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CLAY DIAGENESIS IN THE MAGELLAN BASIN, CHILE

URSULA KELM[1], RAMIRO BONILLA[2], MARÍA EUGENIA CISTERNAS[1], JAIME FALCON[2], CARLOS HERRERO[3], PABLO MELLA[3] and JORGE RODRÍGUEZ[1]

[1] Instituto de Geología Económica Aplicada, Universidad de Concepción, Casilla 4107, Concepción 3, Chile
[2] Departamento de Ciencias de la Tierra, Universidad de Concepción, Casilla 3-C, Concepción 3, Chile
[3] Empresa Nacional del Petróleo (ENAP), José Nogueira 1101, Punta Arenas, Chile

Abstract: The mineralogy of the whole rock and clay size fractions has been determined for 12 boreholes from the Magellan Basin, Chile. The degree of clay diagenesis is assessed and compared to the organic maturity indicator vitrinite reflectance. The whole rock mineralogy is dominated by quartz, albite, high Fe-chlorite with minor illite/muscovite. Diagenetic zeolites are found in the Tertiary strata deposited in a platform environment in the eastern basin area. Laumontite is concentrated in albite rich sediments in the eastern basin area. Laumontite is concentrated in Cretaceous and Tertiary sediments of the Andean foreland. Expandable layers in illite/smectite are reduced to <10% at 4900 m depth in Eocene shales; a general reduction of expandability from 70 to 40% occurs between 1500 and 2500 m throughout the basin. Ro data from the Early Cretaceous Springhill Formation reflect the deepening of the platform towards the West. Clay diagenesis is considered to be due to Tertiary overburden, whereas vitrinite reflectances in the Springhill Formation may additionally have been affected by a terminating Jurassic volcanism.

Key words: basin, illite/smectite, diagenesis, vitrinite reflectance, Chile.

Introduction

The Magellan Basin is located at the southern end of South America. The basin has a NNW trend and covers a surface of about 160,000 km^2, with a maximum length of 700 km and a width of 370 km. The sedimentary fill is over 8000 m in the basin centre (Fig.1). It is the only domestic source of oil and gas for Chile and a major producer for Argentina. Its coal deposits have supplied the coaling port of Punta Arenas, until the construction of the Panama Canal and later the opening of the Río Turbio coal mine in Argentina led to a decline in coal exploitation after World War II (Toenges et al. 1948). The basin is bordered to the West by the Patagonian batholite and the southern Andean chain. Towards the North East its limits are marked by the Deseado Massif, a basement high since the Paleozoic. Towards the South East the basin is linked to the Falkland or Malvinas Basin. The Southern limit is a complicated strike slip fault zone which marks the limits of the South American and Scotia plates.

Most geological studies in the area of the Magellan Basin have concentrated on the improvement of geophysical information (e.g. Kirkpatrick 1990), the establishment of a "unified" basin-wide stratigraphic subdivision (e.g. Natland et al. 1974) and the fold and thrust deformation in the Andean foreland (e.g. Ramos 1989). No systematic study has been done on the mineralogy of the basin fill and its diagenetic alteration with depth. The present study investigates the changes with depth in authigenic clays and zeolites for 12 boreholes and their relationship to the diagenetic history of the basin, and compares them to the indicator of organic maturity, vitrinite reflectance.

Outline of geology

The development of the Magallanes Basin is closely related to the changes in the tectonic regime of Gondwana accompanying the opening of the South Atlantic during the Cretaceous.

During the Early Jurassic an extensional regime (Gust et al. 1985) started to develop on the southern margin of Gondwana, resulting in the normal faulting of the metamorphosed basement into a system of grabens and halfgrabens. Their NNW orientation already indicates the strike of the future basin axis to develop further towards the East. The large scale rise of a mantle plume during Mid-Late Jurassic leads to streching and thinning of the Gondwana continental crust, evidenced by several 1000 m of acid volcanic rocks erupted and deposited in southern Gondwana as a result of anatexis (Bruhn et al. 1978, Suárez & Pettigrew 1976). Extension intensifies during the Upper Jurassic leading to the rupture of the continental crust and the development of a marginal back arc basin (Roca

