Diagenetic character of the Tertiary basin between Los Angeles and Osorno, southern Chile

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ABSTRACT

The diagenetic character of the sedimentary rocks of the Tertiary basin between Los Angeles and Osorno has been assessed according to its clay mineralogy and coal rank. Illite/smectite mixed layering varies between> 90% and >70% on the western basin margin. 30% smectite interlayering is found on the eastern margin at 1,000 m, the maximum depth sampled. Ro values vary between 0.42% and 0.52%. The role of contemporaneous volcanism in basin diagenesis is analysed and dated, and its importance in the diagenetic development of the basin is discussed. Oligocene-early Miocene volcanism changes from rhyolitic to basaltic compositions from north to south. K-Ar ages vary from 28 to 18 Ma for the Los Angeles and Temuco areas. Volcanism is considered to be a producer of abundant sediment rather than a source of permanent elevated heatflow. 70°C is proposed as the burial temperature reached in the western sector of the basin.

Keywords: Diagenesis, Tertiary, Illite-smectite, Vitrinite reflectance, Volcanism, Basin.

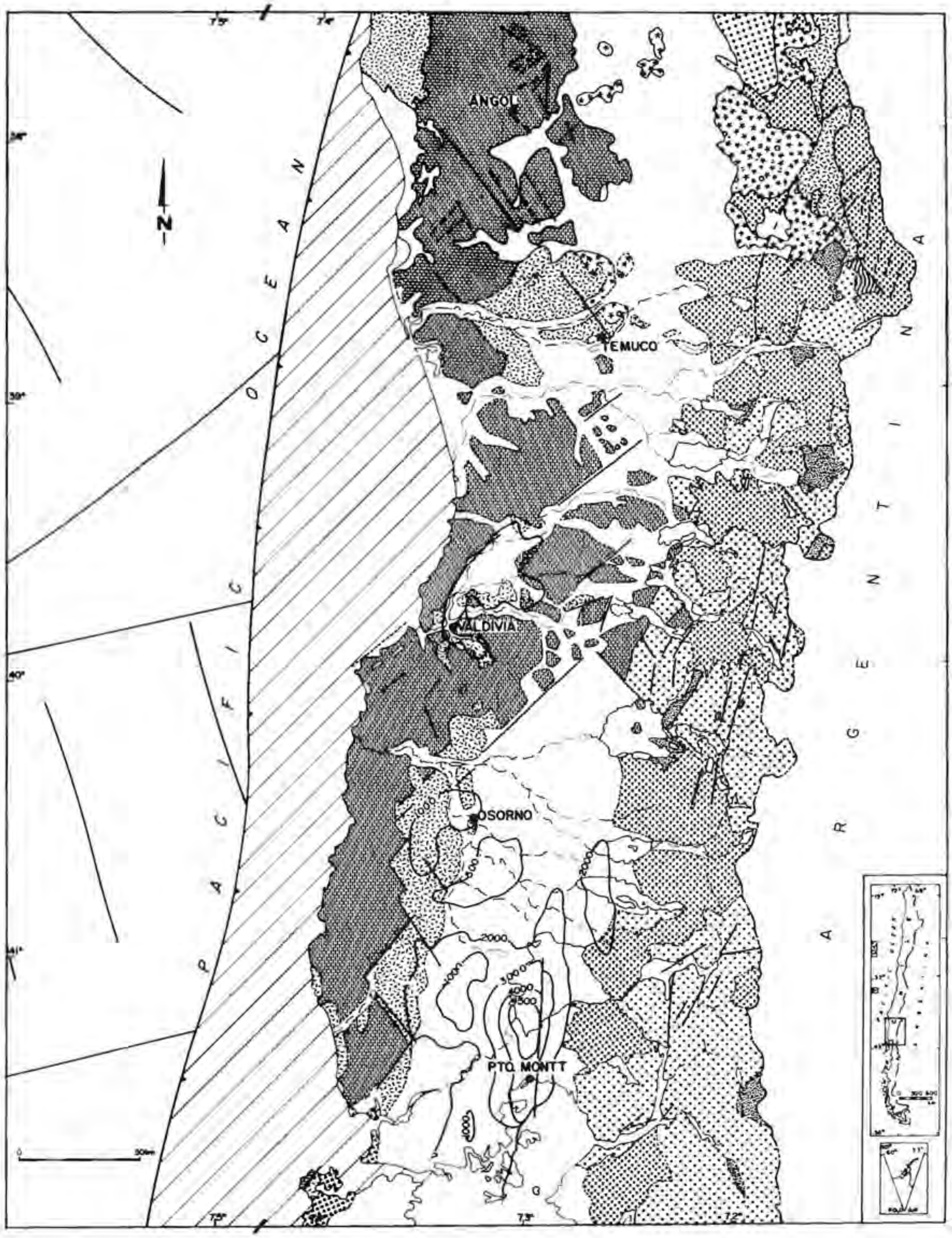
RESUMEN

Carácter diagenético de la cuenca Terciaria entre Los Angeles y Osorno, sur de Chile. Se evaluó el carácter diagenético de las rocas sedimentarias de la cuenca terciaria entre Los Angeles y Osorno con referencia a su mineralogía de arcillas y la madurez de su materia carbonosa. La intercalación illita/esmectita varía entre >90% y >70%, en la margen occidental de la cuenca; en la margen oriental, a la profundidad máxima del muestreo (1.000 m), se detectó una intercalación de esmectita de 30%. Los valores Ro varían entre 0,42% y 0,52%. Se discute el rol del vulcanismo contemporáneo en la diagénesis de la cuenca. El vulcanismo del Oligoceno-Mioceno temprano cambia su composición de norte a sur, pasando ésta de riolítica a basáltica. Las edades K-Ar varían entre 28 Ma y 18 Ma, en las áreas de Los Angeles y Temuco. Se toma al vulcanismo como un productor de abundante sedimentación más que como una fuente permanente de flujo calórico elevado. Se propone que la temperatura de diagénesis alcanzó 70°C en el sector occidental de la cuenca.

Palabras claves: Diagénesis, Terciario, Illita-esmectita, Reflectancia de vitrinita, Vulcanismo, Cuenca.

INTRODUCTION

The Tertiary basin between Los Angeles and Osorno, central southern Chile, has been the subject of regionally restricted studies to date. The stratigraphy and paleogeography have been studied by García


ANGOL
TEMUCO
VALDIVIA
OSORNO
PTO. MONTT
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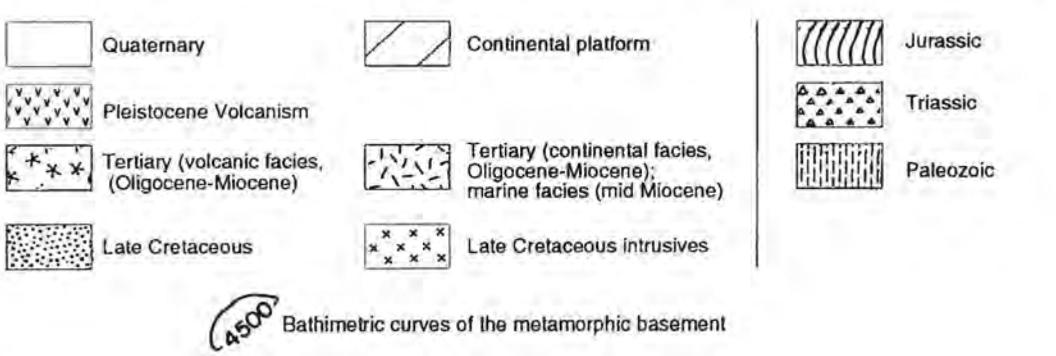
