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## A morphotectonic analysis of central Patagonian Cordillera: Negative inversion of the Andean belt over a buried spreading center?

B. Scalabrino,<sup>1</sup> Y. Lagabrielle,<sup>1</sup> J. Malavieille,<sup>1</sup> S. Dominguez,<sup>1</sup> D. Melnick,<sup>2</sup> F. Espinoza,<sup>3</sup> M. Suarez,<sup>4</sup> and E. Rossello<sup>5</sup>

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[1] We use digital elevation models and satellite imagery data completed with field observations to develop an integrated morphotectonic analysis of the anomalous topography of the Central Cordillera of Patagonia between 46°S and 48°S, in a region overlying subducted segments of the Chile Spreading Ridge. This region shows a number of peculiar features, not expected in a normal subduction-related belt located away from a buried spreading center. First, it is characterized by overall short-wavelength topography and highly contrasted reliefs, typical of deeply incised young mountain belts, but surprisingly, also by an average very low elevation of ~900 m. Second, the Cordillera lacks central high reliefs; instead, there is a central, depressed domain with average low slope gradients including the deepest point of the study area (300 m below sea level in the bottom of Lake General Carrera/Buenos Aires). This depressed area is flanked by western and eastern regions of higher elevation having opposite general slope dips. To the east, the central Patagonian Cordillera is now separated from the flat plains of the Pampean domain (representing its former piedmont) and several elevated basaltic plateaus (mesetas) by 160°N–180°N trending morphotectonic corridors and the western border scarps of the mesetas. These scarps correspond to neotectonic features controlled by recent vertical faults, mostly active after 3 Ma. Remnants of a former peneplain, the Avellanos surface, are widespread within the entire Cordilleran region. From geological evidence, this peneplain formed between 15 and 4 Ma and was connected originally with the mesetas domain and now is dissected by these corridors. It is shown that a negative inversion related to extensional and strike-slip faulting occurred in the frontal region of the Cordillera

at 3 Ma synchronously with the emplacement of magmatic products. Timing of the extensional deformation in central Patagonia is concomitant with the migration at depth of different segments of the South Chile Ridge, which entered the trench at 6 and 3 Ma, respectively, and the consequent opening of a slab window allows asthenospheric hot mantle to reach lithospheric regions. Finally, migration of segments of the Chile Spreading Ridge since 6 Ma triggered regional uplift of the Cordillera followed by limited extension in relation with increased thermal weakening of the crust. **Citation:** Scalabrino, B., Y. Lagabrielle, J. Malavieille, S. Dominguez, D. Melnick, F. Espinoza, M. Suarez, and E. Rossello (2010), A morphotectonic analysis of central Patagonian Cordillera: Negative inversion of the Andean belt over a buried spreading center?, *Tectonics*, 29, TC2010, doi:10.1029/2009TC002453.

### 1. Introduction

[2] Interaction of oceanic and continental lithospheres at active margins usually results in the contraction of the overriding continent and in the building of a linear mountain belt. Anomalies in the evolution of such subduction-related belts along a given margin may develop due to heterogeneities within the downgoing oceanic lithosphere. All along the East Pacific area, active oceanic spreading ridges represent first-order heterogeneities which may enter the trenches, thus affecting significantly the margins of continental upper plate. It is now demonstrated that subduction of an active spreading center leads to the opening of a slab window, triggering in turn drastic changes in the mantle dynamics beneath the orogenic wedge [Thorkelson, 1990, 1996; Breitsprecher and Thorkelson, 2009], and causing visible effects in crustal deformation and surface morphology. Studies of ancient systems implying subduction of spreading ridges have provided important perspectives on the long-term temporal evolution of a ridge subduction event, mostly through the records from midcrustal rocks. These studies often document overall post-orogenic extension, localized tectonic negative inversion and partial collapse of the subduction belt such as in the Northern American Cordillera, in Alaska [Dickinson and Snyder, 1979; Thorkelson, 1990; Sisson and Palvis, 1993; Bradley et al., 2003], and in the Antarctica Peninsula [Garrett and Storey, 1987]. Geological investigations in subduction belt experiencing current spreading ridge subduction are now needed. Indeed, only in such situations, robust links can be established between geological events at the surface and well-constrained

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locations of slab windows at depth. For these reasons, the Chilean–Argentinian central Patagonian Cordillera is a unique natural laboratory to study the consequences of the subduction of an active spreading ridge beneath a continent. Southern Patagonia has been first concerned by the “normal” subduction of the Farallon–Nazca plate followed, after 15 Ma, by the subduction of the active axis of the South Chile Spreading Ridge [Cande and Leslie, 1986; Cande et al., 1987; Bangs et al., 1992]. Magmatic evidence confirming the development of a slab window beneath Patagonia have been reported from investigations within the post-15 Ma volcanic fields across entire southern South America [Ramos and Kay, 1992; Gorrington et al., 1997; Gorrington and Kay, 2001; Espinoza et al., 2005; Guivel et al., 2006; Lagabrielle et al., 2007], but only few morphotectonic studies have been conducted in these regions until now [Lagabrielle et al., 2004, 2007].

[3] In this paper we present the results of an integrated study of the morphological and tectonic evolution of a portion of the central Patagonian belt lying above the current location of subducted segments of the South Chile Spreading Ridge, between 46°S and 48°S. This study is based on original field data enriched with digital elevation models (DEMs) and satellite imagery from selected key areas surrounding the Lake General Carrera/Buenos Aires, a major geomorphological feature of this region. Topographic and morphotectonic data show that the study area is composed of an assemblage of various domains exhibiting contrasted tectonic evolutions in relation with Miocene–Pliocene vertical displacements.

## 2. A Review of the Geological Evolution of Central Patagonia: Relations With the Subduction of the Chile Spreading Ridge

[4] The central Patagonian Cordillera, is a linear mountain range, oriented approximately north to south and extending between 45°S and 48°S, which constitutes the northern continuation of the southern Patagonian Cordillera described by Ramos [1989], Coutand et al. [1999], and Diraison et al. [2000]. It is 200 km in width at the latitude of the Chile Triple Junction and shows a segmented pattern, consisting of four en echelon ranges, trending 160°N–170°N and limited by frontal thrusts [Lagabrielle et al., 2004]. In section 2.1 we provide a review of the basic events that punctuated the geological evolution of central Patagonia, with emphasis on the influences of the Chile Spreading Ridge.

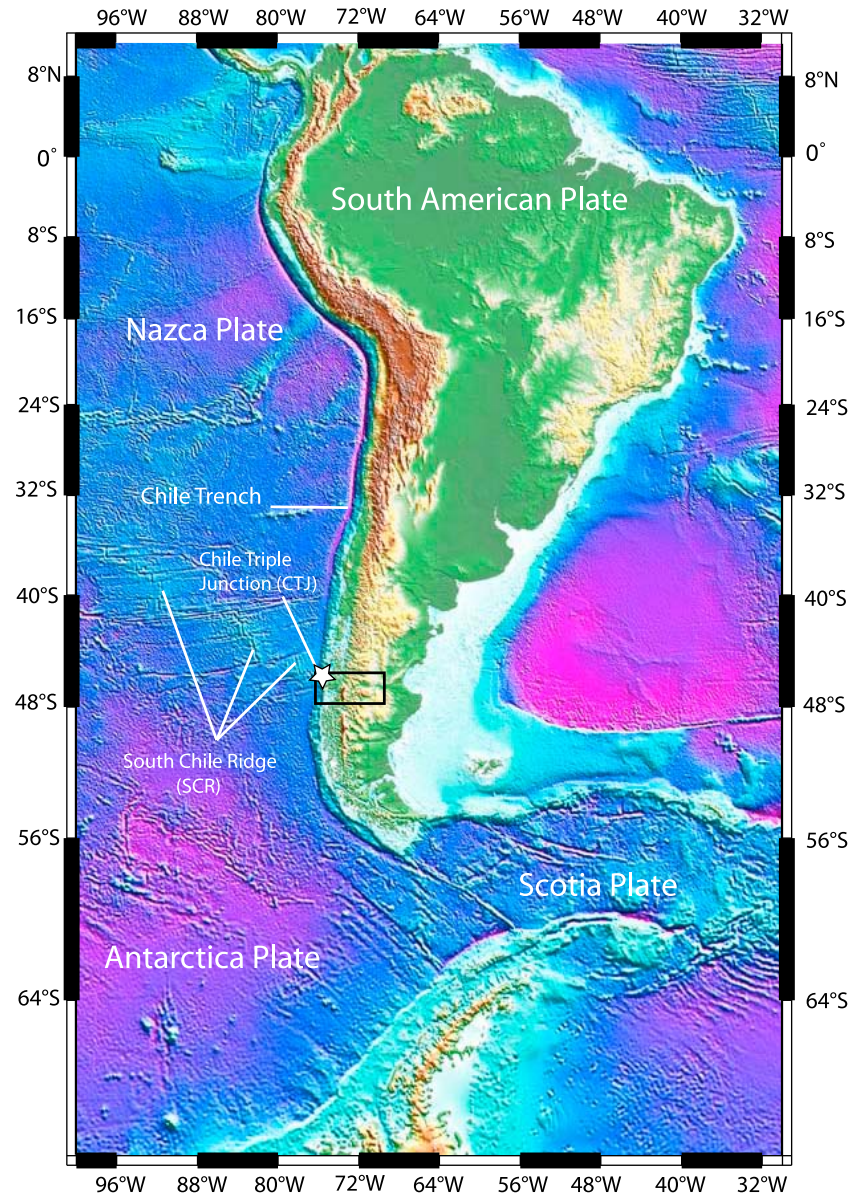
### 2.1. Plate Configuration and Subduction of the Chile Spreading Ridge

[5] The Nazca and Antarctic plates, separated by the active South Chile Spreading Ridge both enter the southern Chile–Peru trench and are presently subducting beneath the South America plate. The Chile Triple Junction (CTJ), the point where the South America, Nazca and Antarctic plates meet, is now located at 46° 12'S, in front of the Taitao Peninsula, the westernmost point of the Chilean coast (Figures 1 and 2). After the collision of the South Chile Ridge with the southern tip of South America at circa 15 Ma [Cande and Leslie, 1986], the Chile Triple Junction migrated northward along the South

American margin to its present-day position. Hence, north of the Chile Triple Junction, the current relative motion vector between the Nazca and South America plates is oriented 80°N with a magnitude of 84 mm/yr [Pardo-Casas and Molnar, 1987; Gripp and Gordon, 1990; DeMets et al., 1990], whereas south of the Chile Triple Junction, current convergence between the Antarctic and South American plates occurs at a rate of 20 mm/yr, in an E–W direction (Figure 2) [Gripp and Gordon, 1990; DeMets et al., 1990]. Oblique subduction has led to strain partitioning in the Cordillera involving complex deformation. North of the Chile Triple Junction, part of the convergence is accommodated along the Liquiñe–Ofqui Zone (LOFZ), a long-lived, right lateral, lithospheric-scale fault system active since the Tertiary [Hervé, 1994; Cembrano and Hervé, 1993; Cembrano et al., 1996, 2002]. The subduction of successive segments of the South Chile Ridge at circa 15 Ma, 6 Ma, 3 Ma and 0.3 Ma [Herron et al., 1981; Cande and Leslie, 1986; Cande et al., 1987; Nelson et al., 1993; Bangs and Cande, 1997; Tebbens and Cande, 1997; Tebbens et al., 1997] led to the progressive opening of the slab window beneath Patagonia (Figure 2) [Ramos and Kay, 1992; Gorrington et al., 1997; Gorrington and Kay, 2001; Lagabrielle et al., 2004; Breitsprecher and Thorkelson, 2009; Scalabrino et al., 2009].

### 2.2. Geological Evolution of Central Patagonia

[6] The neotectonics features described in this paper develop mostly from structures inherited from a rather long tectonic evolution. Since the Late Paleozoic, the western margin of South America has been affected by the eastward subduction of oceanic lithosphere [e.g., Bell and Suarez, 2000]. Jurassic subduction-related acidic volcanics and volcanosedimentary rocks of the Ibañez Group unconformably overlie the Paleozoic basement rocks (Figure 3) [Niemeyer et al., 1984; Charrier et al., 1979; Suarez and de la Cruz, 1996; de la Cruz et al., 2003, 2004; de la Cruz and Suarez, 2005]. The western part of the Patagonian belt is also characterized by exposures of calc-alkaline granitoids forming the Patagonian Batholith, which were emplaced over a continuum subduction environment from the Late Jurassic to the Miocene [Pankhurst et al., 1999; Suarez and de la Cruz, 2001]. In the core of the belt, marine Cretaceous sediments are restricted to isolated sedimentary basins. South of 45°S, the Cenozoic sedimentation recorded the uplift of the Cordillera. Synorogenic clastic deposits (molasse) accumulated in foreland basins that are roughly of the same age all along strike, as well as within one internal basin, the Cosmelli Basin, located immediately south of Lake General-Carrera Buenos Aires [Flint et al., 1994] (Figure 3). The foreland sedimentation changed from marine conditions during the middle Oligocene–early Miocene to continental conditions during the early middle Miocene (Figure 3). The continental molasse locally more than 1000 m thick, consists of fluvial clastic deposits that recorded climate changes from humid to arid due to rain shadow effect of orogeny [Blisniuk et al., 2005]. Between 45°S and 49°S, it ranges in age from 22 to 23 Ma to 16–15 Ma [Frassinetti and Covacevich, 1999; Flynn et al., 2002; Blisniuk et al., 2005]. Since the entire orogeny-related molasse succession was deposited during

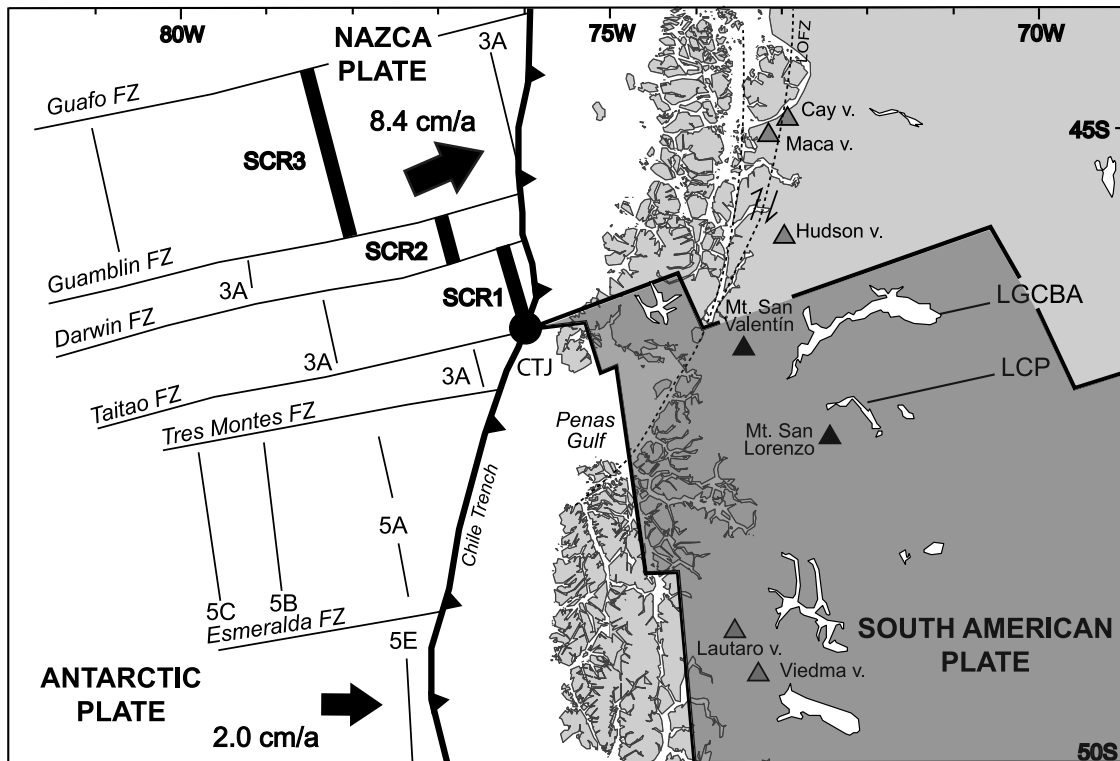


**Figure 1.** Location of the study area in central Patagonia Cordillera (box) and of the Chile Triple Junction (star) on a global digital elevation model of South America and West Antarctic Peninsula together with the bathymetry of the East Pacific Ocean. Land topography is derived from GTOPO30 EROS Data Center, USGS, and seafloor bathymetry is derived from *Smith and Sandwell* [1997].

the late Oligocene to the middle Miocene (30–15 Ma), it is noteworthy that main uplift of the Cordillera occurred prior to 15 Ma, that is prior to the subduction of the SCR [Lagabrielle *et al.*, 2004; Scalabrino *et al.*, 2009].

