Low-grade metamorphism of Mesozoic and Cenozoic volcanic sequences of Patagonia, Chile (43-46°S)

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ABSTRACT

Rocks belonging to various units from the Jurassic to the Neogene were studied in the Chilean Patagonian area between 43 and 46°S. All these rocks were affected by very low to low grade metamorphism in the zeolite, prehnite-pumpellyite and greenschist facies. Differences in grade are related to the age of the rock sequences with the youngest (Tertiary) metamorphosed in zeolite and the oldest (Jurassic) in greenschist facies. Temperatures for the metamorphic processes are in the range 120° to 340°C with P below 2 kb. A thermal imprint of Cretaceous granitoids on the Jurassic rocks exists almost completely obliterating an earlier low-grade regional metamorphic pattern.

Key words: Volcanic rocks, Low-grade metamorphism, Metamorphic facies, P-T conditions, Mesozoic, Cenozoic, Patagonia, Chile.

RESUMEN

Metamorfismo de bajo grado de secuencias volcánicas mesozoicas y cenozoicas de Patagonia (43-46°S), Chile. Rocas de varias unidades expuestas en la Patagonia chilena (43-46°S) con edades entre el Jurásico y el Neógeno fueron afectadas por metamorfismo de muy bajo a bajo grado en facies ceolita, prehnita-pumpellyita y esquistos verdes. Las diferencias en el grado están relacionadas con la edad de las unidades, las más jóvenes (Terciario) metamorfizadas en facies ceolita y las más antiguas (Jurásico) en esquistos verdes. La temperatura del metamorfismo varía entre 120° y 340°C con presión inferior a 2 kb. En las rocas jurásicas existe una impronta térmica relacionada con los granitoides cretácicos la que oblitera un esquema metamórfico regional anterior de bajo grado.

Palabras claves: Rocas volcánicas, Metamorfismo de bajo grado, Facies metamórficas, Condiciones P-T, Mesozoico, Cenozoico, Patagonia, Chile.

INTRODUCTION

Results of a petrological reconnaissance of various Mesozoic and Cenozoic volcano sedimentary rock sequences of Patagonia (43-46°S) are reported with the aim to describe and discuss the characteristics of very low- and low-grade metamorphic phenomena affecting these rocks. The sequences

Revista Geológica de Chile, Vol. 24, No. 2, p. 187-201, 6 Figs., 3 tables, December 1997.

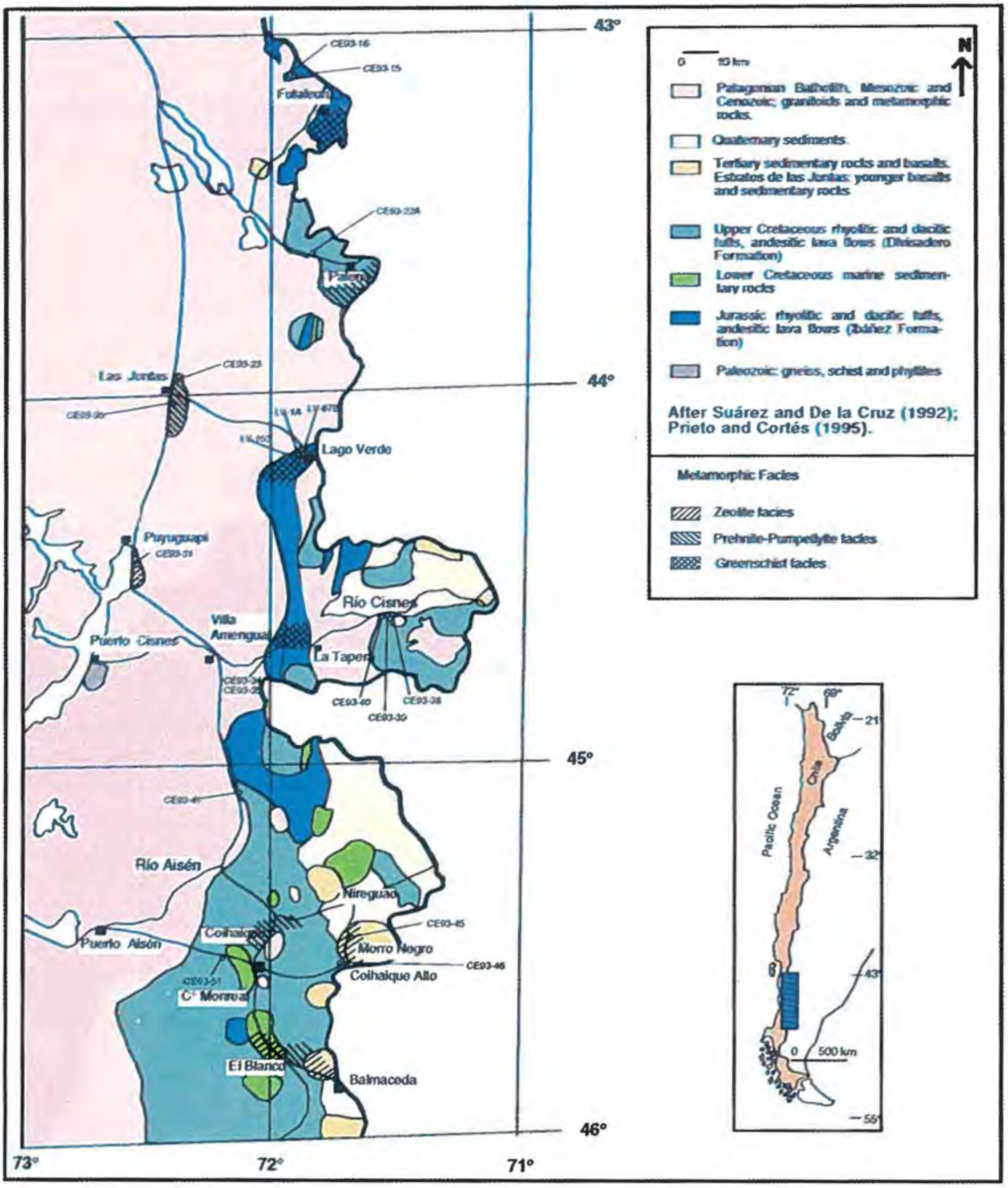

FIG. 1. Geological sketch of the Patagonian region (43°-46°S), showing stratigraphic units (after X. Prieto and J.A. Cortés[1]; M. Suárez and R. De la Cruz[2]), and distribution of metamorphic facies (this paper).

[1] 1995. Geología del sector oriental de la Hoja Río Cisnes (71° a 72°20' LW y-44° a 45° LS.), Región de Aysén. Informe de Avance, Proyecto Aysén NE (Inédito), *Convenio Gobierno Regional XI Región-Servicio Nacional de Geología y Minería*, 50 p.

