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# Seismostratigraphic and structural setting of the Malvinas Basin and its southern margin (Tierra del Fuego Atlantic offshore)

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## ABSTRACT

New multichannel seismic reflection profiles acquired off the Tierra del Fuego Atlantic margin, from the southern part of the Malvinas foreland basin to the inner sector of the Magallanes fold-and-thrust belt, combined with available commercial profiles and exploration wells, allowed to outline the sedimentary architecture of the foreland basin and the structure of its deformed southern margin. Five major unconformities were differentiated within the sedimentary fill of the southern Malvinas basin, which neighbours the offshore extension of the Magallanes basin in Tierra del Fuego. The unconformity-bounded units record the corresponding major evolutionary tectonostratigraphic phases of the southern part of the Malvinas basin, and the development of the Magallanes fold-and-thrust belt during Mesozoic and Cenozoic times: Unit 1 - Pre-Jurassic basement; Unit 2 - Rift phase (Middle - Upper Jurassic); Unit 3 - Sag phase (Lower – Upper Cretaceous); Unit 4 - Foredeep transitional phase (Upper Cretaceous - Middle Eocene); Unit 5 - Foreland phase (Middle Eocene - Pleistocene). The southern edge of the Malvinas basin corresponds to the imbricate basement wedges of the Fuegian Cordillera, which shows a thick-skin structural style developed as a consequence of the Middle Tertiary Andean compressional tectonic phase. Large folds, with low-angle NE-verging thrusts propagated the shortening basin-ward at shallow structural levels. These structures are superimposed by an array of left-lateral strike-slip lineaments pertaining to the EW-trending Magallanes-Fagnano fault system. In the Tierra del Fuego region these structures represent the western segment of the South America – Scotia plate boundary. Several Neogene pull-apart basins were formed along the principal deformation zone in correspondence of step-overs and releasing bends. These basins show an evident asymmetry in the sedimentary architecture, and are bounded by sub-vertical faults that in some cases reach the sea-floor. Other transtensional features were also recognized in the inner sector of the fold-and-thrust belt together with the formation of restricted pull-apart basins.

*KEYWORDS* **Tierra del Fuego Atlantic margin. Malvinas basin. Magallanes fold-and-thrust belt. Tectonic evolution. Seismostratigraphy. Multichannel seismic data.**

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## INTRODUCTION

Several geophysical studies have been carried out in the south-westernmost part of the Atlantic Ocean since the early ’70, most of them focused on oil exploration. The Magallanes and Malvinas foreland basins are the principal basins in this region. The Magallanes basin extends both offshore and onshore, and occupies the central-eastern part of the Tierra del Fuego Island, whereas the Malvinas basin extends exclusively offshore to the east of the Magallanes basin. Most of the available commercial surveys were performed on the undeformed northern sectors of these basins, where important reservoirs have been discovered within the Lower Cretaceous sandstones of the Springhill Formation (Fm) (Galeazzi, 1998, and references therein; Rosello et al., this issue). However, only few and sparse information was available for the southern margins of the Magallanes and Malvinas basins, which structurally correspond to the Magallanes fold-and-thrust belt.

A comprehensive geological and geophysical investigation was launched in this region in 1998 (Fig. 1; *TESAC* and *FORTE* Projects). The main goals of this project were: (a) to characterize the sedimentary setting and the structural relationships between the two foreland basins, the deformed belt and the foredeep developed along their southern margins, and (b) to analyze the sequence of the tectonic episodes that have affected the offshore sector of Tierra del Fuego since the Middle Mesozoic. These tectonic phases have remarkably deformed the sedimentary sequences deposited in the foredeep and in some cases have significantly inverted and/or reactivated, and partially obliterated, previous structures. In some cases this superposition makes difficult to reconstruct the depositional and tectonic histories of both basins. Thus, this paper deals with reconstructing the main-sedimentary events that determined the present structural and stratigraphic framework of the southern margin of the Malvinas Basin.

## PRINCIPAL STRUCTURAL PROVINCES IN THE ATLANTIC MARGIN OF THE TIERRA DEL FUEGO REGION

Three major structural zones may be broadly distinguished in the Atlantic off-shore of the Tierra del Fuego region. These are, from N to S (Fig. 2): 1) The undeformed zone of the Magallanes and Malvinas foreland basins, corresponding to the external foreland which extends N and E of the southern Andean Cordillera; 2) The outer part of the fold-and-thrust belt (OFTB in Fig. 2) corresponding to the southern sector of the Malvinas basin foredeep that is bounded to the S by a system of asymmetric folds and associated thrusts. In this sector, the foreland basin is involved in the compressional deformation associated to the advance of the orogenic wedge, and developed in front of the edge of the southernmost Andes. The inner part of the fold-and-thrust belt (IFTB in Fig. 2) consists of different in-or-out of sequence thrust sheets, which were emplaced northward from the Middle Cretaceous to Tertiary (Miocene) compression. This compressional deformation affected the onshore and offshore

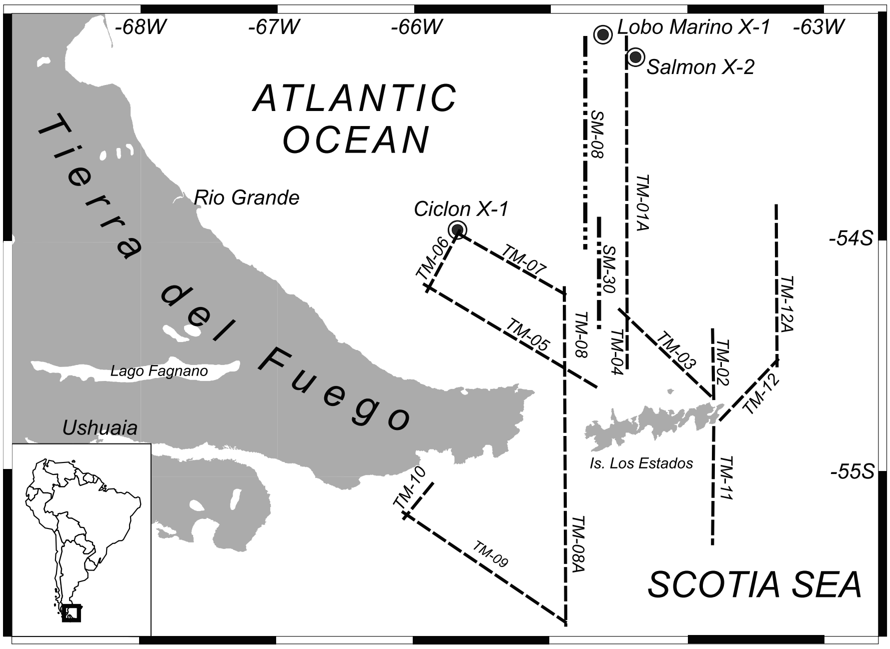

FIGURE 1 **Location map of the TESAC (TM data) multichannel seismic lines (segmented heavy lines) and available SM lines (segmented and dotted lines). Location of stratigraphic wells used in this study is also indicated. The inset shows the general location of the studied area.**