[7] Calc-alkaline to transitional flows dated at 16–14 Ma unconformably overlie the upper beds of the continental molasse south of Lake General Carrera/Buenos Aires in the Paso Roballos area [Espinoza *et al.*, 2006, 2010; Boutonnet *et al.*, 2010]. This short-lived volcanic episode was followed by a magmatic event of regional importance during which large basaltic flows were emplaced over an erosional surface

that truncates the tectonic front [Lagabrielle *et al.*, 2004]. The main period of basalt flooding (main plateau basalts), lasted from 12 to 3 Ma and eruptions occurred mostly along the former tectonic front of the Cordillera. Large remnants of the 12–3 Ma flows now form basaltic plateaus such as the Meseta del Lago Buenos Aires that dominates morphologically the eastern pampean region, and the Meseta Chile Chico lying inside the Cordillera, immediately adjacent to the morphotectonic front. The main plateau period was followed by more sporadic magmatic events between 3 Ma and some ka (postplateau basalts) leaving numerous cones, flows



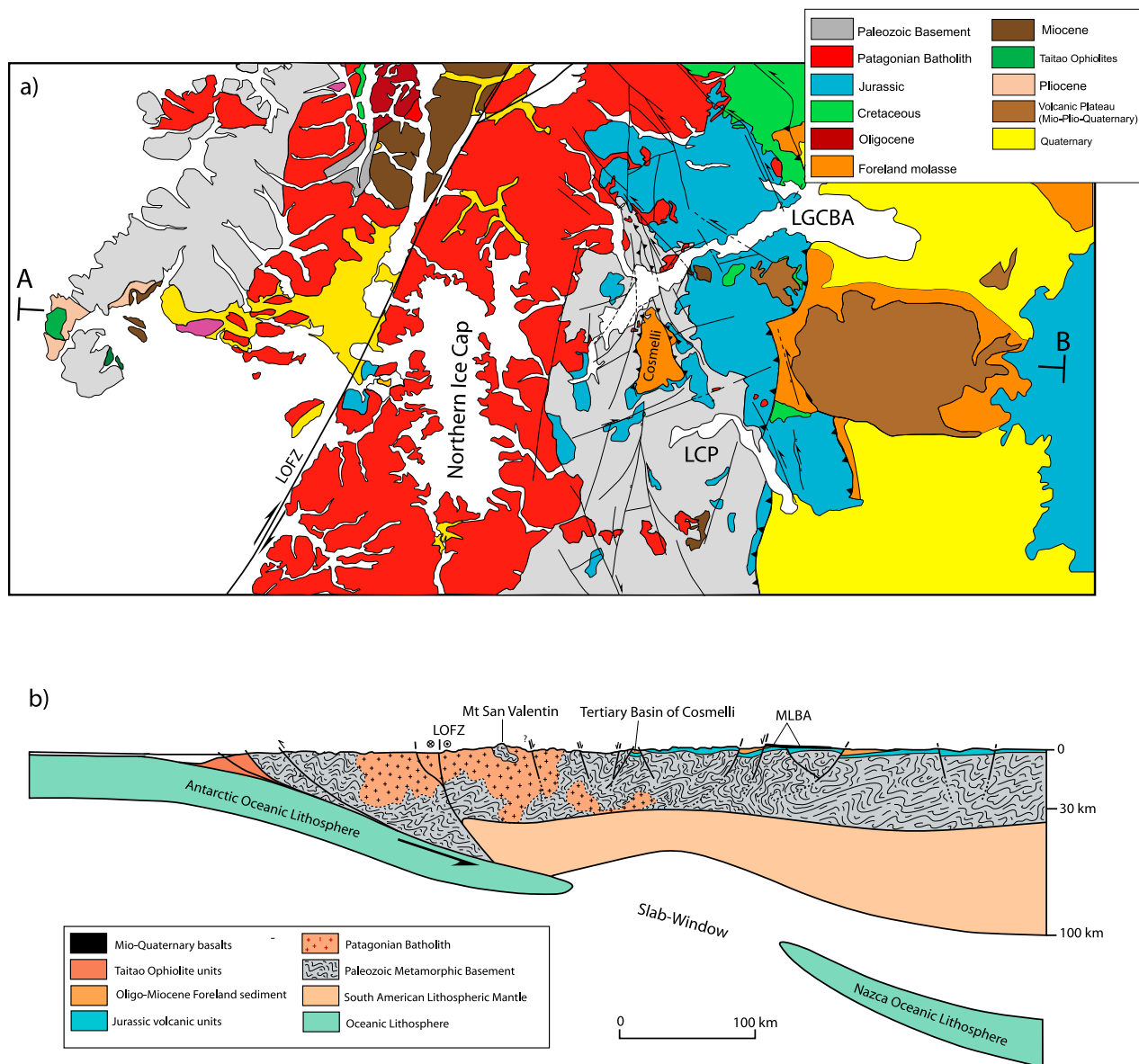
**Figure 2.** Simplified map of the Chile Triple Junction (CTJ) region and plate tectonic frame of the subduction of the South Chile Ridge (SCR). Active segments (SCR1 to SCR4) and transform fault zones (FZ) are shown (adapted from *Tebbens et al.* [1997], *Ramos* [1989], *DeMets et al.* [1990], *Cembrano et al.* [1996], and *Guivel et al.* [1999]). Magnetic anomalies of Nazca and Antarctica plates are also shown. Inferred position of the slab window below South American plate is represented as a dark gray region. LGCBA, Lake General Carrera/Buenos Aires; LCP, Lake Cochrane/Pueyrredón.

and maars on the top surface of the Meseta del Lago Buenos Aires. Lava flows of the main plateau sequence at Meseta del Lago Buenos Aires are interbedded with fluvio-glacial and glacial polymictic conglomerates [*Mercer and Sutter*, 1982; *Espinoza et al.*, 2005; *Lagabrielle et al.*, 2007, 2010]. A significant portion of these deposits are granitoid clasts, indicating that during the late Miocene, some sediments traveled more than 100 km from their source in the western Cordillera, along a main drainage axis now morphologically inverted, forming the top surface of the Meseta del Lago Buenos Aires [*Mercer and Sutter*, 1982; *Lagabrielle et al.*, 2010].

[8] Various plutons have been emplaced and rapidly exhumed during the Tertiary in central Patagonia, indicating important vertical displacements. Plutonic rocks exposed at the summit of Monte San Lorenzo (3706 m above sea level (asl)) yielded biotite K-Ar ages of  $6.6 \pm 0.5$  and  $6.4 \pm 0.4$  Ma [*Welkner*, 1999; *Suarez and de la Cruz*, 2001]. A young pluton at Paso Las Llaves, on the southern coast of the Lake General Carrera/Buenos Aires, has given ages ranging from 10 Ma to 9.7 Ma [*Petford and Turner*, 1996; *Pankhurst et al.*, 1999; *Suarez and de la Cruz*, 2001; *Thomson et al.*, 2001]. Late Miocene plutonic bodies exposed close to the morphotectonic front at Paso Roballos have given ages around 10 Ma [*Ramos*, 1989]. A small pluton exposed south of Lake Gen-

eral Carrera/Buenos Aires (Las Nieves pluton) yielded an age of  $3.2 \pm 0.4$  Ma [*Suarez and de la Cruz*, 2000; *Morata et al.*, 2002]. Several felsic subvolcanic bodies, mostly shallow level plugs, dykes and laccoliths, are exposed along the southwestern border of the Meseta del Lago Buenos Aires, west of Monte Zeballos. They are intrusive into the main plateau basaltic pile of the meseta or into the molasse.  $^{40}\text{Ar}/^{39}\text{Ar}$  and whole rock K-Ar ages dates indicate ages of emplacement between 3.98 and 3.08 Ma, synchronously with that of the more mafic, postplateau basaltic sequence [*Brown et al.*, 2004; *Espinoza et al.*, 2007; *Boutonnet et al.*, 2010].

[9] Petrogenetic studies of the Pliocene to Quaternary postplateau mafic lavas indicate that they were generated from an asthenospheric source and then ascended through a completely opened slab window under the Lago General Carrera/Buenos Aires region [*Gorring et al.*, 2003]. A more recent chronological and petrogenetic study of the Miocene main plateau basalts by *Guivel et al.* [2006] has shown that the spatial distribution and time span of this OIB-like basaltic magmatism are also explained by a model involving the development of a former asthenospheric window, in relation with a tear in the downgoing Nazca slab. Post-3 Ma evolution of the western border of the Meseta del Lago Buenos Aires has been related to the presence of anomalous mantle lying at



**Figure 3.** (a) Simplified geological map of the central Patagonian Cordillera at the latitude of the Chile Triple Junction. LGCBA, Lake General Carrera/Buenos Aires; LCP, Lake Cochrane/Pueyrredón. (b) Schematic lithospheric-scale cross section A–B across Patagonian Cordillera at the latitude of the Chile Triple Junction, inferred from surface geology. Section has no vertical exaggeration. LOFZ, Liquiñe-Ofqui Fault Zone; MLBA, Meseta del Lago Buenos Aires.

depth, due to the presence of subducted segments of the Chile Spreading Ridge [Lagabrielle et al., 2007].

### 2.3. An Updated Geological Cross Section of Central Patagonia

[10] The structural style of the central Patagonian Cordillera at the latitude of the Chile Triple Junction is illustrated by the W–E trending, updated cross section presented in Figure 3b. The section is constructed using data gathered from former studies [de la Cruz et al., 2003, 2004; de la Cruz and Suarez,

2005; Lagabrielle et al., 2004] merged with results of recent structural field works in this region. It confirms that the Cordillera experienced little amount of shortening, in accordance with geophysical informations suggesting that crustal thickness here does not exceed 40 km [Introcaso et al., 1996; Tassara and Yáñez, 2003]. The western part of the section includes the Taitao ophiolite, accreted as a consequence of the collision of the South Chile Ridge with the trench [Mpodozis et al., 1985; Forsythe et al., 1986; Lagabrielle et al., 2000; Veloso et al., 2005]. The Patagonian domain comprised

between the summits of the Northern Ice Cap and the Meseta del Lago Buenos Aires exhibits a thick-skinned tectonic style controlled only by few steeply dipping reverse faults (Figure 3b). These faults are probably reactivated, older normal faults related to the Gondwana breakup that controlled the geometry of the former Cretaceous marine basins [e.g., *Folguera et al.*, 2004]. The current morphotectonic front corresponds to a main fault system that thrust Jurassic units over the late Oligocene–Miocene foreland molasse. However, reverse faults are still observed in the Pampa region east of the front, 450 km far from the trench, suggesting that the contractional strain at the converging margin was distributed over a wide area into the continent. The Tertiary sedimentary Cosmelli basin lies in the central part of the Cordillera domain. It is limited by steeply dipping faults related to the late Oligocene–Miocene compressional event. As discussed in this paper, these reverse faults have probably been reactivated as normal faults due to further extension in the axial domain. The structural pattern of central Patagonia shows clear affinities with the tectonic style of the southern Patagonian Cordillera, as described by *Ramos* [1989], *Diraison et al.* [1997], *Kraemer et al.* [2002] and *Ramos* [2005] despite a lower overall shortening. The deposition of the Rio Frias and Santa Cruz formations as far back as 19 Ma at the latitude of the San Lorenzo massif documents an important compressional event that started around 20 Ma. Farther south, in the Torres del Paine region folded gabbros sills dated at 29.4 Ma also suggest a late Oligocene–early Miocene compressional stress regime [*Altenberger et al.*, 2003].

[11] At the latitude of the Chile Triple Junction, lava flows forming the basaltic plateau of the Meseta del Lago Buenos Aires were emplaced over a 15–12 Ma old peneplain that truncates the compressional structures of the eastern part of the former Cordillera. This confirms that compression along the current topographic front of the Cordillera at the latitude of the triple junction ceased after 15 Ma [*Lagabriele et al.*, 2004; *Scalabrino et al.*, 2009]. However, it is possible that thrust faults have been active during the late Miocene farther west, in various portions of the Central Cordillera such as: the fore-arc region (e.g., in the Taitao Peninsula area), the batholith, and the borders of the Cosmelli basin. An orogenic uplift event occurred at about 6–10 Ma, south of the region of Lake General Carrera/Buenos Aires, in the region of lakes Viedma and Argentino [*Ramos*, 1989; *Kraemer et al.*, 2002; *Ramos*, 2005]. Based on these comparisons, a tectonic uplift partly due to compressional deformation but restricted to the internal Cordillera and to the fore-arc domain, might have occurred during the period 10–6 Ma in central Patagonia.

### 3. Geomorphology of Central Patagonia

[12] In section 3.1, we describe the most peculiar morphological features of the central Patagonian Cordillera based on the analysis of a digital elevation model (DEM SRTM-90 m) in an area of 200 × 200 km between latitudes 46°S and 48°S, from which we extracted topographic profiles and a map of slope gradients (Figure 5).