[2] 1992. Geología de la parte oriental de las hojas Puerto Cisnes, Coyhaique y Chile Chico (Inédito), *Servicio Nacional de Geología y Minería*, Vols. 1 y 2.

studied cover from the middle-late Jurassic to the Neogene and correspond to the Ibáñez Formation (Jurassic) and some coeval units, to the Divisadero Formation (Cretaceous), to the Las Juntas Strata (Paleogene?), and to younger lava flows (Neogene) (Fig. 1). The Mesozoic extrusive activity is mainly represented by calc-alkaline volcanic arcs composed of andesitic stratovolcanoes, dacitic domes and rhyolitic ignimbrites (De la Cruz *et al.* 1994) with minor basalt and basalt andesite flows. The Paleogene rocks represent arc deposits and flood basalts of back-arc or continental intraplate type (X. Prieto and J.A. Cortés)[1]. The Neogene rocks reported correspond mainly to eroded volcanic centres in the Puyuguapi area.

The results presented here are based on the study of a total of about eighty rock samples, mainly of basic and intermediate compositions. The location and other characteristics of the samples studied by electron microprobe (20) are shown in figure 1 and table 1.

Most recent information concerning the stratigraphy, paleogeography, petrology and geochemistry of the Aisén region can be found in Suárez and De la Cruz (1994a); Suárez *et al.* (1994); Belmar (1996a) and Cortés (1996). Preliminary reports concerning the low-grade metamorphic pattern characterizing the sequences mentioned above have been presented by Aguirre *et al.* (1996) and Pavez *et al.* (1997).

TABLE 1. LOCATION OF PROBED SAMPLES FROM PATAGONIA (43-46°S), INDICATING LITHOLOGIC TYPE, METAMORPHIC FACIES AND AGE.

Sample	Rock type	Metamorphic facies	Age	Latitude S	Longitude W
CE93-31A	Basalt	ZEO	TT	44°20.5'	72°34
CE93-31B	Basalt	ZEO	TT	44°20.5'	72°34
CE93-45B	Basaltic andesite	ZEO	TT?	45°23'	71°30
CE93-23	Andesitic breccia		TT	43°57'	72°23.5'
CE93-30	Andesitic tuff	P-P	TT	44°4'	72°26
CE93-39C	Andesite	P-P	TT	44°35.5'	71°28
CE93-40	Andesite	P-P	K	45°22'	71°50'
CE93-46	Basalt		K (77 Ma)	45°29.5'	71°30.5'
CE93-38	Ignimbrite		K	44°36'	71°29.8'
CE93-22A	Andesitic tuff	P-P	K	43°36.6'	71°42'
CE93-51C	Andesite	P-P?	K	45°47'	72°11.5'
CE93-41C	Basaltic andesite	P-P	K	45°15'	72°15'
CE93-16	Andesite	GS	J	43°11'	71°51'
CE93-35B	Basaltic andesite	GS	J	44°43.3'	72°5'
CE93-15	Andesite	GS	J	43°11'	71°51'
CE93-34	Andesite	GS	J	44°44.5'	72°6'
CE93-35A	Basaltic andesite	GS	J	44°43.3'	72°5'
LV-1A	Basaltic andesite		J	44°14'	71°56.5'
LV-67B	Basaltic andesite		J	44°16.2	71°48.5'
LV-103	Andesite		J	44°13'	71°52'

ZEO: Zeolite facies; **P-P:** Prehnite-Pumpellyite facies; **GS:** Greenschist facies.
J: Jurassic; **K:** Cretaceous; **TT:** Tertiary.

STRATIGRAPHY AND LITHOLOGY

The Ibáñez Formation (Niemeyer, 1975), also known as Ibáñez Group (Suárez *et al.* 1996), is a middle Jurassic (160 Ma Ar-Ar in biotite; 144 Ma Ar-Ar in plagioclase from rhyolitic tuffs of the Alto Río Chacabuco; Parada *et al.*, 1996) to Early Berriasian (Covacevich *et al.*, 1994) continental sequence composed of pyroclastic rocks, lava flows and domes of dacitic, rhyolitic and andesitic compositions with a thickness of *ca.* 2000 m. Twenty nine rock samples of the Ibáñez Formation studied by the authors comprise: **a-** amygdaloidal, porphyritic, andesite and basaltic andesite flows; **b-** porphyritic dacite flows with albitized plagioclase and altered amphibole phenocrysts in a felsitic (quartz, plagioclase, iron oxide) groundmass; and **c-** dacitic ignimbrites with chloritized 'fiamme'.

The Divisadero Formation (Heim, 1940 *in* H. Niemeyer *et al.*[3]), or Divisadero Group (Haller and Lapido, 1980), a continental sequence *ca.* 1000 m thick, has given radiometric ages in the interval Hauterivian-post-Albian (Charrier *et al.*, 1978; Pankhurst and Hervé; 1994) and Aptian (109-111 Ma), according to Haller and Lapido (1980) and, more recently, a K-Ar whole rock age of 102±3 Ma (M. Suárez and R. De la Cruz)[4]. It is composed of volcanoclastic and pyroclastic rocks with interlayered lava flows and associated hypabyssal rocks of rhyolitic, dacitic and andesitic compositions. These rocks are probably caldera and stratovolcano deposits with several interlayers of continental sedimentary rocks (H. Niemeyer *et al.*)[3]. Twenty one Cretaceous rocks were studied; they correspond to: **a-** porphyritic, partly amygdaloidal, andesite flows and flow-breccias with plagioclase phenocrysts and intersertal groundmass of plagioclase microliths and iron oxide grains; **b-** amygdaloidal olivine basalts with partially albitised phenocrysts of plagioclase and olivine (ghosts) in a fine-grained groundmass of plagioclase microliths, clinopyroxene (augite), and iron oxides.

The Las Juntas Strata (L. Bobenrieth, F. Díaz, J. Davidson and C. Portigliati)[5] of Paleogene (?) age is a continental conglomerate sequence with interlayered andesite flows. The rocks studied from this sequence (7) correspond to: **a-** poorly amygdaloidal basaltic andesites with plagioclase and clinopyroxene phenocrysts; **b-** porphyritic andesite flows with plagioclase phenocrysts, and **c-** lapilli tuffs containing abundant diabase clasts. Other Paleogene rocks included in this study are olivine, basalts cropping out along the road between El Blanco and Balmaceda which have been assigned to the Balmaceda Basalts (Belmar, 1996b) and whose radiometric age (K-Ar whole rock: 46±2 Ma) is Eocene (Baker *et al.*, 1981; Butler *et al.* 1991).

Neogene basalts from eroded volcanic centres located *ca.* 10 km south of Puyuguapi have been included in this study. The samples collected correspond to: **a-** porphyritic, highly amygdaloidal olivine basalts with plagioclase and fresh olivine phenocrysts in a hyalopilitic groundmass, and **b-** fine to medium-grained, clinopyroxene-rich, amygdaloidal basaltic flows with quench textures.

