Mesozoic sedimentation on an isolated platform at the eastern entrance to the Strait of Magellan, Tierra del Fuego (Chile)

Jesús A. Sánchez

Departamento de Geología, Facultad de Ciencias Físicas y Matemáticas
Universidad de Chile, Casilla 13518, Correo 21, Santiago, Chile
Present address: Sipetrol, Casilla 123, Las Condes CP6760197, Santiago, Chile
jsanchez@sipetrol.cl

Jacobus P. Le Roux

Departamento de Geología, Facultad de Ciencias Físicas y Matemáticas
Universidad de Chile, Casilla 13518, Correo 21, Santiago, Chile
jroux@cec.uchile.cl

ABSTRACT

The Magellan Block, located on the modern Atlantic continental platform opposite the Strait of Magellan (Chile), consists of two parallel, northwest trending horsts partly separated by a central graben. Petroleum has been recovered from the Springhill Formation, deposited on this isolated platform during the Valanginian-Barremanian, since 1994. This formation represents an overall transgressive succession with three subcycles of transgression and regression (parasequences) separated by marine flooding surfaces. The two basal parasequences are related either to minor sea level fluctuations or to fault activity, whereas the uppermost cycle reflects a major transgression affecting the whole Magellan Basin. Depositional facies associations include supratidal, intertidal, barrier beach and shoreface environments, generally showing a clear correlation with the paleotopography of the horst blocks. While barrier beaches formed along the topographically higher areas, inter- and supratidal flats and shoreface sediments were deposited on their land- and seaward sides, respectively. Tidal flats also bordered the shallow embayment formed by the central graben. Continued transgression subsequently drowned the island to form a wide, open platform on which the Estratos con Fravella Formation was deposited.

Key words: Supratidal, Intertidal, Barrier beach, Shoreface, Parasequence.

RESUMEN

Sedimentación mesozoica sobre una plataforma aislada en la entrada oriental del estrecho de Magallanes, Tierra del Fuego (Chile). El Bloque Área Magallanes está situado en el océano Atlántico, dentro de la actual plataforma continental Argentina. Se ubica en la desembocadura oriental del estrecho de Magallanes y consiste de dos cordones de altos estructurales, de orientación noroeste, que constituyen un horst, parcialmente separado por un graben central. En esta estructura se han encontrado y producido hidrocarburos desde el año 1994 desde la Formación Springhill, la cual se depositó durante el Valanginiano-Barremiano. Esta formación representa una transgresión marina regional con tres subciclos de transgresión-regresión (parasecuencias) separados por superficies de inundación marina. Las dos parasecuencias basales están relacionadas con variaciones menores del nivel del mar o por actividad de fallas, mientras que el subciclo superior refleja una gran transgresión, que se extiende en casi toda la cuenca Austral. Las asociaciones de facies depositacionales identificadas incluyen supramareales, intermareales, playa barrera y ambientes de frente de playa, las cuales guardan una relación clara con la paleotopografía del bloque. De esta manera, las playas-barrera se depositaron en torno a áreas topográficamente elevadas, mientras que las facies supramareales e intermareales fueron depositadas hacia las zonas más elevadas, detrás de las playas-barrera. Las facies de frente de playa fueron depositadas hacia la zona baja de estas áreas elevadas. Las planicies intermareales también se depositaron

Revista Geológica de Chile, Vol. 30, No. 2, p. 143-157, 7 Figs., 1 table, December 2003.

en embahiamientos internos dentro del graben central. Finalmente, al progresar la transgresión marina, el sistema depositacional evolucionó hacia una plataforma marina extensa y abierta donde se depositaron las arcillolitas de la Formación Estratos con Favrella.

Key words: Supramareales, Intermareales, Playa barrera, Ambientes de frente de playa, Parasecuencia.

INTRODUCTION

The Springhill Formation constitutes an important hydrocarbon reservoir within the Magellan Basin, from which at least 70 million m^3 of petroleum had been recovered until 1998 (Harambour, 1998). This study focuses on the sedimentology of an isolated section of the Springhill Formation occurring on a segmented horst platform, henceforth referred to as the Magellan Block, 10 km east of the Strait of Magellan. The reservoir, which varies in depth between 1,500 and 1,600 m below sea level, was discovered in 1982 and by the end of 2001 had produced about 4.2 million m^3 of petroleum and 2,800 million m^3 of gas. It is presently being exploited by 85 wells from 5 production platforms.

The objectives of the present investigation were:
- to identify the depositional environments from borehole core logs
- to define electrofacies models from the borehole facies interpretation
- to reconstruct the paleogeography from borehole, electrofacies and seismic data
- to determine the effects of relative sea level changes on the sedimentation patterns

The information and insights gathered from such a study can provide an important tool for the further exploration and exploitation of petroleum, not only in immediately adjacent areas, but also further afield within similar depositional environments.

TECTONIC FRAMEWORK

The Magellan Basin occupies a triangular area of more than 160,000 km^2 south of the triple junction between the Nazca, South American and Antarctic Plates. It has a sedimentary fill reaching a thickness of about 8,000 m along the basin axis and thinning progressively towards the north and east (Pittion and Arbe, 1999), where it is flanked by the Dúngenes-Río Chico Arch (Figs. 1, 2). In the west, the basin terminates against the Patagonian Batholith and the Magellan Fold-Thrust Belt. The southern border is formed by a complex zone of crustal shortening and strike-slip faults generated along the margin of the South American and Scotia Plates (Biddle *et al.*, 1986).

Towards the southeast, the Magellan Basin links up with the Malvinas Basin, which according to Harambour (1998) formed as an extensional rift during the Triassic and Early Jurassic (Fig. 2) when Gondwana began to break apart. Extension in the Rocas Verdes Basin, which existed at this time to the west of the Malvinas Basin (Fig. 2), reached a maximum during the Late Jurassic-Early Cretaceous, coinciding with the generation of oceanic crust (Bruhn *et al.*, 1978; Uliana *et al.*, 1986). During the Late Cretaceous, a thermal sag phase invaded this basin (Fig. 2), which was partially filled with volcaniclastic rocks derived from the west (Biddle *et al.*, 1986; Galeazzi, 1998). At the same time, a passive platform margin developed east of the Rocas Verdes Basin (Harambour and Soffia, 1988). From the Albian until the Tertiary, the westernmost part of the Jurassic rift systems were compressed, causing the closure of the Rocas Verdes Basin and allowing the formation of a folded and thrusted foreland belt (Wilson, 1991). This basin closure implies westward subduction of the ancient oceanic crust (Harambour and Soffia, 1988), part of which was obducted and is presently encountered in the Magellan Fold-Thrust Belt. The resultant tectonic loading caused crustal flexure that controlled the subsequent development of the Magellan Basin (Biddle *et al.*, 1986; Alvarez-Marrón *et al.*, 1993). The latter developed as a foreland basin with a peripheral foreland