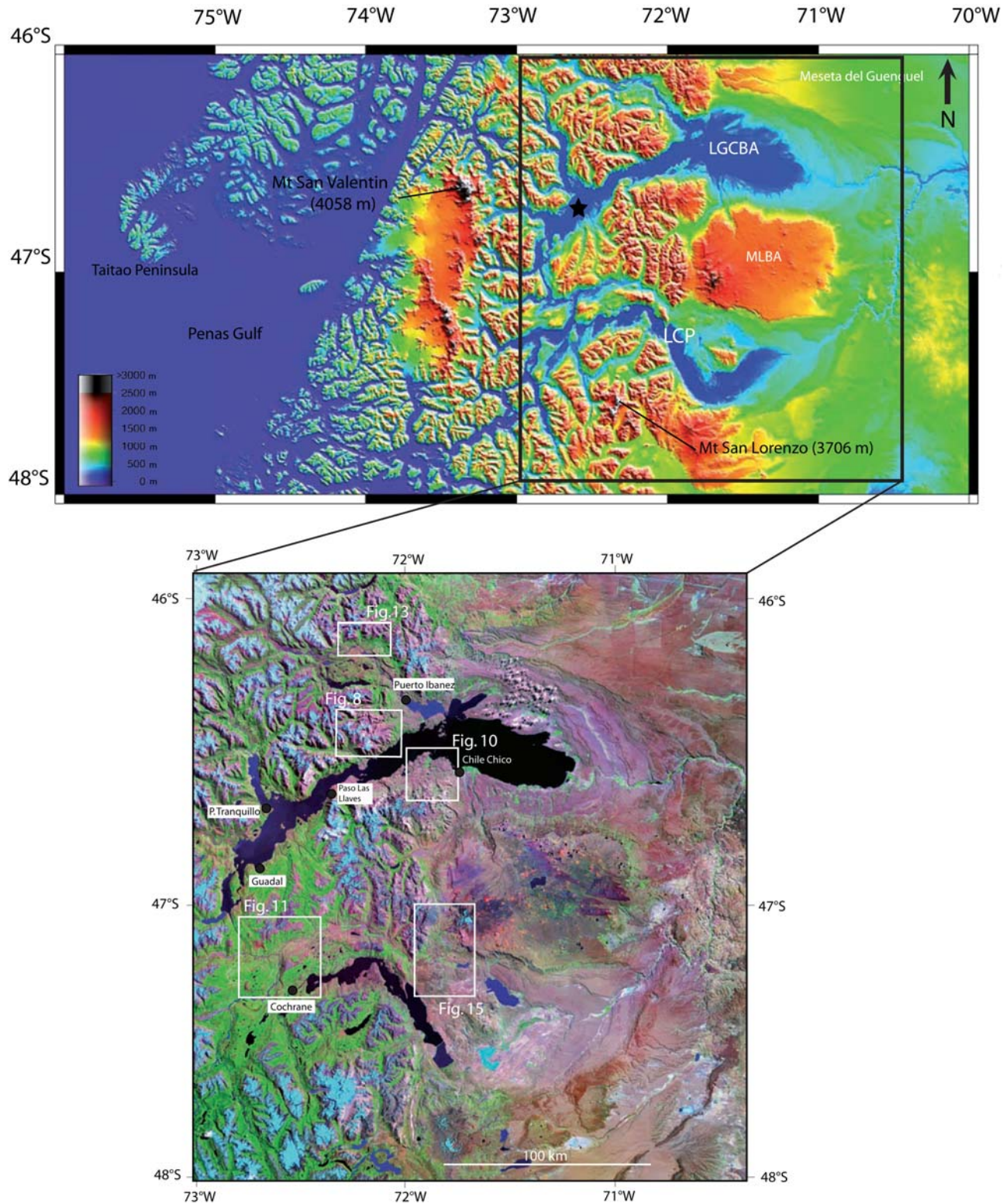
#### 3.1. General Characteristics

[13] As shown on the calculated profile of the mean topography shown in Figure 6, the average elevation of the Cordilleran domain is about 900 m and is characterized by an overall short-wavelength topography. Mean elevation of the peaks is around 2000 m and the valleys show low elevations, some of them lying at sea level. The Monte San Valentin, in the western part of the Cordillera, is the highest summit with an elevation of 4058 m (Figure 4). The central Patagonian Cordillera is flanked to the west by a low-elevated domain limited by the active Liqueñe–Ofqui fault zone that separates the Taitao Peninsula from the continent and representing an extremely sharp boundary between the highest reliefs of the region and the actively subsiding area of the Penas Gulf. To the east, the central Patagonian Cordillera is flanked by the Pampean domain (extending up to the Atlantic coast), characterized by wide areas of homogeneous topography including flat plains and several mesetas (Figures 4 and 5). Figure 6 compiles a series of W–E trending topographic sections of the central Patagonian Cordillera between 46°S and 48°S. All profiles show similar peculiar patterns with two opposite, eastern and western regions of relatively high elevation, bracketing an axial region of lower elevation. This axial depressed region is also characterized by average low slope gradients as shown in Figure 5 and discussed in section 3.4. It occurs surprisingly in a position where higher reliefs should be expected in the case of a normal subduction belt. Both flanking regions of higher elevation are characterized by top surfaces having opposite and low-gradient slopes. The western region includes the high reliefs of the Northern Ice Cap. The eastern region comprises the morphotectonic front of the Cordillera and remarkable flat surfaces gently dipping to the east, corresponding to the mesetas.

[14] The mesetas are currently separated from the remaining Cordillera to the west by a succession of 160°N–180°N trending morphological corridors, delineating the morphotectonic front and corresponding to neotectonic features controlled by recent vertical faults, as described in section 3.5.

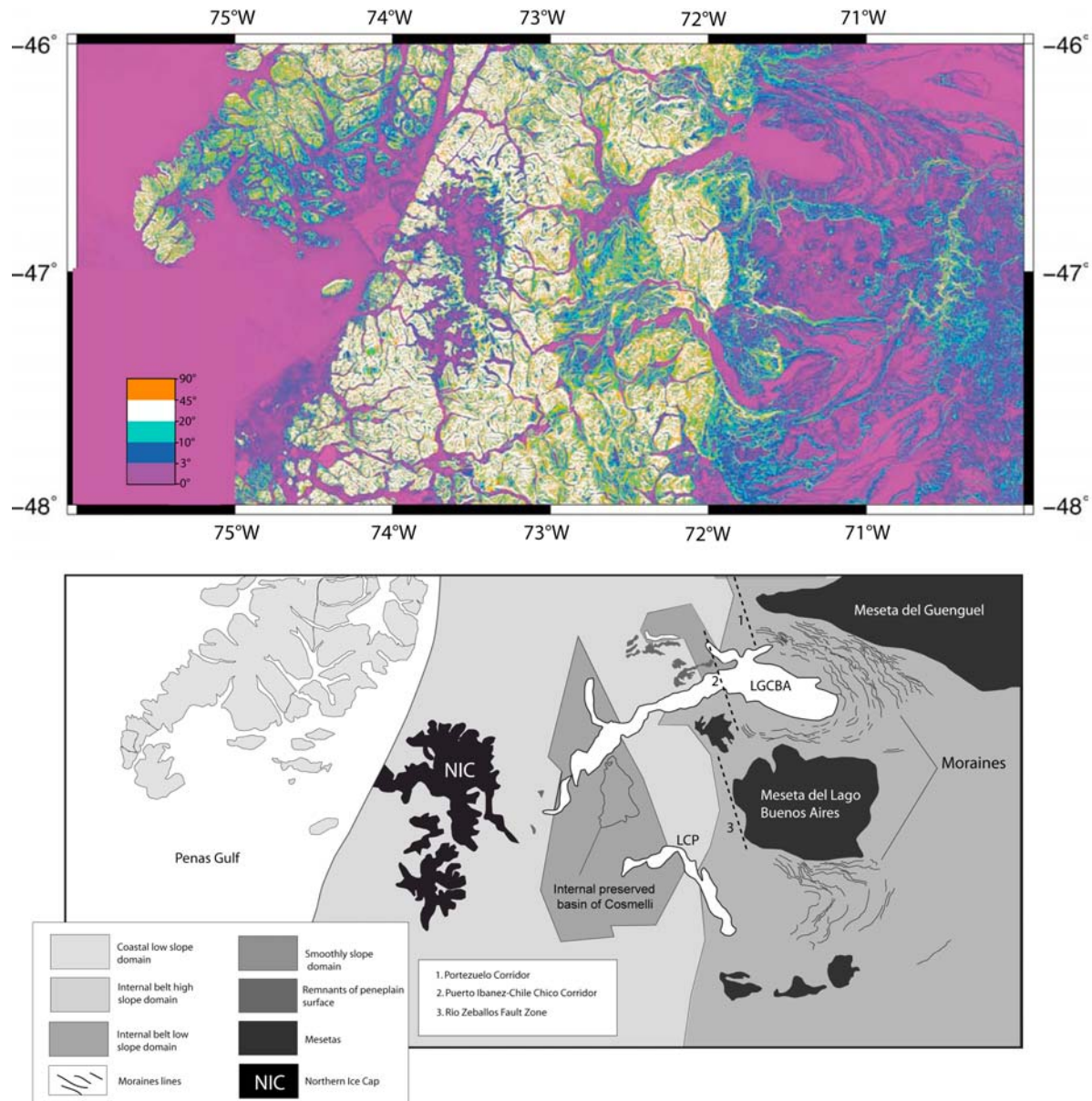
#### 3.2. Mesetas: Remnants of Perched Surface

[15] East of the morphotectonic front, the morphology is characterized by a succession of plateaus of sedimentary and/or volcanic composition. The largest plateau (80 km wide in a W–E direction, ~6000 km<sup>2</sup>) is the flat-topped Meseta del Lago Buenos Aires (Figures 3, 5, 6, and 7), formed by middle Miocene–Pliocene OIB-like basalts interbedded with late Miocene–Pliocene fluvio-glacial deposits. Its elevation ranges from 2700 m (Monte Zeballos) to 1100 m in the eastern side. The second most important plateau is the flat Meseta del Guenguel, located north of the Lake General-Carrera Buenos Aires (Figure 6). It is a depositional surface, composed of late Oligocene–middle Miocene synorogenic sediments, locally overlain by younger coarse fluvio-glacial deposits. Its elevation varies from 1200 to 500 m asl from west to east. Both mesetas show a gentle slope dipping to the east, having very low slope gradient (<10%) (Figures 3–5)



**Figure 4.** Digital elevation model (DEM SRTM-90 m) and Landsat 7 image of the central Patagonian Cordillera at the latitude of the Chile Triple Junction. MLBA, Meseta del Lago Buenos Aires; LGCBA, Lake General Carrera/Buenos Aires; LCP, Lake Cochrane/Pueyrredón. Black star represents the deepest part of the Lake General Carrera/Buenos Aires at approximately 380 m bsl (bathymetry from *Murdie et al.* [1999]).



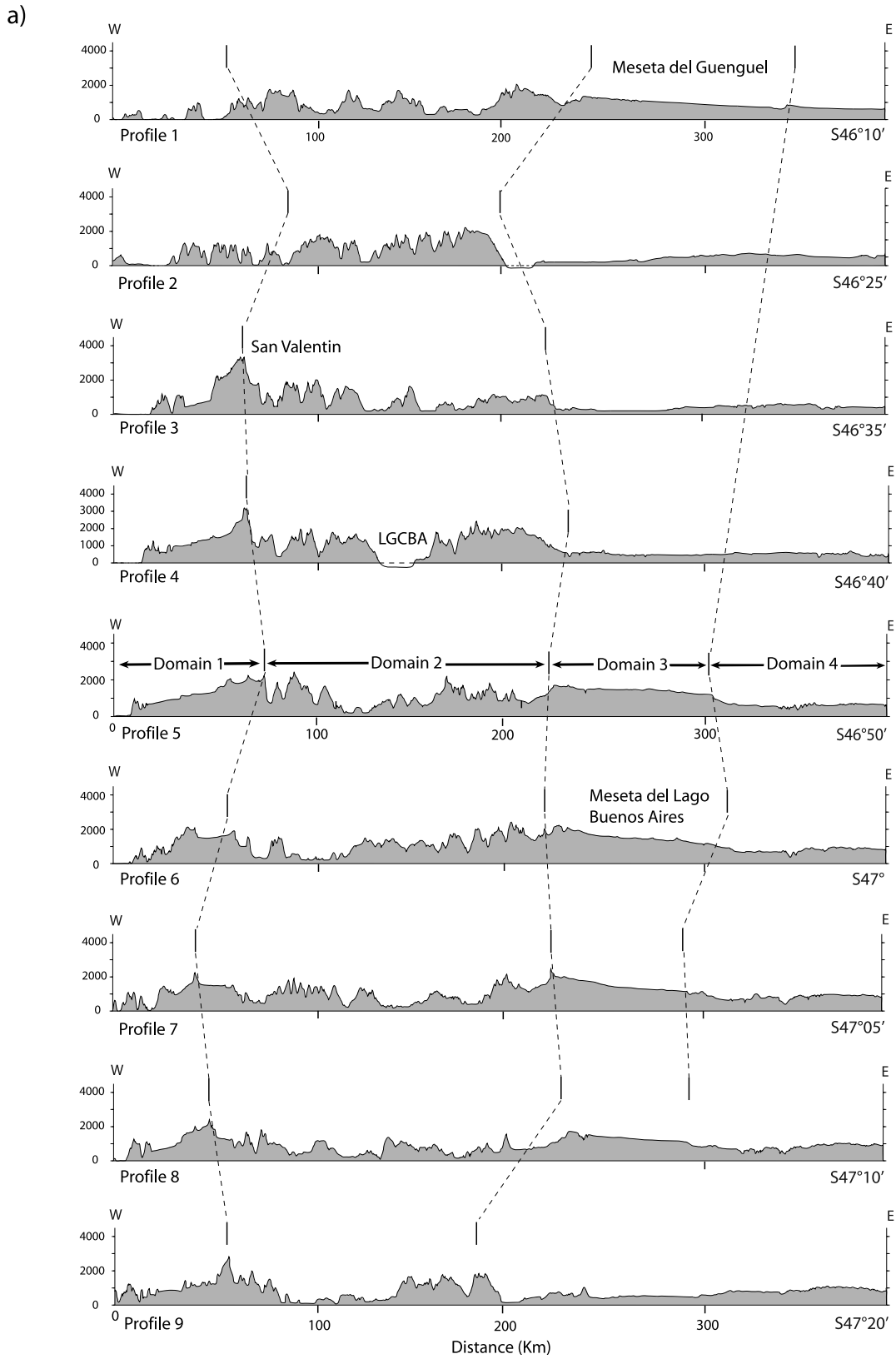


**Figure 5.** Slope gradient digital map of the central Patagonian Cordillera at the CTJ latitude. High-elevated low-relief surface remnants appear as small areas with a local slope less than 10%. The smooth domain within the Cordillera is characterized by local slopes lower than 10% and corresponds to a depressed area including the Oligocene-Miocene internal basin of Cosmelli and the deep floor of the Lake General Carrera/Buenos Aires.

and exhibit a well-developed eastward dendritic relict stream network also indicating an eastward dipping paleoslope, as shown in Figure 7. These plateaus are now disconnected from the rest of the Cordillera by NW–SE oriented depressions forming narrow corridors paralleling the border of the Cordillera as discussed in section 3.5 (Figures 3, 6, and 7). Former tributaries of the ancient fluvial network are abruptly cut by landslides actively scrapping the edges of mesetas (Figure 7), thus confirming recent relief inversion of these plateaus.

### 3.3. Relictual Peneplains Perched Inside the Cordillera

[16] A striking feature of the morphology of the central Patagonian Cordillera is the occurrence of isolated perched, low-relief surfaces. These landscapes are portions of smoothed morphology, representing relicts of a former peneplain characterized by very low slope gradients (<5%), lying 2000 m above sea level in average (Figure 8). They contrast with the surrounding jagged relief of peaks and transverse depressions. Using GIS methods, we mapped these high-elevated surfaces



**Figure 6.** (a) Numerical W–E trending topographic sections of the central Patagonian Cordillera between 46°S and 48°S. (b) Swath profile along the Patagonian Cordillera between 46°S and 48°S showing maximal and minimal elevations of the belt. The calculated mean elevation averaged over the study area is shown by the black line inside the gray domain.

