P–T conditions of metapelites from metamorphic complexes in Aysen, Chile

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Abstract

Pressure and temperature metamorphic conditions were determined for K-white mica and chlorite in metapelites from the eastern Andean metamorphic complex (EAMC) and from the Chonos metamorphic complex (CMC) of southern Chile. The Kübler index (KI) of K-white micas was measured on a <2 μm fraction of 60 metapelites from both complexes. The KI-values obtained from the EAMC vary between 0.26 and 0.16 $\Delta°2\theta$; in the CMC, their range is 0.27–0.17 $\Delta°2\theta$, which indicates that the metamorphic temperatures reached by the metapelites are higher than 300 °C for both complexes. As confirmed by chlorite geothermometer, the temperatures are between 310 and 380 °C. Determination of the metamorphic pressure was carried out through the *b*-parameter of K-white micas and a phengite geobarometer. The *b*-parameter for the EAMC (9.033 ± 0.10 Å) corresponds to a pressure of 4.0 ± 1.2 kbar, and the phengite geobarometer yields pressures of approximately 2.7 kbar. For the CMC, 5.2 ± 0.7 kbar (9.035 ± 0.007 Å) is obtained by *b*-parameter and 3.8 kbar by phengite geobarometer. Although they differ in the pressure values, they are consistent, in that those of the EAMC are relatively lower than those of the CMC. The P–T metamorphic conditions are consistent with a subduction complex along the Gondwandan margin, of which the CMC and EAMC were parts.

Keywords: *b*-parameter; Kübler index; Metamorphic complexes; Southern Chile

1. Introduction

Studies about the metamorphic evolution of sedimentary rocks in terrains such as the Iberian range and the Alps (e.g. Wybrecht et al., 1985; Bauluz et al., 1998; Lopez-Munguira et al., 1998) have established mineral evolution from diagenesis to metamorphism, concentrating on the chemical and crystallographic transformation in the clay-sized fraction of the rocks. This fraction consists of micas, chlorites, kaolinites, smectites, and mixed layer minerals. These transformations are expressed by the crystallochemical parameters of the phyllosilicates. Both the Kübler index (KI), which is measured on K-white micas, and the tetrahedral aluminum content of chlorites (Cathelineau, 1988; Kisch, 1991; De Caritat et al., 1993; Warr and Rice, 1994) depend on temperature. Authors such as Weber (1972) and Velde (1985), among others, have observed several chemical and structural changes in the illite when it passes from the burial diagenesis to the incipient metamorphism:

1. The exchange of the K^+ ion in the interlayer site, which transforms illite into muscovite (Kübler, 1968). Potassium can be supplied by originally K^+-rich detrital micas.
2. The gradual disappearance of expandable layers into mixed layer minerals (e.g. illite/smectite). Smectite transforms into illite through dehydration and K^+ exchange (Eberl, 1980; Velde, 1985).
3. The change of the 1 M-mica polytype, typical in diagenesis, to the 2 M1 polytype in incipient metamorphism (Hunziker et al., 1986; Guidotti et al., 1992).

The changes that affect the structure of the mica are expressed by the variation of the (001) interlayer distance. This *d* parameter is easily analyzed with x-ray diffraction (XRD).

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The KI is defined in a diagram of x-ray intensity v/s °2θ as the full width at the half-maximum peak height (FWHM) of the 10 Å reflection of the illite/muscovite. It is measured in Δ°2θ and diminishes according to the ordering of the illite structure by increases in temperature. The KI can monitor the transition zone from diagenesis to metamorphism s. str., also known as the anchizone. The agreed-on boundary between the diagenetic zone and anchizone is at present KI = 0.42 Δ°2θ, and for the anchizone to epizone limit, it is KI = 0.25 Δ°2θ. These boundaries are associated, respectively, with temperatures of 200 and 300 °C (Kübler, 1968; Warr and Rice, 1994). Concomitant with the changes in white micas, in chlorites a decrease of Si^{IV} (or inversely, an increase of Al^{IV}) and VI vacancy (or inversely, an increase in the Σ^{VI}) has been observed due to the increase of the depth or metamorphic grade in the hydrothermal and/or diagenetic–metamorphic systems (Cathelineau, 1988; Jowett, 1991).

Both the *b*-parameter in K-white micas and the content of Si^{IV} in phengites are controlled by pressure (Sassi, 1972; Guidotti and Sassi, 1986; Massonne and Schreyer, 1987; Massonne and Szpurka, 1997). The geobarometric *b*-parameter is measured on the $6\times d(060,33\bar{1})$ cell dimension of muscovite. This parameter monitors the relative pressure environments of very low to incipient low-grade metamorphic terrains and is used widely as a relative geobarometer for interregional comparisons (Sassi and Scolari, 1974).

The analytical procedure is based on work by Sassi (1972) and Sassi and Scolari (1974) and further development by Guidotti and Sassi (1986). Sassi's (1972) qualitative geobarometer is based on the *b*-parameter value, or more rigorously, $6\times d(060,33\bar{1})$ spacing (Wang et al., 1996; Rieder et al., 1998) of K–Na white micas, which reflects the increasing celadonite substitution $[Al^{IV}_{-1}Al^{VI}_{-1}=Si^{IV}(Fe,Mg)^{VI}]$ that occurs in muscovite with the pressure increase in the Al-rich portion of the nonlimiting muscovite-albite assemblage. The good linear correlation between the value of $6\times d(060,33\bar{1})$ and the celadonite content has been well demonstrated by Guidotti et al. (1989).

In contrast, Massonne and Schreyer (1987) propose a geobarometer in which pressure increase is expressed by an increase of the Si content in phengitic mica in a buffer assemblage with quartz, phlogopite, K-feldspar, and water. Massonne and Szpurka (1997) modify it with new thermodynamic parameters.

These methods are applied to determine the pressure and temperature conditions of metamorphism in the low-grade metapelites of the metamorphic complexes of Aysén. In Aysén, two metamorphic complexes (Fig. 1) are distinguished (Hervé, 1993): the eastern Andean metamorphic complex (EAMC) and the Chonos metamorphic complex (CMC). Both include metapelites and metasandstone-quartzite; in some places, primary sedimentary structures are preserved, but they generally present the texture of mica-quartz schists, with evidence of intense deformation and metamorphic crystallization. The mineralogy of these rocks consists mainly of K-white mica, chlorite, quartz, and albite associated with a low-grade metamorphism. The important presence of white micas in the rocks of both complexes and the absence or unobservability of microscopically metamorphic reactions, such as the formation of biotite, makes the KI and *b*-parameters the only tools to estimate the relative grade of the last metamorphic-tectonic event. This study offers new information about the temperature and pressure metamorphic conditions of the EAMC and CMC.

2. Geological setting

The EAMC and CMC have been subject to studies to examine their similarities and permit a correlation (Miller, 1976). Similarities include their lithology; both consist of metasedimentary rocks (e.g. metapelites, metasandstone, cherts) of low metamorphic grade. The complexes differ in their structural aspects and are considered part of the convergent western margin of Gondwana, in which the EAMC represents a forearc basin position and the CMC corresponds to an accretionary prism.

2.1. EAMC

The EAMC is composed of a mixture of metasandstone, metapelite-schist, metaconglomerate, metachert, and marbles. These lithologies represent a marine platform/slope environment. After deposition, the rocks were affected by at least four deformation events, accompanied by low-grade metamorphism, in the sub-greenschist to greenschist facies (Lagally, 1975; Yoshida, 1981; Ramírez, 1997; Lacassie, 2000).

Niemeyer (1975) distinguishes lower ('unidad inferior') and upper ('unidad superior') units, in which the first unit consists mainly of schists and marbles, and the second corresponds to metapelites, metasandstone-quartzite, and metaconglomerates.

Lagally (1975) names these units the Lago General Carrera Formation and Lago Cochrane Formation. The Lago Cochrane Formation has been assigned an upper Devonian–early Carboniferous age and correlates with the Bahía de la Lancha Formation in Argentina, which has been dated by pollen. These formations are interpreted as turbiditic deposits on a continental platform. The metamorphic grade, according to microscopic mineral assemblages, is greenschist facies.

