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Structural geology of the Fuegian Andes and Magallanes fold-and-thrust belt – Tierra del Fuego Island

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ABSTRACT

A synthesis of the structural geology of the Tierra del Fuego Island, which integrates a new data set derived from field surveys and literature data of the last few years, is here presented. The main geological features of the region developed during the Mesozoic-Cenozoic Andean orogenic cycle that started in the Middle to Late Jurassic with a back-arc extension, crustal stretching and widespread volcanism, related to the break-up of Gondwanaland. An extensional fault system deriving from the mechanical and thermal subsidence led the evolution of the Rocas Verdes marginal basin, which hosts the upper Jurassic volcanoclastic rocks, the lower Cretaceous turbiditic sequences and few isolated elongated ophiolitic complexes. From the Late Cretaceous onward, the orogenic cycle of the Fuegian Andes continued with the shortening and inversion of the back-arc margin through horizontal contraction and crustal thickening. The uplift of the Cordillera, the emplacement of plutonic rocks, and the intracontinental polyphase deformation resulted from thick-skinned tectonics. The thrust system developed from its deeper roots, where the Palaeozoic basement was involved in compressional deformation, and propagated to the shallower stratigraphic levels of the northward verging Magallanes fold-and-thrust belt. The Magallanes foreland basin developed in front of the orogenic wedge that records at least four syntectonic angular unconformities from Late Cretaceous to Lower Miocene. During the Late Cretaceous Andean compression, three distinct phases of penetrative ductile deformation defined by low-greenschist facies assemblages took place, both in the basement and in the cover units. These deformations are related to a single metamorphic event with foliation development, as observed from microscopic analysis of the schist in the Ushuaia area. The first foliation S_1 is preserved either as relic sericite microfolds between microlithons of the dominant S_2, or as early refolded veins of recrystallized quartz. The S_2 foliation is defined by oriented white mica. The crenulation of S_2, which is related to D_3 and occurs in most strained zones, becomes a pressure solution S_3 spaced foliation, lined by opaque minerals. From the Palaeogene to the present, EW sinistral wrench tectonics affected the region as a component of the relative motion between South America and the Antarctic Peninsula. This strike-slip activity is well documented from the Carbajal valley to the Canal de Beagle region south of the Magallanes-Fagnano transform fault system. Restraining bends and overlapping step-over geometry characterize few sectors of the strike-slip faults with pop-ups, pressure ridges and uplifted slivers of crust. Releasing step-over along the transform fault system, both in on-shore and off-shore zones, formed several elongated pull-apart basins with many tens of km in length and a few km in width. The Lago Fagnano represents the main morphotectonic expression of this structural setting. A N-S geological cross-section through the

Fuegian Andes synthesizes all the geological and geophysical data. The major stacks of internal thick-skinned basement involved in the thrusting are high-grade Upper Palaeozoic to Lower Tertiary metamorphic rocks. The geometry of the thrust complex is an upright, south plunging monocline of moderately tilted sedimentary cover strata, as well as related thrusts, faults and chevron folds involving the Upper Jurassic and Cretaceous rocks. The orogenic shortening of the Fuegian Andes, including the Cordillera and the Magallanes fold-and-thrust belt, reaches few hundred kilometres with a left-lateral wrenching component of many tens of meters. The Tierra del Fuego Island is characterized by low magnitude (M<3.5) and shallow crustal earthquakes. The southern part presents strong morphological evidence of Quaternary activity, related to the E-W left-lateral strike-slip faults. The actual deformation pattern presents a horizontal slip component of about 6 mm/year. Moreover, the northern sector of the Island is affected by extensional tectonics related to the normal fault systems of the eastern arms of the Magallanes Strait.

KEYWORDS **Fuengian Andes. Structural geology. Tectonics. Neotectonics. Andes.**

INTRODUCTION

The Fuegian Andes are described as the orogenic belt south of the Magallanes Strait, running along the western and southern margins of the Tierra del Fuego Island (Krank, 1932; Caminos et al., 1981). The Andes stretch for 3,800 km with a N-S trend progressively veering towards E-W in correspondence with the Tierra del Fuego Island and eventually joining the north-western North Scotia Ridge. They also represent the southernmost section of the Andean Cordillera.

The Andean Cordillera is the result of the collision between the subducting Nazca and Antarctic plates beneath the continental South American plate (Figs. 1 and 2; Dalziel and Elliot, 1973; Polonia and Torelli, 2007). In

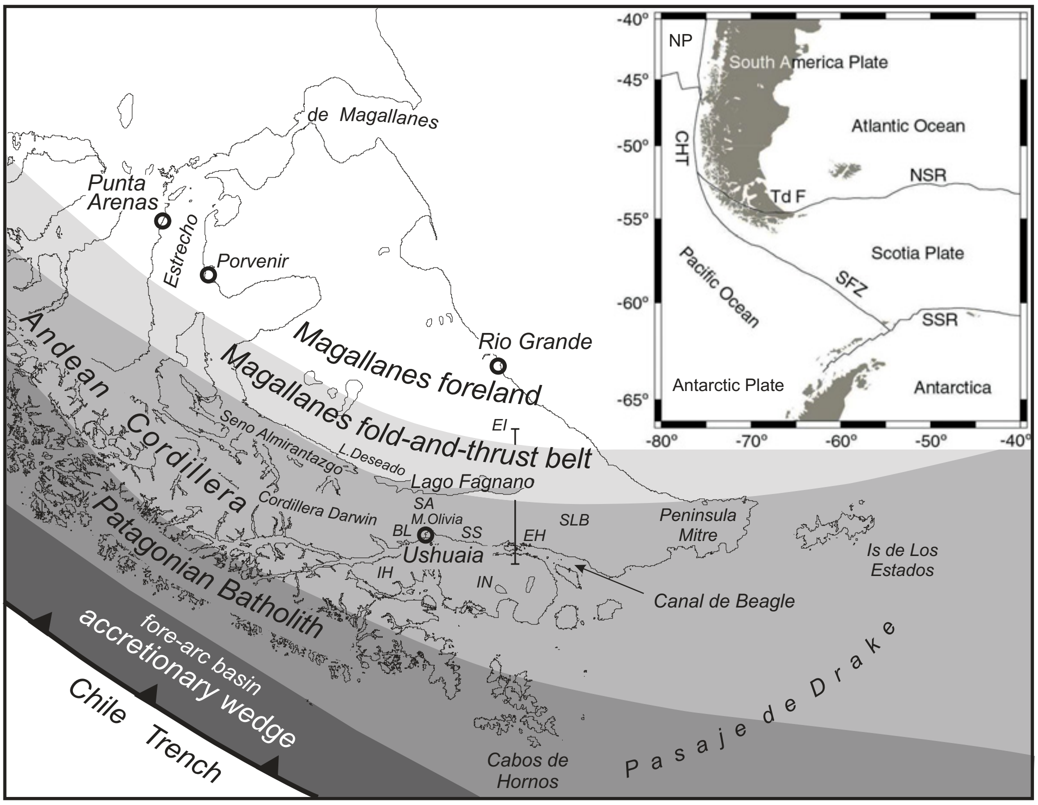


FIGURE 1 **Physiographic and structural provinces in the Tierra del Fuego Island. The trace of section of Figure 6 is indicated. Legend: EI: Estancia Indiana; SA: Sierra de Alvear; SLB: Sierra Lucas Bridges; BL: Bahia Lapataia and Bahia Ensenada; SS: Sierra Sorondo; EH: Enstancia Harberton; IH: Isla Hoste; IN: Isla Navarino; In the inset box, the current plate tectonic frame of the southern tip of South America, Scotia Plate, Antarctica: NP: Nazca Plate; CHT: Chile Trench; TdF: Tierra del Fuego; NSR: North Scotia Ridge; SSR: South Scotia Ridge.**

the southernmost part of the Cordillera, from the Patagonia inland to the Tierra del Fuego Island, both the tectonic collision and crustal thickening decrease (Hervè et al., 2000), with a progressive E-W bending of the structures linked to the wrench tectonism of the Magallanes-Fagnano fault systems (Katz, 1962; Bruhn, 1979; Winslow, 1982; Cunningham, 1993; Klepeis, 1994b; Lodolo et al., 2003; Rapalini et al., 2005). The geometric and kinematic plate reconstructions for the southern margin of Gondwanaland are still not adequately constrained because of the complexity of the tectonic events related to both the extensional phases of the Upper Jurassic and to the shortening of the Andean compressional phase in the Late Cretaceous (Dalziel et al., 1974; Ramos and Aleman, 2002; Hervé et al., 2000; Barker, 2001).

The current geological model of the Fuegian Andes is mainly based on a survey carried out at the beginning of the last century, which produced the first geological map of the Island (published by Bonarelli, 1917; Menichetti and Tassone, 2007), followed by lithological and structural analysis by Krank (1932) and, more recently, several geological surveys of the central part of the Island by Caminos (1980). Biddle et al. (1986), Galeazzi (1998), and Olivero and Martinioni (2001), provided a synthesis of the stratigraphy of the Cenozoic foreland area, while the stratigraphic relationship of the strongly deformed volcanoclastic and terrigenous Mesozoic rocks outcropping in the Fuegian Cordillera remains difficult to define (Caminos, 1980; Winslow, 1982). The structural frame of the area derives mainly from field coastal surveys in the Chilean sector of the Cordillera Darwin (Dalziel and Palmer, 1979; Cunninghan, 1993; Kepleis, 1994a; Kepleis and Austin, 1997), in the Canal de Beagle area (Bruhn, 1979; Suárez et al., 2000) and in the Atlantic coast (Olivero and Malumián, 1999; Lodolo et al., 2003), while inland surveys were carried out in the northern part of the Island (Álvarez-Marrón et al., 1993).

A synthesis of the structural framework of the Tierra del Fuego Island is here presented, by integrating published data and a new data set derived from the last five years of field surveys in cooperation projects between Italian, Argentinean, and Chilean Institutions, within the framework of the Italian Program of Antarctic Researches (PNRA). The data collected have been integrated in a geological cross-section through the orogenic belt, with the aim of obtaining a palinspastic restoration of this portion of the southernmost Andean region. In the proposed cross-section the deep structures are drawn and calibrated with the available reflection seismic profiles and with other geophysical measurements. This methodology has been applied to the extensional Mesozoic basin, as well as to the Mesozoic-Cenozoic contractional orogen and, partially, to the wrench structures.

MORPHOSTRUCTURAL PROVINCES

The Tierra del Fuego Island is triangular in shape with the southern base frayed into several small islands forming the Fuegian Archipelago (Fig. 1). In the north the Island is separated from the South American continent by the Magallanes Strait and by its articulate channels, which bound the western and south-western sides. On the eastern side the NW-SE oriented Atlantic Ocean shoreline is characterised by a large continental platform, which is progressively stretched from Peninsula Mitre and the Isla de los Estados along the North Scotia Ridge. The Drake Passage separates the southern part of the Island and its archipelago from the Antarctic Peninsula (Fig. 1). In the western part, where small islands belonging to the Fuegian Archipelago are located, the South American plate collides with the Chile Trench; south of Cabo de Hornos the trench merges with the Shackleton zone in the westernmost part of the Scotia Sea.

From a structural point of view, and from south to north the region of the Tierra del Fuego Island can be roughly split into several WNW-ESE trending morphostructural provinces (Kranck, 1932; Winslow, 1982; Dalziel and Brown, 1989; Suárez et al., 2000; Olivero and Martinioni, 2001; Fig. 1). The most internal province stretches between the forearc active ocean/continent convergent margin of the Chile Trench and the accretionary wedge in the Pacific Ocean. The Late Miocene accretionary complex that extends along the Pacific margin is separated from the fore-arc basin by an outer-high-arc (Polonia et al., 1999). This complex is joined to the southern archipelago of the Tierra del Fuego along the Canal de Beagle area, where the Mesozoic-Cenozoic Patagonian Batholith crops out. In the fore-arc region a gently slopping area known as "Fuegian Terrace" (Herron et al., 1977) connects the Patagonian batholith to the crest of the accretionary wedge (Polonia et al., 1999).

The Late Cretaceous calc-alkaline plutons of the Patagonian Batholith were emplaced at mid to upper crustal levels into a low-grade metamorphic complex (Hervé et al., this issue), and they were subsequently exhumed (Suárez and Pettigrew, 1976). A mechanism of in-situ diapirism emplacement has been proposed by Suárez et al. (1987) based on field observations of the parallel-to-the-margin concentric foliation of the quartz-monzodiorite and quartz-diorite rocks. The whole area is affected by Cenozoic strike-slip tectonics with a significant extensional component (Polonia et al., 1999; Cunningham, 1993).

The Fuegian Cordillera comprises the northern shore of the Canal de Beagle area, the Isla Navarino, the eastern part of the Isla Hoste and the southern archipelago; it also includes the metamorphic core complex of the Cordillera

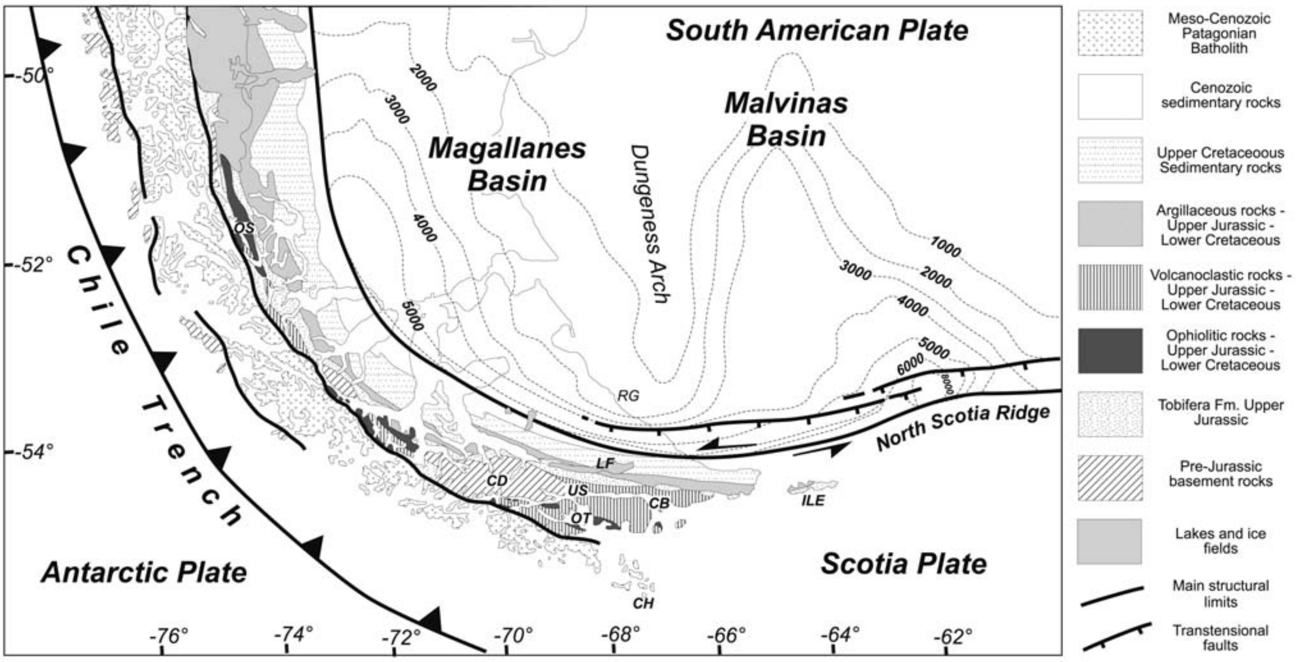


FIGURE 2 **Simplified geological map of the Southern Andes. Map partially compiled from Dalziel (1981) and Wilson (1991). Dashed lines are contours in meters of the sedimentary cover of the Magallanes and Malvinas basins (partially compiled from Biddle et al., 1986; Galeazzi, 1998). Legend: RG: Río Grande; US: Ushuaia; OS: Sarmiento Ophiolites; OT: Tortuga Ophiolites; CD: Cordillera Darwin; ILE: Isla de los Estados; LF: Lago Fagnano; CB: Canal de Beagle; CH: Cabo de Hornos.**

Darwin (Fig.1). Here, the oldest rocks (i.e. polydeformed medium to high-grade metasedimentary and metavolcanic rocks of the garnet and amphibolite facies) that represent the former metamorphic basement of the chain crop out (Dalziel and Brown, 1989; Fig. 3). The continent-ward slope of the mountain belt, also including the range north of Ushuaia, constitutes the Fuegian Cordillera with the main NE verging thrusts complexes. The rocks outcropping here are mainly schists and phyllites in prehnite-pumpellyte to greenschist metamorphic facies (Kohn et al., 1995). The structural style is typical of thick-skinned tectonics, involving the basement rocks with polyphase ductile deformations. In this morphostructural province crop out rocks that display high- to low-grade regional metamorphism and post-tectonic intrusive rocks (Fig. 2).

