# Variation in Lower Cretaceous secondary mineral assemblages and thermal gradients across the Andes of central Chile (30-35°S)

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## ABSTRACT

Stratigraphic sequences of Lower Cretaceous age occur in two belts along central Chile. Between 30° and 35°S, the western belt, situated in the Coast Range is composed of 7-14 km thick intra-arc and forearc sequences dominated by shoshonitic to high-K calc-alkaline volcanic rocks, whereas the eastern belt in the High Cordillera consists of 2-5 km thick back-arc sequences with a smaller proportion of volcanics which have a less alkalic affinity. The rocks in both belts are burial metamorphosed at greenschist, prehnite-pumpellyite and upper zeolite facies. However, their secondary mineral assemblages show differences which indicate that the thermal gradients were *ca.* 20° C $km^{-1}$ in the Coast Range and 45-80° C $km^{-1}$ in the High Cordillera. This suggests that during the Lower Cretaceous, the crust was thinner in the east than in the west, *i.e.*, contrary to the present situation.

*Key words: Zeolite, Prehnite-pumpellyite, Thermal gradient, Wairakite, Lower Cretaceous, Central Chile, Andes.*

## RESUMEN

**Variación de las asociaciones de minerales secundarios y gradientes termales en el Cretácico Inferior en los Andes de Chile central (30-35°S).** En Chile central las secuencias estratigráficas del Cretácico Inferior afloran en dos cinturones de dirección norte-sur. Entre los 30° y 35°S, el cinturón occidental, ubicado en la Cordillera de la Costa, está formado por secuencias de intra-arco y ante-arco de 7-14 km de espesor dominadas por rocas volcánicas shoshoníticas y calco-alcalinas ricas en K, mientras que el cinturón oriental ubicado en la Cordillera de los Andes consiste en una secuencia de tras-arco de 2-5 km de espesor con una menor proporción de rocas volcánicas, las cuales tienen una menor afinidad alcalina. Las rocas de ambos cinturones están metamorfizadas en facies de esquistos verdes, prehnita-pumpellyita y facies alta de ceolita. Sin embargo, sus asociaciones mineralógicas secundarias muestran diferencias que indican que las gradientes de temperatura en la Cordillera de la Costa eran de aproximadamente 20° C $km^{-1}$, y en la Cordillera de los Andes de 45-80° C $km^{-1}$. Esto sugiere que durante el Cretácico Inferior la corteza era más delgada en el este que en el oeste, o sea, una situación opuesta a la actual.

*Palabras claves: Ceolita, Prenita-pumpellyita, Gradiente termal, Wairakita, Cretácico Inferior, Chile central, Andes.*

## INTRODUCTION

During the Lower Cretaceous large volumes of volcanic and volcaniclastic rocks were deposited in a *ca.* 1,200 km long ensialic basin (or series of basins) in central Chile between 25° and 36°S (Fig. 1). These rocks are now present in two north-trending belts, a western one in the Coast Range and an eastern one in the High Cordillera. The western sequences, consisting of >90% of volcanic and volcaniclastic rocks, are 7-14 km thick and intruded by Cretaceous granitoids, whereas such granitoids are absent in the 2-5 km thick eastern sequences which contain a higher proportion of sedimentary rocks. The wide separation between the two sequences (80-150 km), which dip towards each other, can be attributed partly to ensialic spreading-subsidence during volcanism, enhanced by opening during emplacement of granitoids (Levi and Aguirre, 1981; Drake *et al.*, 1982; Åberg *et al.*, 1984).

