Metamorphic and alteration processes in a Jurassic sequence from the Central Patagonian Cordillera, Chubut

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RESUMEN. Procesos de alteración y metamorfismo en una secuencia jurásica de la Cordillera Patagónica Central, Chubut. La secuencia volcánica-jurásica aflorante en el Cerro Cuche (Grupo Lago La Plata) a 43°30'S y 71°12'O, sector este de la Cordillera Patagónica Central, se encuentra afectada por procesos de alteración hidrotermal y/o metamorfismo relacionados a la intrusión de los granitoides del Cretácico tardío-Terciario. Se diferenciaron varias asociaciones metamórficas y de alteración determinándose sus temperaturas de formación en función de inclusiones fluidas y datos pre-existentes en la bibliografía. Las asociaciones son: (1) epidoto + clorita + calcita + cuarzo + albita ± sericita ± prehnita, desarrollada en rocas volcánicas a temperaturas entre 200-270°C, dato que concuerda con temperaturas medidas en inclusiones fluidas en calcita (206-272°C); (2) actinolita + clorita + titanita + cuarzo + calcita en rocas volcánicas a temperaturas alrededor de los 300°C; (3) venas de skarns en rocas sedimentarias caracterizadas por hornblenda + diópido + titanita, probablemente formados a temperaturas entre 450 y 650°C; (4) rocas volcánicas transformadas en hornfels con clinopiroxeno, hornblenda, plagioclasa y titanita formados a una temperatura estimada de 600°C; (5) alteración potásica dada por la presencia de biotita (zurmano y turmalina) en rocas volcánicas, en un rango de temperaturas desde 450° hasta 650°C; (6) alteración argilica, silicificación, desarrollo de pititas y presencia de venas epibermas de cuarzo asociadas con mineralización de Au; temperaturas medidas en inclusiones fluidas en el cuarzo abarcan un rango entre 273° y 345°C. Las temperaturas de las asociaciones de minerales secundarios y su relación espacial con los intrusivos, sugieren una superposición de eventos de alteración/metamorfismo relacionados a los granitoides cretáceos.

Palabras clave: Metamorfismo, Alteración, Volcanitas jurásicas, Patagonia, Argentina
Key words: Metamorphism, Alteration, Jurassic volcanic rocks, Patagonia, Argentina

Introduction

The Jurassic and Cretaceous volcanic rocks of the Patagonian Cordillera crop out as wide linear belts in the southern Andes of Argentina and adjacent parts of Chile. These rocks are believed to represent an arc related to a subduction regime (Haller and Lapido 1980; Ramos 1981) that has persisted from the Jurassic until the present along the western margin of South America.

Geological descriptions of the Jurassic and Cretaceous of the Patagonian Cordillera are usually focused on the granitoids and the geochemistry of volcanic rocks; only exceptionally are the regional or local alterations treated (e.g., Aguirre et al. 1997 for the 43 and 46° S Chilean sector). The present paper describes the regional and local alteration patterns in a Jurassic volcanic and sedimentary sequence that crops out in the cerro Cuche area (Fig. 1) between 43°- 47°S, on the eastern edge of the Central Patagonian Cordillera (CPC) (Haller and Lapido 1980). To the east, the CPC is bounded by the Chubut Precordillera, and to the north and south by the Northern Patagonian Cordillera and the Southern Patagonian Cordillera, respectively. The different types of alteration are described and related to the primary volcanic features and to granitoid intrusions. In addition, a comparison is made with other sectors of the Chilean Cordillera.

The geology of the CPC comprises: (a) Jurassic volcanic and sedimentary rocks; the former are of intermediate composition to the north and acid composition to the south, correlated with the Lago La Plata Group, (b) marine sedimentary rocks deposited in a small Early Cretaceous sea, (c) continental volcanic rocks of Late Cretaceous age, (d) granitoid plutons of Early to Late Cretaceous and Tertiary age (e) Eocene continental basic to acid volcanic rocks with intercalated lacustrine and/or fluvial sedimentary rocks, (f) Oligocene intramontane deposits, (g) Miocene continental sedimentary rocks of lacustrine character, and (h) glacial, colluvial and alluvial Quaternary deposits. The stratigraphy of the Chubut Precordillera is similar to that of the CPC,
Figure 1: Geologic map and distribution of alteration assemblages in the area of cerro Cuche.

the main differences being the presence of Palaeozoic marine sedimentary rocks and Lower Cretaceous basic intrusions in the first one.

