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Significance of ^{40}Ar–^{39}Ar encapsulation ages of metapelites from late Palaeozoic metamorphic complexes of Aysén, Chile

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Abstract – The ages obtained by the ^{40}Ar–^{39}Ar encapsulation technique (retention and total gas ages) on $< 2\ \mu$m fractions of five metapelites from the Eastern Andean Metamorphic Complex and two from the Chonos Metamorphic Complex allow discussion of the latest recorded metamorphic event in each zone. The Kübler Index (KI) of illite/muscovite (principal component of the metapelites) varies between 0.15° and 0.45° $\Delta°2\theta$, indicating regional variation from diagenetic to epizonal metamorphic grade. The ^{40}Ar–^{39}Ar encapsulation analyses reveal ^{39}Ar loss varying between 21 and 25 %, which shows a limited positive correlation with KI values. The obtained retention and total gas metapelite ages reflect distinct metamorphic conditions. Retention ages most probably indicate burial or regional metamorphic events without plutonic influence in the southern Eastern Andean Metamorphic Complex. Total gas ages reflect contact metamorphic ages for metapelites close to intrusions in the northern and southern Eastern Andean Metamorphic Complex and in the Chonos Metamorphic Complex. The thermal overprinting of metapelites occurred in Early Cretaceous times at 130 Ma and 145 Ma and is related to the contact metamorphism of an emplacement pulse of the North Patagonian Batholith. Total gas metapelite ages obtained from the western belt of the Chonos Metamorphic Complex suggest a thermal event related to a distinct pulse of the North Patagonian Batholith.

Keywords: ^{40}Ar–^{39}Ar encapsulation, metapelite, metamorphic complexes of Aysén, Chile.

1. Introduction

The Eastern Andean Metamorphic Complex and the Chonos Metamorphic Complex, our study area in the Southern Patagonian Andes (Fig. 1), are composed of abundant metapelites, which have not been dated until now. The age determination of different metamorphic and/or tectonic events in sedimentary rocks is mainly based on dating alumino-silicate clay minerals such as illite/muscovite or illite/smectite mixtures. Geochronological studies on diagenetic to very low-grade metamorphic pelitic rocks have been generally undertaken by applying the conventional K–Ar technique, but the heterogeneous character of grain-size, composition and origin of the clay minerals leads to serious limitations on the geological meaning of the obtained age.

The conventional ^{40}Ar–^{39}Ar dating technique usually reveals higher precision and more detailed information on the rock itself, but its application has been limited by reactor-induced ^{39}Ar loss due to recoil in very fine-grained clay material of sedimentary rocks (e.g. Turner & Cadogan, 1974; Onstott, Miller & Ewing, 1994). Nevertheless, other detailed studies (Hunziker *et al.* 1986; Kligfield *et al.* 1986; Reuter & Dallmeyer, 1987, 1989; Dallmeyer *et al.* 1989) have shown that recoil-related ^{39}Ar loss is not of major importance in every case.

The introduction of the encapsulation technique for ^{40}Ar–^{39}Ar geochronology allows the collection of the total of ^{39}Ar loss from the sample during irradiation and permits recalculation of the obtained age (retention age, omitting the portion of ^{39}Ar loss) and the encapsulated total gas age or so-called integrated age (including ^{39}Ar loss) (Dong *et al.* 1995). In this way, the recoil effect is monitored and the encapsulated total gas age yields an age comparable to a conventional K–Ar age. Hence, an estimate of the true crystallization age of the sample can be made (York, Evensen & Smith, 1992). On the other hand, the retention age is equivalent to a traditional unencapsulated metapelite ^{40}Ar–^{39}Ar age. In contrast, Dong *et al.* (1995) suggested that the obtained encapsulated total gas age might be younger than the time of mineral growth during low-grade metamorphic conditions. They postulated that K ($^{40}Ar^{*}$) occupies similar incoherent boundary sites as ^{39}Ar in illite packages and therefore will be released as easily under room temperature as ^{39}Ar during irradiation. This implies that the retention age (Dong *et al.* 1995) is closer to the true (re-)crystallization age, in disagreement with the assumption made earlier by York, Evensen & Smith (1992). More recently, Lin, Onstott & Dong (2000) employed microanalytical techniques on fine-grained minerals and suggested that

