

Nature and P-T-t constraints of very low-grade metamorphism in the Triassic-Jurassic basins, Coastal Range, central Chile

Naturaleza y estimación de las condiciones P-T-t del metamorfismo de muy bajo grado en las cuencas del Triásico-Jurásico de la Cordillera de la Costa, Chile central.

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ABSTRACT

Triassic-Jurassic volcano-sedimentary sequences in the Coastal Range of central Chile (34° 45/35° 20'S) from the Vichuquén-Tilicura and Hualañé-Gualleco basins display metamorphic assemblages indicative of very low-grade conditions. Triassic and Lower Jurassic metapelites achieved anchizonal conditions (IC, b_o , coal-rank and fluid inclusions data: $P \approx 1.3$, $T \approx 190$) at 181-184 Ma, under geothermal gradient of $\approx 35^\circ \text{C km}^{-1}$ during extensional geodynamic conditions. Nevertheless, in stratigraphically higher mafic volcanic sequences, of Middle to Late Jurassic age, the presence of chlorite ($X_c = 0.98-0.99$), three types of epidote ($X_{\text{Fe}^{3+}} = 41.14 \pm 0.90$, 30.08 ± 1.53 and 18.05 ± 1.75), titanite, Fe-rich and Fe-poor pumpellyite and hydrogarnet (+albite and quartz) are indicative of re-equilibration under prehnite-pumpellyite facies conditions ($P \approx 3$ kbar, $T \approx 300^\circ \text{C}$) and variable oxygen fugacity. A change from an extensional setting (with maximum basin subsidence and development of burial very low-grade metamorphism in the Triassic-Lower Jurassic metapelitic sequences) to a compressional setting (with local overthrusting of Triassic and Lower Jurassic sequences over Middle to Late Jurassic volcano-sedimentary sequences) is proposed to explain the contrasting metamorphic conditions between Triassic-Lower Jurassic metapelites and Middle-Late Jurassic metabasites.

Key words: Very low-grade metamorphism, Metabasites, Triassic-Jurassic basins, Coastal Range, Central Chile.

RESUMEN

Las secuencias volcano sedimentarias del Triásico-Jurásico en la Cordillera de la Costa de Chile central (34°45'/ 35° 20'S) desarrolladas en las cuencas de Vichuquén-Tilicura y Hualañé-Gualleco evidencian asociaciones metamórficas indicativas de condiciones de muy bajo grado. Las metapelitas del Triásico y Jurásico Inferior alcanzaron condiciones de anchizona (datos de IC, b_0 , reflectividad de vitrinita e inclusiones fluidas: $P \approx 1.3$, $T \approx 190$) a los 181-184 Ma, durante un contexto geodinámico extensional caracterizado por un gradiente geotérmico de $\approx 35^\circ\text{C km}^{-1}$. Sin embargo, en secuencias de rocas volcánicas máficas, estratigráficamente más altas, de edad del Jurásico Medio a Superior, la presencia de clorita ($X_c = 0.98-0.99$), tres tipos de epidota ($X_{\text{Fe}^{3+}} = 41.14 \pm 0.90$, 30.08 ± 1.53 y 18.05 ± 1.75), titanita, pumpellyita rica en hierro y pumpellyita pobre en hierro e hidrogranate (+ albita y cuarzo) es indicativa de un ajuste en el equilibrio metamórfico en las condiciones de la facies prehnita pumpellyita ($P \approx 3$ kbar, $T \approx 300^\circ\text{C}$) y bajo variaciones importantes en la fugacidad de oxígeno. Se propone un cambio en el contexto geodinámico desde un ambiente extensional (en el que se alcanzaría la máxima subsidencia y se desarrollaría el metamorfismo de tipo 'burial' en las secuencias metapelíticas del Triásico- Jurásico Inferior) a un ambiente contraccional, en el que la superposición local de las secuencias del Triásico y Jurásico Inferior sobre las del Jurásico Medio-Superior permitiría alcanzar las condiciones P-T calculadas y, de este modo, justificar las diferencias encontradas entre las condiciones metamórficas de las metapelitas del Triásico-Jurásico inferior y las de las metabasitas del Jurásico Medio-Superior.

Palabras claves: Metamorfismo de muy bajo grado, Metabasitas, Cuencas triásico jurásicas, Cordillera de la Costa, Chile central.

INTRODUCTION

Recent progress on very low-grade metamorphic studies were summarized by Frey and Robinson (1999). For low-grade metapelites, much emphasis has been given in measuring reaction progress (e.g., Merriman and Peacor, 1999) and determining contrasting geotectonic settings (Merriman and Frey, 1999). Numerical maturity models calibrated by vitrinite reflectance data has been demonstrated to be very useful in determining the thermal history during very low-grade metamorphism (e.g., England and Bustin, 1985; Langenberg and Kalkreuth, 1991; Ferreiro Mählmann, 2001). Also, comparison of vitrinite reflectance with clay mineral data can be used as a first approximation of the duration of metamorphism and the thermo-tectonic history (e.g., Bevins *et al.*, 1996; Ferreiro Mählmann, 2001).

In addition, illitic clay minerals have been used in several studies to constrain the timing of very low- and low-grade events. In fact, authigenic illite and mixed illite-smectite have been shown to be reliable 'clocks' at temperatures below $260 \pm 20^\circ\text{C}$ (Hunziker *et al.*, 1986), a property that makes them potentially attractive tools for reconstructing the burial history.

In the central Andes of Chile, near Santiago, very low-grade metamorphism of mafic rocks ranging from zeolite to upper greenschist facies is widespread and has been studied in some detail (Aguirre *et al.*, 1978, 1997, 1999, 2000; Bevins *et al.*, 2003; Levi, 1969; Levi *et al.*, 1982; Robinson *et al.*, 2004; Vergara *et al.*, 1993). However, little is known about low-grade metamorphism in the sedimentary rocks in central Coastal Chile (Ruiz Cruz *et al.*, 2002, 2004).

Belmar *et al.* (2002) determined the P-T conditions of the Triassic-Jurassic basins south of Santiago, by applying the techniques of illite crystallinity (IC), coal rank determination, fluid inclusion microthermobarometry, identification of index minerals and critical mineral assemblages and thermal maturity modelling. Values of $T \approx 190^\circ\text{C}$ and $P \approx 1.3$ kbar were obtained. Belmar *et al.* (2002, 2004) distinguished between regional burial low-grade metamorphic events and local contact metamorphism related to the thermal influence of plutonic intrusions in the Triassic-Jurassic basins. These distinctions are relevant, because the occurrence of intrusions are common in the history of the Andean evolution, with subsidence and magmatic events since Palaeozoic to the present time. Finally, by dating of whole rock and <2 mm size fraction of these Triassic-Jurassic metapelites, Belmar *et al.* (2004) constrained the geochronology of the diagenesis (206 Ma), the anchizonal very low-grade metamorphism (181-184 Ma) and a late hydrothermal event

(155 Ma).

In this study, therefore, the authors aim to distinguish between very low-grade metamorphism in sedimentary rocks, and that present in volcanic mafic rocks of Middle-Late Jurassic age. For this purpose, the well known Hualañé-Gualleco Triassic-Jurassic volcano-sedimentary basins in the Coastal Range of central Chile represent an excellent opportunity to assess metamorphic paragenesis developed in andesitic lava flows, and those developed in the underlying metasedimentary rocks of Triassic-Jurassic age, previously studied by Belmar *et al.* (2002, 2004). In this work, mineral chemistry of metabasites will be used to establish the new P-T metamorphic conditions of this basin. The significance of this very low-grade metamorphism will be then discussed on the basis of its geologic context.