The Jurassic sequence in the CPC treated here belongs to a 500 or more km wide volcanic arc (Page and Page 1993).

Methodology

The alteration study of the Lower Jurassic sequence at Cerro Cuche is based on ca. 100 representative samples of slightly altered to heavily altered rocks. The primary mineralogy and chemical composition of the Jurassic, Cretaceous and Tertiary volcanic rocks and Cretaceous granitoids were described in previous works (Massaferro 1998, 1999).

Secondary mineralogy was determined by means of thin sections, polished sections and X-Ray diffraction techniques. Metallic elements were determined by means of INAA (Instrumental Neutron Activation Analysis) at ACTLABS comercial laboratories of Canada. Amphiboles from four samples were analyzed with electron microprobe (EPMA) at CITEFA (Centro de Investigaciones de las Fuerzas Armadas). Thermometric studies of fluid inclusions in quartz from epithermal veins and calcite of one of the mineral assemblages were carried out using a Chaixmeca heating and cooling stage, with a temperature range between -180° and +600°, at the Departamento de Geologfa de la Universidad de Buenos Aires. Mean density values and homogenization pressures were calculated with the FLINCOR program of Brown (1989).

Geology of the study area

The geology of the cerro Cuche area consists of stratified sequences of Early Jurassic and Tertiary age, Cretaceous granitoid intrusions and Quaternary deposits (Fig. 1).

The Lower Jurassic sequence, which crops out in the central-western part of the area (Fig. 1), comprises subaerial volcanic and marine sedimentary rocks. Continental clastic deposits bearing an Early Eocene fossil flora are intruded by volcanic dykes
and crop out in the north-western corner, whereas Miocene continental clastic rocks and limestones, are exposed in the north-east. The Quaternary sediments include glacial, alluvial and colluvial deposits.

The Cretaceous granitoids are epizonal plutons which intrude the Jurassic-Cretaceous sequences. They are medium-grained granodiorites and tonalites of light grey colour. Locally, up to 1.5 cm long plagioclase and hornblende crystals occur; mafic microgranular enclaves, 20 cm in diameter, are common. The petrographical and chemical characteristics of the granitoids correspond to a hybrid calc-alkaline type (Barbarin 1990), and they belong to the I-type of Chappell and White (1974). Their high MnO and Y contents place these rocks in the non-productive type of Baldwin and Pearce (1982).

A predominant upper mantle source, with contributions from the crust and the subducted slab, coupled with mingling processes during their ascent, have been proposed for their origin (Massaferro 1998, 1999). Some authors (e.g. Haller and Lapido 1980; Baker et al. 1981; Ramos et al. 1982) have suggested that these granitoids represent the roots of the Jurassic magmatic arc, exposed by erosion after the uplift following the Andean orogeny, i.e. during the Tertiary. A statistical plot of all the chronological data known of the Patagonian Batholith (Massaferro 1998) indicate a period of maximum activity between 97 and 102 Ma (Albian). These periods of maximum magmatic activity are coincident with periods of maximum rate of ocean floor spreading and Andean orogeny (Bruce et al. 1991).

The Lower Jurassic sequence

The Lower Jurassic sequence in the cerro Cuche area has a total thickness close to 1000 metres. It is subdivided in three members which interfinger and grade into each other.