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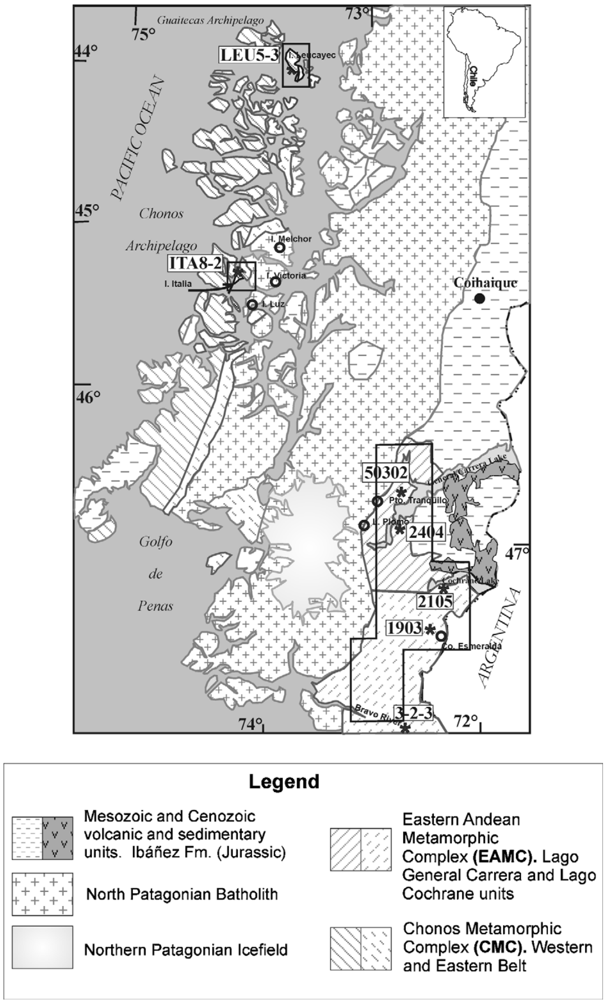

Figure 1. Schematic geological map of Aysén region. The asterisks indicate the location of samples for dating by ^{40}Ar–^{39}Ar encapsulation technique. Unfilled circles indicate existing geochronological data in intrusive bodies.

^{39}Ar recoil loss occurs from within coherent lattice domains and as a consequence, the assumption by Dong *et al.* (1995) should overestimate the retention age. They favour the encapsulated total gas or integrated age as the true crystallization age of the mineral.

Discussion on whether or not ^{39}Ar or ^{40}Ar* has been released during irradiation or under room temperature requires more detailed microanalytical studies, which has not been the aim of the study presented here. The emphasis was rather on comparing new data with the existing geochronological information of the study area and its implications.

This study presents the first ^{40}Ar–^{39}Ar encapsulation data on metapelites from the Eastern Andean and Chonos metamorphics complexes. The Kübler Index (KI) of < 2 μm illite fractions from metapelitic rocks of each study area allows comparison of the KI values with the obtained ^{40}Ar–^{39}Ar encapsulation ages. This allows the latest thermal event affecting each metamorphic complex in the southern Andes to be interpreted.

2. Geological setting

Between 46° and 49° S latitude, the Aysén region of southern Chile is characterized mainly by two metamorphic complexes, which are covered by Mesozoic and Cenozoic volcanic and sedimentary units and intruded by the Meso-Cenozoic North Patagonian Batholith (Fig. 1).

The Eastern Andean Metamorphic Complex is composed of schists, marbles, metasandstones and metapelites. This complex is divided into two units (Lagally, 1975), Lago General Carrera and Lago Cochrane, according to lithological differences and structural deformation styles. The oldest stratified unit unconformably overlying the Eastern Andean Metamorphic Complex rocks is the Late Jurassic Ibañez Formation (rhyolitic to dacitic pyroclastic rocks and lava flows).

The Chonos Metamorphic Complex is composed of metasedimentary and metabasaltic rocks. Hervé *et al.* (1981) distinguished two zones or belts: an eastern belt in which primary structures are preserved and a western belt with no preserved primary structures. The North Patagonian Batholith (Meso-Cenozoic) is characterized by a granitic to monzonitic composition and intrudes the eastern margin of the Chonos Metamorphic Complex and the western margin of the Eastern Andean Metamorphic Complex.

Both complexes were affected by greenschist facies metamorphism (Willner, Hervé & Massonne, 2000; Ramírez & Sassi, 2001) of yet unknown age and show evidence of multiple deformational and metamorphic events revealed by complex folding and deformation of at least two foliation planes.

The Chonos Metamorphic Complex is considered to represent a subduction zone assemblage. In contrast, the Eastern Andean Metamorphic Complex is considered to represent a passive margin succession (Augustsson *et al.* 2006; Faúndez, Hervé & Lacassie, 2002).

According to ages compiled from Bell & Suarez (2000) and Thomson & Hervé (2002), the depositional ages from the Eastern Andean Metamorphic Complex vary between Early Devonian and Triassic, whereas the age of metamorphism is not clearly constrained. Thomson & Hervé (2002) determined a post-metamorphic cooling age of 250 Ma (fission track – FT, zircon) and a U–Pb SHRIMP age on detrital zircon of 354 ± 10 Ma interpreted as a possible maximum depositional age.

