LOW-GRADE METAMORPHISM OF MESOZOIC AND CENOZOIC VOLCANIC SEQUENCES OF PATAGONIA (43° - 46°S), CHILE

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INTRODUCTION

Results of a petrological reconnaissance of Mesozoic and Cenozoic volcano sedimentary rock sequences of Patagonia (43° - 46°SLat) are reported with the aim to describe and discuss the characteristics of very low and low-grade metamorphic phenomena affecting these rocks.The sequences 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 Estratos de Las Juntas (Paleogene?), and to younger lava flows (Neogene) (Fig.1). The Mesozoic extrusive activity is mainly represented by calcoalkaline volcanic arcs composed of andesitic strato volcanoes, 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 (Prieto and Cortés, 1995). The Neogene rocks correspond mainly to eroded volcanic centres in the Puyuhuapi area.

LITHOLOGY

The **Jurassic** rocks comprise: (a) amygdaloidal, porphyritic, andesite and andesitic basaltic flows; (b) porphyritic dacite flows with albitized plagioclase and altered amphibole phenocrysts in a felsitic groundmass; and (c) dacitic ignimbrites with chloritized "fiamme". The **Cretaceous** rocks correspond to: (a) porphyritic, partly amygdaloidal, andesite flows and flow-breccias with plagioclase phenocrysts in an intersertal groundmass of plagioclase and iron oxides ; (b) amygdaloidal olivine basalts with partially albitized phenocrysts of plagioclase and olivine (ghosts) in a fine-grained groundmass of plagioclase microliths, clinopyroxene (augite), and iron oxides. Among the **Tertiary** rocks, those belonging to the Estratos de Las Juntas are represented by: (a) poorly amygdaloidal basaltic andesites with plagioclase and clinopyroxene phenocrysts; (b) porphyritic andesite flows and; (c) lapilli tuffs with abundant diabasic clasts.Those of Neogene age mainly correspond to: (a) porphyritic, highly amygdaloidal olivine basalts with plagioclase and fresh olivine (Fo80-Fo85) phenocrysts in a hyalopilitic groundmass, and (b) fine to medium-grained, amygdaloidal basaltic flows with quench textures.

METAMORPHISM

All the rocks are strongly altered which is reflected in high H_2O contents (0,3 to 8,0%, mean = 3,8%, σ= 2,6 for 9 rocks analyzed chemically) 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 *c.* 80 sections studied (microscope, EPMA, XRD) are combinations of the 18 phases shown in Fig.2. Associations typical of the zeolite, prehnite-pumpellyite, prehnite-actinolite and greenschist facies are represented and no deformational features are recorded, the metamorphic transformations being purely mineralogical.

The ***Tertiary rocks*** have been mainly metamorphosed in the zeolite facies. Low temperature parageneses including zeolites, smectites, interstrafied smectite/chlorite (S/C), and celadonite are common, notably in the Neogene lavas. Among the zeolites, analcite, natrolite-mesolite and phillipsite are represented. In some amygdale cores, tobermorite, a Ca-Al hydrous silicate, has been found rimmed by phillipsite. Mafic phyllosilicates in these Tertiary rocks are mainly interestrafied S/C with average X% (=chlorite content) between 56 and 89; the highest X% values are found in lavas of the Estratos de Las Juntas with compositions corresponding to pycnochlorite. The temperatures of formation of these phyllosilicates, according to the Cathelineau & Nieva (1985) thermometer, are of *c.* 280°C for the Estratos de Las Juntas and of *c.*150°C for the Neogene basalts. The albitization of plagioclase is strong in flows of the Estratos de Las Juntas whereas in the Neogene basalts the original calcic compositions are preserved or only slightly modified. Aragonite filling amygdales was found in Paleogene basalts located 12 km NW of Balmaceda.

In the ***Cretaceous rocks***, the main metamorphic assemblages include pumpellyite, prehnite, epidote, chlorite, and albite. The almost total absence of zeolites , the scarcity of smectites and the considerable amount of chlorite contrast with the features observed in the Tertiary lavas. Pumpellyites have total iron as Fe_2O_3 higher than 10% with XFe^{3+} in the interval 18-33, typical of Fe-pumpellyites in sub-greenschist facies. Fe^{3+} partitioning between pumpellyite, prehnite and epidote in these assemblages takes place with $XFe^{3+}epi > XFe^{3+}pum > XFe^{3+}prh$. Mafic phyllosilicates (mainly pycnochlorite) with X% between 90 and 100 predominate indicating temperatures of formation of 220° - 330°C. Albitization of the plagioclase phenocrysts is intense in most samples with compositions approaching the albite pole; however, relictic plagioclase is found as patches of An_{48} composition.. Titanite contained in some samples is Al_2O_3-rich (4,2-7,3%), a feature diagnostic for subgreenschist facies.