The lower member is a monotonous sequence of lava flows, predominantly of intermediate composition. Pyroclastic rocks, mainly andesitic breccias and tuffs, compose the middle member. General features of the outcrops and the petrographical characteristics indicate a subaerial depositional environment for the rocks of the lower and middle member. The upper member consists of pelitic rocks, sandstones, conglomerates and limestones with algal structures (stromatolites and oncolites) (Massaferro 1998; Massaferro et al. 1998). A level of coquina bearing abundant pelecypods, ammonites, gastropods and corals, assigns a Pliensbachian age to this member, and represents the oldest fossil record for this segment of the Patagonian Cordillera. The depositional environment of the upper member was marine, littoral, with sporadic storm and subaerial exposures (Massaferro et al. 1998).

Primary characteristics of the volcanic rocks

The volcanic rocks of the lower member are mainly andesites and basaltic andesites, with subordinate dacites and rhyodacites. Megascopically, the andesites are aphanitic, but small phenocrysts of plagioclase (andesine-labradorite), pyroxene and hornblende can be observed under the microscope. The groundmass consists of plagioclase microlites and secondary minerals such as chlorite, calcite, sericite and quartz. The dacites have porphyritic textures with plagioclase phenocrysts in an aphanitic matrix of plagioclase microlites and interstitial quartz. In some samples devitrified glass has been observed.

The pyroclastic rocks of the middle member comprise coarse breccias and air-fall tuffs, with scarce intercalations of pyroclastic flows (ignimbrites), of andesitic composition. The air-fall tuffs varies from coarse to fine-grain size with typical red oxidation colours and are composed of different proportions of crystal fragments of quartz and plagioclase, devitrified shards and lithic fragments.

Chemically, the volcanic rocks range from tholeiitic to calc-alkaline of normal K-type. Their chemical signature resembles that of a continental volcanic arc developed on relatively thin crust (Massaferro 1998, 1999). These characteristics seem to be maintained along the N-S and E-W extension of the Jurassic arc, as suggested by a comparison made by Massaferro (1998) of Jurassic rocks from the CPC in Argentina (Haller and Lapido 1980; Haller 1985; Massaferro 1998), and from the Southern Patagonian Cordillera in Argentina and Chile (Baker et al. 1981).

Alteration and metamorphism

The above described sequence has been overprinted by mineralogical, textural and/or chemical changes due to local or regional alteration and/or metamorphic processes. In some cases, a distinction between the results of low grade metamorphism or hydrothermal alteration is very difficult to establish, because of the similar mineralogical assemblage they produce. The only differences are the higher fluid/rock ratios and thermal gradients in the hydrothermal alteration processes.

The local alteration is developed close to the contacts with granitoid intrusions forming either hornfels when the host rock is volcanic, or calc-
silicate veins, when the host rock is a limestone (Fig. 1). Hydrothermal alteration, mainly silicification and pyritisation also occurs in some restricted areas (Fig. 1).

The regional alteration, affecting a more extended area, is characterized by the preservation of the volcanic textures, but a partial to total replacement of the primary minerals by green-colored secondary associations, of inferred low to medium temperature, is observed (selectively pervasive alteration). The chemical analyses of the rocks show a high value for the loss by ignition (1.4-5.2%).

**Secondary mineral assemblages**

The secondary minerals formed by the local or regional processes, replace partially or totally the primary phases, such as pyroxene and plagioclase, or occur in fractures (veins and veinlets). Microscopic observations, together with XRD determinations, show that the secondary minerals can be divided into six different assemblages.

**Assemblage 1:** The andesite and dacite lavas of the lower member and the pyroclastic rocks of the middle member are selectively pervasive altered by:
epidote + chlorite + calcite + quartz + albite ± sericite ± prehnite

Epidote and chlorite predominate in the andesitic rocks, whereas calcite and sericite are common in the dacites. Epidote is usually euhedral but massive when associated with intense silicification. Chlorite is present in veins or as pseudomorphs after amphibole or pyroxene. Anhedral calcite partially replaces plagioclase. Albite is found as fracture fillings or surrounding primary plagioclase, and sericite is present as flakes in plagioclase phenocrysts or microlites. Prehnite forms radial aggregates filling veins, or replaces mafic minerals as individual crystals. Quartz is present in veins, filling vesicles, or as devitrification product of the volcanic glass.

