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Cooling histories and deformation of plutonic rocks along the Liquiñe-Ofqui Fault Zone, Southern Chile (41°-42°15'S)

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ABSTRACT. Structural and microstructural observations combined with apatite and zircon fission-track thermochronology within two sectors of the Main Andean Range in the Los Lagos Region of Chile reveal an episodic history of intrusion and deformation in the North Patagonian Batholith (NPB). A dextral displacement of ~30 km along the Liquiñe-Ofqui fault zone (LOFZ) is inferred from the correlation of corresponding Cretaceous intrusions of the NPB across the fault zone at Reloncaví. Relative uplift of the western block in the late Miocene is indicated by apatite and zircon fission-track cooling histories. Microstructures in samples from Miocene and Cretaceous plutons along the fault zone generally indicate deformation at temperatures below ~300°C, with the exception of some samples from Cretaceous intrusions showing deformation at higher temperatures. In the Hornopirén area, significant relative uplift of the eastern block is indicated by **1.** the different styles of deformation observed across the fault zone, **2.** kinematic analysis of a shear zone in tonalite and **3.** geobarometry of contact metamorphic mineral assemblages. For the plutonic rocks in the Hornopirén area, extremely rapid cooling is indicated by thermochronometry, suggesting the activity of hydrothermal systems or thermal effects of late shallow intrusions.

Keywords: Chile, Liquiñe-Ofqui Fault Zone, North Patagonian Batholith, Fission-track dating, Deformation, Exhumation.

RESUMEN. Historia de enfriamiento y deformación de rocas plutónicas a lo largo de la Zona de Falla Liquiñe-Ofqui, Sur de Chile (41°-42°15'S). Observaciones estructurales y microestructurales, combinadas con resultados de medidas de huellas de fisión en circón y apatita en dos segmentos de la Cordillera Principal de la Región de Los Lagos de Chile revelan una historia episódica de intrusión y deformación del Batolito Norpatagónico (BNP). Se infiere un desplazamiento dextral de ~30 km a lo largo de la zona de falla Liquiñe-Ofqui según la correlación de intrusiones Cretácicas del BNP localizadas en distintos flancos de la zona de falla en el área de Reloncaví. Las historias de enfriamiento de circón y apatita indican un alzamiento relativo del bloque occidental durante el Mioceno Tardío. En general, las microestructuras observadas en muestras de intrusiones miocenas y cretácicas a lo largo de la zona de falla muestran deformación a temperaturas por debajo de los ~300°C, con la excepción de algunas muestras que indican deformación a temperaturas mayores durante el Cretácico. En el área de Hornopirén, se infiere un importante alzamiento relativo del bloque oriental basado en: **1.** los distintos estilos de deformación observados a ambos lados de la zona de falla, **2.** el análisis cinemático en una zona de cizalla en tonalitas, **3.** los datos de geobarometría de asociaciones minerales de la aureola de metamorfismo de contacto. Para las rocas plutónicas del área de Hornopirén, se estiman tasas extremas de rápido enfriamiento según indican los datos de termocronometría, lo que sugiere la actividad de sistemas hidrotermales o efectos termales producidos por intrusivos epizonales tardíos.

Palabras claves: Chile, Zona de Falla Liquiñe-Ofqui, Batolito Norpatagónico, Datación por trazas de fisión, Deformación, Exhumación.

1. Introduction

Thermal and deformation histories of magmatic arc batholiths provide insight into the effects of heterogeneities in the subducting plate on stress and deformation in the upper plate. They also provide important hints on the mechanisms and tectonic processes that lead to the exhumation of plutonic rocks and the development of landscape. In the present case study, we inspect the distribution of different intrusions in the North Patagonian Batholith (NPB, Fig. 1) of southern Chile in space and time and discuss the implications of their cooling and deformation histories, based on recently published low-temperature thermochronometric data (Adriasola *et al.*, 2006) and additional structural and microstructural observations. We refer to the following definitions originally proposed by England and Molnar (1990) and recently used by Reyners and Brandon (2006): rock uplift is the vertical motion of a rock or a portion of the Earth near or at the surface relative to a datum, such as sea level. Surface uplift is the vertical motion of a portion of the Earth's surface with respect to this datum. Denudation is the removal of rock or soil by tectonic and/or surficial processes with respect to a specified point beneath the Earth's surface. Erosion is one of the processes involved in denudation, specifically the surficial removal of mass at a point in the landscape, which occurs by both mechanical and chemical processes. The difference between rock uplift and surface uplift is erosion. Exhumation is the unroofing history or path of a rock towards the Earth's surface, as a result of denudation (Reyners and Brandon, 2006). Exhumation can be tectonic or erosional.

The North Patagonian Batholith in the southern Chilean Andes is traditionally understood to represent a deeply eroded arc that evolved episodically since the Late Jurassic, remaining stationary in its position relative to the trench during Cenozoic times (Fig. 1, Pankhurst *et al.*, 1999; Beck *et al.*, 2000). The earlier stages of plutonic activity of the NPB have been related to changes in certain subduction parameters, such as an increase in convergence rate and a decrease in the angle of subduction (Pankhurst *et al.*, 1999). The latest stages in the evolution of the NPB are probably affected by the northward migration of the Chile triple junction (CTJ) along the Andean margin since about 14 Ma (Cande and Leslie, 1986). As an apparent effect of the oblique ridge subduction, the structural styles differ to the north (pre-ridge collision) and south (post-ridge collision) of Taitao Peninsula, where the CTJ is located at present (Dewey and Lamb, 1992; Diriason *et al.* 1998; Lavenu and Cembrano, 1999). To the north of the CTJ, the most obvious structure is the long-lived intra-arc Liquiñe-Ofqui fault zone (LOFZ, Hervé, 1976; Cembrano *et al.*, 1996, 2000), which has accommodated an arc-parallel component of plate motion and controlled the emplacement of intrusions of the NPB (Hervé *et al.*, 1993, 1996; Pankhurst *et al.*, 1992, 1999; Cembrano *et al.,* 2002). Shaded relief digital elevation modeling (Rosenau *et al.,* 2006), regional and structural field mapping (Thiele *et al.,* 1986; SERNAGEOMIN-BRGM, 1995[1]; Diriason *et al.,* 1998; Arancibia *et al.,* 1999; Lavenu and Cembrano, 1999), microstructural analyses (Cembrano *et al.,* 1996, 2000, 2002; Arancibia *et al.,* 1999), and Ar/Ar laser-total fusion and step-heating geochronology of synkinematic minerals (Cembrano *et al.,* 2000, 2002; López, 2001) in deformed plutonic rocks consistently demonstrate right-lateral transpression along the LOFZ in Late Miocene to Pliocene times. This interpretation is supported by apatite and zircon fission track thermochronometric data collected along the southern Andes between 41° and 47°S, indicating an episode of enhanced cooling and denudation along the LOFZ in the Late Miocene to Pliocene (Thomson *et al.*, 2001; Thomson, 2002; Adriasola *et al.*, 2006). When compared to plate kinematic reconstructions, the episode of denudation seems to be coeval with the arrival and subduction of the northern portions of the Chile Rise beneath Taitao Peninsula (*e.g.*, Cande and Leslie, 1986; Ramos and Kay, 1992) and is therefore proposed to reflect differential block uplift driven by right-lateral transpression along the LOFZ (Thomson *et al.,* 2001; Thomson, 2002; Adriasola *et al.*, 2006).

A more detailed analysis of the cooling histories of intrusive rocks of the NPB between 41 and 42°15'S resulted in the identification of three different classes of plutons within the batholith (Adriasola, 2003; Adriasola *et al*., 2006): **A.** Cretaceous plutons emplaced in the upper crust (less than ~7 km depth); **B.** Cretaceous to Early Miocene plutons with a deeper level of emplacement and **C.** Miocene shallow plutons. The objective of this paper is the correlation between the thermochronometric results and the deformation of the plutonic rocks exposed along the LOFZ in two test areas of the Los Lagos region, with implications on the timing of faulting and the contemporaneous geotherm.

[1] SERNAGEOMIN-BRGM, 1995. Carta Metalogénica Xª Región Sur, Chile. Informe Registrado IR-95-05 (Unpublished), Servicio Nacional de Geología y Minería-Bureau de Recherches Geologiqués et Minières*,* 4 tomos, 10 Vols., 95 mapas. Santiago.

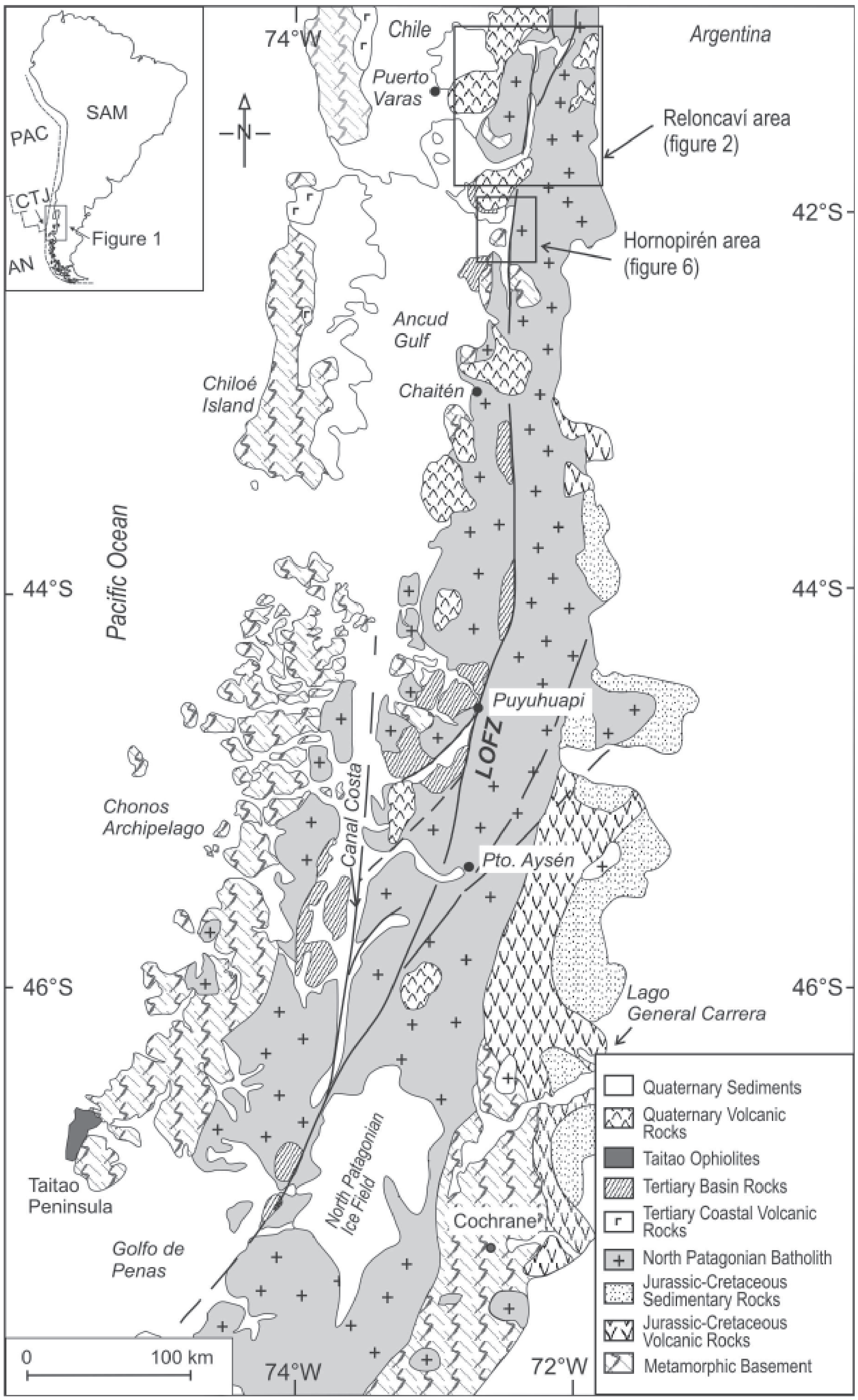

FIG. 1. Geological framework and location of the study area (adapted from Hervé *et al*., 2000). **SAM**: South American Plate. **PAC**: Pacific Plate. **An**: Antarctic Plate. **CTJ**: Chile Triple Junction.