(1968), Palma and Alfaro (1982), Elgueta (1990), Rubio (1990), and Wall and Palma (1991), mainly in association with hydrocarbon exploration studies. Exploration for coal resources has led to a detailed examination of restricted sub-basins along the western margin of the elongated main depression. Oligocene-Miocene volcanism in the basin area is associated with a diastrophic-compressional tectonic setting (Cisternas and Frutos, 1994). The purpose of this study is to summarize the diagenetic development of the Tertiary units. Clay mineralogy and maturity of organic matter are examined. Tertiary volcanic rocks are analysed and dated, and their importance in the diagenetic development of the basin discussed. The genetic subdivisions proposed by Cisternas *et al.* (1993) are used, as they can be applied throughout the basin area.

GENERAL GEOLOGY

The Tertiary rocks of southern Chile lie within a halfgraben structure whose axis (NNE-SSW) coincides approximately with the present 'Valle Central' (Fig. 1). Basement elevations subdivide it in east-west and NNE-SSW directions. The Tertiary rests on Paleozoic, Triassic and, in some parts, Jurassic strata. The Paleozoic basement consists mainly of metamorphic rocks and granitic intrusions. Gravimetric studies (Giavelli, 1990, unpublished ENAP Report) have established the presence of this basement even in the deepest sectors of the basin for profiles taken at the latitude of Temuco. The maximum thickness of the Cenozoic sequence in the Temuco area is 2,000 m, but thickens to over 4,000 m in the south (Katz, 1970). The Tertiary is overlain by continental sequences of Plio-Pleistocene clays, tuffs and breccias.

Previous local studies have subdivided the Tertiary into a variety of local formations. For consistency, the subdivision of the Tertiary into three units (Cisternas *et al.*, 1993a) is used. Unit 1 (early Oligocene-early Miocene) represents a continental infill of the basin, that often overlies the metamorphic basement directly. The dominant sediments are lithic sandstones or lithic rudites that contain clasts of the metamorphic basement material. Tuffaceous siltstones and sandy tuffs are formed by material from a contemporary volcanic arc (Vergara and Munizaga, 1974). Siltstone beds host coal horizons up to 3.5 m thick, which have formed in marginal sub-basins (*e.g.*, Pupunahue) as a result of silting up of the local drainage system. Unit 2 (late Oligocene-early Miocene) is dominated by andesites and tuffs with intercalations of siltstones. These volcanic products are associated to the coastal Miocene volcanic belt (Vergara and Munizaga, 1974). Unit 3 (mid Miocene) overlies pseudoconcordantly units 1 and 2 and represents a change to marine sedimentation, with a progradation from west towards east and in the southern part of the basin from southwest towards northeast. Micaceous claystones, siltstones, and mudstones are the dominant lithologi-

FIG. 1. Geological map of the Angol-Puerto Montt area modified after Laugenie (1982) and Cisternas and Frutos (1994). The position of the oceanic fault zones is indicated. To save space, the width of the continental shelf has been cut between 74° and 75° longitude.



cal types. Benthonic foraminifera are of Serravalian-Langhian age (Marchant, 1990). An increase in thickness of the Tertiary from north to south coincides with the deepening of the basin in the same direction.