Fluid inclusion studies on calcite show that it contains aqueous inclusions with a gas bubble occupying 20%-40% of the total volume. Inclusions have negative crystal shapes and are about 10 μm in size.

The homogenization temperatures obtained range between 206° and 272°C, with a mean value of 226°C. The ice melting point was difficult to observe because of the small size of the inclusions.

**Assemblage 2:** This assemblage is found both in the sedimentary and volcanic rocks of the Jurassic sequence:

\[ \text{actinolite} + \text{chlorite} + \text{titanite} + \text{quartz} + \text{calcite} \]

In the sedimentary rocks of the upper member these minerals are present as dark green veins, up to 1 cm thick, parallel to the stratification. In the volcanic rocks of the lower and middle members they commonly replace phenocrysts or occur in veinlets. Actinolite appears as light green non-pleochroic crystals of fibrous habit. Chlorite is found replacing primary phases and filling vesicles and veinlets, where it has a botryoidal habit.

**Assemblage 3:** This assemblage, which is found only in veins in sedimentary rocks of the upper member, consists of:

\[ \text{hornblende} + \text{diopside} + \text{titanite} \]

The amphibole is prismatic with weak pleochroism (green to yellowish green). According to electron-probe (EPMA) determinations and the classification scheme of Leake et al. (1997) its composition varies between ferro- hornblende and a magnesio-hornblende (Table 1, Fig. 2).

**Assemblage 4:** Granoblastic hornfels is developed at the contact zone between Cretaceous granodiorite and the volcanic rocks of the lower member. It consists of quartz grains with triple junctions, clinopyroxene, hornblende, plagioclase and titanite.

**Assemblage 5:** Fine brown flakes of biotite occur as devitrification products of glass or as partial...
homogenization temperatures vary between 273° and 345°C with a mean value of 322°C. The mean pressure is 110 atm. Assemblage 1: The presence of chlorite without chlorite/smectite mixed layers would indicate replacement of phenocrysts of the volcanic rocks exposed at the top of Cerro Cuche. In some places the biotite is associated with quartz and tourmaline formed after primary feldspar phenocrysts.

**Assemblage 6:** This assemblage is expressed as a local, intense silicification and pyritization of the volcanic rocks of the lower and middle members. A conspicuous red colour of many occurrences is the result of weathering oxidation of pyrite. In other places, however, pyrite is unoxidized and associated with montmorillonite and/or chlorite and minor sericite, corresponding to an argillic alteration. Drilling for mining exploration has been performed in some of these areas.

The red-coloured areas contain a large number of epithermal quartz veins with drusiform and massive textures. They are commonly subvertical, up to 10 m long and 3 m thick, and lack a preferred orientation. They contain wall rock fragments at their contacts. The fluid inclusions were studied in quartz from one vein with an average Au content of 1.3 ppm. The inclusions are aqueous and contain a gas bubble occupying 20%-50% of the total volume. They show negative crystal morphology and are less than 10 μm in size. Ice melting took place at 0°C so the solutions appear to be salt-free. The measured homogenization temperatures vary between 273° and 345°C with a mean value of 322°C. The mean density is 0.65 g/cm³ and the homogenization pressure is 110 atm.

**Table 1:** Microprobe analysis of amphiboles of assemblage 3 (anhydrous recalculated) and formula unit on the basis of 23 O.