2. Geological Setting

The North Patagonian Batholith extends as a continuous plutonic belt along the Main Range of southern Chile between 40° and 47°S (Fig. 1). It intruded a late Paleozoic to early Mesozoic accretionary complex at the eastern margin of the Coastal Ranges (Hervé *et al.*, 2000; Hervé and Fanning, 2001; Martin *et al.*, 1999; Duhart *et al.*, 2001), Jurassic silicic volcanic rocks of the Ibáñez Formation at the eastern flank of the Main Range (Pankhurst *et al.*, 1998, 1999), and the overlying early Cretaceous shallow marine volcano-sedimentary rocks of the Aysén basin (De la Cruz *et al.*, 1996; Suárez and De la Cruz, 2000).

The NPB shows a prolonged history of emplacement. K-Ar, U-Pb and particularly Rb-Sr whole-rock isochron data from plutonic rocks between ~41°S and 47°S reveal a systematic pattern with Jurassic to early Cretaceous intrusions at the eastern and western margins of the NPB, and Miocene ages towards the center (Hervé *et al.,* 1979; Munizaga *et al.*, 1988; Parada *et al.,* 1987; Pankhurst *et al.*, 1992, 1999; Suárez and De la Cruz, 2001). The episodic development of the NPB appears to be correlated with periods of increased convergence rates along the South American margin (Pankhurst *et al.*, 1999). A gap in the plutonic history of the NPB during the early Tertiary coincides with a stage of extension, volcanism along the Coastal Ranges and the development of several intramontane basins beneath the Central Valley (*e.g.*, González, 1989; Muñoz *et al.*, 2000). Enclosed by the main strands of the LOFZ, several marine volcano-sedimentary basins developed unconformably on earlier-exhumed parts of the NPB and are locally intruded by younger Miocene plutons (Rojas *et al.*, 1994; Hervé *et al.*, 1995). The position of the younger intrusives suggests that these fill pull-apart structures at dextral releasing offsets along the LOFZ (Cembrano *et al.*, 1996; Hervé *et al.*, 2000).

The youngest plutons, locally exposed near the LOFZ, are described as syntectonic (Hervé *et al.*, 1993; Pankhurst *et al.*, 1992, 1999), with centimeter- to meter-thick mylonitic bands. According to Ar/Ar dating by Cembrano *et al.* (2000, 2002), many of these were formed in Late Miocene to Pliocene times.

Starting from Pliocene times, and during most of the Quaternary, both glaciation and volcanism have shaped the landscape of the Patagonian Andes, which is presently characterized by low ice-capped topographies with a steep relief (Mercer and Sutter, 1982; Rabassa and Clapperton, 1990; Heusser, 1990; Montgomery *et al*., 2001; Rosenau *et al.,* 2006).

Due to the limited access to outcrops in the study region, two representative areas of the Main Range were sampled for fission track (FT) analysis; these areas show differences in the age and cooling patterns and in the style of deformation and microstructural record of the plutonic rocks exposed along the fault zone. Both areas are discussed separately in the following sections.

3. Methodology

The field observations and sampling for both inspection of microstructures and fission track dating were focussed along the Reloncaví estuary (Figs. 2, 3, 4, 5), to a limited extent across the Lago Todos Los Santos, and along a well-known shear zone (Cembrano *et al.,* 1996) in the Hornopirén area (Figs. 6, 7, 8, 9). The structural relations between plutons and their metamorphic host rock were examined in the field as well as the orientation of foliations and lineations in the shear zones. Due to the rather uniform petrographic character of the plutonic rocks of the NPB, contact and crosscutting relations are difficult to establish without precise geochronologic data. Radiometric ages were compiled from previous reports by Pankhurst *et al.* (1992), Munizaga *et al.* (1988), Carrasco (1995), Cembrano *et al.* (1996, 2000), and SERNAGEOMIN-BRGM (1995[1]), and used as a reference for this study.

Low-temperature cooling histories derived from 51 zircon and 56 apatite FT ages, plus 37 apatite confined track length measurements (Adriasola *et al.*, 2006) were combined with available intrusion ages, and with Ar/Ar or K-Ar cooling ages obtained in the previous studies. The cooling histories were compared with microstructures of plutonic rocks exposed along the main lineaments of the LOFZ (Cembrano *et al.,* 2000).

The first aim was to obtain information on the pattern of magmatic activity within the NPB, along the LOFZ. The second aim was to constrain the timing of deformation in relation to the denudation history using the low-T thermochronologic data and microstructural observations from samples used for FT dating along the LOFZ (all samples from Reloncaví and samples AA39, AA46 and

AA119 from Hornopirén). Accordingly, the present study is biased to observations on *subsolidus* deformation of plutonic rocks sampled for fission track analysis (Adriasola *et al.*, 2006). In addition, information on the kinematics of shear zones is used, and the results are compared with those of previous studies using Al-in-Hb geobarometry and the thermobarometric evaluation of contact-metamorphic mineral assemblages (Parada *et al.*, 1987; Pankhurst *et al.*, 1992; Seifert *et al.,* 2003; Hervé *et al.*, 1996).

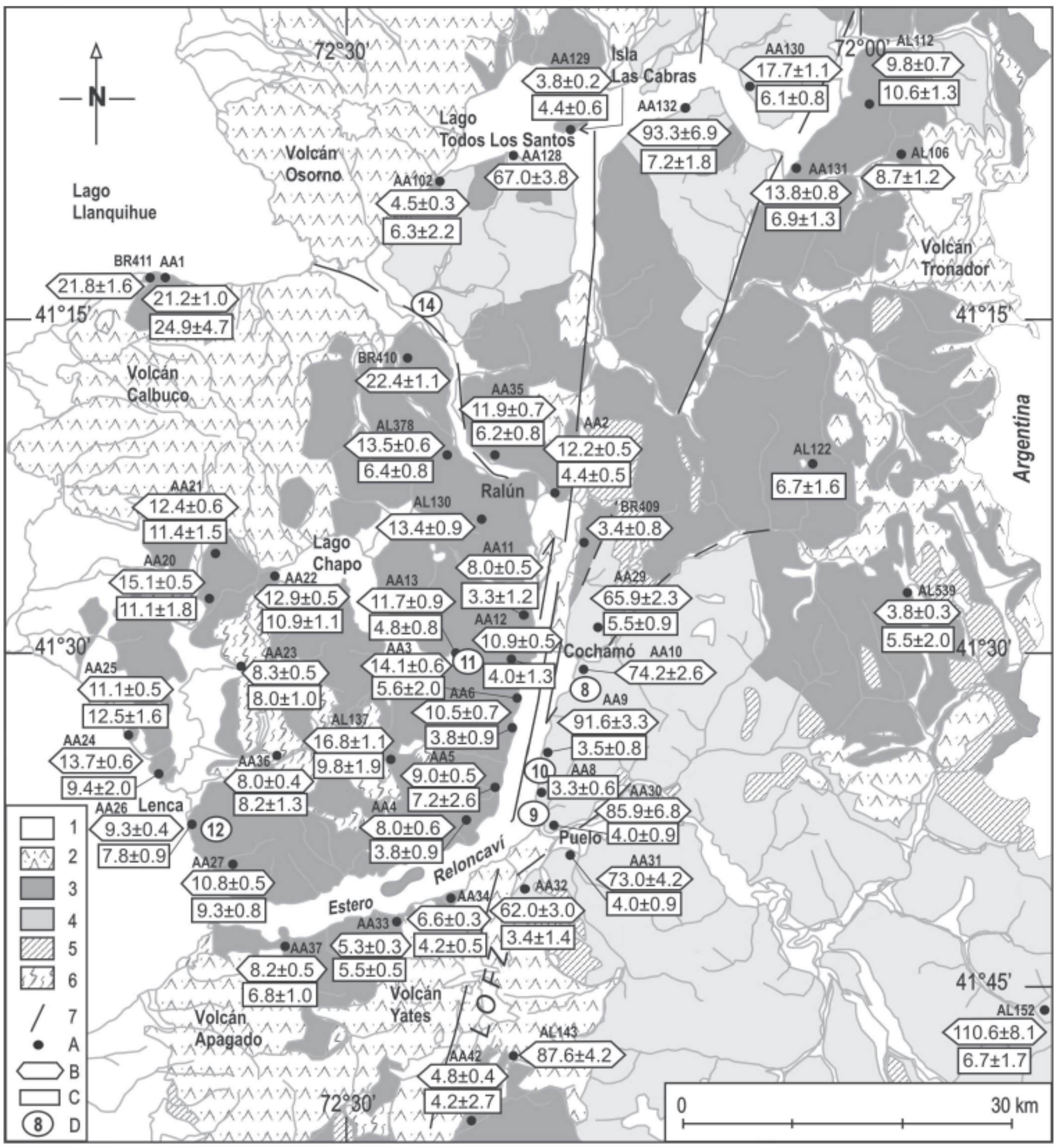

FIG. 2. Geology of the Reloncaví area (after Duhart *et al.*, 2000) and location of zircon and apatite FT ages (after Adriasola *et al.*, 2006). Legend: **1.** Quaternary and recent sediments; **2.** Quaternary to recent volcanic rocks; **3.** Miocene plutonic rocks; **4.** Cretaceous plutonic rocks; **5.** Undifferentiated Meso-Cenozoic volcanic and sedimentary rocks; **6.** Metamorphic basement rocks; **7.** Trace of the Liquiñe-Ofqui fault zone; **A.** Location of sample for fission-track dating and microstructural analyses; **B.** Zircon FT central age (Ma±1σ); **C.** Apatite FT central age (Ma±1σ); **D.** Depth of intrusion (km) estimated by Al-in-Hornblende geobarometry (after Seifert *et al.,* 2003).

