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Glacigenic features and Tertiary stratigraphy of the Magellan Strait (Southern Chile)

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ABSTRACT

The seismostratigraphic and structural analysis of the whole length of the Magellan Strait, from the Atlantic to the Pacific entrance is for first time illustrated on the basis of multichannel seismic (MCS) profiles. The Strait crosses a geologically complex region that includes different morphotectonic provinces, and has been subdivided into three distinct segments, eastern (Atlantic), central, and western (Pacific), being each segment characterized by peculiar sedimentary and tectonic architectures. The MCS profiles shed light on the subsurface of the region in particular on the Quaternary and Tertiary features. In the foreland basin province, the MCS profiles imaged an almost undeformed structural and stratigraphic frame with very thick Cretaceous to Tertiary package. Seismic evidence of deformation of the foreland units occurs in the fold-and-thrust belt province. Along the Cordillera province, the Magallanes-Fagnano transform fault exerts an important morpho-tectonic control that strongly conditions its bathymetric profile. The seismic profiles also highlighted a number of depositional features linked to the up to 150 m thick sedimentary record of the glacial cycles. Whereas the eastern segment (outer foreland province) is devoid of significant glacial-related deposits, the central segment (inner foreland and fold-and-thrust belt provinces) shows evidence of repeated advances and retreats of the Magellan glacier. An important moraine ridge complex, probably corresponding to the glacial advance "D" of Clapperton et al., has been seismically imaged in the central segment, as well as an older, large bank of ice-distal sediments that have been interpreted as proglacial lake deposits, which show evident signs of repeated glacial erosions. Ice-contact features in the form of frontal moraine complexes made up of dipping foreset strata are present in the fjord-like, western segment of the Strait (Cordillera province), along with their related ice-proximal and ice-distal facies. Eventually, the occurrence of pre-glacial sediments tectonized by the Magallanes-Fagnano transform fault has been reported in the same segment. This fact, which is supported by small outcrops reported in the updated geologic map, if substantiated by further investigations (i.e. advanced seismic reprocessing, sea bottom samplings), would prove the relatively young age (Late Miocene?) of the Magallanes-Fagnano transform fault.

KEYWORDS **Seismostratigraphy. Glacigenic features. Magallanes-Fagnano transform fault.**

INTRODUCTION

Until two decades ago the area of the Strait of Magellan had been the object of regional geologic studies aimed at shedding light on the sedimentary and stratigraphic frame of the hydrocarbon-producing foreland basin (Olea and Davis, 1977; Biddle et al., 1986). More recently, research interests have been captured by the problems related to the ice ages and the induced climatic and palaeoenvironmental changes. The glacigenic forms, their distribution, stratigraphy and climatic meaning have been dealt with in numerous works (Caldenius, 1932; Marangunic, 1974; Mercer, 1976; Raedeke, 1978; Prieto, 1988; Porter, 1989; Rabassa et al., 1990; Clapperton, 1992; Clapperton et al., 1995; Brambati et al., 1998; McCulloch and Bentley, 1998; Coronato et al., 1999; Benn and Clapperton, 2000; Bentley et al., 2005) and efforts have been made to date the glacial events (Meglioli et al., 1990; Porter et al., 1992; Anderson and Archer, 1999; Rabassa et al., 2000; McCulloch and Davies, 2001; McCulloch et al., 2005b). All these works, which furnished the overall frame of the last glaciation in the region, are based on analyses of field data collected along the coasts of the Strait.

By contrast, only a few works have treated the Strait area occupied by the sea. These comprise a preliminary seismic report of Brambati and Colantoni (1991) from the Atlantic opening to Cabo Froward and two works of Yanez et al. (1991) and Klepeis and Austin (1997) in which the deep structure along a limited, central segment of the Strait is illustrated. In order to fill this gap, a set of multichannel seismic profiles recorded during three marine geological investigations has been analyzed and interpreted. In this paper we present an inedited frame of the seismostratigraphic characters of the whole length of the Strait. Although no new data about the hydrocarbon producing foreland province are evidenced, the illustrated frame contains a high potential of geologic information concerning the glacial-related aspects of the region.

GEOLOGICAL SETTING

Morphology and structure

The Strait of Magellan crosses the southernmost tip of South America from the Atlantic to the Pacific Ocean for a length of about 560 km, separating Patagonia from Tierra del Fuego (Fig. 1). The Strait may be divided into three segments, each elongated in a main distinct trend. The eastern (Atlantic) segment shows a rough ENE-WSW trend, and extends for nearly 140 km from the Atlantic opening (Punta Dungeness) to the Segunda Angostura. The central segment spans for about another 140 km in N-S direction down to Paso del Hambre (Fig. 1). South of this location the Strait sharply bends to NW, thus forming the western (Pacific) segment, which stretches almost parallel to the Andean Cordillera for nearly 280 km up to the Pacific entrance at Cabo Pilar.

From the Atlantic to the Pacific Ocean the Strait passes through three main morphotectonic provinces (here adapted from Klepeis, 1994) and crosses a variety of rocks that range from Quaternary to Paleozoic in age (Figs. 1 and 2). They are the Magellan Foreland Basin that includes the Atlantic segment and part of the central segment of the Strait; the Magellan Foreland Fold and Thrust Belt made up by deformed Lower Cretaceous to Tertiary sedimentary rocks of the foreland basin; and the Andean Cordillera which occupies most of the Pacific archipelago, composed of Palaeozoic and Mesozoic metamorphic rocks, Jurassic to Cretaceous back-arc basin terranes, and Triassic to Recent granites of the Patagonian batholith (Hervé et al., this issue; Menichetti et al., this issue; Tassone et al., this issue).

The Magellan Strait owes its morphologic shape to the geodynamic, tectonic and glacial events that affected southern South America since the Mesozoic (Bujalesky, 2007). The Pacific, NW-SE striking segment of the Strait is the morphologic expression of the Magallanes-Fagnano Fault System that is the main morphotectonic feature of the region (Cunningham, 1993; Klepeis, 1994; Lodolo et al., 2003). This fault strikes for over 600 km from the Atlantic to the Pacific Ocean, crossing obliquely the Cordillera and the fold and thrust belt provinces. The Pacific segment is shaped as a main, linear and narrow channel 2 to 15 km wide, characterized by a great number of lateral inlets, bays, and channels (Fig. 2). Only in the neighbour of the Pacific mouth, north of Isla Desolación, the Strait widens in an enlargement with consistent sediment infilling. The Pacific segment is the deepest of the three that make up the Strait. A narrow bathymetric depression develops an axial depth between ca. 800 and 1,100 m for about 50 km in the tract from Paso del Mar to Isla Carlos III (Fig. 3).

On the contrary, the shape and direction of the central and eastern segments show very clearly the influence of the glacial expansions that moulded the region since the Upper Tertiary (Mercer, 1976; Coronato et al., 1999; Rabassa et al., 2000). The central segment of the Strait crosses the Magellan Foreland Fold and Thrust Belt province to the south, and the Foreland Basin to the north. Rocks as old as late Jurassic and Lower Cretaceous, involved in NE-verging thrust faults extensively outcrop in the southern part of Peninsula Brunswick and on Isla Dawson (see Fig. 2). Moving to the north, younger rocks with less complex