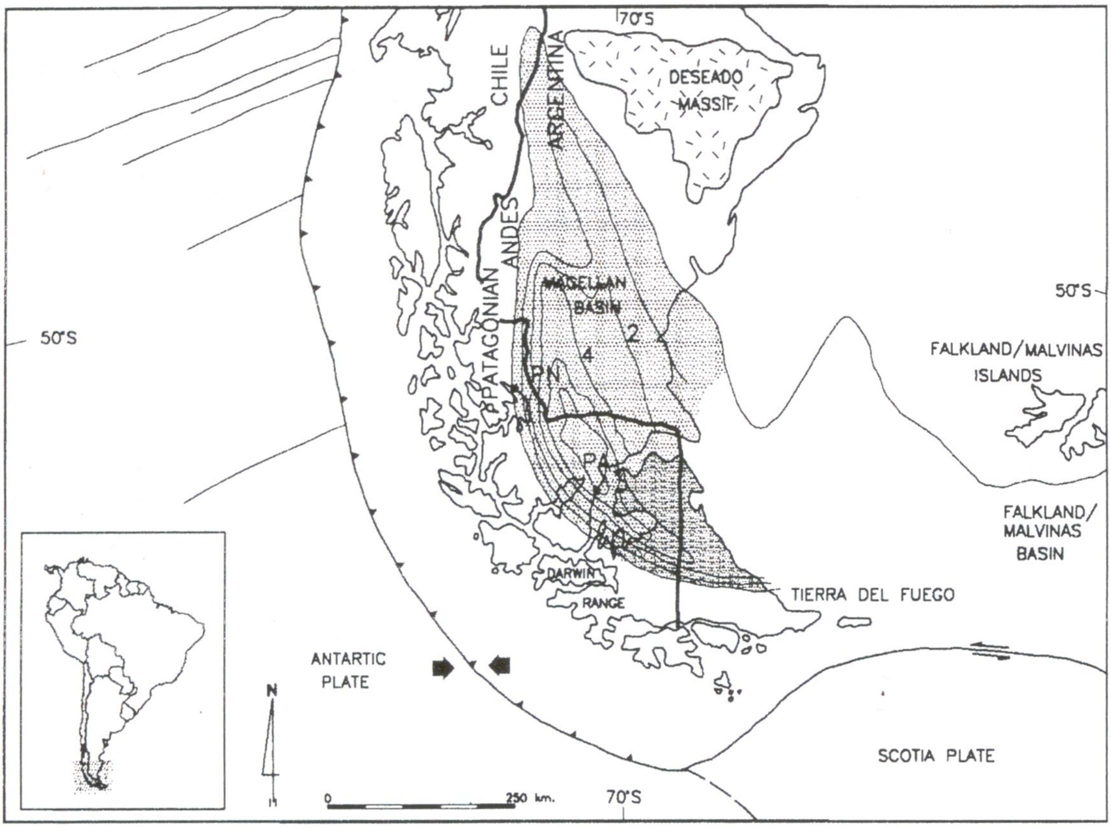

Fig 1: Location of the Magellan Basin, sediment thickness is indicated in km. Modified from Ramos (1989).

Verde Basin) to the West of the present Magellan Basin (Daziel et al. 1974), where tholeiitic volcanism interdigits with acid volcanism (Soffia & Harambour 1989). Rifting ends during the Jurassic-Cretaceous with the splitting up of Gondwana, leaving the Roca Verde Basin at a passive continental margin exposed to continuing thermal subsidence into the late Cretaceous. The subsidence caused a marine transgression.

The definite opening of the Atlantic led to the development of a compressional tectonic regime, thus ending the subsidence of this marginal basin. Compression started in the West, leading the rise of the deformed areas ("Protocordillera") and propagated towards the East (Nelson 1982; Nelson et al. 1980). The isostatic decompensation caused the thickening of the deformed areas (flexure of the lithosphere ahead of a deformation front) and led to the development of a foreland basin towards the Atlantic, the present Magellan Basin (Biddle et al. 1986). The exposed areas of the protocordillera in the West supplied detrital material to the basin (Winn & Dott 1976). In the Senonian, deltaic deposits develop on an eastward tilted platform (Natland et al. 1974).