The external province includes the Magallanes fold-and-thrust belt and it is located north of the Seno Almirantazgo and Lago Fagnano, across the central-northern part of the Island (Fig. 1). Cenozoic sediments that fill the SW part of the Magallanes foreland basin are the product of the erosion of the advancing tectonic wedge where a thin-skinned tectonics style prevails, with shallow NNE verging thrust systems. Tight folds with shallow thrusts were stretched in an E-W direction by the Neogene sinistral strike-slip faults that reach the Atlantic coast (Fig. 2).

In the northern sectors the Fuegian foothills belong to the most external province and are formally recognised as part of the Magallanes foreland basin; the structures in this zone consist of large amplitude folds that gently affected the Neogene terrigenous sediments (Robbiano et al., 1996; Kraemer, 2003).

STRATIGRAPHY

The Mesozoic-Cenozoic stratigraphic succession of the region is broadly known, and excellent reviews have been provided by Olivero and Martinioni (2001) and Olivero and Malumián (this issue); hence only a brief outline is given here (Fig. 3). This stratigraphic record consists of eight major units separated by unconformities that record the tectono-sedimentary events from the extensional Rocas Verdes back-arc basin (Katz, 1972) to the compressional Magallanes foreland basin (Biddle et al., 1986; Fig. 3).

The oldest units are Upper Jurassic submarine volcanic rocks of Lemaire Formation (Tobifera Fm in Chile), which unconformably overlies the Palaeozoic metamorphic basement. The Lemaire Fm consists of about 2,000 m thick rhyolite and slate successions with interlayered basalt bodies, acid volcanic breccias, tuffs, conglomerates and sandstones. The monotonous 6,000 m thick, deep-marine black mudstones, including andesitic volcaniclastic turbidites and tuffs of the Lower Cretaceous Yahgán Fm complete the filling of the Rocas Verdes basin. The Yahgán Fm interfingers northward with about 3,000 m thick sequences made up by dark mudstones and sands of the Lower Cretaceous Beauvoir Fm (Olivero and Martinioni, 2001; Olivero and Malumián, this issue).

The Late Cretaceous-Palaeocene molasse sediments of Co. Matrero, Policarpo and Río Claro Fms record the basin inversion related to the Andean compressional phase and the early development of the Magallanes foreland basin. The foredeep clastic wedges include Palaeocene to Oligocene turbidites with marls, sandstones and conglomerates, which may be split in at least four major unconformity bounded units. Several internal unconformities, synorogenic sequences and growth-strata that developed in front of the shallow thrust structures record the complex and progressive northward shifting of the deformation and of the sedimentary depocenters. The final stage of basin filling consists of Oligocene to Miocene sandstones and mudstones resulting from deposition in shallow marine shelf and deltaic systems. Quaternary continental sediments with glacio-fluvial and glacio-lacustrine facies cover large sectors of the Island especially in the Lago Fagnano area. The total thickness of the foredeep clastic wedge sequence reaches at least 6,000 m (Fig. 2; Tassone et al., this issue).

The stratigraphy recognized from the available data set largely accounts for the wide range of deformation structures, mechanics, and kinematics in the study region. The structural-lithologic assemblages suggest a vertical strength profile with a series of stacked thrust slices confined in multiple weak horizons in the slates and marl of Lemaire Fm and Río Claro Fm (Menichetti et al., 2004). A clear evidence for a major regional detachment surface

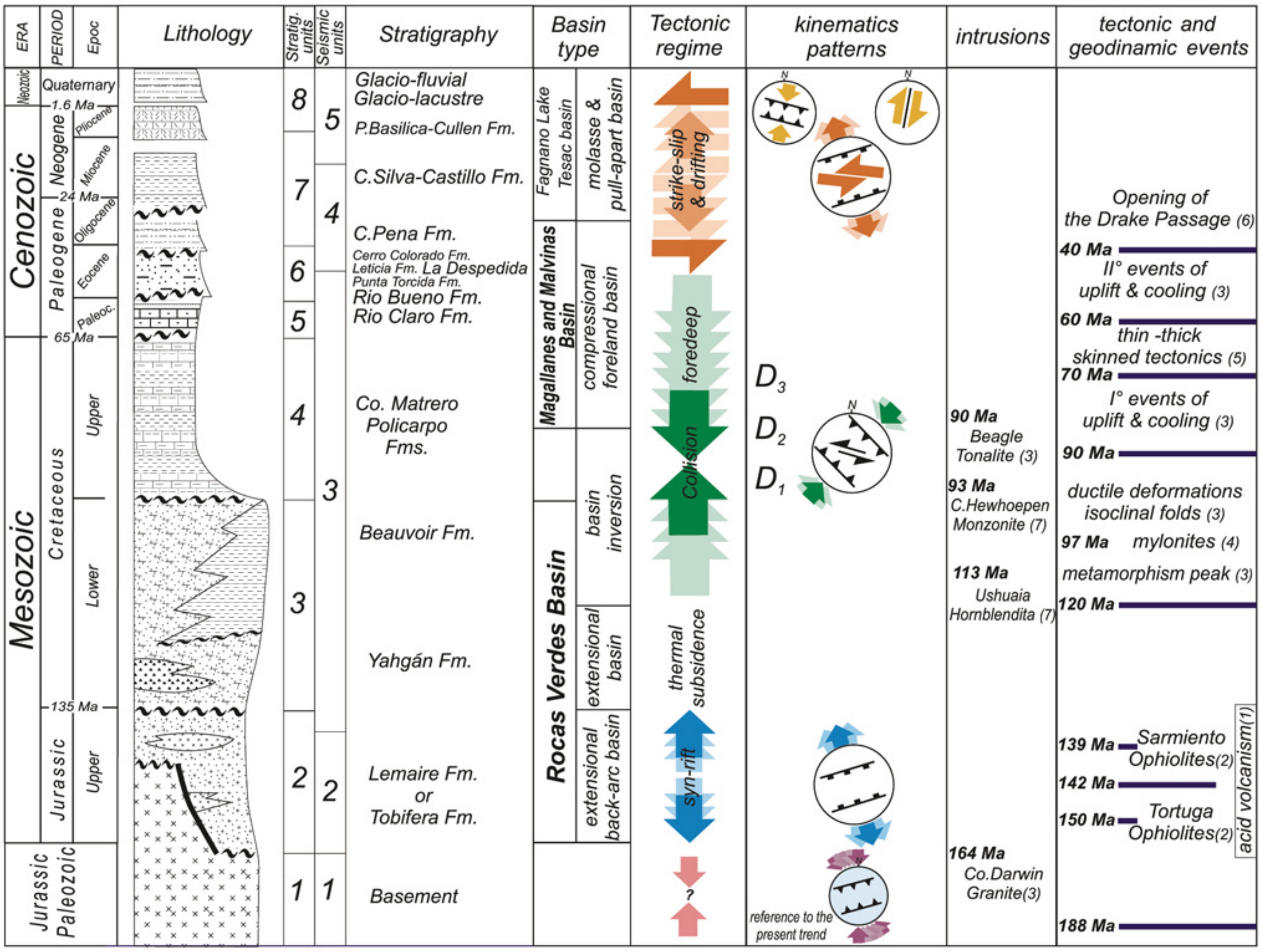


FIGURE 3 **Schematic stratigraphy of the Tierra del Fuego region. The Formation nomenclature is taken according to Olivero and Martinioni, 2001. Eight stratigraphic units and five seismic units are indicated (Lodolo et al., 2003; Tassone et al., 2005). The kinematic patterns are after Lodolo et al., 2002a, 2003. The age of the intrusion and tectonic and geodynamic events are from : (1) Feraud et al., 1999, and Pankhurst et al., 2000; (2) Stern and De Wit, 2003; (3) Kohn et al., 1995; (4) Suárez et al., 1985; (5) Klepeis and Austin, 1997; (6) Geletti et al., 2005; (7) Acevedo et al., 2002.**

at the top of the Palaeozoic basement exists, although its mechanical behaviour and role in the regional tectonics still remains not well constrained.

JURASSIC-LOWER CRETACEOUS EXTENSIONAL PHASE

The first tectonic phase affecting the southern tip of South America was extensional and connected to the back-arc region associated with the south-western subduction zone of the Panthalassan margin (Feraud et al., 1999; Pankhurst et al., 1995, 2000; Fig. 4). The regional crustal stretching could be also partially linked with the Mesozoic Gondwana break-up characterized by Early Jurassic large igneous provinces in South America, followed in the Middle Jurassic by the Weddell Sea oceanic crust formation (Jokat et al., 2003; Fig.4). However, the relationships between the back-arc region with paleopositions of South America and Southern Africa relative to Antarctica (in the general scenario of southern Gondwana), are still debatable as well as the mechanism that triggered the continental break-up.

The whole southernmost Andean region, from the Middle to the Late Jurassic (Dalziel, 1981), was affected by back-arc crustal stretching, which included widespread acid volcanism associated with the Rocas Verdes marginal basin formation (Katz, 1972; Dalziel, 1981; Mukasa and Dalziel, 1996). The time span of this acid magmatism has been constrained by ^{40}Ar/^{39}Ar and SHRIMP U/Pb ages and SHRIMP ages between 188-150 Ma (Feraud et al., 1999; Pankhurst et al., 2000). This volcanic event is represented in the southernmost Andes by the Tobífera Fm (Chile) and Lemaire Fm (Argentina), which include mostly rhyolitic volcanics extruded in a deep-marine volcano-tectonic rift (Hanson and Wilson, 1991). As indicated by recent SHRIMP zircon U/Pb age of 178± 1.4 Ma (Pankhurst et al., 2000) proto-marginal basin magmatism began in Middle Jurassic in the Argentinean Tierra del Fuego. Younger peraluminous granitoids -genetically related to the rhyolitic

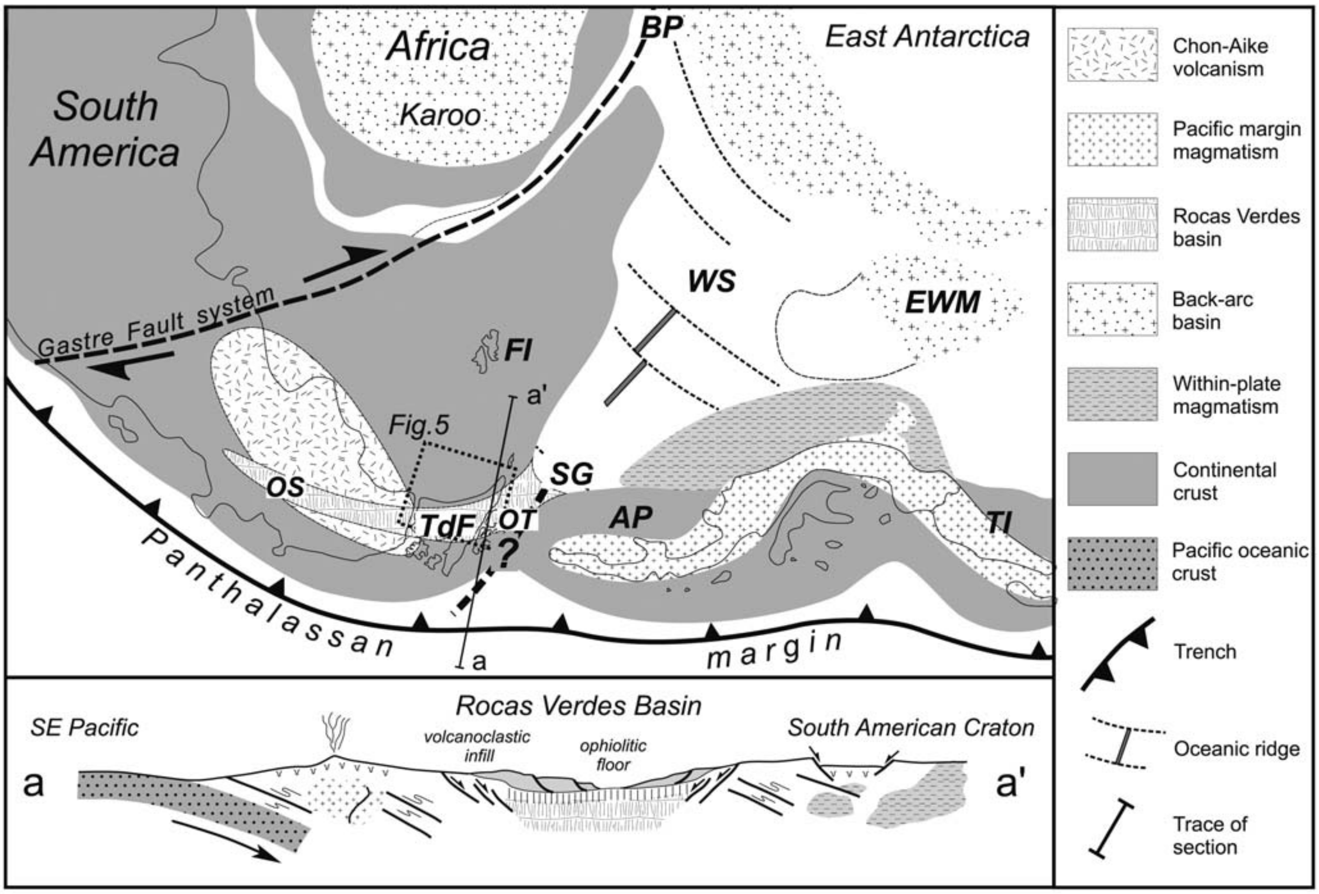


FIGURE 4 **Plate tectonic reconstruction of the southern margin of Gondwana in the Middle Jurassic (after Storey, 1995). Section a-a' after Mukasa and Dalziel (1996). Legend: AP: Antarctic Peninsula; SG: South Georgia; EWM: Ellsworth-Witmore Mountains; FI: Malvinas Islands; TI: Thurstone Island; BP: Buvet plume; OS: Sarmiento Ophiolites; OT: Tortuga Ophiolites; TdF: Tierra del Fuego; WS: Weddell Sea. The box refers to Figure 5.**

magmatism- of the Darwin granite suite were emplaced in Chilean Tierra del Fuego within the basement complex (Nelson et al., 1980) by 164±1.7Ma (zircon U/Pb age; Mukasa and Dalziel, 1996).

Crustal thinning had an effect on the Palaeozoic metamorphic basement, involving large extensional structures. The geometries and the structural features of the basin were controlled mainly by the extensional stress field, with an important component of wrench tectonics.

At least three corridors of oceanic crust are connected in the region by transform faults, over 800 km in length, ranging from the ophiolitic outcrops in the north of the Sarmiento Cordillera to the Tortuga ophiolitic complex in the Cabo de Hornos area in the south (Fig. 2; Stern and De Wit, 2003). In Tierra del Fuego, many of these extensional structures are represented in the field by mafic dyke swarms hosted in the basement rocks and in the Upper Jurassic Tobífera and Lower Cretaceous Yahgán formations (Winslow, 1982; Wilson, 1991; Fig. 3). Large rhyolitic bodies were emplaced at different stratigraphic levels in the Lemaire Fm suggesting the presence of an articulated frame of extensional structures (Hanson and Wilson, 1991), possibly associated with the emplacement of granite bodies in the basement complex within the Cordillera Darwin (Mukasa and Dalziel, 1996).