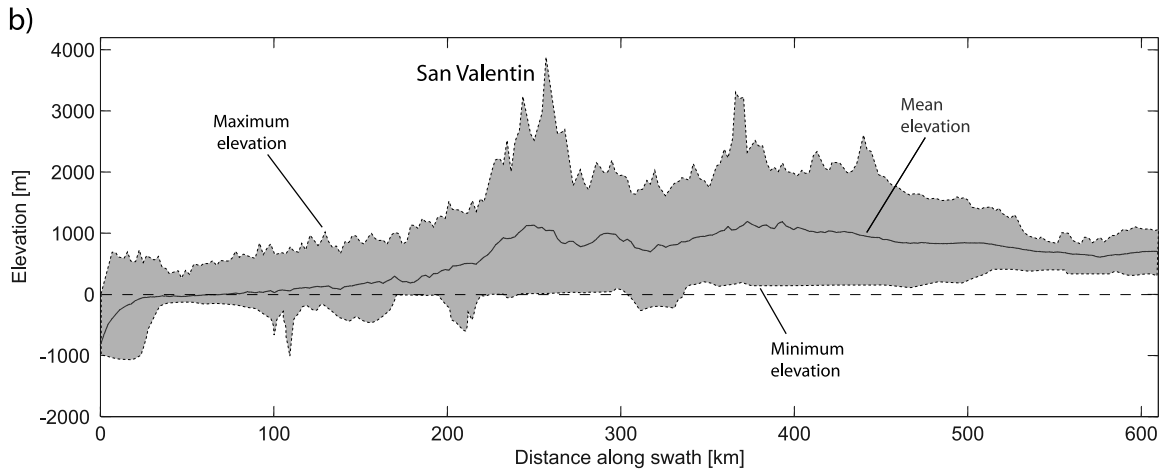


Figure 6. (continued)

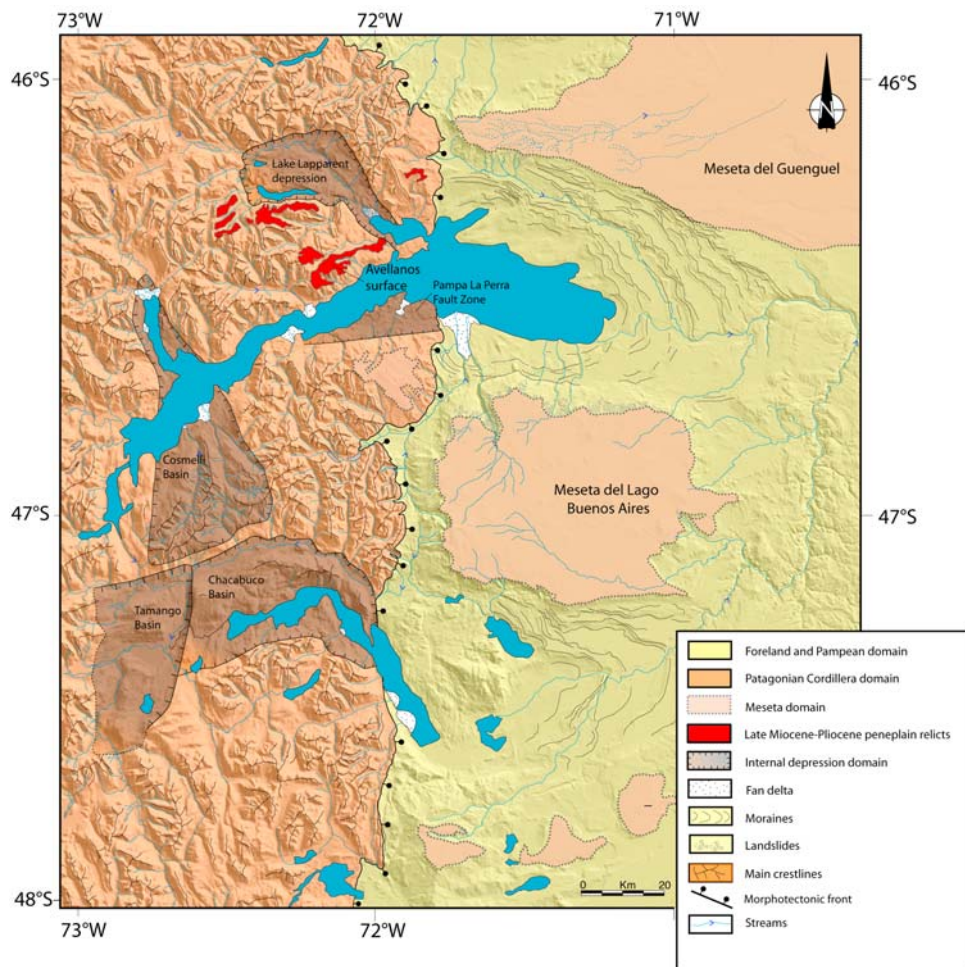
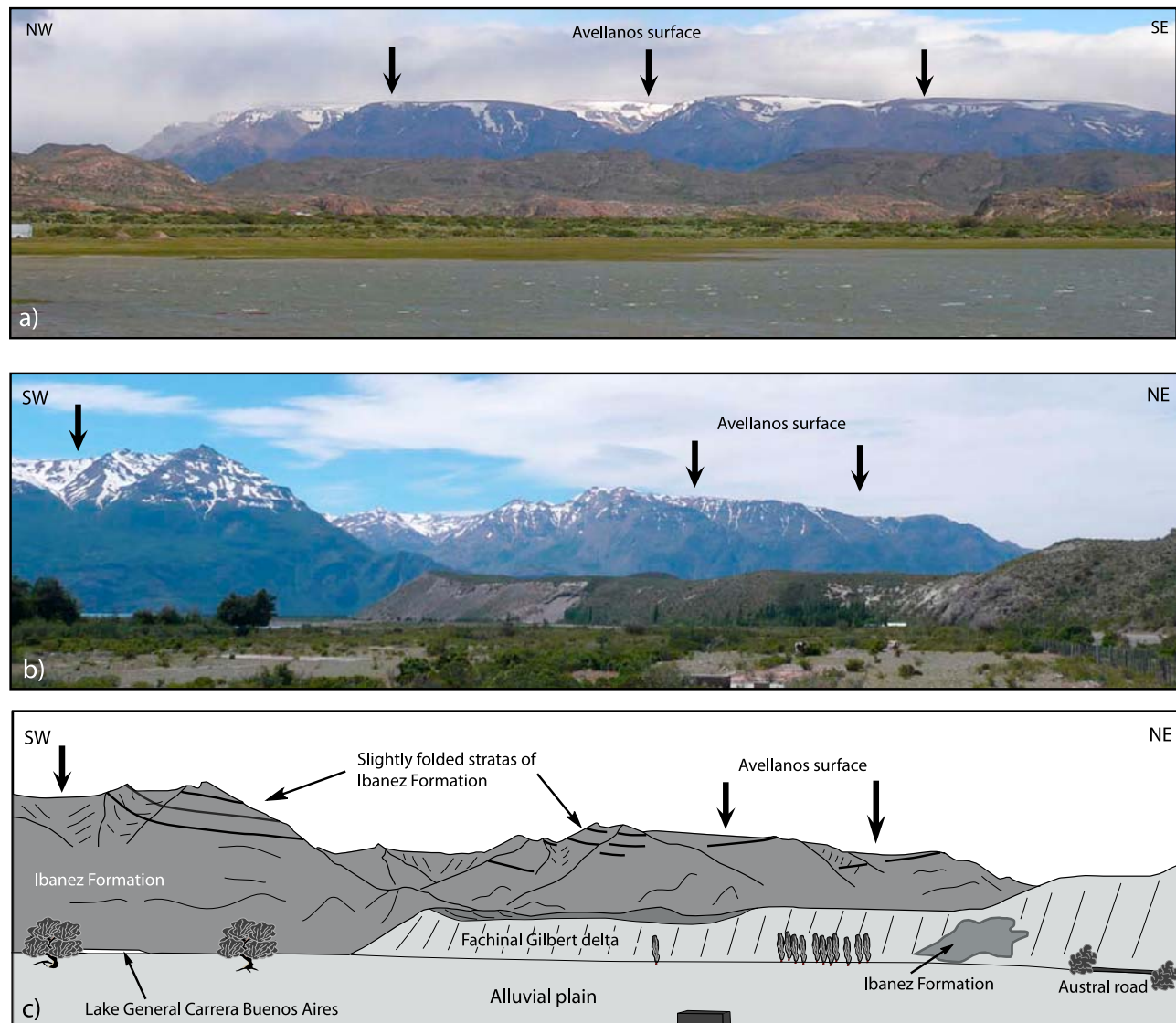


Figure 7. Geomorphological map of the central Patagonian Cordillera showing the main features discussed in text, including relict Miocene-Pliocene surfaces and internal depressions inside the Cordillera and mesetas lying east of the morphotectonic front.



**Figure 8.** (a and b) Two panoramic views of the Avellanos surface capping the reliefs of the northern side of the Lake General Carrera/Buenos Aires, taken from two localities on the opposite side of the lake (see Figure 4 for location). Photograph in Figure 8b illustrates the erosional character of the Avellanos surface cutting the folded strata of the Ibanez Formation. (c) Interpretation of Figure 8b.

within the main Cordillera (Figure 5). Most of them are located north of the Lake General Carrera/Buenos Aires. The most striking surface fragment, named the Avellanos relict surface by *Lagabriele et al.* [2004], is observed west of the City of Puerto Ibáñez and dominates the northern border of the Lake General Carrera/Buenos Aires (Figures 7 and 8). It is a 30 km long, 20 km wide, NE oriented elongated continuous surface. Its western side is notably horizontal along more than 10 km, paralleling the northern edge of the lake, with an average elevation of 2000 m asl. To the east, the Avellanos surface lowers progressively toward the Puerto Ibáñez-Chile Chico fault zone, reaching an elevation below 300 m asl, south of Puerto Ibáñez. Observation of satellite images clearly indicates that the flat, highest portion of the Avellanos surface is continuous with the lowered eastern

portion. North of the Avellanos surface, several remnants of the corresponding former surface can be observed (Figure 7). The largest one is 20 km long and forms the plateau that dominates the southern edge of Lake Lapparent. It is composed of two narrow surfaces joining to their western edge and culminating at an average elevation of 1500 m asl. Other remnants cap the reliefs forming the western and eastern edge of the Lapparent basin. The first one corresponds to three NE trending, parallel segments, almost 10 km long, with an elevation varying from 1400 m to 1600 m asl (Figure 7) and the second one, which is also the easternmost surface in the study area, is located between the Lake Lapparent and the morphotectonic front. It is 5–7 km long, with an elevation of 1500 m asl.

[17] As shown in Figure 8, the Avellanos surface clearly cuts the gently folded strata of the Ibáñez Formation. This indicates an erosional origin for this surface which developed at least since the middle Miocene, after 15 Ma, as it was probably achieved at the end of the main contractional tectonic phase which affected central Patagonia. A flat-lying, 10 m thick transitional basaltic flow was sampled on the top surface of the Avellanos peneplain, yielding a whole rock K/Ar age of  $4.57 \pm 0.27$  Ma [Pelleter, 2003]. This flow correlates with the transitional basaltic flows emplaced on top of the Meseta Chile Chico on the opposite, southern side of the Lake General Carrera/Buenos Aires, which were dated at  $4.4 \pm 0.8$  Ma [Espinoza et al., 2005; Lagabrielle et al., 2007].

### 3.4. Depressions Opening Inside the Central Patagonian Cordillera

[18] Surprisingly, at the latitude of the Chile Triple Junction, the Patagonian Cordillera lowers drastically and a shallow passage at an average elevation of 200 m opens between the Pacific and the Atlantic Oceans (Figure 3). There, the axial portion of the Cordillera is characterized by the presence of deeply incised, transverse depressions. Two of them are now occupied by large postglacial lakes, the Lake General Carrera/Buenos Aires in the center, and the Lake Cochrane/Pueyrredón to the south (Figure 3). The deepest points of Lakes General Carrera/Buenos Aires and Cochrane/Pueyrredón lie at 380 m and 200 m below sea level (bsl), respectively [Murdie et al., 1999]. During the Pliocene-Quaternary glacial stages, these transverse depressions were occupied by glaciers flowing eastward, so that a series of well-developed moraines accumulated on the pampa regions of Argentina, forming large amphitheaters, outlining the maximum extension of the glaciers (Figures 3–5).

[19] The Lake General Carrera/Buenos Aires depression consists of three segments. The deepest segment, to the west trends  $50^\circ\text{N}$  and includes a north to south trending appendix with shallow water (Bahia Murta, 100 m depth maximum). The central segment is about 580 m maximum deep and trends  $60^\circ\text{N}$ . Both western and central segments exhibit rectilinear outline and sharp edges suggesting tectonically controlled borders [Lagabrielle et al., 2004; Scalabrino et al., 2009]. The eastern segment expands out of the Cordillera in an E–W direction and separates the Meseta del Guenguel to the north from the Meseta del Lago Buenos Aires to the south.

[20] The Lake Cochrane/Pueyrredón depression has topographic characteristics similar to that of the Lake General Carrera/Buenos Aires. It forms a transverse corridor at low elevation, including a narrow and deep western segment trending  $50^\circ\text{N}$  (220 m bsl [Murdie et al., 1999]) and an eastern segment with shallow waters, trending  $140^\circ\text{N}$ . The western segment parallels regional lineaments, suggesting tectonically controlled borders (Figure 9). The eastern segment crosscuts the tectonic front of the Cordillera in the area of the Vacas and Yole frontal thrust [Ramos, 1989].

[21] Beside these two major narrow transverse depressions, the internal Cordillera is characterized by the presence of a number of larger depressed areas and smaller basins. By contrast to the entire Cordillera, which is characterized by high slope gradients ( $>20\%$ ) resulting from intensive glacial

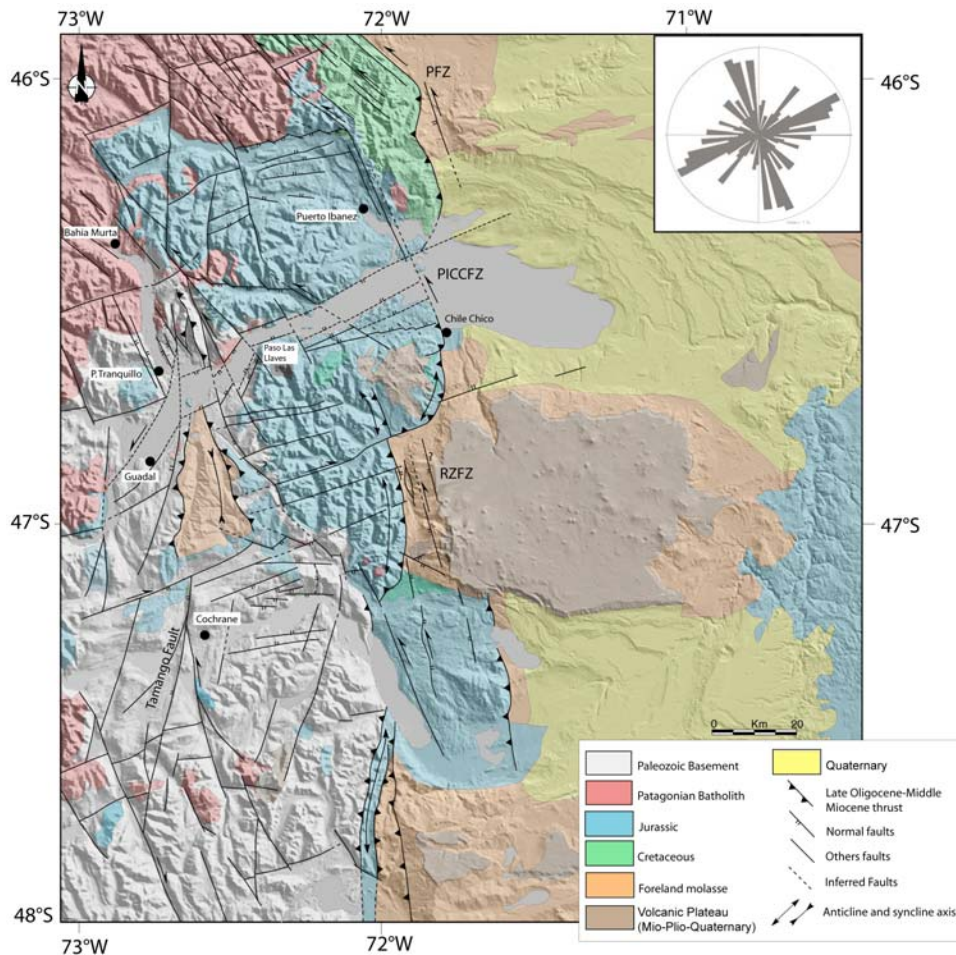
and fluvial erosion, these internal depressed areas have smoothed topography and gentle slopes, as evidenced on the slope gradient digital map of Figure 5. The largest depressed area occupies the axial part of the Cordillera. It is a major morphological feature, well observed on the compilation of topographic profiles of Figure 6. It has a V-shaped outline, pointing to the north and extending from the northern tip of the Lake General Carrera/Buenos Aires to the northern shore of Lake Cochrane/Pueyrredón (Figures 5–7). In this triangular area, the slopes are lower than 15%. Mean elevations are low, ranging from 1200 m asl maximum, to 380 m bsl minimum, corresponding to the deepest point of the Lake General Carrera/Buenos Aires. The topography is characterized by several steps delimited by linear features oriented  $10^\circ\text{N}$ ,  $60^\circ\text{N}$  and  $160^\circ\text{N}$ , isolating subdomains, with differential mean low elevation. The central subdomain has also a V-shaped outline and extends south of Lake General Carrera/Buenos Aires, including the region of the Cosmelli basin. Its floor exposes Paleozoic metamorphic basement, Jurassic volcanic rocks and the molasse deposits of the Cosmelli basin of late Oligocene–middle Miocene age. The summital surface of the central portion of the Cosmelli basin, is not horizontal and lowers gently from south (1500 m) to north (300 m), where it reaches the southern shore of the Lake General Carrera/Buenos Aires (Figure 3).