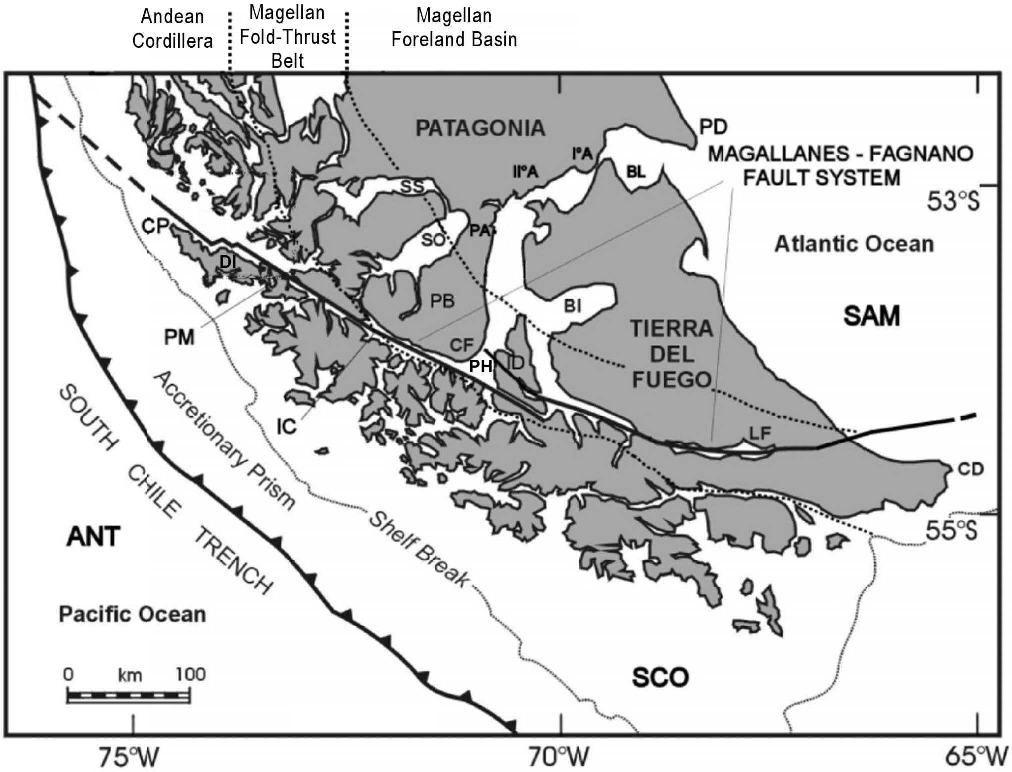

FIGURE 1 **Plate boundaries and morphotectonic provinces at the southern tip of South America. ANT: Antarctic plate; SAM: South American plate; SCO: Scotia plate. Geographic names referenced in this Figure and in the text: I°A, II°A: Primera and Segunda Angostura; BI: Bahía Inútil; BL: Bahía Lomas; CF: Cabo Froward; CP: Cabo Pilar; DI: Isla Desolación; IC: Isla Carlos III; ID: Isla Dawson; LF: Lago Fagnano; PA: Punta Arenas; PB: Peninsula Brunswick; PD: Punta Dungeness; PH: Paso del Hambre; PM: Paso del Mar.**

structure occur. The eastern (Atlantic) segment is a flat, mostly undeformed area belonging to the Magellan Foreland Basin province, covered by a thin sheet of Quaternary sediments of glacial and fluvio-glacial origin.

North of Isla Dawson the central segment has the shape of a wide, elongated basin trending to the north, approximately 90 km long and 30 km wide, from which the wide branch of Bahía Inútil separates. Decreasing bathymetry from south to north (from about 400 m to 50 m) witnesses the persistence in the past of a very large ground-based ice tongue fed from the Cordillera. Eventually, the eastern segment that connects the Atlantic Ocean is characterized by a shallow, almost flat sea bottom averaging 40–50 m.

Stratigraphy of the Magellan foreland basin

The stratigraphy of the foreland basin is well known thanks to the numerous hydrocarbon wells drilled in the region correlated to an extensive seismic exploration. The basin is an asymmetric depression with a NNW trending depocentre axis located near the sub-Andean fold and thrust belt. The more than 7,000 m thick Early Cretaceous to Pliocene sedimentary fill (Olea and Davis, 1977) overlies a pre-Mesozoic schistose and gneissic basement and consists of a sequence of marine clastic sedimentary rocks. The dominating lithotypes mainly range from shales to sandstones, with frequent lateral changes that account for the different formation names (Cañón and Ernst, 1974). The sedimentary infilling can be divided into three major packages corresponding to three major phases of basin development (Biddle et al., 1986): 1) a syn-rift Triassic to upper Jurassic package known as Tobifera Formation (Fm); 2) a late to post-rift sedimentary section of upper Jurassic to upper Cretaceous age; and 3) a foreland basin, east-thinning package of uppermost Cretaceous to Tertiary age.

A final regression in the Miocene transformed the foreland basin in a positive to shallow-water area (Olea and Davis, 1977). During Upper Tertiary and Quaternary the Patagonia and Tierra del Fuego underwent several glacial cycles that moulded the region and left a widespread distribution of glacigenic landforms. The last glacial maximum is represented by the advance B of Clapperton et al. (1995) that culminated at 25,200 – 23,100 calendar years BP (McCulloch et al., 2005b) and was followed by other three minor advances: advance C (sometime before 22,400 – 20,300 cal years BP), advance D (sometime before 17,700 – 17,600 cal years BP) and advance E (15,500 – 11,770 cal years BP).

The Tertiary sequence, as reported from well logs, consists of several stratigraphic units mainly made up by sandstones, siltstones and shales. They are: the Zona Glauconítica (Paleocene to early Eocene), the Bahía Inútil Group (late Eocene to early Oligocene), the Arenisca Arcillosa (late Oligocene to early Miocene), the Brush Lake Fm (Miocene), the Filaret Fm (late Miocene) and the Palomares Fm (Pliocene). The sequence including the upper part of the Bahía Inútil Group, the Arenisca Arcillosa and the Brush Lake Fm is also grouped into the Loreto Fm. The general structure of the Tertiary package is that of a northeastward prograding and thinning wedge topped by a regionally extended unconformity over which a more-or-less continuous layer of Quaternary glacigenic deposits occurs (Biddle et al., 1986).

METHODOLOGY

In 1989, 1991 and 1995 three geological-geophysical cruises were carried out in the Magellan Strait with the aim of outlining the features of the surface sediments and the dynamics of the sedimentary processes (Brambati et al., 1991a). During each cruise mid-penetration, multichannel seismic (MCS) reflection profiles were recorded and bottom sediments sampled (Brambati and Colantoni, 1991; Brambati et al., 1991b). These surveys, which mostly consist of along-strike, GPS-positioned profiles, have a total length of about 1,090 km, as they cover the whole length of the Strait, its adjacent shelves and some lateral branches (Fig. 2). They were acquired using an air-gun source of 10 litres, a streamer 300 m long with 48 channels, record length of 2.5 seconds, sampling rate of 1 millisecond, and 1,200% coverage. Two synchronous G.I. Guns of 3.44 litres each, coupled with a 600 m long streamer were also used.

Despite the high-quality standard in acquisition and processing, MCS data suffer from problems related to