The normal faults system is clearly shown in the seismic reflection profiles both in the Atlantic on-shore and off-shore in the Magallanes and Malvinas basins (Biddle et al., 1986; Robbiano et al., 1996; Galeazzi, 1998; Fig. 5). The extensional structures are characterised by a NW-SE general trend in the Tierra del Fuego region, while in the southern part of the Atlantic off-shore, close to the Fuegian cordillera, they were rotated anticlockwise by Cenozoic compressional and strike slip faults. In the eastern part of the Atlantic off-shore the fault pattern is quite complex probably due to the overlapping of extensional stress field of the Rocas Verdes back-arc basin and the sea floor spreading in the Weddell (Figs. 4 and 5).

The normal fault geometries are composed by a system of asymmetric tilted fault blocks with a NW-SE general trend deformed on a listric normal sole fault, dipping NE and SW. The pattern is constituted by alternating and partially overlapping grabens and half-grabens, with basins a few kilometres wide and tens of kilometres long, and bounded by secondary fault planes. In several areas the basins show roll-over structures with grow-fault systems, a few of them possibly reactivated in later tectonic events. The extensional structures are arranged in a right-stepped geometry with WNW-ESE oriented transfer zones that possibly represent local depressions, where the extensional crustal thinning was renewed by magmatic accretion. More than 2,000 m of the volcanoclastic complex of the Tobífera Fm were deposited in the extensional structures (Fig. 5). A Palaeozoic succession constitutes the basement, which is separated from the Tobífera Fm by a regional unconformity in the Magallanes basin, dated at 150.5 Ma by Biddle et al. (1986).

In the different sectors of the Rocas Verdes basin there was substantial diachroneity, both in the fault evolution and in the basin filling, with the Lemaire/Tobifera Fm from Lower to Middle Jurassic (Mukasa and Dalziel, 1996; Pankhurst et al., 2000) in the Argentinean Tierra del Fuego. As shown by the seismic lines from the Malvinas and Magallanes foreland basins, the Lemaire Fm displays two sedimentary sequences with the same thickness, separated by an unconformity (Galeazzi, 1998); these probably represent Upper Jurassic rift sequences that reflect the mechanical and thermal subsidence of the basin. The normal fault systems include sub-vertical structures with cumulative variable offsets ranging from many hundreds to more than one thousand metres. In this sector of the Rocas Verdes marginal basin, the geometry of the structures allows estimation of the extension, ranging between 15 and 20%. A depth of 10 km for the detachment of the listric sole normal fault can be inferred from geometrical reconstructions, compatible with a thinning extensional crust (Fig. 5). Crustal stretching increases towards the east, where the progressive thinning locally resulted in the formation of the oceanic crust in the Weddell Sea (Fig. 4).

ANDEAN COLLISIONAL PHASE AND RELATED STRUCTURES

In the Late Cretaceous, the variation of the plate drifts that were linked to the opening of the southern oceans changed the regional tectonic regime from extensional to contractional. The Andean Cordillera emerged along the collisional margin by the combined horizontal shortening and crustal thickening of the basement rocks (Dalziel, 1985; Cunningham et al., 1995) and the emplacement of several thrust sheets involving the sedimentary cover.

This second and main tectonic phase affecting the Fuegian region, which is known as the Andean orogeny, was contractional in character and developed after the Lower Cretaceous. It was responsible for the main Cordillera formation, starting with a prevalent thick-skinned tectonic style in the internal orogenic chain zone and culminating into a thin-skinned tectonic geometry in the foreland (Fig. 6; Winslow, 1982; Biddle et al., 1986; Ramos, 1989; Wilson, 1991; Grunow et al., 1992; Álvarez-Marrón et al., 1993; Kepleis, 1994b; Diraison et al., 2000; Kraemer,

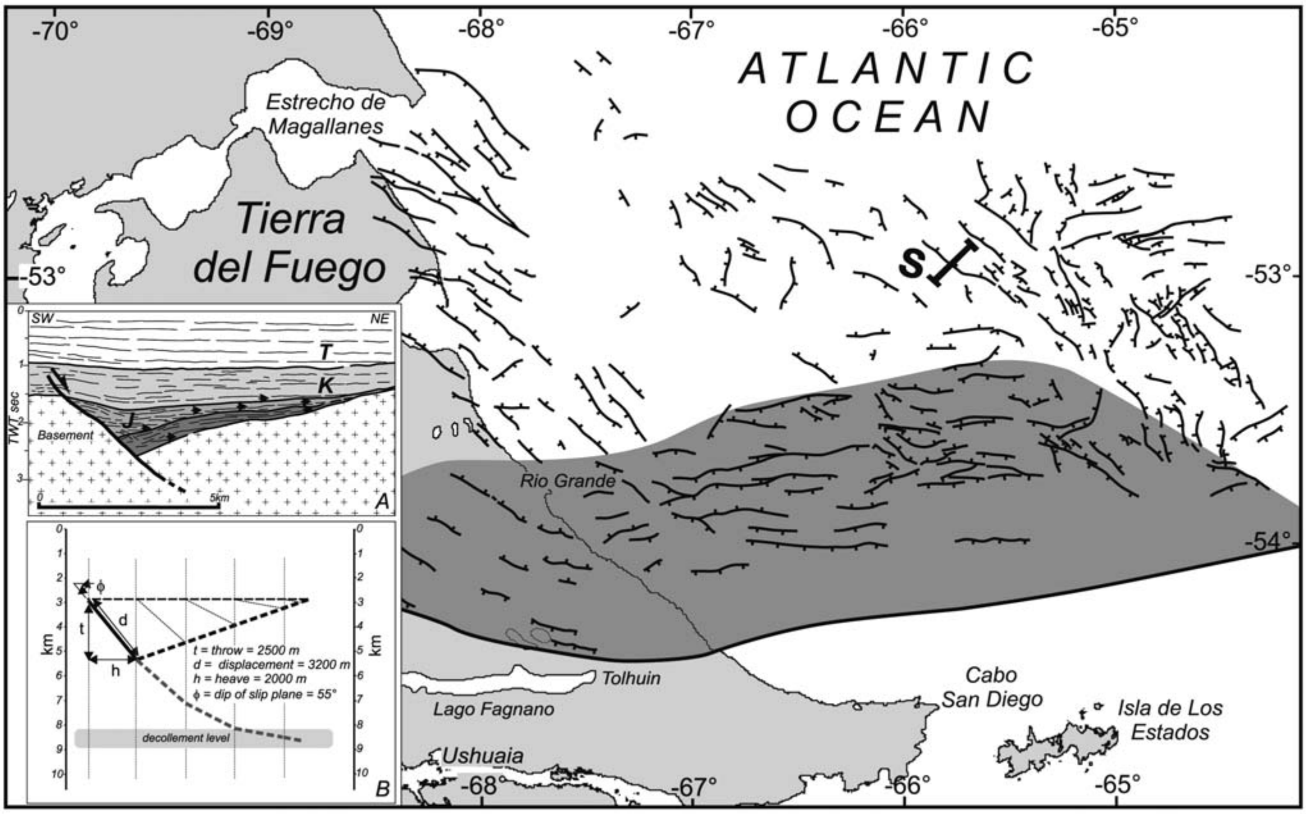


FIGURE 5 **Structural map of the Middle Jurassic rift-phase faults (location shown in Figure 4); in grey the area where the extensional faults are rotated by the Andean compression and strike-slip tectonics, S – trace of the section in the inset box. Off-shore data are prevalently derived from Robbiano et al., 1996 and Galeazzi, 1998. In the inset box: A) Interpreted seismic line of a listric normal fault with a half-graben geometry in the hangingwall. The half-graben is infill with a succession of upper and lower Lemaire Formation, separated by an unconformity (from Galeazzi, 1998). B) Geometrical reconstruction of the décollement level of the listric normal fault using a method that considers the conservation of displacement along the fault, with both throw and heave varying along the fault profile with the strain conditions, with some degrees of angular shear due to bed parallel slip (Williams and Vann, 1987). This geometrical construction does not take into account the compaction of the sedimentary succession in the hangingwall and over estimates the depth of detachment.**

2003). Several basement wedges were uplifted and thrusted towards the N and the NE in complex slices with sole thrusts that splay from the Upper Jurassic layer to ramp through the foreland in the Neogene sedimentary cover (Fig. 6). The estimated age of this deformation phase could be bracketed between the Upper Cretaceous age of the granitoids intruded in the Yahgán Fm (with a K-Ar age of 90 Ma; Fig. 3; Suárez et al., 2000) and the Albian age of the Yahgán Fm successions of eastern Tierra del Fuego (inferred from the occurrence of inoceramid bivalves; Olivero and Martinioni, 1996). Field relations in the whole Tierra del Fuego suggest that the basement-involved thrusting occurred in the Late Cretaceous during and after the generation of the acid volcanic and volcanoclastic rocks (Álvarez-Marrón et al. 1993; Klepeis and Austin, 1997). Finally, radiometric dating of several mylonitic rocks from the southern archipelago has suggested ages ranging from 91 to 130 Ma (Suárez et al., 2000), pointing to an older tectonic event in the Lower Cretaceous. The contractional deformation propagated in- or out-of sequence with a stepped thrust geometry running from the deep internal basement roots to the shallow foreland stratigraphic levels (Fig. 6; Lodolo et al., 2003). This progressive deformation affected the basement during the Late Cretaceous and reached the Yahgán Fm strata in the external domain in the Palaeocene (Olivero and Martinioni, 2001). The sole thrusts in the basement rocks outcrop along the margin of the Cordillera Darwin, where the deformation occurred under brittle condition in greenschist facies (<350°C; Klepeis, 1994b).

In the Tierra del Fuego Island this major tectonic phase can be split into two progressive events that developed during the compressional deformation of the back-arc basin (Fig. 3; Dalziel and Palmer, 1979). The first event in the Upper Cretaceous produced F_1 folds and slaty cleavage S_1 affecting both the Upper Jurassic acid volcanic rocks of the Lemaire Fm, and the Lower Cretaceous volcanoclastic rocks of the Yahgán Fm (Fig. 7). Prehnite-pumpellyte to greenschist metamorphic facies affected the rocks of the internal part of the Cordillera during this deformation (Kohn et al., 1993, 1995). The younger structures are large F_2 folds with a well-developed crenulation cleavage S_2, and they are associated with the formation and emplacement of NE verging fold-and-thrust systems (Fig. 7). The main folds and slaty cleavage and their relationship with the D_2 structures are well exposed in the Bahia Lapataia area (Bruhn, 1979), as well as north of Ushuaia up to the Lago Fagnano area. Along the Canal de Beagle area the deformation associated with the D_1 and D_2 tectonic events is well developed and it decreases towards the north and among the younger stratigraphic levels. The slaty cleavage affecting all the formations has a NW-SE trend and dips towards the south. The fold axes trend from SSE-NNW for F_1 to ESE-WSW for F_2, with an axial plane generally dipping SW at 40°-60° of inclination (Figs. 7 and 8). In the Lemaire and Yahgán Fms located in the Ushuaia area, the slaty cleavage locally features south to south-west dipping extensional lineations that are defined by the alignment and stretching of micaceous minerals and porphyroclasts (Figs. 9A, 9B and 9D). The crenulation cleavage S_2 is well developed in the basement rocks with a NE-SW trend dipping towards SE at a high angle (Figs. 7, 8 and 9C).

At a microscopic scale, the foliation development shows details of the microfabric related to the deformation events: S_1 is defined by its orientation with mica and by relic sericite microfolds between microlithons of the S_2, or early refolded veins of recrystallized quartz; the crenulation cleavage S_2 domain characterized by a pressure solution spaced foliation lined by opaque minerals (Fig. 9C). In the Bahia Ensenada and the Bahia Lapataia area, west of Ushuaia, at least three generations of syntectonic quartz veins can be observed (Fig. 10; Olivero et al., 1997; Menichetti et al., 2004). The first is a few millimetres thin, parallel to the slaty cleavage, and it is involved in both the F_1 centimetre-scale folds and in the metric-scale F_2 folding (Fig. 10). The second is a cross-system, which is a few centimetres thick, sub-perpendicular to the slaty cleavage, and featuring the axial plane of the F_2 folds. The average trend of such extensional veins is N-S and E-W (Fig. 10A). A further subvertical system, with a width of few cm, shows an NE-SW trend. All the quartz veins are involved in the younger thrust and normal fault deformations and point to a substantial presence of fluids during the development and the propagation of the main Andean phase structures.

Penetrative structural fabrics in the shear zones are associated with the main faults and, in some cases, mylonitic deformations, with pervasive foliation and pressure solution cleavage planes, occur. At the microstructural scale the ductile kinematic indicators present fabrics with S-C mylonites, fractured and displaced feldspar grains and rotated porphyroclasts (Fig. 9D).

The rheology of the different geological units and their regional distribution controls the detachment levels and the stepped geometry of the main thrust surfaces. The detachment levels are located between the sedimentary succession and the volcanoclastic basement of the

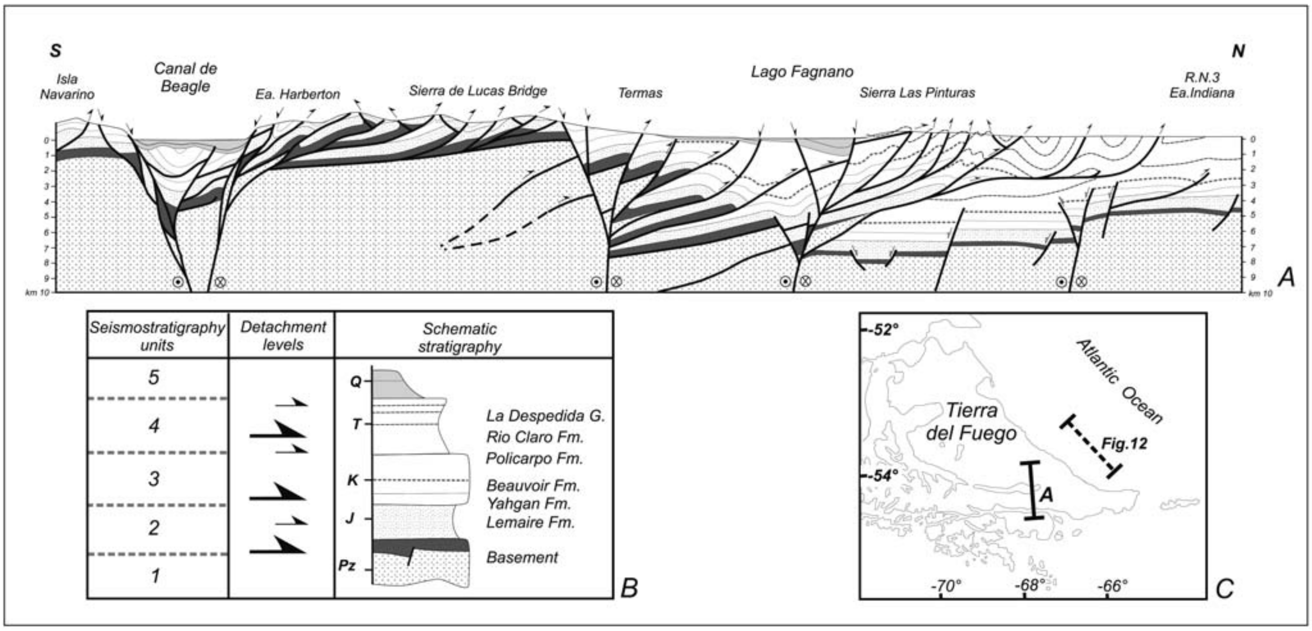


FIGURE 6 **A) North-South schematic geological cross-section through the Fuegian Andes from Isla Navarino - Canal de Beagle to north of the Lago Fagnano. B) Schematic stratigraphy, main detachment levels and seismostratigraphic units are indicated. C) Location of the cross-section and of the seismic line of Figure12.**

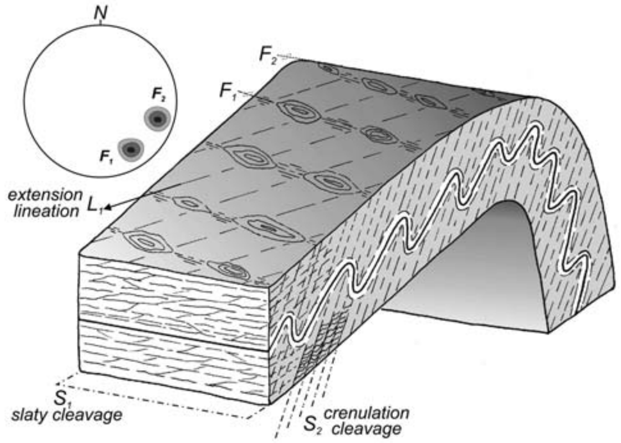


FIGURE 7 **Draft of the structural style, geometry and relationship between the cleavages, the folds and the rock fabrics in the Fuegian Andes observed in the Ushuaia area in the Yahgán and Lemaire Fms. In the upper left lower hemisphere equal area plots contours of the F1 and F2 folds hinges.**

Lemaire Fm, and in the marls of the foreland basin fill. The widest volcanic bodies both of basaltic and rhyolitic composition in the Yahgán Fm make up the core of the largest anticlinal structures and constitute the footwall of the major stacks of the thrust systems. The contacts between the basaltic bodies and the schists in the Yahgán Fm are clearly tectonic with the development of ductile shear zones with C-S structures.

