon fission-track and U-Pb dating: a new approach to understanding hinterland evolution. *Geology*, Vol. 27, p. 235-238.
- Carter, A.; Bristow, C.S. 2000. Detrital zircon geochronology: enhancing the quality of sedimentary source information through improved methodology and combined U-Pb and fission-track techniques. *Basin Research*, Vol. 12, p. 47-57.
- Darwin, C.R. 1846. Geological Observations on South America, being the third part of Geology of the Voyage of the Beagle. *Smith Elder and Co.*, 279 p. London.
- Davidson, J.; Mpodozis, C.; Godoy, E.; Hervé, F.; Pankhurst, R.J.; Brook, M. 1987. Late Paleozoic accretionary complexes on the Gondwana margin of southern Chile: evidence from the Chonos Archipelago. In *Gondwana Six: Structure, Tectonics and Geophysics* (McKenzie, G.D.; editor). *Geophysical Monograph Series*, Vol. 40, p. 221-227.
- Douglass, R.C.; Nestell, M.K. 1976. Late Paleozoic Foraminifera from southern Chile. *U.S. Geological Survey, Professional Paper*, No. 858, p. 47.
- Duhart, P.; McDonough, M.; Muñoz, J.; Martin, M.; Villeneuve, M. 2001. El Complejo Metamórfico Bahía Mansa en la cordillera de la Costa del centro-sur de Chile (39°30'-42°00'S): geocronología K-Ar, ⁴⁰Ar/³⁹Ar y U-Pb e implicancias en la evolución del margen sur-occidental de Gondwana. *Revista Geológica de Chile*, Vol. 28, No. 2, p. 179-208.
- Fang, Z.; Boucot, A.; Covacevich, V.; Hervé, F. 1998. Discovery of late Triassic fossils in the Chonos Metamorphic Complex, southern Chile. *Revista Geológica de Chile*, Vol. 25, p. 165-174.
- Forsythe, R.D. 1982. The late Palaeozoic to early Mesozoic evolution of southern South America: a plate tectonic interpretation. *Journal of the Geological Society, London*, Vol. 139, p. 671-682.
- Forsythe, R.D.; Dalziel, I.W.D.; Mpodozis, C.; Hall, B.; Barrientos, S. 1981. Geologic studies in the outer Chilean fiords, R/V Hero cruise 79-5. *Antarctic Journal of the United States*, Vol. 15, p. 109-111.
- Fortey, R.; Pankhurst, R.J.; Hervé, F. 1992. Devonian trilobites at Buill, Chile (42°S). *Revista Geológica de Chile*, Vol. 19, p. 133-144.
- Frey, M.; De Capitani, C.; Liou, J.G. 1991. A new petrogenetic grid for low-grade metabasites. *Journal of Metamorphic Geology*, Vol. 9, p. 497-509.
- Galbraith, R.F. 1988. Graphical display of estimates having differing standard errors. *Technometrics*, Vol. 30, p. 271-281.

- Galbraith, R.F. 1990. The radial plot: graphical assessment of spread in ages. *Nuclear Tracks and Radiation Measurements*, Vol. 17, p. 207-214.
- Galbraith, R.F.; Laslett, G.M. 1993. Statistical models for mixed fission track ages. *Nuclear Tracks and Radiation Measurements*, Vol. 21, p. 459-470.
- Garver, J.I.; Soloviev, A.V.; Kamp, P.J.J.; Brandon, M.T. 1999. Detrital zircon fission-track thermochronology: practical considerations and examples. In *Fission track analysis: theory and applications* (Martin, S.; Polino, R.; editors). *Memorie di Scienze Geologiche, Padova*, Vol. 51, No. 2, p. 454-456.
- Green, P.F.; Duddy, I.R.; Gleadow, A.J.W.; Tingate, P.R.; Laslett, G.M. 1986. Thermal annealing of fission tracks in apatite 1. A qualitative description. *Chemical Geology (Isotope Geoscience Section)*, Vol. 9, p. 237-253.
- Green, P.F.; Duddy, I.R.; Laslett, G.M.; Hegarty, K.A.; Gleadow, A.J.W.; Lovering, J.F. 1989. Thermal annealing of fission tracks in apatite 4. Quantitative modelling techniques and extension to geological timescales. *Chemical Geology (Isotope Geoscience Section)*, Vol. 79, p. 155-182.
- Halpern, M. 1973. Regional Geochronology of Chile south of 50° latitude. *Geological Society of America, Bulletin*, Vol. 84, p. 2407-2422.
- Hervé, F. 1995. Paleozoic metamorphic complexes in the Andes of Aysén, Southern Chile (West of ?Occidentalía). In *Proceedings of the First Circum-Pacific and Circum-Atlantic Terrane Conference*, p. 64-65. Guanajuato, Mexico.