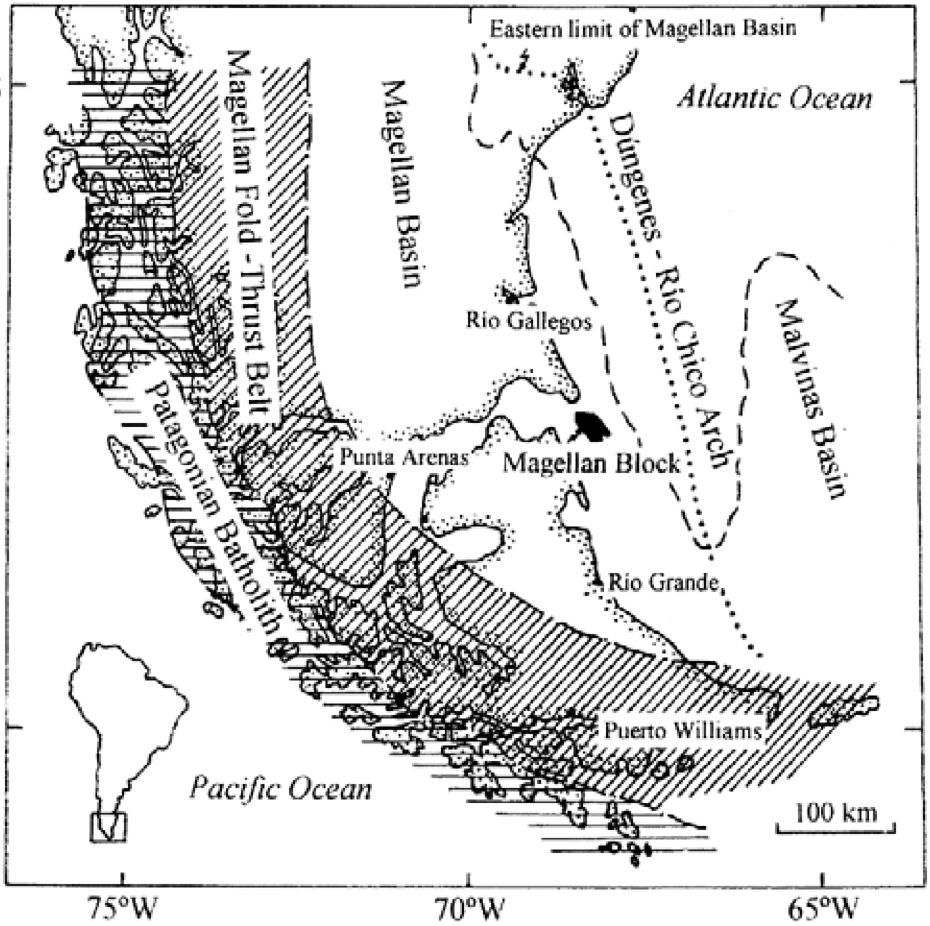

FIG. 1. Locality map showing structural setting of the Magellan Block. The Rocas Verdes Basin is not shown as it is presently occupied by the Magellan Basin.

bulge basin at its easternmost limit (Fig. 2), which was subsequently filled with molasse (Harambour, 1998).

The main structural feature of the Magellan Basin is the presence of normal faults formed during the Triassic/Late Jurassic rifting, some of which were active until the Tertiary (Biddle *et al.*, 1986). These faults have a preferential strike between NW and NNW, with a secondary orientation between NNE and NE (Bravo and Herrero, 1997). Horsts, grabens and semi-grabens are especially well developed on the Springhill Platform, where the study area is characterised by two NW-trending horsts partially separated by a graben. Figure 3 shows the paleotopography of the top of the Springhill Formation (Harambour, 1998), indicating the location of structural highs and depressions in the horst-graben system.

GENERAL STRATIGRAPHY OF THE SPRINGHILL PLATFORM

The stratigraphy of the Springhill Platform includes volcanic, volcaniclastic and sedimentary rocks deposited unconformably on Paleozoic basement rocks and ranging in age from the Jurassic to the Quaternary. Table 1 shows a generalised stratigraphic column as modified from Robbiano (1989).

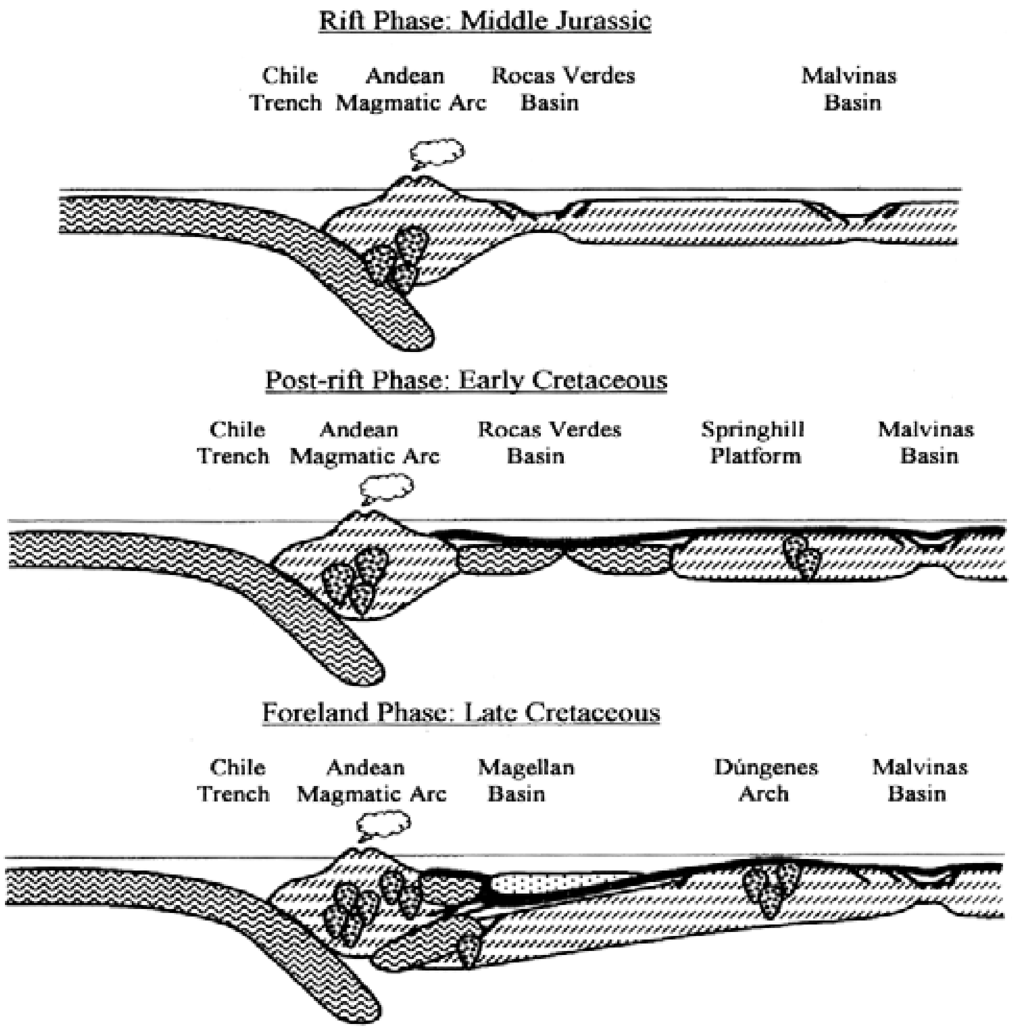

FIG. 2. Geotectonic evolution of the Magellan Basin (modified from Galeazzi, 1998 and Harambour, 1998).