The development of this Tertiary basin has traditionally been associated with an extensional tectonic setting (Vergara and Munizaga, 1974). Recent evaluations of the subduction velocities and shape of the Benioff zone by Cisternas and Frutos (1994) present a more differentiated picture (Table 1, column 2).

TABLE 1. SUMMARY OF THE GEOLOGICAL ENVIRONMENT, TECTONIC SETTING AND MATURITY FOR THE BASIN AREA, INCORPORATING DATA BY ELGUETA AND RUBIO (1991), VERDUGO (1991), CISTERNAS AND FRUTOS (1994), AND THE PRESENT STUDY.

Unit/Age	Tectonic/Sedimentary Environment	Maturity-Gradient
Pleistocene-late Pliocene	Rapid rise of coastal block; fluviatile and volcanoclastic sedimentation in central valley	Borehole temperature gradient 2.24-2.86°C/100 m
Pliocene	Subsidence of coastal in the southern part of the basin; forearc continental	
Unit 3, early Pliocene-late Miocene	Rise of coastal block after compression during late Miocene	
Unit 3 mid Miocene	Subsidence; forearc marine	Ro 0.5%
Unit 2 early Miocene-late Oligocene	Migration of volcanic arc towards the east; andesitic volcanoclastic continental	Rapid sedimentation balancing any increased heatflow
Unit 1 Oligocene	Diastrophic compression due to increase in subduction velocity; forearc continental	Ro 5%
Cretaceous	Main chain arc, intrusives	Increase of gradient, maturation of Jurassic strata
Jurassic	Western margin of backarc marine basin	Ro 2.58-3. 26%, overmature
Triassic	Forearc, continental?	
Paleozoic	Basement formed mainly by schists	

SAMPLING AND ANALYTICAL METHODS

A cover of Quartenary material in the central valley and dense vegetation limit the outcrops of the Tertiary sequences to occasional deep valley cuts along the western basin margin that are dominated by volcanic-volcanoclastic rocks of unit 2. Samples for clay mineralogical and vitrinite reflectance studies were exclusively obtained from cores and cuttings supplied by the Empresa Nacional del Petróleo (ENAP) and Compañía Minera San Pedro de Catamutún (Fig. 2). The maximum depth represented by these samples is 1,000 m below surface. Sandstones have not been sampled systematically, as they were the subject of a previous study (Verdugo, 1991). Sampling localities are depicted in figure 2; all boreholes, except one (Antaro), are located close to the western basin margin. Volcanic rocks were sampled from outcrops in the Los Angeles, Temuco, and coastal Llanquihue areas.

Whole rock and clay size fractions (>0.45<1 µm, >1<2 µm and >2 µm) were analyzed using a Rigaku Geigerflex horizontal goniometer at the following settings: Ni-filtered Cu radiation, divergence slit 0.5 or 1°, receiving slit 0.15 mm, scanning range 3-70° 2θ for whole rock samples and 2-45°2θ for clay mounts. Clay samples were ethylene-glycol treated and heated to 375°C. Vitrinite reflectance (Ro) was measured with a Zeiss MPV 400 and a Leitz Orthoplan microscope under oil immersion. Ba, Rb, and Sr determinations were made using fused beads on a Rigaku 3070 wavelength dispersive X- ray fluorescence spectrometer. REE were determined on a Seiko SPS 1500 ICP after preconcentration following the procedure by Watkin and Nolan (1992). The results presented are based on 160 clay analyses, 20 Ro values, 40 whole rock analyses, and 10 REE determinations.

Two andesite whole rock samples (1119 and LA-8) have been dated by the K-Ar method at the Laboratory of Geochronology of the Chilean Geological Survey (SERNAGEOMIN).

RESULTS

WHOLE ROCK MINERALOGY

The whole rock mineralogy consists of quartz, muscovite/illite, albite, chlorite and smectite. Amounts of albite and chlorite present in a sample show a strong variation within cm-dm intervals. Kaolinite was found in some samples from the Bellavista, Catamutún, Río Blanco, Pupunahue and La Unión localities. The Pupunahue kaolinite seems to be restricted to underclay levels, whereas in other localities, it is not obviously related to coal seams or stratigraphic level, although a link to silty/sandy horizons is observed. It should be noted that these observations do not include sandstones, which may contain kaolinite as pore filling. Siderite was found in three cores of Pupunahue, approximately 3-5 m above the main coal seam.

Clinoptilolite and stilbite/heulandite appear in trace amounts and are linked to horizons with a major volcanoclastic input. The transition from continental units 1 and 2 to marine unit 3 is not marked by a mineralogical change.