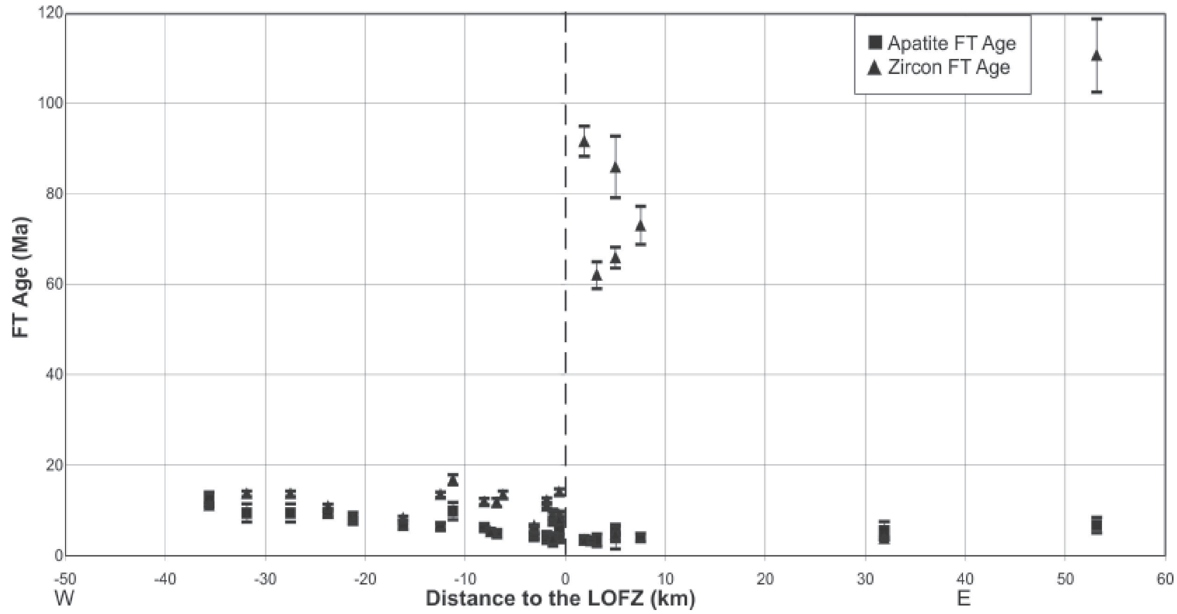

FIG. 3. West to East profile across the Reloncaví Estuary (~41°30'S) showing the zircon and apatite FT ages plotted against their horizontal distance to the main trace of the LOFZ. Error bars at the 1σ level.

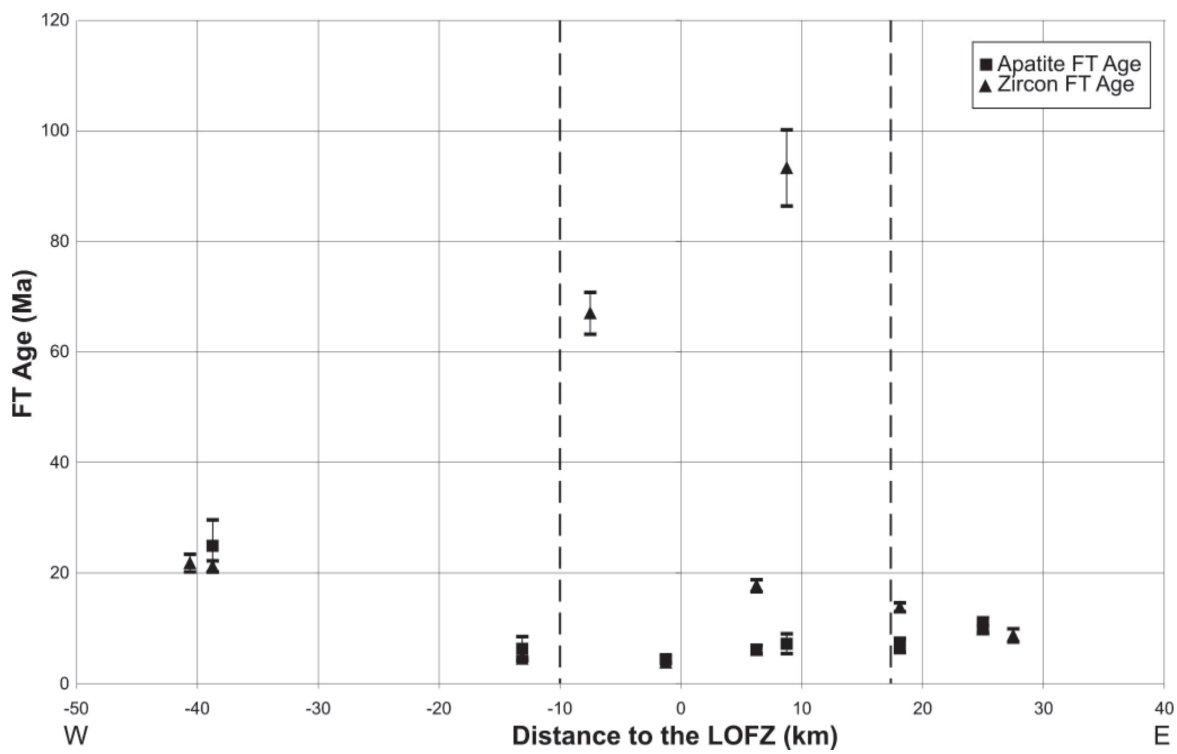

FIG. 4. West to East profile across lago Todos Los Santos (~41°15'S) showing the zircon and apatite FT ages plotted against their horizontal distance to the main traces of the LOFZ. Error bars at the 1σ level.

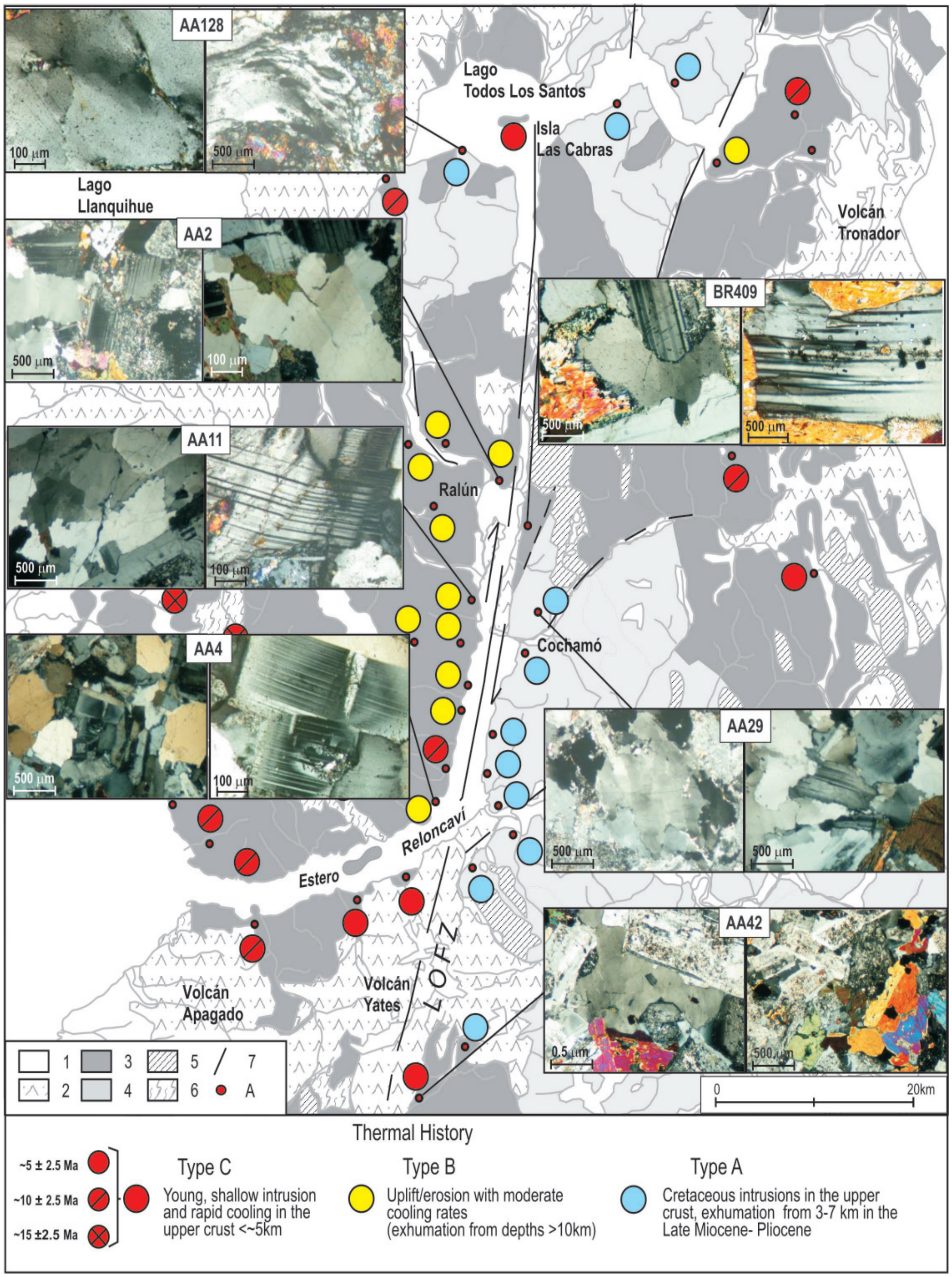

FIG. 5. Distribution of cooling curves obtained for the plutons of the NPB plotted against characteristic microstructures of rocks along the LOFZ in the Reloncaví area (modified from Adriasola, 2003). Legend as in figure 2.

4. Reloncaví Area

4.1. Geologic Setting

The geology of the Reloncaví area is dominated by Cretaceous and Miocene plutonic rocks of the NPB, which were emplaced in sparsely exposed Meso- to Cenozoic volcanic and sedimentary rocks and high grade metamorphic schists of unknown age (Fig. 2, Parada *et al.*, 1987; Thiele *et al.*, 1986; SERNAGEOMIN-BRGM, 1995[1]). To the west of Lenca, the plutonic rocks are bounded by an intramontane basin underlying the Central Valley, which at 42°S is filled with a ~3 km thick sequence of Cenozoic clastic sediments grading laterally into Paleocene to Eocene volcanic deposits. The sequence is uncomformably covered by ~1 km thick glacial deposits intercalated with Quaternary lavas (González, 1989). The stratigraphy of this basin suggests a marked increase in the rate of denudation of the Main Andean Range since the Pliocene (Adriasola *et al.*, 2006).

The structure in the Main Range is represented by two steeply dipping segments of the LOFZ (Fig. 2), juxtaposing Miocene and Cretaceous plutons with sharp contacts. The main trace of the fault zone trends approximately North-South. The second segment strikes NNE and extends continuously in this direction for 90 km, suggesting an origin as a large-scale dextral Riedel shear (Tchalenko, 1970). Recent satellite radar based topographic models combined with structural analyses have led to an alternative structural interpretation, where one of several releasing splays bend towards the east north of Cochamó (Rosenau *et al.*, 2006). This interpretation is consistent with the dextral displacement along the LOFZ. The lineaments defining the fault zone in this area appear to be continuous with other segments of similar characteristics to the north and south. Gravimetric studies in the area of Ralún have depicted a negative Bouguer anomaly, which is interpreted to represent a zone of low-density rocks beneath the Reloncaví estuary at a depth of ~2.2 km, possibly created by brittle deformation along the LOFZ (Thiele *et al.*, 1986).