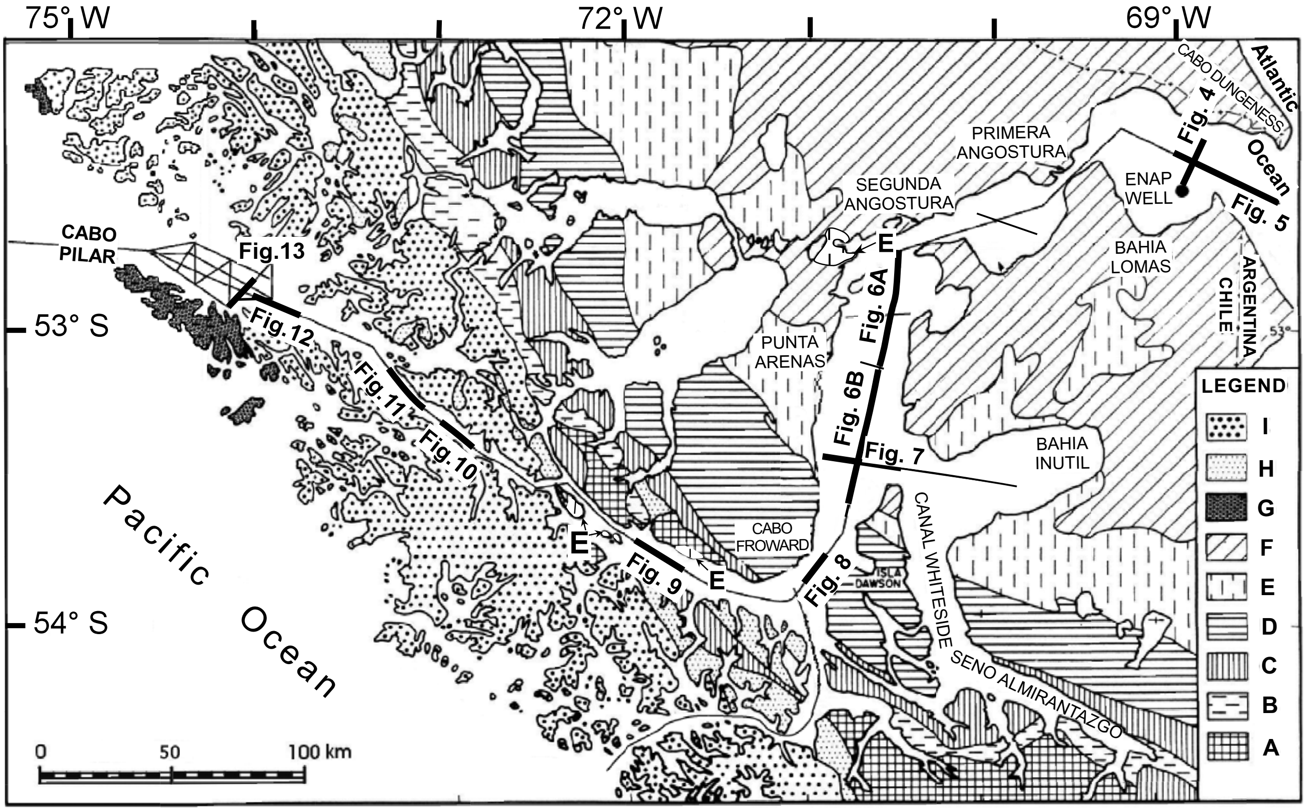

FIGURE 2 | **Geology of the Magellan Strait area (modified from Brambati et al., 1991b and from S.N.G.M., 2003) and location map of the MCS profiles. Symbols: A) Undifferentiated Paleozoic rocks; B) Silica rich volcanic and volcaniclastic Jurassic to Early Cretaceous rocks; C) and D) Early and Late Cretaceous sedimentary rocks, respectively; E) Tertiary marine paralic and continental rocks; F) Quaternary fluvioglacial sediments; G) Undifferentiated Late Paleozoic-Early Mesozoic sedimentary and volcanic rocks; H) Late Jurassic-Early Cretaceous effusive and intrusive rocks; I) Patagonian Batholith.**

bottom multiples and reverberations originating in shallow water areas. Bubble pulse effects of the air-guns are also present and sometimes heavily mask the primary reflections. Another problem arises from the narrowness of many parts of the Strait where strong side-echoes (side-swipe effects) from the steep flanks are often recorded. A third problem, owing to political constraints, is related to the availability of acquiring the seismic lines mostly along axial ship tracklines, a condition that strongly limits the lateral control of any feature.

DESCRIPTION OF THE MCS DATA SET

The seismic characters, structure and geometric relationships of the stratigraphic features, which are imaged in some significative MCS profiles, will be presented for each segment of the Magellan Strait. In some of the figures the profiles have been "squeezed" horizontally, with respect to the original display, to enhance the form and characters of geological features whose horizontal scale is several times the vertical one (up to 100:1).

Eastern (Atlantic) segment

All the seismic profiles from the eastern part of the foreland province show a sub-horizontal or gently inclined package of mostly undeformed or slightly deformed strata. Reverberations are the main noise in this shallow-water area, while side-echoes or basement highs seem present in short tracts of the two Angosturas.

An exploration well in Bahía Lomas, kindly granted by ENAP (Empresa Nacional del Petroleo), links the drilled stratigraphic sequence to the MCS section illustrated in Fig. 4. In the deep part of the section, the top of the syn-rift Tobífera volcanic formation appears as a strong reflector from 1.7 to 2.1 sec t.w.t. Normal faults at

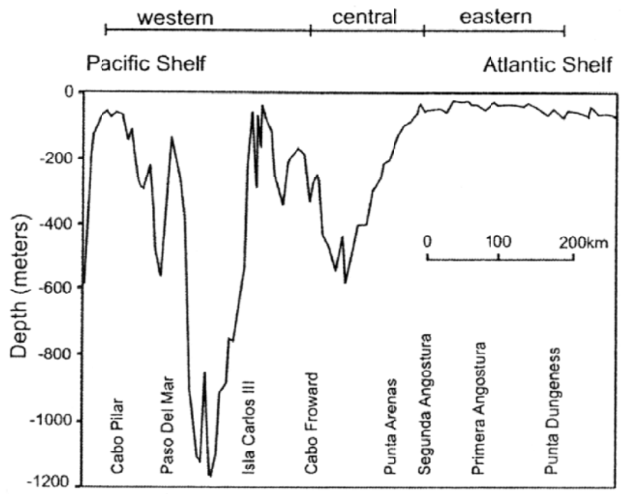

FIGURE 3 **Axial bathymetric profile along the Magellan Strait from the Pacific to the Atlantic shelf (modified from Brambati et al., 1991b).**

the centre of the section outline the flank of a graben and parallel reflections characterize the whole Cretaceous sequence whose top is near 1.0 sec t.w.t. In the overlying Tertiary sequence a high-energy reflection at about 0.6 sec t.w.t. marks the top of the Miocene Brush Lake Fm. Above this reflector the seismic section shows weakly prograding strata that belong to the late Miocene to Pliocene in age Filaret and Palomares Fm. On the easternmost profile (Fig. 5) the syn-rift Triassic-Jurassic sequence is imaged below 1.5 - 1.7 sec t.w.t. as a highly reflective package. It is structured in a horst-and-graben pattern with small-throw normal faults that penetrate into the overlying Cretaceous sequence and sometimes also into the lower Tertiary.

As far as the glacigenic deposits are concerned, the ENAP well in Bahía Lomas reports a very thin blanket (ca. 20 m thick) of Quaternary sediments, generally

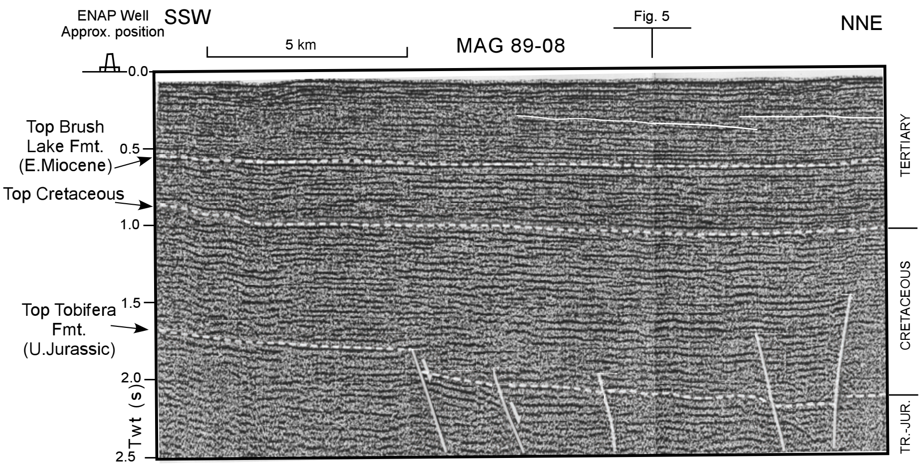

FIGURE 4 **Interpreted MCS profile MAG89-08 across the Atlantic entrance of the Strait in Bahía Lomas. Stratigraphy of the line linked to the well located near the southern edge of the profile (courtesy of E.NA.P.). Notice the gently progradational reflectors in the Tertiary sequence. V.E. ca. 2.5X. Line location in Figure 2.**

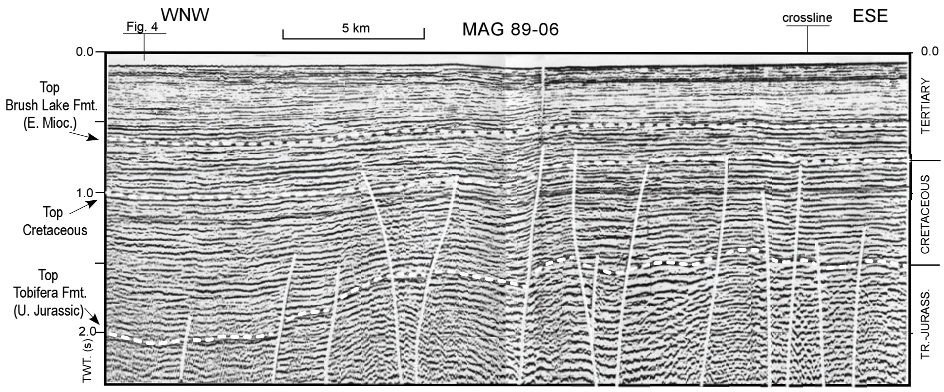

FIGURE 5 **Interpreted MCS profile MAG89-06 along the Atlantic entrance of the Strait. Notice the Triassic – upper Jurassic syn-rift sequence, and the highly reflective sea bottom on the right due to the occurrence of a thin veneer of coarse glaciofluvial sediments. V.E. ca. 3.3X. Line location in Figure 2.**

referred to as "glacial", over an undisturbed Tertiary sequence (Figs. 4 and 5). These deposits, however, cannot be imaged in the MCS profiles because of their reduced thickness. Instead, on the eastern part of Fig. 5 profile and on other MCS profiles on the Atlantic continental shelf, the shallow and flat sea bottom is marked by a high-energy reflection, a peculiarity that is discussed and interpreted later in the text.