TABLE 1. STRATIGRAPHY OF THE SPRINGHILL PLATFORM (MODIFIED FROM ROBBIANO, 1989)

Formation	Dominant lithology	Thickness	Age
	Conglomerate	75 m	Pliocene
Patagonia	Sandstone	350 m	Miocene
Rio Leona	Sandstone	200 m	Oligocene
Campo Bola	Sandstone	200 m	Eocene-Paleocene
Cabeza de León-Upper Inoceramus	Siltstone	240 m	Coniacian-Maastrichtian
Arollo Alfa-Middle Inoceramus	Siltstone	180 m	Cenomanian-Coniacian
Nueva Argentina-Margas Verdes	Limestone	200 m	Aptian-Cenomanian
Pampa Rincón-Lower Inoceramus	Siltstone	160 m	Hauterivian-Aptian
Springhill	Sandstone	220 m	Valanginian-Barremian
Tobifera	Tuff	160 m	Middle-Late Jurassic
Basement	Metamorphic	-	Paleozoic

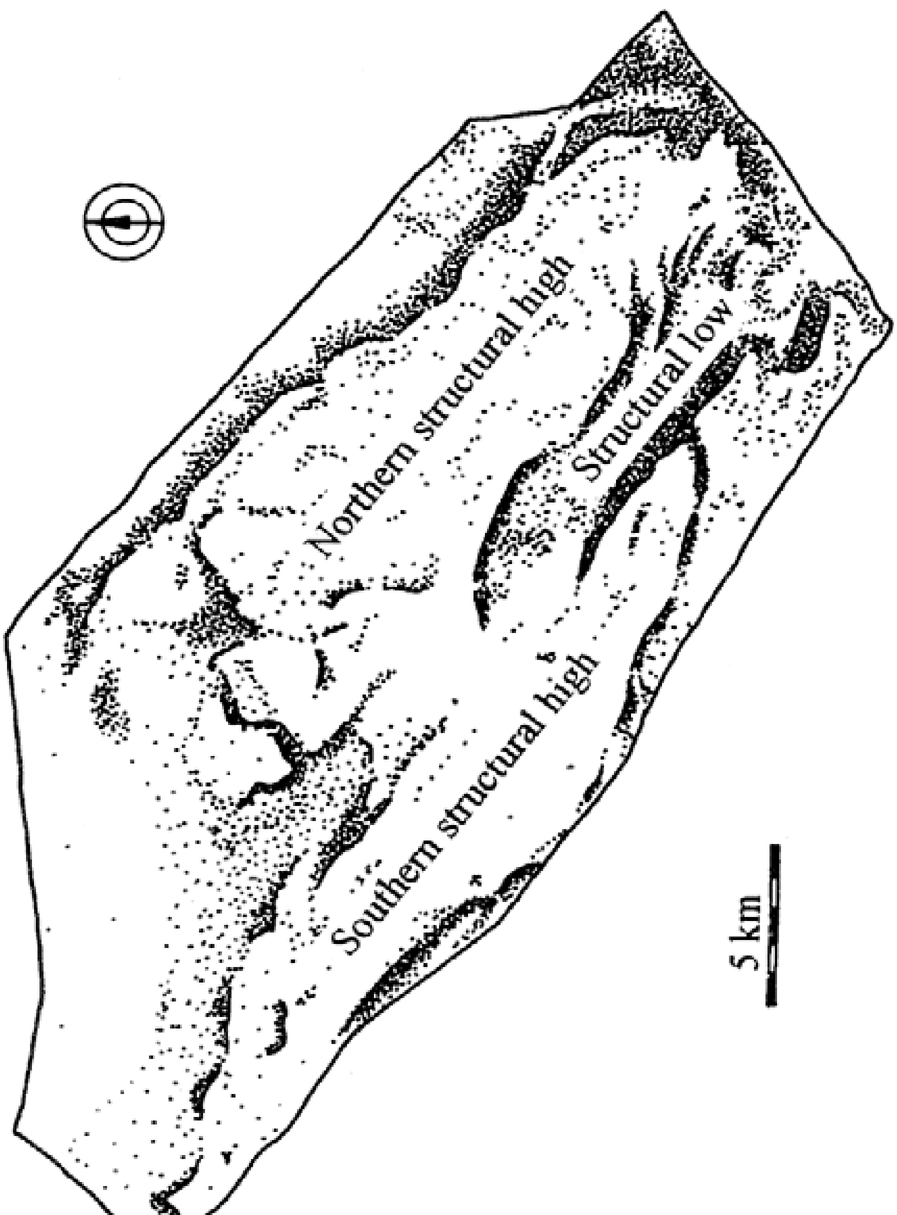

FIG. 3. Three-dimensional view of the Magellan Block, showing paleotopography of the top of the Springhill Formation (after Harambour, 1998).

DEPOSITIONAL ENVIRONMENTS

GENERAL

The paleotopography as established by structural contours of the base and top of the Springhill Formation depicts the Magellan Block as a shallow marine platform separated from other platforms by relatively deep straits (S. Elgueta, 1996[1]). At times the platform emerged to form an island over which transgressive sands were deposited during minor sea level rises. The quartz grains, volcanic fragments and ash particles of the Springhill Formation were derived from the underlying Tobífera Formation (S. Elgueta, 1996[1]), which is composed primarily of ash and lapilli tuff with a rhyolitic composition. Dominant colours range from yellowish brown to reddish brown, indicating an oxidising environment. The contact between the Tobífera and Springhill Formation represents an erosional unconformity.

LITHOFACIES DESCRIPTION AND INTERPRETATION

Facies analysis for this study is based on 11 boreholes, from which core was recovered at depths varying between 1,523 and 1,613 m below sea level. Several sedimentary facies corresponding to different depositional sub-environments were recognised (Fig. 4), which can be grouped into four facies associations.

Facies association A: supratidal environment (supratidal marsh, channel-fill, abandoned channel and mouth bar deposits). Four sub-facies can be recognised within this association. Sub-facies A1 is normally restricted to the structural highs where it may directly overlie the Tobífera Formation. The deposits are composed of carbonaceous mudstones, siltstones and wackes with discrete intercalations of very fine, immature arenites. These are arranged in coarsening-up successions between 3 and 6 m thick, showing a gradual upward increase in the percentage of arenites and a simultaneous decrease in carbonaceous material. The dominant sedimentary structures are horizontal (pinstripe) lamination interrupted by load casts, bioturbation and vertical plant roots up to 20 cm in length (S. Elgueta, 1994[2]). Colours range from light green (wackes) to dark grey (carbonaceous mudstones) and light brown (arenites). Disseminated and nodular pyrites indicate a generally reducing environment. A supratidal marsh environment is envisaged for these deposits, with coarsening-up cycles attributed to the progressive filling of shallow water bodies by their encroaching shoreline deposits, followed by compaction, subsidence and cycle repetition.