- Hervé, F. 2000. Recent progress in the knowledge of the metamorphic complexes of the Patagonian Andes of southern Chile. 17. *Geowissenschaftliches Lateinamerika-Kolloquium. Profil*, Band 18, p. 26. Stuttgart.
- Hervé, F.; Fanning, C.M. 2001. Late Triassic detrital zircons in metaturbidites of the Chonos Metamorphic complex, southern Chile. *Revista Geológica de Chile*, Vol. 28, No. 1, p. 91-104.
- Hervé, F.; Mpodozis, C.; Davidson, J.; Godoy, E. 1981. Observaciones estructurales y petrográficas en el basamento metamórfico del Archipiélago de los Chonos entre Canal King y el Canal Ninualac, Aysén. *Revista Geológica de Chile*, Vol. 13-14, p. 3-16.
- Hervé, F.; Greene, F.; Pankhurst, R.J. 1994. Metamorphosed fragments of oceanic crust in the upper Paleozoic Chonos accretionary complex, southern Chile. *Journal of South American Earth Sciences*, Vol. 7, p. 263-270.
- Hervé, F.; Aguirre, L.; Godoy, E.; Massonne, H.-J.; Morata, D.; Pankhurst, R.J.; Ramírez, E.; Sepúlveda, V.; Willner, A.J. 1998. Nuevos antecedentes acerca de la edad y las condiciones P-T de los complejos metamórficos en Aysén, Chile. In *Congreso Latinoamericano de Geología*, No. 10, Actas, y *Congreso Nacional de Geología Económica*, No. 6, p. 134-137. Buenos Aires.
- Hervé, F.; Aguirre, L.; Sepúlveda, V.; Morata, D. 1999a. Contrasting geochemistry and metamorphism of pillow basalts in metamorphic complexes from Aysén, S. Chile. *Journal of South American Earth Sciences*, Vol. 12, p. 379-388.
- Hervé, F.; Prior, D.; López, G.; Ramos, V.; Rapalini, A.; Thomson, S.N.; Lacassie, J.P.; Fanning, C.M. 1999b. Mesozoic blueschists from Diego de Almagro, southern Chile. In *Proceedings of the Second South American Symposium on Isotope Geology*, p. 318-321. Córdoba, Argentina.
- Hervé, F.; Fanning, C.M.; Bradshaw, J.; Bradshaw, M.; Lacassie, J.P. 1999c. Late Permian SHRIMP U-Pb detrital zircon ages constrain the age of accretion of oceanic basalts to the Gondwana margin at the Madre de Dios Archipelago, southern Chile. In *International Symposium on Andean Geodynamics*, No. 4, *Extended Abstracts Volume*, p. 327-328. Göttingen.
- Hervé, F.; Fanning, C.M.; Pankhurst, R.J. (In press). Detrital zircon age patterns and provenance in the subduction complex of Southern Chile. *Journal of South American Earth Sciences*.
- Hormazábal, L. 1991. Geología del basamento metamórfico del Grupo Smith e Islas Aledañas, entre 45° y 45°15' Lat. S., Aysén, Chile. Memoria de Título (Unpublished), *Universidad de Chile, Departamento de Geología*, 132 p.
- Hurford, A.J. 1990. Standardization of fission track dating calibration: Recommended by the Fission Track Working Group of the I.U.G.S. Subcommission on Geochronology. *Chemical Geology (Isotope Geoscience Section)*, Vol. 80, p. 171-178.
- Hurford, A.J.; Green, P.F. 1983. The zeta age calibration of fission-track dating. *Isotope Geoscience*, Vol. 1, p. 285-317.
- Hurford, A.J.; Hunziker, J.C.; Stöckhert, B. 1991. Constraints on the late thermotectonic evolution of the western Alps: evidence for episodic rapid uplift. *Tectonics*, Vol. 10, p. 758-769.
- IUGS International Stratigraphic Chart. 2002. UNESCO: <http://micropress.org/stratigraphy/tscale.htm>.
- Laslett, G.M.; Green, P.F.; Duddy, I.R.; Gleadow, A.J.W. 1987. Thermal annealing of fission tracks in apatite 2. A quantitative analysis. *Chemical Geology (Isotope Geoscience Section)*, Vol. 65, p. 1-13.
- Leanza, A. 1972. Andes Patagónicos australes. In *Geología Regional Argentina* (Leanza, A.; editor). *Academia Nacional Ciencias*, p. 689-706. Córdoba.
- Lee, J.K.W.; Williams, I.S.; Ellis, D.J. 1997. Pb, U and Th diffusion in natural zircon. *Nature*, Vol. 390, p. 159-161.
- Massonne, H.-J.; Hufmann, L.; Duhart, P.; Hervé, F.; Willner, A.P. 1999. New insights into the structure of the upper Palaeozoic/Mesozoic accretionary wedge complex of the Coastal Cordillera of central and southern Chile. In *International Symposium on Andean Geodynamics*, No. 4, *Extended Abstracts Volume*, p. 492-495. Göttingen.