Mineral associations in the ***rocks of Jurassic age*** are those of highest grade. The common presence of secondary actinolite, and of biotite in some associations, indicate temperatures of the greenschist facies. Pumpellyite is practically absent, only recorded as tiny flakes in some narrow epidote-rich veinlets. Amphibole is the most representative secondary phase. In the classification diagram (Leake, 1978) two amphibole groups are apparent in relation with the value of the ratio $Mg/(Mg+Fe^{2+})$ (Fig. 3). The first, richer in Mg, corresponds to locality 1 in the Futaleufú area and the second, richer in Fe, to locality 12 near La Tapera (Fig.1). In both groups, a linear variation exists with compositions displayed from the actinolite to the ferro-tschermakite-hornblende field. Three areas are identified in the Leake(1978) diagram (Fig.3): (a) weakly altered primary ferro-hornblende; (b) partially transformed primary Mg-hornblende, and (c) metamorphic actinolite and actinolite-hornblende. The very low NaM4 contents in the Ca-amphiboles of the Jurassic rocks indicate (Brown,1977) pressures below 2kb for their formation.These values, added to temperatures as high as 340°C obtained with the chlorite thermometer in these same rocks, indicate metamorphic conditions similar to the Californian Sierra Nevada region (see Brown,1977 and references therein) where batholithic intrusions have strongly influenced the regional thermal gradients.

CONCLUSIONS AND FINAL REMARKS

All the rocks, from Jurassic to Neogene, are affected by non deformative, very low and low-grade metamorphism. The secondary mineral phases and their associations are indicative of the zeolite, prehnite-pumpellyite, prehnite-actinolite and greenschist facies. Differences in metamorphic grade related to the age of the sequences have been established. Thus, zeolite-bearing associations 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. The temperatures inferred for these metamorphic assemblages go from *c.* 120° to near 350°C with pressures probably not exceeding 2 kb. The metamorphism of 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 rati (extensive albitization, formation of chlorite *s.s.*, presence of pumpellyite, etc.). The batholithic intrusions with ages around 95 Ma (see Pankhurst and Hervé,1994) exposed close to or immediately adjacent to the Cretaceous outcrops, have not disturbed the low-grade pattern of the Cretaceous rocks, one which stands close to that of hydrothermal burial metamorphism. Recent estimations of the age of the Divisadero Formation indicate a minimum age of 102 Ma (Belmar, 1996). In central Chile, dating of the low-grade metamorphic phenomena that affected lower Cretaceous rocks has shown that these phenomena occurred about 15 Ma after deposition of the sequence (Aberg *et al.* 1984). If a similar interval could be envisaged for the Aysén region, the metamorphism of the Divisadero Formation could be as young as 87 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 case, the greenschist metamorphism of the Jurassic rocks bears the imprint of a rapidly imposed thermal regime with a low fluid/rock ratio and selective fluid circulation. These characteristics resulted in metastable equilibrium of some primary minerals and patchy growth of secondary phases, *e.g.* partial albitization of plagioclase, partial transformation of primary amphibole into actinolite, persistence of S/C 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 pattern as suggested by the rare presence of pumpellyite in two of the Jurassic rocks studied.

A tentative sequence of events in the region would be: (1) deposition of the Jurassic units followed by a burial metamorphic episode; (2) deposition of the Divisadero Formation (from the Hauterivian to *c.* 102Ma according to Belmar, 1996); (3) batholithic intrusion at *c.* 95 Ma overprinting and obliterating the Jurassic low-grade pattern ; (4) burial hydrothermal metamorphic phenomena affecting the Divisadero Formation (*c.* 87 Ma?); (5) deposition and metamorphism of the Estratos de Las Juntas and metamorphism, mainly hydrothermal, of the Neogene volcanic rocks.