GEOLOGICAL SETTING

The study area is located in the Coastal Range of central Chile between 34°45' and 35°20'S, ca. 300 km southwest of Santiago ([Fig. 1](#)). Late Triassic to Early Jurassic marine to continental sedimentary rocks and Middle to Late Jurassic volcanic rocks are exposed in the region. The sedimentary rocks form part of an almost continuous belt, approximately 60 km long and unconformably overlying a Late Paleozoic metamorphic basement ([Fig. 1](#)). Tectonic development during Triassic times was controlled by continuous movements and differential uplift of the Paleozoic basement until, at least, the Jurassic (Thiele and Morel, 1981). The western Palaeozoic areas were exhumed faster than the eastern area, on which Mesozoic sedimentary rocks were preserved (Thiele and Morel, 1981). Uplift of the western Paleozoic basement during the Late Triassic and Early Jurassic was concomitant with the development of two sedimentary basins, the Vichuquén-Tilicura basin to the north and the Hualañé-Gualleco basin further to the southeast ([Fig. 1](#)). In the northern Vichuquén-Tilicura basin the late Triassic sedimentary rocks are characterized by a marine sequence of shales, sandstones and conglomerates (J. Corvalán¹). The eastern border of the Vichuquén-Tilicura basin ([Fig. 1](#)) and the basement of the Hualañé-Gualleco basin is represented by Carboniferous granitoids (Munizaga *et al.*, 1973). West of the Vichuquén-Tilicura basin ([Fig. 1](#)) a late Palaeozoic metamorphic basement is exposed (González Bonorino and Aguirre, 1970; Munizaga *et al.*, 1973; Hervé *et al.*, 1982), generally interpreted as a transition from weakly deformed retro-wedge sediments exposed to the east (Eastern series) to an accretionary complex in the west (Western Series) (Hervé, 1988; Martin *et al.*, 1999; Willner *et al.*, 2000).

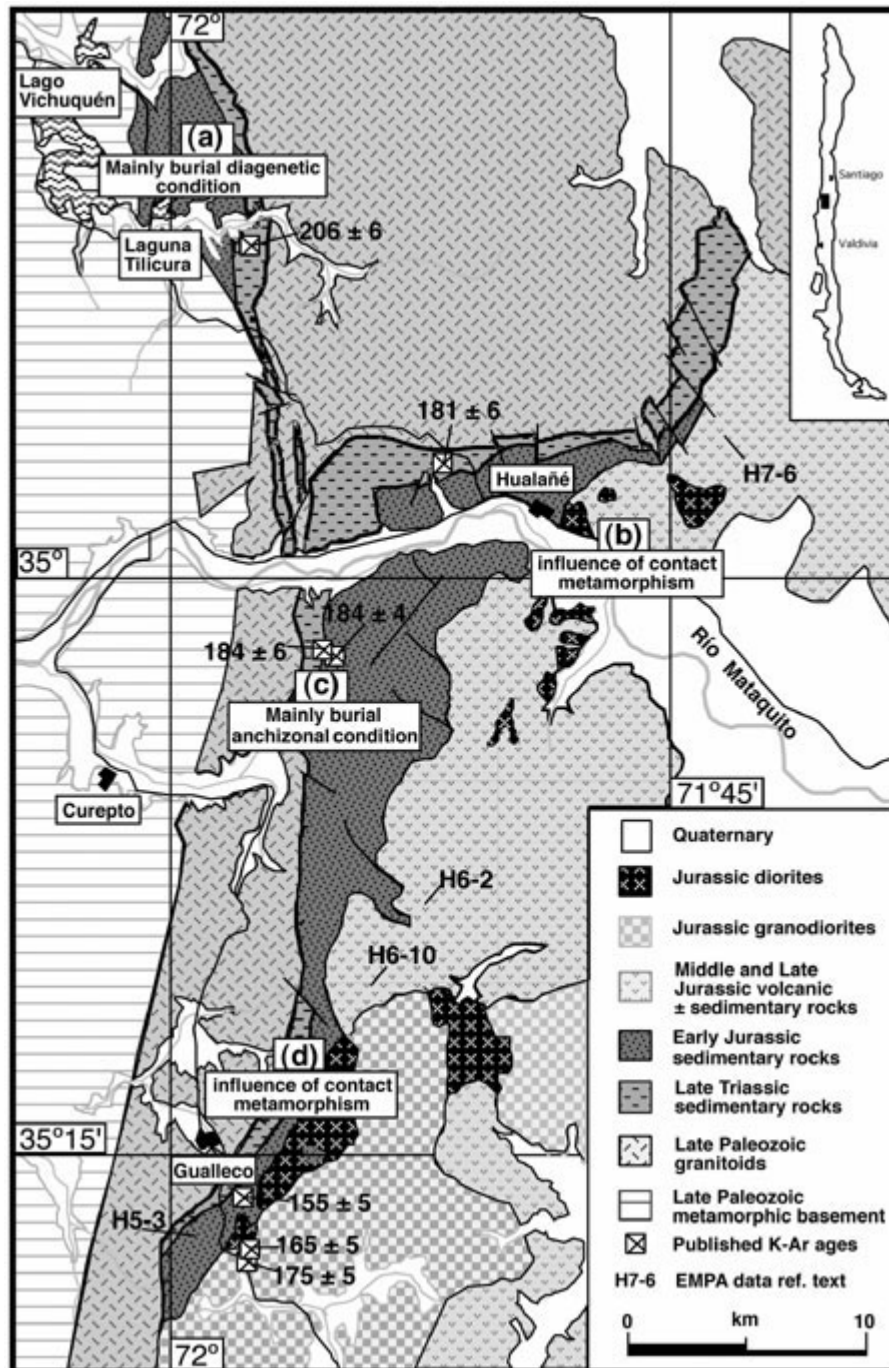


FIG. 1. Simplified geological map (modified from J. Corvalán¹ and Belmar *et al.*, 2002) of the Triassic-Jurassic formations of the Coastal Range in central Chile at 34°45' to 35°20'S, with the Vichuquén-Tilicura basin in the north and the Hualañé-Gualleco basin in the south; location of the analyzed samples used in this work is shown. Areas (a), (b), (c) and (d) after Belmar *et al.* (2004) and referred to in table 1.

The Hualañé-Gualleco basin (J. Corvalán¹) is located between the two homonymous villages (Fig. 1). The Late Triassic to Early Jurassic sequence of mainly sedimentary rocks reaches a maximum thickness of 2600 m at the east of the village of Curepto (Fig. 1). The outcrops are located at both banks of the Mataquito River. The lowest 500 m of the stratigraphic pile corresponds to the Late Triassic unit and comprises predominantly shales with quartzitic sandstones, conglomerates,

subarkoses and subgraywackes. The Hualañé-Gualleco basin was intruded by Jurassic diorites and granodiorites, at 165 ± 5 Ma (K-Ar on biotite) to 175 ± 5 Ma (K-Ar on hornblende) (Gana and Hervé, 1983). Most of the eastern part of the study area is composed of andesitic lava flows, volcanic breccias and minor marine sedimentary intercalations of Middle and Late Jurassic age (Fig. 1), which reach a maximum thickness of ca. 3,600 m and belong to the Altos de Hualmapu Formation (Morel, 1981; Bravo, 2001). No isotopic data are available for this unit, but marine paleontological fauna present in sedimentary rocks, assigned to the Toarcian, indicates the end of the marine sedimentation (Corvalán, 1982). In the southern part of the area, the volcanic units are also intruded by Jurassic diorites and granodiorites similar to those described above (Fig. 1). For a detailed stratigraphic description, columns, profiles and paleontological determination see Belmar *et al.* (2002).