Throughout the whole Mesozoic-Cenozoic sedimentary succession, the orogenic shortening was produced by folds with different scales of magnitude and wavelengths, ranging from centimetres to decametres. The folds are tighter in the southern part and become wider throughout the north, with WNW-ESE trending axes, plunging a few degrees in either quadrant. The axial planes dip to the S and the SW with angles varying from few degrees in the overturned folds to the subvertical in the disharmonic folds that are clearly displayed in the western slope of M. Olivia north of Ushuaia (Kranck, 1932).

In the Darwin Cordillera, in the south-western part of the Tierra del Fuego, the basement rocks show a stronger polyphased deformation and they represent the highest grade metamorphic rocks in the southern Andes (Kranck,

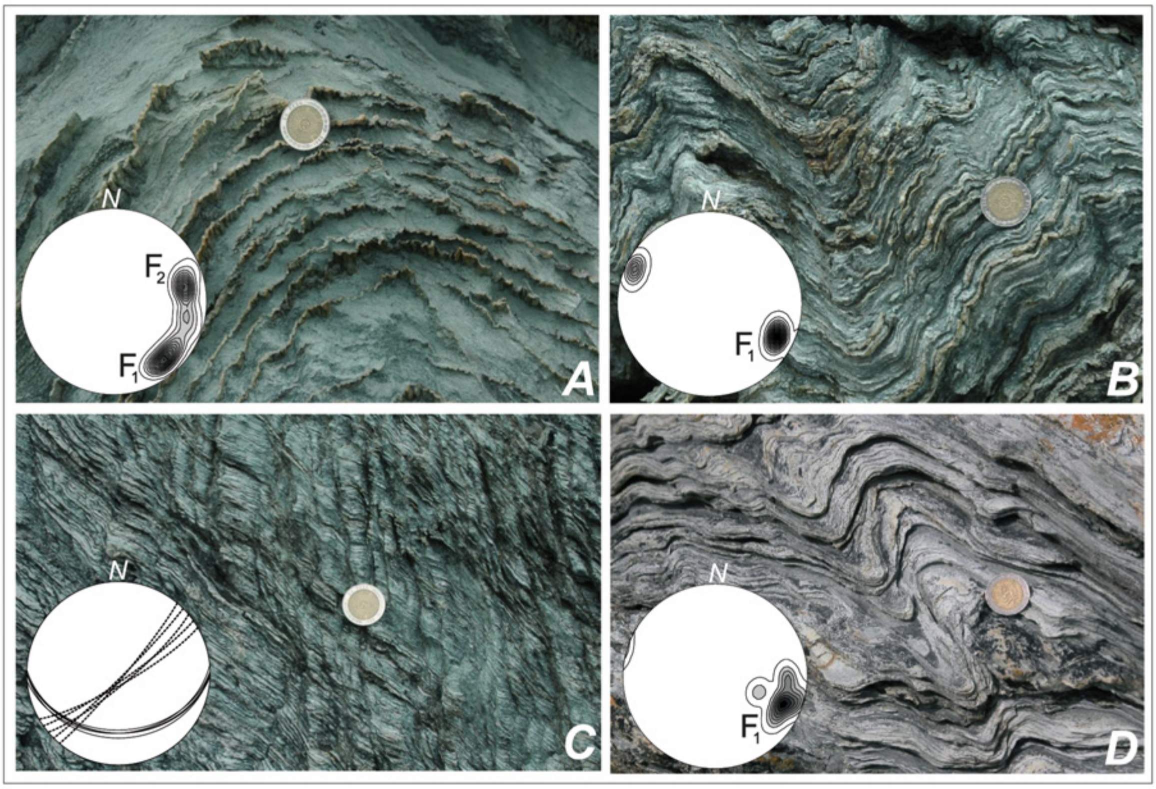


FIGURE 8 **Lemaire Fm outcrops to the West of Ushuaia. A) Bahia Ensenada, outcrop and lower hemisphere equal area plots with Kamb contours every 2 sigma of the hinges of the F1 and F2 folds (n.15). B) Bahia Ensenada outcrop and lower hemisphere equal area plots with Kamb contours every 2 sigma of the hinges of the folds (n.18). C) Bahia Lapataia, outcrop and lower hemisphere equal area plots of the crenulation cleavage S2 (dashed lines) and slaty cleavage S1 (solid lines) planes. D) Bahia Lapataia, outcrop and lower hemisphere equal area plots with Kamb contours every 2 sigma of the hinges of the folds (n.19).**

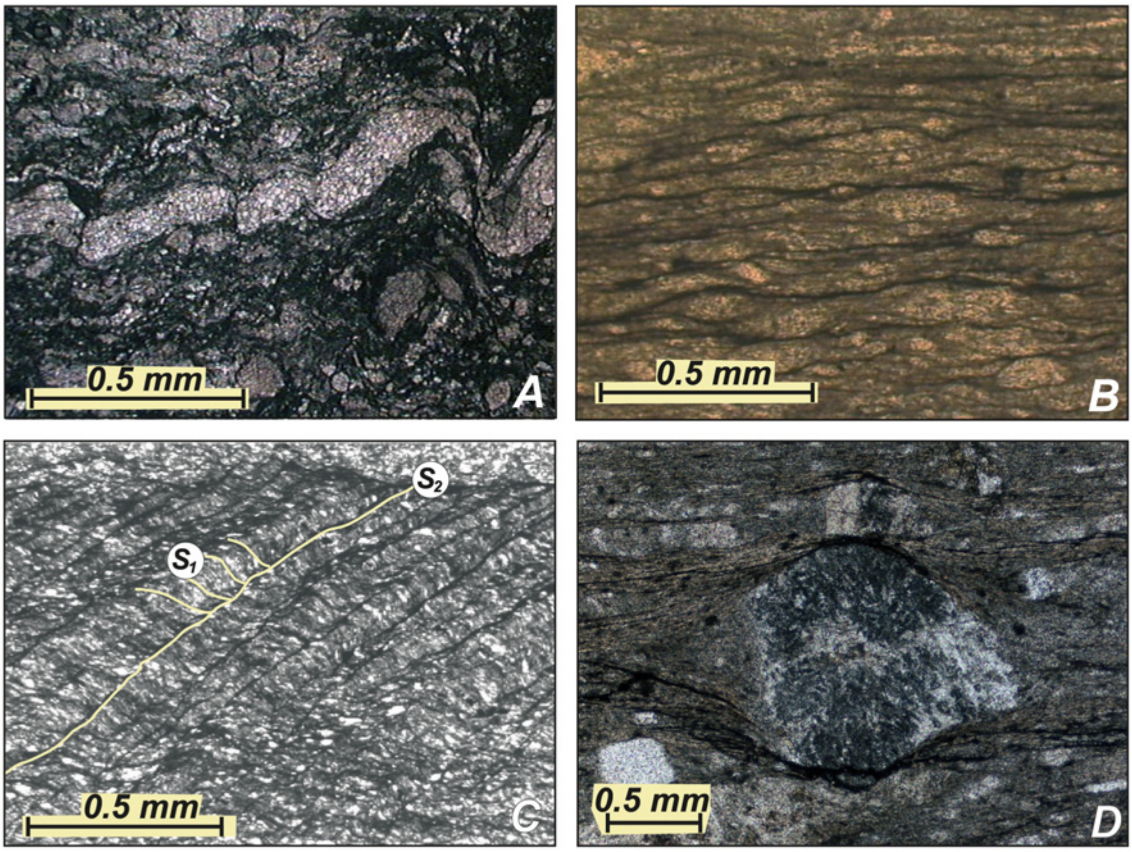


FIGURE 9 **A) Photomicrograph in polarized light of refolded structures affected by subvertical crenulation cleavage in the Schist of the Bahia Ensenada (Lemaire Fm). B) Photomicrograph in unpolarized transmitted light in the phyllite of the Yahgán Formation from the Ushuaia area; subparallel isorientated chlorite and mica minerals extending parallel to slaty cleavage. C) Photomicrograph in polarized light; S1, slaty cleavage and S2, crenulation cleavage affecting the rocks (Lemaire Fm in the Sierra Alvear). D) Photomicrograph in polarized light of the feldspar porphyroclast in the rhyolites of the M. Olivia area (Lemaire Fm).**

1932). A large glacier covers the central part of the mountain range, peaking at over 2,000 m with M. Shipton (2,438 m) and M. Darwin (2,488 m); the local field geology knowledge derives mainly from ship-based surveys carried out along the numerous fjords (Nelson et al., 1980; Dalziel, 1981, 1985; Cunningham, 1993; Klepeis, 1994a). The core of the Cordillera is constituted by the basement rocks, mainly phyllites, amphibolite-grade schist in biotite, staurolite, kyanite, and sillimanite methamorphic zones (Dalziel and Brown, 1989; Kohn et al., 1995). In the Cordillera outcrop two of the oldest distinct felsic plutonic suites (weakly foliated to near mylonitic, felsic orthogneisses), which are intruded by mafic swarms of dikes (mainly amphibolites), both tectonically deformed (Kranck, 1932; Nelson et al., 1980). A later generation of undeformed felsic suite (biotite or hornblende bearing tonalites, and granodiorites) intruded the oldest one. The mafic dike swarms are considered Upper Jurassic in age and they were intruded during the crustal extension of the Rocas Verdes marginal basin. The age of the basement of the Cordillera Darwin is not clearly constrained and it is commonly considered Pensylvanian-Permian in age on the base of the occurrence of fusilinids in the southern Patagonia limestone successions (50° latitude; Cecioni, 1956; Forsythe and Mpodozis, 1979). The basement absolute age has been estimated as belonging to the Middle Jurassic based on the analysis of Rb/Sr and U/Pb ratios in zircon (Hervé et al., 1981; Mukasa and Dalziel, 1996) and the origin can be traced back to the former accretionary wedge along the Pacific margin of Gondwana during the pre-Middle Jurassic time (Forsythe and Mpodozis, 1979; Dalziel and Forsythe, 1986).

For basement rocks in the Cordillera Darwin, Nelson et al. (1980) described up to four deformation events related to the compressional Andean phase: pre-Andean structures (D_0) that developed in the basement rocks, which are better preserved in the northern part of the Cordillera; and three younger Andean structures (D_1, D_2, D_3) that occur both in the basement and cover units (Fig. 11).

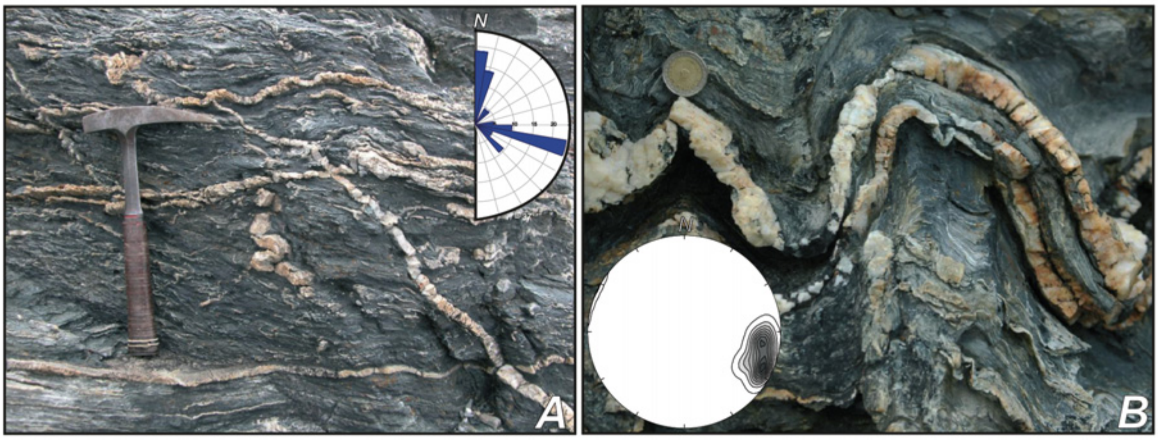


FIGURE 10 | **Bahia Ensenada to the west of Ushuaia (Lemaire Fm). A) Quartz veins arrays in the polyphase deformed schist rocks and rose diagram of the frequency of the direction. B) Folded quartz veins and lower hemisphere equal area plots with Kamb contours every 2 sigma of the hinges of the F2 folds (n.15). See text for discussion and interpretation.**

The D_0 structures, which consist of isoclinal folding of compositional layering and quartz veins, are rarely observed. The D_1 (early Andean) structures are defined by strongly developed foliation. In the cover rocks this foliation is generally schistose, locally mylonitic, sub-parallel to the layers in the southern part of the region; on the other side, in the northern part, the foliation is at high angle to the bedding with slaty cleavage development. The south verging D_2 structures are represented by macroscopic folds with an axial plane crenulation cleavage or strain-slip cleavage, which is more penetrative in the southern flank of the Cordillera Darwin. The D_3 (late Andean phase) structures occur mainly in the basement rocks. These structures consist of open crenulation style folds with axial planes dipping NE with sub-horizontal hinges. A crenulation cleavage is developed locally (Nelson et al., 1980).

Several NE and SW dipping low angle normal faults, with well developed shear zones, crop out in the southern fjords and the northern areas of the Cordillera, respectively. These fault surfaces juxtaposed the Upper Jurassic-Lower Cretaceous rock units over the Mesozoic basement. Extensional structures could be responsible for the rapid uplift of the metamorphic core complex in a transtensional regime in the Tertiary (Dalziel and Brown, 1989). Most of the geometry of the structures displayed in the maps and sections of Klepeis (1994a, b) and Cunninghan (1995) could be interpreted according to this model. In other words, the Tertiary exhumation associated with the E-W shear might reflect heterogeneous transtensional stress fields, whereas the regions under extension could have produced gravitational collapse of thickened crust. This geodynamic model suggests that in the Tierra del Fuego the Cretaceous and the Early Tertiary exhumation processes were markedly heterogeneous; furthermore, they operated during an early contraction phase and the subsequent arc-oblique and arc perpendicular extensional phase.

MAGALLANES FORELAND BASIN

The Magallanes and Malvinas basins are two juxtaposed perisutural basins in the external frontal part of the Andean Cordillera, separated by the Dungeness arch (Biddle et al., 1986, 1996; Galeazzi, 1998; Hervé et al., 2000; Fig. 2). Both developed on continental crust and were filled up by a more than 5,000 m thick Jurassic to Holocene sedimentary wedge, which mainly consists of muddy siliciclastic marine sediments. The multi-stage evolution of both basins was similar but highly diachronic and characterized mainly by the development of different source areas for the clastic sediment contributions (Biddle et al., 1996).