Ramírez (1997) studied the metamorphism of part of the EAMC, the so-called Chacabuco unit, using the 'illite crystallinity index' (now renamed KI) and *b*-parameter, and determined peak metamorphic conditions of 4.6 ± 1.3 kbar and 380 ± 30 °C.

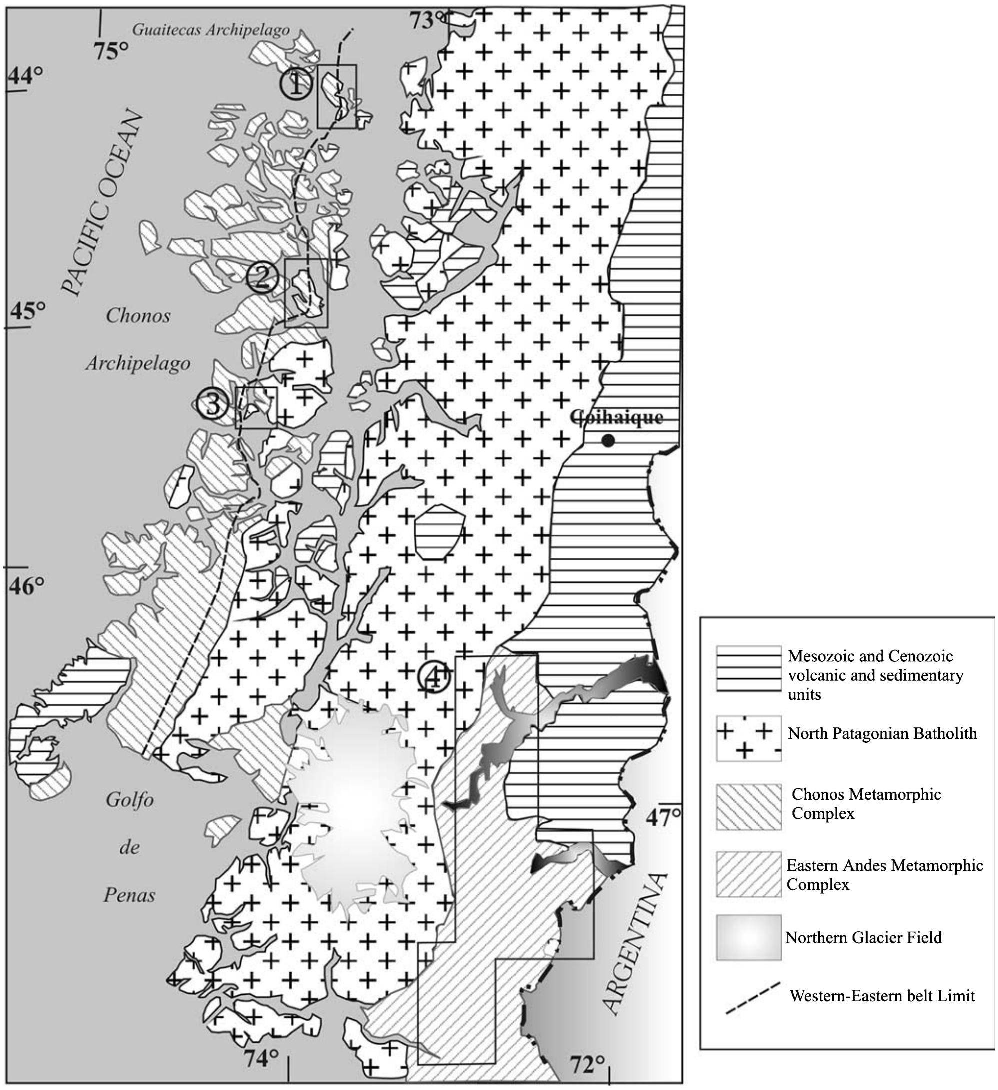

Fig. 1. Schematic geological map of Aysén region. Numbered boxes indicate study zones: (1) Leucayec Island, (2) Teresa Island, (3) Italia Island, and (4) EAMC.

2.2. CMC

The CMC crops out in the insular region of Aysén and consists of metasandstone, chert, metapelites (shales, slates), and greenschists. Hervé et al. (1981) distinguish two structural units for this part of the metamorphic basement: a zone with preserved primary structures (ZEP) and a zone without preserved primary structures (ZSEP). Davidson et al. (1987) define an eastern and a western belt. The eastern belt is characterized by low-grade metamorphism, whereas the western belt is characterized by a higher metamorphic grade (Willner et al., 2000). The CMC is of Late Triassic depositional age (Fang et al., 1998) and interpreted as an accretionary complex.

Garrido (1987) and Hormazábal (1991) carried out studies of metamorphic rocks that belong to the CMC. They applied the illite crystallinity index to metasandstone and metapelites and proposed temperatures of 280–380 °C. However, their measurements were carried out in a unstandardized way. This procedure has been revised by Kisch (1991) and standardization was introduced by Warr and Rice (1994).

3. Methodology

3.1. X-ray powder diffraction

A total of 36 samples of EAMC rocks and 24 samples of CMC rocks were selected and milled in an agate mortar for 5 min. Total-rock XRD analysis of the EAMC samples was performed at the Institut für Mineralogie und Kristallchemie, University of Stuttgart (Germany), on Siemens Bruker-AXS D8 equipment, using Cu Kα radiation and operated at 40 kV and 50 mA. The step width was 0.01°

with 5 s counting time per step; the samples were run between 4 and 80°2θ.

The second group of samples, from the CMC, were analyzed at the GEA Institute (Instituto de Geología Económica Aplicada), University of Concepción (Chile), on Rigaku Geigerflex Dmax equipment. Samples were scanned continuously between 3 and 70°2θ at 1°/min. Copper Kα radiation was used at a 40 kV and 30 mA setting.

3.2. Microprobe analyses

Thirteen thin sections from the EAMC rocks were analyzed on a CAMECA SX50 electron microscope at Ruhr-Universität of Bochum (Germany). The instrumental settings were 15 kV, 10 nA, and 8 μm beam diameter. The following standards were used: jadeite (Na), pyrope (Mg, Al, Si), topaz (F), spessartine (Mn), andradite glass (Fe, Ca), salt (Cl), potassium glass (K), rutile (Ti), and barium glass (Ba).

Eight thin sections from the CMC rocks were analyzed on a CAMECA SU30 electron microprobe at the Department of Geology, University of Chile (Chile). Instrumental conditions were 15 kV, 10 nA, and a beam diameter of 5 μm. The standards used in the calibration were as follows: orthoclase (Al), albite (Na), periclase (Mg), wollastonite (Si), orthoclase (K), wollastonite (Ca), rodonite (Mn), rutile (Ti), and hematite (Fe).

The structural formula for white mica was calculated on the basis of 22 oxygen (21O+(K+Na+(Ba+Ca)/2). All analyses assume Fe total$=Fe^{2+}$. The structural formulae of chlorites were calculated on the basis of 28 oxygen. For each sample, 10–40 points of white mica and chlorite were analyzed.

3.3. Kübler index

The samples were divided in two groups: 36 from the EAMC and 24 from the CMC, taken from Italia, Teresa, and Leucayec Islands. For samples destined for KI determination, the <2 μm fraction was obtained following the recommendations of IGCP 294. The XRD measurements were carried out on a Siemens D 5000 diffractometer with a graphite monochromator at the Department of Physics, University of Chile. Instrumental conditions were 40 kV, 30 mA, and constant time 2 s, with step scanning. Samples of the CMC were scanned with a Rigaku Geigerflex Dmax diffractometer at the GEA Institute, University of Concepción. The instrumental conditions were 40 kV, 20 mA, Ni-filtered Cu Kα radiation, and a continuous scan speed of 1°/min. All samples were air dried and glycolated. No shift of the basal white mica reflection was observed, so the results are discussed using the air-dried scan results.