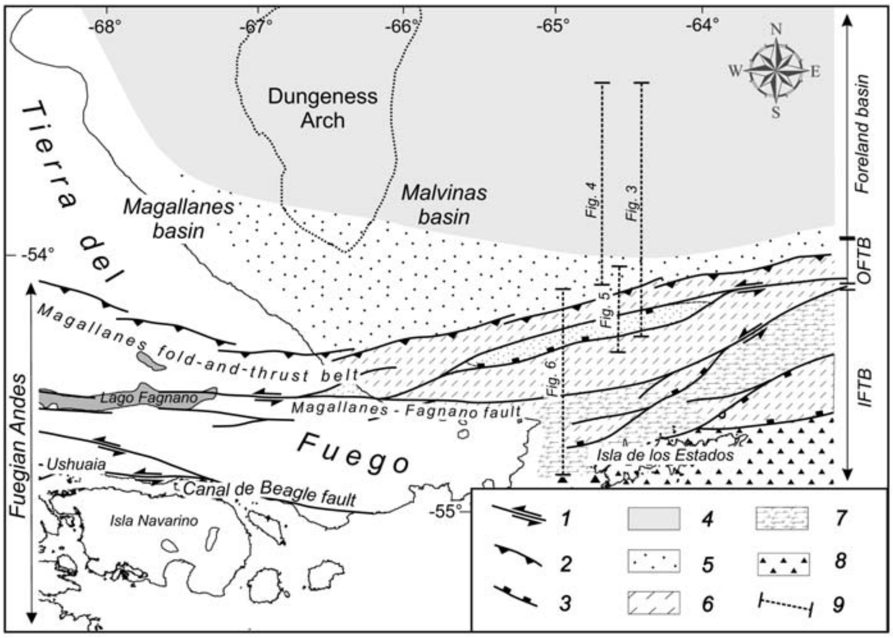

FIGURE 2 | **Simplified structural map with the main structural lineaments of the southern part of the Tierra del Fuego region, and its Atlantic offshore. 1: strike-slip fault; 2: thrust fault with the triangle in the hanging-wall; 3: normal fault with the barbs in the hanging-wall; 4: Plio-Pleistocene sediments; 5: Miocene sediments; 6: Paleogene sediments; 7: Cretaceous metasediments; 8: Upper Jurassic metamorphic rocks; 9: location of the seismic sections with reference to the Figures; IFTB: inner Magallanes fold-and-thrust belt; OFTB: outer Magallanes fold-and-thrust belt.**

southernmost parts of both the Magallanes and Malvinas basins, and partially inverted the Rocas Verdes back-arc basin (Winslow, 1982); and 3) The Late Palaeozoic-Early Mesozoic crystalline polydeformed and metamorphosed rocks of the southernmost Andes, which were part of the ancient accretionary complex developed along the Gondwanaland Pacific margin. This thick-skinned thrust system developed from its deeper roots and progressively propagated to the shallow stratigraphic levels of the northward-verging Magallanes fold-and-thrust belt (Menichetti et al., this issue). The rocks involved in the Andean (Late Cretaceous) compression display oriented fabrics defined by low-greenschist facies assemblages. During this tectonic event three distinct phases of penetrative ductile deformation took place, both in the basement and in the cover units. The uplift of the Cordillera, the emplacement of plutonic rocks, and the intracontinental polyphase deformation are all products of this thick-skinned tectonics.

The Magallanes and Malvinas foreland basins (Fig. 2) developed on the South America continental crust, and are located in front of the Fuegian Cordillera, the southern part of the Andes. This segment of the Andean orogen merges eastward in the North Scotia Ridge through the Magallanes-Fagnano transform fault system (Lodolo et al., 2003). The Magallanes and Malvinas basins are structurally separated by the Dungeness Arch, a basement high that probably developed during a Jurassic rifting phase and remained elevated during the later Mesozoic and Cenozoic tectonic evolution (Zambrano and Urien, 1970). The western and southern boundaries of these basins correspond to the outcrops of the deformed Jurassic-Cretaceous Rocas Verdes marginal basin assemblages (Dalziel et al., 1974), which unconformably overly the Andean crystalline basement.

## *TESAC* AND *SM* MULTICHANNEL SEISMIC REFLECTION SURVEYS

This study is mostly based on multichannel seismic surveys conducted on the Atlantic sector of the Tierra del Fuego continental margin (see Fig. 1), and includes newly acquired multichannel seismic data (*TM* data) and available industrial seismic sections provided by the Secretaría de Minería Argentina (*SM* data).

Seismic lines off the Atlantic coast of Tierra del Fuego were acquired on October 1999 by the oceanographic vessel A.R.A. *Puerto Deseado*, owned by the Argentinean Navy, in the frame of the *TESAC* project (*TM* data). A portable acquisition system was installed onboard, and comprised a 1,200-m-long solid-state streamer with 96 channels, and two GI-guns of 210 cubic inches each. About 900 km of data were collected along twelve seismic lines (TM-01 to TM-12A; Fig. 1), which image the Tierra del Fuego continental platform both N and S of Isla de Los Estados. All the seismic lines were Global Positioning System (GPS)-navigated. The seismic processing applied to the data was carried out at the Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS). Details of the processing sequence can be found in Geletti (2001).

The *TESAC* scientific and *SM* industrial data presented in this work were collected with different purposes and seismic equipments and the processing sequence applied were quite different for the two datasets. However, the different data quality and resolution of the seismic profiles did not significantly hinder a precise correlation of the main identified seismic horizons. Particular care was taken during the processing of the *TM* profiles to remove the strong multiples generally present in the lines acquired on the continental platform in the southern part of the Malvinas basin and in the vicinity of the Isla de Los Estados. Seismic processing generally failed to clearly image the structures beneath these regions, where multiples of the hard basement created many diffractions, negatively enhanced by migration.

## SEISMOSTRATIGRAPHY OF THE TIERRA DEL FUEGO ATLANTIC OFFSHORE

The seismostratigraphic information for the offshore sector of the Tierra del Fuego Island was obtained by correlating seismic lines and exploratory wells, in combination with previous interpretations (Biddle et al., 1986; Yrigoyen, 1989; Galeazzi, 1998; Ramos, 1996; Urien and Zambrano, 1996; and references therein), and published results (Tassone et al., 2001, 2003, 2005; Lodolo et al., 2002a, b, 2003; Yagupsky et al., 2003, 2004; Yagupsky, 2004; Menichetti et al., this issue). The stratigraphy used in the seismic interpretation is derived from available wells published by Galeazzi (1998). In particular, three wells have been considered (Salmon X-2, Lobo Marino X-1, and Ciclon X-1; Fig. 1), because of their vicinity with our *TM* lines and the other presented profiles. Salmon X-2 well is located over SP 600 of seismic line TM-01 (Figs. 1 and 3), Lobo Marino X-1 well is located close to SP 2000 of seismic section SM-08 (Figs. 1 and 4), Ciclon X-1 well is located over shot point (SP) 300 of profile TM-07. Besides the seismic lines presented in this work, the interpretation originally presented by Galeazzi (1998) was also used to: (a) compare the geological structures found in our dataset, (b) correlate regionally the identified unconformities, and (c) assign their ages.