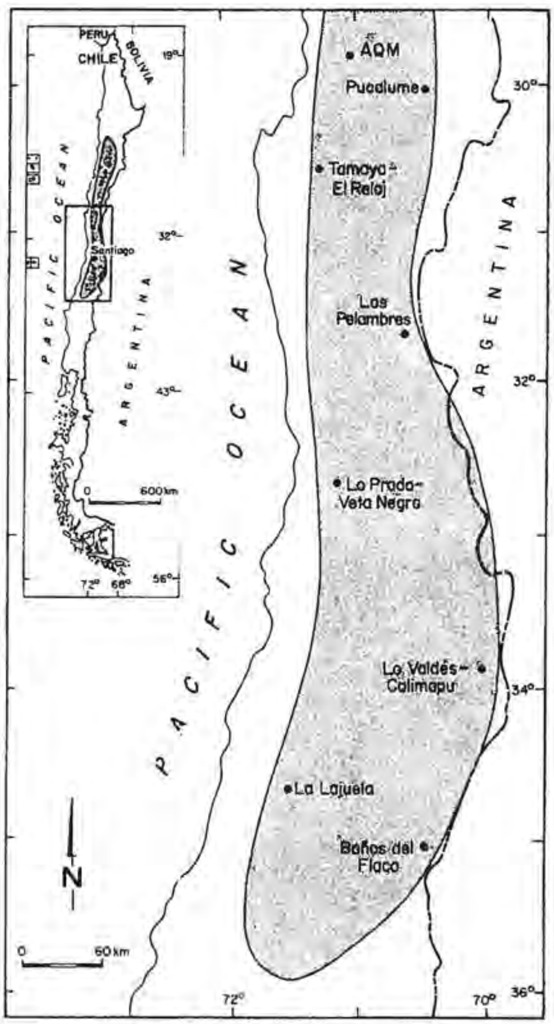


FIG. 1. Approximate boundaries of the early Cretaceous basin in central Chile (light gray) and type localities (dots) of the main formations bordering it in the Coast Range (western side; AQM=Arqueros and Quebrada Marquesa) and the High Cordillera (eastern side). Note that the sampling was not restricted to the type localities. The easternmost extension of the sequences in the High Cordillera is complicated by reverse faulting and is not shown.

This study deals with the Lower Cretaceous units deposited in the southern part of the basin (30-35°S; Fig. 1). Each belt has features in common throughout its north-south extension. The various sequences in the Coast Range show a similar change in depositional environment with the time, and there are overall lithological similarities: a tendency for ignimbrites to occur in the lower part, porphyritic lavas with large plagioclase phenocrysts (ocoites) in the middle part and flow breccias in the upper part of the stratigraphic columns at different latitudes. The sequences in the High Cordillera also resemble each other with regard to depositional environment and to some lithological features (ocoites are common among the lavas). The different formations into which the Lower Cretaceous sequences of the two belts are subdivided (Table 1) can generally be followed along strike for hundreds of km.

According to the pattern of burial metamorphism reported by Levi *et al.* (1989), prehnite-pumpellyite to zeolite facies is the predominant metamorphic grade in the Lower Cretaceous sequences throughout the Andes of central Chile, and the facies series usually persist from tens to more than a hundred kilometers along strike. In addition, these facies also seem to characterize Lower Cretaceous volcanic piles elsewhere along the western continental margin of South America. Here, the authors outline the secondary mineral assemblages in the main Lower Cretaceous formations bordering the southern part of the paleobasin (30-35°S; Fig. 1), which indicates a difference in thermal gradients between the western and eastern sequences, and they mention tectonic implications.

## SAMPLES

This study is based on *ca.* 700 samples from amygdaloidal and other pervasively altered parts (no primary volcanic relics present) of basic and intermediate lava flows, including volcaniclastic rocks dominated by material of this type from the Lower Cretaceous sequences in the Coast Range and High Cordillera. The samples were collected in the type localities of the formations and also in several other cross sections in order to obtain regional significance for the alteration pattern of each formation. No sampling was done in the vicinity of granitoid outcrops, and the material included in this study shows well-preserved volcanic structures without sign of recrystallization.