The standardization of the values (KI_{DP} values from Department of Physics; KI_{GEA} from GEA Institute) obtained from each diffractometer was carried out with the international standards provided by Warr and Rice (1994). The equations representing each case are as follows:

$$KI = 1.6479 \times KI_{DP} - 0.0143; \quad R^2 = 0.8732 \text{ (EAMC)}. \tag{1}$$

$$KI = 1.5728 \times KI_{GEA} - 0.0678; \quad R^2 = 0.8908 \text{ (CMC)}. \tag{2}$$

3.4. b-parameter

Using the procedures defined by Sassi and Scolari (1974), each sample was cut perpendicularly to its schistosity. Quartz of the schist and metallic silicon added into grooves drilled into the rock slices were used as internal standards.

The diffractometric analyses were carried out directly on these slices, ensuring in all cases that the x-ray area was phyllosilicate rich. The 2θ range scanned was 59.0–62.5°. The measurements were carried out at the Department of Mineralogy and Petrology, University of Padova (Italy), using a Phillips PW3710. The working conditions (statistical error 1–2%) guaranteed good resolution. The precision of the measurements was tested on three samples with very different $6 \times d(060, 33\bar{1})$ values by repeating the diffractometric analyses 30 times. The standard deviation

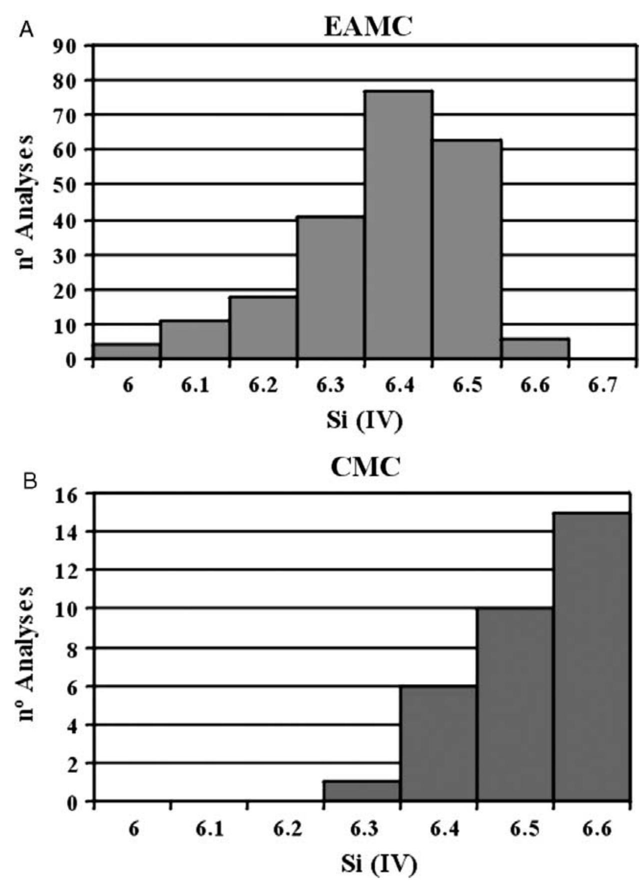

Fig. 2. Si content histogram from microprobe analyses on micas. (A) EAMC, (B) CMC.

obtained is 0.0025. The scans were analyzed statistically by mean values and the relative standard deviation and are presented as cumulative frequency curves.

The cautions issued by Frey (1997) and Essene (1989) were taken into account through the careful analytical procedure (Guidotti et al., 1989). Furthermore, Frey and Robinson (1999) and Wang et al. (1996) have used this method successfully.

4. Results

The results have been divided in two sections for samples from the EAMC and those from the CMC (Fig. 1).

4.1. Chemistry

4.1.1. EAMC

By means of whole-rock XRD analysis, mainly quartz, albite (low temperature), muscovite 2 M1, di-trioctahedral chlorite, and aluminum chlorite were detected.

The chemical composition of white micas in 13 samples was calculated on the basis of 22 oxygen. Because the rocks are fine-grained metapelites, in some cases, only few analyses of apparently single mica phases could be obtained. The results can be divided into two groups: (1) 32% with a formula content of Si (a.p.d.u.f) of 6.0–6.4 and (2) 68% with Si > 6.4 (Fig. 2A). The latter correspond to phengites with an important tschermakitic substitution (Fig. 3A–D).

The chemical composition of the chlorites indicates amesite as their main component. The formula content of Si < 6.0, the low contents of Al^{IV} with respect to Al^{VI}, and the resulting increase in R^{2+} indicates the presence of metamorphic chlorites (Fig. 5).

4.1.2. CMC

Whole-rock XRD identifies three groups of samples: (1) quartz, clinochlore 1 MIIb, albite, and muscovite of the 2 M1 polytype; (2) in the LEU samples (from Leucayec Island), 3T polytype muscovite; and (3) in the TER samples (from Teresa island), both ordered and disordered albite, together with microcline-type K-feldspar.

The microchemistry of the micas indicates that the majority correspond to illite (Figs. 2B, 4A and B). Furthermore, tschermakitic substitution is observed (Fig. 4C and D). The chlorites recognized have a main

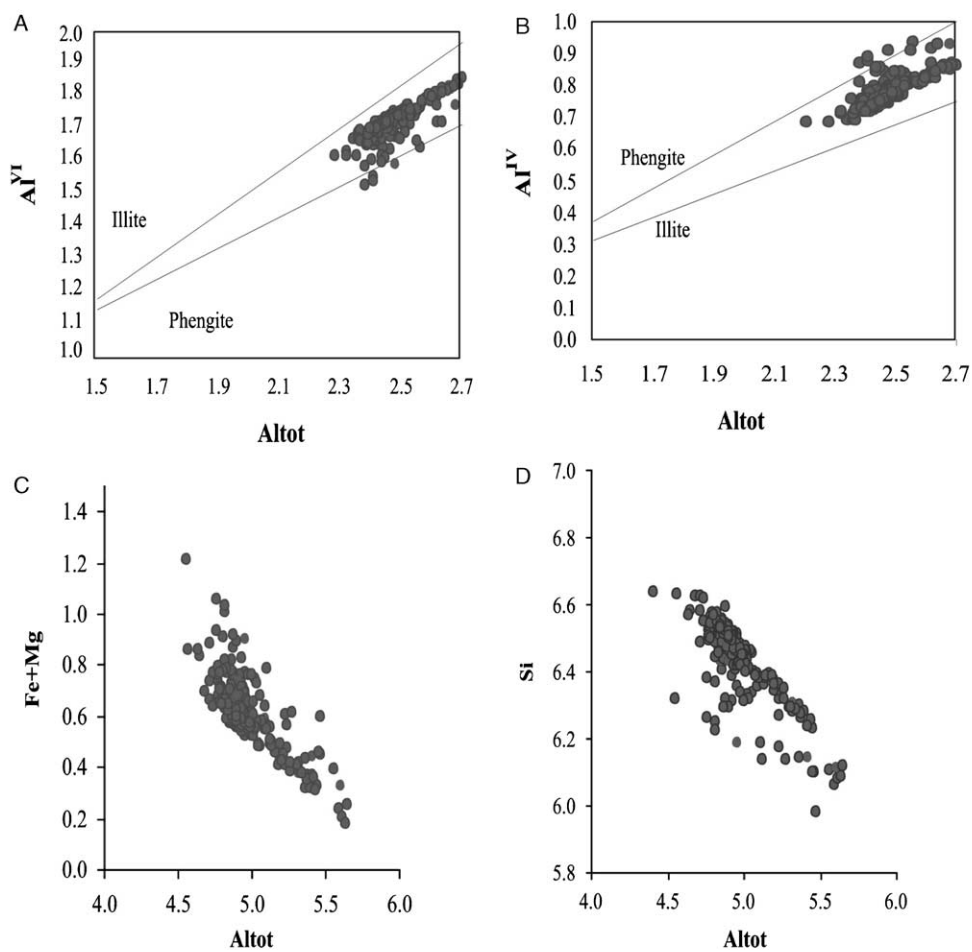

Fig. 3. Determination between illite and phengite of micas from EAMC. (A) Al tetrahedral versus Al total content. (B) Al octahedral versus Al total content. (C, D) Tschermakitic substitutions.