The entire sedimentary succession of the Malvinas basin spans from Jurassic to Holocene. The Jurassic volcanoclastic sediments of the Tobífera Fm overlie a pre-Jurassic basement, constituted mainly by Late Paleozoic low-grade metamorphic rocks affected by several acid

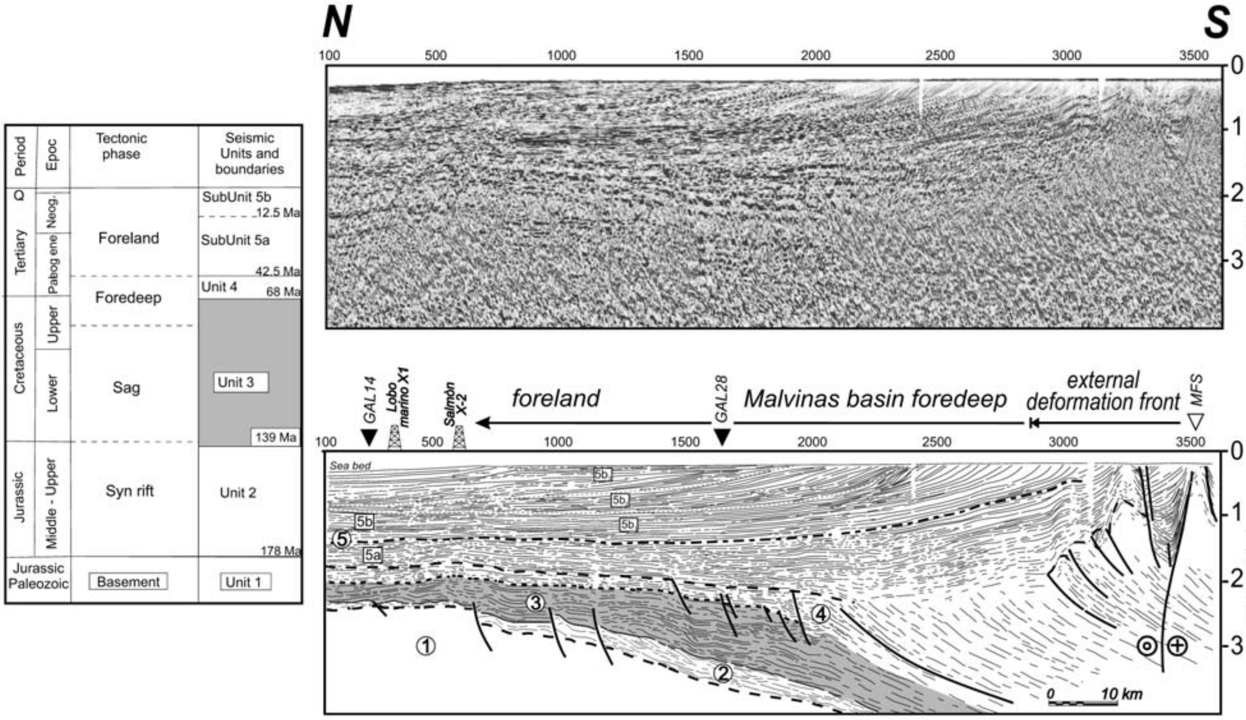

FIGURE 3 **Seismic line TM-01 and line-drawing (see location in Figures 1 and 2) showing the Malvinas basin foredeep, the outer front of the Magallanes fold-and-thrust belt, and the master fault and associated asymmetric basin of the Magallanes-Fagnano transform system. The width of the whole foredeep is about 100 km with a clastic succession spanning from Late Cretaceous to Pleistocene. The sediments prograde northward and the deposition is controlled by the general basin subsidence. The scarcely deformed sediments in the southernmost part of the basin suggest a weak rate of frontal advance of the orogenic wedge. A possible forebulge could be located at about SP 500, without any structural control of the preexisting Jurassic faults. Refer to Figure 5 for additional details of the internal part of the basin. Circled numbers refer to the seismostratigraphic Units mentioned in the text. Locations of the wells used in the stratigraphic calibration are also indicated. MFS: Magallanes-Fagnano fault system. A stratigraphic sketch of the recognized seismic Units is shown to the left.**

intrusions (Mukasa and Dalziel, 1996). An Upper Jurassic - Lower Cretaceous transgressive siliclastic wedge that was fed mainly from the N (Biddle et al., 1986) is overlain by late Cretaceous neritic sediments including mudstones, shales, marls and siltstones. The siliciclastic foredeep deposition started in the Paleogene, with the accumulation of a wedge presenting several unconformities and starved intervals (Galeazzi, 1998). The foredeep sediments derived longitudinally and transversally from the fold-and-thrust belt front located to the south. Shallow marine shelf and fluvial fan systems developed during this evolutionary phase can be easily related to the onshore outcrops . In the Atlantic margin of the Tierra del Fuego Late Cretaceous-Paleocene proximal facies are well known (Olivero and Malumián, this issue).

Two representative seismic profiles presented in Figs. 3 and 4 show the general architecture of the sedimentary sequences deposited in the southern part of the Malvinas basin foredeep and can be used to distinguish the different units within the sedimentary cover, calibrated with wells Lobo Marino X-1 and Salmon X-2 (Galeazzi, 1998). On these seismic profiles, five major unconformities have been identified within the sedimentary fill of the Malvinas basin that overlies the pre-Jurassic basement (Figs. 2 to 8). These unconformities that bound the units, document the major tectono-sedimentary cycles of the region, from the Jurassic extensional phase to the Late Cretaceous - Paleogene Andean compression, and then to the Late Paleogene-Neogene wrench tectonic phase that deformed the southern margins of both the Magallanes and Malvinas basins.

## Unit 1. Pre- Jurassic igneous-metamorphic basement

This Unit occurs at about 2.5-3.0 s two-way traveltime (TWT) (Figs. 3 and 4) and progressively deepens southward with a gentle slope in all the sections. Several south-dipping normal faults rooted in the basement downthrow the reflectors and contribute to the slope geometry. The top of Unit 1 is characterized by a zone of discontinuous and parallel reflections overlying a zone of chaotic reflec-