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<td>0.41</td>
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mineralization

Some small patches of sulfide mineralization occur in the area, associated with the epithermal quartz veins (assemblage 6). They consist mostly of pyrite (visible in hand specimen), minor pyrrhotite, chalcopyrite, and Fe-Ti oxides (magnetite, ilmenite and titanium oxides). Pyrite occurs in veins and disseminations, partly with inclusions of pyrrhotite, chalcopyrite or transparent minerals. It is commonly euhedral to subhedral and has a maximum size of 0.5 mm. Pyrrhotite is disseminated or forms inclusions in pyrite. In some samples pyrrhotite is replaced by a mixture of pyrite and marcasite giving rise to a birdseye texture (Ramdohr 1980). The maximum size of pyrrhotite is 120 μm. Chalcopyrite is scarce and occurs disseminated or as rounded inclusions in the pyrite. Its size varies between 50 μm and 1 μm. Magnetite may be fresh, but is generally slightly altered to hematite along the octahedral planes. Hematite is found as inclusions in pyrrhotite or as verniform inclusions, up to 300 μm size, within ilmenite.

**Discussion**

**P-T conditions, facies and processes**

The problem with the estimation of temperature conditions during either low-grade metamorphism or hydrothermal alteration is the common occurrence of relics of primary minerals, demonstrating that the equilibrium in the system was attained only at a very local scale. However, minerals occurring together in amygdules, veins, or as replacement after a primary phase, may be considered at near equilibrium (Liou et al. 1987). In the present study, some P-T data have been obtained by means of fluid inclusions, but most of the P-T conditions have been estimated from data in the literature based on experimental work and/or direct measurements from modern geothermal systems. The alteration pattern described here (see also Aguirre et al. 1997) is consistent with a shallow level during alteration. The existence of epizonal granitoids, circulating fluids and no deformation fabrics are evidences of this shallow level, typical of volcanic arc settings (Robinson and Merriman 1999), so that data from those systems are likely to apply here. Thus, pressures of less than 2 kb can be considered as likely during the processes of low grade metamorphism, hydrothermal alteration and contact metamorphism described here (cf. Bucher and Frey 1994; Einaudi et al. 1981).

**Assemblage 1:** The presence of chlorite without chlorite/smectite mixed layers would indicate...
temperatures above 260°C (Schiffman and Fridleifsson 1991). However, XRD determinations were not enough to exclude the possible presence of the mixed-layer phase in some samples. If that were the case, then the temperature would be lower, in the range of 200°-260°C. The presence of albite would indicate temperatures of 200°-300°C (Kristmannsdóttir 1979) whereas that of epidote would indicate temperatures of 200°-260°C (Fridleifsson 1991; Kristmannsdóttir 1979). The occurrence of epidote and chlorite without actinolite suggests a temperature range of 240°-280°C (see references in Vergara et al. 1993). Therefore, according to its mineralogy, assemblage 1 might have formed at a temperature range of 200°-270°C which is in good agreement with the fluid inclusion homogenization temperatures of 206-272°C obtained from calcite.

Several processes could have formed this assemblage: a) regional, nondeformative, low-grade burial metamorphism (Coombs 1961), b) contact metamorphism related to a pluton, in which it formed peripheral to the aureole, where the original volcanic textures would be preserved, or c) local alteration processes similar to those taking place at the outermost part of a porphyry copper system where it should be considered a propilitic zone. As it will be explained below there are no clear evidences to determine the origin of this assemblage.

In the first case (regional metamorphism) the assemblage would correspond to prehnite-pumpellyite facies, as indicated by the presence of prehnite and epidote and the absence of actinolite; the absence of pumpellyite could be due to a lower pressure than what is normal for this facies.

Assemblage 2: The appearance of actinolite in the absence of prehnite implies a higher temperature than for assemblage 1. Kristmannsdóttir (1979) mentioned that actinolite forms at temperatures of 280°-300°C. Assemblage 2 would correspond to greenschist facies conditions in rocks affected by burial metamorphism. However, it can also be indicative of contact metamorphism where the fluids probably circulated through the stratification planes and fractures which constitute a zone of weakness.