The investigated formations, their thickness at the type localities and the predominant chemical affinity of their unaltered lavas are given in table 1, along with the secondary mineral assemblages and metamorphic facies. The assemblages consist of various combinations of the listed minerals (given in order of frequency) at the scale of a thin section. They were determined by XRD in all the samples; more than one alteration domain was analyzed in approximately 400 of the samples. Secondary plagioclase, quartz, hematite and titanite are generally present in the assemblages and are, therefore, not listed; the plagioclase ranges from albite of low structural state in greenschist facies rocks to oligoclase of high to intermediate structural state in rocks at zeolite facies (Levi *et al.*, 1989). The stratigraphic descriptions are based on published and unpublished information from Servicio Nacional de Geología y Minería (SERNAGEOMIN, Chile), Departamento de Geología, Universidad de Chile and observations made by the authors.

## COAST RANGE

The Lower Cretaceous units in the Coast Range have a lower part composed of ignimbrites (partly subaqueous), volcaniclastic rocks, limestones and intercalations of basic lavas deposited in a littoral to sublittoral environment; the chemical affinity of the lavas varies along the belt. The upper part is dominated by continental, basic to intermediate lavas and flow breccias of shoshonitic to high-K calc-alkaline chemistry (Levi *et al.*, 1988, Vergara *et al.*, in press). In the following description, the different formations are treated from north to south and the listed mineral assemblages are the characteristic ones. Locally, the sequences constituting the belt are interrupted or incomplete, which in part, is due to emplacement of granitoids.

The Arqueros and Quebrada Marquesa formations have a combined thickness of *ca.* 6 km. The lower unit (Arqueros) is composed of basic and intermediate volcanic rocks with intercalations of littoral limestones, and the upper unit (Quebráda Marquesa) consists of intermediate flow breccias and basic lavas, continental volcaniclastic rocks, limestones with chert and manganiferous strata, and scarce intercalations of littoral volcaniclastic rocks. As seen in table 1, the Arqueros Formation is underlain by two other Cretaceous units with type localities farther south: the Tamaya and El Reloj formations (Fig. 1). They have a combined thickness of *ca.* 1.5 km and are dominated by acid ignimbrites and intermediate to basic lavas, respectively. The mineral assemblages in the Tamaya Formation contain epidote, calcite, chlorite, illite, but they are actinolite-bearing in the lowermost third part of the unit. Assemblages with calcite, chlorite, illite±epidote are found in the El Reloj Formation, and the Arqueros Formation contains epidote, chlorite, K-feldspar, calcite±prehnite, pumpellyite, celadonite. In most of the Quebrada Marquesa Formation the assemblages are chlorite, epidote, K-feldspar, prehnite±calcite, pumpellyite; they are replaced by prehnite, chlorite, calcite, celadonite, K-feldspar, ±laumontite in the uppermost 500 m, followed by swelling chlorite, K-feldspar, laumontite at the top.

The combined thickness of the Lo Prado and Veta Negra formations is *ca.* 14 km. The lower unit (Lo Prado) is composed of forearc turbidites overlain by sublittoral to littoral limestones, acid ignimbrites and subordinate basic lavas and deltaic volcaniclastic rocks. The upper unit (Veta Negra) is a thick monotonous sequence of basic to intermediate lavas and flow breccias with minor intercalations of volcaniclastic