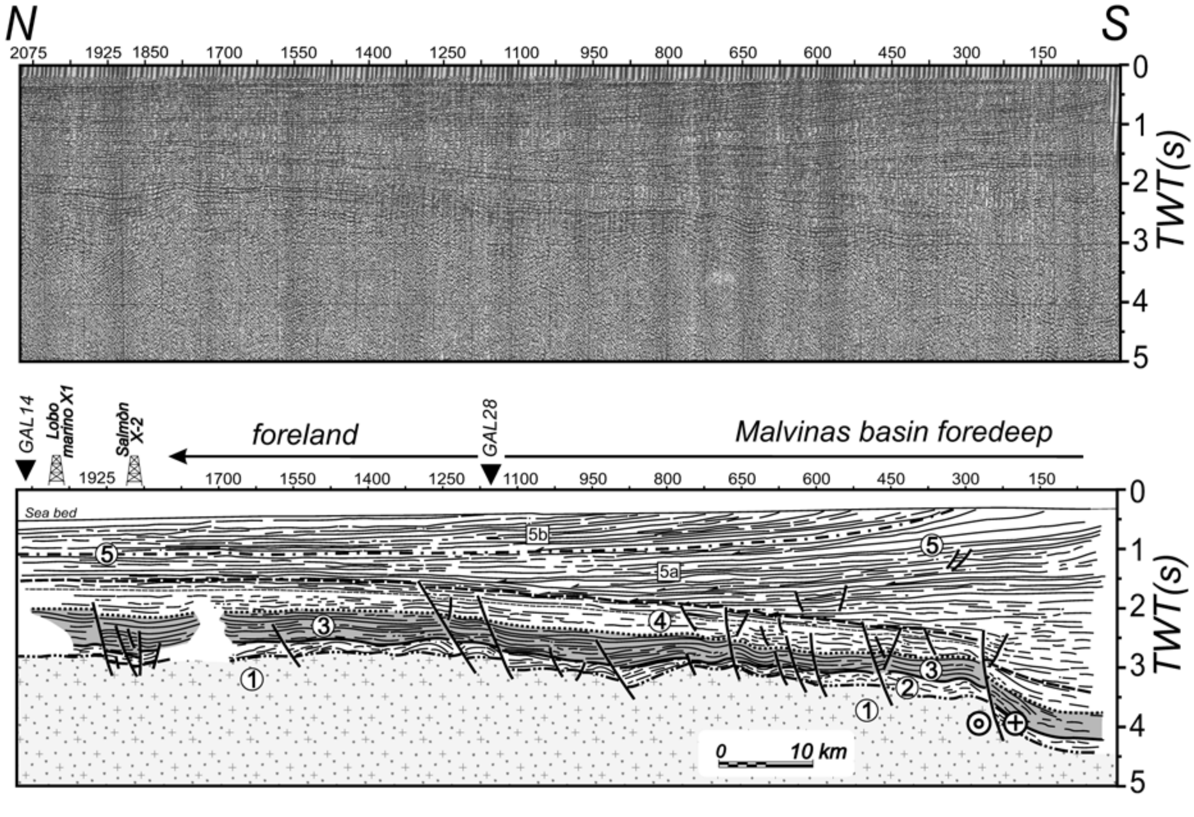

FIGURE 4 **Seismic line SM-08 and line-drawing (see location in Figure 2). This section shows the transition from the foredeep to the foreland of the Malvinas basin, marked by the northward sediment progradation. The normal faults in the southernmost part of the section control the early stage of the foredeep evolution in the Paleogene and are interpreted as a strike-slip structure. This fault system cross-cuts the Lower Eocene reflectors (dashed line between Units 4 and 5) and post dates the initial strike-slip activity in the Fuegian Andes (refer to Figure 5 for more details). The clastic sedimentary wedge depocenters shifted toward N according to the general basin subsidence. There is no evidence of a peripheral bulge forming in response to flexural down-bending of the continental lithosphere resulting from orogenic and topographic load in the classical models of the foreland basins. Several Upper Jurassic extensional faults with half graben geometry are visible in the lower part of the section. Circled numbers refer to the seismostratigraphic Units mentioned in the text and in Figure 3. Locations of the wells used in the stratigraphic calibration are also indicated.**

tors (Figs. 4 and 5) like the one reported for the upper boundary of the acoustic basement of the western Malvinas basin (Galeazzi, 1998). This basement Unit is made up by Paleozoic low-grade metamorphic rocks (Forsythe, 1982) intruded by Jurassic granites (which were tapered at 1,935.5 m.b.s.l. in the Lobo Marino X-1 exploration well and dated about 168 Ma; Yrigoyen, 1989). The basement, which was extrapolated for depths >3.0 s TWT, is seismically homogeneous and with poor lateral continuity and moderate amplitude, resulting in a chaotic arrangement.

## Unit 2. Middle-Upper Jurassic metavolcanoclastic rocks

This Unit unconformably overlies the basement (i.e. Unit 1) and generally shows a strong seismic facies contrast with it. The thickness of this Unit changes since it presents a general wedge-shaped geometry, and appears controlled by a set of S-dipping normal faults that generated half graben structures (Fig. 4, from SP 500 to SP 1,000) where a volcanoclastic suite of tuffs, tuffaceous sandstones and rhyolites (possibly related with the Middle to Upper Jurassic Tobífera Fm), were deposited. The top of this Unit is defined by a regional unconformity which was dated at 150.5 Ma (i.e. Late Jurassic) on the basis of outcrop data from Patagonia (Biddle et al., 1986). Additionally, the ~151 Ma SHRIMP U/Pb in age obtained for the ocean crust of Rocas Verdes Basin in Chile (Calderón et al., 2004) sets an upper time constrain for the effusive activity that resulted in the generation of the Tobífera Fm.

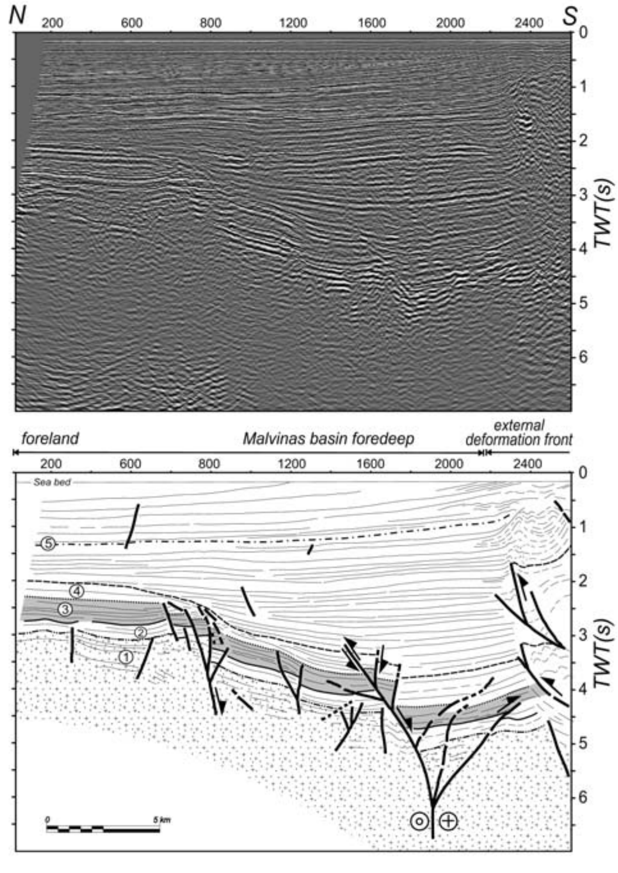

FIGURE 5 | **Seismic line SM-30 and line-drawing (see location in Figures 1 and 2). This profile images the internal part of the Malvinas foredeep basin. The early phase of the foredeep evolution was controlled by a Late Cretaceous left-lateral strike-slip fault located at SP 2,000. Northwards, a flower structure cross-cuts the Lower Eocene reflectors (dashed line between Units 4 and 5) and post dates the early stage of strike slip activity in the Fuegian Andes. The wedge top sediments are slightly folded while the foredeep strata toward N are gently deformed. The size of this foredeep sector is a few tens of kilometers, while the sedimentation is controlled by the general basin subsidence. Circled numbers refer to the seismostratigraphic Units mentioned in the text and in Figure 3.**