The Magallanes basin, known also as Austral basin, began as an extensional basin during the Middle-Late Jurassic to the Early Cretaceous with the eruption/deposition of the Lemaire Fm rocks. This unit consists

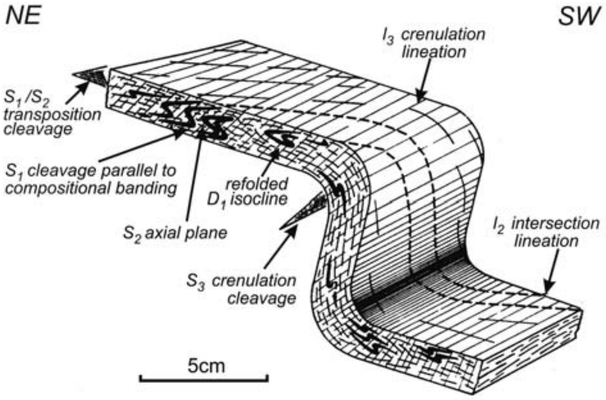


FIGURE 11 | **Sketch from Nelson et al., 1980, of the D3 folds in basement rocks of the Cordillera Darwin and the relationships with the fabric elements of the all three Andean deformation phases.**

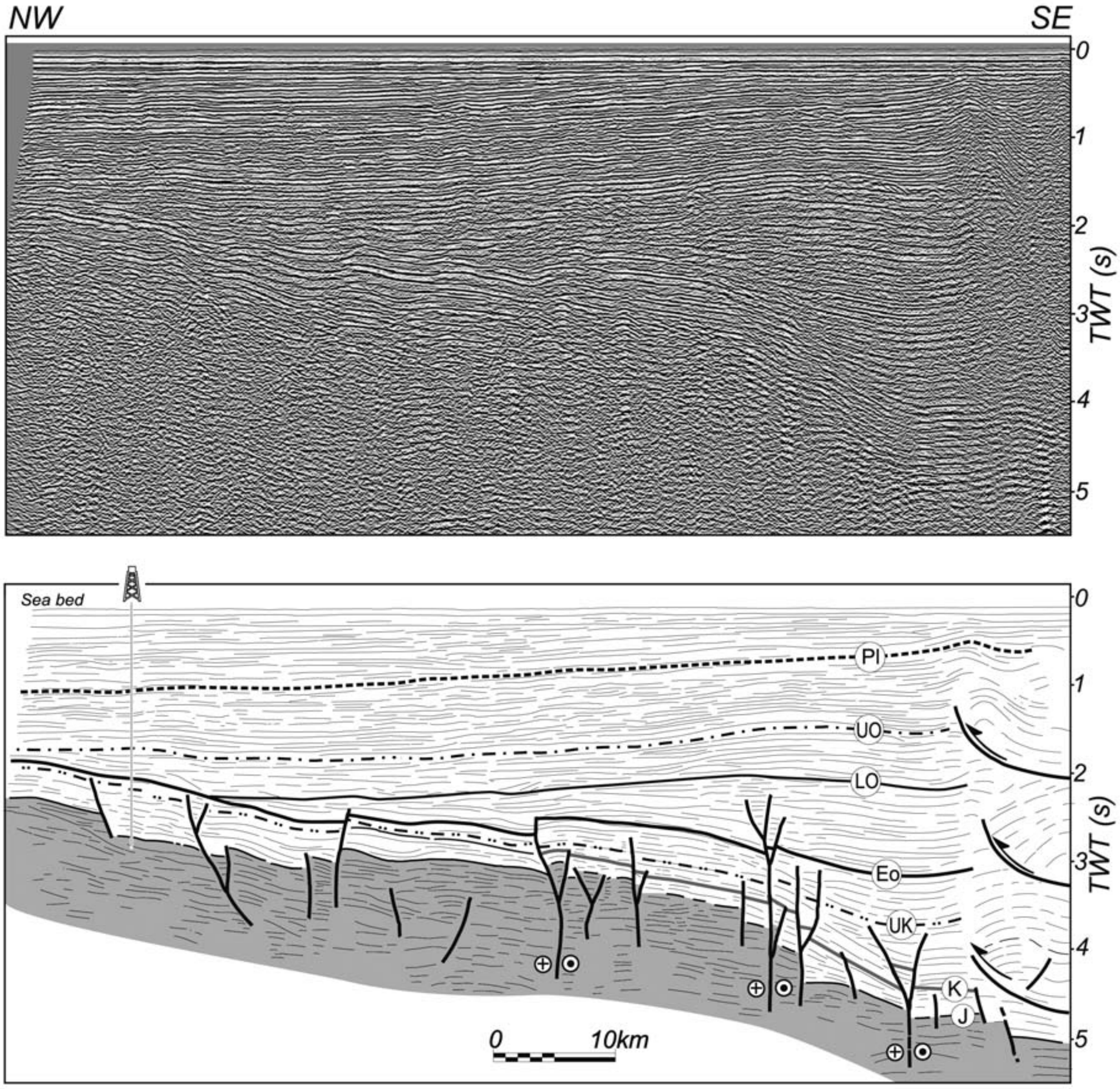


FIGURE 12 **North-South multichannel seismic reflection profile of the Tierra del Fuego off-shore in the Magallanes basin (location shown in Figure 6) and the simplified line drawing. The dating of the seismic reflectors was calibrated with off-shore stratigraphic wells (Tassone et al., this issue). In the south-eastern part of the section the stacks of the thrust sheets of the Fuegian Cordillera are visible. Legend: grey: pre-Jurassic basement; thick lines: faults; J: Jurassic; K: Cretaceous; UK: Upper Cretaceous; Eo: Eocene; LO: Lower Oligocene; UO: Upper Oligocene; Pl: Pliocene.**

of an assemblage of marine and non-marine siliciclastic sediments incorporating volcanic and volcanoclastic rocks (Fig. 3; Biddle et al., 1986). The basin evolution was driven by the back-arc crustal stretching with fault-induced subsidence (Fig. 5; Galeazzi, 1998).

These Jurassic rocks are unconformably overlain by Lower Cretaceous marine mudstones that include sandstones, fluvial-deltaic conglomerates, and tuffs of the Yahgán Fm that corresponds to the Springhill Fm in the northern part of the Tierra del Fuego, both on-shore and off-shore (Olivero and Martinioni, 1996). The clastic wedge is northward transgressive over a sedimentary sequence that thickens southwards, as clearly displayed in many of the exploration reflection seismic lines available for the area (Fig. 12).

In the Magallanes basin the Lower Cretaceous subsidence was driven by thermo-cooling (sag phase) processes that developed after the Jurassic rifting and were active up to the Late Cretaceous (Biddle et al., 1986). From Albian to Early Tertiary times the inversion of the extensional basin was caused by the northward shifting of the compressional tectonic activity. This activity progressively involved the southern basin zones in the fold-and-thrust belt.

At the end of the Cretaceous, in the southernmost part of the Magallanes and Malvinas basins, close to the

Andean orogenic wedge, several E-W trending extensional faults with a significant strike-slip component developed. These transtensional faults are planar, steep, south dipping, and associated with small reverse faults and with minor hanging-wall rotations, showing a classical flower-like geometry characteristic of strike-slip tectonic settings (Yrigoyen, 1989; Robbiano et al., 1996; Fig. 12). The stratigraphic relationships have been calibrated with several off-shore wells located off the Tierra del Fuego Island (Galeazzi, 1998; Tassone et al., this issue). The basin depth varies from north to south, with the tilting of the older units indicating that flower-like structures were active mostly after the Cretaceous, but before the development of the Late-Middle Eocene unconformity (Fig. 12). Later reactivations probably occurred, offsetting the unconformity and forming a subtle anticline over the fault plane. The Magallanes basin developed as a foredeep during the Palaeocene, followed by a full development in the Eocene-Oligocene times, characterised by a compressional tectonic strain field with a significant strike-slip component (Biddle et al., 1986; Olivero and Malumián, 1999). During this tectonic phase, several Jurassic extensional structures were reactivated and likely inverted (Yrigoyen, 1989; Robbiano et al., 1996; Galeazzi, 1998). The Palaeogene transtensional structures are coeval with the development of the Fuegian Cordillera in the internal zone and with the emplacement of the N and NE verging thrust systems. During the same period, along the Cordillera Darwin, extensional and transtensional deformations probably induced the exhumation of the metamorphic core complex (Dalziel and Brown, 1989).

The distribution of the clastic wedge in the Magallanes foredeep basin during the Cenozoic reflects the migration pattern of the depositional system. The propagation of the thrust systems toward the foreland (i.e. towards the active foredeep segments) shifted northeastward the sedimentary depocenters, as shown by the development of angular unconfomities and the thinning trends of the clastic wedges.

The tectonic-sedimentary structures which outcrop in the cliffs along the Atlantic coast can be well related with the unconformities observable in the off-shore seismic lines (Tassone et al., this issue; Fig. 12). At least four syntectonic angular unconformities lie at different stratigraphic levels (i.e. Late Cretaceous, Palaeocene, Eocene and Lower Miocene), including several seismically triggered sand intrusions (in Late Cretaceous, Late Palaeocene and Middle Miocene levels). These syntectonic angular and progressive unconformities constrain the timing of the thrusts propagation in the frontal part of the Fuegian Andes (Olivero and Martinioni, 2001; Lodolo et al., 2002a; Ghiglione and Ramos 2005; Tassone et al., this issue; Olivero and Malumián, this issue).

CENOZOIC WRENCH TECTONICS

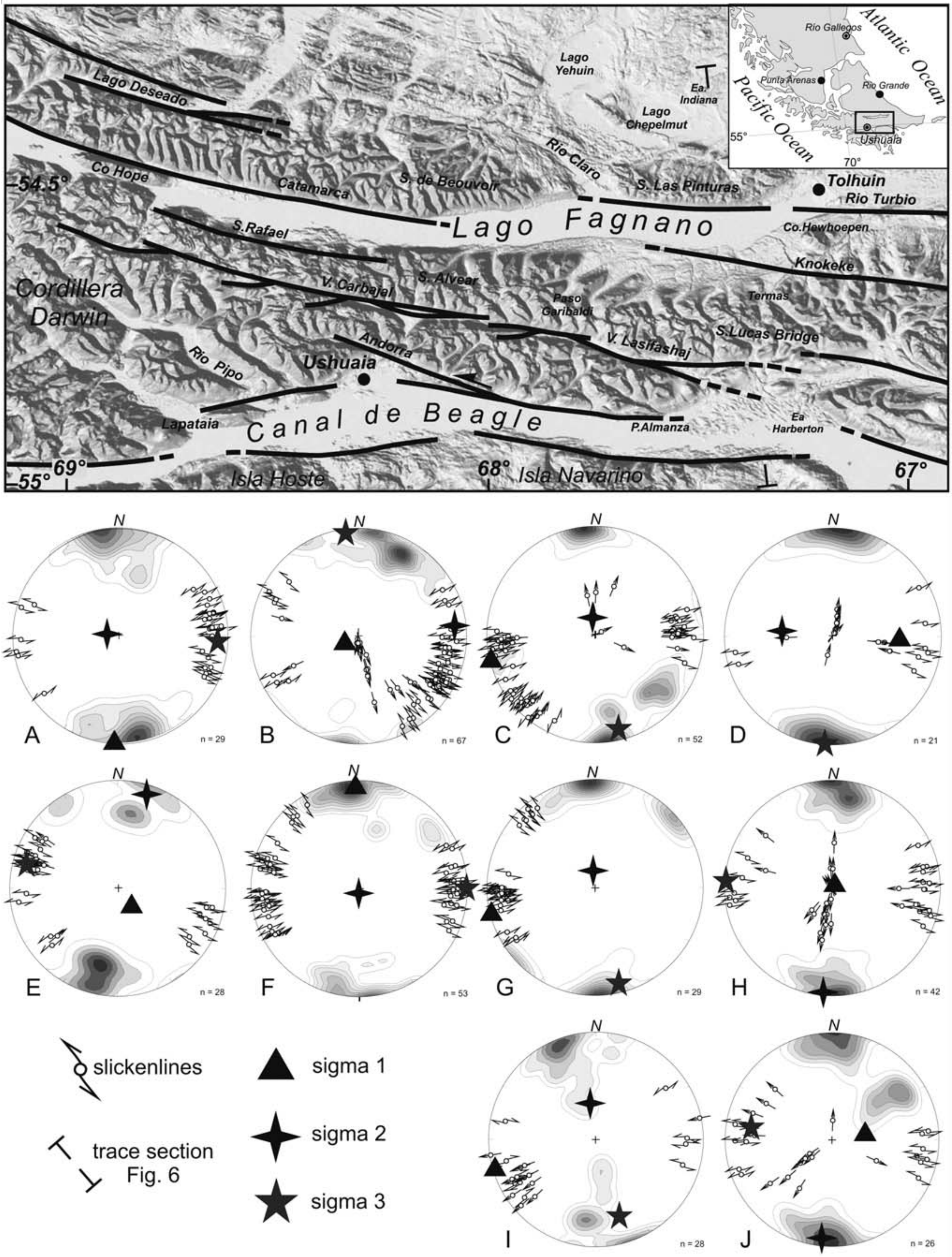
In the Late Cretaceous and especially during the Cenozoic time, a general counter clockwise rotation of the structures of the southernmost Andean Cordillera occurred, as a kinematic component of the relative movements between South America and the Antarctic Peninsula, which from the Late Oligocene might be related to the Scotia Sea development (Cunningham, 1993; Barker, 2001; Lodolo et al., 2003; Geletti et al., 2005). This geodynamic scenario resulted in the development of E-W left-lateral strike-slip faults that affected the southern part of the Tierra del Fuego Island and its Cordillera.

This wrench deformation is partitioned along different faults arrays: the northernmost is known as the Magallanes-Fagnano fault system (MFFS), running for more than 600 km from the Atlantic off-shore, through the Magallanes Strait, to the Pacific Ocean (Cunningham, 1993; Kepleis, 1994b; Lodolo et al., 2003). Other important strike-slip faults that distribute the offset are the Carbajal valley and the Canal de Beagle fault systems (Fig. 13).

The large scale geometry of the MFFS in the Tierra del Fuego has been developing from Oligocene until Quaternary times. During the formation of the MFFS, large brittle structures - more than 50 km in length - were formed by the strike-slip movement (Cunningham, 1993; Kepleis, 1994b). Some of the E-W striking master faults and subsidiary N-S striking extensional splay faults are organized in duplex that occur at regional to local scales (Lodolo et al., 2003).

The geometry, kinematics and timing of deformation of the MFFS are roughly known at a regional scale (Lodolo et al., 2003) with a horizontal offset of many tens of kilometres. Although the kinematics and timing of

FIGURE 13 **Digital elevation model produced from SRTM-3 (3 arc-second resolution) data set (Farr and Kobrick, 2000) of the southernmost part of the Tierra del Fuego Island. Summary lower hemisphere equal area plots of the main fault planes associated with the lineaments. Kamb contours every 2 sigma of the fault planes with slickenlines; orientation of the main stress axes (sigma 1, sigma 2, sigma 3) calculated with Angelier inversion method (Angelier and Goguel, 1979). Number (n) of measurements is indicated for each structural population. A: Lago Deseado; B: Co. Hope Catamarca; C: S. Las Pinturas –Río Turbio; D: S. Rafael – S. Alvear; E: Knokeke-Termas; F: V. Carbajal; G: V. Lasifashaj; H: Canal de Beagle – P. Almanza; I: North Ushuaia; J: Canal de Beagle – Lapataia. The trace of the cross section of Figure 6 is indicated on the eastern side of the map.**


Lago Deseado
Lago Yehuin
Ea. Indiana
Lago Chepelmut
Rio Claro
Co Hope
Catamarca
S. de Beouvoir
S. Las Pinturas
Tolhuin
Rio Turbio
-54.5°
Lago Fagnano
S.Rafael
Co.Hewhoepen
Knokeke
Cordillera Darwin
V. Carbajal
S. Alvear
Paso Garibaldi
Termas
S.Lucas Bridge
V. Lasifashaj
Andorra
Rio Pipo
Ushuaia
Lapataia
Canal de Beagle
P.Almanza
Ea Harberton
69°
68°
67°
-55°
Isla Hoste
Isla Navarino
Atlantic Ocean
Pacific Ocean
Rio Gallegos
Punta Arenas
Rio Grande
Ushuaia
55°
70°
N
A
n = 29
B
n = 67
C
n = 52
D
n = 21
E
n = 28
F
n = 53
G
n = 29
H
n = 42
I
n = 28
J
n = 26
slickenlines
trace section Fig. 6
sigma 1
sigma 2
sigma 3

deformation varies along the strike, most authors agree that sinistral transtensional deformations occurred, at least from the Oligocene, along most of the present-day Atlantic Coast to the western arms of the Magallanes Strait.