TABLE 1. SECONDARY MINERAL ASSEMBLAGES IN THE MAIN FORMATIONS COMPOSING THE LOWER CRETACEOUS SEQUENCES IN THE COAST RANGE AND HIGH CORDILLERA OF CENTRAL CHILE AT DIFFERENT LATITUDES (CF. FIG. 1). THE FORMATIONS OF EACH REGION ARE GIVEN IN THEIR STRATIGRAPHIC ORDER (THE LA LAJUELA FORMATION HAS NOT BEEN SUBDIVIDED FURTHER, DUE TO A LACK OF DETAILED MAPPING). THE LISTED ASSEMBLAGES ARE CHARACTERISTIC OF THE FORMATIONS (OR THEIR UPPER, [MIDDLE] AND LOWER PARTS WHEN MORE THAN ONE ASSEMBLAGE IS GIVEN) AND ALSO OUTSIDE THE TYPE LOCALITIES, SINCE THE FORMATIONS WERE SAMPLED IN SEVERAL CROSS SECTIONS. VOLCANIC TYPE INDICATES THE PREDOMINANT CHEMISTRY FOR THE UNALTERED BASIC TO INTERMEDIATE LAVAS OF EACH FORMATION (SHO=SHOSHONITIC; HK=HIGH-K CALC-ALKALINE, AND MK=MEDIUM-K CALC-ALKALINE). THE THICKNESS REFERS TO THE TYPE LOCALITIES. THE SECONDARY ASSEMBLAGES WERE DETERMINED IN PERVASIVELY ALTERED PARTS OF BASIC AND INTERMEDIATE LAVAS AND VOLCANICLASTIC ROCKS DOMINATED BY CLASTS OF THIS COMPOSITION. THE FOLLOWING ABBREVIATONS ARE USED FOR THE SECONDARY MINERALS. ACT=ACTINOLITE; CAL=CALCITE; CEL=CELADONITE; CHL=CHLORITE; EP=EPIDOTE; ILL=ILLITE (SERICITE). KFS=K-FELDSPAR; LMT=LAUMONTITE; PRH=PREHNITE; PMP=PUMPELLYITE; STB=STILBITE; STP=STILPNOMELANE; SWC=SWELLING CHLORITE (MIXED LAYERING CHLORITE-SMECTITE) AND WA=WAIRAKITE. THE METAMORPHIC FACIES ARE: Z= ZEOLITE FACIES; PP= PREHNITE-PUMPELLYITE FACIES, AND GS= GREENSCHIST FACIES.

| Coast Range (western belt) | | | | | High Cordillera (eastern belt) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Formation | Volcanic type | Thickness (km) | Secondary assemblage | Facies | Formation | Volcanic type | Thickness (km) | Secondary assemblage | Facies |
| **Northern region** | | | | | **Northern region** | | | | |
| | | | SwC, Kfs, Lmt | Z | | | | | |
| Qda. Marquesa | SHO | 2.5 | Prh, Chl, Cal, Cel, Kfs ± Lmt | | | | | | |
| | | | Chl, Ep, Kfs, Prh ± Cal, Pmp | | Pucalume | MK | 2.0 | Chl, Ep, Cal ± Lmt, Prh | Z |
| Arqueros | SHO | 3.0 | Ep, Chl, Kfs, Cal ± Prh, Pmp, Cel | PP | Los Pelambres | MK, HK | 2.5 | Ep, Chl, Cal ± Wa, Pmp | PP |
| El Reloj | SHO | 0.5 | Cal, Chl, Ill ± Ep | | | | | | |
| Tamaya | SHO | 1.0 | Ep, Cal, Chl, Ill | | | | | | |
| | | | Ep, Chl, Cal ± Act | GS | | | | | |
| **Central region** | | | | | **Central region** | | | | |
| | | | SwC, Lmt, Kfs, Prh ± Stb, | Z | | | | | |
| | | | Cal, Ep, Cel | | Colimapu | HK | 1.5 | SwC, Lmt ± Ep, Cal | |
| Veta Negra | SHO, HK | 10.5 | Chl, Kfs, Pmp, Ep ± Prh, Cal, Cel | Z | | | | Chl, Cel, Prh, Pmp, Ep ± Cal, Lmt | Z |
| | | | Chl, Kfs, Ep ± Prh, Cel, Pmp | PP | Lo Valdés | HK | 1.5 | Chl, Ep, Prh, Pmp, Cel, | PP |
| | | | Chl, Ep, Kfs ± Pmp | | | | | Kfs ± Cal, Stp | |
| Lo Prado | MK, HK | 3.5 | Ep, Act ± Cal | GS | | | | | |
| **Southern region** | | | | | **Southern region** | | | | |
| La Lajuela | SHO, HK | 13 | Lmt, Cal, SwC ± Kfs | Z | Colimapu | HK | 1.2 | SwC, Cel, Cal, Lmt ± Wa, Stb | Z |
| | | | Pmp, Kfs, Chl ± Ill, Cal, Ep, Prh | PP | Baños del Flaco | No lava flows | 0.8 | Cal, Chl, ± Ep, Cel, Wa, Prh, Pmp | PP |