## Unit 3. Lower-Upper Cretaceous partially metamorphosed sediments

The lowermost deposits of Unit 3 display onlap terminations against the basement structural highs and downlap terminations over the top of the Middle to Late Jurassic Tobífera Fm. The upper part of this Unit underlies a 68 million years old discordance. Unit 3 displays parallel reflectors with moderate amplitude and continuity, and shows a dominant aggradational arrangement. The seismic sections show that the faults that controlled the sedimentation of Unit 2 were also active during the deposition of the lower Unit 3 (Fig. 3). In many cases, the reflectors are discontinuous. The lower levels of Unit 3 might be correlated with the Lower Cretaceous deposits that filled the Rocas Verdes basin (either Yahgán or Beauvoir Fms), presently exposed in the onshore areas of the inner fold-and-thrust belt (Fig. 2). The uppermost Unit 3 levels would be the offshore equivalents of the onshore Upper Cretaceous formations exposed in Península Mitre (i.e., Estratos Buen Suceso, Bahía Tethis and Policarpo Fms; Olivero and Medina, 2001; Olivero and Malumián, this issue), which were later involved in the Late Cretaceous - Paleogene (Danian) Andean compressional phase.

## Unit 4. Late Cretaceous-Early Paleocene-Middle Eocene terrigenous sediments

Unit 4 overlies a 68 million years old erosive discordance and underlies a 42.5 million years old regional unconformity (Galeazzi, 1994, 1998), thus ranging in age from Late Cretaceous to Middle Eocene. This Unit shows laterally continuous, parallel to sub-parallel reflectors of moderate amplitude and continuity with retrogradational arrangement, along the entire N-S section of the basin (Figs. 3 and 4). The reflectors at the bottom of the Unit display downlap terminations.

The extensional basement faults affected slightly this Unit. In the northern part of the basin, Unit 4 is com-

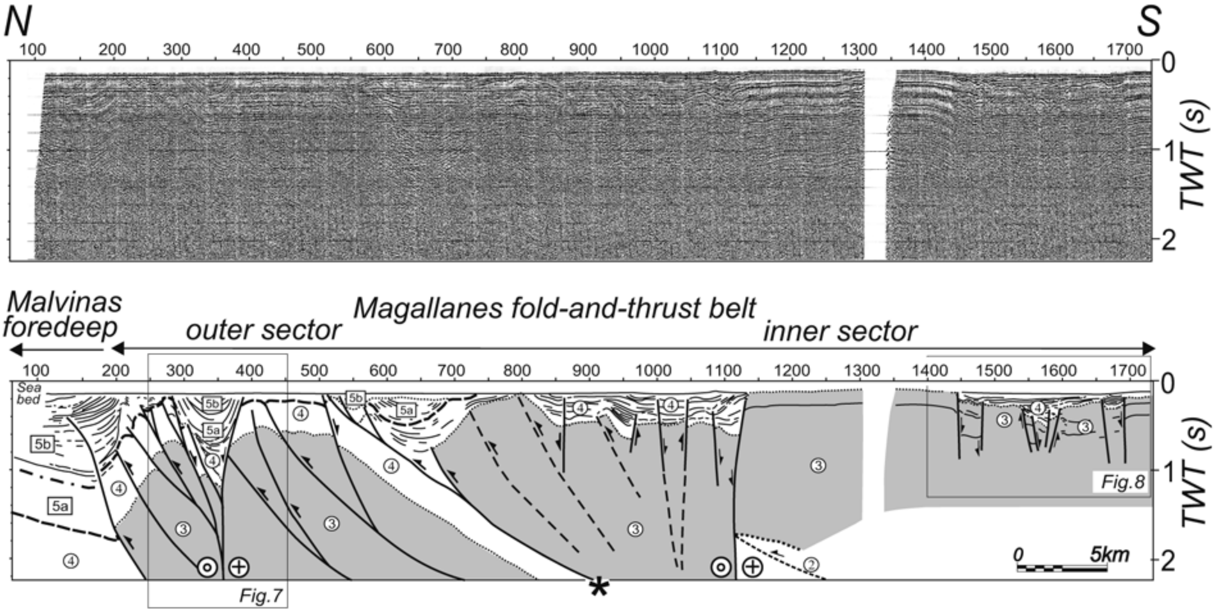

FIGURE 6 | **Seismic line TM-08 and line-drawing (see location in Figures 1 and 2). The line intersects the southernmost part of the Malvinas foredeep and the external and inner sector of the Magallanes fold-and-thrust belt, just to the W of Isla de Los Estados. The wedge top deformed strata are visible in the northern part while the different stacks of the thrust sequences are not very well constrained by the weak penetration of the seismic section. The asterisk indicates one of the main thrust faults of the Magallanes fold-and-thrust belt. The inset frames refer to Figures 7 and 8. Circled numbers refer to the seismostratigraphic Units mentioned in the text and in Figure 3.**

prised between 1.75 and 2.0 s TWT, whereas in the southern sector it occurs between 2.0 and 2.5 s TWT. This Unit is composed of sandstones, glauconitic clays, mudstones, calcareous wackes and micritic limestones of the Arenas Glauconíticas Fm (Galeazzi, 1998). The deposits of Unit 4 fill an asymmetric basin with its maximum thickness in the S (Fig. 3, between SP 3,300 and 3,500).

Unit 4 may be correlated with the Tertiary sediments of the southern parts of the Magallanes and Malvinas foreland basins, which were involved in the fold-and-thrust compressional belt. Along the Atlantic coast of Tierra del Fuego Island, open folding affecting the Tertiary sediments has been reported (Olivero and Malumián, 1999, and this issue; Ghiglione et al., 2002; Lodolo et al., 2003; Menichetti et al., 2004; Ghiglione and Ramos, 2005). We propose the correlation of this Unit with the onshore Tertiary deposits of the Río Claro Group (Lodolo et al., 2003; Olivero and Malumián, 1999, and this issue).

## Unit 5. Middle Eocene-Pleistocene terrigenous sediments

Unit 5 overlies a 42.5 million years old regional unconformity (Galeazzi, 1994, 1998) and presents a complex set of reflectors with several onlaps and northward progradations, with a well developed wedge-shaped geometry. This configuration is quite typical of the foredeep filling, with a progressive shifting of the depositional systems towards the foreland. Given the evident different geometry of the reflectors, this Unit was subdivided into two Sub-units: 5a (Late Eocene-Oligocene-Miocene) and 5b (Miocene-Pliocene-Pleistocene) (Figs. 3 to 8). Two additional, subordinate unconformities were distinguished within this Unit on the basis of the studied seismic sections. The older might be bracketed between 15.5 and 12.5 Ma (i.e. Middle Miocene) and would be overlain by the bottom of Sub-unit 5b; the younger would be dated at 5.5 Ma (i.e. Late Miocene) and would be included in the Sub-unit 5b. Both unconformities were tentatively dated by Galeazzi (1998) on the basis of their correlation with the boundaries of some precise third and fourth order sequences (Mitchum and Van Wagoner, 1991; Vail et al., 1991).