The strike-slip structures present strong morphostructural expressions in the E-W lineaments that are visible in the geographic maps, as well as in satellite images (Lodolo et al., 2002b). Narrow valleys and elongated fjords characterize the southern part of the Tierra del Fuego landscape (Fig. 13). In the field, the E-W Magallanes-Fagnano transform fault consists of several strike-slip structures that represent splay, fault bends and steps distributed along different arrays, spanning from the arms of the Canal de Beagle in the south to the Magallanes-Fagnano fault system in the north (Fig. 13). The strike-slip faults are characterised by kinematics with a significant extensional component, with geometry of negative flower structure along the Canal de Beagle (Figs. 6 and 13) and asymmetric northward dipping normal faults down throw with a cumulative offset of few thousand of meters in the Termas and Paso Garibaldi area (Fig. 13; Menichetti et al., 2004). A complex array of left-lateral, south dipping, sub-vertical strike-slip faults occur along the shoreline of the Lago Fagnano (Figs. 6 and 13). Deformation is mainly brittle, while the kinematic analysis indicates a prevalent left lateral transtensional component (Lodolo et al., 2003; Fig. 14).

Several asymmetric and restricted pull-apart basins, many tens of km long and a few km wide occur along the strike of the Magallanes-Fagnano continental transform fault, both in the Atlantic and in Pacific off-shore (Lodolo et al., 2003; Polonia et al., 1999; Bartole et al., 2000; Menichetti et al., 2004; Tassone et al., this issue). The main strike-slip related basin is represented by the Lago Fagnano, located in the northern flank of the Fuegian Andes and infilling a depression 105 km long, 7 km wide, and 173 m deep below sea level (Lodolo et al., 2003, Lodolo et al., 2007; Waldmann et al., this issue; Fig. 13). The bathymetry of Lago Fagnano shows that the basin consists of at least two main depressions. In the eastern part, between Río Turbio and Río Claro, the lake floor is asymmetric, northward dipping by a few degrees (Lodolo et al., 2003). In the western half, bathymetry is more articulated, with the positive relieves associated to the superficial Co. Hope positive structure. The Fagnano basin was formed by two E-W striking, subvertical master faults (Río Turbio-Sierra Las Pinturas and the Co. Hope-Catamarca faults) that represent the bounding structures of the principal deformation zone of the Magallanes-Fagnano system (Fig. 13). These faults, running roughly parallel along the northern shore of the lake, form a releasing step-over and developed secondary splay transversal extensional structures responsible for the pull-apart basin development (Fig. 13). The Río Turbio-Sierra de las Pinturas fault is subvertical and E-W striking for at least 30 km, with a damage zone commonly made up of less deformed meter-wide cataclasite. Sub-horizontal striae on subvertical surfaces within the cataclasites indicate strike-slip dominant displacement. Kinematic indicators, such as S-C fabrics in the cataclasites, consistently show sinistral strike-slip displacement (Fig. 14). The fault zone is typically formed by two bounding, relatively straight fault segments that are linked by an internal set of splay joints and faults oriented obliquely with respect to the slip direction. Splay fractures can be regarded as extensional fractures and extensional-shear fractures; most of these are filled with hydrothermal minerals such as calcite, plagioclase and chlorite, indicating that fluid transport and precipitation accompanied brittle deformation. South of Tolhuin, the Río Turbio fault cuts across the glacial fluvio-lacustrine Quaternary sediments. The outcrop shows several eroded scarps, thus providing evidence for a recent dip-slip fault reactivation (Lodolo et al., 2003).

In the western part of the lake, the Co. Hope-Catamarca fault strikes WNW to NW and locally features a curved trace (Fig. 13). Between Lago Deseado and Co. Hope it splays off several subsidiary faults with compressional step-overs. These compressional features, along with restraining bend and oblique fold structures, can be linked to the eastern lake floor morphology.

Several sections along the MFFS show down-dip striae on the south-dipping fault surfaces (Fig. 13). Because the present-day expression of the MFFS, we speculate that the fault superposes two major displacements: the first on the older strike-slip event, and the second on a younger normal displacement event (Menichetti et al., 2004). The first event was connected to strong circulation of hydrothermal fluids under low-greenschist facies conditions, whereas the last event relates to the formation of the present-day fault scarp (Fig. 14). Field observations of the strike-slip faults architecture at various scales show that the principal deformation zone distributed and partitioned the offset along different arrays.

According with the analogue models (McClay and Dooley, 1995), the faults step-over has apparently migrated westward along bounding strike–slip faults with respect to their former basinal deposits. The shape and size of the Lago Fagnano pull-apart basin can help to estimate the total displacement along this segment. If we take into account that the main subsiding sector of the depression in the eastern sector of the lake is about 50 km long, this figure could represent an underestimate of the size of the fault's offset.

The wrench structures in the region can be interpreted in terms of different degrees of deformation partitioning

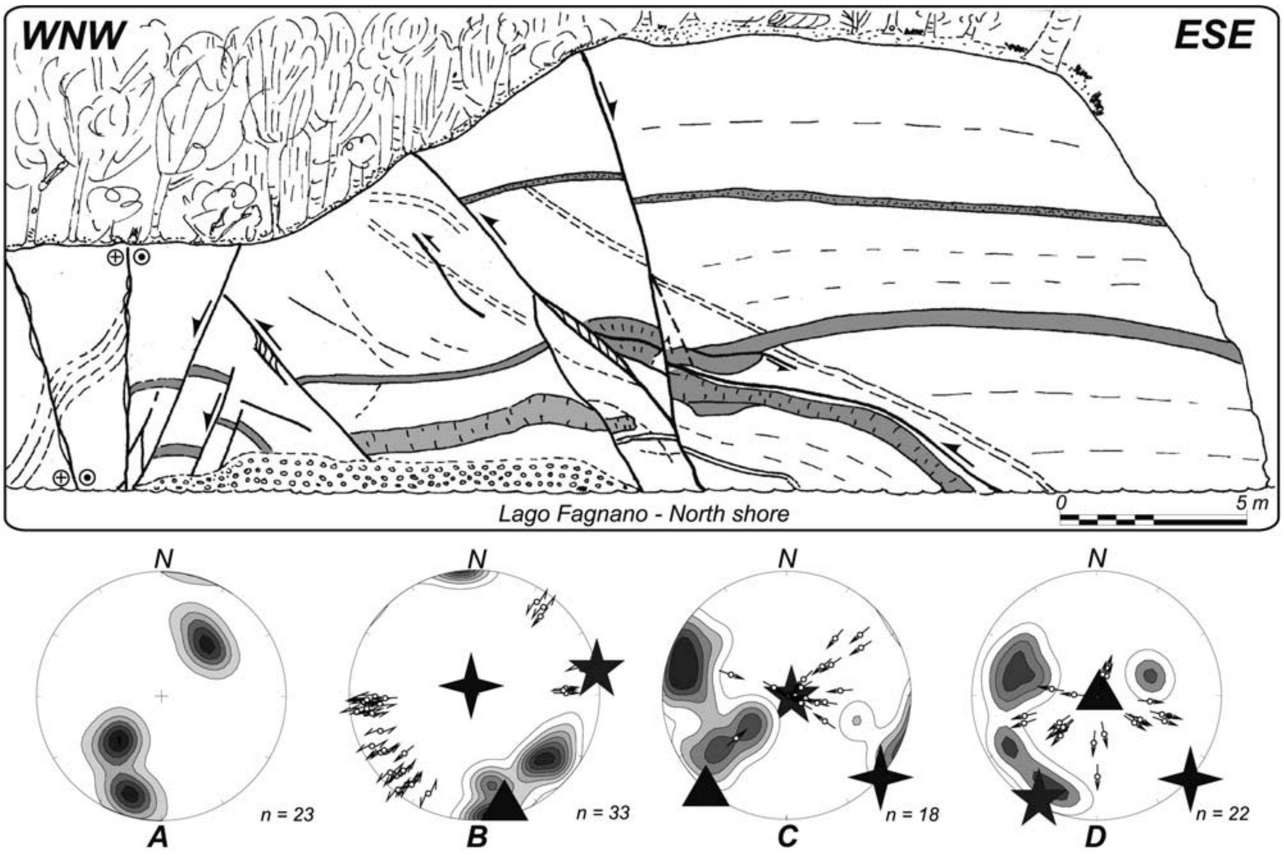


FIGURE 14 **Line-drawing of an outcrop along the northern shore of Lago Fagnano. The cliff shows a complex deformation system with superposition of the younger transcurrent and extensional phase on the Andean compression phase. Field measurements and structural analyses conducted on this outcrop are presented as lower hemisphere equal area plots. Contours every 2 sigma. Orientation of the main stress axes - triangle (sigma 1), cross (sigma 2), star (sigma 3) - calculated with Angelier inversion method (Angelier and Goguel, 1979). A: Kamb contours of the bedding attitude; B: Kamb contours of the left lateral strike-slip faults with slickenlines; C: Kamb contours of the thrusts faults with slickenlines; D: Kamb contours of the normal faults with slickenlines. Number (n) of measurements is indicated for each structural population.**

and plate coupling originating from the relative motion between the South America and the Antarctic Peninsula, likely connected to the formation of the Scotia Sea from the Late-Oligocene (Barker, 2001; Lodolo et al., 2003).

GEOLOGICAL CROSS SECTION OF THE FUEGIAN ANDES

A N-S cross section through the Fuegian Orogen has been constructed by integrating original surface field data with structures observable in the seismic reflection lines (Fig. 6). In the north part of the Island, many industrial on-shore and off-shore reflection seismic lines, obtained by several petroleum companies are available (Cagnolati et al., 1987; Álvarez-Marrón, 1993; Robbiano et al., 1996). In the southernmost off-shore area of the Isla de los Estados and of the Drake Passage, scientific cruises provided new original seismic reflection data set (Lodolo et al., 2002b, b, 2003). Other geophysical data, mainly gravimetric and magnetometric mesurements, are used for constraining the deep geological setting (Tassone et al., 2005).

The southernmost part of the section is located in the Isla Navarino and through the Canal de Beagle. Northwards, this section cuts across the Sierra Lucas Bridges and the Lago Fagnano area, where detailed geological data are available (Suárez et al., 1985; Lodolo, 2002b; Menichetti et al., 2004). The area around the Isla Navarino and the Canal de Beagle is characterized by the presence of E-W trending, left lateral strike-slip faults, which are associated with several normal faults (Cunningham, 1993; Menichetti et al., 2004). These transtensional structures present many fault planes dipping at low angle and are superimposed on the north-verging thrust slices. Cenozoic plutonic rocks are found further to the west in the area of Ushuaia, as well as in the north-eastern part of the Fuegian Cordillera (Olivero and Martinioni, 2001; Acevedo et al., 2002).

In the Sierra Lucas Bridge, the Lemaire Fm is uplifted and a sole thrust leads several duplex that are progressively translated throughout the north along the *décollement* surfaces; these can be found in the Late Jurassic to Cretaceous mudstone and slate levels. The thrust surface is marked by a brittle shear zone a few tens of meters thick where S/C tectonites are very well developed. In the central part of the Cordillera, several thrust slices consist of mylonitic rocks characterised by a strong deformation within ductile regime. The shallow sole thrust structures are exposed in the Termas area and they show at least two main detachment levels, one of which is localized in the Lemaire Fm, and the other in the Cenozoic clastic sediments. These thrust surfaces display a regional continuity along the northern side of the Fuegian Andes (Álvarez-Marrón, 1993; Kepleis, 1994b).

The principal stacks of the internal thick-skinned basement involved in the thrusting are made up by Upper Palaeozoic to Lower Tertiary high grade metamorphic rocks that crop out in the Cordillera Darwin (Nelson et al, 1980; Cunningham, 1995). Towards the east, in the Argentinean sector of Tierra del Fuego, these compressional structures merge in thick mylonitic shear zones formed under greenschist metamorphic conditions. The geometry of the thrust complex is an upright, south plunging monocline of moderate tilted sedimentary cover strata, as well as the related thrust faults and chevron folds that affected both the Upper Jurassic and the Cretaceous rocks (Fig. 6). Two main coaxial populations of WNW-ESE trending macro-and mesoscale structures are identified: 1) large folds and low-angle to bedding-parallel thrusts/*décollements*, and 2) asymmetric chevron folds and moderately steeply SSW dipping thrusts that make a part of the major fold-and-thrusts belt system.

In the internal part of the Fuegian Andes (Fig. 6) the thrust complex includes two south-dipping duplexes, with a sole thrust rooted in the pre-Jurassic basement. The sole thrusts merge northward onto the Jurassic volcanoclastic sediments. In the external sector, a deeper slice of basement leads the edge of the Cordillera in the Magallanes fold-and-thrust belt. The displacement of the major *décollement* thrust sheets is distributed with slip forming ramp anticlines. Folds, thrust faults, and back-thrusts probably accompanied the emplacement of these thrust sheets both below and in front of the Cordillera. Tight folds and associated thrust faults in the Sierra Lucas Bridge were probably generated over the sole thrusts cropping out in the Lago Fagnano area. The cumulative shortening of these structures can be estimated in the order of tens of kilometres across the region.

The area in the north slope of the Cordillera is affected by a northernmost system of left lateral E-W strike-slip faults. The releasing step-over geometry and the kinematic pattern of these structures show a dominant transtension with the formation of the elongated pull-apart basin of the Lago Fagnano. This structure presents in the eastern part a depositional wedge abuts the transform segment, suggesting simultaneous strike-slip motion and transform-normal extension. The sub-vertical nature of the strike slip fault and the strongly asymmetric architecture towards the principal deformation zone of this pull-apart basin suggest a rapid tectonic subsidence.

The external domain of the Cordillera comprises the fold-and-thrust belt where the Cenozoic sediments of the Magallanes basin are involved in the shortening. The shallow structures are tight folds, with imbricate stepped thrust surfaces. On the northern end of the section the structures became wider and the detachment surface is located in the Neogene marl levels.

The deeper structures in this part of the section are clearly displayed in the commercial seismic lines, as well as in the Tierra del Fuego off-shore and on-shore (Lodolo et al., 2003; Fig. 12). In this central part of the section an evident step at the top of the basement rocks occurs, with an offset of a few kilometres. The step corresponds to at least two imbricate slices of the basement in the Fuegian Cordillera, while the total offset includes the further extension related to the Magallanes-Fagnano strike-slip fault system. The deepest structures in the Lago Fagnano area are related to the extensional Jurassic faults that are clearly noticeable in the off-shore seismic lines (Galeazzi, 1998).

The transtensional nature of these faults produces a southward stepped foredeep, which is clearly displayed in all seismic lines in front of the Cordillera and affects both the Magallanes and Malvinas basins. The Eocene age of this deformation is well constrained within seismic lines in the Atlantic off-shore (Robbiano et al., 1996; Galeazzi, 1998).

The shallow structures in the northern part of the section relate to the thin-skinned fold-and-thrust belt in the Magallanes basin. Their geometries reveal a progressive migration of the deformation front and its consequent influence on the sedimentation depocentre in the foreland. The orogenic shortening of the Fuegian Andes, including the Cordillera and the Magallanes fold-and-thrust belt (calculated with simple geometrical assumptions; DePaor, 1988) spans a few hundred kilometres, with a significant left-lateral wrenching component. However, a precise estimate of the amount of crustal shortening across the Cordillera is not possible with the available data and it requires several assumptions, such as the need to adopt a simple-shear model homogeneously distributed across the whole deformed terrain (Ramsay and Huber, 1987). Obviously, the shear strain is not evenly distributed in the Fuegian Cordillera and its variation across the deformed zone is not yet well understood.

NEOTECTONICS

In the Tierra del Fuego region, the continental transform boundary between the South American and the Scotia plates is characterized by low seismicity (M<3.5) with shallow crustal earthquakes. The available focal solutions give a strike-slip motion with a component of transtension one (Pelayo and Wiens, 1989). In 1949 the Tierra del Fuego Island was affected by a M 7.5 earthquake that produced several landslides in the bank of the Lago Fagnano, and local tsunami waves in the westernmost arms of the Magallanes Strait (Lomnitz, 1970; Jaschek et al., 1982).