In the Chonos Metamorphic Complex, Fang *et al.* (1998) determined a Late Triassic (*c.* 220 Ma) depositional age through the presence of *monotis* fossils. A U–Pb SHRIMP age on a detrital zircon grain of 207 ± 6 Ma was interpreted as indicative of a maximum stratigraphic age of 213 Ma (Thomson & Hervé, 2002). Thomson, Hervé & Fanning (2000) determined an age of 200 Ma (FT, zircon) which they and Thomson & Hervé (2002) interpret as indicating post-metamorphic cooling below 260 ± 40 °C.

3. Methodology

Seven metapelitic samples were analysed. Two samples from the western belt of the Chonos Metamorphic Complex, one from Italia Island (ITA8-2) and one from Leucayec Island (LEU5-3), and five (50302, 2404, 2105, 1903 and 3-2-3) from the Eastern Andean Metamorphic Complex (Fig. 1).

Sample preparations for Kübler Index determination and encapsulated ^{40}Ar–^{39}Ar geochronology were undertaken at the Geology Department, University of Chile. Samples of less than 2 μm grain-size were separated from the metapelites employing the methodology for Kübler Index determination described in Ramírez *et al.* (2005). KI standards SW-1, SW-2, SW-4 and SW-6 were used, as recommended and described by Warr & Rice (1994).

The $^{40}Ar/^{39}Ar$ analyses were carried out at the Radiogenic Isotope Geochemistry Laboratory at the University of Michigan, Ann Arbor, following the preparation and analytical procedure described in Dong *et al.* (1995). The standard used was the MMhb-1 hornblende of Samson & Alexander (1987). Isotopic ratios were analysed using a VG-1200s Mass Spectrometer with Daly detector. Duplicates were determined for samples 1903, 2105, 2404, ITA8-2 and LEU5-3. Absolute and stratigraphic ages are referenced according to the Geological Time Scale (Gradstein *et al.* 2005).

4. Results

4.a. Kübler Index (KI)

The analysed material of each sample comprises a fine 2 μm grain fraction of chlorite and mica (illite/muscovite), with some quartz and albite (Fig. 2).

The metamorphic grade of the Eastern Andean Metamorphic Complex determined by the KI method indicates epizone grade for samples 50203, 2404, 2105 and 1903 ((0.22 $^\circ\Delta 2\theta$); (0.23 $^\circ\Delta 2\theta$); (0.15 $^\circ\Delta 2\theta$); (0.22 $^\circ\Delta 2\theta$) Kübler Index, respectively). The southernmost sample (3-2-3) yields a KI of 0.45 $^\circ\Delta 2\theta$, representing diagenetic grade (Table 1).

From the Chonos Metamorphic Complex, sample LEU5-3 indicates an epizonal grade (0.18 $^\circ\Delta 2\theta$) and ITA8-2 shows an anchizone grade (0.26 $^\circ\Delta 2\theta$) (Table 2).

According to the thermal data inferred by the Kübler Index, the epizonal samples were subjected

Table 1. ^{40}Ar–^{39}Ar encapsulation ages obtained from the Eastern Andean Metamorphic Complex (samples listed from north to south)

Sample	KI ($^\circ\Delta 2\theta$)	% ^{39}Ar loss	Retention age Ma ($\pm 2\sigma$)	Total gas age Ma ($\pm 2\sigma$)
MI85-12 50203	0.22	21.5	164.8 ± 0.8	131.1 ± 0.6
MI85-10 2404	0.23	23.7	166.0 ± 0.6	128.6 ± 0.4
MI85-11 2404	0.23	23.7	167.3 ± 0.8	129.5 ± 0.6
MI85-8 2105	0.15	21.2	225.8 ± 1.6	180.8 ± 1.4
MI85-9 2105	0.15	21.9	222.0 ± 0.6	176.2 ± 0.6
MI85-6 1903	0.22	24.9	191.6 ± 1.8	145.3 ± 1.4
MI85-7 3-2-3	0.45	22	281.7 ± 1.6	223.2 ± 1.4

KI – Kübler Index.