Assemblage 3: The presence of diopside and hornblende filling fractures would indicate amphibolite facies conditions, i.e. a higher metamorphic grade than assemblage 2. As the fracture fillings constitute a calc-silicate assemblage developed in pelites and limestones, they could be considered as skarn veins. At a pressure of 2 kb, diopside forms from actinolite at 540°C (Bucher and Frey 1994). Mineral associations in skarns similar to those of assemblage 3, developed at temperatures of 450°-650°C and pressures of 0.3-3 kb (Einaudi et al. 1981). Since the distribution of this assemblage is restricted, the most likely explanation for its origin is contact metamorphism. Although the host rocks are not in visible contact with a granitoid, the presence of a hidden intrusion could be suggested because of the spatial relationship between assemblage 3 and assemblage 5 (hydrothermal alteration).

Assemblage 4: These hornfelses are typical of contact metamorphism, with recrystallization of primary minerals and obliteration of the original volcanic textures. The presence of clinopyroxene indicates temperatures higher than 540°C (Bucher and Frey 1994). Intruding granitic magmas typically have temperatures of 800°C; the temperatures in contact zones reaches a 60% of this value, 480°C, and if the country rock had a temperature of ca. 100°C (Winkler 1976), then a temperature of about 580°C could be inferred.

Assemblage 5: Assemblage 5 can be interpreted as representing a potassic alteration zone, similar to that described by Lowell and Gilbert (1970) in relation to...
to porphyry intrusions. As such, a range of temperatures between 450°-600°C might be estimated (Pirajno 1992). The presence of tourmaline indicates a high boron content of the circulating fluids. The predominance of biotite and/or the absence of K-feldspar could be related to a dioritic composition of the porphyry (Hollister 1978). Such a composition, would result in a low silica content and a high Na₂O/K₂O ratio in the circulating fluids, compatible with the formation of biotite (and albite) instead of the K-feldspar-rich assemblage, that precipitates from fluids related to a typical quartz monzodiorite porphyry. The lack of K-feldspar in this association could also be controlled by the relatively silica-poor, predominantly andesitic wall rock, with a relatively high Na₂O/K₂O ratio.

Assemblage 6 and related mineralization: Leaching of the country rocks by acid epithermal solutions, might have generated this assemblage. Such process would result in residual silica and argillic alteration. The pressure and temperature conditions of the circulating fluids could be inferred from fluid inclusions in the quartz veins. They yielded a mean pressure of 110 atm (80-170 atm) and temperatures of 273-345°C. Values above 300°C are usually considered to be too high for an epithermal environment (Lattanzi 1991; Hedenquist et al. 1996), but some authors extend the limit up to 350°C (e.g. Pirajno 1992). Therefore an epithermal origin for the solutions could be sustained. The inferred very low, and even the lack of salinity of the solutions would suggest dilution of magmatic fluids with meteoric water. There is no evidence of boiling, such as coexistence of vapour-rich and liquid-rich inclusions, which is common in epithermal systems. This might suggest that the portion of the vein analyzed, formed at a depth below the boiling zone. Therefore, the present level of exposure might represent a deeper part of the epithermal system. Thus, because of the lack of boiling, no metal precipitation occurred. The Au-bearing parts of the quartz veins would thus now have been eroded, which is consistent with the low concentration of metals in the quartz veins (Table 2). However, the Au content of the quartz veins, in spite of the low values, constitutes a positive anomaly, when compared to the country rocks (Jurassic andesites) and to the granitoids. The positive correlation of W, As, Co and Sb with Au, suggests that these elements may constitute a guide for the exploration of Au in the study area.

Drusiform texture indicates slow crystallization of prismatic quartz crystals, in fractures and open spaces, from hydrothermal solutions oversaturated in SiO₂. A drop in temperature and pressure, promotes silica precipitation. The sulfide mineralization is usually related to the epithermal quartz veins or to zones of intense silicification. The mineral association pyrite (± pyrrhotite and minor chalcopyrite) has a very low Cu content, which could either be an original feature or be the result of deposition of Cu at greater distance or depth.