PETROLOGY AND PRIMARY MINERALOGY

Chemical analyses (ICP) of 'fresh' non-amygdaloidal rocks with basic to intermediate composition (not shown) were carried out at the University of Marseille (France, J.C. Germanique, analyst), whereas mineral determinations were performed using a CAMECA-CAMEBAX electron microprobe (15 kV, 12 nA, 20 s and 1 μ beam width) at the University of Montpellier (France).

The chemistry of the Jurassic and Cretaceous lavas permits the authors to classify them as basalts, andesites and dacites with calc-alkaline affinity. The Tertiary (Neogene) lavas analysed included basalts and andesites with alkaline chemical affinity, a tendency already established by Demant *et al.* (1994) for the basalts of the Puyuguapi area.

Main primary probed minerals present in the Jurassic lavas of intermediate and basic compositions are calcic plagioclase (An_{68}-An_{54}) and calcic amphiboles corresponding to ferro-hornblende, ferro-tschermakitic hornblende and ferro-tschermakite (Fig. 2) according to Leake's classification (1978). In the basic Cretaceous rocks studied, calcic plagioclase (An_{93}-An_{51}) is the main phase and clinopyroxenes ($Wo_{38}En_{44}Fs_{18}$) are abundant. Fresh olivine (Fo_{85}-Fo_{80}) phenocrysts appear only in one of the samples (CE93-46, Morro Negro), whereas olivine crystals totally replaced by chlorite are present as ghosts in basaltic andesites cropping out at the western extreme of Puente Guillermo. In basic

[3] 1984. Hojas Península de Taitao y Puerto Aysén, Región de Aysén del General Carlos Ibáñez del Campo (Inédito), *Servicio Nacional de Geología y Minería*, 80 p.

[4] 1994b. Estratigrafía del Jurásico-Cretácico inferior de la Cordillera Patagónica Oriental (45°-47°S), Chile: Facies, paleogeografía Proyecto Aysén NE (Inédito), *Convenio Gobierno Regional XI Región-Servicio Nacional de Geología y Minería*, 82 p.

[5] 1983. Complemento del Mapa Metalogénico XI Región. Sector Norte Continental comprendido entre los 45°S y el límite con la X Región (Inédito) *Servicio Nacional de Geología y Minería/Corporación de Fomento de la Producción*, 271 p.

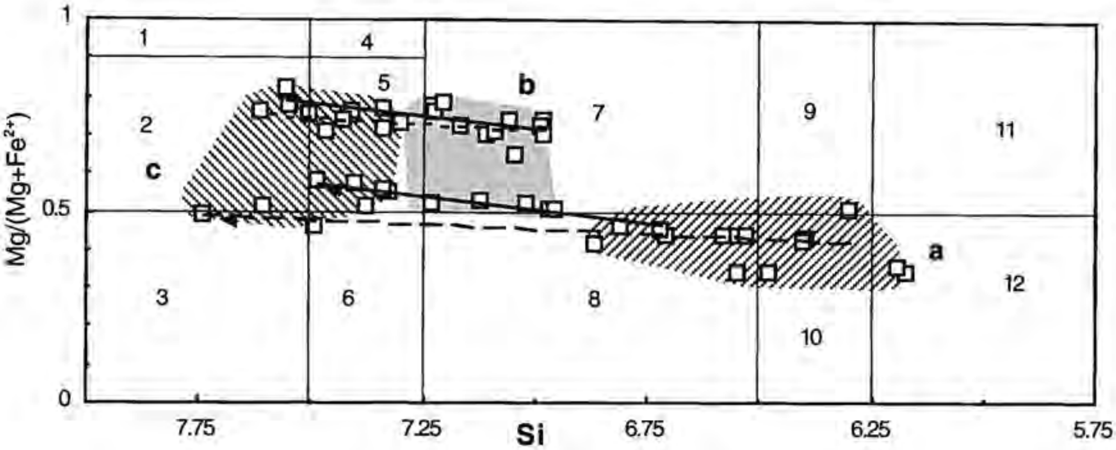

FIG. 2. Patagonian (43-46°S), Jurassic amphiboles plotted on the classification diagram of Leake (1978). **a-** igneous amphiboles; **b-** partially transformed igneous amphiboles; **c-** metamorphic amphiboles. Arrows show the main transformation trends. **1-** tremolite; **2-** actinolite: **3-** ferro-actinolite; **4-** tremolitic hornblende; **5-** actinolitic hornblende; **6-** ferro-actinolitic hornblende; **7-** magnesium hornblende; **8-** ferro-hornblende; **9-** tschermakitic hornblende; **10-** ferro-tschermakitic hornblende; **11-** tschermakite; **12-** ferro-tschermakite. Cation values are calculated based on 23 oxygens.

rocks from Las Juntas (Paleogene?) clinopyroxene phenocrysts ($Wo_{41}En_{39}Fs_{20}$-$Wo_{44}En_{46}Fs_{10}$) are accompanied by plagioclase (An_{57}-An_{43}) partially albitised. Olivine (Fo_{83}-Fo_{84}) and calcic plagioclase (An_{72}-An_{75}) are abundant as phenocrysts in the Neogene basalts from Puyuguapi. Other basic rocks, tentatively assigned to the Tertiary, crop out along the road from Ñirehuao to Coihaique Alto and at Estero Buitreras, north of La Tapera. Clinopyroxenes in the former locality are in the range ($Wo_{52}En_{33}Fs_{15}$-$Wo_{47}En_{41}Fs_{12}$), whereas in the latter they cover the interval ($Wo_{45}En_{38}Fs_{17}$-$Wo_{43}En_{45}Fs_{12}$).

According to the contents in Ti, Ca, Na and Cr in the pyroxenes, a transitional trend from sub-alkaline to alkaline affinity is apparent in the avas with ages from Cretaceous to Tertiary. An orogenic setting for these volcanic products is also suggested by the pyroxene composition according to the diagrams by Leterrier *et al.* (1982).

METAMORPHISM

MINERAL ASSEMBLAGES

Most of the rocks studied are strongly altered which is reflected in high H_2O^+ contents (up to 8.0%, mean = 4.1%, σ = 2.6 for 8 rocks analysed) and in the presence of a variety of secondary minerals. These appear as replacement of primary minerals, filling amygdales and veinlets, and as patchy alteration of glassy and intergranular groundmass.

The secondary associations found in the *ca.* 70 sections studied by different methods (microscope, EPMA, XRD) are combinations of the following phases (Fig. 3): zeolites, celadonite, calcite, aragonite, albite, potash feldspar, quartz, kaolinite, iddingsite, smectite, chlorite, white mica, titanite, prehnite, pumpellyite, epidote, actinolite and biotite. Associations typical of the zeolite, prehnite-pumpellyite and greenschist facies are represented among these rocks. No deformational features are recorded, the metamorphic transformations being purely mineralogical.