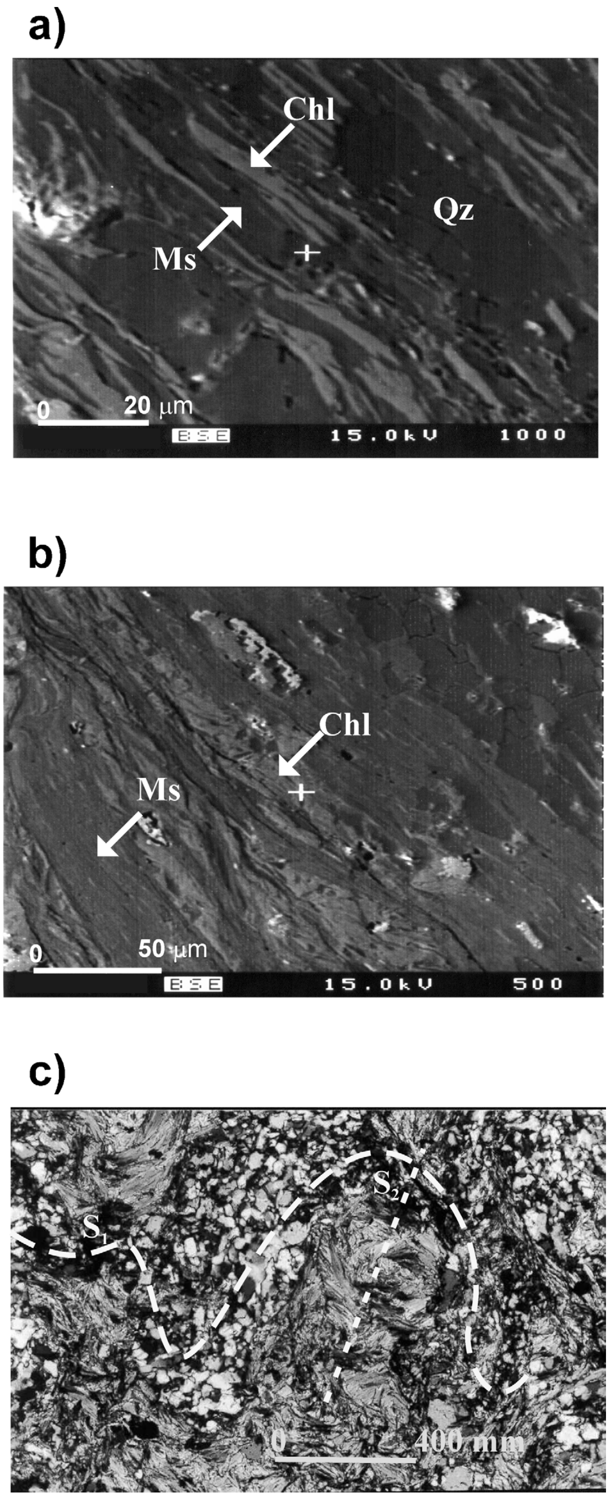

Figure 2. (a) Microphotography of SEM from sample 50302. Mica and chlorite are orientated to the foliation plane; quartz band is recrystallized. (b) Microphotography of SEM from sample 2404, item A. (c) Photography of optical microscope from sample LEU5-3, showing two foliations S1 and S2.

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Table 2. ^{40}Ar–^{39}Ar encapsulation ages obtained from the Chonos Metamorphic Complex (samples listed from north to south)

Sample	KI (°Δ2θ)	%^{39}Ar loss	Retention age Ma (±2σ)	Total gas age Ma (±2σ)
MI85-3 LEU 5-3	0.18	21.5	180.5 ± 0.8	142.3 ± 0.6
MI85-4 LEU 5-3	0.18	22.3	183.8 ± 0.8	146.6 ± 0.6
MI85-1 ITA 8-2	0.26	13.3	168.2 ± 0.8	146.9 ± 0.8
MI85-2 ITA 8-2	0.26	–	168.8 ± 0.8	146.5 ± 0.8

KI – Kübler Index.

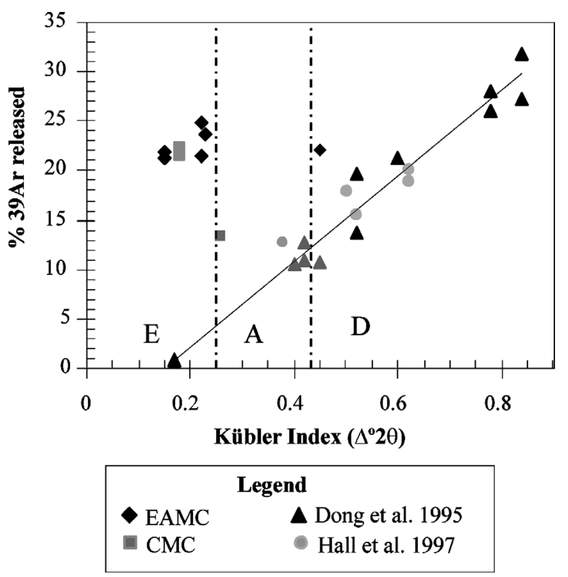

Figure 3. Correlation diagram of Kübler Index (KI) and % ^{39}Ar released from analysed samples of Eastern Andean Metamorphic Complex (EAMC) and Chonos Metamorphic Complex (CMC). Also shown are data from Dong *et al.* (1995) and Hall *et al.* (1997).

to temperatures over 300 °C, whereas the diagenetic samples were subjected to temperatures under 200 °C. Anchizone samples represent temperatures between 200 and 300 °C (Warr & Rice, 1994).