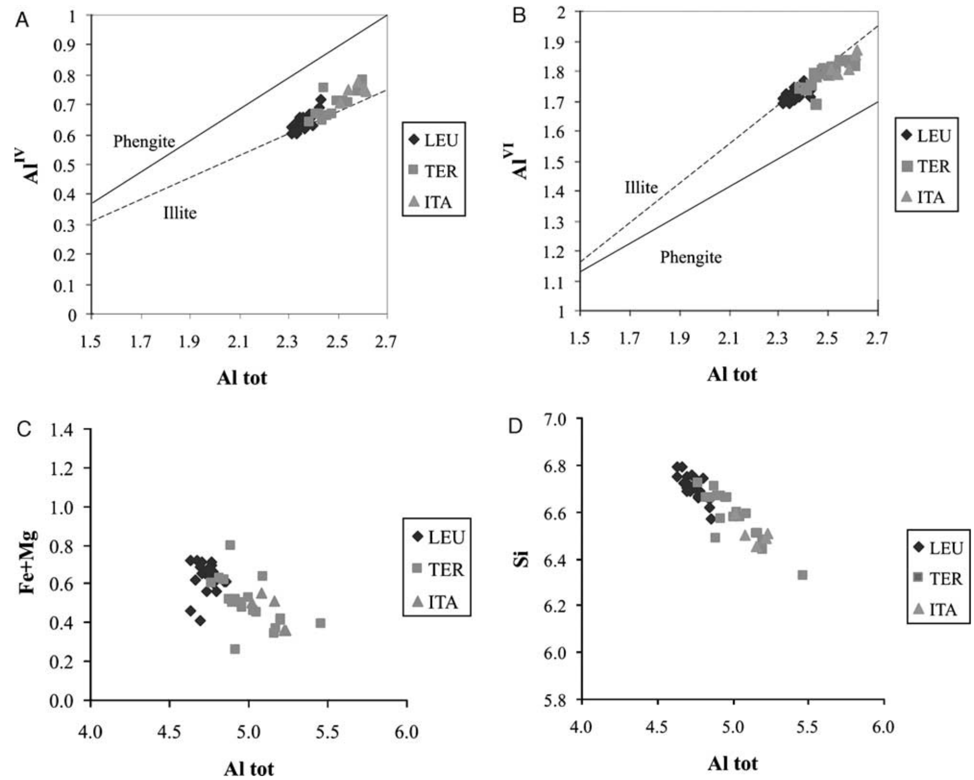

Fig. 4. Determination between illite and phengite of micas from CMC. (A) Al tetrahedral versus Al total content (Weaver and Broekstra, 1984). (B) Al octahedral versus Al total content. (C, D) Tschermakitic substitutions.

component of amesite and have a characteristically metamorphic origin (Fig. 5).

4.2. Kübler index

Fig. 6 shows the regional distribution of the KI values for the CMC and EAMC.

4.2.1. EAMC

The KI values obtained for the EAMC (Fig. 6) vary between 0.26 and 0.16 $\Delta°2\theta$ and are grouped in two areas. Low values corresponding to the anchizone/epizone boundary are concentrated south of Cochrane and found in a more dispersed (wider) area near Bertrand Lake.

4.2.2. CMC

The KI values for Italia Island vary between 0.27 and 0.19 $\Delta°2\theta$; three are anchizonal, and the rest are epizonal. For Teresa Island, the values vary between 0.25 and 0.16 $\Delta°2\theta$, and all are inside the epizone. However, to the southwest, samples have the lowest values of KI and form part of the eastern belt. For Leucayec Island

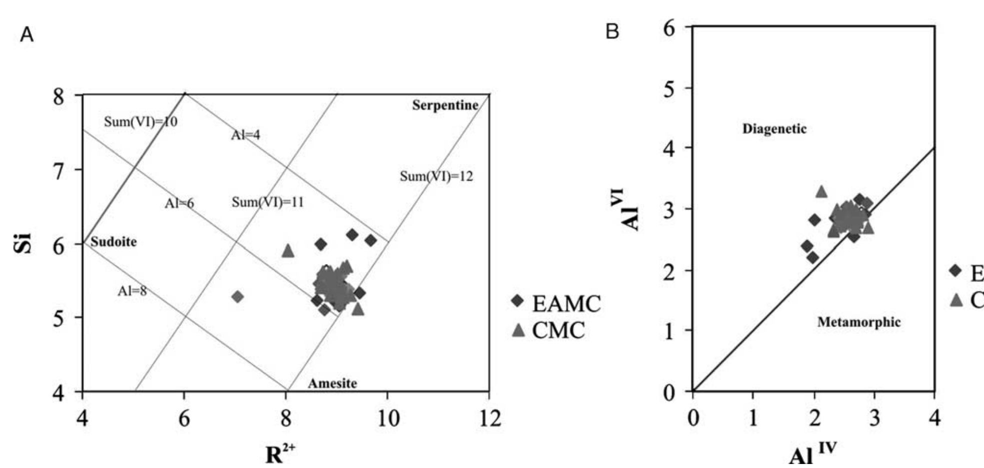

Fig. 5. Determination between diagenetic and metamorphic chlorite (Wiewiora and Weiss, 1990). (A) Compositional vectors, Si versus R^{2+}($R^{2+}=Mg^{2+}+Fe^{2+}$). (B) Tetrahedral Al versus octahedral Al.

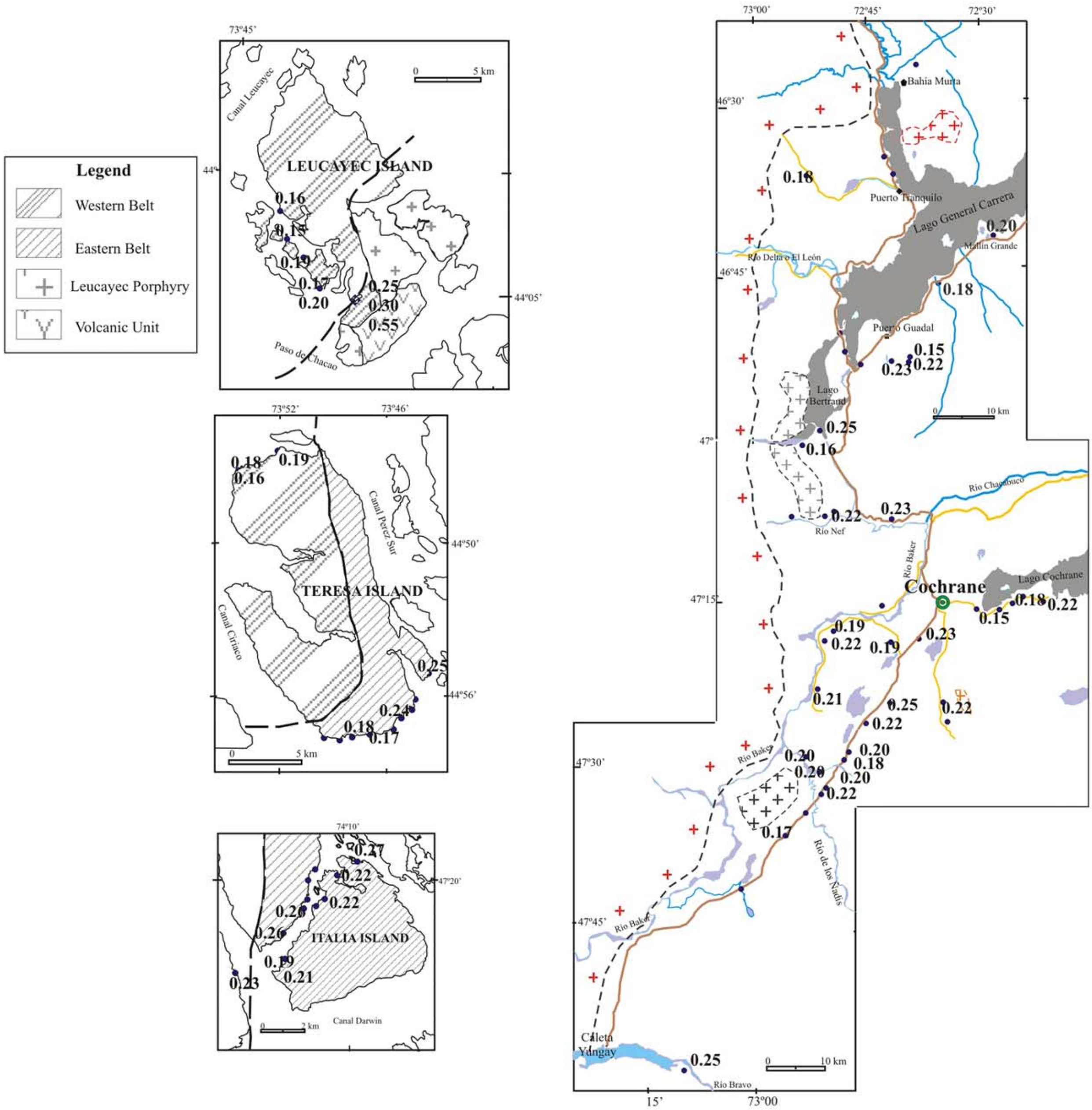

Fig. 6. Distribution of KI values in the study zones, calculated according to Eqs. (1) and (2).