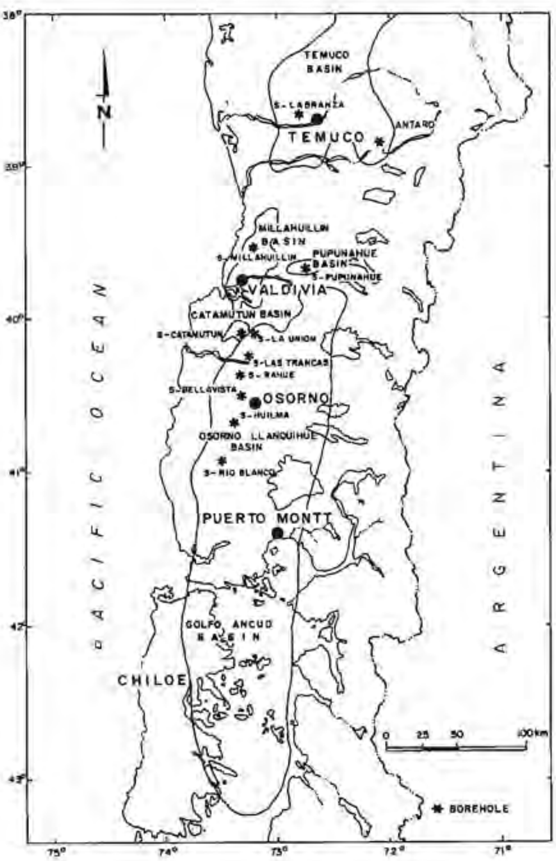


FIG. 2. Borehole locations sampled in this study. Black line marks the limits of the Osorno, Millahuillín and Temuco sub-basins.

MINERALOGY OF THE CLAY SIZE FRACTIONS

The clay size fractions are dominated by smectite, illite/muscovite, discrete chlorite and traces of quartz and plagioclase (albite) at all localities (Table 2). Discrete chlorite, quartz and feldspar decrease from the 2 µm to the >1>2 µm fraction. They almost disappear in the finest >0.45< 1 µm fraction. In contrast, the intensities of the smectite peaks increase and peaks broaden with decrease in grain size (Fig. 3). The peak shift of smectite in response to glycolation does not vary in-between the size fractions for an individual sample. The presence of illite/muscovite in the finest fraction is recognized by a high-angle shoulder of the smectite first basal reflection in air-dried state. Kaolinite, where present, is a mixture of 1MD and 1T polytypes, with a dominance of the latter. Illite-smectite mixed layering varies between >90% smectite and >70 % smectite for samples from the western basin margin. No systematic decrease was observed over the sampled depth interval of *ca.* 600 m on the western basin margin. Mixed layering percentages were determined using the method of Moore and Reynolds (1989). In the only borehole from the eastern basin margin, Antaro, 30% smectite interlayering (R1 ordering) was found at the deepest level of this 1,000 m borehole. This ordered illite/smectite is associated with the first appearance of laumontite. No ordered chlorite-smectite mixed layering was found in any of the samples. Also, chlorites show symmetric 003 reflections, which are considered to be a demonstration of a lack of low percentage smectite mixed layering in this mineral.

TABLE 2. SUMMARY OF THE MINERALOGY, NUMBER OF BOREHOLES PER LOCATION AND OF SAMPLES AVAILABLE.

Locality	Borehole No. per Location/Sample No./ Max. depth sampled	Quartz	Albite Illite	Muscovite (discrete)	Chlorite	Kaolinite	Illite/Smectite (S) (interlayered)	Heulandite/ Clinoptilolite stilbite	Siderite
Antaro	1/20/1000	***	**	**	**		** 70.90%S (30%S)	* (Laumontite)	
Bellavista	1/4/687	***	**	**	**		**70-90%S		
Catamutún	2/5/228	***	*		*	*	** 70-90%S	*	
Huilma	1/4/109	***	**	*	**		** 70-90%S		
Labranza	4/40/627	***	**	**			** 70-90%S	*	
Pupunahue	3/56/162	***	**	**	**	*	** 70-90%S		*
Millahuillin	1/6/493	***	**	**	**	*	** 70-90%S		
Rahue	1/1/272	***		***	***		***70-79%S		
Rio Blanco	1/11/615	***	**	**	**	**	** 70-90%S		
Las Trancas	1/5/688	***	**	**	**	**	** 70-90%S	*	
La Unión	1/8/492	***	**	**	**		** 70-90%S	*	

*** mineral present in all samples; ** mineral present in most samples; * mineral present in some samples.

ZEOLITES

Clinoptilolite and stilbite (or another member of the heulandite sub-group) were found in trace amounts in horizons which have a strong volcanoclastic influence as noted by their high contents of feldspar. A more detailed identification of the zeolites has not been possible, due to their low concentration. Unspecified zeolites have been identified in lithic conglomerates of unit 2 from the Temuco area by Verdugo (1991). Laumontite has been identified at a depth of 1,000 m in the Antaro borehole.