4.b. ^{40}Ar–^{39}Ar encapsulation data

4.b.1. Eastern Andean Metamorphic Complex

The amount of ^{39}Ar loss corresponds to the ^{39}Ar which was captured in a quartz vial during irradiation and then analysed. For the five metapelite samples of the Eastern Andean Metamorphic Complex with KI index values ranging between 0.15 and 0.45 (°Δ2θ), the amount of ^{39}Ar loss varies from 21 to 25 %, and shows no correlation with increasing metamorphic grade (Fig. 3).

The retention ages from the Eastern Andean Metamorphic Complex are listed from north to south in Table 1. Samples located to the north of Lake Cochrane show Middle Jurassic ages, whereas samples located to the south of Lake Cochrane show Early Jurassic, Late Triassic and Permian ages. The diagenetic grade sample (0.45 °Δ2θ) yields an age of 281.7 ± 1.6 Ma and represents the oldest age obtained.

The total gas ages from the same samples show similar variation but are generally younger than the retention ages, varying from Early Cretaceous to Late Triassic (Table 1).

4.b.2. Chonos Metamorphic Complex

The amount of ^{39}Ar loss in samples ITA8-2 (epizone) and LEU5-3 (anchizone) is 13 and 22 %, respectively (Table 2).

The retention age obtained from the Leucayec Island metapelite indicates an Early Jurassic age and that from Italia Island a Middle Jurassic age. The total gas ages from the same samples are both Late Jurassic–Early Cretaceous (142–146 Ma). Retention ages from the same samples are thus 20–40 Ma older than the total gas ages.

5. Discussion

5.a. KI versus ^{39}Ar loss

The relation between KI and the amount of ^{39}Ar loss shows a very limited correlation. This observation clearly contradicts the findings of Dong *et al.* (1995) and Hall *et al.* (2000), who found that a decrease in the amount of ^{39}Ar loss is correlated with increasing metamorphic grade (decrease in KI).

Our studied samples were most likely affected by several metamorphic overprints, such as burial, regional and/or contact metamorphism. Therefore, KI values obtained from the smallest minerals will indicate the metamorphic grade from the latest metamorphic or, in a more general sense, latest thermal event affecting each study area. Various metamorphic overprints registered in one sample might contradict the relatively straightforward relation of ^{39}Ar loss to changes in the associated metamorphic grade as presented by, for example, Dong *et al.* (1995). Furthermore, since nearly all analysed samples (except 2105 and 3-2-3 from the Eastern Andean Metamorphic Complex) were collected close to plutons or small intrusions, they might not reflect burial or regional metamorphism. Instead, they are suggested to represent contact metamorphic conditions which might not produce KI in the same way and therefore do not fit into the graphical interpretation presented by Dong *et al.* (1995) (Fig. 3).

5.b. Geochronology of the area

5.b.1. Age of Eastern Aandean Metamorphic Complex

The retention ages from the Eastern Andean Metamorphic Complex vary from north to south (Fig. 4). The Cochrane Lake approximately divides the Eastern Andean Metamorphic Complex into two areas (Lagally, 1975). Towards the north (Puerto Tranquilo), the