rocks of brackish-water and continental type. The facies distribution is similar to that in the Bustamante Hill area situated 90 km farther south (Levi *et al.*, 1989, and references therein), where the existence of burial metamorphism was first established in the Andes. The mineral assemblages in the lowest 1 km of the pile are epidote, actinolite±calcite; the rest of the Lo Prado Formation contains chlorite, epidote, K-feldspar±pumpellyite. The assemblages change upwards to chlorite, K-feldspar, epidote±prehnite, celadonite, pumpellyite in the *ca.* 1 km thick lower member (Purehue) of the Veta Negra Formation. The *ca.* 5 km thick middle member (Ocoa) is characterized by monotonous assemblages with chlorite, K-feldspar, pumpellyite, epidote±prehnite, calcite, celadonite, whereas swelling chlorite, laumontite, K-feldspar, prehnite±stilbite, calcite, epidote, celadonite are found in the *ca.* 4.5 km thick upper member (Cerro Morado) of the Veta Negra Formation.

The La Lajuela Formation is a 13 km thick pile of acid ignimbrites and basic to intermediate lavas with intercalations of littoral limestones. The lower and middle parts of the formation have assemblages with pumpellyite, K-feldspar, chlorite±illite, calcite, epidote, prehnite, and the upper 3 km contain laumontite, calcite, swelling chlorite±K-feldspar. Additional work in this less known formation will probably result in a more detailed picture.

## HIGH CORDILLERA

The Lower Cretaceous sequences in the High Cordillera consist of littoral to sublittoral limestones with intercalations of basic to intermediate lavas in the lower part, and continental volcaniclastic rocks and intermediate to basic lavas in the upper part. Lava flows form a major part of the sequences in the north. They become less common toward the south; in the southernmost part of the sampled area, they are virtually absent. The unaltered lavas have a less alkalic affinity than at corresponding latitudes in the Coast Range (Table 1). The stratigraphy of the eastern part of the High Cordillera is complicated by Cenozoic reverse faulting, and the Lower Cretaceous sequences are not treated in the present paper. The sampled units and mineral assemblages are described below from north to south.

The 2 km thick Pucalume Formation consists of volcaniclastic rocks and lacustrine limestones with intercalations of basic to intermediate lavas in its base. It is underlain by the Los Pelambres Formation, whose type locality is situated farther south (Fig. 1), where the unit is *ca.* 2.5 km thick. The latter formation is composed of intermediate to basic volcanic rocks and minor acid ignimbrites with intercalations of volcaniclastic rocks and a few littoral limestones. The secondary mineral assemblages in the two units are epidote, chlorite, calcite ± wairakite, pumpellyite (Los Pelambres; the wairakite has a wide distribution along the strike of the formation), and chlorite, epidote, calcite±laumontite, prehnite (Pucalume).

The Lo Valdés and Colimapu Formations have a combined thickness of *ca.* 3 km. The lower unit (Lo Valdés) is composed of sublittoral to littoral limestones, volcaniclastic rocks and evaporites (gypsum), with intercalations of intermediate to basic lavas, submarine as well as continental. The upper unit (Colimapu) is made up of continental volcaniclastic rocks with some limestones of marine, brackish-water as well as lacustrine type, and intercalations of intermediate lavas. The mineral assemblages in the Lo Valdés Formation are chlorite, epidote, prehnite, pumpellyite, celadonite, K-feldspar±calcite, stilpnomelane. The Colimapu Formation contains chlorite, celadonite, prehnite, pumpellyite, epidote±calcite, laumontite in its lower and middle parts, passing into swelling chlorite, laumontite±epidote, calcite in the uppermost 200 m.