During the Late Maastrichtian and Paleocene the subdivision of the basin develops with a platform (marine) in the East and an elongated (NNW) depression in the West. During the Eocene the depocentre shifts towards the East, evidenced by a progressive discordance over the platform sediments of the Upper Cretaceous (Natland et al. 1974). From the Late Tertiary to the present, the subsidence of the western sector diminishes, with marine sediments being replaced progressively by fluviatile and deltaic sediments. These host important coal deposits (Brunswick Peninsula, Isla Riesco, Llanos de Diana, Chile, and Río Turbio, Argentina). During the Pliocene the entire region emerges. Pyroclastic fluviatile sequences receive their material from a magmatic arc developed in the eastern part of the present Precordillera (Michael 1983). During the Pleistocene an isolated volcanic episode is registered north of the Straight of Magellan (Skews 1980).

The bathymetrical subdivision of a platform area where sediments are only accessed by boreholes and a deeper depocentre towards the West with outcrops in the thrusted and folded Andean foreland, gave rise to distinct unit and formation names (ENAP 1978). In the case of the platform sediments matters are further complicated by cross border Chilean/Argentinian discrepancies in unit definition. There have been only few comprehensive attempts of a basin wide stratigraphic correlation (e.g. Biddle et al. 1986). Fig.2 is a simplified representation of the most recent work in progress of this kind (Mella, personal communication).