Central segment

It is formed by a wide elongated basin that progressively deepens southward and ends at the narrow of Paso del Hambre, between Península Brunswick and Isla Dawson. The two profiles presented, the northern and southern parts of the same seismic line, image a more-or-less stratified upper seismic unit with different thicknesses, unconformably overlying a downward-undefined lower unit. We first describe the characters of the lower unit, then those of the most interesting, although much thinner, upper unit.

In the northern profile (Fig. 6A), approximately from Punta Arenas to the Segunda Angostura, the lower seismic unit (LU) is composed of a thick complex of northward prograding strata characterized by a group of high-energy horizons that can be followed from about 0.4 to 1.5 sec t.w.t. The southern profile (Fig. 6B), from about the northern tip of Isla Dawson to Punta Arenas, outlines the innermost tract of the foreland basin. It shows that most of the seismic energy is reflected by the upper reflective seismic unit (UU), about 150 m thick, which rests over a poorly reflective lower unit (LU), in which the outermost structures of the fold-and-thrust belt province, mostly consisting of gentle folds, can be recognized.

An erosional unconformity separates the Tertiary sequence from the more reflective, upper seismic unit (UU) whose thickness, reflection characters and external shape vary consistently along this sector of the Strait (Fig. 6A and B). Near the centre of the northern profile (Fig. 6A) two coalescing, upward-convex relieves form a reflection-free feature about 5 km large, rising 30 - 50 m above sea floor. Another isolated relief with the same seismic characters occurs about 4 km to the north. These features lie over a thin layer (<50 m) of few stratified reflections, gently dipping southward, located above the top-Tertiary unconformity. The lateral extension of these relieves and of the underlying stratification are controlled by a cross-line on which they appear as an almost continuous, about 13 km long ridge that extends across this segment of the Strait, with a relief up to 50 m high, and rests over a thin stratified layer.

Another Quaternary feature occurs on the profile of Fig. 6A, near its left margin. It is a buried, stratified double-mounded feature, with the steeper side to the south and with an asymmetric depression (ca. 1 km large, ca. 40 m deep) at its culmination. It is about 9 km large in the profile, and about 80 m thick at the centre. The internal prograding reflectors downlap onto the Tertiary bedrock, which is moulded as a rugged surface with some incisions that are up to 35-40 m deep.

The profile of Fig. 6B shows an upper reflective seismic unit resting on the Tertiary, weakly reflective basement. It is arranged in the form a large bank, about 35 km long in the profile, with thicknesses ranging from ca. 130-150 m to the south and ca. 80-100 m to the north. Five depositional members, labelled with Roman numerals I to V, can be distinguished internally. They are separated by boundaries that reveal complex relationships of deposition and erosion. In the cross section of Fig. 7 the bank-like depositional unit described above is imaged as three distinct, but seismically similar bodies, separated by wide depressions in which the Quaternary sediments are very thin or absent. The boundaries of the members are flat or weakly dipping surfaces that alternate with ramps, labelled ES in Fig. 6B and in Fig. 7, along which the reflections are laterally truncated. Also the external surface of the unit is moulded in a flat-and-ramp shape.

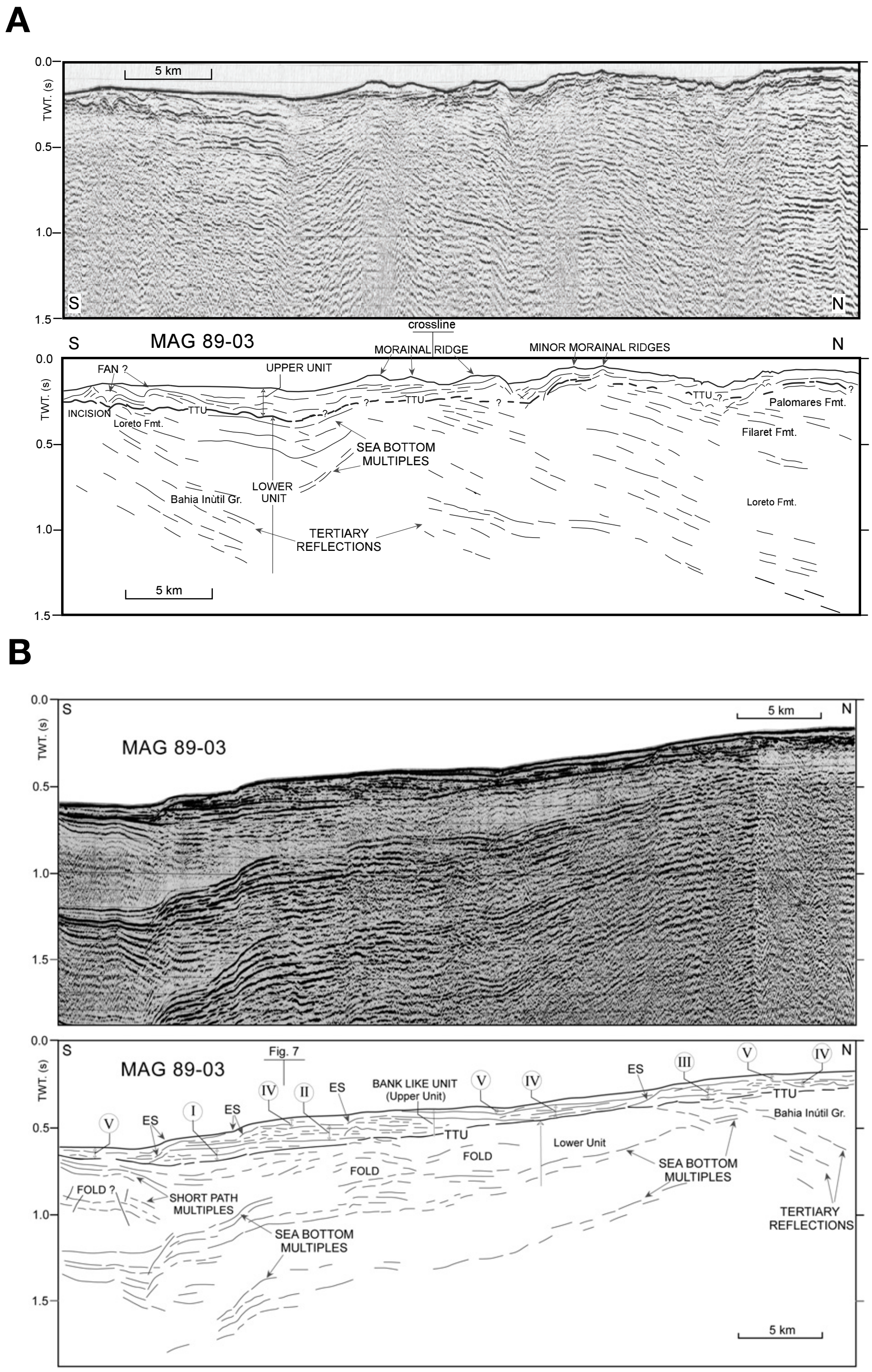

FIGURE 6 **A) MCS profile MAG89-03 (north) along the central segment of the Magellan Strait, line drawing and interpretation. The vertical exaggeration enhances the northward dipping configuration of the Tertiary sequence (lower seismic unit) and the geometric characters of the glacigenic features (upper seismic unit). TTU: Top Tertiary unconformity. V.E. ca. 6.6X in the Tertiary. Line location in figure 2. B) MCS profile MAG89-03 (south) along the central segment of the Magellan Strait, line drawing and interpretation. ES: erosive scarp; TTU: Top Tertiary unconformity; Roman numerals I to V refer to the stratified members forming the upper seismic unit, interpreted as a bank of proglacial lake sediments. Evidence of folding occurs in the lower, poorly-reflective unit (Tertiary). V.E. ca. 10X in the upper unit. Line location in Figure 2.**

The southernmost segment of the Strait between Cabo Froward and Isla Dawson is called Paso del Hambre, which is part of the fold-and-thrust belt province. The profile in Fig. 8 crosses the trace of the Magallanes-Fagnano transform fault (see Fig. 2) that runs along this province forming a complex system of left-stepped normal faults, en-echelon grabens and push-up features (Lodolo et al., 2003).