The present day deformation pattern, as measured by the re-occupation of DGPS stations located on both sides of the main wrench faults of the South American and Scotia plates, suggests a horizontal slip of about 6 mm/year (Del Cogliano et al., 2000; Smalley et al., 2003), while plate tectonic models indicate about 22 mm/year (De Meet et al., 1990).

The Magallanes-Fagnano fault system outcrops in the intermountain valley on the western sector of Lago Fagnano, where aligned fault scarps, truncated vegetation, and sag ponds suggest a fault trace in the Quaternary alluvial cover. Subvertical WNW-ESE extensional faults, with a significant sinistral strike-slip component, are common in the area (Kepleis, 1994b). In the Lago Deseado area, a scarp of a few meters within Pleistocene glacial deposits, displays extensional deformations (Fig. 15). These sediments are dissected by several sets of subvertical south dipping normal faults. The kinematics analysis of the fault populations in the Lago Deseado area shows a prevalent left lateral trastensional strain field (Fig. 13).

In the eastern part of Lago Fagnano, abundant morphological evidence of Quaternary activity of the fault is found with linear truncation of river meanders, drag of river valleys and hang valleys (Lodolo et al., 2002b). A WE scarp of about 1 m, which is associated with a stepped gravel barrier on the Lago Fagnano shore, formed during the 1949 earthquake by enclosing a sag pond of the lower Río Turbio valley. Along the ruptured trace, a small outcrop of cross-stratified glacio-fluvial sediments occurs, showing several sets of sub-vertical, S-dipping normal faults (Lodolo et al., 2002b). Along the Atlantic coast a system of N-S trending, subvertical dextral strike-slip faults offset the actual shoreline and the coastal cliffs a few tens of meters. The main morphostructural lineaments mapped for the whole Tierra del Fuego Island on the panchromatic SPOT mosaic images, are mostly E-W oriented, with secondary NS lineaments (Lodolo et al., 2002a).

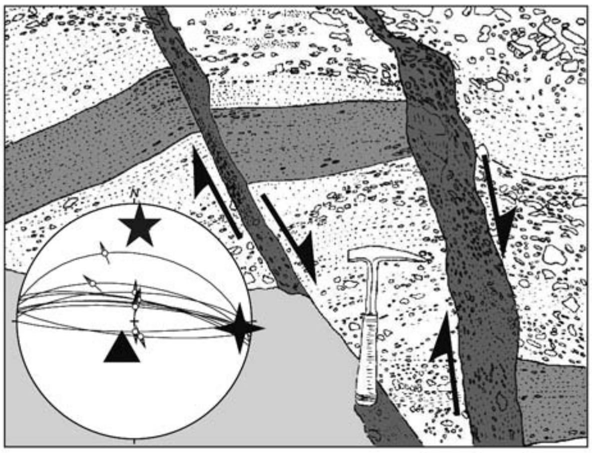


FIGURE 15 | **Line drawing of a glacio-fluvial sand and gravel outcrop located in the Lago Deseado area. A scarp of few meters displays extensional deformations with a fault gouge. Fault planes great circles in the lower hemisphere equal-are plot show the fault and related striae (arrow) of the hangingwall. The orientation of the main stress axes – triangle (sigma 1), cross (sigma 2), star (sigma 3) – are calculated with Angelier inversion method (Angelier and Goguel, 1979).**

In the northern part of the Island, around the area of the Magallanes Strait, strong morphostructural evidence of normal faulting are and recognisable both on the field and on satellite and digital elevation model maps. This is particularly displayed in the drainage network, as well as in the segmented and aligned scarps, triangular facets, and slope breaks (Diraison et al., 1997; Fig 15). They are part of a system of ENE-WSW trending normal faults, with one of the main structures represented by the depression running from Bahia San Sebastian on the Atlantic coast to Bahia Inútil in the Magallanes Strait. The Quaternary activity of these structures is also visible in the Magallanes Strait's seismic lines (Lodolo et al., 2003; Fig. 16). These extensional structures have been interpreted by Diraison et al. (1997) as an expression of a Neogene rift system initiated by a counter clockwise rotation of the foreland in the concave side of the Andean Cordillera. The geometry of the N-S dextral strike-slip faults, together with the NW-SE trending fold-and-thrust belt and NE-SW trending extensional features, is consistent with the general E-W left lateral transform system that has affected the whole southern tip of the South American plate since the Palaeogene (Lodolo et al., 2002b).

CONCLUDING REMARKS

The geological study of the Tierra del Fuego has shown that the area has been affected by at least three complex tectonic evolutionary phases: extensional in the Late Jurassic-Early Cretaceous, compressional

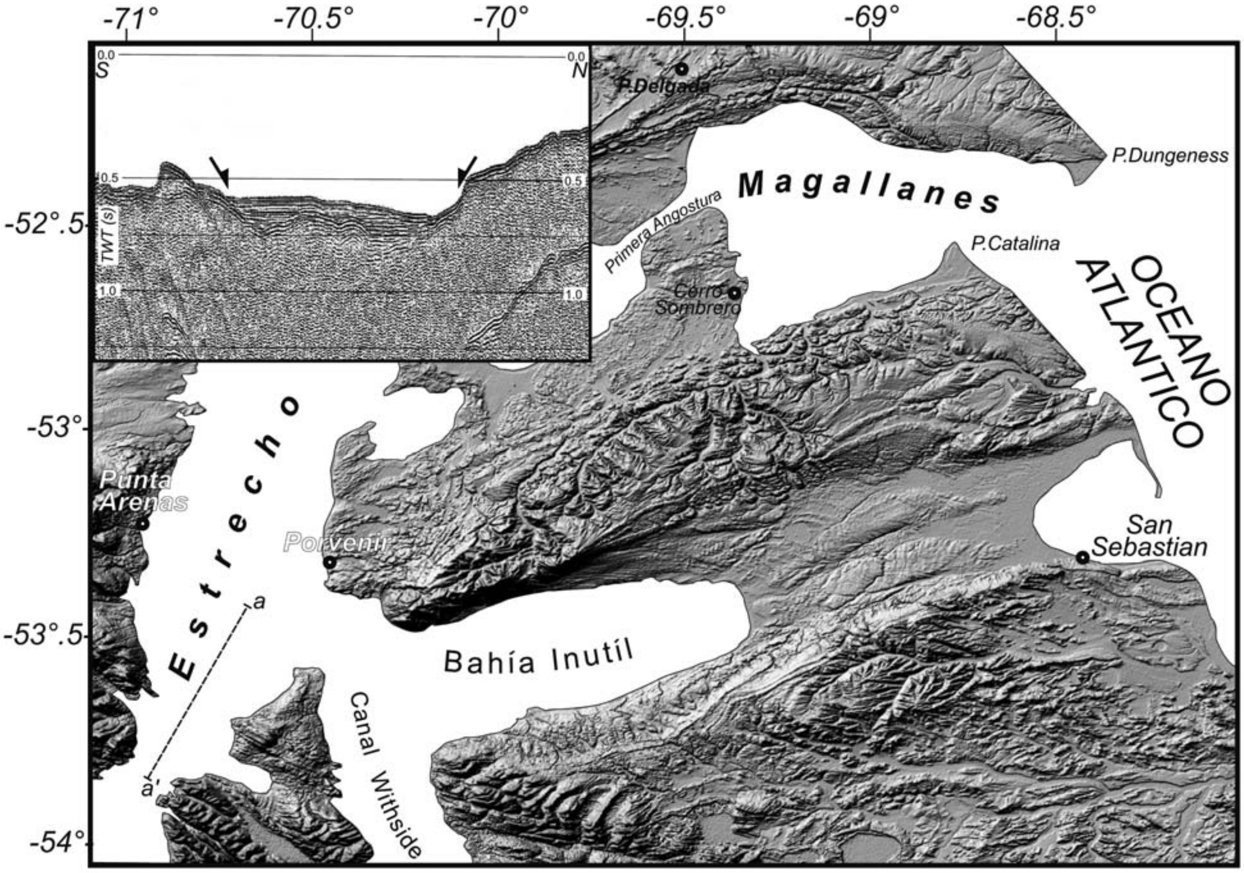


FIGURE 16 **Shaded relief image of the northern part of the Tierra del Fuego produced from SRTM-3 (3 arc-second resolution) data set (Farr and Kobrick, 2000). The main morphostructural features between the Atlantic Ocean and Magallanes Strait, related to the NE-SW trending extension fault systems are clearly visible. In the inset box, near-trace monitor of seismic reflection profile (a-a´ section) acquired in the Central part of the Magallanes Strait (from Lodolo et al., 2003). The extensional faults related to the Bahía Inútil and San Sebastian graben extend to the south-west in the Magallanes Strait.**

from the Late Cretaceous-Palaeocene to Eocene, and strike-slip from the Oligocene onwards. This latter phase gave rise to structures superimposed to the previously existing geologic features and possibly resulted in their reactivation.

Despite more than a century of geological research, the main outline of the structural geology of the Tierra del Fuego Island was based on a sparse data set that, in many instances, has been extrapolated over hundreds of kilometres. In spite of the availability of remote sensing observations and surveys, large areas of the region remain unknown and there are severe gaps in the geological knowledge, such as the geology of the Cordillera Darwin in the west, the loci of the metamorphic core, and the nature of the basement rocks. The general uplift and exhumation of the area related to the extensional faults is derived from thermochronologic data, while the role of the transtensional structures is not well understood.

The whole tectonic evolution of the Fuegian Andes must be considered in all its complex stages and in terms of deformation histories, which involve the fabrics, the strains and the rotation of the structures. The actual complex strain field might derive from strain partitioning. This involves the distribution of deformation, the orientation and/or intensity of the field in various domains and it may be facilitated by reactivation of pre-existing zones of structural weakness that are in suitable orientation to minimize the tectonic work.

The large outcrops of the Lemaire Fm in the Fuegian Andes require further investigation, from both the structural point of view and in terms of deformation mechanisms and rheology of the faults. The stratigraphic relationship between the Lemaire Fm, which is rich in acidic volcanic fragments, and the andesitic composition of the volcanoclastic turbidites of the Yahgán Fm, is in many cases so ambiguous that it suggests unrelated and/or complex paleogeographic frameworks and calls for further petrographic studies and more precise chronological subdivision.

The stratigraphic and structural relationships between Lemaire/Tobifera and Yahgán rocks are clearly defined in the western part of the Island, along the Cordillera Darwin, and are remarkably imaged on seismic lines acquired in the Atlantic offshore. There is also strong evidence that the pre-Jurassic basement rocks were involved in the Andean tectonic phase but the magnitude of the shortening is very difficult to estimate along the Fuegian Andes.

The outcrops on the western part of Lago Fagnano, together with the location of the boundary between the Fuegian Andean chain and the Magallanes foreland suggest the presence of Mesozoic-Cenozoic strike-slip faults that need to be confirmed along the Cordillera. Strike-slip faults paralleling the trench are a common feature in various sectors of the Andean Cordillera and their presence in Tierra del Fuego needs to be further investigated.

The Cenozoic EW sinistral wrench tectonics that characterizes the region was superposed on earlier tectonic weakness zones and likely inverted or reactivated them. The occurrence of major belts of mylonitic rocks along the Fuegian Cordillera associated with shear zones might indicate strike-slip activity since the Mesozoic. The several pull-apart basins located along the Magallanes-Fagnano fault system show complex sedimentary architectures with different subsidence rates. The geometry and the distribution of positive and negative structures along the principal deformation zones of the strike-slip fault arrays, as well as the alternation of restraining and releasing structures, seem to be controlled by the preexisting basement structures.

The nature of the progressive bending of the Andean Cordillera from a N-S trend towards an E-W orientation in correspondence with the Tierra del Fuego Island could be related to an orocline process. Palaeomagnetic and structural data indicate that such rotation may be interpreted as a tectonic bend marked by the left-lateral wrench faults along the North Scotia Ridge.

The tectonic evolution of the Fuegian Andes since the Mesozoic is linked to the general plate tectonic frame of the Gondwana margin where intracontinental deformation, bending and strike-slip faulting played an important role in shaping the southernmost Cordillera. The progressive decrease of the shortening and the increase of the wrenching along the Chile Trench and their relationship with the geodynamics of the area is still an open problem, which need furthers investigations both onshore and offshore.

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REFERENCES

Acevedo, R.D., Linares, E., Ostera, H., Valín-Alberdi, M.L., 2002. Hornblendita Ushuaia (Tierra del Fuego): Petrografía, geoquímica y geocronología. Revista de la Asociación Geológica Argentina, 57(2), 133-142.

Álvarez-Marrón, J., McClay, K.R., Harambour, S., Rojas, L., Skarmeta, J., 1993. Geometry and evolution of the frontal part of the Magallanes foreland thrust and fold belt (Vicuña area), Tierra del Fuego, southern Chile. American Association Petroleum Geologist Bulletin, 11, 1904-1921.

Angelier, J., Goguel, J., 1979. Sur une méthode simple de determination des axes principaux des contraintes por une population de failles. Comptes Rendus Royale Académie Sciences de Paris, 288, 307-310.

Barker, P.F., 2001. Scotia Sea regional tectonic evolution: implications for mantle flow and paleocirculation. Earth-Science Reviews, 55, 1-39.

Bartole, R., Colizza, E., De Muro, S., Colautti, W., 2000. The Pacific Entrance of the Magellan Strait: Preliminary results of a seismic and sampling survey. Terra Antartica Reports, 4, 81-94.

Biddle, K.T., Snavely III, P.D., Uliana, M.A., 1996. Plateau de las Malvinas. In: Ramos, V.A., Turic, M.A. (eds.). Geología y recursos naturales de la plataforma continental Argentina. 13 Congreso Geológico Argentino y 3 Congreso de Exploración de Hidrocarburos, Relatorio, 225-252.

Biddle, K.T., Uliana, M.A., Mitchum, R.M., Fitzgerald, M.G., Wright, R.C., 1986. The stratigraphic and structural evolution of the central and eastern Magallanes Basin, southern South America. International Association of Sedimentologists, Special Publication, 8, 41-61.

Bonarelli, G., 1917. Tierra del Fuego y sus turberas. Anales del Ministerio de Agricultura de la Nación (Argentina), 12, 3, 1-86.

Bruhn, R.L., 1979. Rock structures during back-arc basin deformation in the Andes of Tierra del Fuego. Geological Society of America Bulletin, 90, 998-1012.

Cagnolatti, M., Covellone, G., Erlicher, J., Fantin, F., 1987. Fallamiento y plegamiento de cobertura al suroeste del Río Grande, Cuenca Austral- Tierra del Fuego. 10 Congreso Geológico Argentino, 1, 149-152.

Caminos, R., 1980. Cordillera Fueguina. Córdoba, Geología Regional Argentina, 2, 1463-1501.

Caminos, R., Haller, M., Lapido, J., Lizuain, O., Page, A., Ramos, V.A., 1981. Reconocimiento geológico de los Andes Fueguinos. Territorio Nacional de Tierra del Fuego. VIII Congreso Geológico Argentino, San Luis, Argentina, Actas, 3, 759-786.

Cecioni, G., 1956. Primeras noticias sobre La existencia del Paleozoico Superior en el Archipiélago Patagonico entre los paralelos 50° y 52°S. Universidad de Chile, Facultad de Ciencias Físicas y Matemáticas, Anales, 13, 183-202.

Cunningham, W.D., 1993. Strike-slip faults in the southernmost Andes and the development of the Patagonian orocline. Tectonics, 12(1), 169-186.

Cunningham, W.D., 1995. Orogenesis at the southern tip of the Americas: the structural evolution of the Cordillera Darwin metamorphic complex, southernmost Chile. Tectonophysics, 244, 197-229.

Cunningham, W.D., Dalziel, I.W.D., Lee, T.Y., Lawver, L.A., 1995. Southernmost South America–Antarctic Peninsula relative plate motions since 84 Ma: implications for the tectonic evolution of the Scotia arc region. Journal of Geophysical Research, 100, B5, 8257-8266.

Dalziel, I.W.D., 1981. Back-arc extension in the southern Andes: A review and critical reappraisal. Phylosophical Transactions of the Royal Society A-300, 319-335 .

Dalziel, I.W.D., 1985. Collision and Cordilleran orogenesis: an Andean perspective. In: Coward, M.P., Ries, A.C. (eds.). Collision Tectonics. Geological Society of London Special Publication, 19, 389-404.