PREVIOUS WORK ON THE VERY LOW-GRADE METAMORPHISM OF THIS AREA

Diagenetic to very low-grade metamorphic P-T conditions have been determined for Late Triassic to Early Jurassic sedimentary rocks from the Vichuquén-Tilicura and the Hualañé-Gualleco basins in central Chile using illite crystallinity Kübler Index (KI, Kübler 1967, 1984), coal rank data, K-white mica b cell dimension (Sassi and Scolari, 1974), characteristic mineral assemblages and fluid inclusion data (Belmar *et al.*, 2002). A burial-related diagenetic to low-grade metamorphic event, recorded in both basins, is locally overprinted in the Hualañé-Gualleco basin by contact metamorphism around the Jurassic dioritic to granodioritic intrusions (Fig. 1). Diagenetic conditions prevailed in the northern Vichuquén-Tilicura basin, whereas in the southern Hualañé-Gualleco basin low-grade metamorphism is observed with an increase in metamorphic grade from north to south. Epizonal conditions are locally reached south of the Hualañé-Gualleco basin. Low-pressure conditions were determined by Belmar *et al.* (2002) using the geobarometer of the b cell dimension of K-white mica. A time-interval of ca. 20 Ma between diagenesis (206 ± 6 Ma) and anchizonal very low-grade metamorphism (181 ± 6 - 184 ± 4 Ma, K-Ar ages on the $< 2 \mu\text{m}$ grain size fractions of shales) was recorded by Belmar *et al.* (2004). A subsidence rate of ca. 120 m/Ma was proposed for these Triassic-Jurassic basins, and a thermal influence on this very low-grade burial regional metamorphism was invoked (Belmar *et al.*, 2004).

Contact metamorphic field relationships between Jurassic intrusions and Jurassic sedimentary rocks are only visible in fresh roadcuts, only few meters away from intrusions near Gualleco. A hornfels facies assemblage with quartz, plagioclase, flakes of biotite with inclusions of Ti-Fe-phases and anhedral ferrosilite was characterized by electron microprobe analyses (Belmar *et al.*, 2002).

ANALYTICAL METHODS

Previous work on ca. 100 samples including shales, slates of Late Triassic to Late Jurassic age, carried out by Belmar *et al.* (2002), was presented above. The present work comprises additional sampling and studies principally on metabasites of Middle to Late Jurassic age allowing a new interpretation of P-T-t conditions.

Chemical analyses and scanning electron microscope (SEM) images of minerals were obtained using a JEOL JXA-8600 Superprobe at the University of Basel (Switzerland). Olivine (Mg, Fe, Si), orthoclase (K, Al), synthetic graptolite (Mn), albite (Na) and wollastonite (Ca) were used as standards. All elements were measured using wavelength dispersive spectrometry, an accelerating voltage of 15 kV and a beam current of 10 nA. In general, counting times for major and minor elements were 10 s and 20 s, respectively and the background counting time was set to 5 s. The beam was focused to a spot size of 2 mm. Data were reduced using the PROZA correction program for all silicates, except data from pumpellyite and epidote, on which the program ZAF (due to the high Fe-content) was used.

RESULTS

METAPELITES

Results from various analytical methods are presented by Belmar *et al.* (2002) and summarized here in [table 1](#). The Coal Rank values (R_{max}) vary in a similar manner to the Kubler Index (KI) data, showing a good correlation between each other, with a general increase southward with considerable scatter in the data. The highest coal rank of the meta-anthracite stage is found in the vicinity of granodioritic-dioritic intrusions.

TABLE 1. SUMMARY OF METAPELITES VERY LOW-GRADE METAMORPHISM IN THE TRIASSIC-JURASSIC METAPELITES FROM THE VICHUQUÉN-GUALLECO BASINS, COASTAL RANGE, CENTRAL CHILE.

Basin sub-zone area of figure 1	Vichuquén-Tillicura	Hualañé-Gualleco		
	(a)	Center (c)	East (b)	South (d)
Kubler Index				
Range (Δ^2Q)	0.20 to 0.40	0.43 to 0.52	0.46 to 0.31	0.29 to 0.5
stage	High diagenetic zone	Low anchizone	Anchizone/diagenesis	Epizone/anchizone
Coal rank				
R_{max} %	2.8 to 3.1	2.9 to 4.1	5.5 to 7.5	4.9 to 6.5
stage	Anthracite	Meta-anthracite	High meta-anthracite	High meta-anthracite
Fluid inclusion				
Temperature in °C	-	179± 4 , 190± 10	223± 12	-
Pressure in Kbar	-	1.4 ; 1.3	1,3	-
Mineral index				
XRD	Illite/smectite	Pyrophyllite-paragonite	Paragonite	Hornfels facies
Illite/smectite ordering				
% Illite	65 to 85 %	85 to 90 %	100%	100%
Temperature in °C	170 to 190	150 to 230	-	-
Pressure in Kbar		< 1.5	-	-
K-Ar (Ma) date sediments				
<2µm size fraction	206±6	181±6;184±4,184±6	-	155±5
whole rock	395±12	221±7,559±16,219±7	-	174±5
K-Ar (Ma) date Intrusion				
Biotite		-	-	165±5
Hornblende		-	-	175±5
Contact metamorphism				
Temperature in °C		-	-	655 to 691
Pressure in Kbar		-	-	<4

In the northern part of the Hualañé-Gualleco basin, coal rank values increase from west to east. Samples with values $>6\%$ R_{max} have textures of natural coke and pyrolitic carbon, which is formed after chemical cracking of volatiles. The pyrolitic carbon forms spherical fibrolitic bodies (<50 mm) with helicitic extinction (anisotropic fibroblastic structure showing Brewster cross) and display optical features of a short and fast thermal overprint, as described by Ferreiro Mählmann (2001). As in the southern part of the Hualañé-Gualleco basin,

the highest coal rank is also associated with textures of pyrolitic carbon.

METABASITES

In the upper part of the Jurassic unit, southeast of the Río Mataquito, the sedimentary rocks are increasingly interbedded with the Middle to Late Jurassic porphyritic andesitic lavas and breccias from the Altos de Hualmapu Formation (Morel, 1981). They contain euhedral plagioclase and augite as the main phenocrysts set in a cryptocrystalline to microcrystalline groundmass. Chlorite and calcite are the main alteration minerals and plagioclase is partly to completely albitized ($An_{0.4-21}Or_{0.4-0.5}$ but mostly from $An_{0.4}Or_{0.4}$ to $An_8Or_{0.4}$).