- Miller, H. 1976. El basamento de la Provincia de Aysén (Chile) y sus correlaciones con las rocas premesozoicas de la Patagonia Argentina. In *Congreso*

- Geológico Argentino*, No. 6, Actas, p. 125-141. Bahía Blanca.
- Miller, H. 1979. Das Grundgebirge der Anden im Chonos-Archipel, Region Aisén, Chile. *Geologische Rundschau*, Vol. 68, p. 428-456.
- Miller, H.; Sprechmann, P. 1978. Eine devonische Fauna aus dem Chonos-Archipel, Region Aisén, Chile, und ihre stratigraphische Bedeutung. *Geologisches Jahrbuch*, Vol. B28, p. 37-45.
- Mpodozis, C.; Forsythe, R. 1983. Stratigraphy and geochemistry of accreted fragments of the ancestral Pacific floor in southern South America. *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 41, p. 103-124.
- Munizaga, F.; Hervé, F.; Drake, R.; Pankhurst, R.J.; Brook, M.; Snelling, N. 1988. Geochronology of the Lake Region of south-central Chile (39°-42°S): Preliminary results. *Journal of South American Earth Sciences*, Vol. 1, p. 309-316.
- Pankhurst, R.J.; Weaver, S.D.; Hervé, F.; Larrondo, P. 1999. Mesozoic-Cenozoic evolution of the North Patagonian Batholith in Aysén, southern Chile. *Journal of the Geological Society*, Vol. 156, p. 673-694. London.
- Pankhurst, R.J.; Riley, T.R.; Fanning, C.M.; Kelley, S.P. 2000. Episodic silicic volcanism in Patagonia and the Antarctic peninsula: Chronology of magmatism associated with the break-up of Gondwana. *Journal of Petrology*, Vol. 41, p. 603-625.
- Rahn, M.K.; Brandon, M.T.; Batt, G.E.; Garver, J.I. 2000. Fission-track annealing in 'zero-damage' zircons: field constraints and an empirical model. In *International Conference on Fission Track Dating and Thermochronology*, No. 9, Abstracts, p. 271. Lorne, Australia.
- Ramos, V.A. 1989. Andean foothills structures in northern Magallanes Basin, Argentina. *American Association of Petroleum Geologists, Bulletin*, Vol. 73, p. 887-903.
- Ramírez, E. 1997. Geología del Valle del Río Chacabuco, XI Región de Aysén. Memoria de Título (Unpublished), Universidad de Chile, Departamento de Geología, 71 p.
- Riccardi, A.C. 1971. Estratigrafía en el oriente de la Bahía de la Lancha, Lago San Martín, Santa Cruz, Argentina. *Museo de La Plata, Revista*, Vol. 7, p. 245-318.
- Salot, P. 1969. Étude géologique dans l'île de Chiloé (Chili). *Bulletin de la Société Géologique de France*, Série 7, Vol. 11, p. 388-399.
- Sepúlveda, V. 2000. Geología de la Hoja Villa O'Higgins, Región de Aysén, Chile. Memoria de Título (Unpublished), Universidad de Chile, Departamento de Geología, 71 p.
- Servicio Nacional de Geología y Minería (SERNAGEOMIN). 1982. Mapa geológico de Chile (Escobar, F.; editor). Talleres Gráficos Instituto Geográfico Militar. Santiago.
- Sircombe, K.N. 1999. Tracing provenance through the isotope ages of littoral and sedimentary detrital zircon, eastern Australia. *Sedimentary Geology*, Vol. 124, p. 47-67.
- Stiefel, J. 1970. Das Andenprofil im Bereich des 45. südlichen Breitengrades. *Geologische Rundschau*, Vol. 59, No. 3, p. 961-979.
- Tagami, T.; Galbraith, R.F.; Yamada, R.; Laslett, G.M. 1998. Revised annealing kinetics of fission tracks in zircon and geological implications. In *Advances in Fission-Track Geochronology* (Van den haute, P.; De Corte, F.; editors). Kluwer Academic Publishers, p. 99-112. Dordrecht.
- Thomson, S.N.; Hervé, F.; Stöckhert, B. 2001. Mesozoic-Cenozoic denudation history of the Patagonian Andes (southern Chile) and its correlation to different subduction processes. *Tectonics*, Vol. 20, p. 693-711.
- Willner, A.P.; Hervé, F.; Massonne, H.-J. 2000. Mineral chemistry and pressure-temperature evolution of two contrasting high-pressure-low-temperature belts in the Chonos Archipelago, southern Chile. *Journal of Petrology*, Vol. 31, p. 309-330.
- Yamada, R.; Tagami, T.; Nishimura, S.; Ito, H. 1995. Annealing kinetics of fission tracks in zircon: an experimental study. *Chemical Geology (Isotope Geoscience Section)*, Vol. 122, p. 249-258.