(Ramírez et al., 2002), values vary between 0.20 and 0.15 $\Delta°2\theta$, so the epizonal values prevail, with three exceptions that have lower KI values: one diagenetic and two anchizonal. All are geographically very near to one another (Fig. 6).

4.3. Chlorite geothermometry

4.3.1. EAMC

Table 1 shows the mean temperature range, 317–403 °C, according to Cathelineau (1988). Sample 2404 has two groups of values from four analyses: a mean value lower than 300 °C and one >300 °C.

4.3.2. CMC

In all analyses with both geothermometry methods, the average temperatures are higher than 300 °C. However, the temperatures obtained by Cathelineau (1988) are lower than those obtained by Jowett (1991), as is shown in Table 2.

4.4. b-parameter

4.4.1. EAMC

Fig. 7 shows that the *b*-parameter values vary between 9.000 and 9.050 Å. Their distribution is heterogeneous within the study area.

Table 1
Temperatures *T*1 and *T*2 obtained by Cathelineau's (1998) and Jowett's (1991) geothermometers, respectively, from samples from the EAMC

EAMC	*T*1	*T*2
1202	365±14 (6)	
1501	365±5 (2)	375(1)
1604	370 (1)	
2102	365±5 (8)	
2106	372±3 (2)	
2302	369±25 (4)	
2404	254±10 (3)/363 (1)	261±11 (3)/370 (1)
2501	368±6 (11)	
2704	357±19 (8)	359 (1)
2801	370±9 (10)	382 (1)
2802	339±14 (5)	
50302	387±8 (4)	

All *T*2 were calculated for chlorites with a Fe/(Fe+Mg) ratio of <0.6. The number of chlorite analyses for each sample is indicated in parentheses.

The average *b*-parameter value is 9.026 Å, with a standard deviation of 0.013. The majority of the values fall between 9.040 and 9.025 Å, and 50% of them are greater than 9.020 Å (Fig. 8). The cumulative frequency curve points to an intermediate pressure regime, between the curves of the New Hampshire and Eastern Alps terrains (Sassi and Scolari, 1974).

On the basis of the average temperatures of 320–400 °C, as determined by the geothermometers of Cathelineau (1988) and Jowett (1991), a pressure of 4.2±1.0 kbar is obtained, according to Guidotti and Sassi (1986) (Fig. 9).

4.4.2. CMC

Fig. 7 shows the homogeneous values of the *b*-parameters obtained from CMC rocks of Italia, Teresa, and Leucayec Islands, which average 9.035±0.006, 9.037±0.008, and 9.035±0.006 Å, respectively. For all three islands, the average *b*-parameter value is 9.036±0.007 Å. For Leucayec Island, samples LEU3-1, LEU3-2, and LEU4-2 have been grouped separately because of their vicinity to a contact aureole.

The distribution of the *b*-parameter measurements does not show any tendency within the islands. On a regional CMC level, a slight increase is observed to the north; Italia Island presents lower values than Leucayec Island. Fig. 8 shows the *b*-parameter cumulative frequency curves for each island, as well the grouped CMC curve. According to Sassi and Scolari (1974), pressure regimes represented by these values are close to the intermediate pressures of collision environments, with a similar slope as the Otago curve.

Table 2
Temperatures *T*1 and *T*2 obtained by Cathelineau's (1998) and Jowett's (1991) geothermometers, respectively, from samples from the CMC

CMC	*T*1	*T*2
LEU3-2	326±7 (4)	336±8 (4)
LEU5-3	363±6 (3)	372±6 (3)
LEU7-2	346±11 (7)	356±11 (7)
TER10-1	375±17 (9)	385±18 (9)
TER4-2	339±41 (4)	377±10 (2)
ITA4-2	350±32 (3)	361±33 (3)

All *T*2 were calculated for chlorites with a Fe/(Fe+Mg) ratio of <0.6. The number of chlorite analyses for each sample is indicated in parentheses.

On the basis of the temperature of 345±47 °C obtained by the geothermometer of Cathelineau (1988), a pressure of 5.2±0.7 kbar is obtained, using Guidotti and Sassi's (1986) graph (Fig. 9).

4.5. Phengite geobarometer

4.5.1. EAMC

The mica analysis with a phengite component and the corresponding temperature assumed by Cathelineau's (1988) values for each sample provide pressures between 2.5 and 3 kbar (Fig. 10).

4.5.2. CMC

Only Leucayec Island contains phengitic mica, with an Si content of 6.7 a.p.f.d.u. Assuming a temperature of 363±6 °C, the pressures are 3.5 and 3.9 kbar. These samples do not have a buffer assemblage; therefore, the pressure is considered a minimum pressure of metamorphism.

4.6. Thermobarometry

In this section, we present some results from the phengite-chlorite assemblage thermobarometer (Vidal et al., 2001) using a microprobe analysis of phengite-chlorite pairs and applying the TWQ software modified by Vidal et al. (2001), which shows P–T conditions with reaction curves from phases in the rock.

In sample 2704 from the EAMC, we obtained two intersection points (Fig. 11): between a first group that includes a ferroamesite component but excludes an aluminoamesite component and a second group with inverse conditions. The first point is 6.9 kbar and 390 °C (Fig. 11A), which results from the intersections of the following multivariant reactions:

1. Daphneite+5 Aluminoceladonite=5 Ferroceladonite+Clinochlore.
2. 5 Aluminoceladonite+FerroAmesite=Clinochlore+4 Ferroceladonite+$Muscovite_{phengite}$.
3. FerroAmesite+Ferroceladonite=$Muscovite_{phengite}$+Daphneite.
4. 5 FerroAmesite+5 Aluminoceladonite=4 Daphneite+Clinochlore+5 $Muscovite_{phengite}$.