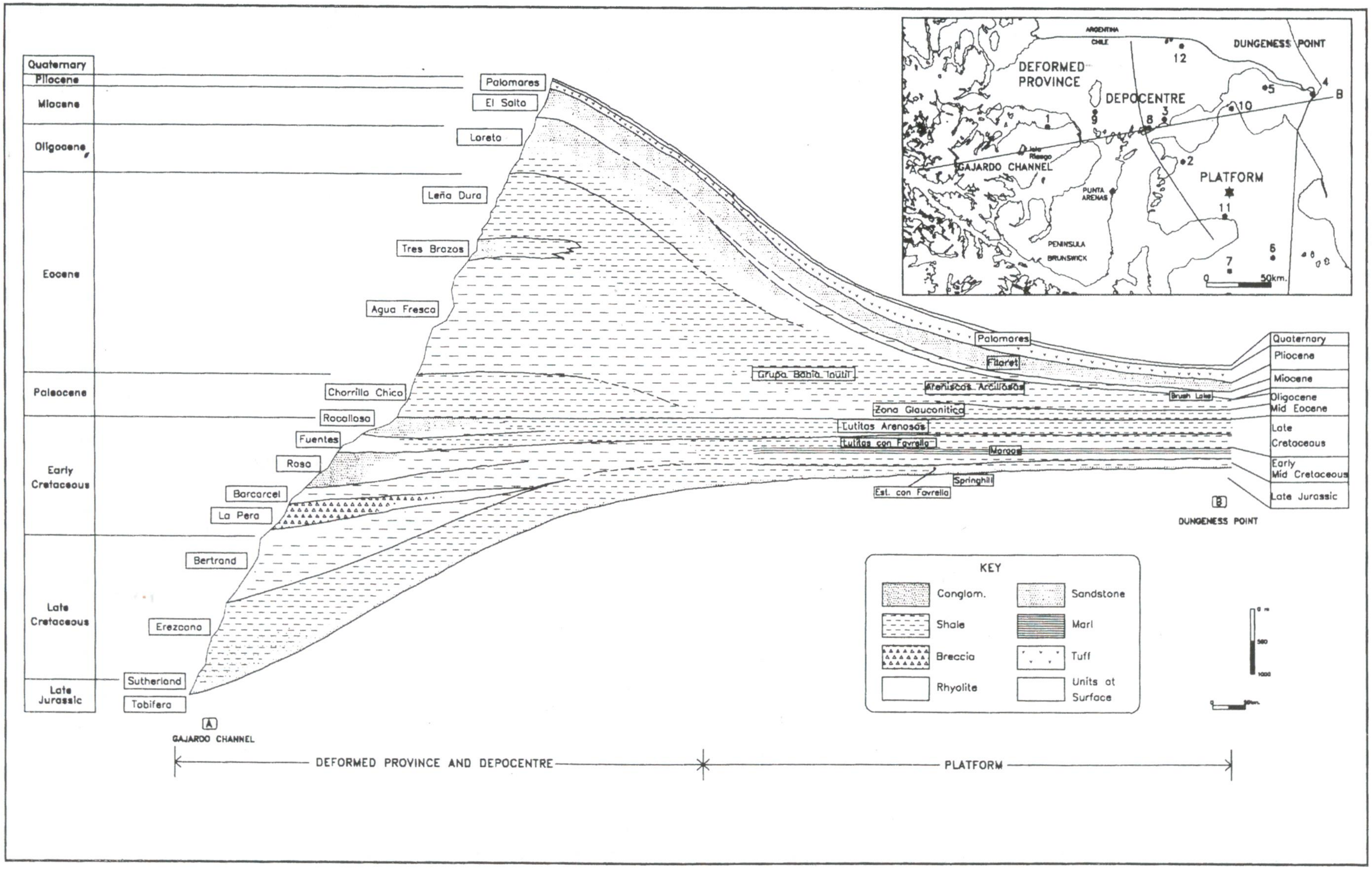

Figure 2: Sedimentation in an East-West cross section of the Magellan Basin. Insert shows the location of the boreholes used in this study: (1) Chilenita 2, (2) Clarencia 1A, (3) Dorado Sur 1A, (4) Dungeness Norte 1A, (5) Erizo XE2, (6) Estero Wilson 1A, (7) Evans 1, (8) Gregorio 1, (9) Manzano 7, (10) Picton 1, (11) Puerto Nuevo1, (12) Vania 1, (*) Centenario.