MINERAL CHEMISTRY

ZEOLITES

The authors have found zeolites only in rocks of Tertiary age where they fill amygdales and veinlets. According to their compositions, four groups can be

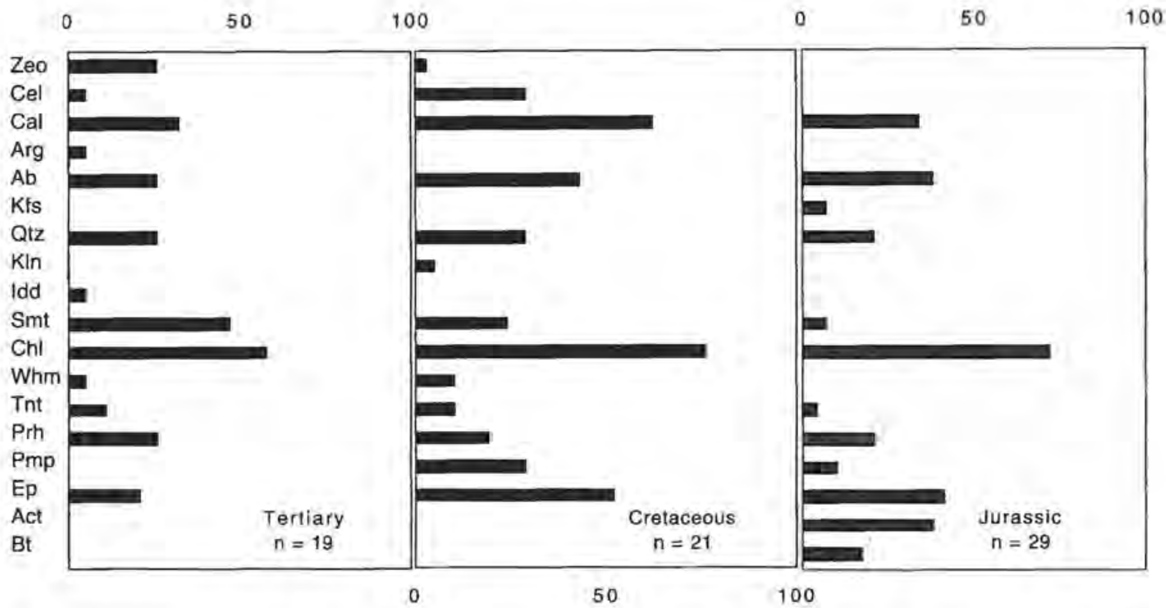

FIG. 3. Frequency of metamorphic minerals in the Mesozoic and Cenozoic volcanic rocks of Patagonia (43- 46°S). **Zeo:** zeolite; **Cel:** celadonite; **Cal:** calcite; **Arg:** aragonite; **Ab:** albite; **Kfs:** K-feldspar; **Qtz:** quartz; **Kln:** kaolinite; **Idd:** Iddingsite; **Smt:** smectite; **Chl:** chlorite; **Whm:** white mica; **Tnt:** titanite; **Prh:** prehnite; **Pmp:** pumpellyite; **Ep:** epidote; **Act:** actinolite; **Bt:** biotite.

distinguished: Na-, NaCa-, KCaNa- and KNaCa-zeolites (Table 2, analyses 1, 2, 3 and 4). The microprobe analyses enable their identification as analcite and as various species with compositions between natrolite, mesolite and phillipsite based on pure end members taken from Gottardi and Galli (1985). In some amygdale cores, in basalts from the Puyuguapi area, tobermorite, a Ca-Al hydrous silicate, has been found rimmed by phillipsite.

Most recently, however, Pavez *et al.* (1997) have reported the presence of abundant laumontite in Cretaceous volcanic tuffs and breccias from Cerro Monreal, 30 km south-southeast from Coihaique (Fig. 1) and Suárez (written communication, 1997) has pointed out the presence of possible zeolites in the Cretaceous basalts of Morro Negro (77±3 Ma, K-Ar whole rock, Baker *et al.* 1981) and in basaltic andesites from Loncomahuida which are assigned to a pre-Morro Negro volcanic event.

MAFIC PHYLLOSILICATES

They are mainly present in amygdales and veinlets and as partial or total replacement of ferromagnesian primary minerals, notably of olivine.

Mafic phyllosilicates in the Tertiary rocks are mainly interstratified smectite/chlorite (S/C) belonging to the trioctahedric saponite-chlorite series (Fig. 4) with average chlorite layer content Xc% between 56 and 89 obtained following the method by Wise (Bettison and Schiffman, 1988). The highest Xc% values correspond to mafic phyllosilicates in the oldest Tertiary lavas, *i.e.*, those of the Las Juntas Strata (Table 3).

In the Cretaceous rocks the mafic phyllosilicates correspond to pycnochlorite with Xc% in the range 83-97 (Table 3) and to specimens belonging to the chlorite-celadonite series (Fig. 4).

Ripidolite and brunsvigite with minor pycnochlorite and diabantite are the mafic phyllosilicates in the Jurassic rocks studied with Xc% ranging from 75 to 93 (Table 3). In many individuals the composition approaches the pure chlorite end member (Fig. 4).

The contents of Si and total interlayered cations Σ (Ca, Na, K) in the mafic phyllosilicates studied tend to decrease from the younger (Tertiary) to the older (Jurassic) rocks as the transition from S/C to chlorite takes place (Table 3).

Biotite is present in some hornfelsic volcanic rocks of Jurassic age along the road from Villa Amengual to La Tapera. It is characterized by Mg/(Mg+Fe^{2+}) values [mg] from 0.37 to 0.42 and K_2O contents in the interval 7.5 -10.1%.

TABLE 2. SELECTED MICROPROBE ANALYSES OF THE MAIN METAMORPHIC MINERALS FROM PATAGONIA (43-46°S). TOTAL IRON AS FE^{3+} FOR ZEOLITES, PREHNITES, PUMPELLYITES, EPIDOTES AND TITANITES; AND AS FE^{2+} FOR AMPHIBOLES AND WHITE-MICAS.

Zeolites

SAMPLE	CE93.31A	CE93-31B	CE93-31B	CE93-31A
Analysis	1	2	3	4
Age	Tertiary	Tertiary	Tertiary	Tertiary
SiO_2	55.16	44.99	52.01	48.09
TiO_2	0.00	0.00	0.00	0.00
Al_2O_3	23.01	26.08	23.82	21.79
Cr_2O_3	0.00	0.00	0.00	0.00
FeOt	0.02	0.00	0.04	0.01
MnO	0.00	0.00	0.07	0.01
MgO	0.00	0.00	0.00	0.00
CaO	0.03	5.74	5.07	3.52
Na_2O	14.18	10.07	3.07	4.95
K_2O	0.04	0.04	7.23	7.16
Total	92.44	86.91	91.30	85.54
Number of oxygens	*96*	*80*	*32*	*32*
Si	32.13	23.68	10.45	10.41
Ti	0.00	0.00	0.00	0.00
Al	15.79	16.17	5.64	5.56
Cr^{3+}	0.00	0.00	0.00	0.00
Fe^{3+}	0.01	0.00	0.00	0.00
Mn^{2+}	0.00	0.00	0.01	0.00
Mg	0.00	0.00	0.00	0.00
Ca	0.02	3.23	1.09	0.82
Na	16.02	10.27	1.20	2.08
K	0.03	0.02	1.85	1.98
Scat.	63.99	53.38	20.25	20.84
Si/Al	2.03	1.46	1.85	1.87
E%	-1.74	-3.49	7.97	-2.19