The second point is 6.7 kbar and 386 °C, close to the preceding value (Fig. 11B), and is defined by the intersections of the following reactions:

5. Daphneite+5 Aluminoceladonite=5 Ferroceladonite+Clinochlore.

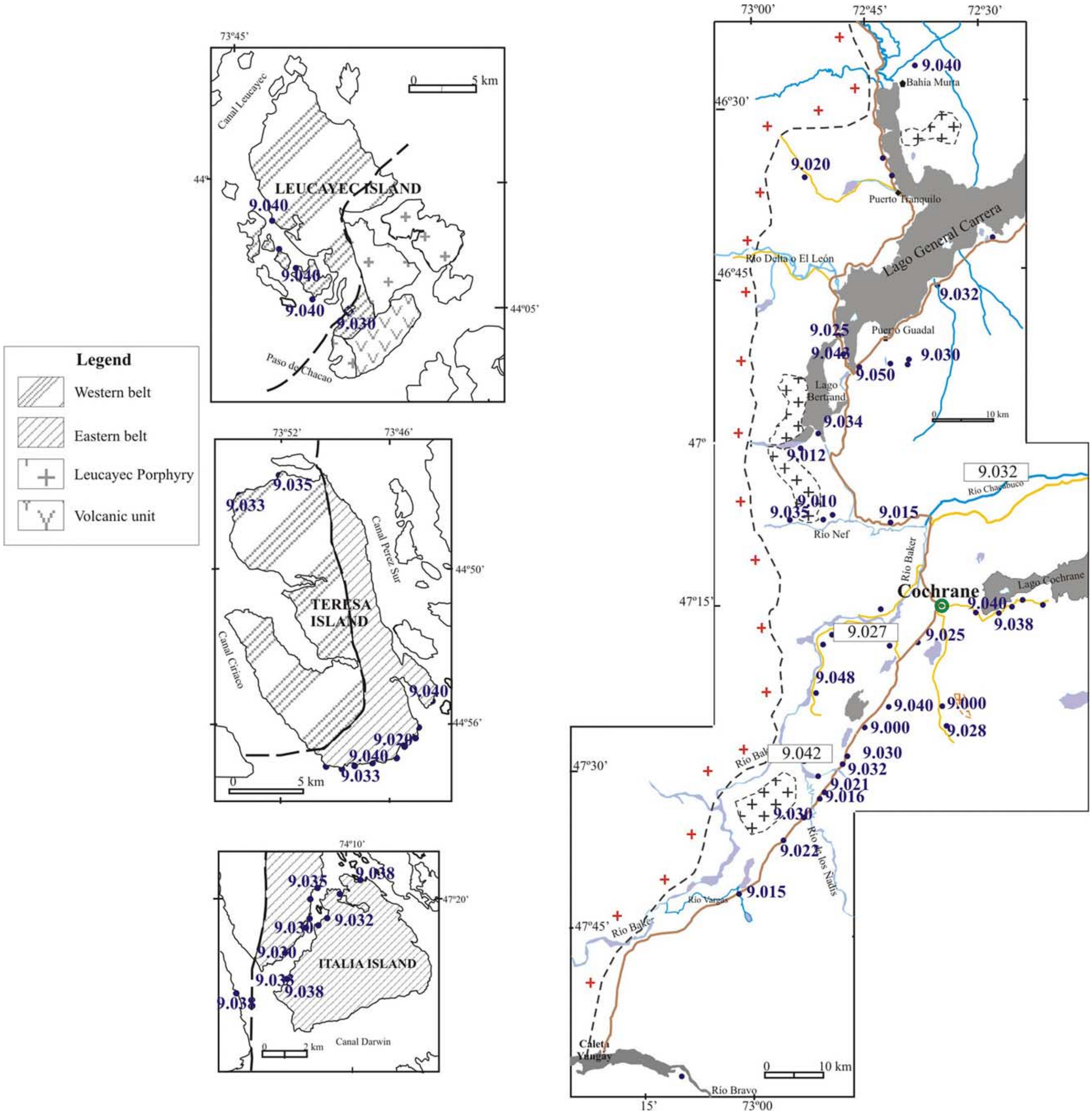

Fig. 7. Distribution of b-parameters in the study zones. Numbers in box indicate means of the b-parameters from an area within EAMC (Ramírez and Sassi, 2001).

6. Aluminoceladonite + Aluminoamesite = Clinochlore + $Muscovite_{phengite}$.
7. 5 Ferroceladonite + 5 Aluminoamesite = Daphneite + 4 Clinochlore + 5 $Muscovite_{phengite}$.
8. Daphneite + 4 Aluminoceladonite + $Muscovite_{phengite}$ = 5 Ferroceladonite + Aluminoamesite.

For two samples from the CMC, it was possible to apply the thermobarometer. For a mineral pair from sample TER10-13, an intersection point that includes two amesite components (ferro and alumino) was found. The intersection point is 373 °C and 8.6 kbar (Fig. 12A) and results from the following reactions:

1. 5 Ferroamesite + 4 Clinochlore = 5 Aluminoamesite + 4 Daphneite.
2. 5 Ferroamesite + 5 Aluminoceladonite = 5 $Muscovite_{phengite}$ + Clinochlore + 4 Daphneite.
3. Aluminoceladonite + Aluminoamesite = Clinochlore + $Muscovite_{phengite}$.
4. 5 Ferroamesite + 4 Aluminoceladonite = 4 $Muscovite_{phengite}$ + Aluminoamesite + 4 Daphneite.

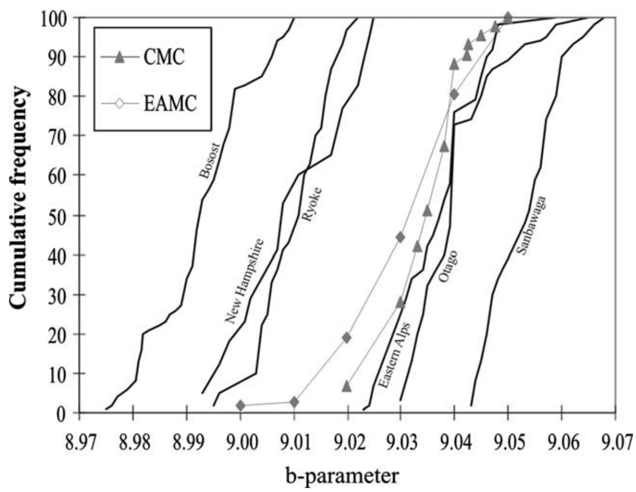

Fig. 8. Cumulative frequency versus *b*-parameter in the CMC and EAMC and comparison with other metamorphic terrain curves (Sassi and Scolari, 1974).

In sample LEU 7-2, two intersection points were found, according to the amesite component. With a ferroamesite component (Fig. 12B), an intersection point at 4.1 kbar and 316 °C was obtained from the following reactions:

1. Daphneite + 5 Aluminoceladonite = 5 Ferroceladonite + Clinochlore.
2. 5 Aluminoceladonite + Ferroamesite = Clinochlore + 4 Ferroceladonite + $Muscovite_{phengite}$.
3. Ferroamesite + Ferroceladonite = $Muscovite_{phengite}$ + Daphneite.

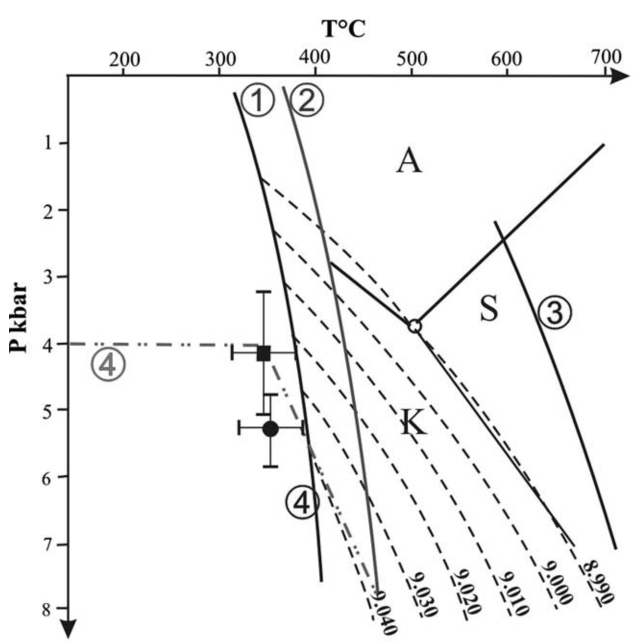

Fig. 9. P–T graph with *b*-parameter isopleth (Guidotti and Sassi, 1986). Square represents the *b*-parameter average value of the EAMC and dot represents the value of the CMC. Bars indicate (±) standard deviation. Numbered circles indicate the reaction curves (thick lines): (1) kaolinite dehydration; (2) pyrophyllite dehydration; (3) St + Qz + Ms = Al–Si + Bt + H_2O; and (4) glaucophane stability.