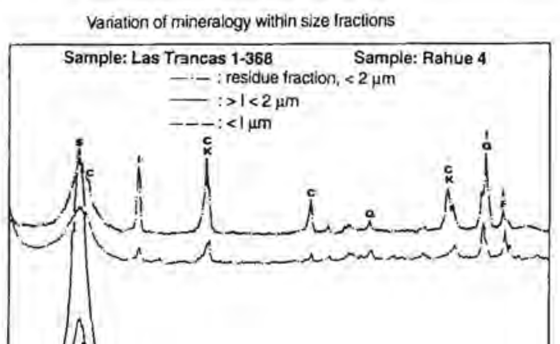


FIG. 3. Change in mineralogy with decreasing grain size for the >2 µm, >1<2 µm and <0.45<1 µm fractions for samples Las Trancas 1-368 and Rahue 4 (bold). S=smectite; I=illite/ muscovite; C=chlorite; Q=quartz; F=feldspars.

MATURITY OF COALY MATTER

Vitrinite reflectances (Ro) have been determined on samples taken from coal seams as well as from coaly matter dispersed in the sediments. Ro values for continental unit 1 are <0.52% Ro. Some samples from marine unit 3 show values slightly >0.50% Ro, due to the presence of finely disseminated pyrite. In the La Unión area there is a slight increase in vitrinite reflectances from 0.42 to 0.52% Ro over a depth interval of 200 m, but more data covering a larger depth interval are needed to confirm this trend (Fig. 4). Coal samples from Millahuillín show signs of incipient hydrocarbon migration and have a source rock potential (M. Mukhopadhyay, Dalhousie University, Canada, personal communication, 1993). No reflectance data are available from the eastern basin margin.

TERTIARY VOLCANISM

Volcanic and sub-volcanic rocks assigned to unit 2 have been sampled at surface level in the Los

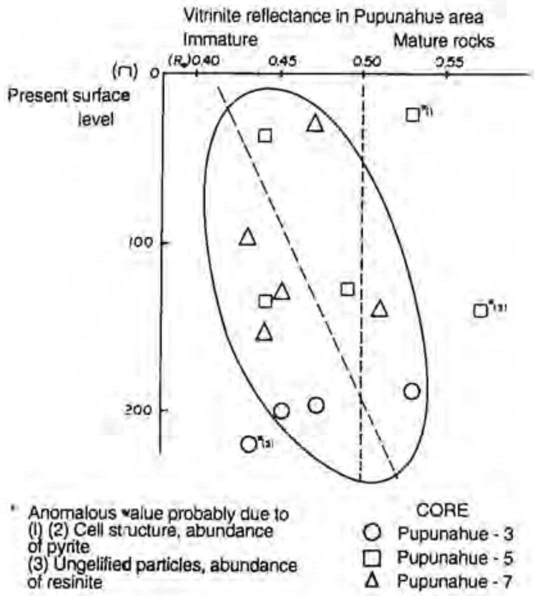


FIG. 4. Plot of vitrinite reflectances *versus* depth for 3 Pupunahue boreholes.

Angeles, Temuco and Llanquihue areas (Troncoso, 1993). In the Los Angeles area, the rocks are porphyritic with 20-40% phenocrysts, dominated by zoned plagioclase, orthopyroxene or amphibole, and quartz in the most acid compositions. The Temuco samples are similar, but amphibole is more widespread. The Llanquihue samples have intergranular sub-ophitic textures, dominated by plagioclase with interstitial clinopyroxene. Except for the southernmost area, the volcanism has a clear calc-alkaline character (Fig. 5), with dominant andesites and dacites, while some samples from the northernmost Los Angeles area have a rhyolitic character. This coincides with a reduction in SiO_2 content from north to south. Only three samples are available from the Llanquihue area. Using the AFM diagram of Irvine and Baragar (1971), a tholeiitic character is observed for these southern samples (Fig. 6). MORB normalized trace element patterns (after Pearce, 1983) are shown in table 3 and figure 7 where the Llanquihue samples stand out with lower light incompatible element ratios. The volcanic rocks show chlorite and occasional epidote and there is sericitization of plagioclase (Troncoso, 1993). K-Ar whole rock ages are 18.8±3.9 Ma for a Los Angeles sample (LA-8: 2.137% K; 1.917nl/g radiogenic Ar; 34% atmospheric Ar) and 22.9±0.9 Ma for a Temuco sample. Additional dates of 20.2±Ma and 28.8±1 Ma for the Temuco area have been provided by Rubio (1993).

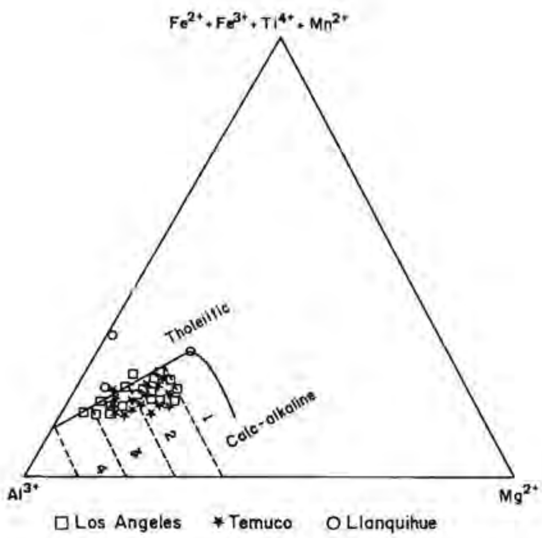


FIG. 5. Cation diagram after Jensen (1976), modified from Troncoso (1993). **Field 1: basalt; Field 2: Andesite; Field 3: dacite; Field 4: rhyolite.**