Superposition of regional and local metamorphic and/or alteration processes and comparison with other sectors of the Patagonian Cordillera

The processes of regional non-deformative metamorphism and hydrothermal alteration have many features in common. If similar physical and chemical conditions characterize both processes, similar rocks and mineral assemblages would be produced. However, major differences are a considerably higher fluid/rock ratio and a higher thermal gradient during the hydrothermal alteration. Therefore, calling a process alteration or metamorphism and choosing names for the different assemblages could be a matter of scale, of the presence/absence of gradients in the field and of the possible influence of intrusions. Considering the numerous intrusive bodies of Late Cretaceous and Tertiary age cropping out in the study area, it is likely that alteration patterns documented here were overprinted by these intrusions, which might have obscured earlier secondary processes. These intrusions could be cropping out or be hidden near the surface.

Hence, the magmatic Jurassic sequence at Cerro Cuche and its surroundings seems to be affected by a superposition of regional and local metamorphic and/or alteration events, similar to those described in coeval arc sequences in the CPC in Chile, west of the study area (Aguirre et al. 1997). A first episode of regional low-grade metamorphism or hydrothermal alteration affected the entire Jurassic column, producing the minerals of assemblage 1. As explained above, it is impossible on the basis of mineralogy and without field evidence to establish whether low-grade metamorphism or hydrothermal alteration was the main process. This episode was prior to the intrusion of Cretaceous granitoids and probably unrelated to it. The lack of a pattern suggesting burial metamorphism (i.e. different facies developed gradually in the volcanic pile) could be due either to insufficient thickness of the Jurassic sequence (ca 1000 m) or to a low thermal gradient. Another explanation could be that the contact effects from the subsequently emplaced Cretaceous granitoids partially obliterated the regional metamorphic pattern, as in the Chilean part of the CPC. Hence, the rare and sporadic presence of pumpellyite in Jurassic rocks described by Aguirre et al. (1997) was attributed to the thermal effects of granitoid intrusions. The rise in temperature caused by the intrusion
of Cretaceous granitoids would have been the cause of the formation of assemblage 2. Closer to the contacts, skarn and hornfels with mineral assemblages 3 and 4 would be generated. Hydrothermal processes would give rise to the potassic alteration of assemblage 5, and late magmatic fluids, mixed with meteoric water, would have produced at the end argillic alteration, epithermal quartz veins, silicification and sulfide mineralization (assemblage 6) present in some sectors.

Conclusions

The work carried out on secondary minerals and their spatial relationships with the intrusive rocks, suggest that the patterns of alteration present in the Jurassic sequence of Cerro Cuche and its surrounding area might be explained by a superposition of local and regional metamorphic and/or alteration processes. The resultant secondary minerals could be divided into six different assemblages.

The sequence was affected, in first place by hydrothermal alteration very similar to a regional low-grade metamorphism, characterized by the presence of epidote, chlorite, calcite, quartz, albite, sericite and prehnite (assemblage 1). Thermometric fluid inclusions studies in calcite of this assemblage show a mean temperature of 226°C for the solutions responsible for this alteration, in good agreement with the estimated conditions from literature data. The intrusion of Cretaceous granitoids would locally have raised the temperature, producing contact metamorphism and obliterating the pre-existent regional pattern. Next to the contact, either skarns (assemblage 3) or hornfels (assemblage 4) were formed, depending on the composition of the wall rock. Assemblage 3 probably developed at temperatures of 450°-650°C and hornfels at 600°C. Away from the contact, the metamorphic processes would have attained greenschist facies conditions giving rise to assemblage 2, at a temperature of about 300°C. Hydrothermal alteration processes are also present as potassic alteration (assemblage 5), with estimated temperatures between 450° and 600°C; and argillic alteration associated with epithermal quartz veins and sulfide mineralization (assemblage 6). Fluid inclusion studies on quartz veins point to a temperature range of 273°-345°C.

A similar pattern of alteration is described for the adjacent Chilean sector and probably this situation could be extrapolated to other sectors of the CPC where the Jurassic arc and its roots are exposed.

Chemical analyses have revealed a maximum Au concentration of 1.3 ppm in the quartz veins. As there is no evidence for boiling, it is thought that the level of emplacement of these veins was below the boiling zone preventing metal deposition in economic values.

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