Sub-facies A2 shows a very irregular distribution throughout the study area. It is characterised by fine- to medium-grained, poorly sorted, quartzose to sublithic arenites with abundant volcanic ash. These deposits occur in cycles varying in thickness between 2 and 3 m, commonly overlying erosional basal contacts and displaying weak fining-upward trends. They are interpreted as channel-fill deposits. Carbonaceous laminae, carbonised plant fragments and siltstone intercalations become more common towards the tops of the individual cycles, probably reflecting incipient channel abandonment (Reading, 1986).

Related to sub-facies A2 and closely associated with it, are greenish grey siltstones and mudstones displaying diffuse, parallel lamination locally disturbed by slumping (sub-facies A3). Plant fragments and carbonised roots, as well as lenses of coarse sandstone up to 10 cm thick, occur within the mudrocks, with mud pellets locally forming a basal lag. The thickness of individual units ranges from 2 to 9 m and both their basal and upper contacts are erosional. These sediments evidently represent low-energy environments following a period of active erosion. They are therefore considered to be abandoned channel deposits.

Sub-facies A4 is formed by quartzose, medium- to coarse-grained, grey to greyish brown sandstones with abundant carbonaceous material. The sandstones are immature with moderate sorting, forming normally graded lithosomes 10 to 50 cm thick, in coarsening-upward successions ranging between 3 and 5 m. Massive sandstone generally

---

[1] 1996. Análisis secuencial de facies de la Formación Springhill en el pozo AMXE-5, Area Magallanes, Argentina (Inédito). *Sipetrol S.A.*, 20 p.

[2] 1994. Informe preliminar sobre ambientes de sedimentación de la Formación Springhill en el Área de la Anomalía Magallanes (Inédito). *Sipetrol S.A.*, 10 p.

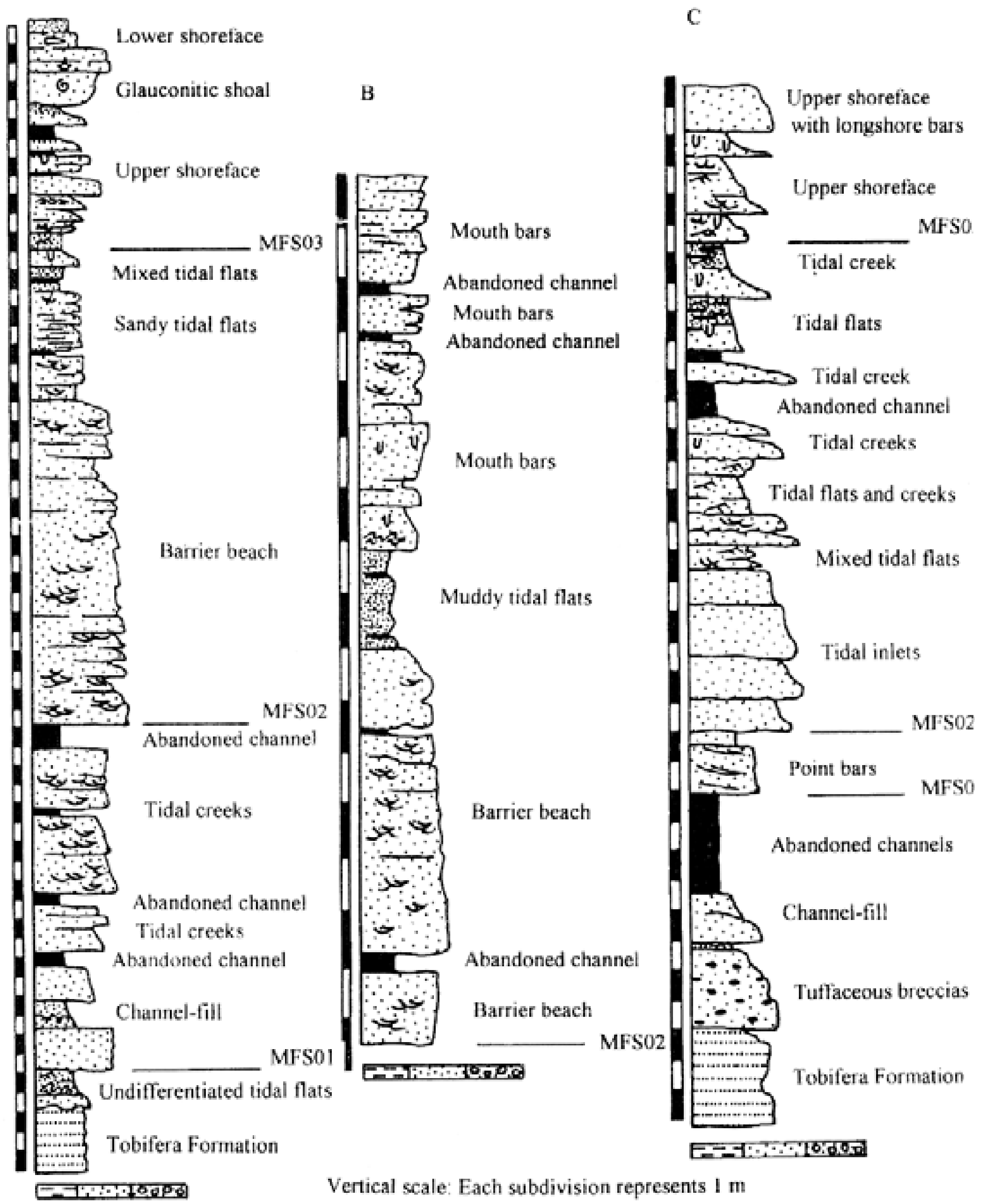

FIG. 4. Vertical columns based on borehole core logs, showing the different facies associations and flooding surfaces MFS01, MFS02 and MFS03. Traditional symbols are used to indicate sedimentary structures. Borehole positions (A, B and C) are indicated in figure 6.

overlies an irregular, erosive base, grading upward into current ripple cross-laminated sandstone with plant material concentrated along the foresets. Locally, coal seams up to 10 cm thick, normally associated with pyrite and siderite nodules, may be present. The origin of these cycles is attributed to small creeks descending from the surrounding structural highs and depositing their sediment load in a progradational manner as mouth bars (Reading, 1986). Progressive lowering in the energy level locally led to channel abandonment, as evidenced by the presence of coal seams.

Facies association B: intertidal environment (muddy and sandy tidal flat, tidal creek and tidal inlet deposits). This association is also represented by four sub-environments. Sub-facies B1 is characterised by rhythmic intercalations of fine to very fine, quartzose sandstones and varicoloured (predominantly greenish to greyish) mudrocks. Stratification varies between 0.5 and 2 cm in thickness, with carbonaceous material concentrated along the contacts. Sedimentary structures include parallel lamination, ripple cross-lamination and undulose stratification partially destroyed by bioturbation. Soft sediment folds and small pyrite nodules are also present. The thickness of sub-facies B1, which is considered to represent muddy tidal flats, varies between 1 and 5 meters. Channel-fill, abandoned channel and mouth bar deposits, as described above, also occur within this facies.