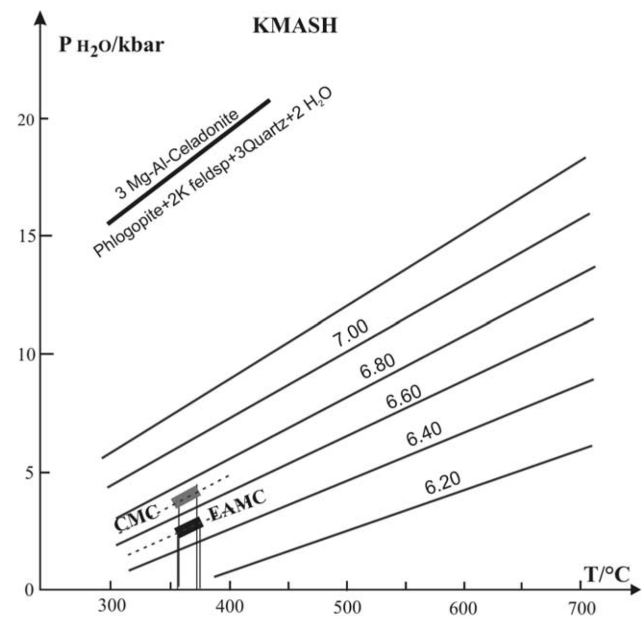

Fig. 10. P–T graph with Si content on isolines (modified from Massonne and Szpurka, 1997). Bars indicate ranges for each complex, depending on the Si content of micas.

4. 5 Ferroamesite + 5 Ferroceladonite = 5 $Muscovite_{phengite}$ + Clinochlore + 4 Daphneite.

With an aluminoamesite component, the intersection point is 6.0 kbar and 344 °C (Fig. 12C), as generated by the following reactions:

5. Daphneite + 5 Aluminoceladonite = 5 Ferroceladonite + Clinochlore.
6. Aluminoceladonite + Aluminoamesite = Clinochlore + $Muscovite_{phengite}$.
7. 5 Aluminoamesite + 5 Ferroceladonite = 5 $Muscovite_{phengite}$ + 4 Clinochlore + Daphneite.
8. $Muscovite_{phengite}$ + 4 Aluminoceladonite + Daphneite = Aluminoamesite + 5 Ferroceladonite.

5. Discussion

5.1. Geothermometry

The rocks of the EAMC reach metamorphism temperatures greater than 300 °C, according to KI values, and are dominantly epizonal or incipient greenschist facies (KI > 0.25 $\Delta°2\theta$). This finding agrees with the temperatures of 320–390 °C obtained for chlorite using the geothermometers of Cathelineau (1988) and Jowett (1991). Hervé et al. (1999) find temperatures of approximately 360 °C from metabasalt mineralogy, which coincide with the temperature determinations from metapelites.

Leucayec Island belongs to the western CMC (ZSEP) belt. The KI values are epizonal (Ramírez et al., 2002),

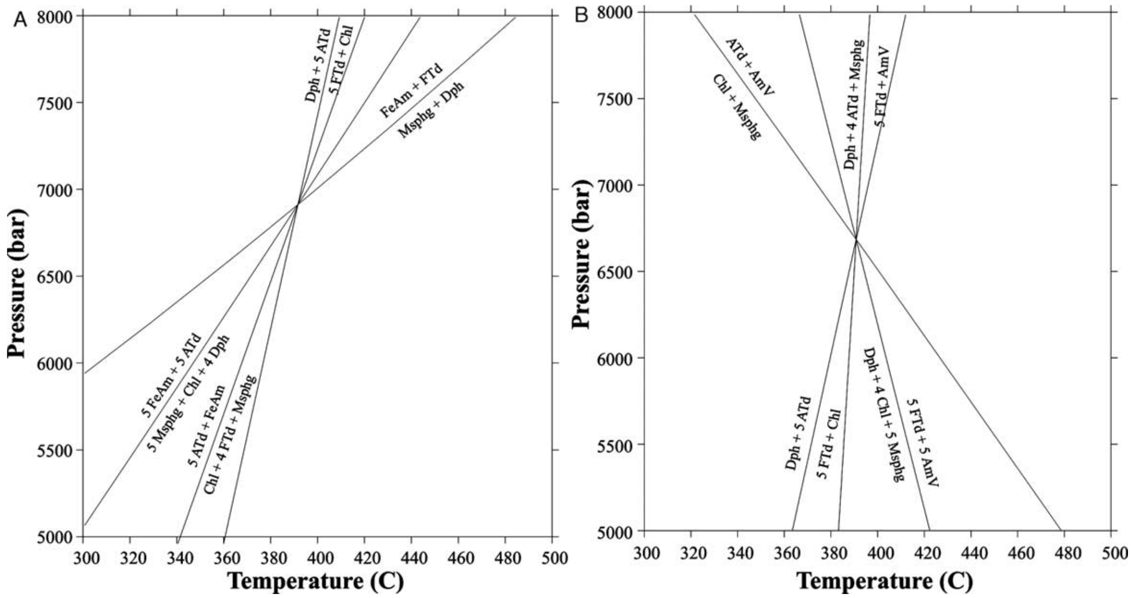

Fig. 11. P–T estimate using TWQ software, modified by Vidal and Parra (2001), on sample 2704 from the EAMC. Included phases: muscovite phengitic (Msphg), aluminoceladonite (ATd), ferroceladonite (FTd), daphneite (Daph), clinochlore (Chl), ferroamesite (FeAm), and aluminoamesite (AmV). (A) P–T estimate using ferroamesite; (B) P–T estimate using aluminoamesite.

except for two anchizonal and one diagenetic value. The diagenetic sample LEU3-2 indicates temperatures of illite formation below 200 °C. However, chlorite geothermometry for this sample indicates temperatures above 300 °C, which suggests that two different thermal processes affected the micas. The fraction <2 μm of the illites represents a last retrograde metamorphic-hydrothermal episode linked to nearby Leucayec porphyry copper deposit development (Fuenzalida and Spring, 1979). This possible late event is evidenced only in the fine, neoformed mineral fraction. For other samples, chlorite temperatures agree with epizonal KI measurements

Teresa Island presents epizonal KI values for both eastern (ZEP) and western (ZSEP) belt sections. No difference appears between the two belts, in contrast to the study by Garrido (1987), which indicates an increase in the metamorphic grade to the west. For both belts, chlorite geothermometers are greater than 300 °C and thus agree with the KI values.

Italia Island is part of the eastern belt (ZEP), and KI values border the anchizone/epizone limit, in line with determinations by Hormázabal (1991). Similar to the other islands, chlorite temperatures exceed 300 °C. However, temperatures between 250 and 280 °C obtained for metabasalts of the eastern belt (Willner et al., 2000) using mineralogical zonation in garnets and conventional geothermobarometry based on mineral associations are lower than those obtained herein. They suggest two patterns of metamorphism, retrograde for the eastern belt and prograde for the western belt, as well as a P–T gap between belts. The values obtained here are from rocks located north of the sites studied by Willner et al. (2000), in what may be a gradational contact. Therefore, the gap in P–T conditions may not exist along the entire contact between the eastern and western belts.

Overall, similar temperatures were obtained for both the CMC and the EAMC, even using geothermometers based on minerals of different size scales. The analyzed minerals for the KI determinations are fine-grained white mica fractions of <2 μm, whereas the minerals selected for the chlorite geothermometer have a minimum size of 5 μm to enable monophase analysis by the electron microprobe.

5.2. Geobarometry

Pressures obtained in both metamorphic complexes from the *b*-parameter and phengite barometer are slightly inferior in the EAMC compared with those of the CMC. The larger data set from the *b*-parameter shows that both complexes fall within the intermediate pressure range (Sassi and Scolari, 1974). According to Padán et al. (1982), this crystallographic parameter is not influenced by crystal size, unlike KI observations.

The tectonic settings suggested for the evolution of the CMC and EAMC are represented by a subduction zone (Willner et al., 2000) and a passive margin basin (Lacassie, 2000), respectively. This suggestion indicates a higher P–T gradient for the former and possibly a more moderate one for the latter.

The cumulative frequency curve of *b*-parameter values in the EAMC (Fig. 8) is located between those of the collisional orogenic environments of the New Hampshire and Eastern Alps (Sassi and Scolari, 1974), which indicates a high P–T gradient, though inferior to those developed in an accretionary prism, such as the Sanbagawa belt.