Data from oil exploration wells indicate that Sub-unit 5a is composed of mudstones with interlayered lithic, quartz and glauconitic sandstones, and limestones. These foreland deposits are located at <1.75 s TWT in the northern areas and increase their thickness southwards where they are comprised between 2.5 s TWT and the sea-floor. This section is strongly progradant northwards and shows a wedge-shaped geometry in the foredeep area. Sub-unit 5a is correlated with La Despedida and Santo Domingo Groups of the onshore areas in the central part of Tierra del Fuego Island (Olivero and Malumian, 1999, and this issue).

Overlying the 15.5-12.5 Ma unconformity, the Sub-unit 5b displays oblique progradant geometry (Sangree and

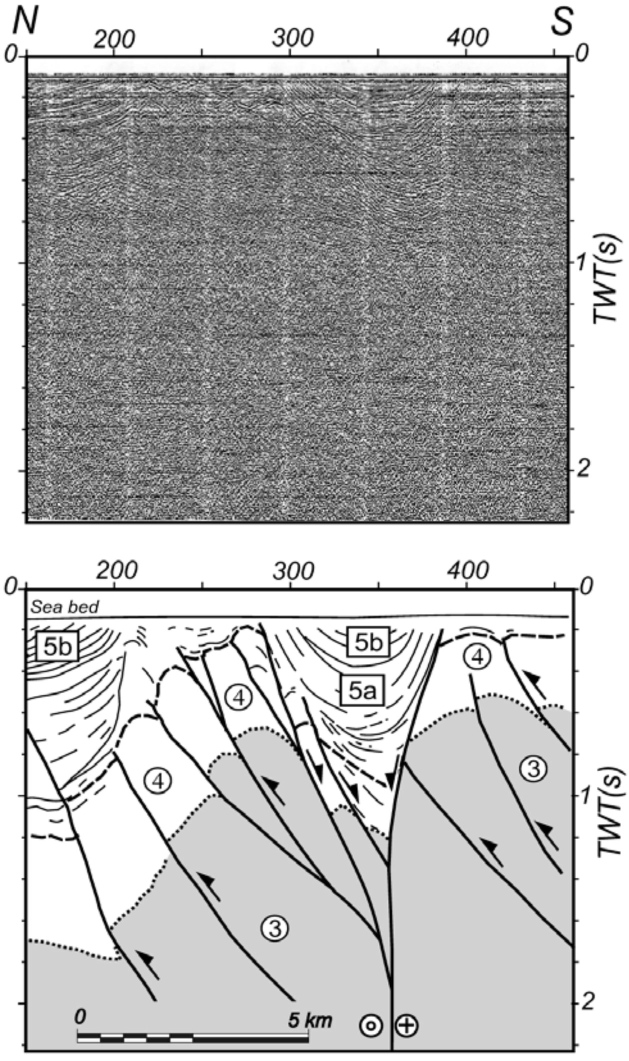

FIGURE 7 **Northern part of seismic line TM-08 and line-drawing (see location in Figure 6), showing the sedimentary architecture of a pull-apart basin developed along the Magallanes-Fagnano strike-slip tectonic lineament. The sub-vertical transtensional structures cut the thrust fault system, inverting such planes in the external sector (after Lodolo et al., 2003). Circled numbers refer to the seismostratigraphic Units indicated in Figure 3.**

Widmier, 1977). It is characterized by a curve wedge shape, with upward concavity and oblique reflectors of variable (increasing upwards) dip. At the southern tip of the basin, the Sub-unit occurs between 1.5 s TWT and the sea-floor; the thickness decreases northwards to around 0.5 s TWT. The seismic reflectors show high amplitude and continuity with downlap terminations over the base. The deposit geometry points to a basin margin with a main sedimentary source area located to the S. The uppermost levels of Sub-unit 5b overlying the 5.5 Ma discontinuity up to the sea-floor display oblique progradant geometry (Fig. 3). This Sub-unit is related to Estratos de La Maria Luisa, Irigoyen Fm and Quaternary sediments in the onshore areas (Lodolo et al., 2002a, 2003; Menichetti et al., 2004; Olivero and Malumián, 1999, and this issue).

## TECTONOSEDIMENTARY EVOLUTION OF THE TIERRA DEL FUEGO ATLANTIC OFFSHORE

### Units 1, 2 and lower part of Unit 3

The seismic reflection sections of the Malvinas basin show the presence of normal faults affecting Units 1 and 2 (Fig. 4). These extensional faults have a NW-SE general trend in the Atlantic offshore, while close to the Fuegian Cordillera they appear rotated anticlockwise during the Cenozoic compressional and transcurrent evolutionary phases (Biddle et al., 1986; Robbiano et al., 1996; Galeazzi, 1998; Menichetti et al., this issue). A system of asymmetric tilted fault blocks was deformed on a south-dipping listric normal sole fault. The geometrical pattern is constituted by alternating and partially overlapping grabens and half-grabens, which were bounded by secondary faults. In several areas (Fig. 4, between SP 650 and SP 1,250) the basin shows roll-over structures with growth-fault systems; a few of them were possibly reactivated in further tectonic events (Fig. 3, SP, 1000). The extensional structures are arranged in a right-stepped geometry with WNW-ESE-oriented transfer zones that possibly constitute local depressions, where the extensional crustal thinning was renewed by magmatic accretion (Menichetti et al., this issue). In the extensional lows, more than 2,000 m of the volcanoclastic complex of the Tobífera Fm were deposited over the pre-Jurassic basement.

In the seismic lines of the Malvinas and Magallanes basins, the Tobífera Fm displays two sedimentary sequences of the same thickness separated by an unconformity (Galeazzi, 1998). These probably represent Jurassic rift sequences, which reflect the mechanical and thermal subsidence of the basin. The normal fault systems include sub-vertical structures with cumulative variable offsets from several hundred to more than one thousand meters.

Within the Rocas Verdes basin there was an important diachroneity both in the fault evolution and in the basin filling, with the Tobífera Fm dated Middle Jurassic in the Tierra del Fuego Island (Mukasa and Dalziel, 1996; Pankhurst et al., 2000). In this marginal basin, the geometry of the structures allows estimation of the extension, ranging from 15 to 20% (Menichetti et al., this issue). A depth of 10 km for the detachment of the listric sole normal fault may be inferred from geometrical reconstruction, compatible with a thinning extensional crust (Menichetti et al., this issue). Crustal stretching increases towards W and SW, where the progressive thinning locally allowed the formation of the oceanic crust (Dalziel et al., 1974).