Structural highs and small basins formed by half-grabens characterize this segment of the Strait. Although there is no seismic evidence of ice-related features, bottom samplings recovered muddy sands and mud of glacial origin (Brambati et al., 1991b) along with bedrock samples referable to sedimentary Cretaceous rocks (S.N.G.M., 1982; S.N.G.M., 2003).

Western (Pacific) segment

Shaped as a very long fjord opened at both extremities, this is the longest segment of the Strait, which is tectonically controlled by the Magallanes-Fagnano fault and characterized by numerous basins and sills. The Isla Carlos III plays an important role as a morpho-tectonic divide separating an eastern, relatively shallow-water sector from a western deep-water sector.

The southeast sector of Isla Carlos III, characterized by variable bottom morphologies, shows scarce seismic evidence in terms of both thickness and length of features and sediments related to the glacial cycles. Basement reflections and diffractions are the dominating seismic signals. The occurrence of coarse relict sediments at the bottom surface has been ascertained in numerous sampling stations (Brambati et al., 1991b). On the contrary, the deeper sector northwest of Isla Carlos III has numerous and well preserved ice-related features. In the subsurface, groups of few sparse reflectors and numerous regularly inclined reflections prove the occurrence of stratified rocks over the basement signals. The profile in Fig. 9 images a short piece of the first sector and, at the same time, summarizes its peculiarities. The structural high with a rough surface in the centre-left is internally unreflective and can be easily referred to the units of the Cordillera Darwin. On the contrary, the smooth wavy feature on the right is characterized in the subsurface by a sequence of inclined, nearly-parallel reflections on which the bubble effect of the seismic source interfere. These strata dip to the northwest (apparent dip ca. 20°) and almost annul their steepness just beyond the top of the feature. The overall frame is that of a sedimentary feature of diagenized rocks, clearly eroded at the surface and also slightly folded. Stratified reflections are still evident for more than 20 km to the east and ca. 6 km to the west of the structural high, with changes in dip direction.

The sector northwest of Isla Carlos III up to Paso del Mar is the narrowest and deepest part of the Strait, marked by steep sides with numerous indentations and inlets whose direction and frequency are intimately linked to the system of fractures of the Patagonian batholith. It is characterized by numerous big, irregular basement highs sometimes cropping out at the sea bottom, which alternate with zones of regular morphology. Figures 10 and 11 show examples of the bottom and subsurface morphology of this sector where three seismic units, with distinct characters, can be distinguished. The upper unit (UU in Fig. 10) is a wedge-shaped, northwestward thinning 100 to 70 m thick blanket. This unit is characterized by inclined reflections in the hill (right side of Fig. 10) that grade into sub-horizontal hummocky- to-parallel reflections towards the deeper zone of the basin to the northwest. In the deeper profile in Fig. 11 the upper unit is up to ca. 170 m thick, and has a semitransparent internal character and few horizontal reflections. The intermediate unit (IU) is characterized by both hyperbolic signals and groups of coherent, gently-dipping reflectors, predominantly in the upper part, where the contact with the upper unit is often of erosive type. Locally, it is very thick and its lower boundary is not distinct, merging downward into the lower, full-of-hyperbolas unit (LU).

The deep basin described in Figs. 10 and 11 ends at Paso del Mar where the sea bottom rises at a shallow sill (-216 m; see Fig. 3) and the Magellan Strait opens into a

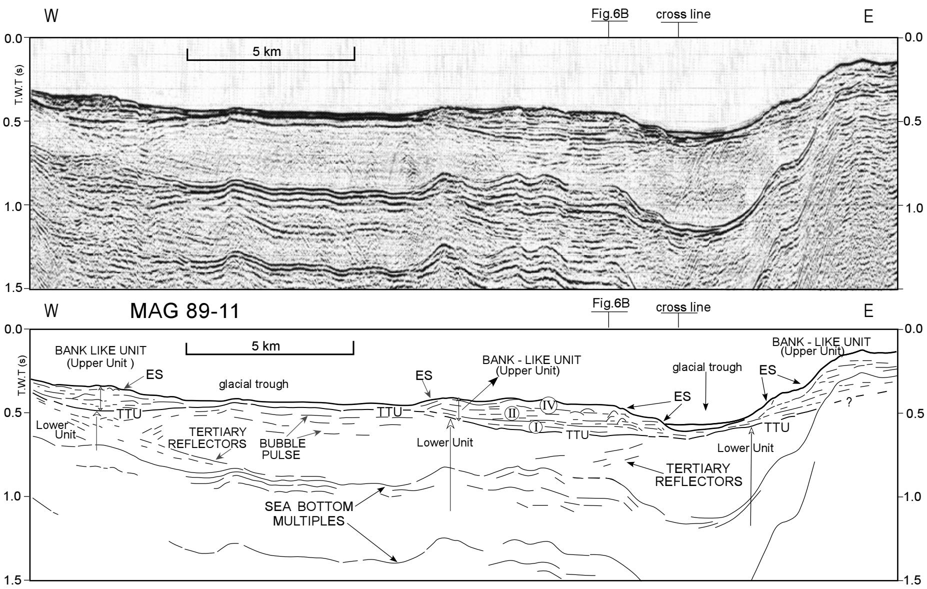

FIGURE 7 **MCS profile MAG89-11 across the central segment of the Magellan Strait, line drawing and interpretation. Notice the wide U-shaped troughs that are thought to represent surfaces of erosion of the Magellan glacier. Upper seismic unit interpreted as a bank of ice-distal proglacial lake sediments. Symbols are as in figure 6B. V.E. ca. 8.5X at sea bottom. Line location in Figure 2.**

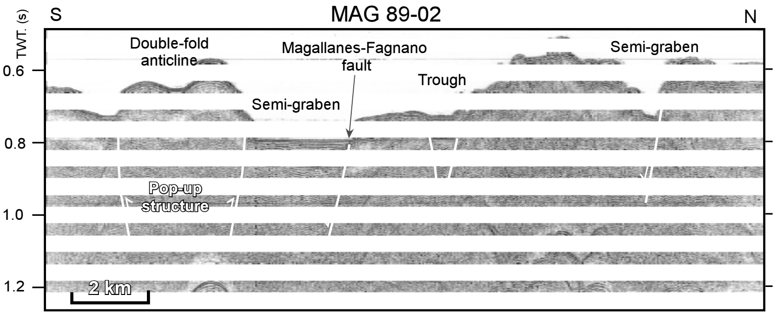

FIGURE 8 **Interpretation of MCS profile MAG89-02 along Paso del Hambre in the southernmost part of the central Magellan Strait. Notice the half-graben and the near "push-up" structure linked to the Magallanes-Fagnano fault. Other smaller positive and negative features can be recognized in the section. Modified from Lodolo et al. (2003). V.E. ca. 13X at sea bottom. Line location in Figure 2.**

larger, less deep basin. Figure 12 shows the sill, very likely made up of a basement high with the bedrock outcropping (granite after S.N.G.M., 1982) and the nearby basin. The associated smaller high reveals a complex internal structure. It is an irregular mounded feature rising ca. 190 m above the flat basin floor, although deeply rooted and interfingered into the thick sedimentary infilling of the basin (about 800 m). Its basinward side is characterized by numerous steeply dipping (ca. 13°) clinoform reflections that outline three main stacked, wedge-shaped figures interfingered in the basin sediments at different depths, down to the base of the feature at 1.5 -1.6 sec t.w.t.