[22] The western branch of the Cochrane/Pueyrredón depression connects to a region of relatively low relief and very low elevation named the Tamango basin (Figure 5). This region has a losangic shape and is delineated by  $10^\circ\text{N}$ ,  $45^\circ\text{N}$  and  $160^\circ\text{N}$  lineaments (Figure 9) which affect Paleozoic metamorphic rocks and Mesozoic formations.

[23] An additional remarkable topography anomaly of the central Patagonian Cordillera is the rhomboidal basin of Lake Lapparent, lying north of the Lake General Carrera/Buenos Aires at an average elevation of 500 m (Figures 3, 6, and 7). This depression, whose contours might recall that of pull-apart basins, is 40 km long and 20 km wide. It sharply opens inside the high-elevated system of peneplain remnants described above. Tectonic lineaments abruptly limit the depression from the Cordillera reliefs. Slopes inside the depression are lower than 10% with minimal values in the northeastern and eastern corners of the depression.

### 3.5. The $160^\circ\text{N}$ Tectonic Corridors

[24] The eastern orogenic front is marked by a topographic jump of several hundreds meters, due to the easterly vergent thrust system, juxtaposing Paleozoic and Mesozoic units of the main Cordillera, over the Mesozoic–Cenozoic foreland deposits to the east. In the study area four segments of the orogenic front have been distinguished from north to south: the Portezuelo Segment, the Chile Chico Segment, the Las Horquetas Segment and the Paso Roballos Segment [Lagabrielle et al., 2004]. The Chile Chico Segment connects to a marked tectonic lineament oriented  $160^\circ\text{N}$ – $\text{N}170^\circ\text{N}$  observed in topography, air photos and satellite images across the Lake General Carrera/Buenos Aires that extends northwest of Puerto Ibáñez, named the Puerto Ibáñez–Chile Chico fault zone. The northern portion of this fault system forms the eastern boundary of the Lake Lapparent depression.



**Figure 9.** Structural and geological map of the central Patagonian Cordillera at the latitude of the Chile Triple Junction extracted from field observations, DEMs, and satellite images (Landsat 7 and Spot 5). The map shows the main tectonic features discussed in text. The inset shows a rose diagram that is constructed from a compilation of all the features shown in the map.

A major lineament oriented  $160^{\circ}\text{N}$ – $170^{\circ}\text{N}$ , paralleling the Paso Roballos segment separates the Cenozoic formations of Meseta del Lago Buenos Aires from the rest of the Cordillera (Figure 5).

#### 4. Tectonic Contribution to the Present-Day Morphology

[25] The morphology of the central Patagonian Cordillera at the latitude of the Chile Triple Junction exhibits a complex pattern including peaks and narrow valleys at an average low regional elevation of 900 m, defining a short-wavelength topography with mean amplitude of 2000 m. This topography is interrupted by narrow and deep corridors and by flat floored depressions. The region is also characterized by the presence of remnants of former flat surfaces forming large mesetas outside the Cordillera or found as relicts capping reliefs inside the Cordillera itself. In this section, we discuss the tectonic significance of the sharp boundaries of the depressed areas and of the  $160^{\circ}\text{N}$  trending corridors on the basis of (1) the interpretation of combined

DEM and satellite images of tectonic lineaments and (2) field tectonic analysis.

##### 4.1. Analysis of Tectonic Lineaments

[26] Lineaments are natural simple or composite pattern linear or curvilinear features discernible on the Earth's surface. In the geologic sense, these features may depict crustal structure or may represent zones of structural weakness. Lineaments of a mountain belt are commonly interpreted as tectonic features, even if glacial and fluvial erosion increase them. The fault distribution derived from the Landsat ETM+7 and DEM SRTM-90 m analysis is shown in Figure 9. A total of 250 lineaments were observed, concentrated in the eastern part of the belt. Fault extraction from the Landsat and DEM maps provides similar identification and distribution. Faults are usually rectilinear and 5 to 50 km long. Their distribution in a rose diagram shows two dominant groups close to  $45^{\circ}\text{N}$ – $60^{\circ}\text{N}$  and  $160^{\circ}\text{N}$ – $170^{\circ}\text{N}$  directions. The first group corresponds to features controlling the internal depressions of Lake Lapparent, the western branch of Lake General Carrera/

Buenos Aires, the northern part of the Lake Cochrane/Pueyrredón area (Figure 9). The second group is mainly developed along the tectonic front and at the oblique corridors (Figure 9). It is noteworthy that these two dominant orientations parallel the directions of the fracture zones and spreading axis of the subducting south Chile Spreading Ridge.

## 4.2. Tectonic Origin of the Intra-Cordillera Depressions

### 4.2.1. Lake General Carrera/Buenos Aires Depression

[27] Previous work by *Lagabriele et al.* [2004, 2007] already suggested that the depression of Lake General Carrera/Buenos Aires has a tectonic origin, although glacial erosion probably increased to some extent the width and depth of this main morphological corridor. Indeed, the abrupt margins of the central segment of Lake General Carrera/Buenos Aires parallel the 50°N–60°N and 90°N trending faults well observed in the surrounding terranes on both satellite and DEM images (Figure 9). Numerous highly dipping faults are well exposed along the southern margin of the lake, forming the 90°N trending 40 km long Pampa La Perra fault zone (Figure 10) [*Lagabriele et al.*, 2004]. This important tectonic boundary consists of a succession of en echelon, 50°N–60°N oriented fault segments, some kilometers long each, defining three north facing main steps inducing progressive lowering northward. Field observations and fault analysis confirm that these fault segments have normal and transtensional throws, consistent with the tectonic subsidence of the lake basement [*Lagabriele et al.*, 2004]. Local throw along one single fault may reach 10 m as observed within a fault zone well exposed along Rio el Bano (Figure 10).

[28] The Pampa La Perra fault zone controls the present-day topography of the south margin of the lake. This topography strongly contrasts with the aspect of the northern margin, consisting of one single south facing scarp. Therefore, as illustrated by the north to south cross section shown in Figure 10, the overall topography of the Lake General Carrera/Buenos Aires depression is typically asymmetrical, a character which is also found in other depressions of central Patagonia, as shown in sections 4.2.2 and 4.2.3. Such morphological asymmetry cannot be explained easily by pure glacial processes.

[29] In the surroundings of the north to south appendix of Lake General Carrera/Buenos Aires (Bahia Murta), rocks of the metamorphic basement and of the overlying Ibáñez Formation are affected by 160°N trending faults, paralleling the shores of the lake. This pattern contrasts with the fault distribution controlling the central segment (Figure 9), which suggests also a strong tectonic control on the depression here.

[30] On the opposite side of the Lake General Carrera/Buenos Aires, east of Guadal, the Tertiary Cosmelli molasse

basin is more than 20 km long (Figure 9). As illustrated by cross section in Figure 3, the Cosmelli basin is interpreted as a pop-down basin, deformed as an open synclinal, controlled by thrust faults of Oligocene–middle Miocene age. The Cosmelli basin is only present on the southern side of the lake, and does not show any equivalent on the northern side, where only basement rocks are exposed, but where thrusts can be traced in the continuation of the thrusts bounding the basin. This observation demonstrates that the Lake General Carrera/Buenos Aires depression corresponds to a major, 40°N trending tectonic boundary, along which significant post late Miocene–Pliocene vertical displacements have occurred. It implies relative uplift of the northern shore of the Lake and a regional northward tilt of its southern border during the Pliocene–Pleistocene. This regional tilt is also demonstrated by the geometry of the molasse sequences in the Cosmelli basin itself. The sandstones beds of the marine and continental molasse (Guadal and Santa Cruz–Galera formations, respectively) are continuously exposed along both edges of the basin. The upper beds of the Guadal Formation are a well-defined stratigraphic marker, originally horizontal. Elevation of the Guadal–Santa Cruz formations limit decreases progressively from ~1000 m asl in the south to ~300 m asl in the north, close to the southern shore of Lake General Carrera/Buenos Aires [*Flint et al.*, 1994; *Ray*, 1996; *de la Cruz and Suarez*, 2005], confirming long-wavelength deformation of the crust adjacent to the Lake General Carrera/Buenos Aires fault system.

[31] Finally, two important features have to be stressed here: (1) the preservation of the molasse deposits at low elevation implies that this region has experienced very little, post-Miocene fluvio-glacial erosion with respect to the surrounding areas and (2) the general tilt of the Cosmelli basin implies postsedimentary differential vertical displacements, consistent with a tectonic subsidence with maximum values close to the axis of Lake General Carrera/Buenos Aires.

[32] Few kilometers east of Cosmelli basin, the 10 Ma old plutonic body of Paso Las Llaves is crosscut by several normal and strike-slip faults varying from 50°N to 130°N in direction. Several faults parallel the southern edge of the depression in this area. Exposure of this pluton here demonstrates the post-10 Ma age of the Lake General Carrera/Buenos Aires depression. Faulting in turn demonstrates a post-10 Ma tectonic activity, involving mostly transtensional displacements consistent with a tectonic control of this depression [*Lagabriele et al.*, 2004]. Additional fault data have been obtained along the Austral Road, east of Paso Las Llaves, where the Ibanez Formation which forms the southern edge of the lake is affected by 30°N to 100°N and 160°N normal to strike-slip trending faults which bearing striae having pitches ranging from 45° to 85°, confirming transtensional to extensional deformation in this region.

**Figure 10.** (a) The Lake General Carrera/Buenos Aires depression. The white line shows the central segment of the lake. (b) NW–SE oriented topographic profile across the central segment of the lake. The outlined portion shows the location of Figure 10d. (c) Schematic interpretation of the central segment of the lake illustrating the asymmetrical character of this depression. (d) Interpreted Spot 5 image showing the southern edge of the central segment of the lake in the area of the Pampa la Perra Fault Zone. The outlined portion shows the location of the Rio El Bano conjugate normal faults. (e) Photograph of the Rio El Bano conjugate normal faults belonging to the Pampa la Perra fault zone.

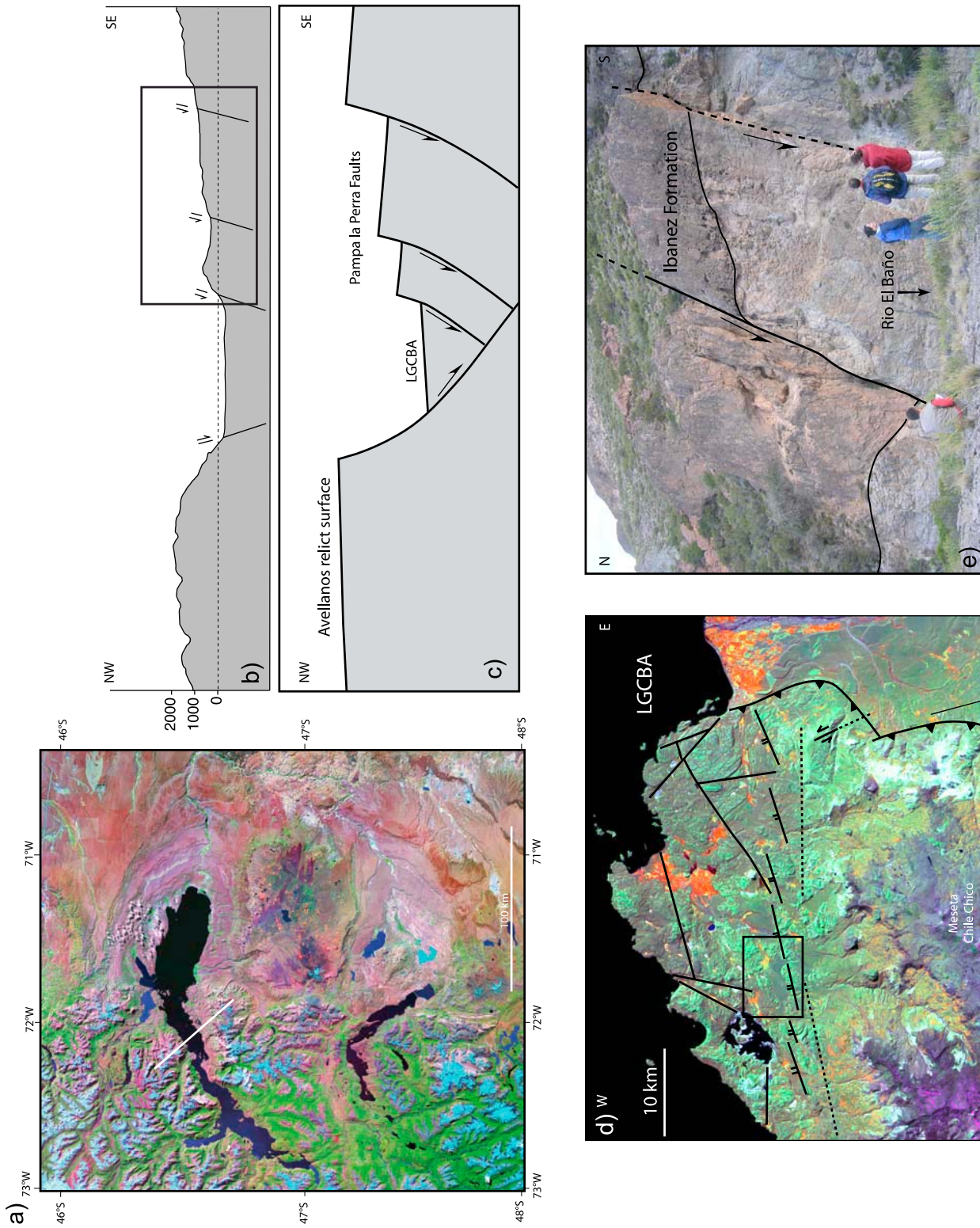
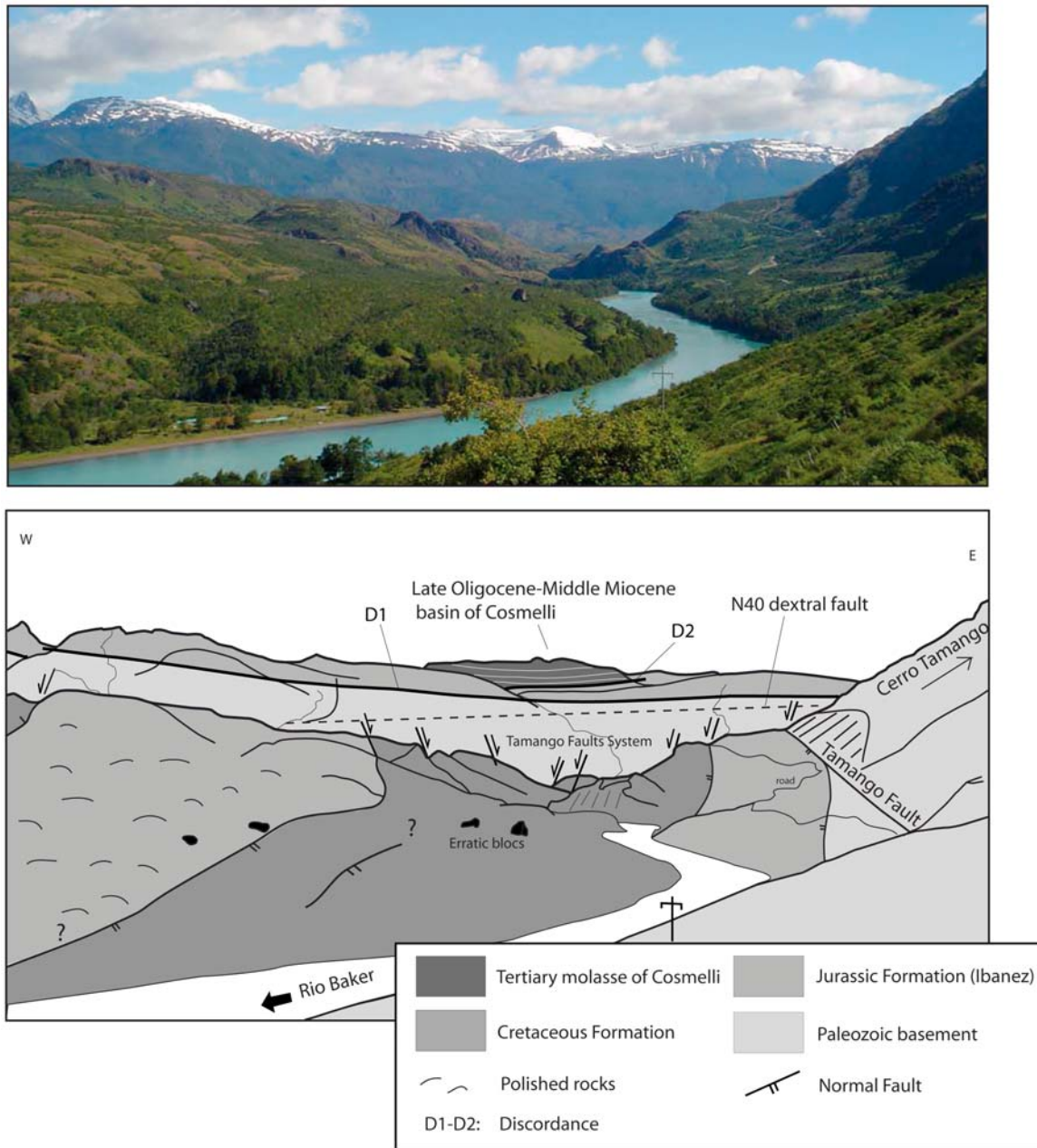