Following the interpretation of the map by SERNAGEOMIN-BRGM (1995[1]), and assuming that the Cretaceous parts of the NPB were emplaced simultaneously and originally formed a coherent intrusive complex, a dextral displacement of ~30 km is inferred from the relative position of Cretaceous plutons along the Reloncaví estuary. This inferred displacement would compare well to the inferred amount of extension associated with mid-Tertiary pull-apart basins mapped to the south of the study area (*e.g.,* SERNAGEOMIN-BRGM, 1995[1]; Cembrano *et al.*, 1996).

Rosenau *et al.* (2006) argue that several brittle faults in the Main Cordillera show mutual cross-cutting relationships, which-at a larger scale-have offset the main Northern-Southern trending segment of the LOFZ by linkage with a hidden Northeastern-trending fault segment beneath Lago Todos Los Santos. There, they infer a local offset of about 10 km by fault-linkage, supported by information on the paleostress field obtained from brittle faults using magmatic dikes as offset markers.

In general, the plutons consist of coarse-grained granodiorite and tonalite with minor diorite, monzonite and granite. Mafic and granodioritic dikes are frequently observed within the plutons to the W of the Reloncaví estuary. The rocks exposed along the fault zone show a foliation that appears unrelated to tectonic deformation in places. Magmatic foliation and compositional layering were recognized within plutons near Ralún and on Isla Las Cabras.

A series of discrete conjugate sets of steeply dipping faults trending NNE to ENE was observed to cut the intrusives along the eastern border of the LOFZ between 41°15' and 41°30'S.

A more detailed study, based on kinematic analyses on fault striations in this area was carried out by Cembrano *et al.* (2000). Applying the stress inversion method of Carey and Brunier (1974), they described two homogeneous (*i.e.*, kinematically compatible) fault populations. The first population includes faults striking between NNW and Northeast and right-lateral slip, faults striking ENE to Eastwest with left-lateral kinematics, and faults striking WNW with reverse-slip displacement. For this first fault population, the inverted principal stress directions correspond to σ_1=219°, 05°; σ_2=110°, 75°; σ_3=310°, 14°. Accordingly, the orientations of the principal stress directions for the first fault population are compatible with an overall right-lateral sense of displacement of the LOFZ. The age of this population was assigned to the Pliocene and the Quaternary, based on regional correlations with similar trending faults exposed in the Hornopirén area (Cembrano *et al.*, 2000). Close to Ralún, Thiele *et al.* (1986) described NS to NNE-striking wrench faults cutting marine terraces and Quaternary volcanic rocks.

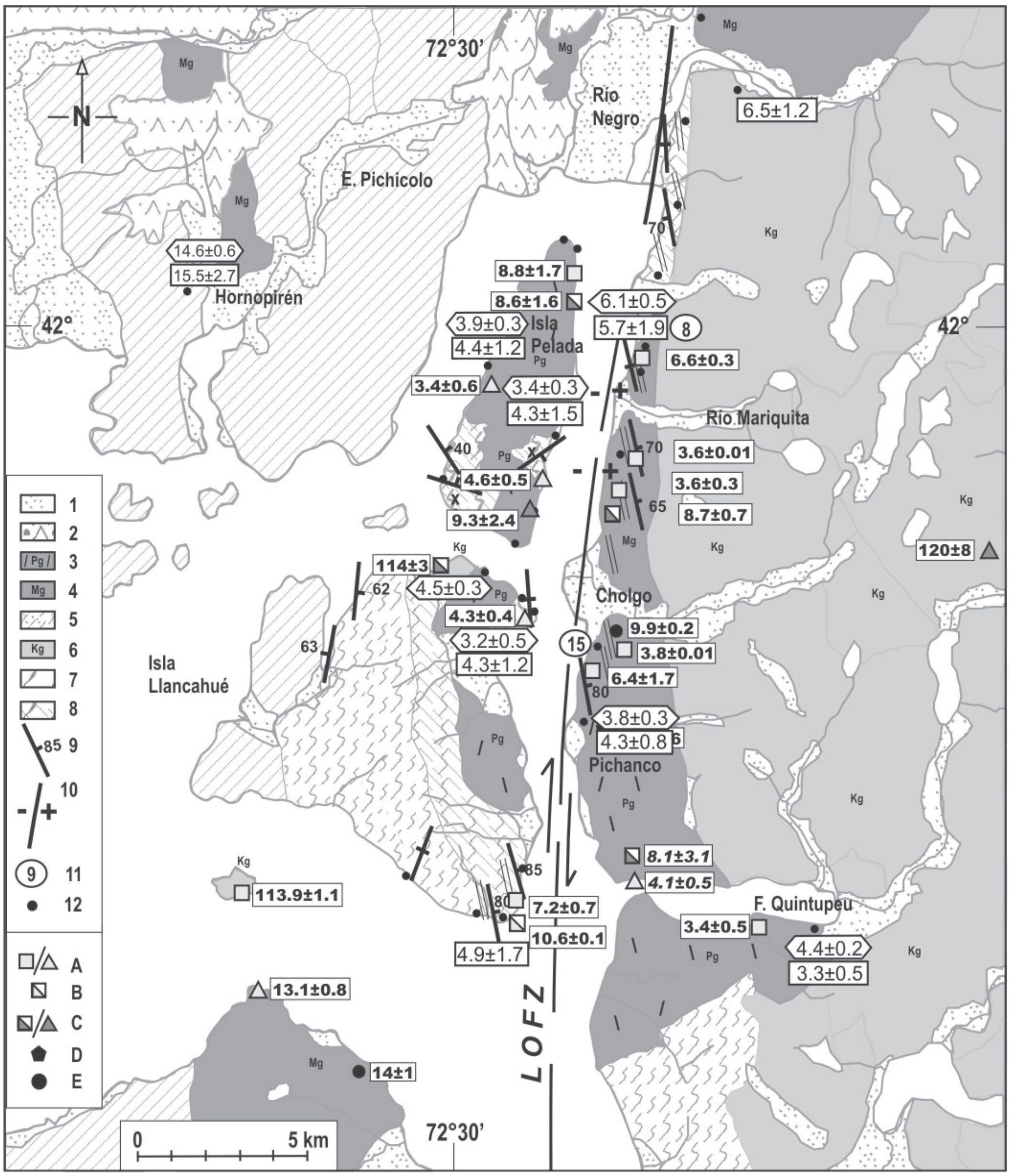

FIG. 6. Geology of the Hornopirén Area (modified after Hervé *et al.*, 1979; SERNAGEOMIN-BRGM, 1995[1]; Cembrano *et al.*, 1996) and location of samples for microstructural inspection and zircon and apatite FT ages (after Adriasola *et al.*, 2006). Legend: **1.** Quaternary to recent sediments; **2.** Quaternary and recent volcanic rocks; **3.** Late Miocene-Pliocene plutonic rocks; **4.** Miocene plutonic rocks; **5.** Tertiary volcanic rocks; **6.** Cretaceous plutonic rocks; **7.** Metamorphic basement rocks; **8.** Contact metamorphic aureoles; **9.** Strike/dip of foliation; **10.** Area of relative block uplift; **11.** Depth of emplacement (km) estimated by Al-in-Hornblende geobarometry (after Hervé *et al.*, 1996; Seifert *et al.*, 2003); **12.** Samples for FT dating and microstructural analyses. The K-Ar and Ar/Ar isotopic dates are from SERNAGEOMIN-BRGM (1995[1]), the Rb-Sr whole rock isochron from Pankhurst *et al.* (1992), the Ar/Ar stepwise heating ages for finely recrystallized biotites in deformed tonalites from Cembrano *et al.* (2000), all shown in italics; **A.** Ar/Ar/K-Ar biotite; **B.** Ar/Ar muscovite; **C.** Ar/Ar/K-Ar hornblende; **D.** Rb-Sr whole rock; **E.** U-Pb zircon; **F.** Zircon FT central age (Adriasola *et al.,* 2006); **G.** Apatite FT central age (Adriasola *et al.,* 2006).

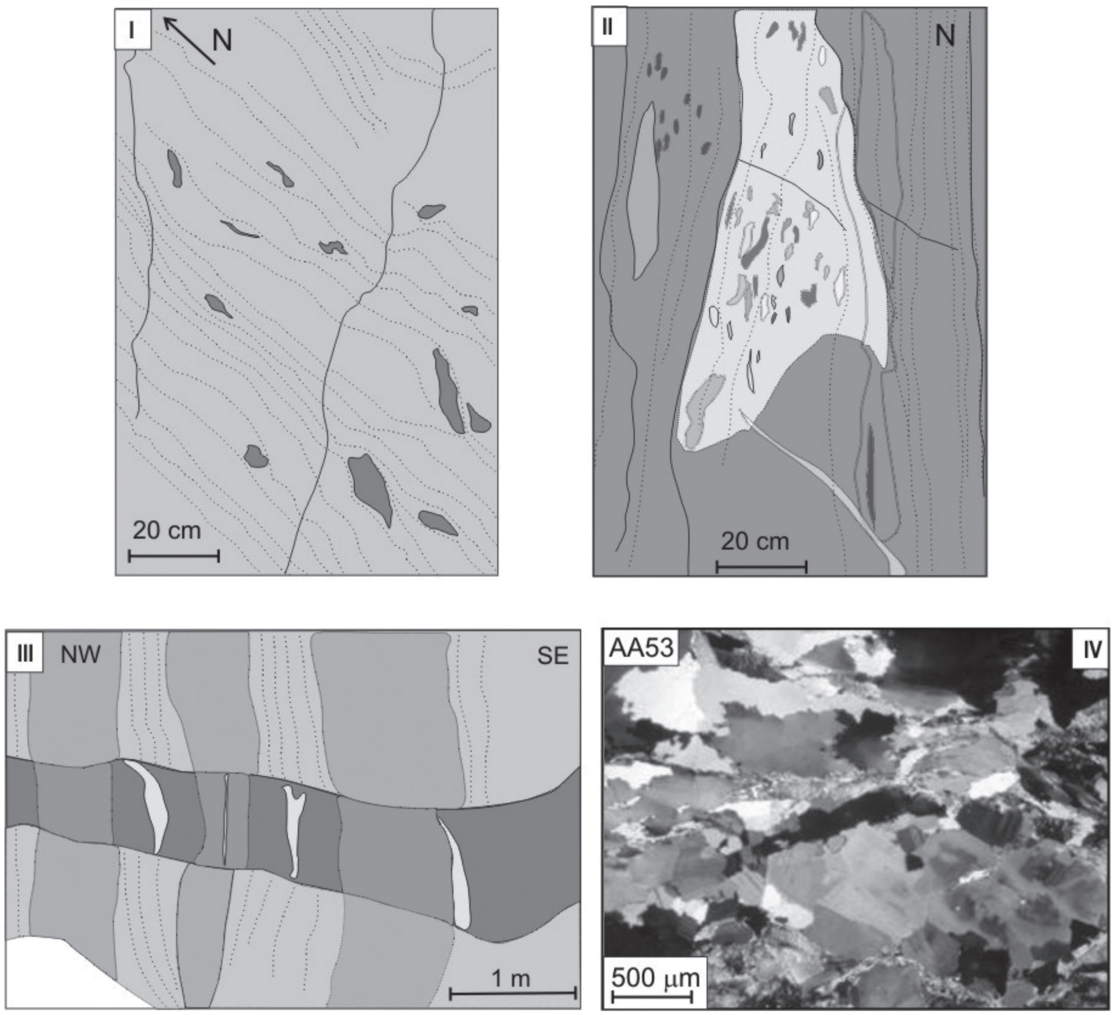

FIG. 7. Field sketches (plates I to III) and one photomicrograph (plate IV) showing the tectonic foliation roughly overprinting earlier magmatic flow structures in the foliated tonalites from the eastern block of the LOFZ at Hornopirén. The magmatic foliation (dashed lines, plates I to III) shows deflections around large microgranitoid enclaves (with darker colors). Additional magmatic flow structures include domains with lensoid compositional heterogeneity (in gray and white tones, plates II and III). Locally, a mafic dike cuts through the magmatic foliation (plate III). The tectonic foliation is defined by flattened quartz and feldspar aggregates (plate IV), and dark-colored fine-grained steep-dipping shear zones that strike NNW to NS (plate III). Plate IV shows a photomicrograph in polarized light of sample AA53 (Cholgo unit; Cembrano *et al.*, 1996, 2000). The aligned feldspar grains surrounded by aggregates of quartz, biotite and amphibole indicate a magmatic origin for the fabric. Flattened quartz domains (top of plate IV) display variable fabrics ranging from undulatory extinction to deformation lamellae. See text for discussion. Location of the sample is shown in figure 8.