## Uppermost Unit 3 and Unit 4

In the Late Cretaceous, the tectonic regime progressively shifted from extensional to compressional, leading to the development of the Andean Cordillera (Winslow, 1982; Diraison et al., 2000). This tectonic phase involved the Rocas verdes marginal basin, with horizontal contraction and crustal thickening, and resulted in polyphasic deformations in a thick-skinned tectonic style. In the Fuegian Andes, several slices of the basement rocks were thrusted toward the South America craton, with a total crustal shortening of hundreds of kilometers (Menichetti et al., this issue).

The analysis of the seismic sections in the Malvinas basin shows that there was a general increasing deformation along its southern margin, which resulted in a progressive migration of the foredeep/chain system and involvement of the inner sectors of the foredeep basin in the compressional processes. The external front of the deformation belt is shown in Fig. 3 (at about SP 3,200), and in Fig. 6 (at about SP 200). Figure 3 also shows the presence of an asymmetric and restricted basin, bounded by a major sub-vertical fault to the S, and centered at about SP 3,400. This basin is developed within the main deformation zone of the Magallanes-Fagnano fault system, along which other asymmetric basins have been recognized (Lodolo et al., 2003). Along the Atlantic margin of the Tierra del Fuego, outcropping foredeep sediments progressively become younger moving northward (Olivero and Malumián, this issue). The orogenic system developed at the end of the Mesozoic, from its internal deeper roots, S of the Isla de los Estados, and progressively propagated to the shallow stratigraphic levels of the northward-verging orogen, involving the basin deposits.

A simple foredeep/chain system has been proposed for the Andean Cordillera sector in the Tierra del Fuego Island, where the orogenic deformation migrated toward N and imposed a tectonic and topographic load over the continental lithosphere of South America (Ghiglione and Ramos, 2005). The resulting flexural down-bending of this lithosphere produced the subsidence and the development of the Magallanes and Malvinas peripheral foreland basin system and the spatial and temporal evolution of the associated depositional zone (Olivero and Malumián, this issue).

The action of the transcurrent tectonism has been significant for the basin evolution, as is well recorded by the downlap terminations of the reflectors at the bottom of the Unit 4 (Figs. 3 and 4) which is correlated to the beginning of the transpressional evolutionary stage. The inner part of the foredeep basin is shown in Fig. 5, where two major strike-slip faults down throw the basement for at least 2.0 sec TWT (from SP 800 to SP 2,000). The lateral continuity and the geometry of this structure are displayed also in Fig. 4 at SP 250. These faults show a typical flower-like structure, which indicates a significant component of slip motion. Splays of normal faults are present in the northern part and compressional faults in the southern one. These strike slip faults have driven the development of a main depocenter in the Malvinas basin, and probably contributed to the main basin subsidence of the foredeep. These faults are rooted in the basement and the age of their activity may be inferred from the unconformity that bounds the top of Unit 4, which corresponds to the Middle Eocene. It is possible to infer that these strike-slip faults inverted some of the extensional Mesozoic structures (SP 2,000 in Fig. 5).

The sedimentary wedge of the Malvinas foredeep consists of several wedge-top, N-dipping siliciclastic Pliocene-Pleistocene units that are transgressive over Upper Miocene deposits that are included in an underlying succession spanning from Upper Oligocene to Miocene (Figs. 3 and 5). This underlying succession consists of a progradational sedimentary wedge of glauconitic sandstones, limestones, claystones and tuffs (Galeazzi, 1998). In the inner sector, the succession consists of Paleocene-Eocene wedge-shaped, onlapping megasequences. In the southern part, the whole stratigraphic succession is strongly involved in the

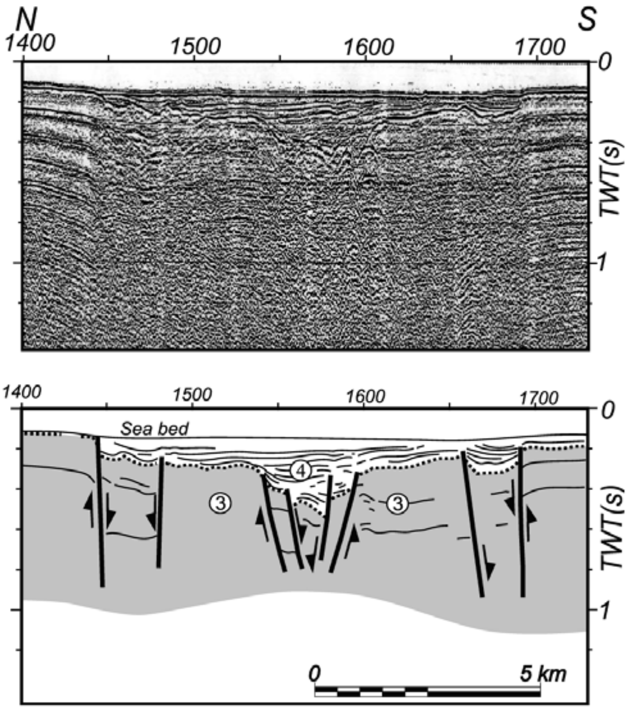

FIGURE 8 **Southernmost part of seismic line TM-08 and line-drawing (see location in Figure 6). The line shows a shallow extensional Paleogene basin. In spite of the poor resolution of the line, the different sedimentary architecture of this basin with respect to the pull-apart basin in Figure 7, is made evident. Circled numbers refer to the seismostratigraphic Units illustrated in Figure 3.**

deformation (Figs. 3 and 5), mainly the Late Cretaceous neritic siliciclastic facies (Olivero and Malumián, this issue) that form the early stage of the foredeep evolution and the sedimentary filling.

### Sub-Units 5a and 5b

The geometry and the Neogene kinematic history of the southern sector of both Magallanes and Malvinas basins are well preserved in several outcrops of the Tierra del Fuego Island, where the Late Cretaceous/Paleogene compressional structures are cut by strike-slip faults (Cunningham, 1993; Lodolo et al., 2003; Menichetti et al., this issue). The EW-trending system of strike-slip faults generated complex geometries like releasing step-overs, restraining bends, pop-ups, pressure ridges and uplifted slivers of crust (Lodolo et al., 2003; Fig. 2). Restraining bends and overlapping step-overs are distributed along the entire Fuegian Cordillera and are subordinated in size with respect to the releasing zones. The releasing step-overs along the fault system formed several elongated pull-apart basins with a size of the order of many tens of km in length and a few km of width. In the Atlantic off-shore of the Tierra del Fuego Island, at least two other basins bounded by sub-vertical discontinuities that reach the sea-floor, present a strong asymmetric architecture (Fig. 3, SP 3,400), and displaying increasing sedimentary thickness towards the master fault.

## DISCUSSION AND CONCLUDING REMARKS

A set of multichannel seismic reflection profiles acquired in the southern part of the Malvinas basin and across the Magallanes fold-and-thrust belt were analyzed. These data have allowed to document the stratigraphic setting of the foreland basin and the structural framework of its deformed inner and outer front. The unconformities identified on the seismic profiles have been calibrated with industrial wells, and five principal unconformities which bound sedimentary Units were recognized in the sedimentary fill. This, in turn, has allowed to describe the tectono-stratigraphic phases occurred along the Atlantic margin of the Fuegian Andes.