Sub-facies B2 forms fining-upward successions varying between 2 and 5 m in thickness, which consist of fine to medium sandstones showing parallel lamination and ripple cross-lamination. Greenish grey mudrocks become increasingly common towards the tops of the cycles. Pyrite and siderite nodules (less than 1 mm in diameter) are generally concentrated along specific horizons. Deposition probably took place on sandy tidal flats. Channel-fill deposits, including point bar sandstones with epsilon cross-lamination, as well as tidal inlet deposits are associated with this facies.

Sub-facies B3, interpreted as mixed tidal flat deposits, combines the characteristics of muddy and sandy tidal flat facies and is typically associated with channel-fill and abandoned channel deposits. Also associated with this sub-facies are quartzose, fine-grained sandstones with erosional basal contacts, intercalated with laminated, carbonaceous mudrocks. Parallel lamination and small-scale cross-lamination characterise the finest beds, which vary in thickness between 10 and 20 cm. Plant remains also form discrete laminae up to 1 cm thick, which are locally destroyed by bioturbation (*Arenicolites*). This is similar to heterolithic cross-lamination, indicating deposition from suspension during the slack-water period between tides. These deposits probably formed in tidal creeks.

Medium to very coarse-grained, quartzose sandstones occurring in lenticular units 1 - 3 m thick, compose sub-facies B4. The typically fining-upward cycles grade from 30 to 40 cm thick conglomerates filling erosional scours at the base, to sandstones showing medium-scale cross-stratification with foresets dipping at 5-10°. These deposits are interpreted as tidal inlets. Intraformational clasts of greenish siltstone and mudstone tend to concentrate at the tops of cycles and were probably derived from the adjacent tidal flats (Weimer *et al.*, 1982; Reineck and Singh, 1980).

Facies association C: barrier bar/barrier island environment (barrier beach deposits). These deposits consist of texturally mature, coarse to very coarse, well-sorted quartzose sandstones occurring in aggradational bodies 6 - 15 m thick. Sedimentary structures include swash cross-lamination and medium-scale, low to very low angle planar cross-lamination. Beds vary in thickness between 4 and 10 cm and may show well-developed coarsening-up trends. Reactivation surfaces are overlain by thin laminae with heavy mineral concentrations. This facies occurs in all the lower-lying areas of the platform and constitutes the main petroleum reservoir in the Springhill Formation of the Magellan Block. It is considered to represent barrier beach deposits.

Facies association D: shoreface environment (upper and lower shoreface deposits with sandy shoals). This facies association can be divided into two sub-environments. Sub-facies D1 is represented by fine to coarse sandstones intercalated with organic-rich siltstones. Set thicknesses range between 2 and 7 m, with beds varying between 5 and 60 cm in the case of coarse or medium sandstone, to 0.5-3 cm for fine sandstones and 0.2-1 cm for siltstone. Sedimentary structures are dominated by parallel and lenticular lamination that may be bioturbated in places (*Arenicolites*). The coarser sandstones are generally not bioturbated (suggesting higher energy conditions) and show medium-scale planar and possibly trough cross-stratification. An upper shoreface environment is envisaged.

Sub-facies D2 is composed of medium- to coarse-grained glauconitic arenites and wackes with bioclasts of belemnites, gastropods and bivalves (S. Elgueta, 1996[2]). In general, the deposits have a massive appearance, which may be due to bioturbation. *Skolithos oblicuos*, for example, tends to be concentrated in zones less than 1 m thick. The glauconite occurs as oval pellets, together with chlorite and rhyolitic fragments giving the sandstones a deep green colour. The sandstone lithosomes have thicknesses varying between 2 and 5 m and their contacts with overlying dark grey, glauconitic siltstones are normally sharp. They are interpreted as sandy shoals within the lower shoreface deposits represented by the siltstones.

ELECTROFACIES DESCRIPTION AND INTERPRETATION

Gamma rays emitted by radioactive elements (K, Th or U) in the deposits are measured in API (American Petroleum Institute) units, as related to standards in Houston, Texas. Shale generally contains more radioactive elements and therefore shows a higher gamma radiation than clean sandstones. Gamma logs are therefore useful to distinguish between these rocks and are also helpful in the identification of fining- or coarsening-upward cycles.

Sonic logs measure the time required for the rocks to propagate compressional sound waves, usually measured in ft/s but expressed as the reciprocal value ms/ft (D_t). As porosity determines the sonic velocity to a large extent, dense rocks such as dolomite have low D_t values, compared to the higher values of porous rocks such as clean sandstone.

By studying the geophysical characteristics of the various lithofacies identified in the borehole core logs, electrofacies models can be established (Rider, 1996) to help recognise these facies in percussion boreholes. The shape of the curves can also assist in determining the depositional environment. For example, boxcar-, funnel- and bell-shaped patterns of gamma logs can be correlated with beach sands, prograding barrier islands and intertidal point bars, respectively (Fig. 5). Several electrofacies associations were thus determined in the Springhill Formation.

Facies association A: supratidal environment. These facies are characterised by an irregular gamma ray pattern with intermediate values (50-100 API). Abandoned channels and channel-fill deposits show fining-upward trends as indicated by an upward increase in the API values. The sonic logs display high values varying between 110 ms/ft for immature sandstones and 50 ms/ft for carbonaceous mudstones. Contacts with other facies associations are gradual, especially in the case of intertidal deposits.

Facies association B: intertidal environment. Muddy tidal flats typically generate a very irregular gamma ray pattern without clear trends (Fig. 5). Values fluctuate between 100 and 150 API. The sonic logs have flat profiles around 100 ms/ft. Immature tidal creek sandstones cause a distinct drop in radioactivity to around 50 API, whereas the sonic log also shows a decrease in propagation time to

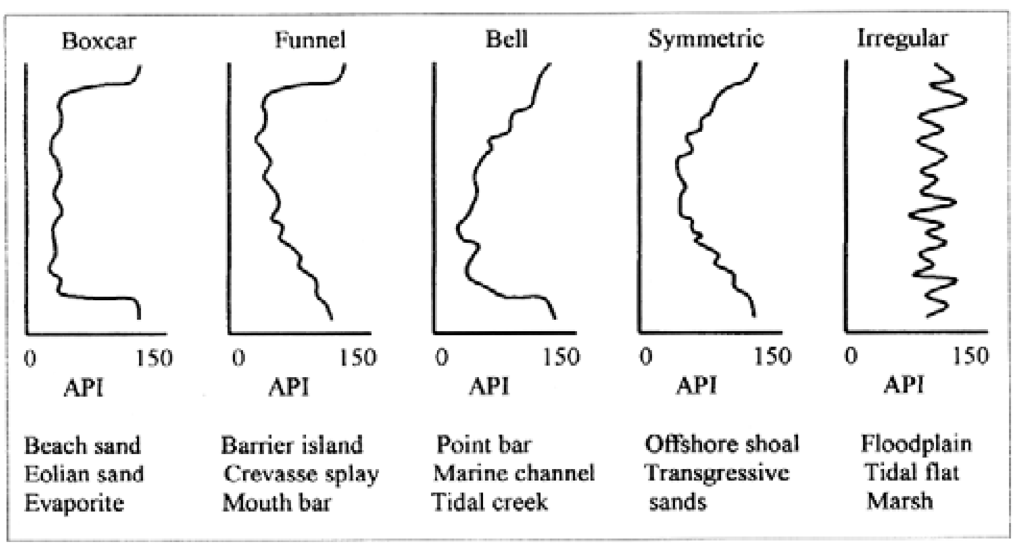

FIG. 5. Environmental interpretations of gamma log patterns (adapted from Cant, 1992).

highly irregular values remaining below 100 ms/ft.