The second population includes fault planes striking mainly NNE to Eastwest with reverse dextral-slip and faults striking WSW-ENE (115°-144°) with reverse left-lateral slip. Their inverted principal stress directions are σ_1=275°, 05°; σ_2=184°, 12°; σ_3=25°, 77°. This population was interpreted to represent a distinctive, Eastwest trending, compressional event. Cembrano *et al*. (2000) suggested an Upper Miocene or younger age for it based on the their observations that the faults cut both Cretaceous and Miocene plutonic rocks.

Crystallization depths for the plutons of the NPB based on Al-in-hornblende geobarometry indicate some variations across the LOFZ (Seifert *et al.*, 2003). Cretaceous plutons at the eastern border of Reloncaví estuary yield depths between 8 km and

10 km, whereas slightly deeper levels (10 km to 14 km) were obtained for plutons exposed to the west of the fault zone. Typical errors for Al-in hornblende geobarometry are at least of 0.1 GPa, or ~2 km (*e.g.,* Hervé *et al.*, 1996).

In contrast, westward from the estuary and away from the fault zone, outcrops of the metamorphic basement display contact aureoles with andalusite, K feldspar and sillimanite (Parada *et al.*, 1987). Based on the intersection of the *andalusite=sillimanite* equilibrium curve proposed by Holdaway (1971) and the *muscovite+quartz=andalusite+K-feldspar* $+H_2O$ equilibrium curve (Spear and Cheney, 1989; St. Onge, 1984), this contact metamorphic assemblage suggests low pressures (similar to 0.2 GPa) and hence a shallow depth of emplacement (similar to 5 km) for these western plutons.

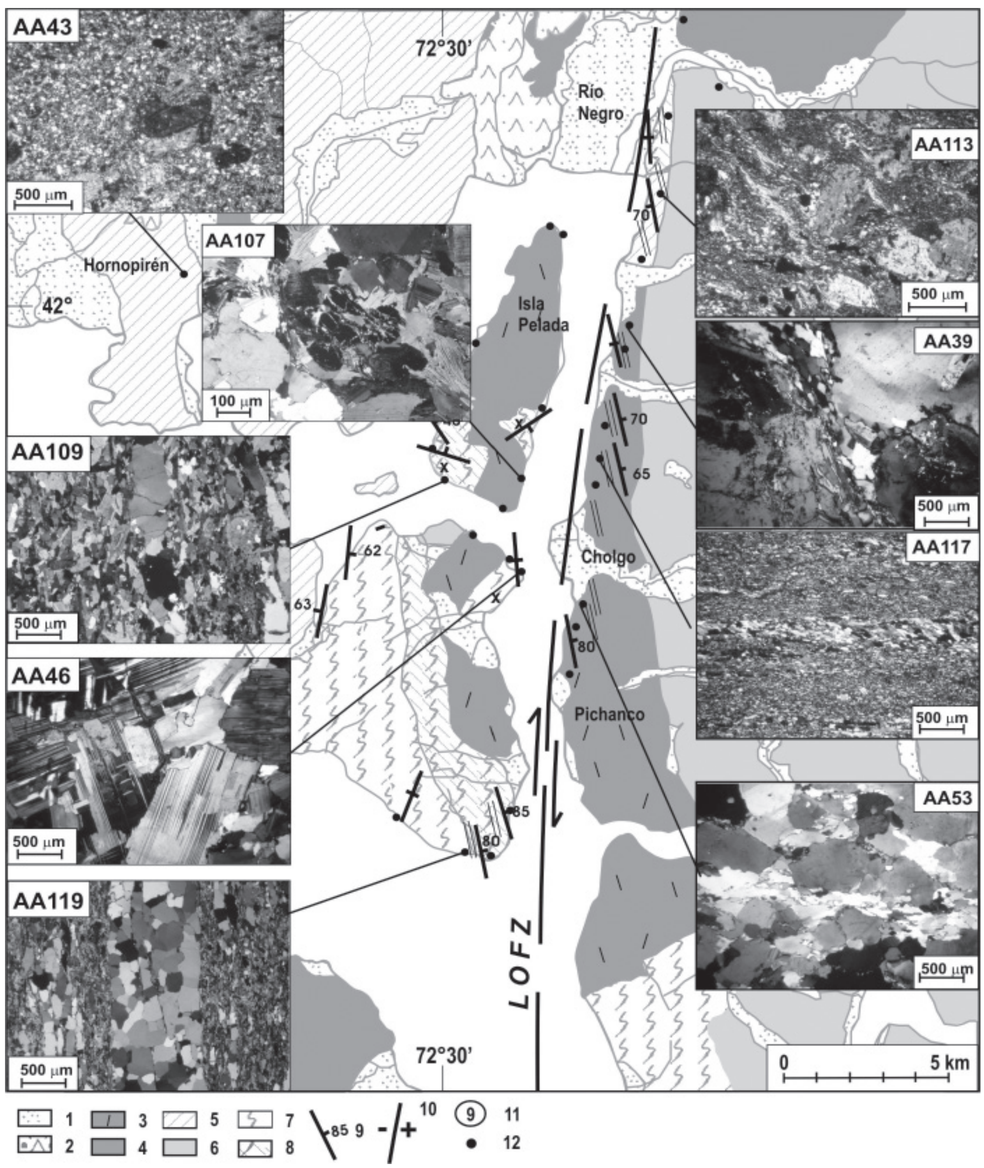

FIG. 8. Typical microstructures of deformed plutons from the eastern and western blocks at Hornopirén, indicating contrasts in the conditions of deformation along and across the LOFZ. Legend as in figure 2.

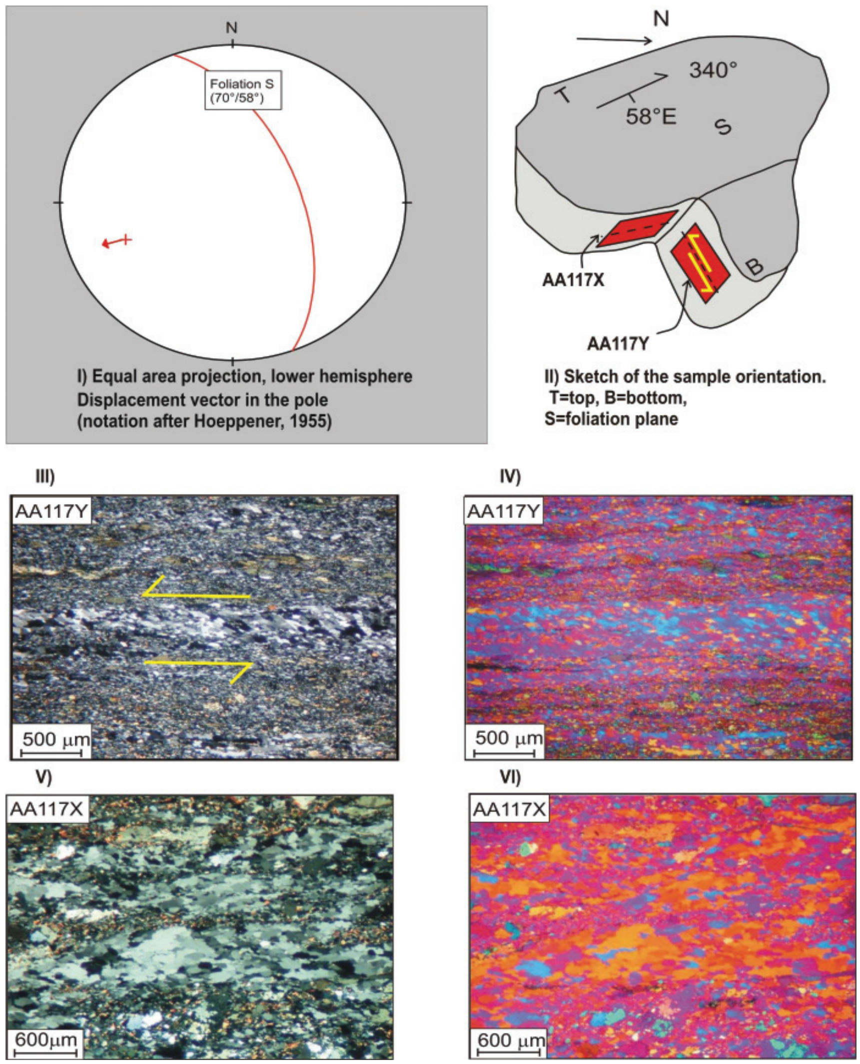

FIG. 9. Photomicrographs of SC-fabrics in sample AA117, at the eastern side of the LOFZ in the Hornopirén area. A marked obliquity in the quartz shape preferred orientation (SPO) is visualized by the arrows in image III. The images IV and VI, with the compensator red I inserted, reveal a pronounced SPO of quartz. Kinematic reconstruction indicates a reverse displacement, with the eastern block of the LOFZ uplifted. Refer to figure 8 for location.