Chlorite is the most common metamorphic mineral, mostly replacement patches inside plagioclase and clinopyroxene phenocrysts, as inclusions in vugs and also as interstitial material in the groundmass. Most chlorite is pale-green, although yellowish- green pleochroic types appear with anomalously deep blue to brownish grey interference colours. Microprobe analyses of chlorite (Table 2a) were normalized to 28 oxygens and fulfill the criterion $(\text{Na}+\text{Ca}+\text{K}) \text{ a.p.f.u.} < 0.20$ as a constraint for microprobe analyses uncontaminated by other phases (Schmidt *et al.*, 1997). Projection of chlorite composition on the Al_{total} versus non-interlayer cations (NIC) diagram (Fig. 2a) indicates a rather homogenous composition in all analysed samples, close to the clinochlore end-member. X_c values (proportion of chlorite layers in mixed-layer chlorite/smectite calculated from microprobe analyses after the Wise method, in Bettison and Schiffman, 1988) range from 0.98 - 0.99; low $\Sigma (\text{Na}+\text{K}+\text{Ca}) \text{ a.p.f.u.}$ values (<0.2 , Fig. 2b) is consistent with the very low contents of interlayered smectite.

TABLE 2a. CHLORITE ANALYSES, STOICHIOMETRY CALCULATED ON THE BASIS OF 28 OXIGENS.

Sample	H6-10 Mean n=60	St. dev.	H6-2 Mean n=45	St. dev.	H7-6 Mean n=67	St. dev.	H5-3 Mean n=14	St. dev.
SiO ₂	27.09	1.70	27.65	0.80	28.82	1.35	25.95	0.96
TiO ₂	0.07	0.19	0.05	0.05	0.03	0.05	0.24	0.27
Al ₂ O ₃	17.66	1.27	15.68	0.86	15.86	1.20	17.09	0.84
FeO	23.04	1.60	29.66	1.02	25.15	1.39	31.22	2.37
MnO	0.64	0.42	0.66	0.09	0.45	0.10	0.61	0.20
MgO	17.26	0.55	13.08	0.53	16.02	1.16	9.75	1.97
CaO	0.11	0.12	0.08	0.05	0.19	0.27	0.18	0.26
Na ₂ O	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.05
K ₂ O	0.03	0.04	0.03	0.03	0.02	0.02	0.15	0.20
Total	85.92	1.92	86.91	1.15	86.55	1.72	85.22	0.88
Si	5.78	0.16	6.04	0.11	6.15	0.16	5.86	0.13
Ti	0.01	0.03	0.01	0.01	0.01	0.01	0.04	0.04
Al total	4.44	0.39	4.05	0.22	3.99	0.31	4.55	0.25
Al(iv)	2.22	0.16	2.09	0.11	2.14	0.16	2.41	0.13
Al(vi)	2.22	0.23	1.96	0.12	1.85	0.17	2.14	0.18
Fe ⁺²	4.11	0.35	5.42	0.24	4.49	0.32	5.90	0.55
Mn	0.12	0.07	0.12	0.02	0.08	0.02	0.12	0.04
Mg	5.49	0.31	4.26	0.17	5.10	0.36	3.28	0.61
Ca	0.03	0.03	0.02	0.01	0.04	0.06	0.04	0.06
Na	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02
K	0.01	0.01	0.01	0.01	0.00	0.01	0.04	0.05
Xc	0.98	0.11	0.94	0.05	0.89	0.07	-	-
T°C	296	25	253	23	237	20	-	-
NIC	19.84	0.67	19.65	0.30	19.34	0.40	-	-
IC	0.04	0.03	0.03	0.02	0.05	0.06	-	-

Notes: T°C Cathelineau (1988); NIC = Si+Al+Fe+Mg+Mn; IC = Na+K+Ca; Xc = Proportion of Chl in Chl/Smc; all Fe assumed to be Fe²⁺; n= 60= number of analyses; St dev= standard deviation; H5-03 chlorite from retrograde in hornfels facies, no sence temperature calculation.

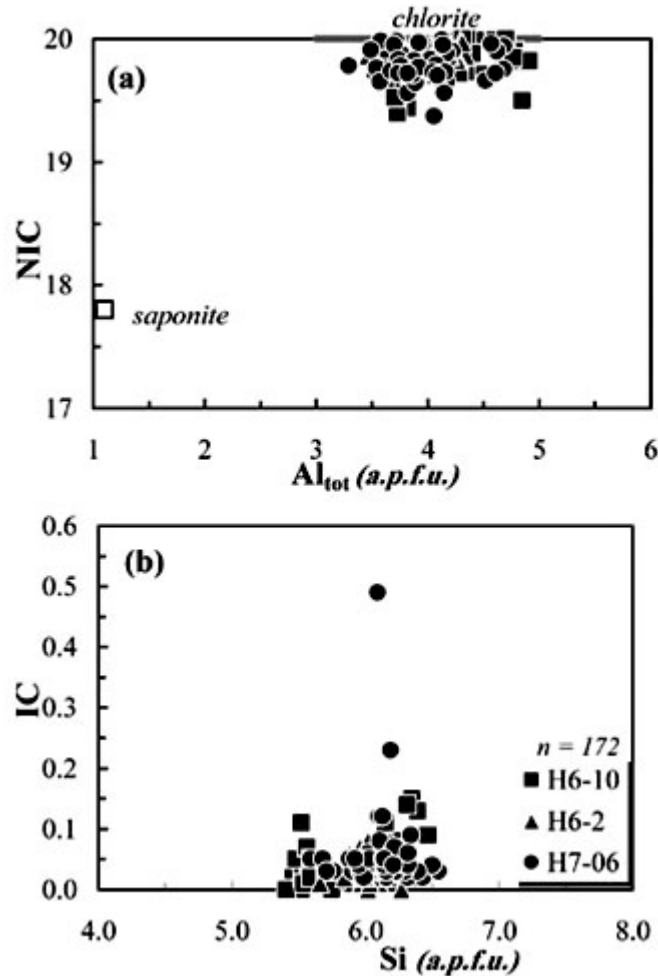


FIG. 2. Mafic phyllosilicate compositions from the Middle and Late Jurassic volcanic rocks of the Hualañé-Gualleco basin; **(a)** non-interlayer cations (NIC = Si+Al+Fe+Mg+Mn+Ti a.p.f.u.) versus total Al (a.p.f.u.). Different symbols represent analyses from different samples (see location of analysed samples on Fig. 1). Ideal end-member of saponite, shown by open squares, and chlorite solid solution compositional range from Schiffman and Friedleifsson (1991) and slightly modified by Robinson *et al.* (1993); **(b)** interlayer cations (IC = Ca+Na+K, a.p.f.u.) versus Si (a.p.f.u.). Data with IC<0.2 and Si >6.0 can be considered as chlorite without smectite layers.

Epidote occurs frequently in the lava flows; it is associated with chlorite, titanite, magnetite, calcite and, locally, pumpellyite and hydrogarnet. Epidote replaces plagioclase and clinopyroxene phenocrysts along fissures, and it is also observed (in minor amounts) as small crystals in the groundmass and (preferentially) filling the cores of vugs and interstices. Three types of epidote are distinguished in the sampling area (Table 2b): (1) brownish variety with a pistacite ($X_{Fe^{3+}}$) contents from 39.7 to 42.7; (2) yellow variety, that always occurs inside the brownish one (Figs. 3, 4a), having $X_{Fe^{3+}}$ values of 26.6-32.9 and (3) is of yellow pale green colour with $X_{Fe^{3+}} = 15.4$ to 21.1. In addition another type of epidote, characterised by the presence of Ce, Nd and La, suggesting an allanitic component, was occasionally detected.