Sandy tidal flats typically display fining-upward patterns in their gamma rays, fluctuating between 30 and 60 API. The sonic profile shows a slight increase in propagation time to between 70 and 90 ms/ft due to the increased presence of siltstones. Tidal inlet and tidal creek deposits cause marked local variations in this pattern. Where inlet facies predominate, the gamma ray log shows very low radioactivity that may locally drop to 20 API. The pattern is very irregular with sharp changes between these coarse deposits and the medium to fine sandstones of the intertidal flats. The sonic profile shows a highly indented pattern.

Mixed tidal flats produce profiles similar to sandy and muddy tidal flats, with the exception of areas where channels predominate. Here, the interbedded sandstones and siltstones cause major variations in the profiles. The sandstones generally have a higher radioactivity, which varies between 35 and 50 API, whereas the sonic logs are similar to the sandy and muddy tidal flat profiles.

Facies association C: barrier beach environment. These deposits display very low, constant values of radioactivity ranging between 15 and 25 API. The profiles have a typical boxcar pattern (Fig. 5) indicating cycles 10-15 m thick. The sonic profile is variable between 120 and 80 ms/ft, with an irregular pattern that imitates the shape of the gamma rays. In areas where the sandstones are cemented with quartz overgrowing kaolinite, much lower values are recorded. In general, the contacts with other facies are sharp, probably indicating erosion. Where this facies overlies the Tobífera Formation, a radiometric anomaly with a very high value of 125 to 200 API indicates an unconformity with heavy mineral concentrations.

Facies association D: shoreface environment. Both the upper and lower shoreface facies have a basal zone characterised by intercalated mudstones and siltstones, which produce gamma ray values between 90 and 130 API. The presence of interbedded coarse-grained sandstones may cause the value to drop to 50 API. Both upper and lower shoreface facies display marked coarsening-upward trends, but two distinct patterns are discernible at the top. Upper shoreface facies, where sand ridges dominate, show aggradational profiles marked by very low radioactivity (25-40 API). Lower shoreface facies, on the other hand, are characterised by sand shoals with slight coarsening-up trends, which produce a funnel-shaped pattern (Fig. 5). Values of radioactivity in this case vary between 40 and 50 API. Sonic profiles do not exhibit any clear trends, but the values remain fairly constant between 100 and 80 ms/ft.

SEISMIC FACIES DESCRIPTION AND INTERPRETATION

A seismic survey was undertaken in the central part of the Magellan Block, covering an area of 180 km² (74% of the study area) by a rectangular grid with a line spacing of 26.7 m. Seismic surveys are based on sound waves produced by explosions. Detecting and recording devices automatically indicate the time at which the seismic wave arrives at the detector, which depends on the refractive or reflective nature of the strata. At the interface between strata of different acoustic impedance, some seismic waves are reflected back to the surface while others are refracted and travel along the refracting interface for some distance before returning to the surface.

The reflection seismograph surveys used in this study measure the elapsed time between the moment of detonation and the arrival of the reflected wave at the detectors. Where an acoustic impedance interface can be consistently identified over a wide area, it constitutes a geophysical marker bed, which is commonly the bedding plane of some geological rock unit. Reflection seismology is better suited for detailed surveys than refraction seismology, so that the detonation points are generally more closely spaced and the detectors are placed in overlapping configurations.

The upper contact of the Springhill Formation, referred to as TAS, is a prominent reflection surface discernible over the whole area. As this was considered to be a time marker, it was restored to the horizontal plane and used as a reference surface. The program Surfer Slice of GEOQUEST was subsequently employed to generate sections parallel to TAS. The time lag with reference to the latter varied between 12 and 18 milliseconds, which implies rock intervals of 15 to 25 m. The seismic properties are expressed as different colours on a map, with red and orange hues corresponding to positive amplitudes in the horizontal section transmitting the seismic waves, whereas darker tints (black and grey) reflect negative amplitudes.

For each of the 6 sub-platforms located within the Magellan Block, facies associations established by geophysical methods and borehole information were correlated with the seismic profiles.

Barrier beach associations are generally characterised by yellow, orange and red colours, although dark grey tints occur in some areas. Intertidal associations are white, light grey, yellowish white and light orange. Where tidal creeks abound, whitish grey, pale yellow, light orange and even deep red colours are typical. Tidal inlet channels generally produce light grey tints.

PALEOGEOGRAPHIC MODEL

The spatial and temporal distribution of the depositional facies described above forms the basis of a paleogeographic model for the Magellan Block (Fig. 6). An isopach map of the succession between seismic marker C11, located in the lower part of the Pampa Rincón Formation (Middle Aptian) and the top of the Tobífera Formation, was used here as a base map, as it best represents the paleotopography of the study area. This is preferred to isobathic maps of the top or base of the Springhill Formation, which have both been affected somewhat by later tectonic movements.

Figure 3 shows two belts of structural highs trending towards to the northwest, parallel to the main faults. The northern horst is a more prominent feature, but it loses its relief towards the northwest where it becomes relatively flat. The southern horst, by contrast, has a more pronounced topography in the northwest where it has been segmented extensively by faulting. A graben located between the two horsts disappears in the central platform area where the uplifted blocks merge. In general, the paleotopography appears to have been relatively flat, with the first marine sedimentation affecting only the lowest lying areas, from where it onlapped onto the structural highs.

The first stage of landscape evolution in the Magellan Block was the development of many collapse faults and semi-grabens subsequently filled by the Tobífera volcaniclastic succession. These deposits, which include volcanic breccias, acid lapilli tuffs and ash falls, were apparently laid down subaerially. The Springhill Formation was then deposited unconformably over the Tobífera Formation as a transgressive, dominantly paralic succession (Biddle *et al.*, 1986; Robbiano, 1989; Arbe, 1989). Three cycles of transgression (designated MFS01, MFS02 and MFS03) can be discerned on the basis of a change from shallow to deeper water facies associations (Figs. 4 and 7). Flooding at the base of the Springhill Formation was less extensive than that characterising the top of the formation, in that the former reflects fluctuations between supratidal and intertidal associations, whereas the latter varies between intertidal and shoreface associations.