### Rift phase. Mechanical and thermal subsidence. Rocas Verdes back-arc basin (Early Jurassic - Late Cretaceous)

The geodynamic history of the Tierra del Fuego Atlantic margin initiated with the normal faulting associated with the Middle Jurassic to Lower Cretaceous Gondwana break-up. This event, which caused crustal stretching and widespread siliceous volcanism in the Extra Andean Patagonia and Antarctic Peninsula (Vaughan and Storey, 2000), culminated in the Southernmost Andes with the development of the Rocas Verdes back-arc basin (Dalziel, 1981), later followed by a sag basin phase. The crustal thinning involved the Palaeozoic metamorphic basement, with the development of extensional structures associated with the ensialic Rocas Verdes back-arc basin formation (Dalziel et al., 1974; Mukasa and Dalziel, 1996). The basin geometry and structure, mainly controlled by the regional extensional stress field, show also an important wrench component in the Tierra del Fuego region. Many of the extensional structures are related to mafic dyke swarms hosted in the basement rocks and in the Tobífera (Middle-Upper Jurassic) and Yahgán (Lower Cretaceous) Fms (Winslow, 1982; Wilson, 1991).

The extensional regime originated NW-SE grabens and semi-grabens in the Palaeozoic crystalline basement (Unit 1). Simultaneously, huge volumes of magmatic and pyroclastic materials were produced (Unit 2, Tobífera or Lemaire Fm). The South America drift was accompanied by thermal subsidence of the lithosphere from Late Jurassic to Late Cretaceous, with accumulation of post-rift sediments (Unit 3).

### Andean Compression. Malvinas basin foredeep transitional phase (Late Cretaceous-Middle Eocene)

The compression that accounts for the Andean deformation along the Pacific margin of the South America continent initiated in the Late Cretaceous with the development of a thick-skin tectonic style. This process produced the inversion and closure of the Rocas Verdes basin and the uplift of the internal part of the orogen, starting up the tectonic subsidence in the Magallanes and Malvinas basins. This phase marked the beginning of the system chain/foredeep in the Maastrichtian. During the Tertiary, the development of the Magallanes fold-and-thrust belt began, and progressively migrated towards the foreland with the incorporation of the inner part of the foredeep. This tectonic process occurred simultaneously with the sedimentation, and contributed to the development of the thrust front. In the Malvinas basin, the foredeep was settled in the Early Tertiary (coeval with Unit 4) and changed to be a foreland basin *sensu stricto* since the Middle Eocene (Unit 5).

An important component of strike-slip stress field in this region may have been active since around 100 Ma, associated with the relative motion between the Antarctic Peninsula and South America. It was proposed (Klepeis, 1994a, b) that the Magallanes-Fagnano transform system might have undergone strike-slip movements before the Oligocene development of the transform boundary between the Scotia and South America plates along the

North Scotia Ridge. Since Middle Cretaceous, the inner sectors of the Fuegian Andes would have undergone transcurrent motion in the Beagle Channel region (Cunningham, 1993, 1995), and other strike-slip lineaments, paralleling the Magallanes-Fagnano transform system, occur in the Tierra del Fuego region.

Since the Middle Eocene, an important change occurred in the geometry and depositional setting of the Malvinas basin. This change is the result of the beginning of a compressional tectonic regime, possibly with strike-slip components, in the southernmost Tierra del Fuego region. The compression and formation of thrust faults allowed the propagation towards N of the Andean orogen, triggering the downwarping of the crust in the sector adjacent to this axis of deformation, with the consequent generation of space to accommodate sediments. The mechanical subsidence was probably accentuated by the activity of the transtensional structures generated during the Paleocene in the foredeep region, where a significant deepening of the Middle Eocene unconformity is observed, severely modifying the geometry of the basin. Some of the old high-angle normal faults associated with the Jurassic rift were reactivated, increasing their displacements. As a result, a deep depocenter was developed adjacent to the orogenic front. Some sub-vertical faults in the basement underwent inverse reactivations, developing positive flower structures. This structural pattern originated by strike-slip movements, with transtensional and transpressional structures striking E-W, which affected the southern sector of the basins during the Early Cenozoic, as recognized by Robiano et al. (1996) in the Austral basin and by Yrigoyen (1989) and Galeazzi (1998) in the Malvinas basin. The subsidence of the foredeep was possibly increased by transtensional mechanisms, overlapped to the normal faulting that had resulted from the Jurassic rifting. The rise of the Andean Cordillera in this region also produced a new sedimentary source in the southern margin. This regime was also registered during the Paleogene in the inner sector of the fold-and-thrust belt. A series of folds of kilometric scale are observed, likely transported by blind thrust faults, slightly deforming the overlaying Miocene strata. The inner fold-and-thrust belt shows possible Cretaceous and Jurassic outcrops on the sea-floor. Onshore at the same latitude, between the Beagle Channel and the Lago Fagnano, Caminos (1980) described the presence of folds within the Cretaceous Yaghán Fm, whose axial plane cleavages show E-W strikes and sub-vertical inclinations.

## Wrench tectonics. Malvinas basin foreland phase (Middle Eocene-Pleistocene)

South of the Magallanes-Fagnano fault system, the outer fold-and-thrust belt affects the Tertiary sediments, deposited syn-tectonically in the frontal synclines and dorsal limbs of the anticlines. Galeazzi (1998) identified the first evidence of the development of the fold-and-thrust belt and the associated foreland basin in the Malvinas basin, and dated Middle Eocene. The compressional front would have ended in the Oligocene (Álvarez-Marrón et al., 1993; Klepeis, 1994a; Menichetti et al., this issue), and then changing to a new strike-slip tectonic regime that was superposed to the structures previously formed by the fold-and-thrust belt and the foredeep geometries. These later strike-slip faults are possibly related to the opening of the Drake Passage and the subsequent formation of the Scotia plate during the Early Oligocene/Late Miocene time span as proposed by Geletti et al. (2005), and Lodolo et al. (2006). The Middle Eocene to Pleistocene foreland development is recorded in the sedimentary wedge of Unit 5.

The relationship between the tectonic events affecting the area from Late Cretaceous to Miocene can be analyzed in the frame of the general relative movements between the Antarctica Peninsula and South America plates. The presence in the southern tip of South America of an important transform plate boundary active since the Jurassic is well documented (Mukasa and Dalziel, 1996). It is more difficult to define the extent of the contribution of this lineament in the shaping of the Malvinas foredeep. The Magallanes basin, located in front of the Andean Cordillera, with its axis paralleling the mountain chain, represents a classic foredeep basin, where the temporal persistence of the Dungeness Arch during the Cenozoic compression could have represented its peripheral bulge. The Malvinas basin, on the other hand, with its E-W oriented axis, could represent a smaller foredeep basin, where strike-slip tectonism had a stronger influence with respect to the compression in shaping the geometry of the basin and its geodynamic evolution.

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