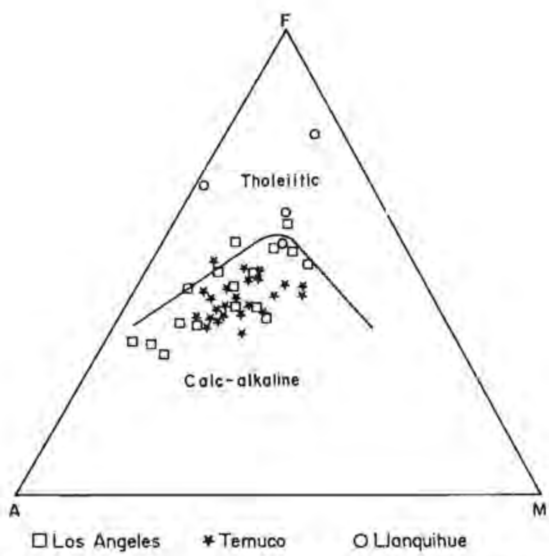


FIG. 6. AFM plot after Irvine and Baragar (1971), modified from Troncoso (1993). **A:** Na_2O+K_2O; **F:** $FeO+0.8998\ Fe_2O_3$; **M:** MgO.

TABLE 3. RARE EARTH AND TRACE ELEMENT ANALYSIS OF TERTIARY VOLCANIC ROCKS INCORPORATED IN FIGURE 7.

Sample No.	Lu	Hf	Yb	La	Er	Gd	Ho	Dy	Sm	Sc	Y
LA-8	0.34	0.97	2.54	7.90	1.22	3.48	0.48	3.85	2.31	28.40	24.00
LA-11	0.17	1.91	1.18	8.20	1.07	2.43	0.10	2.04	1.54	11.90	11.60
LA-38	0.70	3.58	4.46	22.40	1.98	6.93	1.58	7.13	6.24	13.10	42.90
LO-2	0.12	2.95	0.82	14.40	0.69	2.45	0.55	2.27	2.36	6.50	7.80
LO-3	0.05	2.65	0.62	10.50	0.66	2.20	0.33	1.53	1.50	4.68	7.00
TE-3	0.36	2.77	2.20	15.90	1.43	3.71	0.55	3.83	3.16	17.60	20.70
TE-6A	0.46	1.87	2.86	8.50	1.38	4.42	0.75	4.52	2.66	19.20	25.20
TE-21	0.35	2.26	1.96	11.70	1.14	3.52	1.17	3.65	2.82	14.10	19.20
3028	0.47	2.87	3.12	7.70	1.78	4.80	0.66	5.47	6.35	40.90	30.80
3098	0.46	3.77	2.87	11.40	1.72	5.59	1.57	5.74	4.08	26.30	29.50

	Eu	Pr	Nd	Ce	Sr	Rb	Ba	Zr	K_2O(%)	P_2O_5(%)	TiO_2(%)
LA-8	1.04	2.43	11.70	19.20	312.0	16.5	270.5	112.3	1.15	0.13	0.96
LA-11	0.91	1.87	11.40	19.60	353.6	36.3	311.6	124.3	1.41	0.11	0.68
LA-38	1.66	4.97	32.70	39.60	256.8	69.7	416.8	189.7	2.75	0.08	0.61
LO-2	0.68	3.83	15.30	32.50	111.7	109.8	380.1	112.1	n.a.	n.a.	n.a.
LO-3	0.63	2.60	10.80	24.00	328.2	80.9	243.4	119.7	n.a.	n.a.	n.a.
TE-3	1.12	3.56	15.10	34.10	398.9	41.8	385.1	142.3	1.42	0.09	0.69
TE-6A	1.09	1.93	12.40	18.50	784.3	21.0	375.3	174.7	2.03	0.08	0.57
TE-21	1.04	2.62	15.40	27.80	600.3	29.0	340.1	160.5	1.54	0.11	0.71
3028	1.49	3.51	16.00	20.30	198.3	0.0	104.3	120.0	0.22	0.18	1.90
3098	1.73	5.24	22.40	28.00	351.3	5.10	226.8	180.2	n.a.	n.a.	n.a.

Note: Values in ppm except K_2O, P_2O_5 and TiO_2 in weight %.