Figure 7 displays a profile based on borehole, seismic and geophysical data. The basal cycles consist of very immature, poorly sorted volcaniclastic deposits, which occur throughout the study area, and occasionally, contain interbedded diamictites. The latter were probably derived from the active fault scarps. A poorly developed intertidal association with channel-fill, abandoned channel and muddy tidal flats predominated during this time, with direct marine influence restricted to grabens developing between the active faults.

The intermediate part of the Springhill Formation is characterised by barrier beach facies, consisting of tabular, coarse sandstone bodies that accumulated preferentially in the central graben area against the structural highs (Figs. 4, 6). These facies interfinger towards the platform interiors with intertidal associations consisting of muddy or mixed tidal flats with abundant tidal creeks. The latter developed especially in areas characterised by the presence of numerous faults.

The upper Springhill cycles typically contain well-developed, widely distributed intertidal associations of tidal flats and creeks. In general, these deposits represent the filling of the accommodation

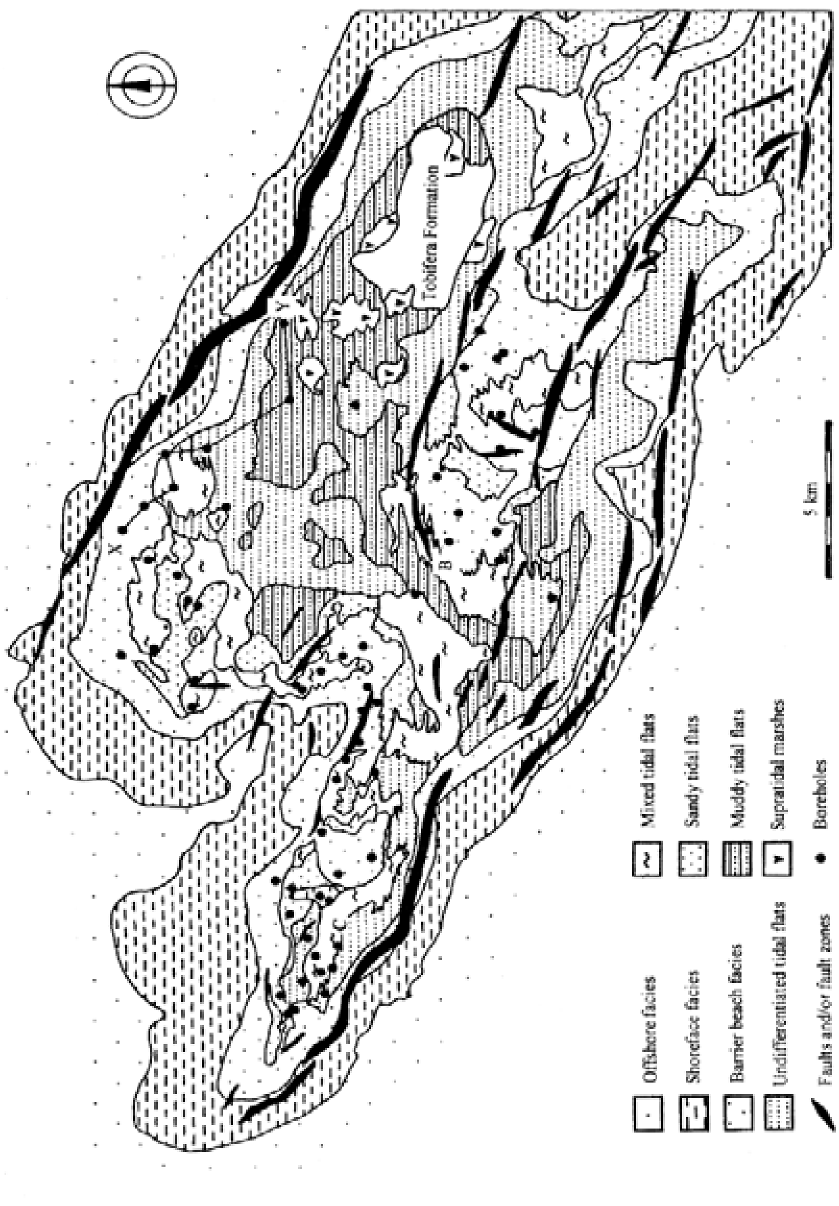

FIG. 6. Paleogeographic model of the Magellan Block showing distribution of major facies associations and boreholes.

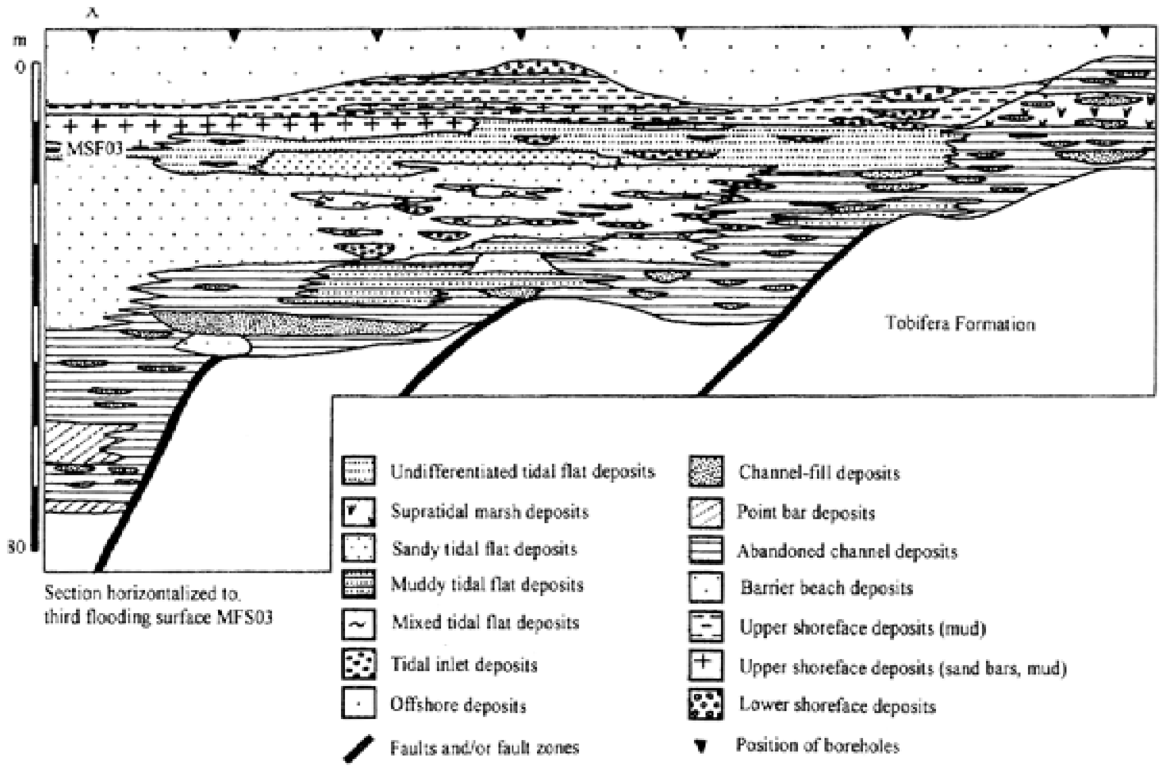

FIG. 7. Typical profile of vertical facies associations in the Magellan Block based on borehole, seismic and other geophysical data. The section line (X-Y) is indicated in figure 6.

space created by MFS02, with the depositional environments migrating towards zones more protected from direct wave action. Towards the structural highs, there is an incremental change from mixed or sandy tidal flats to supratidal marshes (Figs. 6, 7).