The Baños del Flaco Formation and the southern continuation of the Colimapu Formation above it, have a combined thickness of *ca.* 2 m. The former unit consists of littoral to sublittoral limestones and volcaniclastic rocks (no lava flows reported), and the latter has a lithology similar to that in its type locality, although lavas are uncommon here. According to recent works (Wyss *et al.*, 1994; R. Charrier, oral communication, 1994), the unit here referred to as Colimapu might be late Cretaceous in age. Mineral assemblages with calcite, chlorite±epidote, celadonite, wairakite, prehnite, pumpellyite are found in the Baños del Flaco Formation, and swelling chlorite, celadonite, calcite, laumontite±wairakite, stilbite occur in the Colimapu Formation.

## DISCUSSION AND CONCLUSIONS

In volcanic rocks affected by very low-grade metamorphism the mineral assemblages represent only local domains of equilibrium, even when the samples come from pervasively altered parts (Liou *et al.*, 1987). For basic and intermediate volcanic rocks and volcaniclastics of corresponding composition, the assignment to the upper part of the zeolite facies is based on the occurrence of laumontite. The stable association of pumpellyite and epidote (±prehnite) coupled with the absence of laumontite and actinolite is definitive for the prehnite-pumpellyite facies, and the appearance of actinolite (±epidote; no pumpellyite or prehnite present) defines the lower limit of the greenschist facies (Liou *et al.*, 1987, and references therein).

All the Lower Cretaceous sequences outside contact metamorphic aureoles around granitoids in central Chile, show a general increase in grade from zeolite to prehnite-pumpellyite facies with stratigraphic depth. However, there are marked differences in mineral assemblages and thickness of the sequences between the western and the eastern belts (Table 1). The 7-14 km thick piles in the Coast Range are characterized by monotonous assemblages corresponding to prehnite-pumpellyite facies (locally with greenschist facies in the lowermost part), grading upwards into laumontite-bearing zeolite facies assemblages. In contrast, some of the prehnite-pumpellyite facies assemblages of the 2-5 km thick sequences in the High Cordillera are wairakite-bearing, and in the overlying rocks at zeolite facies (Table 1); laumontite coexists with epidote and locally with wairakite or stilbite.

Calculation of paleothermal gradients depends on unknown factors such as the $P_{total}$, the $P_{fluid}/P_{total}$ ratio and the amount of dissolved matter in the circulating fluids (Liou *et al.*, 1987, 1991; Frey *et al.*, 1991, and references therein). However, on the basis of temperature estimates for the appearance of specific secondary minerals and key assemblages currently used in the literature on low-grade metamorphism, and the thicknesses of the units containing them, gradients of *ca.* 20° C $km^{-1}$ or less are obtained for the Lower Cretaceous sequences in the Coast Range, and of 45- 80° C $km^{-1}$ for those in the High Cordillera as explained in the following paragraphs. The temperature values the authors used for the calculation of the gradients are: 325° C for the transition between the greenschist and prehnite-pumpellyite facies; 190° C for the transition between the latter facies and the laumontite-bearing zeolite facies; 225-250°C for the sporadic appearance and the steady presence of epidote in the assemblages, respectively; 225°C for the disappearance of swelling chlorite and appearance of chlorite in otherwise similar assemblages; in addition, the presence of wairakite in the assemblages indicates a temperature gradient of 70-80°C $km^{-1}$ (cf. Kristmannsdóttir, 1985; Liou *et al.*, 1987, 1991; Frey *et al.*, 1991, and references therein).