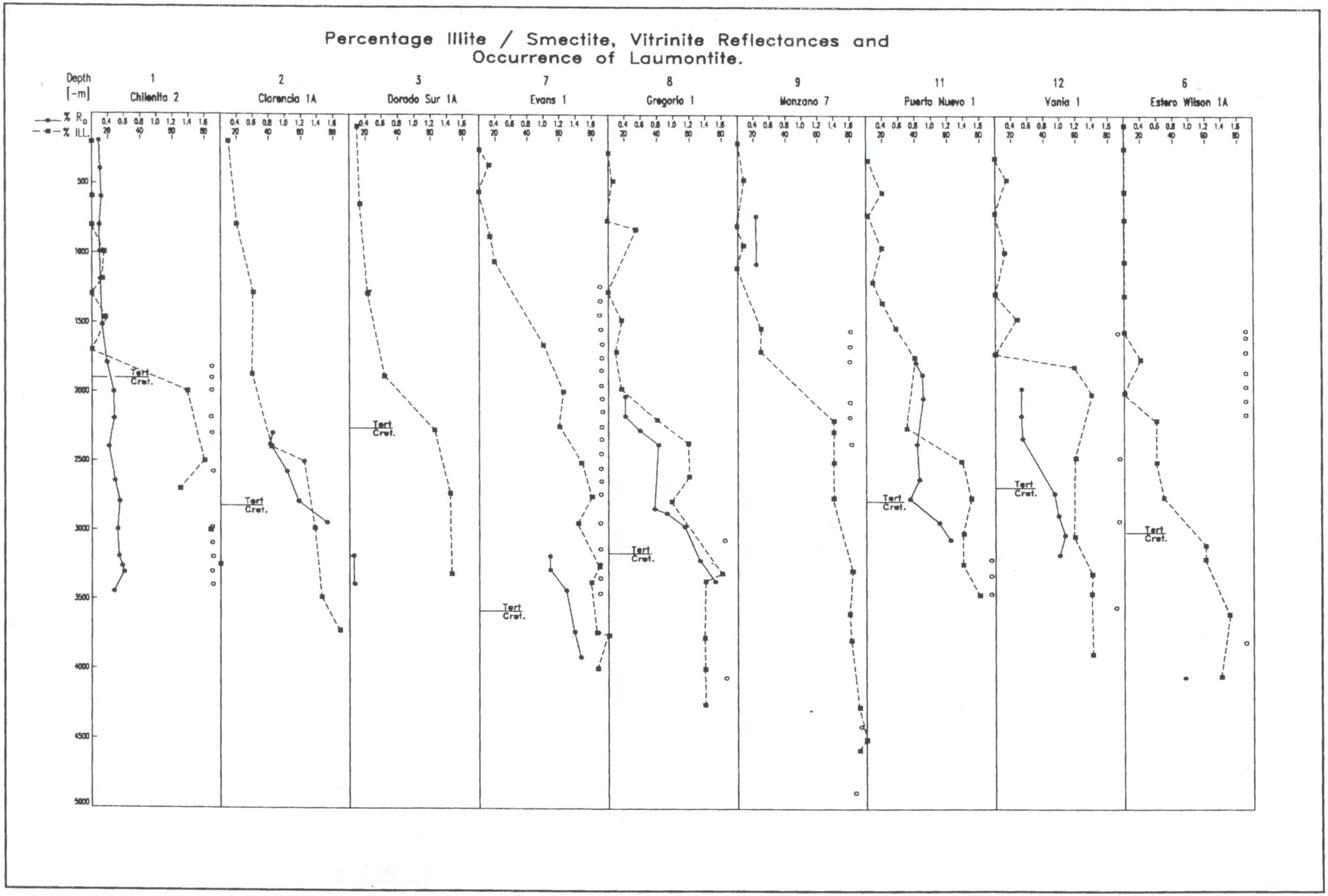

Fig 3: Boreholes Dungeness Norte 1A,Erizo XE2 and Picton 1 are not included as their maximum depth is less the 2200 m. No decrease of expandability of illite/smectite is observed in that intervall. Occurrence of laumontite is shown by open circles.

Methods

Due to the general lack of mineralogical information across the basin, boreholes were selected along aproximate East-West and North-West - South-East cross sections (Fig.2 insert). Preference was given to boreholes with well preserved cuttings and cores, i.e. exploration boreholes. Twelve boreholes have been sampled for cuttings at 100 m intervals. Core material has been used for the Jurassic-Early Cretaceous Springhill Formation, which is the main oil and gas producer of the basin, as well as for most samples obtained from the Vania borehole, which has been cored over most of its depth. The whole rock mineralogy has been determined by X-ray diffraction (XRD) for all samples using a Rigaku Rad II diffractometer fitted with a horizontal wide angle goniometer using Ni-filtered Cu-radiation at a 40KV, 20mA setting. Oriented clay mounts (>0.45µm and >1<2 µm fractions) have been prepared using ultrasonic disaggregation, centrifugation and membrane filtration at 200 to 500 m intervals. Existing information on vitrinite reflectances has been incorporated (ENAP, internal reports); data for the Estero Wilson borehole have been measured for this study. Thin sections have been prepared mainly from the Springhill Formation. Details of its mineralogy, diagenesis and formation water composition form part of a complementary publication.

Results

The whole rock mineralogy is dominated by variable proportions of quartz, feldspar (albite), high Fe-type chlorite, a 10 Å phyllosilicate (generally illite-muscovite, partly glauconite) and smectite. Minor phases are zeolites, amphiboles, calcite, pyrite and hematite.

Quartz is the dominant mineral in almost all samples. The contents of a 10 Å phyllosilicate is low throughout the basin. Albite is present regularily and in all boreholes, in all formations. A notable decrease of this mineral is seen in the Cretaceous strata of the Dungeness Norte 1A and Erizo XE2 boreholes. Both are located on the most elevated sector of the platform.

The Late Cretaceous and Tertiary strata contain diagenetic zeolites such as heulandite, mordenite, analcime, clinoptilolite, stilbite and stellerite. Boreholes with the most regular presence of these diagenetic zeolites are located on the platform area. Boreholes situated close to the thrust and fold belt (e.g. Chilenita 2, Estero Wilson 1A and Evans 1) are almost devoid of them. On the other hand laumontite is abundant in these three boreholes below an average depth of 1500 m (Fig.3). The mineral is found sporadically in the boreholes Dungeness Norte 1A, Erizo XE2, Puerto Nuevo 1 and Vania 1.