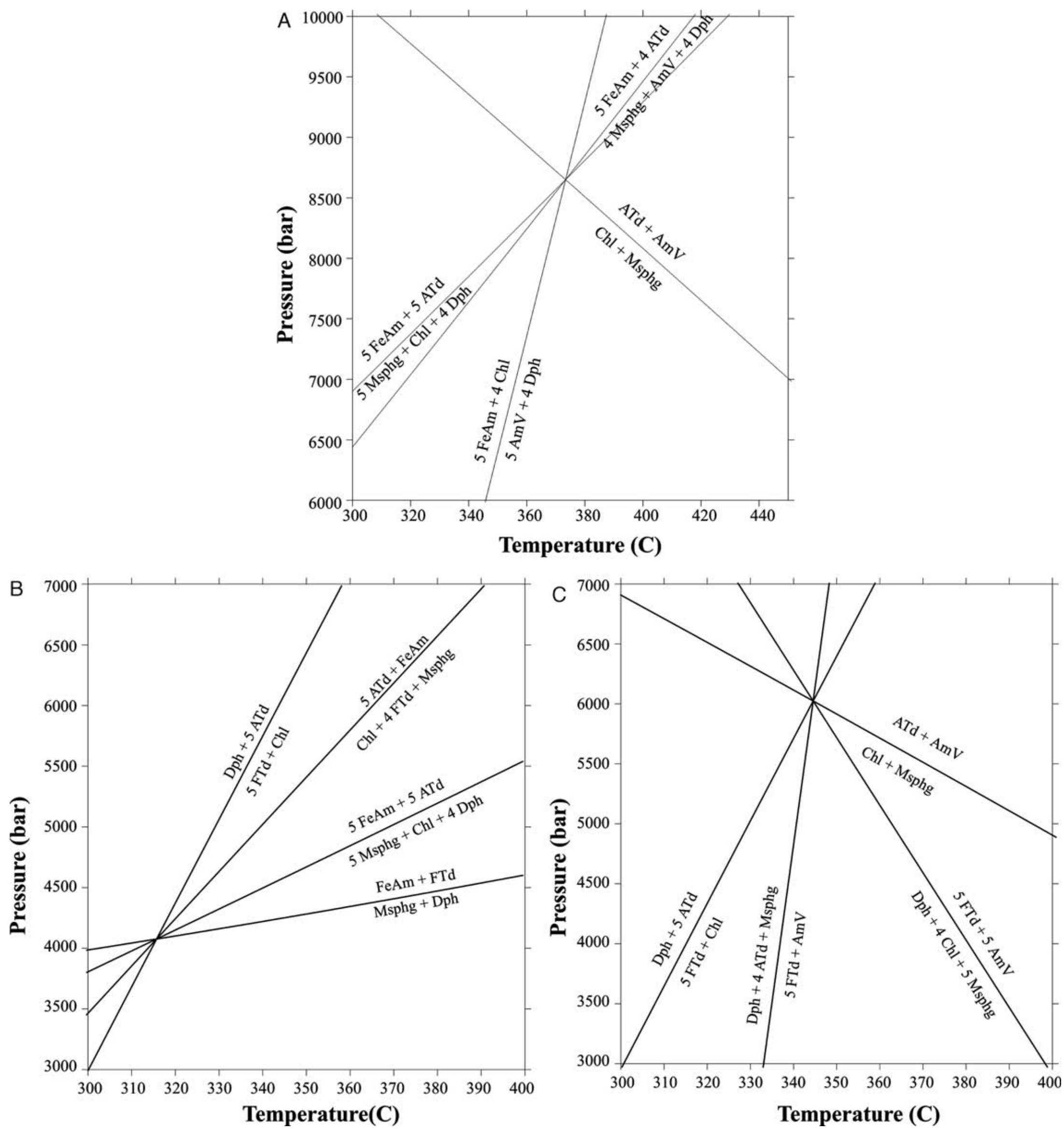

Fig. 12. Using the TWQ software modified by Vidal and Parra (2001), (A) P–T estimate for sample TER10, (B) sample LEU7-2 including only ferroamesite, and (C) sample LEU7-2 including only aluminoamesite. Included phases: muscovite phengitic (Msphg), alumino-celadonite (ATd), ferroceladonite (FTd), daphneite (Daph), clinochlore (Chl), ferroamesite (FeAm), and aluminoamesite (AmV).

The cumulative frequency curve of the CMC is located closer to the Eastern Alps' curve than the frequency curve of the EAMC, which points to a slightly higher P–T gradient for the CMC. The gradients of both Aysén complexes differ from those of extensional settings such as Bosost and Ryoke.

Bell and Suárez (2000) indicate the Río Lácteo Formation in Argentina originated in the crystalline nucleus of an orogenic mountain range, probably as the result of a collision of microplates, rather than as the result of a forearc accretion, comparable to the Otago schists of New Zealand. The Río Lácteo Formation correlates with the Lago General Carrera Formation (Lagally, 1975). The *b*-parameter cumulative frequency curve for Otago (Fig. 8) plots close to and on the high pressure side of the Eastern Alps environment, and its slope is similar to the CMC curve. Further analyses of metapelites from the western belt of the CMC, outside any influence of the Patagonian batholith, are needed to provide unequivocal pressure evidence from metapelites and support Willner et al.'s (2000) proposed model of an accretionary prism.

5.3. Geothermobarometry

In this first application of the phengite-chlorite geothermobarometer (Vidal and Parra, 2001), interesting values have been obtained from the three samples in which mineral pairs were analyzed. From the phengite-chlorite pair of sample 2704 (EAMC), the pressures and temperatures are inside the ranges determined previously for this complex by the previously mentioned geothermometers and geobarometers. However, the temperature of 388 °C is higher than the temperature estimated for the same sample by KI, which is close to the limit between anchizone/epizone and near 300 °C. This difference may be because the minerals analyzed are of the <2 μm fraction, whereas the crystal analyzed by Vidal and Parra (2001) is >5 μm. The micas from these two populations may record different moments in the P–T evolution of the rock.

From the phengite–chlorite pair of sample TER10-13 (western CMC belt), the obtained pressure (8.6 kbar) coincides with that (8–10 kbar) estimated by Willner et al. (2000), but the temperature is slightly lower than their estimation of 380 °C. For sample LEU7-2 (localized on the western belt), the temperature values obtained by Cathelineau (1988) and the pressure values obtained by the geobarometer of the *b*-parameter differ from those obtained by the geothermobarometer, as well as from those of the western belt of the CMC, as defined previously. The values obtained in this case by the geothermobarometer are close to those of the eastern belt.

6. Conclusions

The application of different geothermometry and geobarometry methods according to the phyllosilicate mineralogy of low-grade metapelites lacking index minerals enabled us to obtain metamorphic temperature and pressure conditions in both the EAMC and the CMC. The KI values in white micas indicate that the metamorphic grade in the EAMC and CMC exists in the epizone, with some anchizone KI values in the southern areas of the CMC. The temperatures calculated by Cathelineau's (1988) method in chlorites are considered more representative than those obtained from Jowett's (1991) geothermometer because they are closer to the predicted temperatures from their KI values. The pressures obtained by Guidotti and Sassi's (1986) method are considered more representative than those obtained from the phengite geobarometer (Massonne and Szpurka, 1997) because the latter indicates only minimum pressures due to the absence of the buffer paragenesis. Therefore, the metamorphic conditions for the studied metapelites are as follows: In the EAMC, the temperatures vary between 320 and 390 °C, and the mean pressure is 4.0 ± 1.2 kbar. In the CMC, the temperatures vary between 310 and 390 °C, and the mean pressure is 5.2 ± 0.7 kbar. These results are consistent with the interpretation that the CMC is a subduction complex subject to a higher P–T metamorphic gradient than is the EAMC, which evolved in a more inboard continental environment in the Gondwana margin.

For further application of Vidal and Parra's (2001) phengite-chlorite geothermobarometer, a larger set of P–T values and the relation of chlorite and phengite crystal sizes must be taken into account, so that we may obtain the P–T evolution curve of these mineral phases.

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