In the northern part of the Coast Range studied here, greenschist facies assemblages are present only in the lowermost 300 m of the pile (in the Tamaya Formation; Table 1) and zeolite facies assemblages in the uppermost 500 m of the Quebrada Marquesa Formation. An estimated temperature difference of 135°C between the upper and lower boundaries of the 6.2 km thick sequence at prehnite-pumpellyite facies yields a gradient of 22°C $km^{-1}$. In the central part of the Coast Range (the Lo Prado and Veta Negra formations) the corresponding sequence at prehnite-pumpellyite facies is 8 km thick, leading to a gradient of 17°C $km^{-1}$. A similar value (20°C $km^{-1}$, reported as 20-30°C $km^{-1}$ in Aguirre *et al.*, 1989) is obtained for the southern continuation of these two formations in the Bustamante Hill area (Fig. 1), based on a thickness of 7 km for the sequence at prehnite-pumpellyite facies described by Levi *et al.* (1982). It should be pointed out that these gradients would be even lower if the existence of greenschist facies assemblages at the bottom of the piles were influenced by heat from intruding granitoids. In the southern part of the Coast Range (the La Lajuela Formation, with, at least, a 7 km thick sequence containing prehnite-pumpellyite assemblages) the calculated gradient is less than 20°C $km^{-1}$.

The high variance expressed by coexistence of laumontite and epidote, or laumontite and other zeolite species in the three upper formations along the High Cordillera (Table 1) indicates high gradients (Boles, 1981). The upper limit of these gradients can be estimated at 70-80°C $km^{-1}$, when wairakite is present in prehnite-pumpellyite as well as zeolite facies assemblages. Wairakite was unreported from the Lo Valdés and Colimapu formations, but the gradients there, were in any case, higher than in the Coast Range as suggested by a change from zeolite facies assemblages with laumontite and swelling chlorite to prehnite-pumpellyite assemblages, rich in epidote within a vertical distance of 1.3 km; this corresponds to a gradient of *ca.* 45°C $km^{-1}$.

The considerably higher gradients in the High Cordillera compared to those in the Coast Range are of regional significance and cannot be ascribed to isolated geothermal fields, because the spatial distribution of key assemblages is correlated with stratigraphic depth on a regional scale. The lower gradients in the Coast Range are coupled with a prevalence of shoshonitic to high-K calc-alkaline compositions of the volcanic rocks; granitoids are frequent and ignimbrites characterize some levels in the stratigraphic columns. This is in clear contrast to the conditions in the High Cordillera where the gradients are higher, the volcanic rocks are less alkalic, and ignimbrites and granitoids are virtually absent. Perhaps, it is no coincidence that wairakite was unreported from the Lo Valdés and Colimapu formations in the 33-34°S sector of the Cordillera; the volcanism here is somewhat more alkalic in nature than to the north and south, where wairakite occurs (Table 1). Volcanic piles metamorphosed at prehnite-pumpellyite and zeolite facies with wairakite-bearing assemblages and high thermal gradients have also been reported from the Casma marginal basin, of similar age in western Perú (Offler *et al.*, 1980; Levi *et al.*, 1989, and references therein). A comparison between gradients, volcanic geochemistry and tectonic setting of the Lower Cretaceous sequences in the Bustamante Hill area, western Perú, the Patagonian Andes of southernmost Chile and the Western Cordillera of Colombia showed that high gradients were coupled with strong extension and absence of or only a thin continental crust where tholeiitic or medium-K calc-alkaline volcanic rocks erupted; low gradients were related to a thick continental crust with more alkalic volcanics (Aguirre *et al.*, 1989; Atherton and Aguirre, 1992). In the present paper the authors show a similar relationship across the Lower Cretaceous basin of central Chile, with higher gradients in the east (the back-arc region according to Nasi and Thiele, 1982; Charrier, 1984; Charrier and Muñoz, 1994) where extension was larger, whereas the gradients were low to very low and the volcanism was more alkalic in the western intra-arc and forearc regions overlying a Paleozoic basement. The difference in thermal gradients supports an earlier conclusion based on the geochemistry of the volcanic rocks (Levi *et al.*, 1988): the crust in central Chile was thinner in the eastern than in the western margin of the Lower Cretaceous basin, contrary to the present Andean type situation.

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