4.2. Zircon and apatite fission-track cooling histories

In this paper, we summarize the zircon and apatite FT ages from the Reloncaví area discussed in detail by Adriasola *et al.* (2006). This earlier report focuses on the post-emplacement cooling histories of the NPB and the exhumation history with respect to the movements along the LOFZ. Here, these histories are discussed with respect to the age of faulting and the conditions of deformation in the plutonic rocks exposed along the fault zone. The location of the samples that yielded apatite and zircon FT ages is shown for reference in figure 2. The apatite FT ages (for track length distributions refer to Adriasola *et al.,* 2006) range between early Miocene and Pliocene, and can be as young as ~5 to 3 Ma along the LOFZ. The Zircon FT ages range between Cretaceous and Pliocene. In general, the zircon FT ages are similar to or younger than Rb-Sr, K-Ar and Ar/

Ar ages obtained from nearby outcrops (Munizaga *et al.*, 1988; Carrasco, 1995; SERNAGEOMIN-BRGM, 1995[1]). The zircon FT ages are interpreted to represent the time of post-emplacement cooling to temperatures of around 280±30°C (*e.g.*, Tagami and Shimada, 1996; Thomson *et al.*, 2001) and their locations correlate well with the distribution of the plutonic units of the NPB outlined in the geological map of SERNAGEOMIN-BRGM (1995[1]; Fig. 2). Instead, the spatial distribution of zircon FT ages shows no systematic relation with the trace of the LOFZ. Pliocene zircon FT ages are found in higher parts of the batholith near the main Andean divide, the northern shore of Lago Todos Los Santos, and sporadically along the eastern side of the Reloncaví estuary. Cretaceous zircon FT ages are found at the eastern shore of the Reloncaví estuary, along the southern shore of Lago Todos Los Santos and in the southeastern part of the study area (Figs. 2, 3 and 4).

The overall distribution of zircon and apatite FT ages with respect to the LOFZ is summarized in E-W-striking transects across Lago Todos Los Santos and Puelo in figures 3 and 4. In both figures, the patterns indicate that the main episode of cooling and denudation along the fault zone is late Miocene to Pliocene in age. In order to discriminate different types of post-magmatic cooling histories within the NPB in the Reloncaví area, 46 cooling paths were determined combining the apatite and zircon FT ages with other radiometric ages from related outcrops published elsewhere (Fig. 5; for compilation of age data refer to Adriasola *et al*., 2006). The data allow a classification into three different types of cooling histories: type-A curves are characterized by very slow cooling (< 3°C/Myr) after emplacement in the Cretaceous, followed by a stage of increased cooling rates since the late Miocene (~50°C/Myr). The Cretaceous age of emplacement is inferred from K-Ar and Ar/Ar ages obtained for correlated outcrops in the study area (Carrasco, 1995; SERNAGEOMIN-BRGM, 1995[1]), which yield a minimum age of intrusion, which is expected to be close to the actual age for shallow intrusions into a cool upper crust. Type-B curves display relatively moderate and steady cooling rates (~20° to 50°C/Myr) since the Early Miocene. Type-C curves are characterized by rapid cooling following emplacement at a shallow crustal level (>50°C/Myr).

The distribution of type-A and type-B cooling curves with respect to the position of the main trace of the LOFZ along the Reloncaví estuary (south of 41°15') indicates simultaneous unroofing of plutons emplaced at different crustal levels along the fault zone. Early Miocene granitoids emplaced at depths >10 km were exhumed along the western side of the LOFZ, while at the same time shallower emplaced (<10 km) Cretaceous plutons on the eastern side of the fault zone were unroofed. Accepting that the Cretaceous plutons with type-A curves cooled very slowly during most of the Cenozoic implies that these remained at near constant depths previous to their final exhumation. Therefore relative uplift of the western block along the fault zone is inferred. This interpretation is consistent with kinematic data from Neogene fault planes at the eastern side of the Reloncaví estuary reported by Cembrano *et al.* (2000).

North of 41°15', relative uplift of the eastern block along the LOFZ is inferred at the eastern margin of Lago Todos Los Santos, along the large Riedel shear type fault branch diverging eastwards from the main strand of the LOFZ (Figs. 4, 5). This differential uplift pattern is compatible with a series of reverse and dextral faults mapped along the eastern margin of the Main Cordillera in Argentina between 40º and 42ºS (Diriason *et al.,* 1998). These faults juxtapose pre-Neogene basement blocks above Early Miocene lacustrine sedimentary rocks of the Ñirihuau basin. Furthermore, large-scale East-West to ENE-WSW striking lineaments bridging across the LOFZ to the eastern side of the Andean Range suggest restraining stepovers (*e.g.,* Rosenau *et al*., 2006). Similar differential block exhumation patterns were derived in the southern part of the NPB from kinematic analyses by Cembrano *et al.* (2002) and FT thermochronology by Thomson (2002). A major uplifted central block is located between two major segments of the LOFZ that diverge northwards from Golfo de Penas to Canal Costa and Puyuhuapi (~44º-46ºS, 73ºW; Fig.1).

The cooling history of sample AA130 (Figs. 2, 4) with an early Miocene zircon FT age may be inconsistent with the model, however. The sample has a markedly younger zircon FT age than the rest of the samples of Cretaceous plutons in the Reloncaví area. The zircon FT central age of sample AA130 is subject to a large dispersion, indicating a discordant distribution in the individual FT grain ages (*e.g.,* Galbraith and Laslett, 1993; Brandon, 2002). The sample is derived from a mapped pluton of Cretaceous age. It is located at a distance of 5 km from an early Miocene stock, whose sub-surface shape is unknown. It is possible that heat input from that young and possibly underlying intrusion has led to annealing of fission tracks (*e.g.,* Tagami and Shimada, 1996) accumulated during the earlier history of the Cretaceous pluton.

Type-C curves are found widespread in the Reloncaví Area, indicating the presence of shallow young intrusions emplaced into exhumed original deeper levels of the NPB. The cooling ages tend to become younger towards the fault zone, suggesting a structural control on the emplacement of the late shallow intrusions (Adriasola *et al*., 2006). Also, thermal effects due to hydrothermal circulation along the fault zone cannot be excluded, leading to some very young (*e.g.,* samples BR409, AA34, AA42, AA129; Fig. 2) zircon and apatite FT ages with wide age dispersions along the fault zone (*e.g.*, Thomson, 2002; Adriasola *et al.*, 2006).

4.3. Microstructures of plutonic rocks along the LOFZ

The microstructures of samples AA2, AA4, AA11, and BR409 taken from Miocene plutons along the western shore of the Reloncaví estuary show mechanical twinning and microcracking in plagioclase, undulatory extinction in quartz, and bent or slightly kinked biotites (Fig. 4). The microfractures in feldspar are sealed with fine-grained sheet-silicates, epidote and (in places) calcite, suggesting solution transfer at low temperatures (*e.g*., Chester and Logan, 1987; Evans, 1988). In general, the observed microstructures are consistent with deformation at very low-grade conditions (below ~300°C; *e.g*., Stöckhert *et al*., 1999).

Samples from Cretaceous plutons located on the eastern side of the estuary indicate scarce evidence of ductile deformation, with the exception of sample AA29, near Puelo. In this sample, inhomogeneously deformed plagioclase grains were observed together with a variety of quartz deformation fabrics, ranging from undulatory extinction to subgrain boundaries. The latter microstructures of quartz indicate recovery during deformation by dislocation creep at elevated temperatures. This deformation could have been driven by internal stresses originating during cooling of the intrusion, or related to tectonic activity along the LOFZ in the Cretaceous when the rocks still resided near their original level of emplacement.

Another exception was found in sample AA128, from the western side of the Lago Todos Los Santos. There, significant deformation is recorded in the quartz fabrics, characterized by undulatory extinction and grain-boundary migration recrystallization. Feldspar porphyroclasts are rotated within the quartz matrix. The biotite crystals are kinked and fractured, and often recrystallized into fine-grained aggregates. Based on the microstructures of quartz and feldspar, this deformation probably took place at temperatures of about 300 to 350°C (*e.g.,* Simpson, 1985; Stöckhert *et al.*, 1999). A zircon FT age of 67±4 Ma from this sample provides a lower age bound to this deformation, which therefore is pre-Tertiary.

Despite the differing post-magmatic cooling histories of the plutons exhumed along the fault zone, no significant differences could be established in the microstructural record of deformation across the LOFZ. This can be best explained by the fact that the differences in the crustal level exhumed in the late Cenozoic cover temperatures below those required for dislocation creep of quartz to become effective (*e.g.,* Stöckhert *et al.*, 1999; Brix *et al.*, 2002). The variable record of earlier ductile deformation at depth, in contrast, is not related to the late Cenozoic denudation episode revealed by fission track thermochronometry. The movements along the LOFZ are probably reflected by brittle structures (*e.g.,* Cembrano *et al.*, 2000; Rosenau *et al.*, 2006).

Samples AA4 and AA42 taken from rapidly cooled Miocene plutons at the south- western shore of the estuary show little deformation. Oscillatory zoning in plagioclase is conspicuous in these rocks, which may reflect cyclic changes of *e.g.,* pressure within a shallow magma chamber, related to volcanic eruptions. Similar textures have been reported from shallow-level plutons in the coastal magmatic arc of northern Chile (Grocott *et al.*, 1994).

5. Hornopirén Area

5.1. Geologic Setting

The geology at Hornopirén is represented by a small plutonic complex of Late Miocene to Pliocene age that intruded Cretaceous parts of the NPB, Cenozoic volcanic rocks, and metamorphic basement rocks. A well-known shear zone affects the rocks along the main Northsouth trending segment of the LOFZ, which has been described by Cembrano *et al.* (1996, 2000). Tonalites of Miocene age located at the eastern border of the LOFZ display zones with a pronounced fault-related foliation overprinting a previous magmatic foliation (Figs. 6, 7). The magmatic foliation is defined by the alignment of anisometric euhedral feldspar grains, with deflections around large microgranitoid enclaves, and by domains with lensoid compositional heterogeneity (*e.g.,* Paterson *et al.*, 1998; Vernon, 2000; Vernon *et al.,* 2004). Locally, mafic dikes cut through the foliation.

The superimposed tectonic foliation is defined by flattened quartz and feldspar aggregates. It trends predominantly in a NNW direction and dips steeply to the E. Towards the north, near Río Negro, the foliation is observed to continue beyond the plutons within their metamorphic host rocks. The obliquity of the foliation with respect to the orientation of the main trace of the LOFZ suggests a dextral sense of shear (Cembrano *et al.,* 2000). In the area of Cholgo, Cembrano *et al.* (2000) described a NNE-SSW-striking foliation with a spacing in the centimeter range, making up an angle of 15-25° with the main schistosity. From these observations a dextral sense of shear along the LOFZ is inferred.

Towards the south, the foliation within the plutonic units disappears near Pichanco, where undeformed coarse-grained tonalites and granodiorites suggest a post-tectonic emplacement. This interpretation is supported by one U-Pb intrusion age of 9.9 Ma for the deformed rocks near Cholgo (Cholgo unit) reported by Cembrano *et al.* (2000), and one Rb-Sr whole-rock isochron age of *ca.* 5 Ma for a coarse grained tonalite with associated fine-grained diorites and aplites near Pichanco, reported by Pankhurst *et al.* (1992).

Plutons located at the western side of the LOFZ are predominantly dioritic to tonalitic in composition, and often display compositional layering with aplitic segregations. These were observed in unfoliated and weakly deformed rocks.

Outcrops of quartz-mica schists at the south-eastern shore of Llancahué Island instead show a very regular NNW-trending and steeply dipping foliation, following the general tectonic grain (Fig. 6). The metamorphic basement rocks on other parts of the island display a foliation following the regional trend and being disrupted by contact aureoles. On the eastern side of the island, metasedimentary rocks are intercalated with basic volcanic rocks, some of which display pillow structures. The mafic rocks are considered as remnants of an ophiolite of unknown age in the metamorphic rocks interpreted as an accretionary complex (Pankhurst *et al.*, 1992). For the basement rocks on Llancahué island, Cembrano *et al.* (2000) described a progressive west-to-east change in metamorphic grade from greenschist to amphibolite facies near the contact with intrusive rocks.