Figure 10





**Figure 11.** Panoramic view and schematic interpretation of the Cerro Tamango Fault Zone on the western border of the Lake Cochrane/Pueyrredón area (see Figure 4 for location).

**4.2.2. Cochrane/Pueyrredón Lake Area and the Tamango Basin**

[33] The Cochrane/Pueyrredón Lake consists of the juxtaposition of 40°N–50°N and 140°N–160°N trending portions, indicating also a morphological control by the two sets of faulting directions determined by the extraction of tectonic lineaments. The first set has similar orientation to the fault system which controls the central segment of Lake General-Carrera Buenos Aires depression. The second one parallel the group of faults mainly developed along the tectonic front and within the oblique corridors (Figure 9).

[34] The eastern border of the Tamango basin is controlled by a 40 km long, 10°N trending fault, corresponding to a major fault system named the Tamango Fault Zone [*de la Cruz et al., 2004*] (Figure 11). At Cerro Tamango, 10 km north of the city of Cochrane, faulting of Mesozoic formations against the Paleozoic basement is observed. Here, the Tamango Fault Zone consists of a main 10°N fault, and of numerous highly dipping 150°N and 40°N trending minor normal faults (Figure 11). Cretaceous marine sediments (Toqui and Apeleg formations), together with Jurassic volcanic rocks are down faulted with respect to the Paleozoic

basement (Figures 9–11). Therefore, the Tamango Fault Zone likely represents the eastern margin of a recent narrow hemigraben. Remnants of the Mesozoic cover are only preserved in the northeast corner of the Tamango basin, suggesting regional tilting to the northeast of the depression floor, in a way similar to tilting observed south of the Lake General Carrera/Buenos Aires depression.

[35] North of the western branch of the Lake Cochrane/Pueyrredón, several 40°N–65°N, 90°N and 150°N trending highly dipping faults delineate depressed areas, which are separated by the E–W trending, 1500 m high, Cordón Chacabuco ranges. These mountains represent a horst with respect to the flanking parallel basins (Figure 9).

#### 4.2.3. Lake Lapparent Area

[36] Recent field data obtained in the Lake Lapparent depression yield crucial informations on the role played by Neogene normal faulting events in the morphological evolution of the central Patagonia. This basin is a sharply defined rhomboidal topographic low resembling pull-apart grabens, with an area of ~800 km<sup>2</sup> (Figures 3, 9, and 12). The Lake Lapparent is 20 km long and occupies the southern part of the basin; it has a linear outline suggesting again a strong tectonic control of the depression. The average depth of the depression's floor is 500 m asl, and peaks dominating the basin have a mean elevation of 1500 m, with a maximum of 2318 m at Cerro Castillo. Only Mesozoic volcanic rocks of the Ibáñez Formation are exposed in this area [Niemeyer, 1975; Bruce, 2001].

[37] As observed on Landsat and DEM maps, the Lapparent basin is bounded by 10°N, 45°N and 160°N linear features that define scarps locally 1500 m high (Figure 12). The eastern limit of the Lapparent depression is delineated by a series of 160°N oriented faults belonging to the northern end of the Puerto Ibáñez-Chile Chico tectonic corridor. On the opposite side, the basin is limited by a major 170°N trending fault zone. To the south, the basin is outlined by the narrow E–W Lake Lapparent, flanking a zone of relatively high elevation topped by remnants of the Miocene–Pliocene penplain (see section 3). Figure 12 compiles a series of parallel N–S oriented topographic profiles across the Lake Lapparent region, extracted from the DEM database. As illustrated by profiles 1, 2 and 3, the topography of the region also exhibits an asymmetrical character. To the north, the continuous reliefs of the main Cordillera are sharply cut along the northern boundary of the basin, while the southern border exhibits a smoother topography with moderate to low reliefs, consisting in a succession of north facing scarps. These scarps connect progressively the southern, high-elevated regions of the border of the basin to the floor of the depression, a flat area gently dipping to the north.

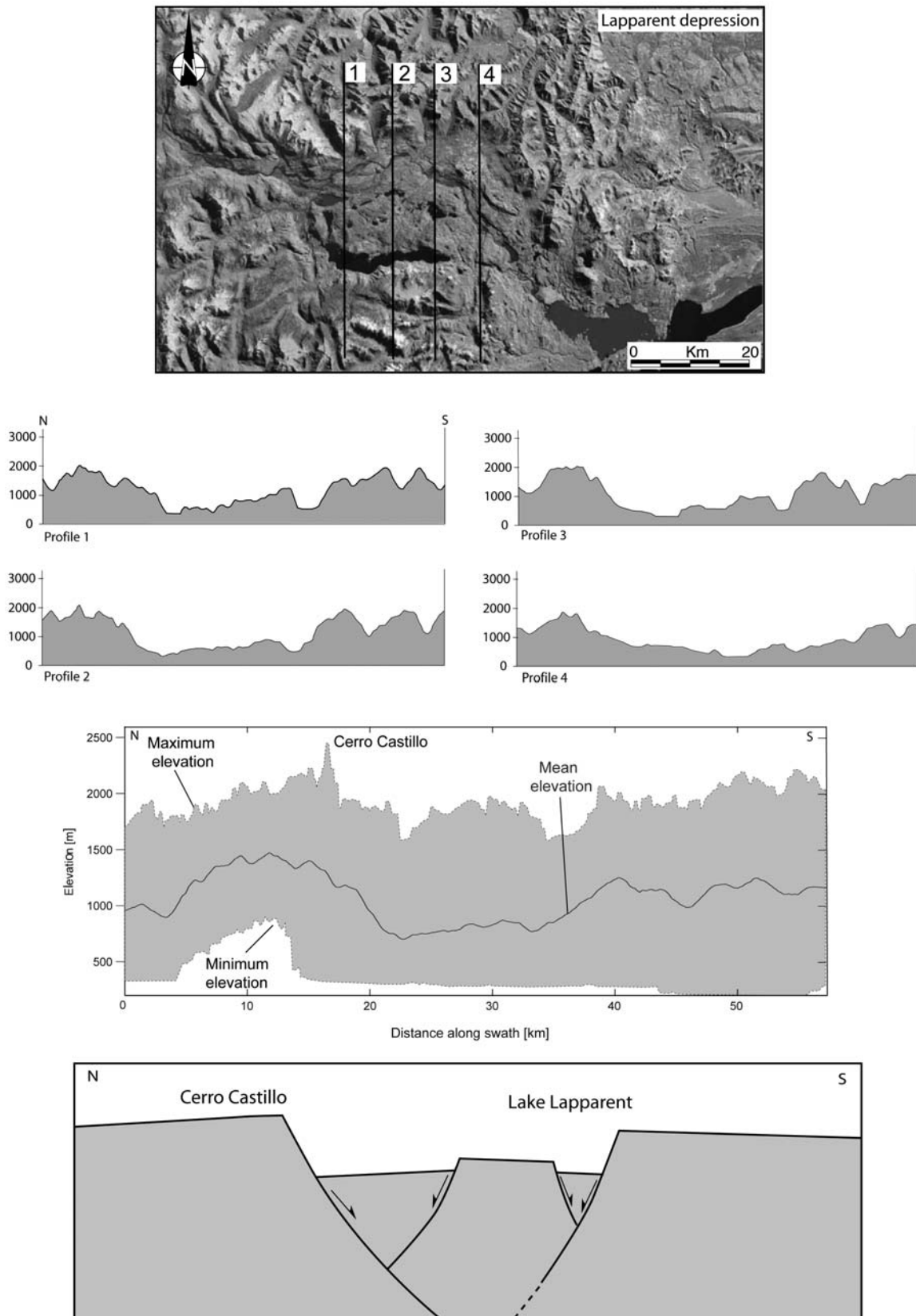
[38] The morphology of the northern flank of the Lapparent basin is dominated by the existence of a series of triangular facets trending 65°N to 130°N, suggesting recent uplift of the Cerro Castillo area (Figures 9, 13, and 14). Field observations confirm the presence of important tectonic displacements along this boundary. In the NE corner of the depression, the contact between fossiliferous marine Cretaceous sediments (Apeleg Formation) with Jurassic volcanic rocks found at the same elevation, is a major normal fault (Figure 14). This

fault zone is well exposed and shows a 3 m thick, subvertical gouge with poorly preserved high-dip striae indicating normal displacement. The marine beds of the Apeleg Formation are dipping to the north, indicating block tilting in relation with normal displacement along this fault. Numerous evidence of normal faulting consistent with a recent subsidence of the basin is found within the entire Lake Lapparent area. To the south, the Lake occupies an incised valley controlled by 110°N trending faults (Figure 14), and normal faults were analyzed in the eastern part of the basin, along the Rio Ibanez gorges [Lagabrielle *et al.*, 2004]. On the western side of the basin, relicts of the late Miocene–Pliocene erosional surface are affected by 45°N trending normal faults which separate tilted blocks (Figure 14). These faults connect to the 160°N trending lineament forming the western tectonic limit of the basin. On its eastern side, 120°N to 160°N trending sinistral strike slip and 10°N to 120°N oriented normal faults belonging to the Puerto Ibáñez-Chile Chico fault zone, crosscut the Jurassic volcanic rocks. Inside the basin, the glacially polished volcanic rocks (roches moutonnées) are affected by numerous 20°N to 160°N fractures and faults.

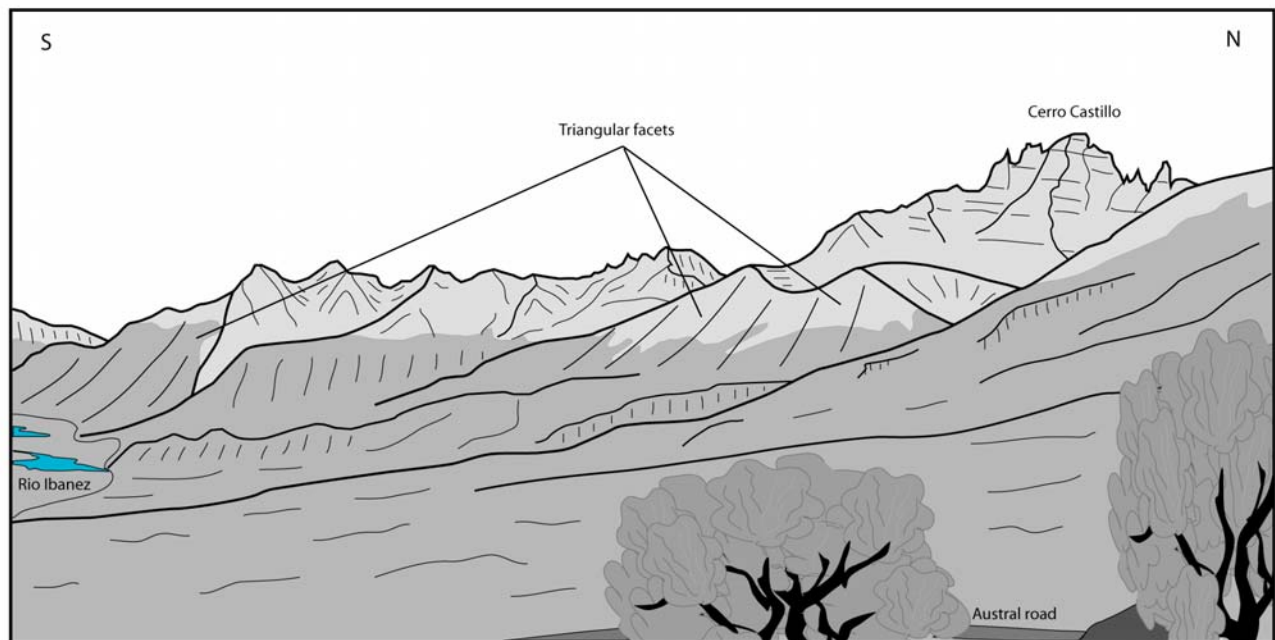
#### 4.3. Faulting Along the 160°N Oriented Corridors: Geometrical and Chronological Constraints From the Rio Zeballos Fault Zone

[39] As expected in the case of a well developed compressional orogenic system, the eastern front of the Cordillera is marked by a topographic jump, facing to the east, of several hundreds meters, corresponding to the frontal thrusts. However, the frontal region of central Patagonia displays an unusual character, due to the presence of 180°N to 160°N oriented linear depressions developed at the foot of a series of west facing scarps. Due to these depressions, there is a noticeable disconnection between the Cordillera and its former piedmont. The 180°N to 160°N oriented linear depressions correspond to tectonic lineaments well observed in satellite images: the Puerto Ibáñez-Chile Chico fault zone and the Rio Zeballos fault zone. We concentrate here on the latter fault zone exposing a series of recent magmatic rocks allowing precise dating of the tectonic events which strongly modified the morphology of the frontal region during Pliocene–Quaternary times.

[40] The Río Zeballos corridor extends east of the morphotectonic front and delineates the western border scarp of the Meseta del Lago Buenos Aires. It corresponds to a major fault zone, the Río Zeballos Fault Zone, oriented 160°N–170°N, which crosscuts the late Miocene–Pliocene lava flows of the Meseta del Lago Buenos Aires and the underlying Río Zeballos Group synorogenic sediments [Lagabrielle *et al.*, 2004, 2007] (Figure 15). Previous works in this region have provided good evidence of post-Pliocene tectonic disruption along this fault zone as follows. (1) Close to Rio Jeinimeni, a 6 Ma basaltic dyke is offset by 150°N to 160°N sinistral strike-slip faults [Pelleter, 2003; Lagabrielle *et al.*, 2004]. (2) Along the Leonera river, a complex of 170°N to 50°N steeply dipping normal and reverse faults (defining flower structures) crosscuts the late Miocene molasse deposits [Lagabrielle *et al.*, 2004]. (3) Along the Alto Rio Ghio, con-



**Figure 12.** Numerical N–S trending topographic sections of the Lapparent basin and swath profile showing maximal and minimal surfaces of the Lapparent area. The average elevation is shown by the dark line.