Although the sampling intervals of 200–500 m are comparatively coarse, the following observations are possible: The dominant authigenic mineral is illite/smectite, a minor presence of low charge corrensite is found in the Springhill Formation. Traces of discrete chlorite (high Fe-type) are present throughout the basin, together with quartz and feldspar. The presence of this mineral is more pronounced in the >1<2 µm fraction than in the >0.45<1µm fraction, indicating a clastic origin. Sometimes the quartz content of the >0.45<1µm fraction is surprisingly high when compared to other basins (e.g. Kelm et al. 1994). This may be due to the disintegration of quartz overgrowths during the ultrasonic disaggregation proceedure. Kaolinite appears to be bound to sandier lithologies, e.g. the Springhill sandstone. A reduction of the percentage of expandable (smectite) layers in illite/smectite from approximately 70% to 40% occurs between 1500 and 2500 m throughout the basin. This decrease is accompanied by the appearance of laumonite in the Chilenita 2, Estero Wilson 1A and Evans 1 boreholes. Lowest expandability of <10% is found at the bottom of the deepest Manzano 7 borehole in the Agua Fresca Formation. Boreholes terminating in the Springhill sandstone at >3000 m depth (Clarencia 1A, Dorado Sur 1A, Evans 1, Estero Wilson 1A, Gregorio 1, Puerto Nuevo 1, Vania 1) display illite percenages of 70% together with kaolinite and low charge corrensite. In shallow boreholes (<2200 m) from the northeastern sector of the platform (Erizo XE2, Dungeness Norte 1A, Picton 1) expandability does not decrease below 70%.

Thin sections from the Springhill sandstone indicate advanced lithological maturity by concave grain contacts, pressure solution and fracturing.

Vitrinite reflectances Ro:

Scattered vitrinite reflectance data are available for Chilenita 2 , Clarencia 1A, Evans 1, Gregorio 1, Puerto Nuevo 1 and Manzano 7 boreholes. Reflectance measurements of 0.70% Ro from Early Cretaceous sediments of the Centenario borehole are included in order to demonstrate changes of organic maturity for the platform area. Data are from four sources, only the Chilenita 2 borehole has a complete depth profile of vitrinite reflectances by a sole laboratory. Vitrinite reflectances vary between 0.32% and 0.45% for the Loreto Formation. Data are from the western basin margin, where coals are close to surface level (Peckett and Elena Mines, CORFO, 1981). Boreholes located on the platform area show an increase of Ro from 0.70% to 2.04% for the Springhill Formation and overlying “Estratos con Fravrella” with increasing proximity to the platform edge on the West. The borehole Vania 1 displays an exceptionally high Ro of 3.39% at 1000 m. This is most likely to be an effect of contact metamorphism. A dioritic intrusion is logged between 1075 m and 1140 m depth.

Discussion

Discussion will follow the order of the presentation of results under the preceeding point. As the study is based on two widely spaced cross sections it is difficult to correlate whole rock mineralogy with respect to the stratigraphic position of the sample, in particular as a correlation of stratigraphy througout the basin is still under discussion (Biddle et al. 1986). At the present stage, sampling intervals and the distance between the boreholes are too large in order to make an attempt of mineralogical correlation among them.

The occurrence of albite is linked for the Cretaceous and Tertiary strata to the presence of chlorite and zeolites, thus manifesting a volcanoclastic influence in the sediment. In the boreholes Dorado Sur 1A, Dungeness Norte 1, Erizo 1A, Manzano 7, Picton 1 and Vania 1, albite may be as abundant as quartz up to a maximum depth of 800 m. This may correspond to products of the volcanoclastic Palomares Formation and a volcanic/subvolcanic event manifested by a dioritic dike in the Vania borehole in the Loreto Formation in the northern Magellan Basin. For the boreholes Dorado Sur 1A, Dungeness Norte 1A, Erizo XE2 and Manzano 7 the increased content of albite is accompanied by the presence of analcime, mordenite, heulandite, stellerite and clinoptilolite in the Tertiary strata ('Grupo Bahía Inútil, Brush Lake, Filaret and Palomares Formations). Which of these diagenetic level zeolites is present depends on the respective activities of Na, K and Ca (Gotthardi & Galli 1985), thus indicating a closed system on the 100 m interval scale of sampling.