The Magellan Strait ends in a wide basin, bordered to the southwest by Isla Desolación, included between the sill of Paso del Mar and a second sill (-110 m) at Cabo Pilar (see Fig. 2). This basin is asymmetric both in along-strike and in cross sections. Its deepest bathymetric and structural depressions are located to the southwest, close to Isla Desolación. Its strike-slip origin and linkage to the Magallanes-Fagnano fault have been treated in Bartole et al. (2000) and Lodolo et al. (2003). The cross section of Fig. 13 shows the half-graben structure of the basin, due to the south westward tilting of the basement (granites of the Patagonian batholith and Paleozoic to Mesozoic volcanic and sedimentary rocks). The sedimentary infilling, up to about 1,200 m thick with a weak sedimentary growth toward the fault, is represented by medium to high amplitude reflectors of high continuity, alternated with bands of acoustically transparent texture. Lateral facies changes characterize the southeastern part of the basin and several unconformities occur at different stratigraphic levels below 1.0 sec t.w.t. (Fig. 13). Most of the unconformities have erosional characters with reflection truncations and wide incisions.

INTERPRETATION OF THE MSC DATA

The stratigraphy of the ENAP well located on the Atlantic side is inadequate for granting an unambiguous distinction of the sedimentary infilling of the entire Strait. Nonetheless, an approximate stratigraphic subdivision can be made with the consultation of the geologic map of Chile (S.N.G.M., 1982; S.N.G.M, 2003) and with comparisons with the literature data. Keeping this limiting condition in mind, we attempted a geologic interpretation of the illustrated sections. The thicknesses of the surficial glacigenic features have been estimated assuming an average velocity of 1,700 m/sec, and those of the sediments in the basins with a velocity of 2,000 m/sec.

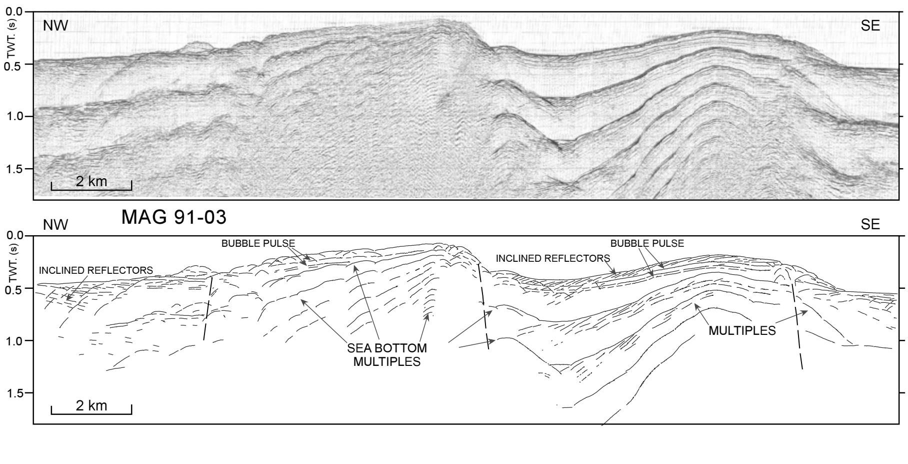

FIGURE 9 **MCS profile MAG91-03 along the western segment of the Magellan Strait, line drawing and interpretation. Basement highs and likely Tertiary in age stratified inclined reflections are frequent features in this relatively shallow water sector. V.E. ca. 3.3X at sea bottom. Line location in Figure 2.**

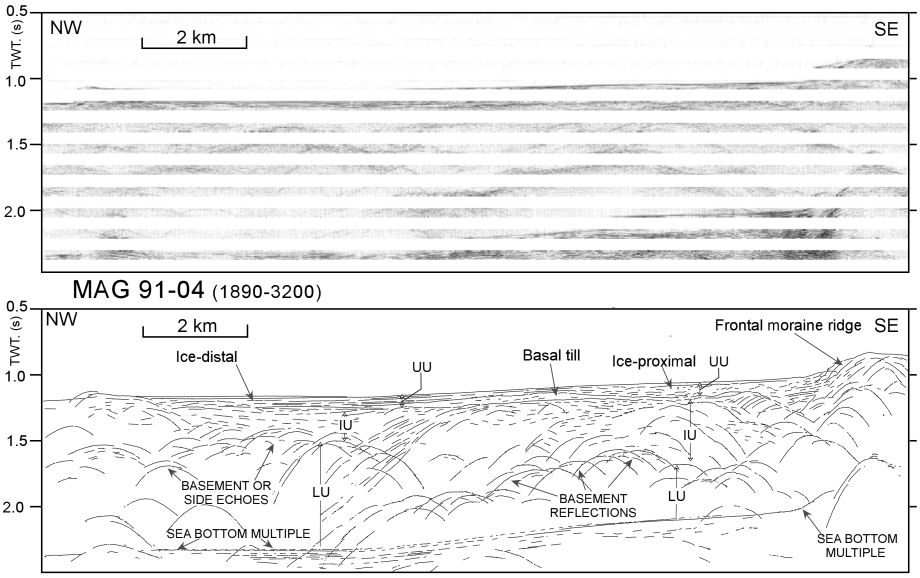

FIGURE 10 **MCS profile MAG 91-04 along the western segment of the Strait, line drawing and interpretation. A moraine ridge with its associated ice-proximal and ice-distal deposits can be recognized in the upper seismic unit (UU). IU: intermediate seismic unit. Prominent hyperbolae in the lower unit (LU) are basement reflections and side echoes from the deep and steep flanks of the Strait. V.E. ca. 3.3X at sea bottom. Line location in Figure 2.**

Interpretation of the eastern segment

Even if the interpretation of the deep structure and stratigraphy of this segment of the Strait (Figs. 4 and 5) does not add any new result with respect to the previous studies (Olea and Davis, 1977; Biddle et al., 1986), the new data can however be drawn from the most surficial sediments. In Bahía Lomas a thin layer of Quaternary glacial deposits (ca. 20 m thick) has been ascertained in the ENAP well. Since their evidence in terms of seismic resolution in this segment is generally weak or null, we may infer that here the Quaternary is much reduced, or even lacking. More to the east up to the nearby continental shelf, the seismic response of the sea bottom in the MCS profiles helps us to confirm the occurrence of glacial-derived deposits. Quaternary deposits forming recessional moraines, drift, outwash channels and other glacial features are abundant in the inland area around the Atlantic segment of the Magellan Strait (e.g. Caldenius, 1932; Marangunic, 1974; Clapperton, 1992; Benn and Clapperton, 2000; Rabassa et al., 2000). During the last glacial maximum the Atlantic continental shelf was affected by numerous fluvial systems that drained the melting waters from the main ice sheets of the region (Coronato et al., 1999). Bottom samplings from the eastern Magellan segment recovered gravels and sandy gravels of morainal and fluvio-glacial origin (Brambati et al., 1991b), and coarse fluvial deposits have been sampled up to 150 km off the Atlantic entrance of the Strait (Brambati et al., 1991a). These evidences allow us to interpret the high-reflective sea bottom in the profile of Fig. 5, and in other profiles on the shelf, as the widespread occurrence of coarse sediments. These are very likely of glaciofluvial origin, which are characterized by a high acoustic impedance with respect to the underlying finer, upper Tertiary sediments.

Interpretation of the central segment

The interpretation of the thick prograding sequence that makes up the lower seismic unit of the profile in Fig. 6A, although far from the stratigraphic link of the ENAP well, can be made by merely taking into consideration the geometric characters of the Tertiary sequences (Biddle et al., 1986) and the outcrops of the Tertiary units (S.N.G.M., 2003). We believe that the lower unit is composed of strata of the Bahía Inútil Group, followed upward by the Loreto, Filaret and Palomares Fms, as illustrated in the line-drawing and interpretation (Fig. 6A). The comparisons with the geologic map (S.N.G.M., 2003) also lead us to interpret the weakly reflective lower unit in Fig. 6B as pertaining to the lower Tertiary formations (mostly the Bahía Inútil Group) outcropping with many NW-SE trending folds on both sides of this segment of the Strait. The low reflectivity of the lower unit in this profile can be ascribed to the southward increasing folding of the Tertiary sequence.