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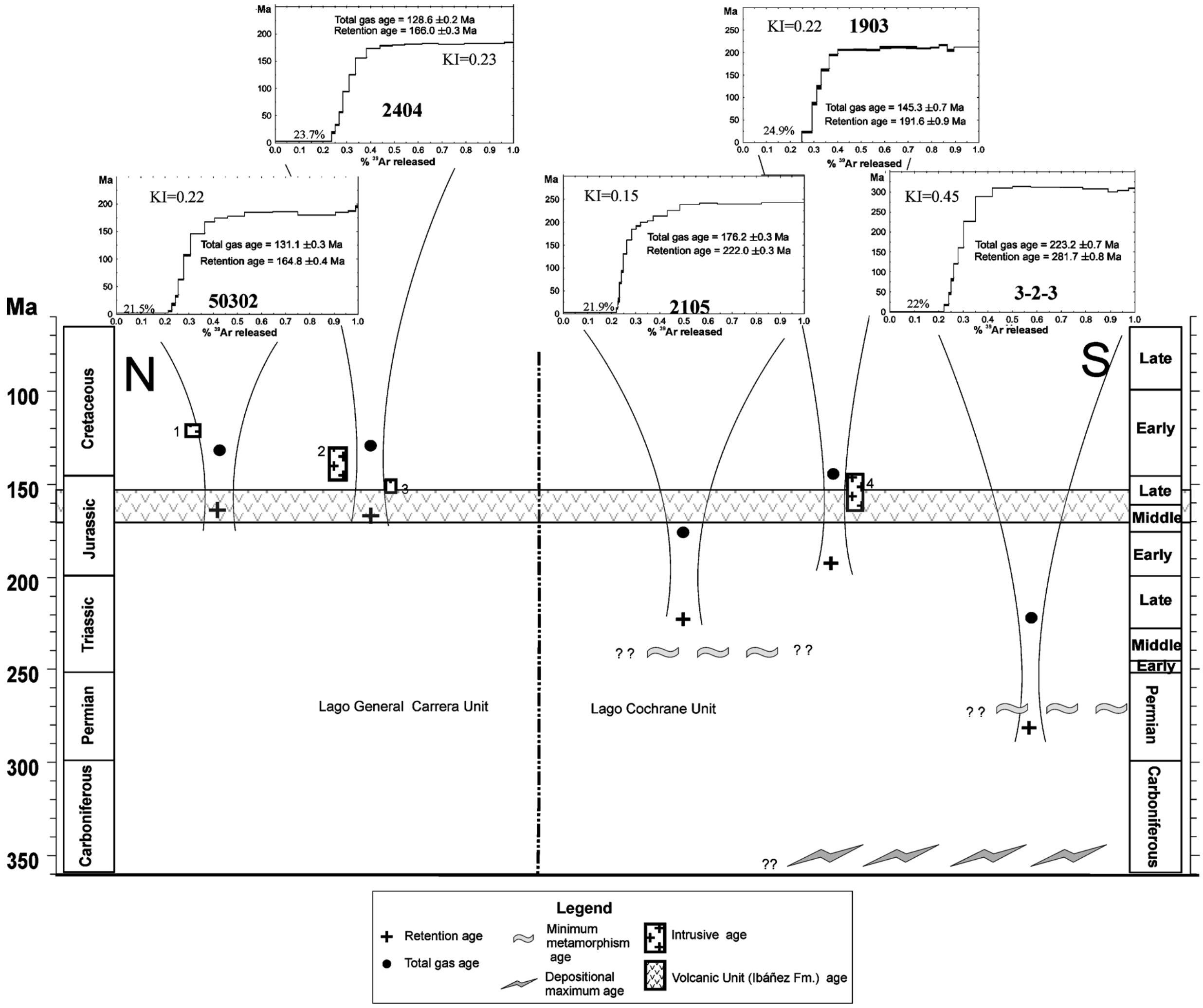

Figure 4. Schematic variation of ^{40}Ar–^{39}Ar encapsulated ages, north to south from Eastern Andean Metamorphic Complex. The small graph shows the retention age (Ma) versus fraction of ^{39}Ar released (Hall *et al.* 2000), including total gas age and Kübler Index (KI) value of the sample. The height of the small square indicates the approximate error of the age of the intrusive. 1 – K–Ar age on biotite minerals collected near Puerto Tranquilo. 2, 3 – K–Ar age on biotite next to Lake Plomo (Suarez & De la Cruz, 2001). 4 – Ar–Ar age on biotite at Cerro Esmeralda (Parada, Palacios & Lahsen, 1997). Minimum depositional ages from Augustsson *et al.* (2006) and maximum depositional ages from Thomson, Hervé & Fanning (2000); units according to Augustsson *et al.* (2006). Ages of volcanic units from Pankhurst *et al.* (2000).

retention ages are 164.8 ± 0.4 Ma (50302) and 166.0 ± 0.3 Ma (2404; Lago Plomo) (Middle Jurassic) and total gas ages are 131.1 ± 0.3 Ma (50302) and 128.6 ± 0.2 Ma (2404), all younger than in the southern area. The oldest ages are obtained for the southern area (3-2-3; Bravo River), with a retention age of 281.7 ± 0.8 and a total gas age of 223.2 ± 0.7 Ma (Permian–Triassic).

In the southern section, Thomson, Hervé & Fanning (2000) interpret the U–Pb age of *c.* 350 Ma on detrital zircon collected close to O'Higgins Lake, southern Bravo River, to represent the maximum depositional age of the Cochrane unit from which sample 3-2-3 was collected. The minimum depositional age of this area is 270 Ma (FT, detrital zircon) (Thomson, Hervé & Fanning, 2000). The latter age is close to but not concordant with the retention age of sample 3-2-3 and can be interpreted as a metamorphic age of the lithological unit. In contrast, the total gas age of 3-2-3 is younger than the minimum depositional age and cannot be related to any known geological or thermal event in the area.

The northernmost sample (2105) from the area south of Lake Cochrane yields a retention age of 222.0 ± 0.3 Ma and a total gas age of 176.2 ± 0.3 Ma. Whereas the total gas age cannot be related to any known geological event, the retention age is only slightly younger than the minimum depositional age given by zircon FT data of 238 Ma (Augustsson *et al.* 2006) and is concordant with the recognized metamorphism of Late Permian to Middle Triassic age.