The first zeolite not to form at surface conditions (Tschernich 1992) or very low grade metamorphic zeolite (Liou et al. 1987), laumontite, is regularily found in the Cretaceous and Early Tertiary strata of the Chilenita 2, Evans 1A and Estero Wilson 1A boreholes (Fig. 3), however they are devoid of diagenetic zeolites in the Late Tertiary. Above boreholes are located closest to the fold and thrust belt (Fig.2 insert) which delimits the basin against the Andes to the West and South. Laumonite has been described microscopically as a porefilling and grain replacement by Smith (1977) in the Tres Brazos Formation of the Ultima Esperanza area (West of Puerto Natales, apoximately 250 km North West of Punta Arenas). The formation of laumonite is favoured by a high Ca activity which could be caused by the alteration of plagioclase. The absence of diagenetic zeolites in the area closest to the rising Andes, which are considered to be the prime source of sediment during the Tertiary, in particular of volcanoclastic material (Winn & Dott 1976; Michael 1983), may be due to a lack of conservation of volcanic ash by intense transport and "dilution" with quartz rich sediment. In addition a good drainage system in the eastern foreland of the Andes should have prevented the formation of high salinity waters (aquifers), which favour the formation of zeolites instead of smectites from volcanic material (Tschernich 1992). More stagnant hydrological conditions are to be expected for the northeastern sector of the platform area with a low relief and slope and less accumulation of sediment.

The low contents of a clastic 10 Å phase (illite-muscovite) reflects the lack of this material in the source areas of sediment, e.g. they are devoid of micaceous schists.

Kaolinite is occasionally present in the continental Tertiary strata and concentrated in the coarse size fraction. It is considered to be a weathering product. The presence of Notofagus (S. Palma, personal communication) indicates a humid, temperate climate, favourable for the formation of kaolinite.

The use of clay minerals as indicators of thermal maturity has first been developed in the Cretaceous and Tertiary shales Gulf Coast area (Perry & Hower 1970; Hower et al. 1976), with the transition of illite/smectite being the most widely used relative indicator. Primary factors controlling the reaction are temperature and the availability of potassium. There is an ongoing discussion as to the exact crystallographic nature of the diminution of the number of smectite layers and the final development of illite, the mayor points of view have been summarized by Pollastro (1990). In the Magellan Basin almost all illite/smectite is randomly ordered. Only for the Vania 1, Estero Wilson 1A and Clarencia 1A boreholes R1 ordered material has been found. Due to the scarcity of ordering is not attempted to delimit a 100°C–110°C isograd as proposed by Hoffman & Hower (1979) for the formation of R1 ordered material and considered as inorganic indicator for the onset of hydrocarbon generation (Pollastro 1990). The transition from a randomly ordered highly expandable to a R1 ordered illite/smectite has been found to occur over a short depth and temperature range (Pollastro 1990), the cause for this has not yet been fully explained. In the present case sampling intervals of 200–500 m are too wide in order to determine if this rapid conversion also applies to the Magellan Basin. With a data at hand a gradual transition over 500 m depth span is likely, closer sampling would probably reveal a zigzag pattern, similar to the description from the Santa Monica Basin, California (Pollastro 1990, Fig.20), with jumps of up the 20% expandability between adjacent samples. Illite/smectite data do not reflect the sedimentary unconformity across the Cretaceous/Tertiary limit for the platform area. For the shallowest boreholes (Erizo XE2, Picton 1 and Dungeness Norte 1A) expandabilities are no lower the 70% in the Springhill Formation, whereas ethylene glycol non-expandable illite is found at the bottom of the Manzano 7 borehole which only penetrates into Eocene shales. This indicates that the mineralogical maturity is due to the Tertiary overburden throughout the basin. For the Spinghill Formation low charge corrensite accompanies smectite percentages of 30%. Chang et al. (1986) associate the occurrence of corrensite to depths slightly below the onset of illite/smectite ordering. However in the present case,

Table 1: Vitrinite reflectances (depth [m]/Ro [%]/number of measurements). Letters indicate different laboratories.