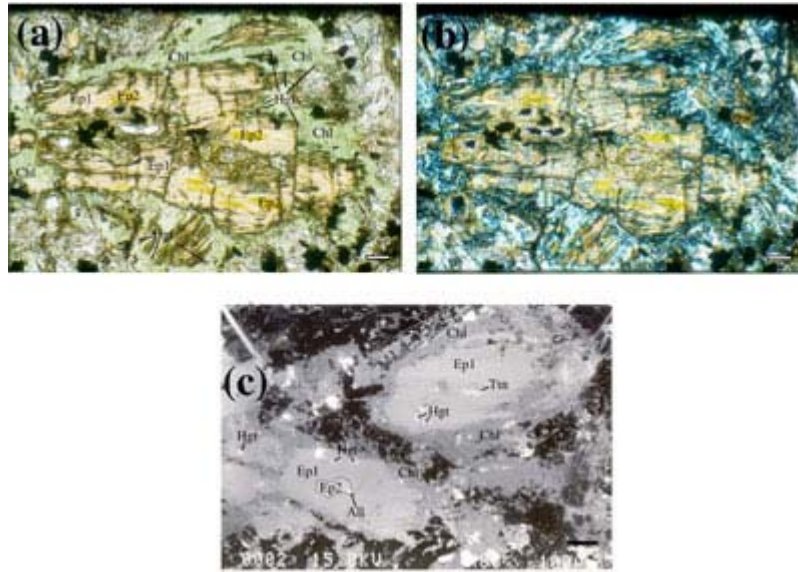


FIG. 3. Microphotographs of two types of epidote (iron-poor Ep1 and iron-rich Ep2) coexisting with chlorite (Chl) and small crystals of hydrogarnet (Hgt) from Middle-Late Jurassic volcanic rocks of the Hualañé-Gualleco basin (sample H7-10). (a) = plane light; (b) crossed polars. Scale bar = 0.2 mm. (c) Back-scattered electron image of sample H7-10 showing small allanite crystals (All) overgrow by Ep2 and Ep1. Small idiomorphic hydrogarnet (Hgt) and irregular titanite (Ttn) are also present. Scale bar = 100 μm .

TABLE 2b. EPIDOTE ANALYSES, BASED ON 12.5 OXYGENS.

	Type 1 Mean n=15	Type 2 St. dev.	Type 3 Max. value	Min. value	Mean n=45	St. dev.	Max. value	Min. value	Mean n=13	St. dev.	Max. value	Min. value
SiO ₂	36.49	0.34	36.82	35.76	37.28	0.87	38.91	35.09	37.78	1.15	39.52	36.28
TiO ₂	0.08	0.06	0.21	0.00	0.12	0.18	0.59	0.00	0.04	0.05	0.12	0.00
Al ₂ O ₃	17.87	0.36	18.39	17.00	21.89	0.71	23.74	20.30	25.64	1.05	27.27	24.23
Fe ₂ O ₃	19.56	0.51	20.60	18.86	14.75	0.89	16.21	12.67	8.85	0.94	10.28	7.52
MnO	0.09	0.06	0.18	0.00	0.18	0.15	0.77	0.00	0.13	0.13	0.48	0.00
MgO	0.05	0.03	0.15	0.02	0.12	0.16	0.67	0.00	0.01	0.02	0.08	0.00
CaO	22.19	0.50	23.18	21.13	22.35	0.42	23.15	21.52	22.97	0.36	23.54	22.05
Na ₂ O	0.02	0.03	0.10	0.00	0.01	0.01	0.05	0.00	0.01	0.01	0.04	0.00
K ₂ O	0.01	0.01	0.02	0.00	0.01	0.01	0.03	0.00	0.01	0.01	0.03	0.00
Total	96.35	1.10	97.55	92.93	96.72	1.88	100.86	92.19	95.44	2.50	99.47	92.55
Si	3.03	-	-	-	3.02	-	-	-	3.03	-	-	-
Al (iv)	0.00	-	-	-	0.00	-	-	-	0.00	-	-	-
Al (vi)	1.75	-	-	-	2.09	-	-	-	2.42	-	-	-
Ti	0.00	-	-	-	0.01	-	-	-	0.00	-	-	-
Fe ³⁺	1.22	-	-	-	0.90	-	-	-	0.53	-	-	-
Mn	0.01	-	-	-	0.01	-	-	-	0.01	-	-	-
Mg	0.01	-	-	-	0.01	-	-	-	0.00	-	-	-
Ca	1.97	-	-	-	1.94	-	-	-	1.98	-	-	-
Na	0.00	-	-	-	0.00	-	-	-	0.00	-	-	-
K	0.00	-	-	-	0.00	-	-	-	0.00	-	-	-
XFe ³⁺	41.14	0.90	42.67	39.67	30.08	1.53	32.90	26.57	18.05	1.75	21.12	15.40

Titanite occurs as dusty granules or small spherical aggregates at the rim of vugs and interstices associated with chlorite, epidote (Fig. 3c) as well as dispersed spots in the groundmass. Al_2O_3 contents range between 2.0-4.8 wt% and Fe_2O_3 between 1.4-7.8 wt% (Table 2c). These values are similar to those of titanites developed in prehnite-pumpellyite facies terranes in central Sweden (Nyström, 1983) and in the meta-andesites of the Celica Formation in southwestern Ecuador (Aguirre, 1992).

TABLE 2c. TITANITE ANALYSES, CALCULATED ON THE ARBITRARY ASSUMPTIONS 4 SI PER FORMULA UNIT.

	Mean n= 18	St. dev.	Minimum value	Maximum value
SiO_2	30.48	1.56	27.23	34.79
TiO_2	32.12	2.15	28.33	38.41
Al_2O_3	3.18	0.67	2.00	4.82
Fe_2O_3	3.56	1.74	1.41	7.78
MnO	0.12	0.25	0.00	1.10
MgO	0.19	0.44	0.00	1.40
CaO	26.48	1.04	24.35	27.57
Na_2O	0.02	0.01	0.00	0.04
K_2O	0.02	0.01	0.00	0.04
F	0.23	0.11	0.18	0.27
Total	96.38	1.77	92.42	98.81
Si	4.00	-	-	-
Ti	3.18	-	-	-
Al	0.49	-	-	-
Fe^{3+}	0.23	-	-	-
Fe^{2+}	0.12	-	-	-
Mn	0.01	-	-	-
Mg	0.04	-	-	-
Ca	3.73	-	-	-
Na	0.00	-	-	-
K	0.00	-	-	-
F	0.02	-	-	-

Pumpellyite is present in only one of the studied sample from the northeasternmost part of the Hualañé-Gualleco basin (sample H7-06, Fig. 1). Pumpellyite is associated with hydrogarnet-epidote-chlorite-titanite-calcite-magnetite; this assemblage is reported for the first time in this area. Although optically homogeneous, two intergrown pumpellyite types can be distinguished chemically (Table 2d and Figs. 4a, 4b). Pumpellyite of type 1 has FeO^* contents between 9.25 and 11.75 wt% and Al_2O_3 contents between 19.69 and 21.64 wt%. Pumpellyite of type 2 has lower FeO^* values, ranging between 5.56-8.8 wt%, and Al_2O_3 values ranging between 21.24 and 23.03 wt% (Fig. 4a, b).

TABLE 2d. PUMPELLYITE ANALYSES, BASED ON 16 CATIONS.