E% = Cationic charge balance (*in* Gottardi and Galli, 1985)

Amphiboles

SAMPLE	CE93.35b	CE93.35a	CE93.15
Analysis	5	6	7
Age	Jurassic	Jurassic	Jurassic
SiO_2	43.16	49.95	52.01
TiO_2	0.55	0.20	0.28
Al_2O_3	9.92	5.06	3.77
Cr_2O_3	0.04	0.00	0.00
FeOt	22.21	19.52	11.15
MnO	0.82	0.83	0.56
MgO	7.47	10.02	15.89
CaO	11.88	12.17	12.41
Na_2O	1.06	0.44	0.69
K_2O	0.99	0.25	0.26
Total	98.10	98.44	97.02
Number of oxygens	*23*	*23*	*23*
Si	6.546	7.376	7.500
AlIV	1.454	0.624	0.500
AlVI	0.321	0.258	0.141
Cr^{3+}	0.005	0.000	0.000
Fe^{3+}	0.637	0.297	0.222
Ti	0.063	0.022	0.030
Mg	1.689	2.205	3.415
Fe^{2+}	2.180	2.114	1.123
Mn^{2+}	0.105	0.104	0.068
Ca	1.931	1.926	1.918
Na	0.312	0.126	0.193
K	0.192	0.047	0.048
SCat.	15.434	15.099	15.158

Prehnites

SAMPLE	CE93-30	CE93.22A	CE93-35a
Analysis	8	9	10
Age	Tertiary (Las Juntas)	Cretaceous	Jurassic
SiO_2	42.71	43.04	43.96
TiO_2	0.06	0.10	0.00
Al_2O_3	21.76	21.89	22.27
Cr_2O_3	0.25	0.00	0.00
FeOt	3.08	3.80	4.37
MnO	0.20	0.00	0.05
MgO	0.00	0.00	0.18
CaO	26.16	26.71	26.15
Na_2O	0.08	0.01	0.01
K_2O	0.00	0.01	0.05
Total	94.30	95.56	97.04
Number of oxygens	*11*	*11*	*11*
Si	3.011	3.000	3.011
Al	1.808	1.797	1.798
Ti	0.003	0.005	0.000
Cr^{3+}	0.014	0.000	0.000
Fe^{3+}	0.164	0.199	0.225
Mn^{2+}	0.012	0.000	0.003
Mg	0.000	0.000	0.019
Ca	1.976	1.994	1.919
Na	0.011	0.001	0.001
K	0.000	0.001	0.004
Scat.	6.999	6.998	6.980
XFe_{3+}	8.30	9.98	11.13

Pumpellyite

SAMPLE	CE93-41C
Analysis	11
Age	Cretaceous
SiO_2	36.69
TiO_2	0.02
Al_2O_3	22.29
Cr_2O_3	0.00
FeOt	8.65
MnO	0.08
MgO	2.50
CaO	22.75
Na_2O	0.03
K_2O	0.00
Total	93.01
Number of oxygens	*24.5*
Si	5.962
Al-z	0.038
SUM Z	6.000
Al-y	3.998
Ti	0.002
Fe-y	0.000
SUM Y	4.000
Fe-x	1.056
Mg	0.606
Al-x	0.233
Cr^{3+}	0.000
Mn^{2+}	0.011
SUM X	1.907
Ca	3.961
Na	0.010
K	0.000
Mn-w	0.000
SUM W	3.971
Scat.	15.878
XFe^{3+}	19.84%

Epidotes

SAMPLE	CE93.51C	CE93-35b
Analysis	12	13
Age	Cretaceous (Divisadero)	Jurassic
SiO_2	37.31	38.87
TiO_2	0.07	0.58
Al_2O_3	23.25	21.96
Cr_2O_3	0.00	0.00
FeOt	13.73	15.30
MnO	0.54	0.23
MgO	0.00	0.20
CaO	22.76	22.35
Na_2O	0.02	0.41
K_2O	0.01	0.01
Total	97.69	99.91
Number of oxygens	*12.5*	*12.5*
Si	2.986	3.046
Aliv	0.014	0.000
Ti	0.004	0.034
Alvi	2.180	2.028
Fe^{3+}	0.826	0.901
Cr^{3+}	0.000	0.000
Mn^{2+}	0.036	0.015
Mg	0.000	0.013
Ca	2.716	2.611
Na	0.002	0.035
K	0.001	0.001
Scat.	8.765	8.684
XFe^{3+}	27.35%	30.76%

Titanite

SAMPLE	CE93.16
Analysis	14
Age	Jurassic
SiO_2	30.79
TiO_2	38.38
Al_2O_3	0.78
Cr_2O_3	0.03
FeOt	0.77
MnO	0.08
MgO	0.00
CaO	28.60
Na_2O	0.02
K_2O	0.04
Total	99.46
Number of oxygens	*20*
Si	4.045
Ti	3.792
Al	0.120
Cr^{3+}	0.003
Fe^{3+}	0.069
Mn^{2+}	0.008
Mg	0.000
Ca	4.025
Na	0.004
K	0.006
Scat.	12.072

White-micas

SAMPLE	CE93.39C	CE93.38
Analysis	15	16
Age	Tertiary	Cretaceous
SiO_2	50.55	50.47
TiO_2	0.01	0.01
Al_2O_3	35.46	27.92
Cr_2O_3	0.00	0.01
FeOt	0.88	4.73
MnO	0.01	0.04
MgO	0.23	2.02
CaO	0.37	0.10
Na_2O	0.29	0.08
K_2O	9.99	10.64
Total	97.78	96.01
Number of oxygens	*22*	*22*
Si	6.468	6.758
Aliv	1.532	1.242
Ti	0.001	0.001
Alvi	3.816	3.165
Cr^{3+}	0.000	0.001
Fe^{2+}	0.094	0.529
Mn^{2+}	0.001	0.004
Mg	0.044	0.403
Ca	0.050	0.014
Na	0.071	0.021
K	1.631	1.818
Scat.	13.708	13.956
Si/Aliv	4.223	5.444

TABLE 3. COMPOSITIONAL CHARACTERISTICS AND TEMPERATURE OF FORMATION OF MAFIC PHYLLOSILICATES. PATAGONIAN REGION (43-46°S).