At about 5 km distance from sample 1903, an intrusive tonalite yields U–Pb zircon and K–Ar (biotite) ages of 155 ± 10 Ma and 156–157 Ma, respectively (Middle Jurassic–Late Jurassic: Parada, Palacios &

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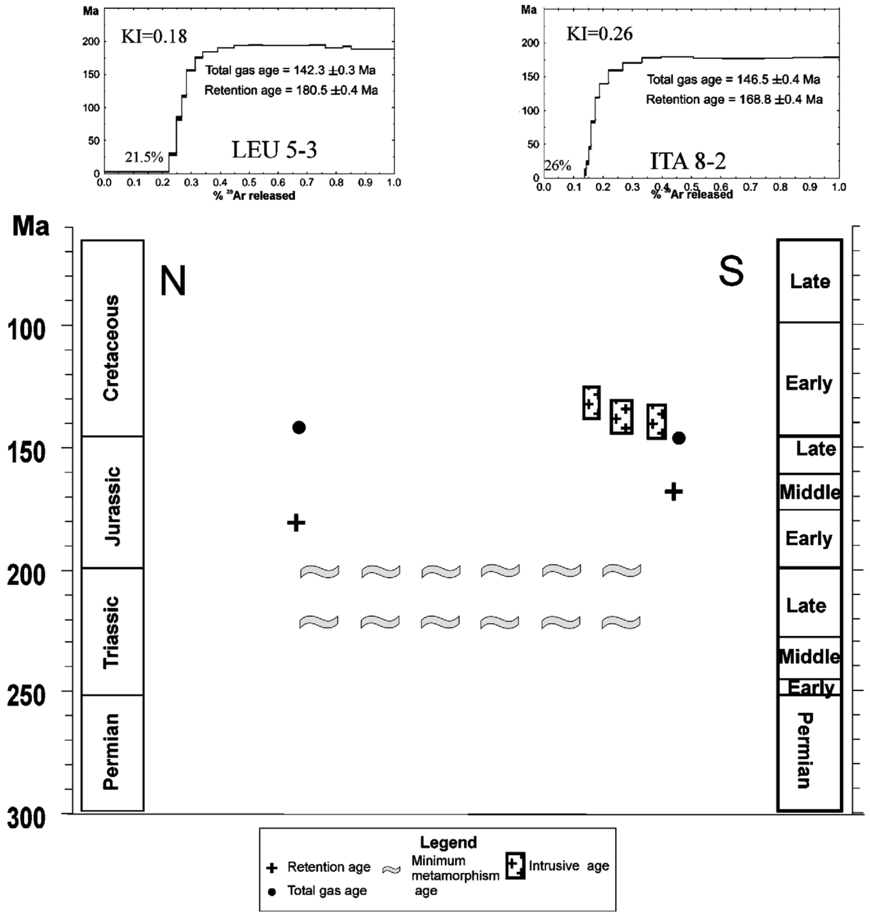

Figure 5. Schematic variation of ^{40}Ar–^{39}Ar encapsulated ages from Leucayec and Italia islands, Chonos Metamorphic Complex. The small graph shows the retention age (Ma) versus fraction of ^{39}Ar released (Hall *et al.* 2000) including total gas age and Kübler Index (KI) value of the sample. Depositional ages according to Fang *et al.* (1998), and Hervé, Fanning & Pankhurst (2003). Intrusive ages of Victoria (132.8 ± 6.5 Ma), Melchor (137.6 ± 6.0 Ma) and Luz (140.1 ± 6.3 Ma) islands from Pankhurst *et al.* (1999).

Lahsen, 1997), which were interpreted as crystallization ages. Two younger whole rock K–Ar ages from the same tonalite of 140 ± 4 and 142 ± 5 Ma have been interpreted as ages of a later stage of mineralization (Parada, Palacios & Lahsen, 1997). The latter ages are concordant with the total gas age of 145.3 ± 1.4 Ma of sample 1903, whereas the retention age of the metapelitic sample (191.6 ± 0.9 Ma) is older than the intrusion ages and apparently has no geological significance.

Intrusive bodies located about 10 km to the north of metapelite samples 50302 and 2404 (Fig. 4) suggest a close relationship between this intrusive event and the obtained encapsulation ^{40}Ar–^{39}Ar ages, suggesting contact rather than burial or regional metamorphism. Jurassic plutons of the General Carrera and Plomo Lakes yield ages varying from 140 Ma to 155 Ma (Fig. 4) (Suárez & De la Cruz, 2001). The total gas ages of samples 50302 and 2404 (128.6 Ma to 131.1 Ma), whereas the retention ages (164.8 Ma to 167.3 Ma) are older than the postulated intrusion ages and are thus apparently geologically meaningless.