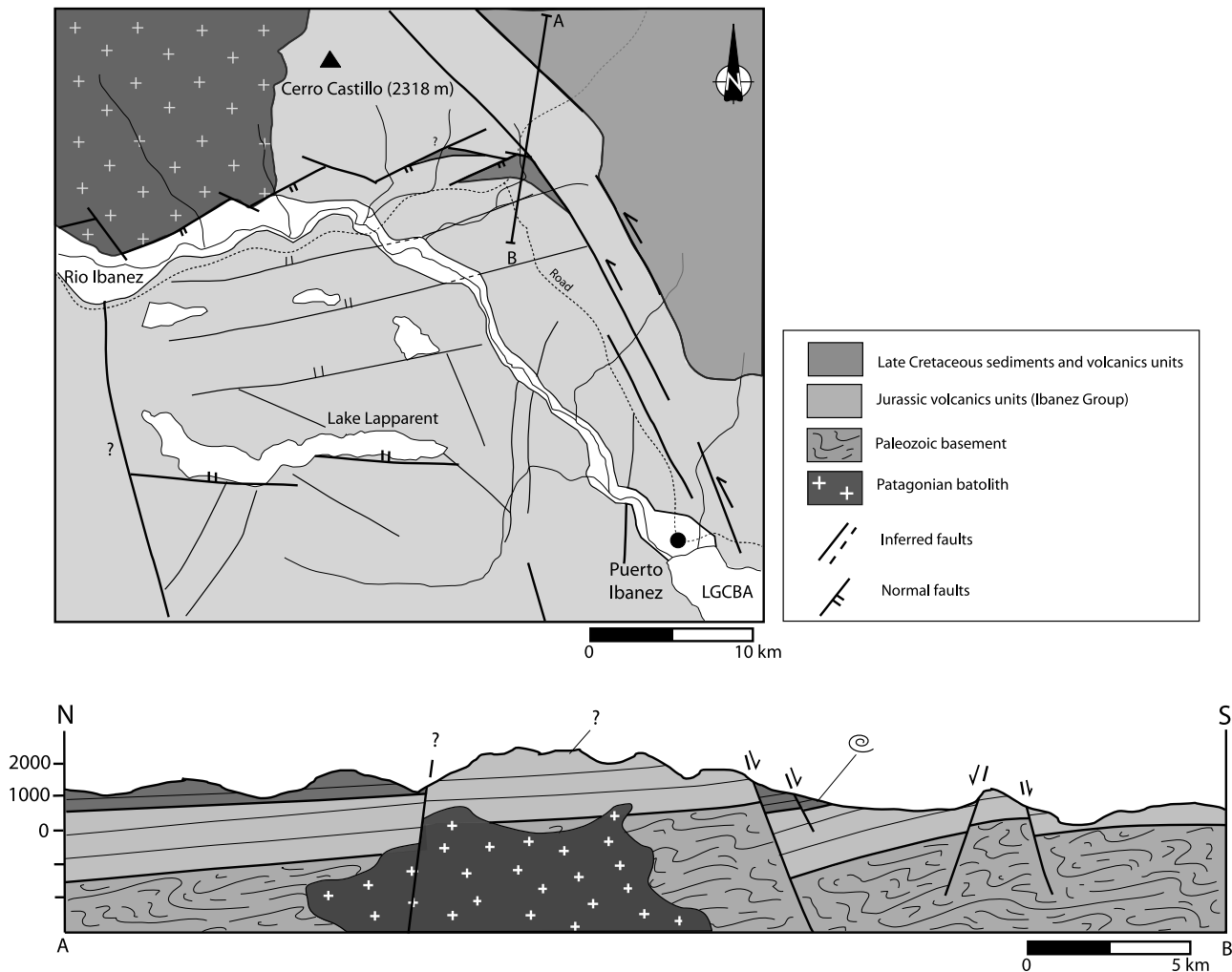


**Figure 13.** Panoramic view and schematic interpretation of the triangular facets forming the northern border of the Lake Lapparent depression (see Figure 4 for location).

jugate normal faults crosscut 5 Ma dykes and control the development of a paleovalley infilled with lavas dated from 7 to 3 Ma [Lagabrielle *et al.*, 2007; Boutonnet *et al.*, 2010]. (4) Plutonic felsic bodies dated around 3 Ma are aligned along the 160°N trending western scarp of Meseta del Lago Buenos Aires [Espinoza *et al.*, 2007].

[41] Updated structural map and cross sections of this key area, based on new field data, are presented in Figure 15.

Frontal tectonics is marked by easterly verging faults that thrust the Jurassic volcanics of the main Cordillera over either remnants of Cretaceous sedimentary basin or Miocene molasse deposits. The Jurassic beds are locally verticalized due to this compressional deformation. Marks of post-compressional deformation are only observed locally, due to frequent covering by Quaternary deposits and recent landslides. Normal faults crosscutting the beds of the Río Zeballos

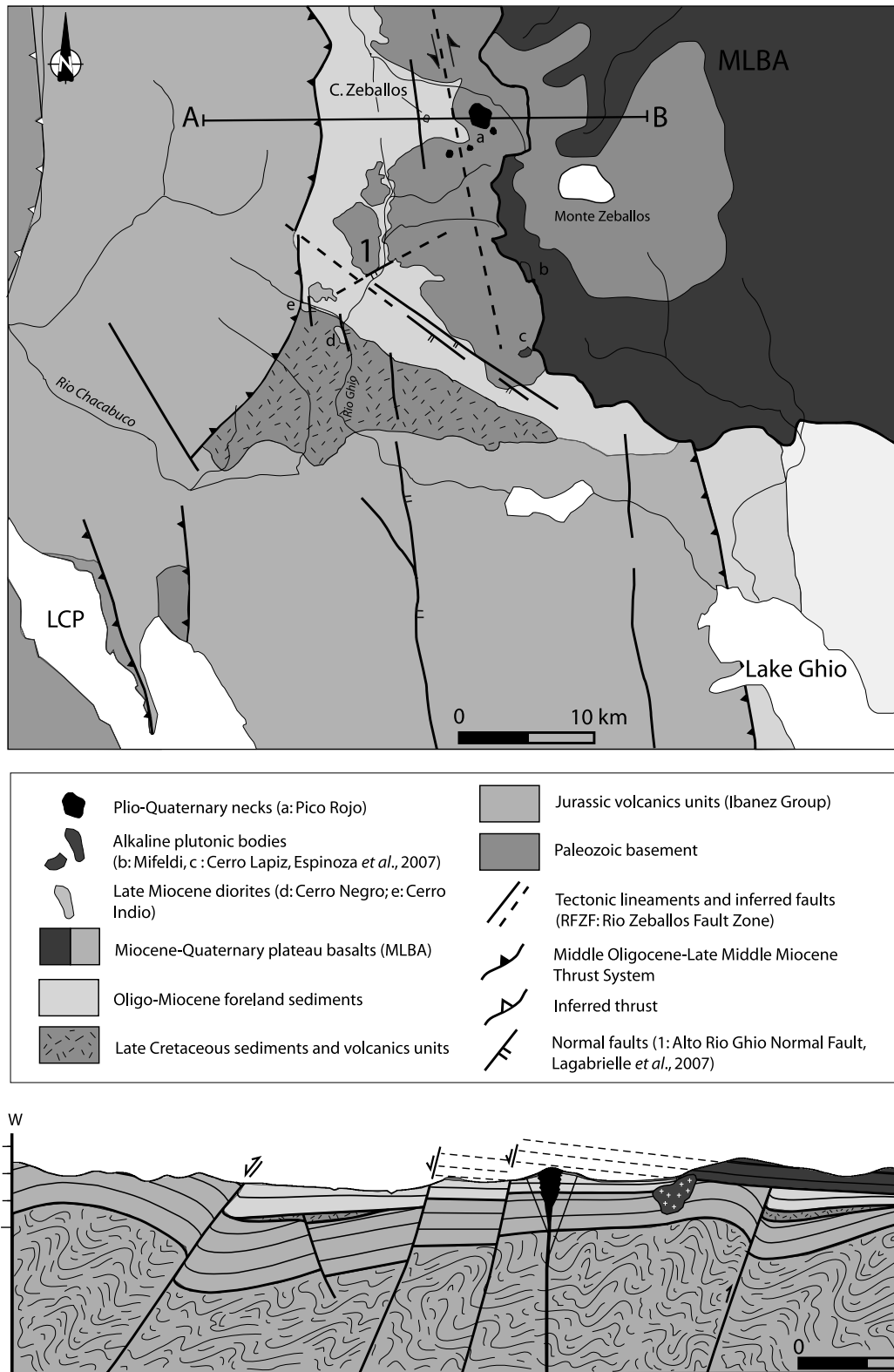


**Figure 14.** Simplified map and cross section A–B of the Lake Lapparent depression showing the main structural and orographic features. Tectonic features include lineaments observed from satellite images, together with strike-slip and normal faults observed in the field. Cross section A–B has no vertical exaggeration.

Group are observed in the Portezuelo area. South of the Portezuelo, on the west side of Río Ghio, plutonic bodies of middle Miocene age (Cerro Indio and Cerro Negro, dated at circa 12 Ma [Ramos, 2002]) are affected by easterly high dipping  $160^{\circ}\text{N}$  trending normal faults, showing well-preserved striae having pitches ranging from  $70^{\circ}$  to  $85^{\circ}$ . In addition, the beds of the molasse outcropping all along the border of the Meseta del Lago Buenos Aires are systematically affected by a  $160^{\circ}\text{N}$  vertical schistosity. This is well observed at Cerro Zeballos.

[42] Despite a reduce number of exposures demonstrating mesoscale faulting, there are geomorphological and geological evidence indicating that this corridor represents a region of major disruption of the previous front of the Cordillera. The lava flows and interbedded tills dated between 5 Ma and 3 Ma and forming the summital beds of the Meseta del Lago Buenos Aires at an elevation of 2000–2500 m are also

exposed in the Portezuelo area and in the Río Ghio valley, 700 m below. This demonstrates the relative uplift of the border of the meseta by at least 700 m. This relative uplift is corroborated by the presence of relict of calc-alkaline to transitional flows dated at 16–14 Ma, unconformably overlying the upper beds of the Zeballos Group exposed at Cerro Zeballos summit. These lavas represent the base of the meseta and are found here at an elevation of 1970 m, about ten meters beneath the basal levels of the main meseta immediately to the east (Figure 15). The most important evidence come from several felsic subvolcanic bodies (Mifeldi pluton, Cerro Lapiz, Pico Rojo) aligned along the  $160^{\circ}\text{N}$ – $170^{\circ}\text{N}$  direction which have been emplaced within the Zeballos Fault Zone between 4 and 3 Ma [Brown *et al.*, 2004; Espinoza *et al.*, 2007; Boutonnet *et al.*, 2010]. Exposure of these bodies indicates that a major tectonic disruption occurred along the Zeballos Fault Zone at 3 Ma or imme-



**Figure 15.** Simplified map and cross section A–B of the southern part of the Rio Zeballos Fault Zone close to the Meseta del Lago Buenos Aires showing the main structural and orographic features. Tectonic features include lineaments observed from satellite images, thrusts faults [after Lagabrielle et al., 2004], strike-slip faults, and normal faults. Cross section A–B has no vertical exaggeration. LCP, Lake Cochrane/Pueyrredón; MLBA, Meseta del Lago Buenos Aires.

diately after, causing the relative uplift of the western border of the meseta with respect to the Cordillera.

## 5. Discussion and Conclusion

### 5.1. Central Patagonia Cordillera: An Unusual Regional Morphotectonic Pattern

[43] This compilation of morphological and tectonic data concerns a portion of the Patagonian Cordillera located at the latitude of the Chile Triple Junction, that is in a region characterized by the occurrence of subducted segments of the Chile Spreading Ridge at depth. A number of striking characters can be extracted from our analysis. Some of them are not encountered in normal subduction ranges, i.e., in orogens which are not affected by the subduction of an active spreading ridge.

[44] 1. The central Patagonian Cordillera is characterized by an overall short-wavelength topography and highly contrasted reliefs, typical of deeply incised young mountain belts, but also by an average very low elevation of only ~900 m.

[45] 2. The morphology strongly differs from that of the northernmost Andes. It shows a central, depressed domain, with lowest elevation reaching 300 m below sea level flanked by western and eastern regions of higher elevation having opposite general slope dips. The axial depressed region is also characterized by average low slope gradients and occurs in a position where higher reliefs should be expected in the case of a normal subduction belt.

[46] 3. Remnants of a former peneplain, the Avellanos surface, locally of erosional origin are widespread within the entire region. Some of these remnants are lying at 2000 m elevation. From geological evidence this peneplain formed between 15 and 4 Ma over the entire region and connected formally with the meseta domain.

[47] 4. To the east, the central Patagonian Cordillera is now separated from the Pampean domain of flat plains and elevated mesetas, representing its former piedmont, by 160°N–180°N trending morphological corridors and west facing scarps. These scarps correspond to neotectonic features controlled by recent vertical faults, mostly active after 3 Ma.

[48] In the core of the Cordillera, 200 km long fault-controlled, linear depressions correspond to asymmetrical tectonic basins. These depression are now occupied by Quaternary glacier valleys and have developed after 10 Ma, crosscutting the entire belt. This left a main morphological imprint at the scale of entire southern South America. Indeed, at the latitude of the Chile Triple Junction, there is a connection between the Atlantic and Pacific oceans at an elevation of only 200 m. Beside these linear depressions, the Cordillera is cut by polygonal depressions of lesser extent, some of them displaying features typical of tectonically controlled basins such as the Lake Lapparent depression.