Sample	H7-06 Mean n=12	Type 1 St. dev.	Min. value	Max. value	H7-06 Mean n=14	Type 2 St. dev.	Min. value	Max. value
SiO ₂	36.68	0.58	35.77	37.40	37.10	0.32	36.69	37.75
Ti ₂ O ₃	0.05	0.06	0.00	0.18	0.05	0.05	0.00	0.16
Al ₂ O ₃	20.70	0.81	19.69	21.64	22.08	0.45	21.24	23.03
FeO	10.12	0.75	9.25	11.75	7.75	0.90	5.56	8.80
MnO	0.10	0.06	0.00	0.20	0.12	0.09	0.02	0.26
MgO	2.10	0.76	1.17	3.98	2.29	0.36	1.82	2.92
CaO	21.72	1.22	19.94	23.55	22.49	0.35	22.01	23.22
Na ₂ O	0.02	0.02	0.00	0.06	0.02	0.02	0.00	0.05
K ₂ O	0.02	0.02	0.00	0.08	0.02	0.01	0.00	0.04
Total	91.49	0.77	90.29	92.88	91.89	0.70	90.60	93.14
Si	6.11	-	-	-	6.10	-	-	-
Ti	0.01	-	-	-	0.01	-	-	-
Al	4.06	-	-	-	4.28	-	-	-
Fe ²⁺	1.41	-	-	-	1.07	-	-	-
Mn	0.01	-	-	-	0.02	-	-	-
Mg	0.52	-	-	-	0.56	-	-	-
Ca	3.87	-	-	-	3.96	-	-	-
Na	0.01	-	-	-	0.01	-	-	-
K	0.00	-	-	-	0.00	-	-	-
XFe	25.77	2.03	23.28	29.06	19.91	2.09	14.63	22.19

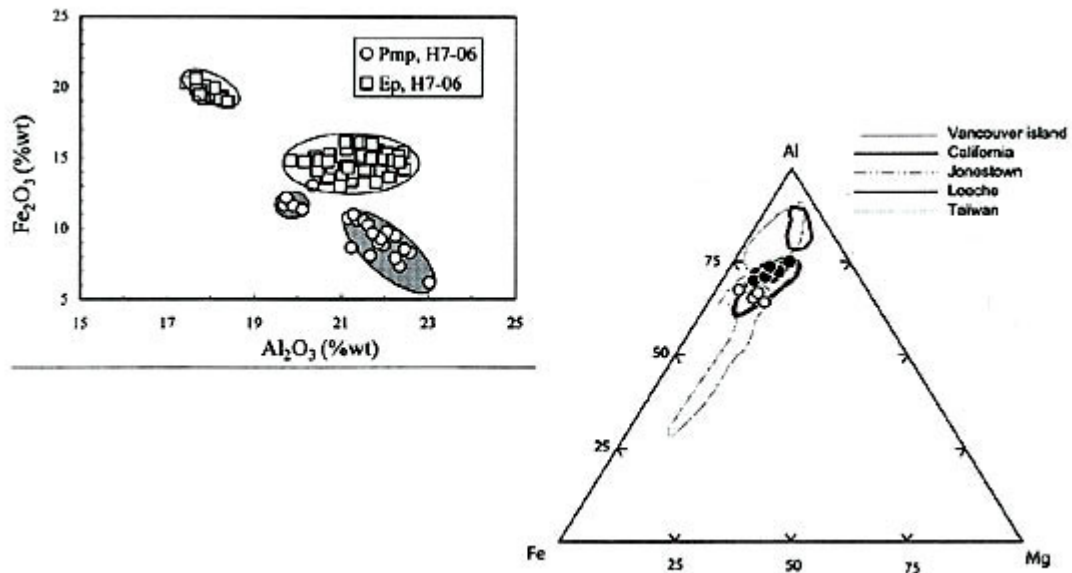


FIG. 4. Compositional diagrams for epidote and pumpellyite in sample H7-06. (a) Al_2O_3 (wt%) versus Fe_2O_3 (wt%) for epidote (white squares) and pumpellyite (white circles) showing the high- and low-iron groups. (b) Al: Fe:Mg diagram (Coombs *et al.*, 1979) for pumpellyite. Circles in white: iron rich pumpellyite; circles in black: iron poor pumpellyite.

Reference fields taken from Coombs *et al.* (1979) and Liou and Ernst (1979).

Hydrogarnet from the same thin section (H7-06) occurs as framboidal grains with a diameter of up to 20 μm within chlorite patches of the groundmass and also in chlorite-epidote vugs (Fig. 3). Hydrogarnet analyses ($\text{And}_{57} - \text{Gro}_{43}$, XFe^{3+} values ranging from 53.3 to 62.7%, and low MgO (max. 0.36 wt% contents) have low totals (between 95 and 99 wt%, Table 2e), a feature which shared by framboidal grandites and attributed by Coombs *et al.* (1977) to fluid-filled microcavities.

TABLE 2e. HYDROGARNET ANALYSES, BASED ON 24 OXYGENS.

Sample	H7-06 Mean n=32	St. dev.	Min. value	Max. value
SiO_2	35.72	0.99	34.39	37.71
TiO_2	0.34	0.08	0.18	0.50
Al_2O_3	8.84	0.36	8.25	9.71
Cr_2O_3	0.02	0.03	0.00	0.08
Fe_2O_3	18.33	0.75	17.14	19.74
MnO	0.19	0.06	0.08	0.36
MgO	0.14	0.08	0.00	0.36
CaO	33.16	0.42	32.39	33.86
Na_2O	0.03	0.02	0.00	0.08
K_2O	0.01	0.01	0.00	0.02
V_2O_5	0.41	0.09	0.29	0.54
Total	96.85	1.12	94.70	99.13
Si	5.94	-	-	-
Al(IV)	0.09	-	-	-
Al(VI)	1.64	-	-	-
Cr	0.00	-	-	-
Ti	0.04	-	-	-
Fe^{3+}	2.29	-	-	-
V^{3+}	0.05	-	-	-
Mn	0.02	-	-	-
Mg	0.03	-	-	-
Ca	5.91	-	-	-
Na	0.01	-	-	-
K	0.00	-	-	-
XFe^{3+}	56.95	1.54	53.34	59.41
Grs (%)	42.58	-	-	-
Adr (%)	57.36	-	-	-

All Fe assumed to be Fe^{3+} .

DISCUSSION

P-T CONDITIONS OF VLGM IN METAPELITE

In table 1 the main parameters for determination of metamorphic grade and P-T-t conditions are summarized from Belmar *et al.* (2002, 2004). In the study area, the maturation of organic matter (coalification) and Kübler index increase simultaneously up to anchizonal conditions representing the low-grade metamorphic burial event. Nevertheless, certain samples violate this general trend. The highest vitrinite reflectance values are due to a high temperature heating event caused by the local emplacement of intrusions nearby, because of the highest sensitivity of the maturation of organic matter to temperatures with respect to the KI (Belmar *et al.*, 2002).

The mineral index identified using XRD (Belmar *et al.*, 2002) are characteristic for each metamorphic zone. Thus, sedimentary rocks with illite/smectite are located in the high diagenetic zone; paragonite is present from the beginning of the anchizone to the lower epizone; and pyrophyllite appears in the anchizone.

The interpretation of fluid inclusion data (Belmar *et al.*, 2002) indicates that this very low-grade metamorphism was formed during a burial-induced heating event at $T \leq 190^\circ\text{C}$ and $P \leq 1.3$ kbar. Assuming $P_{\text{fluid}} = P_{\text{total}}$, an overburden of *ca.* 4.8 km can be deduced (rock density $\gg 2.7$) and the prevailing geothermal gradient was calculated to be $>35^\circ\text{C}/\text{km}$. These low-pressure conditions are consistent with b_0 measurements carried out in illites from associated metapelites (Belmar *et al.*, 2002) (Fig. 5).