In Fig. 6A, as described before, two upward-convex surficial relieves occur in the upper unit near the centre of the profile. Features that have similar external shape, dimensions and reflection characters are reported in the literature from regions that underwent the grounding of large ice sheets and interpreted as frontal morainal belts. Examples are from Lake Superior (Landmesser et al., 1982), the Gulf of Alaska (Carlson, 1989), the northwest Spitsbergen fjords (Sexton et al., 1992), the central Chilean fjords (Stravers and Anderson, 1997), the west Shetland shelf of north-west Britain (Stocker, 1997), and Lake Melville, Labrador (Syvitski, 1997). We can thus interpret the double-mounded relief of Fig. 6A as a prominent frontal moraine complex and the underlying

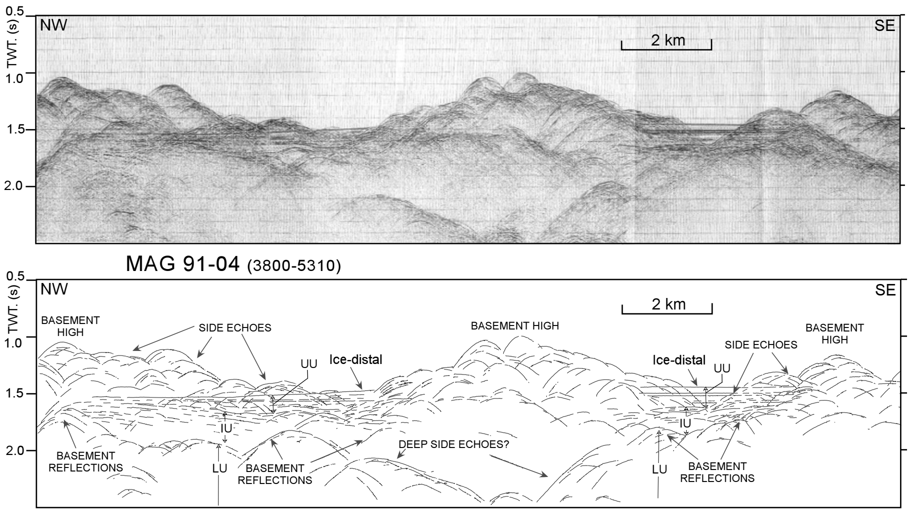

FIGURE 11 **MCS profile MAG91-04 along the western segment of the Strait, line drawing and interpretation. The narrow and deep basin in this sector of the Magellan Strait is a tectonically-induced depression linked to the Magallanes-Fagnano transform fault. The upper semi-transparent seismic unit (UU) is interpreted as representing an ice-distal facies. Other symbols as in Figure 10. Sea bottom at about -1,100 m on Figure left. V.E. ca. 3.3X at sea bottom. Line location in Figure 2**

reflective layer as a stack of ice-contact deposits (MacLean, 1997; Stocker, 1997) or alternatively, as ice-proximal deposits (DaSilva et al., 1997; Stravers and Anderson, 1997) accumulated during a preceding glacial cycle. The position of the mounded ridge fits well with the limit of the glacier advance D of Clapperton et al. (1995) dated sometime before 17,700 – 17,600 calendar years BP (McCulloch et al., 2005b). The reflection-free relieves of Fig. 6A may thus represent a cross-section seismic image of the frontal moraine of this glacial event, located off the city of Punta Arenas. Other minor ridges that occur about 5 to 10 km more to the north may tentatively be referred to the advances B and/or C of Clapperton et al. (1995).

The interpretation of the stratified double-mounded feature at the southern margin of the profile of Fig. 6A is ambiguous. From its stratified, prograding configuration it can be inferred that sedimentation occurred in a subaqueous environment, however a glaciofluvial origin (outwash delta?) cannot be excluded. The direction of progradation of the internal reflectors is consistent with a source area located south of and close to the feature. Since many ice advances and retreats affected the Strait during Quaternary, it is possible to think of it as the seismic image of one or two fan-like features built up near the ice front. Because its stratigraphic position is lower than the frontal moraine ridge (Fig. 6A) we may deduce that it is relatively older in age.

In Fig. 6B and Fig. 7 a large up to 130-150 m thick reflective bank characterized by five depositional members is imaged. As previously described, the upper surface of the bank and its internal unconformities are affected by lateral truncations of the reflectors. Truncations at the flanks of banks and ridges are described in the central Ross Sea (Shipp and Anderson, 1997), in western Norway (Aarseth, 1997a) and in central Norway (Ottesen, 1997)

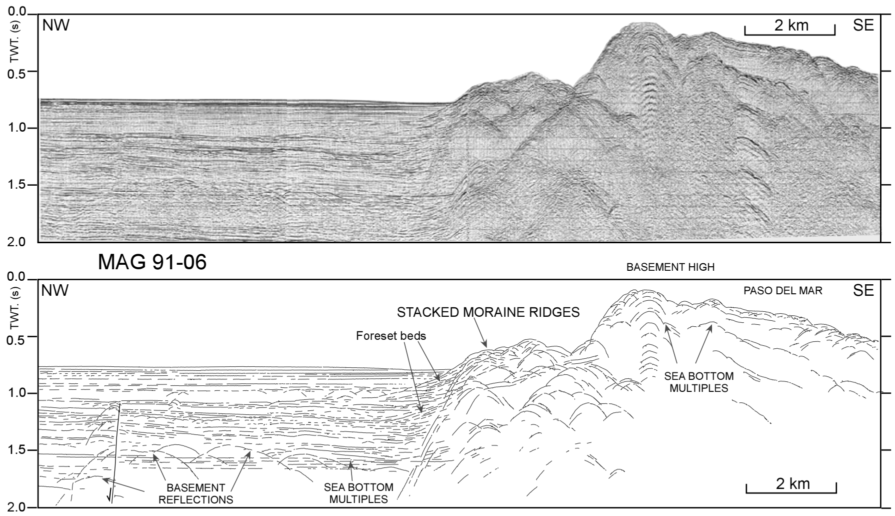

FIGURE 12 **MCS profile MAG91-06 at Paso del Mar, along the western segment of the Strait, line drawing and interpretation. The complex of steeply-dipping strata interfingered with basin sediments is interpreted as a stack of moraine fronts formed by repeated ice advances. V.E. ca. 3.3X at sea bottom. Line location in Figure 2.**

and are interpreted as features and troughs due to the erosion of paleo-ice streams. The wide U-shaped depressions and the evidence of erosion, both at the internal boundaries and at the external surface of the bank-like unit in Fig. 6B and Fig. 7, lead us to consider these wide depressions as relict scours of ice-flows. As for the origin of the members of the bank-like unit, reflection characters and parallel internal configuration of members I, II and III, infer that their deposition occurred in a standing environment, distal with respect to the ice front. The stratified, although irregular internal configuration of the other two members (IV and V) leads us to interpret them as ice-proximal/ice-distal deposits. Since several works documented that proglacial lakes were repeatedly formed in the central Magellan Strait during the last glaciation (Clapperton, 1992; Clapperton et al., 1995; McCulloch and Bentley, 1998; Anderson and Archer, 1999; Benn and Clapperton, 2000; McCulloch et al., 2005a), on the basis of the seismic characters we interpret the five-member unit of Fig. 6B and Fig. 7 as composed of ice-distal/ice-proximal glaciolacustrine sediments that were first deposited and afterwards partially eroded by repeated glacial events.

The most interesting aspect of the southernmost part of the central segment of the Magellan Strait (see the profile in Fig. 8) is the coexistence of positive and negative structures like the double-fold anticline and the small basin at its right. Since compressional and extensional structures are common in many transform contexts of the world (Sylvester, 1988) we interpret these two features as push-up and half-graben structures, respectively, formed by the movements of the Magallanes-Fagnano fault. Other minor, similar features occur on the right-hand side of the profile.

Interpretation of the western segment

In this segment the Isla Carlos III separates two sectors of different morphologic and seismostratigraphic characters. The most interesting peculiarity southeast of the island is the smooth stratified feature shown on the right side of Fig. 9. Three alternative interpretations can be proposed to this feature (literature examples in parenthesis for comparison): 1) it may be the relict of a moraine front with internal steeply dipping foreset beds (Aarseth, 1997b; Lyså and Vorren, 1997), the front being subsequently eroded by a glacial advance that also moulded its surface; 2) it may represent a glaciotectonic deformation of proglacial sediments with the formation of a fold and an angular unconformity (Stravers, 1997); eventually 3) it may be referred to (from Eocene to ?) Miocene continental sediments (conglomerates, sands, silt and peat) present in small outcrops (labelled E in Fig. 2) on the southern coast of Peninsula Brunswick (about 25 km northwest of Cabo Froward (S.N.G.M., 1982), on three small islands and on the eastern half of Isla Carlos III (S.N.G.M., 2003). Among these three possibilities we prefer the last, since: a) the glaciogenic/glaciotectonic origin seems incompatible with the length of the stratified facies and with its changes in dip direction; and b) it is consistent with the relatively young age of the Magallanes-Fagnano transform fault (around 9.5 – 7.2 Ma after Lodolo et al., 2003). If this is the correct interpretation, we can consider the fault as the cause of the tilting and folding of the Tertiary continental sediments of the feature. Multiple advances of grounding glaciers could have caused the erosional unconformity at the sea bottom.