Sample	Points	Type	Xc% chlorite			Temperature, C° (*)			Σ(Ca,Na,K)			Si			AGE
			Minimum	Average	Maximum	minimum	average	maximum	minimum	average	maximum	minimum	average	maximum	
CE93-45B	10	D	52	56	60	118	137	152	0.276	0.318	0.352	6.670	6.766	6.882	Tertiary
CE93-39C	11	P	72	79	93	234	252	290	0.107	0.140	0.185	5.811	6.052	6.163	Tertiary
CE93-23	9	P-d-b	72	83	98	197	234	275	0.081	0.135	0.217	5.909	6.163	6.390	Tertiary, Las Juntas
CE93-30	7	P	79	89	96	255	290	319	0.039	0.094	0.291	5.631	5.810	6.033	Tertiary, Las Juntas
CE93-40	7	R-p	88	95	98	314	334	346	0.031	0.047	0.072	5.464	5.543	5.667	Cretaceous
CE93-22A	17	D-p	76	83	95	183	219	278	0.068	0.128	0.319	5.888	6.253	6.480	Cretaceous
CE93-51C	12	P-r	90	94	100	280	304	338	0.006	0.027	0.049	5.518	5.730	5.879	Cretaceous
CE93-41C	13	P	93	97	99	268	284	307	0.046	0.063	0.103	5.709	5.850	5.952	Cretaceous
CE93-35B	4	R-B	74	93	100	295	330	344	0.005	0.117	0.405	5.476	5.497	5.520	Jurassic
CE93-35A	6	B-p-d	35	75	94	158	260	302	0.023	0.277	0.834	5.741	6.000	6.633	Jurassic

D- diabantite; **P**- pycnochlorite; **B**- brunsvigite; **R**- ripidolite (according to Hey, 1954).

Principal phyllosilicate in upper case; accesory phyllosilicate in lower case.

(*) Based on the Al^{IV} content p.f.u. calculated with 28 oxygens (Cathelineau and Nieva, 1985; Cathelineau, 1988).

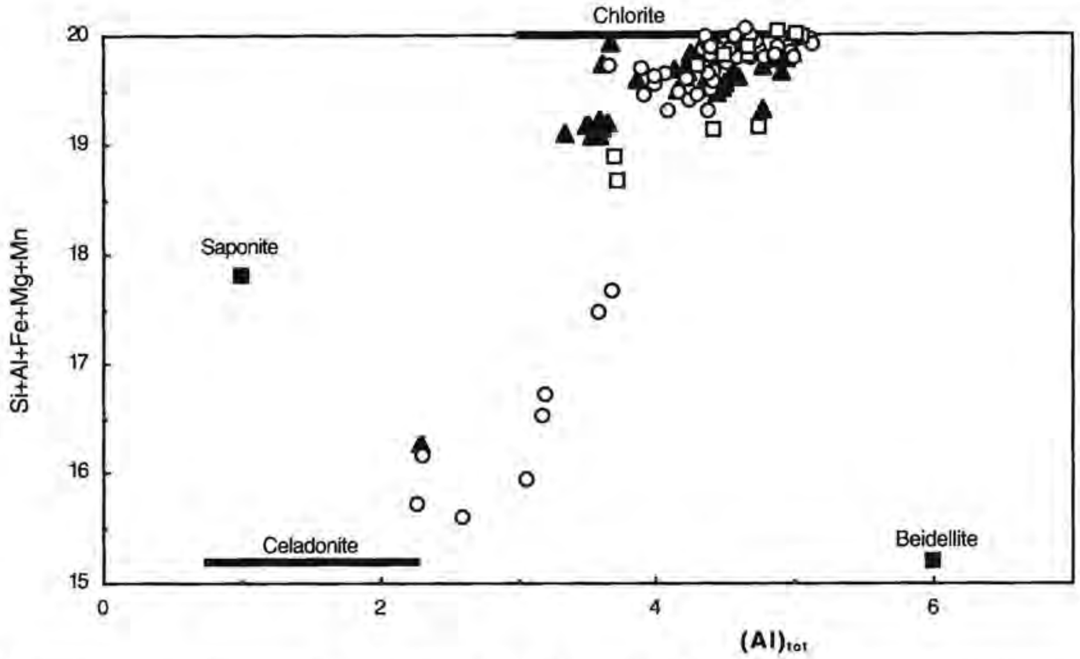

FIG. 4. Altotal *versus* non-interlayered cation totals (Si+Al+Fe+Mg+Mn) in mafic phyllosilicates from volcanic rocks of Patagonia (43-46°S). All cation values are calculated based on a chlorite formula with 28 oxygens. Saponite and chlorite are end members for the trioctahedral series and saponite and beidellite for the dioctahedral series. ▲ Tertiary rocks; ○ Cretaceous rocks; □ Jurassic rocks.

FELDSPARS

In the Tertiary sequences, albitisation of plagioclase is strong in flows of the Las Juntas Strata with An content mostly below 6%, whereas in the Neogene basalts from Puyuguapi the original Ca-rich compositions are mostly preserved or slightly modified. Albitisation is intense in most of the samples of Cretaceous age with compositions close to the albite pole. However, intermediate compositions in the range An_{20}-An_{32} are also present. K-feldspar $An_5b_{48}Or_{47}$ appears in one of the probed sections.

Feldspars in the Jurassic rocks are characterized by higher contents of the Or molecule with compositions ranging from sodi-calcic ($An_{13}Ab_{78}Or_9$-$An_{33}Ab_{62}Or_5$) to sodi-potassic ($An_0Ab_{73}Or_{27}$-$An_7Ab_{50}Or_{43}$) to potassic ($An_0Ab_3Or_{97}$- $An_1Ab_4Or_{95}$).

AMPHIBOLES

They are only present in the rocks of Jurassic age where they fill veinlets and appear as crystal agglomerates in the groundmass. Two secondary amphibole groups (Fig. 2) are distinguished in relation with the value of the ratio $Mg/(Mg+Fe^{2+})$. The first, Mg-rich, corresponds to the Futaleufú area and the second, Fe-rich, to the La Tapera area. A linear trend between Si and $Mg/(Mg+Fe^{2+})$ can be established in samples from both groups with compositions displayed from the actinolite to the ferro-tschermakite-hornblende field. Microscopic analysis suggests that, in group b, the amphiboles richer in Fe correspond to primary phases partially transformed into more actinolitic terms (group c), whereas the amphiboles richer in Mg from group b would represent more advanced stages in the evolution of a primary phase (group a) toward a metamorphic state (group c). In conclusion, based on these observations, three fields can be identified in the Leake diagram (Fig. 2): **a-** weakly altered primary ferro-hornblende, with values of Na_2O% between 1.22 and 0.76 and SiO_2% between 40.29 to 45.42 (*e.g.*, analysis 5 in Table 2); **b-** partially transformed primary Mg-hornblende, with Na_2O% ranging from 0.54 to 0.22 and SiO_2% from 47.16 to 52.10 (*e.g.*, analysis 6 in Table 2), and **c-** metamorphic actinolite and actinolite-hornblende with Na_2O% in the interval 0.35 to 1.20 and SiO_2% from 48.05 to 54.47 (*e.g.*, analysis 7 in Table 2).