A second major NNW-NS striking lineament related to the LOFZ can be traced between Rio Negro and the western shore of Llancahué Island (*e.g.,* SERNAGEOMIN-BRGM, 1995[1]). In this area, particularly along the western shore of the Llancahué and Pelada islands, the foliation of the basement rocks reveals a variable orientation and there is no evidence of any pervasive deformation related to movement along the LOFZ.

5.2. Zircon and Apatite fission-track cooling histories

The location of the samples that yielded apatite and zircon FT ages in the Hornopirén area is shown on figure 6. The apatite FT ages are similar across the fault zone and range from 6.5±1.2 Ma to 3.3±0.5 Ma. Their track-length histograms display long tracks with relatively narrow standard deviations (Adriasola *et al.*, 2006) supporting rapid cooling below about 120°C (*e.g.,* Gleadow *et al.,* 1986).

The zircon FT ages range between 6.1±0.5 Ma and 3.2±0.3 Ma, overlapping with the apatite ages within 1σ error. In view of the differing temperature ranges of the apatite and zircon partial annealing zones (Wagner and Reimer, 1972; Hurford, 1986; Wagner *et al*., 1994), the similar ages imply very rapid cooling. Relatively large errors and high age dispersions obtained for the apatites are mainly due to the presence of inclusions and the paucity in spontaneous tracks (Adriasola *et al.*, 2006). Figure 10 shows cooling curves determined by correlation of the apatite and zircon FT ages with reported Ar/Ar cooling and magmatic intrusion ages from nearby outcrops of comparable plutonic rocks. The curves indicate cooling rates in excess of 100°C/Myr on both sides of the fault zone, taking into account the uncertainties of the different thermochronologic methods. Within the context of a magmatic arc, the high rate of cooling probably reflects hydrothermal circulation (*e.g.,* Kukowski, 1992), for which there needs to be no record in the present level of exposure, and/or a shallow depth of emplacement of the magma chamber in the upper crust.

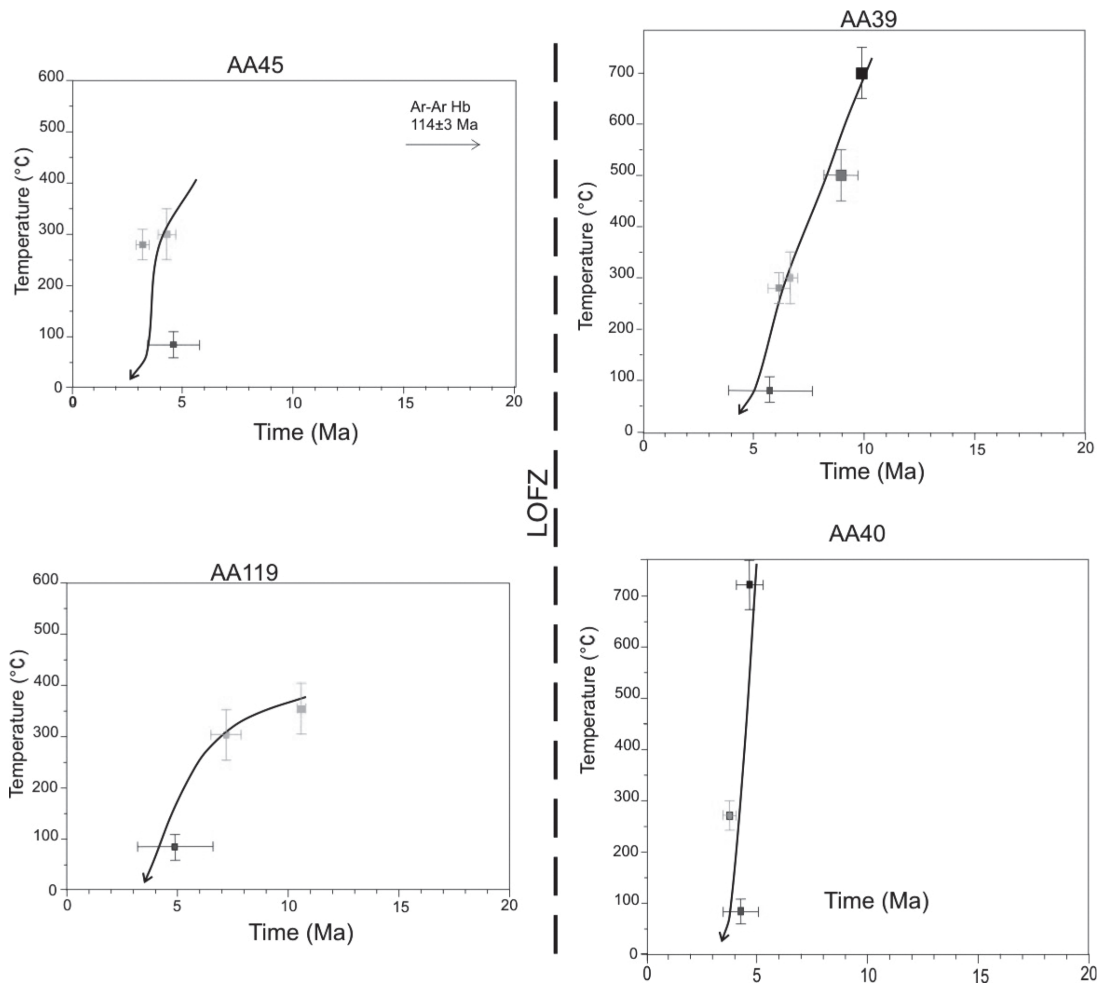

FIG. 10. Temperature-time paths of representative samples along the eastern and western blocks of the LOFZ in the Hornopirén Area. The isotopic ages are from Pankhurst *et al.* (1992), SERNAGEOMIN-BRGM (1995[1]), and Cembrano *et al.* (2000), the FT ages from Adriasola *et al.* (2006). The suggested closure temperatures are: U-Pb and Rb-Sr: ~750-650°C (magmatic emplacement); Ar/Ar muscovite: 400-300°C; K-Ar and Ar/Ar biotite: 350-300°C; zircon FT: 320-230°C; apatite FT: 120-60°C. See text for discussion.

5.3. Microfabrics in samples from the eastern block

In general agreement with previous observations from this part of the study area (Cembrano *et al*., 1996, 2000), the microfabrics of the foliated tonalites reveal solid-state deformation overprinting a previous magmatic foliation (Figs. 7, 8). The magmatic origin of the fabric (Paterson *et al*., 1989) is evident from the alignment of the feldspar crystals, surrounded by aggregates of quartz, biotite, and amphibole. The quartz domains display variable fabrics, ranging from undulatory extinction and deformation lamellae to subgrains and grain boundary migration (*e.g*., sample AA53 in figure 8). Plagioclase grains display deformation twins and kink bands, and frequently fragmentation. In places, the cracks are sealed with quartz and biotite. The magmatic biotite and amphibole crystals are often kinked and fractured, and locally replaced by fine-grained aggregates of the same minerals (Figs. 7, 8). The quartz microstructures indicate deformation at the greenschist facies conditions at temperatures of *ca*. 300° to 400°C (*e.g*., Simpson, 1985; Stöckhert *et al*., 1999).

Well-developed S-C fabrics (Lister and Snoke, 1984; Dell' Angelo and Tullis, 1989; Paterson *et al*., 1998) at the microscopic scale were observed in two samples within shear zones near Río Mariquita (samples AA117 and AA126, Figs. 8, 9). For the sake of clarity it should be noted that two distinct types of microfabrics have been referred to as S-C fabrics (Fig. 11, Lister and Snoke, 1984); the first type can alternatively be described as a shear band foliation, whereas the second type represents an oblique shape-preferred orientation (SPO). In both types of S-C fabrics, the relation between shear bands and schistosity or oblique SPO indicates the sense of shear (Lister and Snoke, 1984).

In the studied samples (AA117 and AA126, Río Mariquita, Fig. 8), the S-planes are defined by the SPO of flattened quartz grains about 0.1 mm in diameter, which is oblique to the shear bands (C-planes). In places, the shear bands anastomose around feldspar porphyroclasts. For the investigated samples, the S-C fabrics indicate a dip-slip displacement with relative upward motion of the eastern block. The orientation of sample AA117 and the thin sections together with the vector of displacement (Hoeppener, 1955) is shown in figure 9. Sections AA117X and AA117Y are cut perpendicular to the foliation plane S (oriented N340°W/58°E). Section AA117X is parallel to the strike, and AA117Y parallel to the dip of the foliation. Asides from the above-discussed magmatic lineation in the Cholgo unit, no lineation on the S or C planes was discernible in the field.

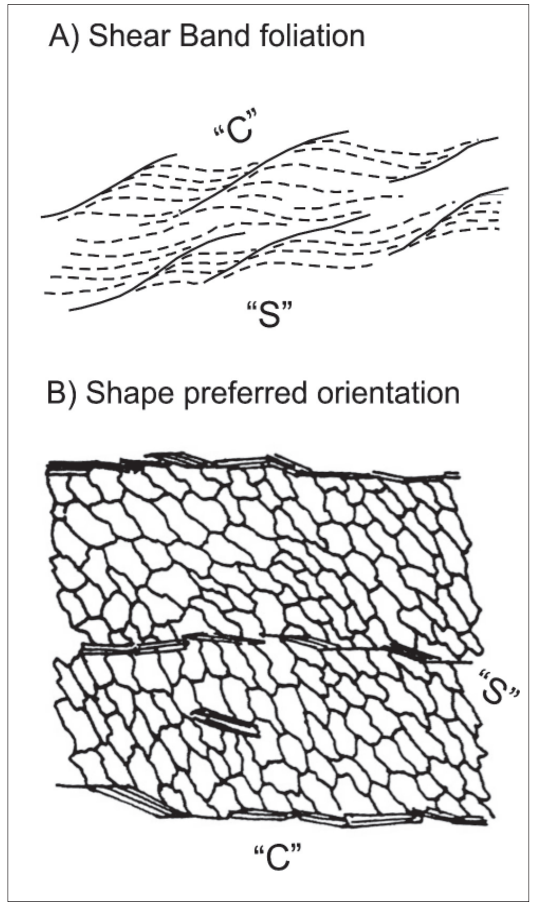

FIG. 11. Two different types of S-C fabrics (Lister and Snoke, 1984), both of which indicate the sense of shear. In both examples, the shear sense is sinistral for the observer.

5.4. Microfabrics in samples from the western block

Towards the west of the main N-S-striking strand of the LOFZ, the microstructures of the plutonic rocks indicate either some deformation at low temperatures, or only very weak deformation at all (*e.g.*, samples AA107-AA45 in figure 8). In sample AA45, the feldspars show microfractures, widespread mechanical twins and kink bands. Quartz fabrics are characterized by undulatory extinction and deformation lamellae; optically visible subgrains are locally developed. Biotites are kinked and fractured. Other samples from different parts of the western block show less deformation, except for some plagioclase with deformation twins, quartz with undulatory extinction, and biotites with some kink bands. Such microstructures are indicative of weak deformation at temperatures near or below about 300° (*e.g.,* Stöckhert *et al*., 1999).