5.b.2. *Age of the Chonos Metamorphic Complex*

A zircon FT age of 210 ± 12 Ma (Thomson, Hervé & Fanning, 2000) was obtained in the eastern belt, which is interpreted to represent the minimum depositional age of the Chonos Metamorphic Complex. The metapelite sample LEU5-3 yields a retention age of 180.5 ± 0.4 Ma, whereas the total gas age is 142.3 ± 0.3 Ma. The latter age is concordant with geochronological Rb–Sr (whole rock) ages of 137.5 ± 6.5 Ma, and 140.1 ± 6.3 Ma obtained from plutons at Melchor and Luz Islands, respectively (Fig. 5; Pankhurst *et al.* 1999) and in consequence reflects the time of this intrusion event of the North Patagonian Batholith. The retention age from Chonos Metamorphic Complex sample LEU5-3 is slightly younger than the suggested minimum depositional age and apparently without geological meaning.

Sample ITA8-2 experienced anchimetamorphic temperatures between 200 and 300 °C, and gives a retention age of 168.8 ± 0.4 Ma and a total gas age of 146.5 ± 0.4 Ma. Whereas total gas ages from LEU5-3

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and ITA8-2 are concordant and are very close to or partly overlap the intrusive ages quoted above, the retention ages are discordant and not related to any known geological or thermal event of the area and are therefore possibly meaningless.

6. Conclusions

The encapsulated ^{40}Ar–^{39}Ar ages obtained from the Eastern Andean Metamorphic Complex, except those from Lake Cochrane (2105) and the Bravo River (3-2-3), are younger than the expected metamorphic ages in both study areas. Both the Chonos Metamorphic Complex and the Eastern Andean Metamorphic Complex were polydeformed, and thus very possibly metamorphosed before the intrusion of the North Patagonian Batholith. The white micas in the analysed rocks are well oriented along the main foliation planes in the metapelites.

Previous investigations through FT dating of detrital zircons (Thomson, Hervé & Fanning, 2000) have determined that cooling below the $260 \pm 40\,^{\circ}C$ closure temperatures of zircon takes place at 200 Ma in the Chonos Metamorphic Complex and 270 Ma in the Cochrane unit of the Eastern Andean Metamorphic Complex. In Thomson & Hervé (2002), it is noted that FT zircon ages are partly reset at a temperature above $240 \pm 20^{\circ}C$ with a possible total reset at $310 \pm 20^{\circ}C$. The obtained results are in accordance with the Late Triassic depositional age of the Chonos Metamorphic Complex and with the Late Devonian–Early Carboniferous depositional age of the Eastern Andean Metamorphic Complex. The North Patagonian Batholith shows an Early Cretaceous age at its western margin (Pankhurst *et al.* 1999), where it is in contact with the Chonos Metamorphic Complex and is characterized by some Late Jurassic satellite bodies near its eastern margin, where it intruded the Eastern Andean Metamorphic Complex.

Closed system behaviour for Ar retention on fine-grained authigenic illite minerals is suggested at a temperature below $150\,^{\circ}C$ (Hunziker *et al.* 1986). In this case it can be expected that the thermal history of the Chonos Metamorphic Complex and Eastern Andean Metamorphic Complex metapelites close to and reset by intrusions (plutons and stocks) did not reach temperatures higher than $150\,^{\circ}C$, from the intrusive emplacement until present times.

The good correlation of the intrusive ages with the obtained encapsulated ^{40}Ar–^{39}Ar total gas ages in the metapelites suggests that the latter reflect the thermal resetting of the country rock ages produced during emplacement of nearby intrusions. However, this process did not generate obvious contact metamorphic recrystallization textures in the observed rocks, nor did it produce a resetting of the zircon FT ages. The latter is not necessarily contradictory since the analysed illite and zircon minerals are not from the same sample. Resetting did not affect the southernmost and lower grade sample in the Eastern Andean Metamorphic Complex. The encapsulated ^{40}Ar–^{39}Ar retention age might therefore indicate the 'true' age of diagenesis for this sample, that is, 281.7 ± 1.6 Ma.

^{40}Ar–^{39}Ar encapsulation data on metapelites could not discriminate which of the retention or total gas ages generally represent geologically meaningful burial or regional metamorphic ages. Nevertheless, we can suggest with the data presented herein, that encapsulated total gas ages represent contact metamorphic ages and therefore are geologically meaningful in the metapelites of anchi- and epizonal grades that are in close relationship with intrusive bodies. In contrast, retention ages, in case of diagenetic grade and great distance to any intrusion, might represent 'true' stratigraphic ages, and in case of very low-grade metamorphic conditions retention ages most probably represent burial or regional metamorphic events.

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