PREHNITES, PUMPELLYITES AND EPIDOTES

Prehnite is found in veinlets and patches in some of the Tertiary rocks (Las Juntas Strata) with XFe^{3+} ranging from 7.7 to 8.3% with an average of 8.0% (Table 2, analysis 8). In other of the Tertiary lavas, the XFe^{3+} of prehnite ranges from 7.0 to 13.3% with average of 11.0%.

In the Cretaceous rocks, pumpellyite, prehnite and epidote are associated in the same samples. The pumpellyites have total iron content as Fe_2O_3> 10%, typical of Fe-pumpellyites in sub-greenschist facies (Fig. 5). Ferric iron partitioning between pumpellyite (Table 2, analysis 11), prehnite (Table 2, analysis 9) and epidote (Table 2, analysis 12) takes place in these assemblages with XFe^{3+}_{pmp} (19.8 - 33.4%) $\geq XFe^{3+}_{epi}$ (18.5 - 33.3%) $> XFe^{3+}_{prh}$ (4.0-12.4%).

Epidote and prehnite are rather abundant in amygdales and veinlets of the Jurassic rocks and are characterized by higher XFe^{3+} values (averages of 27.3% and 9.6% respectively) compared with those present in the Tertiary and Cretaceous lavas. The ferric iron partitioning between epidote (Table 2, analysis 13) and prehnite (Table 2, analysis 10) is here XFe^{3+}_{epi} (18.4-34.2%) $> XFe^{3+}_{prh}$ (5.7-11.1%). Pumpellyite is practically absent from the Jurassic rocks and has been only recorded as tiny flakes in some narrow epidote-rich veinlets.

OTHER METAMORPHIC MINERALS

Titanite is present as small grains, associated with epidote, chlorite and calcite, in veinlets and amygdales in samples from the Jurassic to the Tertiary. The Al_2O_3 content is high (4.2-7.3%) for titanites in the Cretaceous rocks, a feature diagnostic for subgreenschist facies (Coombs *et al.*, 1976). Titanite (Table 2, analysis 14), present in only one of the Jurassic samples, is very low in Al_2O_3 and Fe_2O_3, (<1%), a characteristic of titanite in greenschist facies.

White-mica has been found in Tertiary and Cretaceous rocks (Table 2, analyses 15 and 16, respectively) as small patches in plagioclase phenocrysts. The Si/Al^{IV} in these micas is in the range 3.52-5.44 indicating a moderately phengitic component.

Kaolinite appears filling vesicles in some of the Cretaceous lavas and aragonite in amygdales was found in the Balmaceda basalts.

P-T CONSTRAINTS

The metamorphic assemblages described permit the authors to establish the metamorphic facies represented and, in a first approximation, to outline the P-T conditions of metamorphism based on the petrogenetic grid by Frey *et al.* (1991). According to

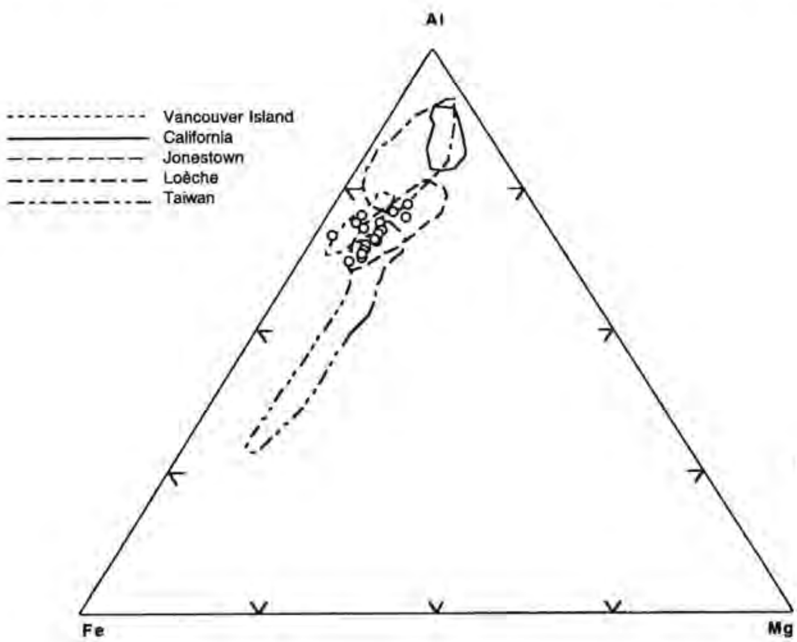

FIG. 5. Compositional diagram for pumpellyites in Cretaceous volcanic rocks of Patagonia (43-46°S). Cation values are calculated based on 24.5 oxygens Reference fields taken from Coombs *et al.* (1976).

this grid, the Tertiary rocks including low temperature minerals such as zeolites, smectites, interstratified smectite/chlorite (S/C), and celadonite, which are representative of the zeolite facies, suggest temperatures below 200°C. The metamorphic assemblages including pumpellyite, prehnite, epidote, chlorite and albite (zeolites absent), which characterize the Cretaceous rocks, are diagnostic of the prehnite-pumpellyite facies indicating temperatures from 175 to 280°C and pressures between 0.5 and 4.5 kbar. Finally, the common presence of secondary amphibole, mainly actinolite, and the appearance of biotite in some assemblages of the Jurassic rocks, indicate temperatures typical of the greenschist facies *i.e.*, >275°C.

In order to quantify the intensive variables, some empirical geothermobarometric methods can be used.

Concerning the temperature, the Cathelineau thermometer (Cathelineau and Nieva, 1985, Cathelineau, 1988) based on the Al^{iv} content of chlorites has given values of *ca.* 280°C for the chlorites of the Paleogene Las Juntas Strata and of *ca.* 190°C (and as low as 150°C) for chlorites in the Neogene basalts (Table 3). The chlorites contained in the Cretaceous rocks indicate temperatures in the interval 220-330°C, whereas those in the Jurassic samples indicate values up to 340°C. However, the Cathelineau geothermometer has been criticized by different authors (de Caritat *et al.* 1993; Jiang *et al.* 1994) and its results, when applied to volcanic rocks, should be critically considered. On the other hand, the presence of actinolite+epidote coexisting with chlorite, marks the transition from the subgreenschist to greenschist facies at a temperature of about 280±30°C (Bucher and Frey, 1994). Finally, the presence of biotite in some of the Jurassic rocks marks the highest temperature reached by the metamorphism, above 400°C according to Bucher and Frey (1994).