The accommodation space generated by the third major (maximum) flooding event (MFS03) was filled by shoreface deposits over the whole platform area, but preferentially in the deeper zones. In some areas, longshore bars developed homogeneous sandstone bodies in the proximal shoreface association, while sand was also deposited in more distal shoals.

Offshore deposits are only encountered in the deeper areas outside the Magellan Block, consisting of intercalated mudrocks and fine, greyish green sandstones forming part of the Estratos con Fravella Formation overlying the Springhill Formation.

CONCLUSIONS

In the Magellan Block, the Springhill Formation represents the basal unit deposited at the beginning of the Early Cretaceous transgression. Its sedimentary facies reflect paralic conditions developing over the two structural highs formed by northwest trending horst islands. The original paleotopography on these islands was relatively flat, but was later accentuated by reactivation of the numerous faults transecting the platform during the synrift stage of the Late Cretaceous to Tertiary.

The depositional model of the area corresponds to a system of barrier beaches accumulating against the topographically higher areas. Between these beach systems and the island interiors, inter- and supratidal flats developed, apparently without lagoons. At the same time, shoreface sediments were deposited on the seaward side of the barrier systems. The central graben probably formed a shallow embayment with tidal flats developing along its shoreline. Offshore deposits of the Estratos con Fravella Formation later formed on wide, more open platforms.

Three cycles of sea level transgression and regression, corresponding to parasequences separated by marine flooding surfaces, are recognised. The two basal parasequences underlying MFS01 and MFS02 (Fig. 7) may be related to minor sea level fluctuations, or alternatively, to fault activity in the area. The uppermost cycle, on the other hand, corresponds to a major transgressive event that can be recognised throughout the Magellan Basin, with MFS03 reflecting the maximum flooding surface. The Springhill Formation within the Magellan Block thus represents a typical parasequence set of fourth to fifth order.

ACKNOWLEDGEMENTS

The authors wish to thank H. Bahlburg (Westfälische Wilhelms-Universität Münster), S. Harambour (Sipetrol, Santiago) and L.A. Spalletti (Museo Nacional de La Plata, Buenos Aires) for their thorough reviews and positive criticism, which assisted the authors in improving this paper. Permission from SIPETROL and REPSOL-YPF to publish the results of this study is gratefully acknowledged.

REFERENCES

Alvarez-Marrón, J.; McClay, K.R.; Harambour, S.; Rojas, L.; Skármeta, J. 1993. Geometry and evolution of the frontal part of the Magallanes foreland thrust and fold belt (Vicuña Area), Tierra del Fuego, Southern Chile. *American Association of Petroleum Geologists, Bulletin*, Vol. 77, No. 11, p. 1904-1921.

Arbe, H.A. 1989. Estratigrafía, discontinuidades y evolución sedimentaria del Cretácico en la Cuenca Austral, Provincia de Santa Cruz. *In* Cuencas Sedimentarias Argentinas (Chebli, G.A.; Spaletti, L.A.; editors). *Universidad Nacional de Tucumán, Serie Correlación Geológica, No. 6,* p. 419-442.

Biddle, K.T.; Uliana, M.A.; Mitchum, R.M.; Fitzgerald, M.G.; Wright, R.L. 1986. The stratigraphy and evolution of the central and eastern Magallanes Basin, Southern South America. *International Association of Sedimentologists,* Special Publication No. 8, p. 41-61.

Bravo, P.; Herrero, C. 1997. Reservorios naturalmente fracturados en rocas volcánicas jurásicas, Cuenca de Magallanes, Chile. *In Simposio Bolivariano de Exploración en Cuencas Subandinas, No. 6, Actas,* p. 66-84. Cartagena de Indias, Colombia.

Bruhn, R.; Stern, C.; De Witt, M. 1978. Field and geochemical data bearing on the development of a Mesozoic volcano-tectonic rift zone and back-arc basin in southernmost South America. *Earth and Planetary Science Letters,* Vol. 41, p. 32-46.

Cant, D.J. 1992. Subsurface facies analysis. *In* Facies Models: Response to Sea level Change (Walker, R.G.; James, N.P.; editors). *Geological Association of Canada,* p. 195-218.

Galeazzi, J.S. 1998. Structural and stratigraphic evolution of the western Malvinas Basin, Argentina. *American Association of Petroleum Geologists, Bulletin,* Vol. 82, No. 4, p. 594-636.

Harambour, S.M. 1998. Structural evolution of the Magallanes Block, Magallanes (Austral) Basin, offshore Argentina, South Atlantic. M.Sc.Thesis (Unpublished), *University of London, Royal Holloway,* 136 p.

Harambour, S.M.; Soffia, J.M. 1988. Transición desde margen pasivo a cuenca de antepaís: modelo de evolución para el extremo norte de Última Esperanza, Magallanes, Chile. *In Congreso Geológico Chileno, No. 5, Actas,* Vol. 1, p. 385-402. Santiago.

Pittion, J.L.; Arbe, H.A. 1999. Sistema petrolero de la Cuenca Austral. *In Congreso de Exploración y Desarrollo de Hidrocarburos, No. 4, Actas,* Vol. 1, p. 506. Mar del Plata, Argentina.

Reading, H.G. 1986. Sedimentary Environments and Facies. *Blackwell Scientific Publications,* 615 p.

Reineck, H.E.; Singh, I.B. 1980. Depositional Sedimentary Environments. *Springer-Verlag,* 549 p. New York.

Rider, M. 1996. The Geological Interpretation of Well Logs. *Whittles Publishing,* 280 p.

Robbiano, J.A. 1989. Cuenca Austral Sector Costa Afuera. *In* Cuencas Sedimentarias Argentinas (Chebli, G.A.; Spalletti, L.A.; editors). *Universidad Nacional de Tucumán, Serie Correlación Geológica,* No. 6, p. 493-512.

Uliana, M.; Biddle, K.; Phelps, D.; Gust, D. 1986. Significado del volcanismo y extensión mesojurásico en el extremo meridional de Sudamérica. *Asociación Geológica Argentina,* Vol. 40, Nos. 3-4, p. 231-253.

Weimer, R.J; Howard, J.D.; Lindsay, D.R. 1982. Tidal flats and associated tidal channels. *In* Sandstone Depositional Environments (Scholle, P.A.; Spearing, D.; editors). *American Association of Petroleum Geologists, Memoir,* Vol. 31, p.191-245.

Wilson, T.J. 1991. Transition from back-arc to foreland basin development in the southernmost Andes: Stratigraphic record from the Ultima Esperanza District, Chile. *Geological Society of America, Bulletin,* Vol. 102, p. 98-111.

Manuscript received: November 27, 2001; accepted: July 20, 2003