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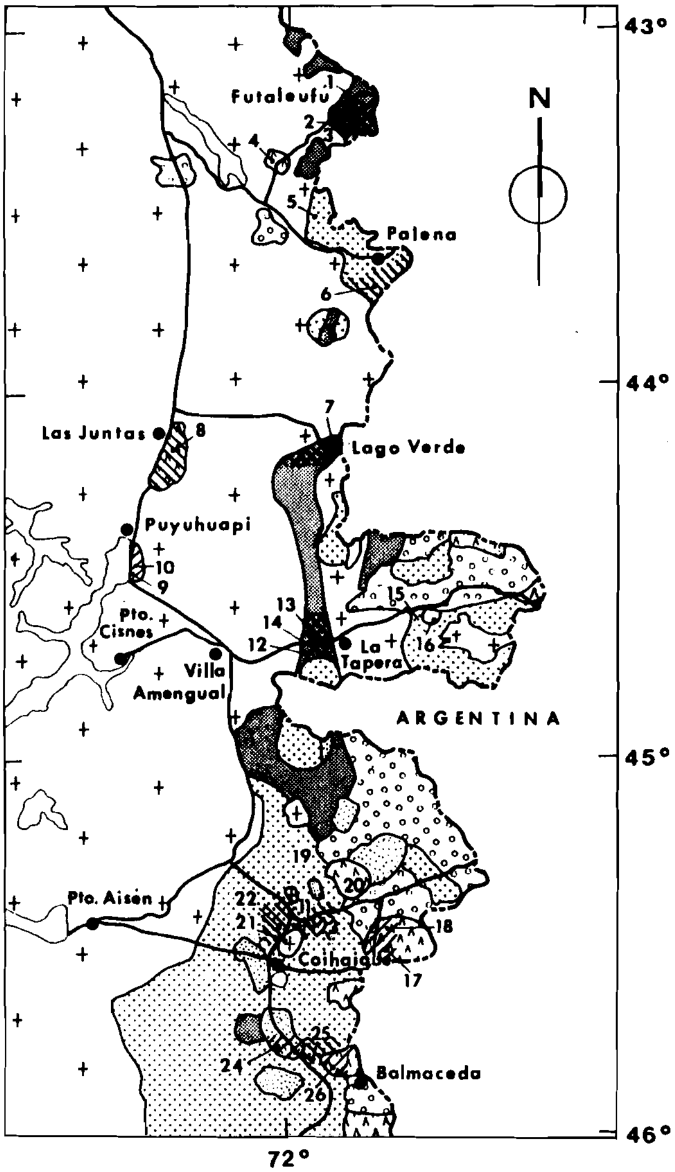

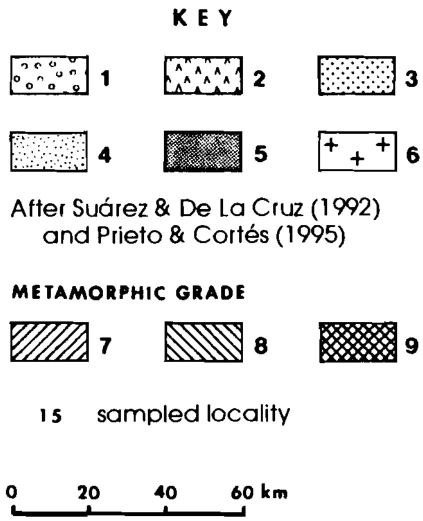

Figure 1. Geology of the Patagonian region (43º-46ºS) showing distribution of metamorphic facies and localities sampled.

1.- Quaternary sediments, 2.-Tertiary sedimentary rocks and basalts; 3.- Upper Cretaceous rhyolitic and dacitic tuffs, andesitic lava flows; 4.- Lower Cretaceous marine sedimentary rocks; 5.- Jurassic rhyolitic and dacitic tuffs, andesitic lava flows; 6.-Patagonian Batholith: granitoids and metamorphic rocks; 7.- Zeolite facies; 8,- Prehnite-pumpellyite facies; 9.- Greenschist facies.

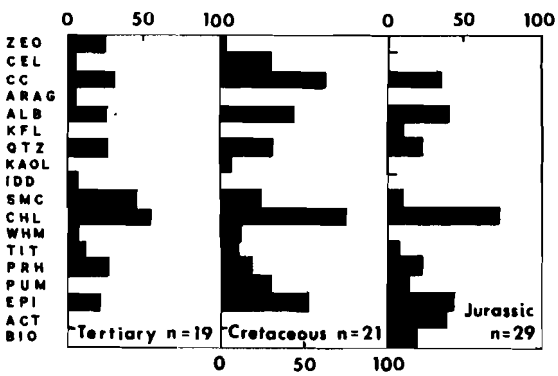

Figure 2.-Frequency of metamorphic minerals in the Mesozoic and Cenozoic volcanic rocks of Patagonia (43º-46ºS)

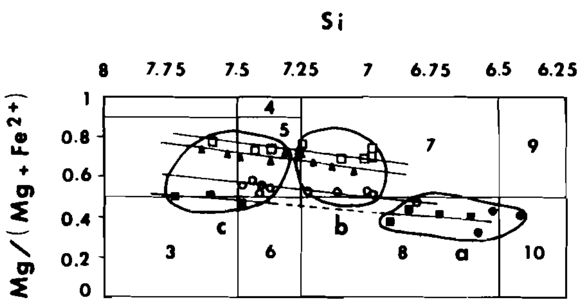

Figure 3.-Composition of amphiboles in rocks of Patagonia (43º-46ºS). Classification and fields according to Leake, 1978.