The range of pressures can be approached using amphibole compositions. Thus, for the Jurassic rocks, the only ones in which these minerals have been found, the geobarometric estimations based on the crossite content (Na^{M4}) of calcic amphiboles (Brown, 1977) has been applied. The basic assumption of this method is that at pressures below that of the blueschist facies the crossite component of Ca-amphibole should be pressure-dependent, provided the amphibole coexists with albite+iron oxide+chlorite, which is the case in in the authors' samples. The results obtained for the Jurassic Ca-amphiboles indicate pressures below 2kb for their formation (Fig. 6). These values, added to temperatures as high as 340°C obtained with the chlorite thermometer in these same rocks, indicate metamorphic conditions similar to those established for the Californian Sierra Nevada region (Brown, 1977 and references therein) where batholithic intrusions have strongly influenced the regional thermal gradients.

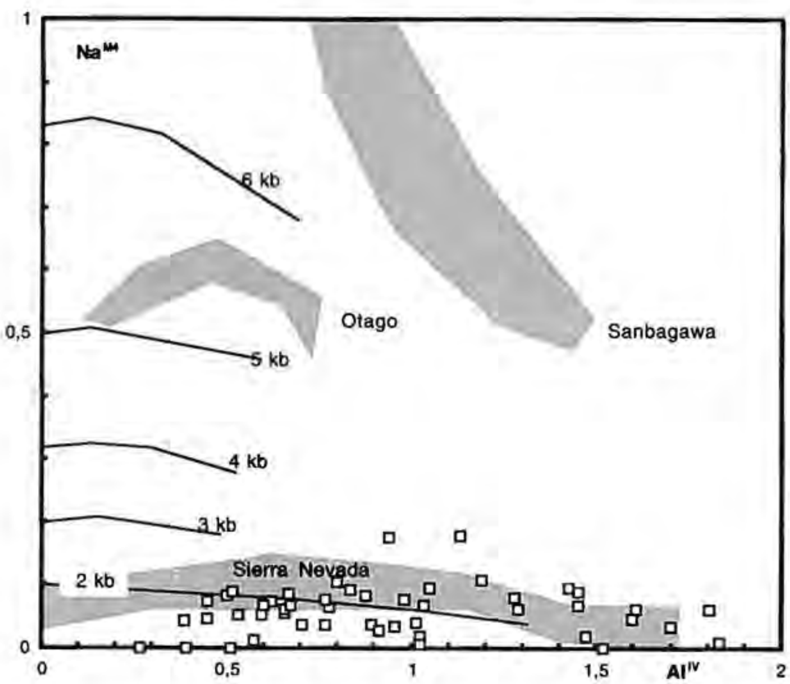

FIG. 6. Al^{IV} *versus* Na^{M4} in calcic amphiboles (accompanied by the buffer assemblage albite, chlorite, iron oxide) from Jurassic rocks of Patagonia (43-46°S). Cation values are calculated based on 23 oxygens; geobarometer after Brown (1977).

DISCUSSION AND CONCLUSIONS

All the rocks, from Jurassic to Neogene, have been affected by non deformative, very low and low-grade metamorphism. The secondary mineral phases and their assemblages are indicative of the zeolite, prehnite-pumpellyite and greenschist facies. Differences in metamorphic grade related to the age of the sequences studied have been established. Thus, zeolite-bearing assemblages are present in the youngest, Neogene rocks; pumpellyite coexisting with prehnite and epidote is characteristic in the Cretaceous volcanic rocks, whereas the presence of actinolite, in places related to biotite, has been only recorded in the Jurassic rocks. A similar increase in the metamorphic grade with stratigraphic depth (age) has already been established for the Mesozoic-Cenozoic volcanic sequences of the Central Andes (Levi *et al.*, 1989).

The temperatures inferred for these metamorphic assemblages go from *ca.* 120° to near 340°C with pressures probably not exceeding 2 kbars. The assemblages and the characteristics of individual mineral phases show that the metamorphism affecting the Cretaceous rocks is the most pervasive and probably took place in a fairly thick subsiding pile under a slowly rising thermal gradient in an environment with a high fluid/rock ratio (extensive albitisation, formation of mafic phyllosilicates with a high Xc%, presence of pumpellyite, etc.).

The batholithic intrusions with ages around 95 Ma (Pankhurst and Hervé, 1994) exposed close to or immediately adjacent to the Cretaceous outcrops, have not disturbed the low-grade pattern of these rocks, one which stands close to that of hydrothermal burial metamorphism. Most recent estimations of the age of the Cretaceous Divisadero Formation indicate a minimum value of 102 Ma (Belmar, 1996a). In Central Chile, dating of the low-grade metamorphic phenomena (prehnite-pumpellyite facies) that affected lower Cretaceous rocks has shown that these phenomena occurred about 15 to 25 Ma after deposition of the volcanic sequence (Åberg *et al.*, 1984, Morata *et al.*, 1997). If a similar interval could be envisaged for the Aisén region, the metamorphism of the Divisadero Formation could be as young as 80 Ma, that is subsequent to the main batholithic intrusions in the region. This would explain the preservation of the low-grade metamorphic pattern observed.

Contrasting with the previous situation, the greenschist facies metamorphism of the Jurassic rocks bears the imprint of a rapidly imposed thermal regime with a rather low fluid/rock ratio and a selective fluid circulation. These characteristics resulted in metastable equilibrium of some primary minerals and patchy growth of secondary phases, *e.g.*, partial albitisation of plagioclase, generation of K-rich feldspar, partial transformation of primary amphibole into actinolite, persistence of S/C mafic phyllosilicates, sporadic biotite formation. The thermal influence of the Cretaceous batholithic intrusions on the Jurassic sequence is, thus, quite apparent and could be partly explained by the screen position of the main belts of these rocks in the region (Fig. 1). It is possible, however, that this batholith-related thermal metamorphism overprinted a pre-existent burial regional pattern in the Jurassic rocks as suggested by the rare and sporadic presence of pumpellyite in two of the samples studied.

In conclusion, a possible sequence of events in the region is as follows: **1-** deposition of the Ibáñez volcanic sequence during the Jurassic followed by a burial metamorphic episode; **2-** deposition of the Divisadero Formation (from the Hauterivian to *ca.* 102 Ma according to Belmar, 1996a); **3-** batholithic intrusion at *ca.* 95 Ma overprinting, and almost completely obliterating, the Jurassic low-grade pattern; **4-** burial hydrothermal metamorphic phenomena affecting the Divisadero Formation (*ca.* 80 Ma?) and preserving the older greenschist assemblages of the Ibáñez Formation, most probably due to weak reaction kinetics; **5-** deposition and metamorphism of the Las Juntas Strata and metamorphism, mainly hydrothermal, of the Neogene volcanic rocks.

ACKNOWLEDGEMENTS

This research has been funded by FONDECYT Projects 92 0914 and 1950544, by the CNRS-CONICYT agreement and by the CE Project CT1I (00.33), all of which are duly thanked. DM acknowledges a University of Cádiz grant. Suggestions and criticism from the referees D.S. Coombs (University of Otago), B. Levi (University of Stockholm) and M. Suárez (Servicio Nacional de Geología y Minería), largely improved the manuscript and are gratefully acknowledged.

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Manuscript received: June 11, 1997; accepted: November 7, 1997.