### 5.2. Negative Inversion of the Frontal Thrusts and Disruption of the Avellanos Surface

[49] Our analysis suggests a former connection between the depositional surface forming the summital regions of the mesetas and the remnants of the Avellanos peneplanation

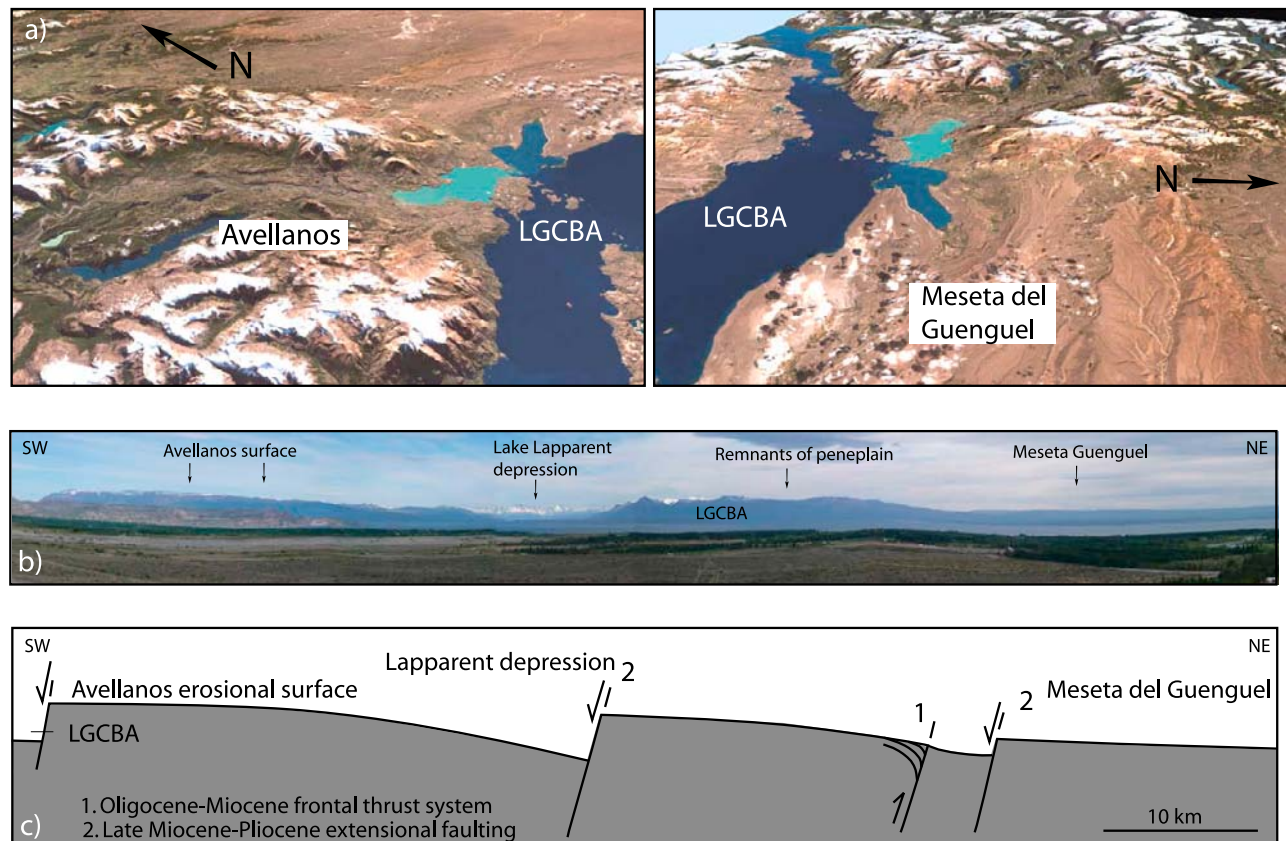
surface exposed in the core of the Cordillera. Interbedding of tills including clasts of the Patagonian batholith and lava flows of the Meseta del Lago Buenos Aires [Mercer and Sutter, 1982; Lagabrielle *et al.*, 2007] demonstrates such continuity. As reported in detail in section 2.2, the age of the upper beds of the molasse, the age of lavas locally capping the Avellanos surface, and the age of the basal flows of the Meseta del Lago Buenos Aires strongly constrain the age of the regional Patagonian peneplain between 15 Ma and 4.5 Ma.

[50] Geological and geomorphological features reported in sections 2 and 3 collectively demonstrate that a major neotectonic event occurred around 3 Ma corresponding to (1) the tectonic disruption of the former low-relief Avellanos surface along faults oriented 40°N to 70°N and 160°N, inside the Cordillera (Figure 16), and (2) the relative uplift of the Cordillera piedmont along the 160°N–180°N trending corridors, in the frontal region. Onset of the erosional dissection of the Avellanos surface and of the borders of the elevating mesetas started at that time, but evidence of normal faulting around 6 Ma have been reported in the Rio Zeballos area [Lagabrielle *et al.*, 2007].

[51] We finally enhance that a negative inversion of the frontal region of the Cordillera occurred at 3 Ma. Vertical offset probably did not exceed 1000 m maximum as observed in the Monte Zeballos region. This represents relatively reduce amount of displacement, but it is enough to significantly impact the regional landscape, inducing the cuesta-like reliefs corresponding to the western edges of the successive mesetas. Such relatively low displacement cannot lead to the neoformation of young, crustal-scale faults, and we infer that the frontal thrusts of the Cordillera have been reactivated as normal faults during this period. It is noteworthy that these thrusts are most probably themselves inverted normal faults, inherited from the mid-Cretaceous extensional phase which affected South America in relation with the opening of the South Atlantic [Folguera *et al.*, 2004]. This scenario has been retained as the main hypothesis in the evolutionary model proposed in Figure 17. The occurrence of local, abundant 3 Ma old magmatic products strongly suggests a rooting of these faults deep into the crust, as expected for major tectonic boundaries active since Mesozoic times.

[52] Tectonic inversion in the frontal region due to normal faulting was coeval with collapse of distributed basins inside the Cordillera, and with regional tilt of crustal blocks separated by normal faults. The Lapparent basin is one of the best examples of intra-Cordilleran tectonic depressions. It displays a number of important characteristics: (1) the outlines of the basin are very sharp and linear, (2) triangular facets occur on its northern border, and (3) tilted floor to the north indicates flexural deformation linked with normal faulting evoking rollover style of deformation over a main normal fault. Asymmetrical morphology is also reported from the study of the western and central segments of the Lago General Carrera/Buenos Aires and of the Tamango basin.

[53] Finally, the post-3 Ma brittle deformation involves differential tilting of an assemblage of crustal blocks having typical sizes of 20–30 km. This pattern is the key to describe the morphotectonic evolution of central Patagonia. This tectonic style accounts well for the progressive lowering of the



**Figure 16.** (a) Two panoramic views showing the Lake Lapparent depression, the Meseta del Guenguel, and the Avellanos surface. These views are constructed from a DEM draped with Landsat 7 images. (b) Panoramic photograph of the frontal region of the central Cordillera taken from a view point at the southern edge of the Lake General Carrera/Buenos Aires, south of Los Antiguos (Argentina). (c) Tectonic interpretation of the panorama shown in Figure 16b.

Avellanos peneplain surface toward the east (Figure 16). Similarly, flexure-driven, eastward tilting of main crustal blocks main explain the regional eastward slope of the Meseta del Lago Buenos Aires and Meseta del Guenguel.

### 5.3. Origin and Significance of the Avellanos Surface

[54] The origin of the high-elevated peneplain of the central Patagonian Cordillera is an important issue that implies further studies and more detailed investigations and dating. However, in a preliminary approach this surface can be viewed as the consequence of one of two opposite peneplanation processes. The first model derives from the classical view of mountain chains peneplanation by long-term erosion that smoothes relief and progressively lowers elevation of the entire belt near sea level, as described by *Davis* [1899]. According to this model, observations of remnants of pene-

plain lying at 2000 m would imply that the entire central Patagonian Cordillera was capped by a low-elevation surface which has been uplifted to 2000 m during the Pliocene. The second model implies processes of peneplanation at high elevation, resulting from the rise of the base level as described by *Babault et al.* [2005] in the case of Pyrenean belt. According to this model, high-elevation peneplanation of the Patagonian Cordillera might have started during its tectonic uplift, under the condition that the foreland molasse basins became closed, thus cutting the links with the global marine base level. This might have occurred around 22 Ma during the transition from the marine to the continental molasses. This hypothesis can explain the high-elevated position of remnants of peneplains at 2000 m and the occurrence of fluvio-glacial deposits since 7 Ma in the piedmont region, implying elevated reliefs of the Cordillera at that time [*Lagabrielle et al.*, 2010, and references therein].

**Figure 17.** Late Mesozoic–Cenozoic morphostructural evolution of the central Patagonian Cordillera at the latitude of the Chile Triple Junction (no vertical exaggeration). This interpretation is based on the hypothesis that the main faults in this region are inherited features which have been inverted few times during this tectonic evolution. This was the case for the frontal thrusts which accommodated extension during the negative inversion of the piedmont domain after 3 Ma, as well as for some main faults controlling basins inside the Cordillera.



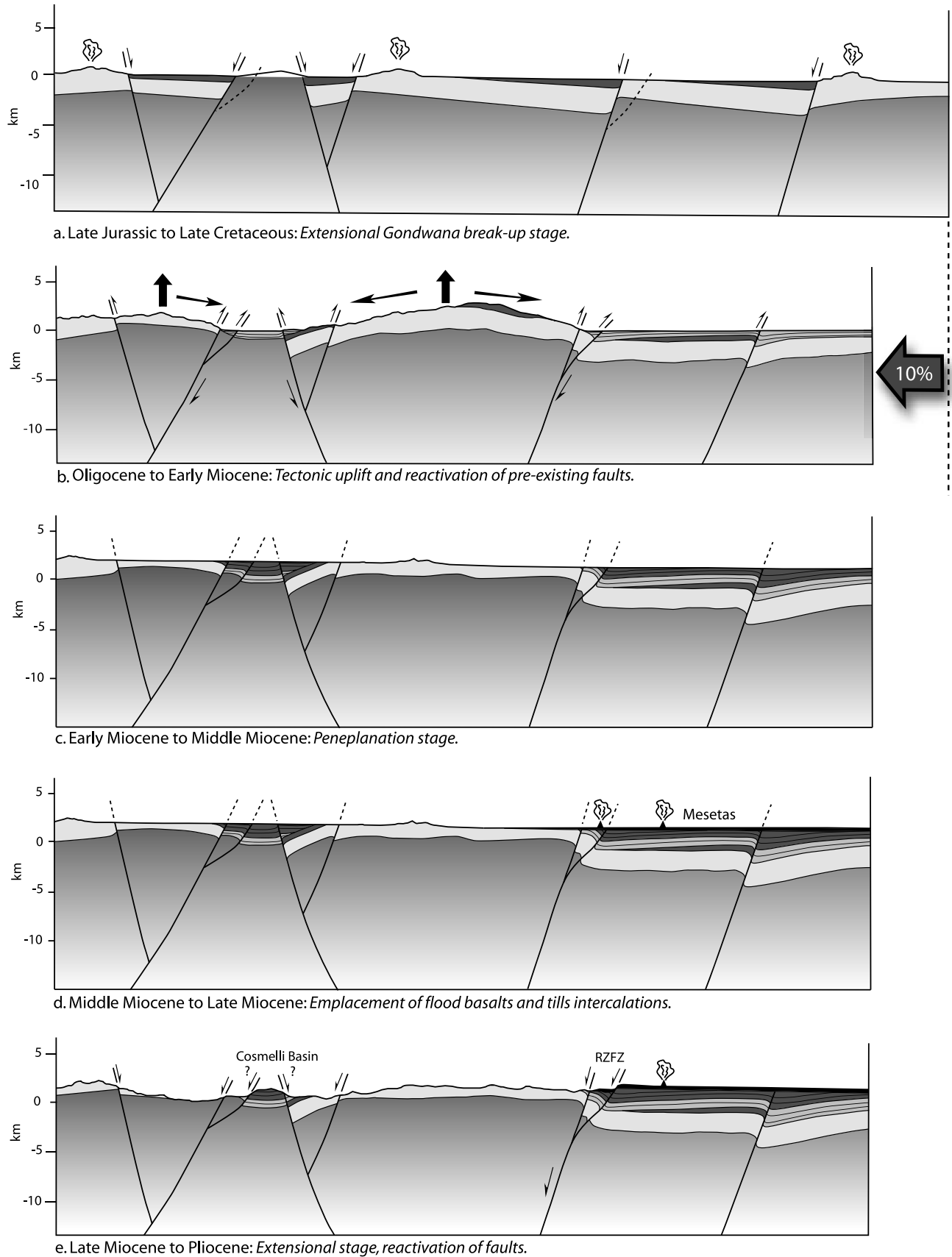


Figure 17

[55] Whatever peneplanation model is retained, it is noteworthy that during the late Miocene–Pliocene, the morphology of the Patagonian Cordillera was totally different from the current one. The depressions of lakes General Carrera/Buenos Aires and Cochrane/Pueyrredón did not exist. Glaciers and rivers were flowing to the east producing a regional surface erasing the reliefs and depositing the upper sequences of the molasse basins. The region was characterized by a continuous slope connecting the high reliefs of the Central Cordillera to these now elevated fluvio-glacial depocenters.

#### 5.4. Links With the Subduction of the Chile Spreading Ridge

[56] The timing of the extensional deformation deduced from this work is synchronous with the migration at depth of segments of the South Chile Ridge which entered the trench around 6 and 3 Ma, resulting in the opening of an asthenosphere window beneath central Patagonia [Lagabrielle *et al.*, 2004; Breitsprecher and Thorkelson, 2009, and references therein]. The opening of asthenospheric slab windows allows hot mantle to reach lithospheric regions. This model was proposed by Murdie *et al.* [2000] in the case of central Patagonia in order to explain the large negative Bouguer anomaly reaching  $-160$  mGal measured in the central part of the study area. This is also consistent with local features such as the high heat flow values measured from bottom sediments of the Lake General Carrera/Buenos Aires [Murdie *et al.*, 1999] and the eruption of the Murta basalts with oceanic mantle affinity during the Quaternary, in a valley close to the Lake Lapparent depression [Demant *et al.*, 1998; Guivel *et al.*, 2006]. The presence of abnormal hot mantle at depth is confirmed by evidence at a regional scale including (1) low  $V_s$  velocities at 100 km depth revealed by seismic tomography [Heintz *et al.*, 2005], (2) abnormal terrestrial high heat flow values at around  $160$  mW/m<sup>2</sup> along the Patagonian Cordillera [Hamza and Munoz, 1996], (3) high heat flow values, and (4) thin lithosphere less than 100 km [Artemieva, 2006].

[57] The tectonic events described in this work occurred synchronously with magmatic activity in central Patagonia. We have evidenced a clear relationship between the negative inversion of the frontal region and the emplacement of felsic and basic magmas around 3 Ma along the Cordillera front, preferentially in the Rio Zeballos region but also within the Cordillera itself. This magmatic activity has been regarded as the consequence of a thermal anomaly linked to the presence of hot mantle beneath the South America plate, replacing a normal, colder slab [Morata *et al.*, 2002; Guivel *et al.*, 2006; Espinoza *et al.*, 2007; Lagabrielle *et al.*, 2007].

[58] Progressive replacement of cold lithosphere by hot mantle may drive overall uplift followed by regional collapse due to weakening of the base of the mountain belt. Uplift of the entire Cordillera occurred first as a consequence of crustal shortening during a long period of normal subduction starting

around 30 Ma, prior to the collision with the South Chile Ridge at 15 Ma in southern Patagonia. This compressional phase is also recorded and well described along the Patagonia Cordillera south to latitude 52°S [Ramos, 1989; Diraison *et al.*, 1997; Kraemer *et al.*, 2002; Altenberger *et al.*, 2003; Ramos, 2005]. Compression resumed in the frontal region of central Patagonia, around 13–12 Ma as demonstrated by the fact that the base of the Meseta del Lago Buenos Aires is not involved in any post-12 Ma thrusting. However, localized compressional deformation may have occurred in more internal regions of the central Patagonian Cordillera in a period between 10 and 6 Ma. This event is not documented in the studied region, but some areas of southern Patagonia experienced compressional deformation between 10 and 6 Ma [Kraemer *et al.*, 2002; Ramos, 2005]. This tectonic event might have contributed to the exhumation pulse which occurred at around 8 Ma in central Patagonia [Thomson *et al.*, 2001].

[59] The Avellanós surface was progressively established on the piedmont and eastern flank of the proto-Cordillera. We do not have any informations allowing to depict the original overall shape of this surface in the period 15–3 Ma. We may suspect that it connected to higher reliefs to the west, which are now eroded or collapsed. A possible evolution is that the migration of a segment of the Chile Spreading Ridge at 6 Ma triggered regional uplift of the Cordillera, causing or increasing the doming of the Avellanós surface. In a second stage, around 3 Ma, when a second segment of the Chile Spreading Ridge entered the trench, this dome has been dissected and interrupted by a series of tectonically controlled depressions in relation with increased weakening of the crust. This hypothesis accounts well for the current morphology of the Central Cordillera, characterized by a central depressed region. This peculiar pattern shows striking affinities with rift topographies having uplifted shoulders and an internal depression controlled by linear faults. Typical rift morphology is also reported farther south in Patagonia where extension has been shown to be still active from structural analysis [Diraison *et al.*, 1997] and based on the study of the morphology and the distribution of volcanic centers [Mazzarini and d'Orazio, 2003]. A change from compressional to tensional tectonics also occurred at 12 Ma at the latitude of the Torres del Paine pluton [Altenberger *et al.*, 2003]. For these authors, ridge subduction and the change in convergence rates related to the presence of the triple junction are a possible mechanism accounting for the initiation of an extensional tectonic regime in the upper plate.

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