Chilenita 2	Clarencia 1A	Estero Wilson 1	Evans 1	Gregorio 1	Manzano 7	Puerto Nuevo 1	Vania 1
200/0.34%/54	2300/0.82%/22	4061/0.97%/52	3200/1.10%/28	2050/0.42%/21	752/0.45%/21	1800/0.87%/15	2000/0.50%/22
400/0.32%/52	2400/0.79%/28	(D)	3300/1.13%/31	2200/0.41%/18	1103/0.44%/54	1900/0.88%/13	2200/0.50%/28
600/0.34%/46	2600/0.97%/18		3450/1.28%/38	2300/0.58%/24	(C)	2050/0.88%/19	2350/0.53%/23
800/0.33%/50	2800/1.14%/24		3750/1.38%/34	2400/0.80%/14		2400/0.81%/22	2750/0.97%/8
1000/0.34%/52	2950/1.45%/27		3900/1.40%/24	2850/0.73%/24		2852/0.84%/21	2900/1.00%/13
1200/0.34%/54	3200/1.99%/30		(B)	2900/0.88%/12		2800/0.71%/17	3051/1.09%/11
1531/0.37%/49	3300/2.04%/38			3000/1.13%/11		2950/1.07%/29	3200/1.01%8
1600/0.39%/51	(A)			3250/1.31%/29		3100/1.20%/11	(B)
1750/0.41%/48				3400/1.48%/20		(B)	
2000/0.50%/45				(B)			
2200/0.46%/23							
2400/0.46%/43							
2650/0.51%/49							
2800/0.56%/46							
3000/0.57%/23							
3200/0.57%/23							
3246/0.58%/34							
3300/0.60%/20							
3446/0.46%/11							
(A)							

corrensite is associated with sandstones, where it is reported to form at higher temperatures (Hoffman & Hower 1986) due to an external control of the pore fluid composition compared to a more closed hydrological system in shales.

Vitrinite reflectances give a cumulative record of the temperature history and thermal maturity. The scarcity of vitrinite reflectance data in this basin is not only due to a limited choice of samples for exploration purposes, but also due to the lack of conservation by reworking and oxidation (e.g. Enap internal reports on "Manzano 7", "Clarenica 1A", "Dorado Sur 1A"). The problem is particularily manifested for the continental Tertiary sequences. The increase of maturity for the Springhill Formation from values of 0.70% Ro (Centenario borehole) to 2.04% in the Clarencia 1A borehole, accompanies the westward tilt and deepening of the platform close to its Northwest striking limit (Fig.3), A "jump" of approximately delta 0.20% is evident across the Cretaceous/Tertiary limit for the Clarencia 1A, Gregorio 1, Puerto Nuevo 1 and Vania 1 boreholes, all of them are located at the western limit of the platform, where a sedimentary discordance exists between the two periods. This gap is not seen for the Chilenita 2 borehole (Fig.3) on the western basin margin.

For inorganic and organic maturity indicators a concordant increase in thermal maturity is seen in the Tertiary strata. In case of the illite/smectite transition, maturity would be entirely controlled by the Tertiary overburden. This is demonstrated by the deepest borehole Manzano 7 where only <10% expandable layers are left in Eocene shales at 5000 m depth. The strong increase in vitrinite reflectance for the Springhill Formation observed when approaching the western limit of the platform is concomittant with the deepening of the Springhill Formation. Additionally the possibility of a "head start" for Ro in the western part cannot be ruled out. Vitrinite may have received an early diagenetic maturity push, when the area was still under the influence of a fading Jurassic volcanism. Such environment would imply an elevated heatflow for the directly overlying Springhill Formation until the thermal adjustment of the area to a passive back arc basin was complete. Biddle et al. (1986) demonstrate for the Manzano 7 and Evans 1 boreholes a change in the curvature of the subsidence curves at the end of the mid Cretaceous. This could have implied an adjustment of the heatflow environment from a control by back arc volcanism with the presence of oceanic crust (Roca Verde Basin) to a control by sedimentary overburden.

Conclusions

Analysis of the mineralogy of the whole rock and clay size fractions for the Magellan Basin show a dominance of quartz, albite, high Fe-chlorite with a minor presence of illite/muscovite. Diagenetic zeolites are limited to Tertiary strata of the northeastern platform area where conditions for their formation appear to have been more favourable than in the Andean foreland to the West. Laumonite is concentrated in boreholes of the foreland area, where the availability of plagioclase and sufficient overburden permited its formation. The illite/smectite transition is controlled by the accumulation of Tertiary sediment leading to the formation of almost non expandable illite in the deepest (5000 m) borehole. For the vitrinite reflectances an increasing Ro in the Springhill Formation from the centre of the platform towards its western margin is attributed to the deepening of burial, but an influence of elevated heatflow from the terminating Jurassic volcanism is considered possible. A reflectance gap is observed across the Cretaceous-Tertiary border for boreholes located on the platform, reflecting a discordance found in the sediments in the eastern parts of the basin.

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