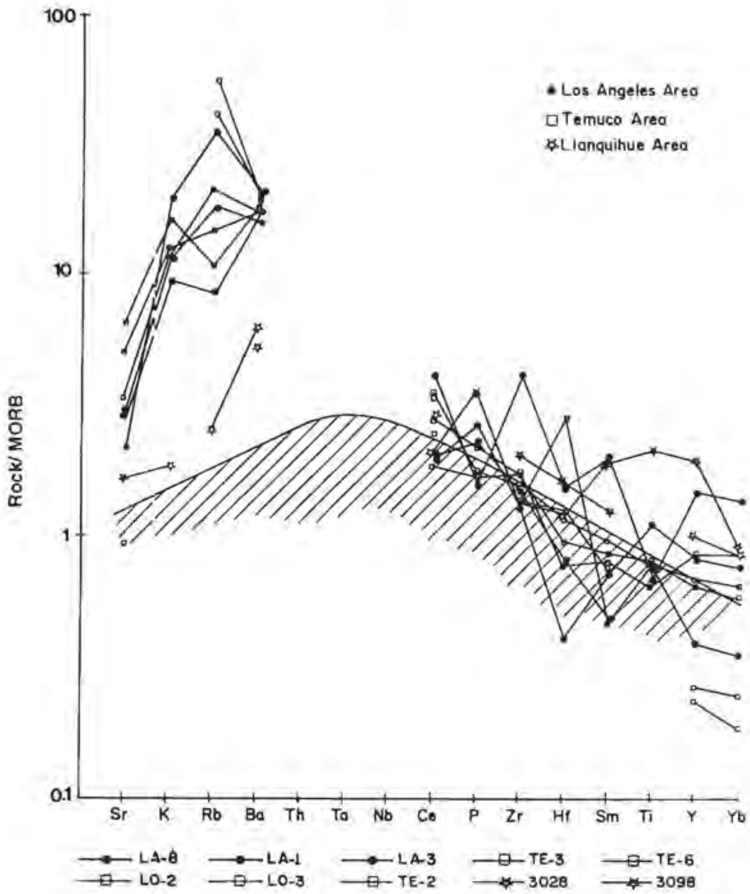


FIG. 7. MORB normalized trace element diagram (after Pearce, 1983). **Shaded area:** within plate component; **white area:** enrichment in subduction zone fluids; **dots:** Los Angeles area; **squares:** Temuco area; **stars:** Llanquihue area.

DISCUSSION

WHOLE ROCK MINERALOGY

Whole rock mineralogy in the shales is strongly influenced by the changing amount of volcanoclastic input. No change in mineralogy is noted with the change from a continental to marine environment. This may be due to a reworking of sediment during the advance of the sea.

MINERALOGY OF THE CLAY SIZE FRACTIONS

The disappearance of illite/muscovite, discrete chlorite, as well as feldspars and quartz in the finest grained >0.45<1 µm fraction suggests that these minerals do not reflect the diagenetic alteration of the samples (Kelm and Robinson 1989). Only smectite, which dominates the finest-sized fraction is considered to be representative of diagenetic grade. The decrease in peak intensities for kaolinite with reducing grain size may be due either to a clastic origin of the mineral or the generally larger crystallite size of kaolinite compared to smectite.

As the smectite content oscillates, rather than systematically varies between >90% and >70% interlayering for the depth interval sampled on the western basin margin, and only a first isolated occurrence of R1 ordered illite/smectite has been found at the bottom of the borehole Antaro, a larger depth interval should be sampled to observe a systematic change in mineralogy if deeper boreholes become available. The first appearance of laumontite close to R1 ordered illite/smectite, suggests that mineralogical changes can be expected for greater depth. The dominance of highly expandable smectite is concomitant to the still lacking importance of chlorite/smectite interlayering (Kübler *et al.*, 1979, in Kisch, 1987). The symmetry of the 003 discrete chlorite reflections demonstrates a lack of alteration, *i.e.*, incipient expandability of this mineral. This may be due to the exclusive use of core samples instead of outcrop material.

ZEOLITES

The zeolites found have been described from incipient medium-grade diagenetic environments (Gottardi and Galli, 1985; Iijima, 1988). They correspond, in grade, to the phyllosilicates and organic maturity (see below). The first appearance of laumontite at the bottom of borehole Antaro corresponds to a grade 2 level of diagenesis (Küb er *et al.*, 1979, in Kisch, 1987). However, there are few data available on the stability conditions of the heulandite group minerals (Iijima, 1988), as they may display a wide range of chemical compositions, thus, making them nondiagnostic with respect to the diagenetic grade.

MATURITY OF COALY MATTER

Coaly matter has remained at an immature stage and only reaches the lower limit of catagenesis or the oil window (Teichmüller, 1987). Organic matter is classified as type II-III kerogen.

TERTIARY VOLCANISM

Many questions remain unanswered with respect to Tertiary volcanism. Differences in the composition and age of the volcanism were shown by Cingolani *et al.* (1991), for areas to the south and west of this basin, who associated early Tertiary volcanism with rhyolitic compositions which are rare in younger episodes. New K-Ar ages based on andesites display a regular spread of volcanic activity during latest Eocene-mid Miocene times for the Los Angeles and Temuco areas. MORB normalized trace element patterns (Pearce, 1983, Fig. 7) show a strong influence of subduction zone fluids (Thorpe *et al.*, 1984 in Wilson, 1988). Samples from the Llanquihue coast show trace element patterns with lower incompatible element ratios.

DIAGENESIS AND BASIN DEVELOPMENT

The diagenesis of the Tertiary sediments in this area should be assessed with due consideration of the older and younger lithologies. Table 1 summarizes conditions of sedimentation, tectonic movements and the maturity for the Cenozoic strata of the region. Knowledge about Triassic to Cretaceous units is limited due to the lack of outcrop. The only information on the thermal maturity of sediments is from the Jurassic (east of Temuco) with Ro varying between 2.58% and 3.26% (Verdugo, 1991), and thus, at an overmature stage. Intense intrusive activity during the Cretaceous may be the cause of this advanced maturation.