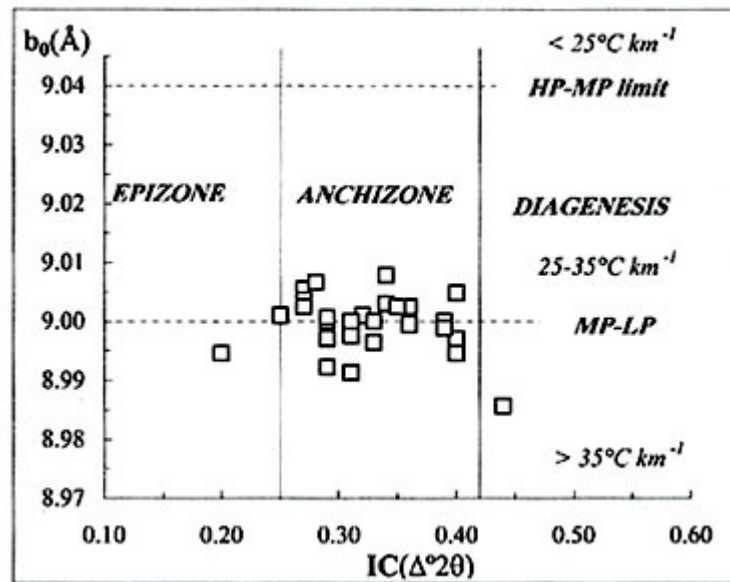


FIG. 5. Illite crystallinity - Kübler index (IC) versus b_0 data of illites from metapelites from the Triassic-Jurassic sequences in the Vichuquén basin. HP, MP and LP = high, middle and low pressure and inferred geothermal gradient according to the b_0 data (Guidotti and Sassi, 1986). IC and b_0 data from Belmar *et al.* (2002).

P-T CONDITIONS OF VLGM IN METABASITES

Pumpellyite is one of the most representative mineral index of very low-grade metamorphism in metabasites; its coexistence with other calc-aluminium silicate (epidote, actinolite and/or prehnite), together with chlorite and quartz, define different metamorphic facies in a P-T space (Frey *et al.*, 1991). Systematic analyses of pumpellyites has established a qualitative relationship between pumpellyite composition (mostly in relation with the $\text{Al} \leftrightarrow \text{Fe}^{3+}$ substitution) and P-T conditions during low-grade metamorphism (see Beiersdorfer and Day, 1995 for a review). Iron-rich pumpellyites with variable Al-content are relatively common in the lowest grade assemblages and seem to be characteristic of low metamorphic grade (*e.g.*, Schiffman and Liou, 1980); whereas aluminous varieties are restricted to the pumpellyite-actinolite and even to the blueschist-facies zones. Moreover, the effective compositions of precursor minerals seems to be a major factor controlling pumpellyite composition. According to the Al:Fe:Mg projection (Fig. 4a), pumpellyites from the Jurassic rocks studied plot in the prehnite-pumpellyite facies field (straddling the Jonestown and Vancouver island reference fields). The occurrence of pumpellyite types (with different Al_2O_3 content; Table 2b, Fig. 4b) in the same sample is (probably) best interpreted in terms of evolving $f\text{O}_2$ conditions. In fact, variations in the $\text{Al} \leftrightarrow \text{Fe}^{3+}$ content in

pumpellyite is typical, not only at a same sample level, but also inside a same crystal.

The hydrogarnet-pumpellyite-chlorite-epidote (\pm prehnite) assemblage may form during the burial induced metamorphism of basic rocks in prehnite-pumpellyite facies (Coombs *et al.*, 1977; Morata *et al.*, 2003) or even in the upper zeolite facies (Aguirre 1992). Coombs *et al.* (1977) state that grandite-chlorite assemblages are common in metabasites of very low metamorphic grade, but are eliminated before the onset of greenschist facies conditions because grandite is incompatible with chlorite in the presence of quartz under such conditions. Therefore, the mineral assemblage hydrogarnet-pumpellyite-chlorite-epidote (+qz) in sample H7-06 indicates (higher) zeolite to lower greenschist facies conditions, which correlate with the observed KI, b_0 and coal rank data of metapelites from Belmar *et al.* (2002).

'Chlorite thermometry' in very low-grade metamorphic rocks (Cathelineau, 1988) has been reviewed by De Caritat *et al.* (1993) and Merriman and Peacor (1999). Although its usefulness has been questioned (Essene and Peacor, 1995; Shau *et al.*, 1990; Jiang *et al.*, 1994; Schmidt *et al.*, 1999), the 'chlorite geothermometer' has been applied to four samples of this study. The andesite H7-06, located east of Hualañé, containing the assemblage chlorite - hydrogarnet - epidote-pumpellyite, yielded a temperature of $237 \pm 20^\circ\text{C}$ ($n=67$); two other volcanic rocks, located ESE of Curepto (H6-2; H6-10; table 2a), containing no diagnostic assemblages, yielded chlorite temperatures of $253 \pm 23^\circ\text{C}$ ($n=45$) and $296 \pm 25^\circ\text{C}$ ($n=60$). These temperatures are lower than those obtained from experimental data on the stability of hydrogarnet (Liou *et al.*, 1983) which indicate a minimum temperature of *ca.* 340°C (Fig. 6). On the other hand, according to Rossman and Aines (1991) and Amthauer and Rossman (1998), the water content of hydrogarnet increases with decreasing temperature and/or pressure. In our case, the low (2-4 wt%) H_2O calculated in the hydrogarnet is consistent with this T value.

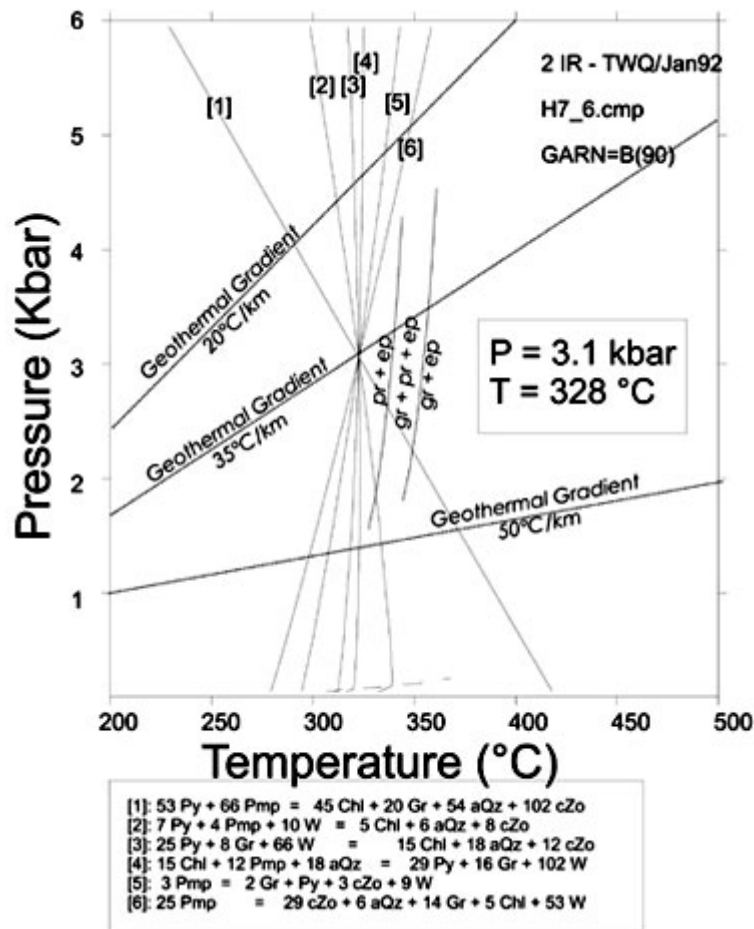


FIG. 6. P-T diagram in the CaO-MgO-Fe₂O₃-Al₂O₃-SiO₂-H₂O (CMFASH) system calculated using the GEO-CALC software (Berman *et al.*, 1987). Thermodynamic data base from Berman (1988) including solid-solution model of garnet from Berman (1990). Six multivariant reactions were modelled using pumpellyite (Pmp), hydrogarnet (Py and Gr), chlorite (Chl), epidote (cZo), quartz (aQz) and water (W). Reaction curves for the hydrogarnet (gr), prehnite (pr) and epidote (ep) from Liou *et al.* (1983).