In the deep sector northwest of Isla Carlos III (Figs. 10 and 11) the upper unit (UU) has the distinctive seismic characters of a frontal moraine ridge (the hill) built up over a basement high, with associated ice-proximal deposits (Fig. 10) that grade to ice-distal facies towards the northwest (Figs. 10 and 11; Landmesser et al., 1982; Lyså and Vorren, 1997; DaSilva and Anderson, 1997; Stravers and Anderson, 1997). The thin semitransparent lens of Fig. 10 with high-amplitude boundaries, interposed between the upper and the intermediate unit, is interpreted as representing a basal till. Interpretation of the intermediate unit (IU) is less unambiguous. This chaotic, weakly reflective unit, in fact, could be seen either as a thick accumulation of more-or-less stratified till deposited in the structural lows of the basin, or as a sequence of pre-glacial sediments, teconized by the activity of the Magallanes-Fagnano fault. Further processing and migration of the MCS profile, aimed to clarify the internal geometry, could help to the solution of the problem. Eventually the lower unit (LU), full of hyperbolic

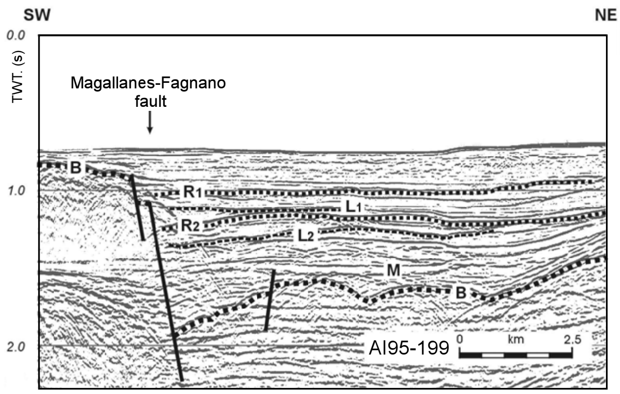

FIGURE 13 **Interpretation of MCS profile ITA95-199 at the Pacific entrance of the Magellan Strait. Seismic facies changes and several unconformities characterize the basin filling. On the left notice the upthrown basement block related to the Magallanes-Fagnano fault. B: top of seismic basement; M: seafloor multiple; R1, R2 and L1, L2: erosional regional and local unconformities. Modified from Bartole et al. (2000). V.E. ca. 3X at the basement. Line location in Figure 2.**

diffractions, can be easily referred to the rocky basement (granites) whose fjord-like shape gives rise to both primary and side-echoes.

The prograding characters of the small mounded feature at the foot of the basement high at Paso del Mar (see Fig. 12) resemble those described in the literature for the morainal ridges in the fjords of western Norway (Aarseth, 1997b), northern Norway (Lyså and Vorren, 1997), central Chile (Stravers and Anderson, 1997) and southern Chile (DaSilva and Anderson, 1997). Its overall geometry leads us to think of it as a complex of stacked moraine ridges, each built up by a stable glacier front during repeated glacial re-advances. As an alternative interpretation the feature may be seen as a complex of submarine landslides and slumps induced by the activity of the Magallanes-Fagnano fault. Gravity-driven depositional processes, such as debris-flows and slides, have been described as frequent phenomena in ice-proximal settings (Vanneste and Uenzelmann-Neben, 1997; Whittington and Niessen, 1997). Even though a glacial origin for this complex feature seems the most probable, a tectonically-induced gravity component cannot be ruled out.

The basin in Fig. 13 is an example of asymmetric depression linked to the relatively recent development of the Magallanes-Fagnano transform fault (9.5 – 7.2 Ma after Lodolo et al., 2003). Its location at the western end of the Strait, where numerous valleys join together from the Andean Cordillera and from Isla Desolación, made this basin the main recipient of the ice flowing toward the Pacific continental shelf during the glacial ages (Raedeke, 1978). A gravity core in the basin witnesses that marine conditions controlled the sedimentation of the last 21,680 years B.P. (Colizza et al., 2004), that is also during the advances D and E of the last glaciation (Clapperton et al., 1995; McCulloch and Bentley, 1998). However, during the former more intense Pleistocene ice advances, the tectonically-controlled depth of the sill at Cabo Pilar could have played a critical role in isolating the basin from the Pacific, thus favouring the deposition of glacial sediments. The high accumulation of ice could have also favoured the grounding of the glacier at the bottom of the basin. Consequently, it is reasonable to infer that, while the surficial sediments penetrated by the core are of marine origin, a significative portion of the sedimentary filling is composed of glacial sediments with frequent lateral facies changes and erosional unconformities. Unconformities with seismic characters similar to those imaged in Fig. 13 have been documented from many glaciated continental margins, as the Antarctic Peninsula (Bart and Anderson, 1995), the Svalbard margin (Solheim and Andersen, 1997), the Ross Sea shelf (De Santis et al., 1995) and the Gulf of Alaska (Carlson and Bruns, 1997). Therefore, it is possible to consider the erosional unconformities shown in Fig. 13 as ice-contact features formed during the most intense ice advances.

CONCLUDING REMARKS

The MCS exploration along the channels of the Magellan Strait has represented an exclusive opportunity in providing an inedited image of the subsurface geology across the southern Andean orogen and its adjacent foreland basin. The analyses' profiles brought to an interpretation whose main results are synthesized in the following points:

1) The Strait may be differentiated into three parts (eastern, central and western) with peculiar trends on the basis of its acoustic and geometric characters that reflect the different morphotectonic provinces of the region: foreland, fold-and-thrust belt, and Cordillera, each characterized by peculiar sedimentary and tectonic architectures.

2) The foreland basin infilling is characterized by north-eastward prograding geometry and a south-westward thickening. It rests over a syn-rift upper Jurassic basement that can be seismically imaged only in the easternmost MCS profiles. It is possible to operate an approximate stratigraphic subdivision of the Tertiary package in the foreland province (eastern and central parts) thanks to a drilling (ENAP well) on the Atlantic side of the Strait and by means of correlations with the updated geology of the area.

3) The mid-penetration profiles have emphasized a number of glacigenic features that have been recognized and genetically interpreted on the basis of their external shape and acoustic characters. They are particularly abundant along the central and westernmost segments of the Strait, and are represented by ice-contact, ice-proximal and ice-distal deposits along with features of ice erosion. On the contrary, the eastern segment is devoid of glaciogenic deposits of significant thickness.

4) The position of the frontal moraine ridge of the advance D of Clapperton et al. (1995) has been recognized in the central segment of the Strait (Fig. 6A) as a seismically transparent and continuous relief. Other prominent features have been found in the same segment, such as the prograding fan-like feature (Fig. 6A) and the bank-like unit interpreted as a proglacial lake sequence (Fig. 6B). Because of their stratigraphic position with respect to the moraine ridge, they are constrained in time to older glacial events.

5) The relatively shallow bathymetry of the eastern part of the western segment of the Strait (Isla Dawson to Isla Carlos III) is an important topographic factor that favoured the erosion at the base of the ice flows, while the deeper bathymetry of the western part (Isla Carlos III to Paso del Mar) permitted the deposition of well-preserved glacigenic deposits. In particular, the complex of stacked moraine fronts figured at the sill of Paso del Mar (Fig. 12) points out the importance of the morphological barriers in controlling the position of the glacier front during successive advances.

6) As for the role of the Magallanes-Fagnano fault is concerned, the profiles would prove the occurrence of folded and faulted Tertiary sediments, probably of Miocene age (S.N.G.M., 1982, 2003) outcropping at sea bottom and in the subsurface between Isla Carlos III and Isla Dawson (Fig. 9). Since the Magallanes-Fagnano transform fault, whose activity took place around 9.5 – 7.2 Ma (Lodolo et al., 2003), accounts for much of the tectonization of the western segment of the Strait, it can be inferred that the fault postdates the deposition of the same sediments.

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