Samples of mica schists from Llancahué Island reveal quartz layers displaying an isometric polygonal grain shape, with straight or simply curved grain boundaries (*e.g.*, samples AA119 and 109 in figure 8), indicating grain growth at very low stress and elevated temperatures (*e.g.,* Bons and Urai, 1992; Paschier and Trouw, 1996), which in this case is possibly driven by heat from an underlying intrusion. For these outcrops, muscovite and biotite Ar/Ar total fusion ages of 10.6±0.1 Ma and 7.6±0.7 Ma, respectively, have been reported by Cembrano *et al.* (2000) and interpreted as synkinematic, based on related S-C fabrics in the biotite and muscovite bearing domains, which indicate a dextral sense of shear. Similar and younger Ar/Ar and

K-Ar biotite ages, partly as young as 3.4±0.6 Ma, were also reported from weakly deformed plutons on the islands west of the LOFZ (Fig. 6, SERNAGEOMIN-BRGM, 1995[1]; Cembrano *et al.*, 2000). The younger ages were interpreted by Cembrano *et al.* (2000) as ages of deformation along the fault zone. Based on the new FT results (Adriasola *et al.,* 2006), these data could also represent cooling ages following magmatic activity that post-dated earlier deformation along the LOFZ.

5.5. Cooling Histories and Deformation

In the Hornopirén area, thermochronologic data sets on both sides of the LOFZ indicate extremely rapid cooling of the plutonic rocks between ~6 Ma and 3 Ma (Fig. 10). These extreme cooling rates reconcile with simulated time-temperature histories of shallow intrusives (Kukowski, 1992). However, cooling following shallow magmatic intrusion cannot alone explain the apatite FT data, as similar rapid cooling at temperatures below 120°C (*i.e.,* through the apatite PAZ) is also observed along the LOFZ beyond the young plutons. This indicates enhanced uplift and erosion localized along the fault zone (Thomson, 2002; Adriasola *et al*., 2006).

Contact metamorphic mineral assemblages comprising andalusite, cordierite, and sillimanite in pelitic schists and gneisses of the basement rocks of Llancahué Island are reported by Pankhurst *et al.* (1992). These assemblages indicate low-pressure conditions (similar to 2 kbar, Holdaway, 1971; Spear and Cheney, 1989), and support the inferred shallow level of emplacement for the plutons exposed on the island.

Al-in-hornblende barometry on the plutonic rocks to the east of the LOFZ yields crystallization depths of ~15 km at Cholgo and of ~8 km near Río Mariquita (Hervé *et al.*, 1996; Seifert *et al.*, 2003). In contrast, on the western side of the fault zone, the metamorphic associations in contact aureoles suggest shallower levels of intrusion for the plutons on Llancahué Island (~6 km; Pankhurst *et al.,* 1992). If the exposed plutonic rocks on both sides of the fault zone represent a single contemporaneous magma chamber, relative uplift of the eastern block is indicated by these results. This interpretation is supported by the conditions of deformation, which are observed to differ across the fault zone, with temperatures of about 300-400°C for the eastern block and only up to 300°C for the western block (Fig. 8), and by the shear sense indicated by the S-C fabrics of the deformed tonalite near Río Mariquita. In addition to the previously reported S-C fabrics indicating dextral strike slip at greenschist facies conditions in the tonalites at Cholgo (Cembrano *et al.*, 1996, 2000; López, 2001), our observations suggest that deformation here was locally partitioned during dextral displacements of the LOFZ. López (2001) analysed the age of deformation of a highly strained tonalite at Cholgo by means of the Ar/Ar stepwise heating method, using inhomogeneously deformed amphibole and recrystallized biotite. Variable individual grain ages in amphiboles and biotites with magmatic fabrics were obtained. The hornblende grains are characterized by excess Ar and geologically meaningless apparent ages, while the fine-grained biotites yielded ages as young as 3.7 Ma. Similar results on other samples of foliated tonalites exposed in places along the LOFZ are taken to indicate the age of ductile deformation in the present level of exposure along the fault zone (Cembrano *et al.,* 2000, 2002).

Considering a wider temperature range for the cooling histories in the eastern block, three possible interpretations arise:

a) The Miocene plutons with ductile shear zones from Río Mariquita and Cholgo represent deeper levels of the NPB, rapidly exhumed after emplacement. Significant denudation would then have occurred in a single event in the Late Miocene or Pliocene.

b) The sheared plutons were syntectonically emplaced at a shallow level and ductile deformation took place within the short time span of post-magmatic cooling. However, this interpretation is in conflict with the Al-in-Hornblende geobarometry results.

c) The deformed plutonic rocks were affected by later hydrothermal activity or shallow intrusions. Hot springs and small monogenetic magmatic centres are found between Llancahué Island and Río Negro supporting the presence of active hydrothermal/magmatic systems along the LOFZ in this area. If this is true, the timing of exhumation along the fault zone cannot be inferred from the thermochronometric results.

Structural information, like the continuity of the foliation of the plutons with that of the host rocks (Figs. 7, 8), the S-C fabrics (Fig. 9), and the elongated geometry of the plutons discernible on the map (Fig. 7) unfortunately do not allow to discriminate the three cases.

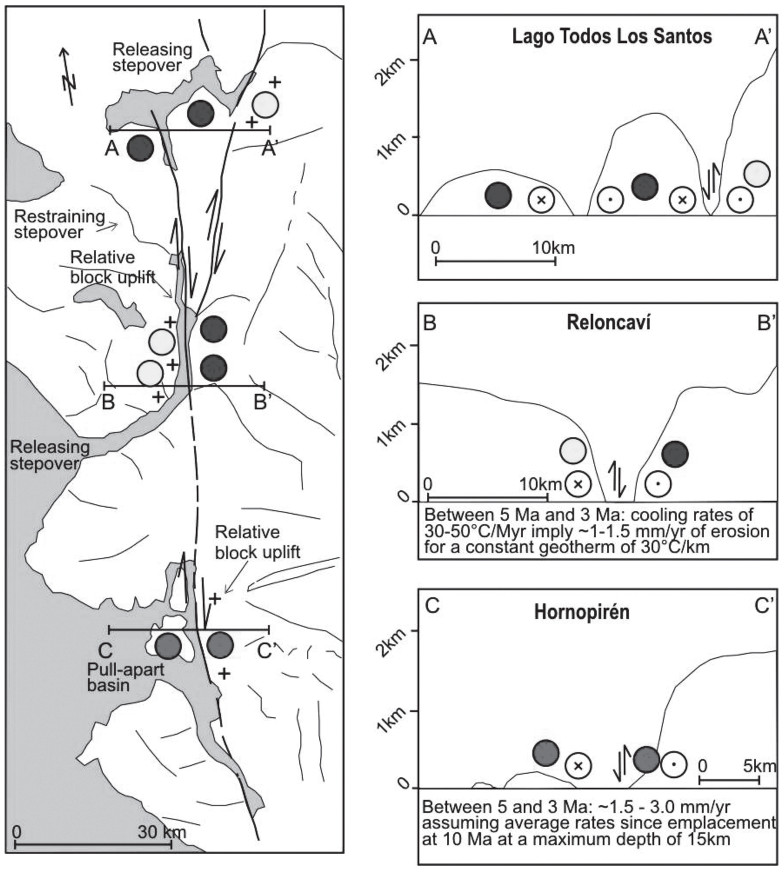

FIG. 12. Structural scheme of the LOFZ in the studied areas, with the outlined areas of major denudation in the Late Miocene-Pliocene based on new structural and geomorphologic studies (Rosenau *et al.*, 2006). Estimates of denudation rates are taken from Adriasola *et al.* (2006).

6. Discussion and Conclusions

An episodic history of pluton emplacement and deformation of the intrusive rocks of the NPB is documented in the areas of Reloncaví and Hornopirén, which comprise two contiguous segments of the LOFZ. The different styles of deformation recorded in the exposed plutons appear to be related to their cooling paths, which in turn is controlled by **1.** the poorly specified size, shape, and depth of emplacement of individual magma chambers that make up the NPB; **2.** by their position with respect to the LOFZ; **3.** the localization of deformation in shear zones on various length scales; **4.** the contemporaneous tectonic activity along the LOFZ and finally **5.** by a variable vertical post-magmatic component of displacement along the fault zone. Although the isolated outcrops sampled for fission track analysis do not allow an unequivocal interpretation, the (micro)structural record largely reconciles with the thermal and denudation histories derived from fission track thermochronometry (Adriasola *et al.,* 2006).

In the Reloncaví area, a dextral displacement of 30 km is inferred from the reconstruction of the position of Cretaceous plutons across the LOFZ, with relative uplift of the western block along the Reloncaví estuary. The contemporaneous relative uplift of the eastern block at Hornopirén could possibly be a consequence of block segmentation along releasing and restraining stepover structures (Fig. 12). Other examples of large-scale strike-slip fault systems, with block segmentation through releasing and restraining stepovers, are the San Andreas Fault (Sylvester, 1988), the Echo Hills in Southeastern Nevada (Aydn and Nur, 1985), or the Atacama Fault in northern Chile (Reijs and McClay, 1998). Well-defined 'pop-up' structures are rarely described, probably because of the complex geometries of the fault systems and because they are regions of uplift that rapidly become eroded after formation.

Within the Reloncaví area, the exhumed plutons with steady and moderate cooling rates typically record deformation at temperatures below ~300°C. Some samples of Cretaceous plutons in the area also display a record of deformation at higher temperatures, suggesting earlier tectonic activity (although not necessarily related to the LOFZ proper) at greater depth. For granite sample AA128, the high-T deformation must be older than 67±3.8 Ma, as the quartz microfabrics indicate deformation at temperatures above *ca*. 300°C, hence above the partial annealing zone for fission tracks in zircon (Stöckhert *et al.*, 1999; Brix *et al.*, 2002).

Within the Hornopirén area, significant uplift of the eastern block is indicated by the marked differences in the style and degree of deformation across the fault zone, consistent with the thermochronometric results (Adriasola *et al.*, 2006). Relative uplift of the eastern block is supported by kinematic indicators in sheared tonalites, and by geobarometric information from contact metamorphic mineral assemblages. Late Miocene-Pliocene syntectonic emplacement of plutons in the Hornopirén area may have obliterated earlier stages of deformation and intrusion along the LOFZ.

The results deviate somewhat from previous observations and interpretations for these areas. Based on Ar/Ar geochronology in plutonic rocks with ductile deformation, Cembrano *et al.* (2000, 2002) proposed that the crustal levels presently exposed along the LOFZ represent a level corresponding to the crustal brittle-ductile transition zone, with the need of significant denudation within the past ~4 Ma. It should be born in mind, however, that the past geotherm in the arc region is likely to be highly variable in time, being controlled by magmatic heat advection, convective circulation, and denudation related to topography (Kukowski, 1992; Mancktelow and Grasemann, 1997). Therefore, cooling histories cannot be directly translated into denudation histories. The observations discussed in the present study suggest that ductile deformation along the LOFZ has either occurred **1.** episodically following pluton emplacement at deeper crustal levels, possibly overprinted by later magmatic activity or **2.** that the ductile deformation occurred during post-magmatic cooling of shallow syntectonic intrusions.

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