The inconsistency between calculated chlorite temperatures and those estimated from hydrogarnet stability, as well as the occurrence of zoned pumpellyite and epidote, all indicate non-equilibrium crystallisation conditions.

Middle-Late Jurassic andesite sample H7-06 contains the low-variance assemblage pumpellyite-epidote-chlorite-hydrogarnet-quartz-albite. The thermodynamic data of Berman (1988, 1990), coupled with available solid solution models (Powell *et al.*, 1993) and mineral chemistry (Tables 2a, 2b, 2c, 2d), allowed us to locate metamorphic reactions among those minerals on the P-T diagram of figure 6. In the six component system (SiO₂-Al₂O₃-MgO-Fe₂O₃-CaO-H₂O) used in figure 6, there are only 2 independent reactions relating the 7 minerals end members (pyrope, grossular, pumpellyite, clinozoisite, chlorite, quartz and water); therefore the six reactions intersect at the same point at ≈3.1 kbar and ≈328°C (Fig. 6), implying a dominant geothermal gradient of ≈35°Ckm⁻¹ (assuming 3.3. km kbar⁻¹).

SIGNIFICANCE OF THE VLGM

The P-T conditions established for the assemblage pumpellyite-epidote-chlorite-hydrogarnet-

quartz-albite in Middle-Late Jurassic lava flows from the Hualañé-Gualleco basin permit the discussion of the geodynamic evolution of the Triassic-Jurassic volcano-sedimentary basins in the Coastal Range of central Chile. Assuming a Carnian-Norian age (≈ 220 Ma, Geological Time scale of the Geological Society of America, 1999) for the deposition of the Triassic sediments (Corvalán, 1982), a time-interval of *ca.* 40 Ma was obtained by Belmar *et al.* (2004) between deposition and the anchizonal very low-grade metamorphism. According to these authors, an overburden of *ca.* 4.8 km for the anchizonal conditions, corresponding to a high geothermal gradient of $>35^\circ\text{C}/\text{km}$, was calculated. With these figures, the subsidence rate in an extensional geodynamic setting would be of *ca.* 120 m/Ma (Belmar *et al.*, 2004). The geothermal gradient implies that the very low-grade metamorphism could be not only dominated by burial but also controlled by the high regional thermal anomaly related to extension. A zircon fission track age of 206 ± 12 Ma (Willner *et al.*, in press) from Paleozoic granitoids east of the Lago Vichuquén fits the extensional model, with sedimentary basin subsidence, proposed here.

Nevertheless, according to this model, the P-T conditions obtained for the assemblage pumpellyite-epidote-chlorite-hydrogrossular-quartz-albite (≈ 3 kbar and $\approx 330^\circ\text{C}$, Fig. 6) in Middle-Late Jurassic lavas are not consistent with an evolution of the Triassic-Jurassic basins only controlled by subsidence. K-Ar ages available for this area (Belmar *et al.*, 2004) date the diagenesis of sediments at 206 Ma and the anchizone at 184-181 Ma. K-Ar ages of dioritic intrusions range from 165 ± 5 to 175 ± 5 Ma. P-T conditions of the hornfels facies assemblage (ferrosilite-magnesiohornblende-ferroactinolite, biotite together with chlorite, plagioclase and stilpnomelane) in Triassic metapelites range from 655°C to 691°C with pressure <4 kbar (Belmar *et al.*, 2002). Then, assuming a post-Toarcian age (Middle-Late Jurassic, <180 Ma, Geological Time Scale of the Geological Society of America, 1999) for andesitic lavas (as previously indicated), genesis of the assemblage pumpellyite-epidote-chlorite-hydrogarnet-quartz-albite, restricted to these rocks, could not be related with the episode during which maximal anchizonal burial metamorphism (184-181 Ma) was achieved on older Triassic metapelites.

Pumpellyite is a typical metamorphic mineral generated in burial and regional metamorphism. Moreover, the metamorphic assemblage observed in Jurassic lavas is typical of very low-grade metamorphism, excluding the possibility for this assemblage to be a consequence of thermal metamorphism due to the dioritic intrusions.

Therefore the mechanism proposed to explain the genesis of these very low-grade assemblages must be related with another metamorphic event, younger than the burial metamorphism responsible for anchizonal conditions in Triassic metapelites. A change from an extensional (latest Triassic - Middle Jurassic) to compressional (Kimmeridgian- Tithonian) regime has been proposed by Charrier and Muñoz (1994) for the central Chilean Andes. Over this geodynamic setting, and based in the authors' P-T calculations, the authors propose an overthrusting of the Triassic and Lower Jurassic sequences which could favour the increase in lithostatic pressure giving the P-T conditions necessary for the metamorphism in the prehnite-pumpellyite facies.

Hence, two types of very low-grade metamorphism can be differentiated in the studied area. The first one was related with burial, thermally induced, achieving maximal metamorphic conditions of anchizone in Triassic-Jurassic metapelites and dated at 184-181 Ma (Belmar *et al.*, 2002, 2004). A second metamorphic event is observed in Middle to Late Jurassic lavas, with P-T conditions of ≈ 3 kbar and $\approx 330^\circ\text{C}$, inferred to have been related to overthrusting and crustal thickening following a change from an extensional to a compressional regime.

CONCLUSIONS

In the Triassic-Jurassic basins of the Coastal Range of central Chile ($34^\circ 45'/35^\circ 20'S$) sedimentary and intercalated volcanic sequences, restricted to the Middle-Late Jurassic, display evidence of mineralogical re-crystallisation under very low-grade metamorphic conditions. Crystallographic parameters measured in Triassic and Lower Jurassic metapelites (IC and b_0), together with coal and fluid inclusion data are consistent with anchizonal conditions under a $\approx 35^\circ\text{C}/\text{km}$ -1 thermal gradient in an extensional setting, developed during 181-184 Ma (Belmar *et al.*, 2002, 2004). Nevertheless, metamorphic minerals found in stratigraphically younger Middle-Late Jurassic volcanic rocks are consistent with a very low-grade metamorphism developed under prehnite-

pumpellyite facies. Pumpellyite composition, chlorite thermometry and P-T calculations indicate $P \approx 3$ kbar and $T \approx 300$ °C. These P-T conditions are inconsistent with a simple model for metamorphism dominated by burial. Local overthrusting of the Triassic-Lower Jurassic sequences as consequence of a geodynamical change from extensional to compressional regime is proposed in order to re-equilibrate Middle and Late Jurassic volcanic rocks under the estimated P-T conditions.

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NOTES

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