The diagenetic level of Tertiary sediments, as judged by their clay and zeolite mineralogy, is a grade 2 diagenetic level (Kübler *et al.*, 1979, in Kisch 1987). The deepest level of borehole Antaro may represent the first indicator of increased dehydration of smectite with depth. The first appearance of laumontite underlines the imminent mineralogical changes at this level. Deeper boreholes would be needed to confirm this. The absence of fine grain-size fraction chlorite indicates a lack of chloritization of smectite in the samples analyzed. This process acquires importance with a reduction of expandable layers to approximately 30% (Kisch, 1987), a stage only 'touched upon' in the present study. The maturity of coaly matter has reached an upper eogenetic, incipient catagenetic stage, equivalent to the inorganic scale when using the comparison proposed by Kübler *et al.* (1979, in Kisch, 1987).

Oligocene-early Miocene volcanism has not resulted in a more advanced mineralogical or organic maturity with respect to the younger marine sediments, nor is there evidence of contact metamorphic heating in the mineralogy or maturity of the coals. Any possible increase in heatflow due to volcanic activity must have been counteracted by rapid and abundant volcanoclastic sedimentation. The change from volcanoclastic to marine sedimentation is linked to block-like subsidence movements and marks the onset of a compressional crustal regime (mid-Miocene, Table 1). The late Miocene-early Pliocene period corresponds to a rapid uplift of the coastal block in response to compression during the late Miocene.

A period of subsidence during the Pliocene is postulated by Cisternas and Frutos (1994) for the southern part of the basin. During this time, much of the fluviatile and volcanoclastic overburden has been accumulated to generate a diagenetic grade 2 in the Tertiary sediments, which are now within 1,000 m from surface level. Rapid uplift and erosion of the coastal block occurred in the late Pliocene bringing the sub-bituminous coal deposits of La Unión (Unit 1) within 5 m of surface level.

BURIAL TEMPERATURE ESTIMATION

An estimation of the burial temperatures and/or the geothermal gradient is difficult to define with the present data. There is no information available on the overburden removed. Even though three possible approaches are considered:

- Thiele *et al.* (1986) postulated a rapid uplift of 0.6-2 km/Ma for the main cordillera during the Miocene. Assuming similar values from late Pliocene times onwards, this would permit an accumulation of, at least, 2,000 m of sediment. A comparison of this overburden estimate with studies by *e.g.*, Hower *et al.* (1976), Boles and Franks (1979) and Deconinck and Bernoulli (1991) in the Gulf coast area and the Lombardian basin suggests a 'normal' temperature gradient for the basin area on grounds of mineralogy and Ro values;
- borehole temperatures are available from the Labranza boreholes (Verdugo, 1991). They gave uncorrected gradients between 2.24°C and 2.96°C/100 m. Temperatures have been measured in the basement and continental units. No details are available on the conditions of measurement and on the possible presence of aquifers. Therefore, the information should be handled with great caution;
- the uncertain nature of associating diagenetic mineralogy and vitrinite reflectances with burial temperatures has been pointed out by Kisch (1987), Velde (1985) for minerals, and Teichmüller (1987) for coals. The principal reasons are sluggish reaction rates and the influence of the whole rock chemical composition for smectite conversion, and uncertainties in the effect of heating time on coal. Smectite-illite transitions have often been described (*e.g.*, Hower *et al.*, 1976), and most cases show a rapid transition zone where the reduction of >70% smectite interlayering to 30% occurs. Data by Hower (1981) link highly expandable smectite sequence to maximum temperatures of *ca.* 70°C. A smectite layer content of 30-20% is associated with temperatures of *ca.* 90-100°C, which here would be applicable only to the eastern basin margin.

The estimation of a gradient using the difference in Ro of 0.1% over a 220 m depth interval in the Pupunahue area (Fig. 4) results in an unrealistic gradient of >10°C/100 m and is discarded due to the scattered data.

Given the available data, the authors considered it difficult to favour one of the three approaches, as each one of them would require more information to be used for safely modeling burial temperatures and gradient; nevertheless, for the western basin margin a tentative burial temperature of 70°C is proposed to serve as a basis for discussion for future studies on this subject.

CONCLUSIONS

The Tertiary sediments between Los Angeles and Osorno have reached an eogenesis or incipient catagenesis grade (equivalent to grade 2 diagenesis) up to a maximum depth of 1,000 m. Illite/smectite interlayering varies from >90 to >70% on the western basin margin. 30% smectite interlayering was found in one sample from the eastern margin with laumontite occurring close by. Ro values vary between 0.42% and 0.52%. The rhyolitic to andesitic/dacitic volcanism for the Los Angeles and Temuco areas has yielded Oligocene-mid Miocene whole rock K-Ar ages. The Llanquihue basalts have not been dated.

The overburden required for the formation of sub-bituminous coal is considered to be the result of intense sedimentation towards the basin centre with concomitant rapid uplift of the Coastal Cordillera during the late Miocene-early Pliocene, followed by subsidence during most of the Pliocene. Burial temperatures and geothermal gradients are difficult to estimate, but temperatures of *ca.* 70°C with normal heatflow are proposed on the western basin margin as a basis for discussion for future studies.

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