Dalziel, I.W.D., Brown R.L., 1989. Tectonic denudation of the Darwin metamorphic core complex in the Andes of Tierra del Fuego, southernmost Chile: implications for Cordilleran orogenesis. Geology, 17, 699-703.

Dalziel, I.W.D., Elliot, D.H., 1973. The Scotia Arc and Antarctic margin. In:. Nairn, A.E.M., Stehli, F.G. (eds.). The Ocean Basin and Margin I. The South Atlantic, 171-245.

Dalziel, I.W.D., Forsythe, R.F., 1986. Andean evolution and the terrane concept. In: Howel, D.G. (ed.). Tectonostratigraphy Terranes of the Circum-Pacific Region. American Association Petroleum Geologist, Houston, 565-581.

Dalziel, I.W.D., Palmer, K.E., 1979. Progressive deformation and orogenic uplift at the southern extremity of the Andes. Geological Society of America Bulletin, 90, 259-280.

Dalziel, I.W.D., de Witt, M.J., Palmer, K.F., 1974. Fossil marginal basin in the southern Andes. Nature, 250, 291-294.

Del Cogliano, D., Perdomo, R., Hormaechea, J.L., 2000. Desplazamiento entre placas tectónicas en Tierra del Fuego. Actas de la XX Reunión Científica de la AAGG, Mendoza.

DeMets, C., Gordon, R.G., Argus, D.F., Stein, F., 1990. Current plate motions. Geophysics Journal International, 101, 425-478.

De Paor, D.G., 1988. Balanced sections in thrust belts. Part I: Construction. American Association Petroleum Geologist Bulletin, 72(1), 73-90 .

Diraison, M., Cobbold, P.R., Gapais, D., Rossello, E.A., 1997. Magellan Strait: Part of a Neogene rift system. Geology, 25(8), 703-706.

Diraison, M., Cobbold, P.R., Gapais, D., Rossello, E.A., Le Corre, C., 2000. Cenozoic crustal tickening, wrenching and rifting in the foothills of the southernmost Andes. Tectonophysics, 316, 91-119.

Farr, T.G., Kobrick, M., 2000. Shuttle Radar Topography Mission produces a wealth of data. EOS American Geophysical Union, 81, 583-585.

Feraud, G., Alric, V., Fornari, M., Bertrand, H., Haller, M., 1999. ^{40}Ar/^{39}Ar dating of the Jurassic volcanic province of Patagonia: migrating magmatism related to Gondwana break-up and subduction. Earth and Planetary Science Letters, 172, 83-96.

Forsythe, R.D., Mpodozis, C., 1979. El Archipiélago Madre de Dios, Patagonia Occidental, Magallanes: rasgos generales de la estratigrafía y estructura del basamento pre Jurásico Superior. Revista Geológica de Chile, 7, 13-29.

Galeazzi, J.S., 1998. Structural and stratigraphic evolution of the Western Malvinas Basins. American Association Petroleum Geologist Bulletin, 82(4), 596-636.

Geletti, R., Lodolo, E., Schreider, A.A., Polonia, A., 2005. Seismic structure and tectonics of the Schackleton Fracture zone (Drake passage, Scotia Sea). Marine Geophysical Researches, 26(1), 17-28.

Ghiglione, M.C., Ramos, V.A., 2005. Progression of deformation and sedimentation in the southernmost Andes. Tectonophysics, 405, 25-46.

Grunow, A.M., Dalziel, I.W.D., Harrison, T.M., Heizler, M.T., 1992. Structural geology and geochronology of subduction complexes along the margin of Gondwanaland: New data from the Antarctic Peninsula and southernmost Andes. Geological Society of America Bulletin, 104, 1497-1514.

Hanson, R.E., Wilson, T.J., 1991. Submarine rhyolitic volcanism in a Jurassic proto-marginal basin, southern Andes, Chile and Argentina. In: Harmon, R.S., Rapela, C.W. (eds.). Andean magmatism and its tectonic setting. Geological Society of America Special Paper, 265, 13-27.

Herron, E.M., Bruhn, R., Winslow, M., Chuaqui, L., 1977. Post Miocene tectonics of the margin of Southern Chile. In: Talwani, M., Pitman, W.C. III (eds.). Island Arcs, Deep Sea Trenches and Back Arc Basins. Washington, D.C., American Geophysical Union, 273-284.

Hervé, F., Calderón, M., Faúndez, V., 2008. The metamorphic complexes of the Patagonian and Fuegian Andes. Geologica Acta, 6(1), 43-53.

Hervé, F., Demant, A., Ramos, V.A., Pankhurst, R.J., Suárez, M., 2000. The Southern Andes. In: Cordani, U.G., Miliani, E.J., Thomaz Filho, A., Campos, D.A. (eds.). Tectonic Evolution of South America. Rio de Janeiro, 605-634.

Hervé, F., Nelson, E., Kawashita, K., Suárez, M., 1981. New isotopic ages and the timing of orogenic events in the Cordillera Darwin, southernmost Chilean Andes. Earth and Planetary Science Letters, 55, 257-265.

Jaschek, E., Sabbione, N., Sierra, P., 1982. Reubicación de sismos localizados en territorio argentino (1920-1963). Universidad de La Plata, Pub. Obs. Astr., Serie Geofísica, tomo XI, 1.

Jokat, W., Boebel, T., König, Meyer, U., 2003. Timing and geometry of early Gondwana breakup. Journal of Geophysical Research, 108 (B9), 2428, doi:10.1029/2002JB001802.

Katz, H.R., 1962. Fracture pattern and structural history in the sub-Andean belt of southernmost Chile. The Journal of Geology, 70(5), 595-603.

Katz, H.R., 1972. Plate tectonics-orogenic belt in the southeast Pacific. Nature, 237, p. 331.

Klepeis, K.A., 1994a. A relationship between uplift of the metamorphic core of the southernmost Andes and shortening in the Magallanes foreland fold and thrust belt, Tierra del Fuego. Tectonics, 13, 882-904.

Klepeis, K.A., 1994b. The Magallanes and Deseado fault zones: major segments of the South American-Scotia transform plate boundary in southernmost South America, Tierra del Fuego. Journal of Geophysical Research, 99, 22,001-22,014.

Klepeis, K.A., Austin, J.A., 1997. Contrasting styles of superposed deformation in the southernmost Andes. Tectonics, 16, 755-776.

Kohn, M.J., Spear, F.S., Harrison, T.M., Dalziel, I.W.D., 1995. ^{40}Ar/^{39}Ar geochronology and P-T-t paths from the Cordillera Darwin metamorphic complex, Tierra del Fuego, Chile. Journal of Metamorphic Geology, 13, 2, 251- 270.

Kohn, M.J., Spear, F.S., Dalziel, I.W.D., 1993. Metamorphic P-T paths from the Cordillera Darwin: a core complex in Tierra del Fuego, Chile. Journal of Petrology, 34, 519-542.

Kranck, E.H., 1932. Geological Investigations in the Cordillera of Tierra del Fuego. Acta Geographica, 4, 2, 133 pp.

Kreamer P.E., 2003. Orogenic shortening and the origin of the Patagonian orocline (56°lat). Journal of South America Earth Sciences, 15, 731-748.

Lodolo, E., Lippai, H. Tassone, A., Zanolla, C., Menichetti, M., Hormaechea, J.L., 2007. Gravity map of the Isla Grande de Tierra del Fuego, and morphology of Lago Fagnano. Geologica Acta, 5(4), 307-314.

Lodolo, E., Menichetti, M., Tassone, A., Sterzai, P., 2002a. Morphostructure of the central-eastern Tierra del Fuego Island from geological data and remote-sensing images. EGS Stephan Mueller Special Pub. Series, 2, 1-16.

Lodolo, E., Menichetti, M., Tassone, A., Geletti, R., Sterzai, P., Lippai, H., Hormaechea, J.L., 2002b. Researchers target a continental transform Fault in Tierra del Fuego. EOS Transactions AGU, 83(1), 1-6.

Lodolo, E., Menichetti, M., Bartole, R., Ben Avram, Z., Tassone, A., Lippai, H., 2003. Magallanes-Fagnano continental transform fault (Tierra del Fuego, southernmost South America). Tectonics, 22(6), p. 1076, doi: 1029/ 2003T C0901500,2003.

Lomnitz, C., 1970. Major earthquakes and tsunamis in Chile during the period 1535 to 1955. Geologische Rundschau, 59, 938-960.

McClay, K., Dooley, T., 1995. Analogue models of pull-apart basins. Geology, 23, 711-714 .

Menichetti, A., Tassone, A., 2007. GEOSUR 2004. Mesozoic to Quaternary evolution of Tierra del Fuego and neighbouring austral regions I. Geologica Acta, 5(4), 283-286.

Menichetti, M., Acevedo, R.D., Bujalesky, G.G., Cenni, M., Cerredo, M.E., Coronato, A., Hormachea, J.L., Lippai, H., Lodolo, E., Olivero, E.B., Rabassa, J., Tassone, A., 2004. Geology and geophysics of Isla Grande de Tierra del Fuego. Field-trip guide. Geosur 2004, Buenos Aires-Ushuaia, 39 pp.

Mukasa, S.B., Dalziel, I.W.D., 1996. Southernmost Andes and South Georgia Island, North Scotia Ridge: zircon U-Pb and muscovite TMAr/39Ar age constraints on tectonic evolution of southwestern Gondwanaland. Journal of South American Earth Sciences, 9, 349-365.

Nelson, E.P., Dalziel, I.W.D., Milnes, A.G., 1980. Structural geology of the Cordillera Darwin - collisional style orogenesis in the southernmost Chilean Andes. Eclogae Geologicae Helvetiae, 73(3), 727-751.

Olivero, E.B., Malumián, N., 1999. Eocene stratigraphy of southeastern Tierra del Fuego Island, Argentina. American Association of Petroleum Geologist Bulletin, 83, 295-313.

Olivero, E.B., Malumián, D.R., 2008. Mesozoic-Cenozoic stratigraphy of the Fuegian Andes, Argentina. Geologica Acta, 6(1), 5-18.

Olivero, E.B., Martinioni, D.R., 1996. Sedimentología de las Formaciones Lemaire y Yahgán (Jurásico-Cretácico) en Tierra del Fuego. XIII Congreso Geológico Argentino and III Congreso de Hidrocarburos, Buenos Aires, Actas, II, 45-59.

Olivero, E.B., Martinioni, D.R., 2001. A review of the geology of the Fuegian Andes. Journal of South American Earth Sciences, 14, 175-188.

Olivero, E.B., Acevedo, R.D., Martinioni, D.R., 1997. Geología del Mesozoico de bahía Ensenada, Tierra del Fuego. Revista de la Asociación Geológica Argentina, 52(2), 169-179.

Pankhurst, R.J., Rapela, C.R., 1995. Production of Jurassic rhyolite by anatexis of the lower crust of Patagonia. Earth and Planetary Science Letters, 134, 23-36.

Pankhurst, R.J., Riley, T.R., Fanning, C.M., Kelley, S.P., 2000. Episodic silicic volcanism in Patagonia and the Antarctic Peninsula: chronology of magmatism associated with the break-up of Gondwana. Journal of Petrology, 41, 605–625.

Pelayo, A.M., Wiens, D.A., 1989. Seismotectonics and relative plate motions in the Scotia Arc region. Journal of Geophysical Research, 94, 7293-7320.

Polonia, A., Torelli, L., 2007. Antarctic/Scotia plate convergence off southernmost Chile. Geologica Acta, 5(4), 295-306.

Polonia, A., Brancolini, G., Torelli, L., Vera, E., 1999. Structural variability at the active continental margin off Southernmost Chile. Journal of Geodynamics, 27, 289-307.

Ramos, V.A., 1989. Andean foothills structures in Northern Magallanes Basin, Argentina. American Association of Petroleum Geologists Bulletin, 73, 887-903.

Ramos, V.A, Aleman A., 2002. Tectonic evolution of the Andes. In: Cordani, U.G., Miliani, E.J., Thomaz Filho, A., Campos, D.A. (eds.). Tectonic Evolution of South America. Rio de Janeiro, 635-685.

Ramsay, J.G., Huber, M.I., 1987. The techniques of modern structural geology. Academic Press, vol. 2, 700 pp.

Rapalini, A.E., Lippai, H., Tassone, A., Cerredo, M.E., 2005. An AMS and paleomagnetic study across the Andes in Tierra del Fuego. 6 ISAG, Barcelona, España, Actas, 596-599.

Robbiano, J.A., Arbe, H., Gangui, A., 1996. Cuenca Austral Marina. In: Ramos, V.A., Turic, M.A. (eds.). Geología y Recursos Naturales de la Plataforma Continental Argentina. 13 Congreso Geológico Argentino, and 3 Congreso de Exploración de Hidrocarburos, Buenos Aires, Relatorio, 323-342.

Smalley, R. Jr., Kendrick, E., Bevis, M.G., Dalziel, I.W.D., Taylor, F., Lautià, E., Barriga, R., Casassa, G., Olivero, E., Piana, E., 2003. Geodetic determination of relative plate motion and crustal deformation across the Scotia-South America plate boundary in eastern Tierra del Fuego. Geochemistry Geophysics Geosystem, 4, 9, 1070, doi:10.1029/2002GC000446.

Stern, C.R., De Wit, M.J., 2003. Rocas Verdes ophiolites, southernmost South America: remnants of progressive stages of development of oceanic-type crust in a continental margin back-arc basin. In: Dile, Robinson P.T. (eds.). Ophiolites in Earth History. Geological Society of London, Special Publication, 218, 665-683.

Storey, B.C., 1995. The role of mantle plumes in continental breakup: case histories from Gondwanaland. Nature, 337, 301-308.

Suárez, M., Pettigrew, T.H., 1976. An upper Mesozoic island arc-back-arc system in the southern Andes and South Georgia. Geological Magazine, 113, 305-328.

Suárez, M., Hervé, M., Puig, A., 1985. Hoja Isla Hoste e islas adyacentes. Servicio Nacional de Geologia y Mineria de Chile, 133.

Suárez, M., Hervé, F., Puig, A., 1987. Cretaceous diapiric plutonism in the southern cordillera, Chile. Geological Magazine, 124(6), 569-575.

Suárez, M., De La Cruz, R., Bell, C.M., 2000. Timing and origin of deformation along the Patagonian fold and thrust belt. Geological Magazine, 137(4), 345-353.

Tassone, A., Lippai, H., Lodolo, E., Menichetti, M., Comba, A., Hormachea, J.L., Vilas, J.F., 2005. A geological and geophysical crustal section across the Magallanes-Fagnano fault in Tierra del Fuego. Journal of South America Earth Science, 19, 99-109.

Tassone, A., Lodolo, E., Menichetti, M., Yagupsky, D., Caffau, M., Vilas, J.F., 2008. Stratigraphic and structural setting of the Malvinas Basin and its southern margin (Tierra del Fuego Atlantic offshore), Geologica Acta 6(1), 55-57.

Waldmann, N., Ariztegui, D., Anselmetti, F.S.,, Austing Jr, J.A., Dunbar, R., Moy, C.M., Recasens, C., 2008. Seismic stratigraphy of Lago Fagnano sediments (Tierra del Fuego, Argentina) – A potential archive of paleoclimatic change and tectonic activity since the Late Glacial. Geologica Acta, 6(1), 101-110.

Williams, G.D., Vann, I., 1987. The geometry of listric normal fault and deformation in the hangingwalls. Journal of Structural Geology, 9, 789-795 .

Wilson, T.J., 1991. Transition from back-arc to foreland basin development in the southernmost Andes: Stratigraphic record from the Última Esperanza District, Chile. Geological Society of America Bulletin, 103, 98-111.

Winslow, M.A., 1982. The structural evolution of the Magallanes Basin and neotectonics in the southernmost Andes. In: Craddock, C. (ed.). Antarctic Geoscience. Madison, University of Wisconsin Press, 143-154.

Yrigoyen, M.R., 1989. Cuenca de Malvinas. In: Chebli, G., Spalletti, L. (eds.). Cuencas Sedimentarias Argentinas. Universidad Nacional de Tucumán, Serie Correlación Geológica 6, 481-491.

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