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Orogenesis of the Patagonian Andes as reflected by basin evolution in southernmost South America

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ABSTRACT

The sedimentary succession preserved in the Patagonian Andean fold-thrust belt reflects a basin inversion: from the early extensional phase of basin evolution to the subsequent contractile phase associated with Andean orogenesis. In the latest Jurassic, extension associated with the initial break-up of southern Gondwana culminated in the development of a quasi-oceanic extensional basin referred to as the Rocas Verdes Basin. Volcanic rocks and volcaniclastic strata of the Upper Jurassic Tobífera Formation and fine-grained clastic strata of the Lower Cretaceous Zapata Formation filled this basin. Compression associated with the onset of the Andean orogeny resulted in uplift along the western basin margin and concurrent foreland subsidence. A deep-water depositional phase, possibly enhanced by flexural loading of obducted ophiolitic blocks over the attenuated crust, is marked by turbidites of the Punta Barrosa Formation. The Punta Barrosa Formation crops out along the southern Patagonian Andean belt and was derived from mixed sources, including the juvenile volcanic arc and pre-Upper Jurassic metamorphic basement complexes exposed in the Andean belt. The shale-rich Upper Cretaceous Cerro Toro Formation represents the climax of deep-water sedimentation. Provenance data indicate that the Andean arc was partially isolated by uplifted thrust sheets periodically, during which time an increased amount of detritus was derived from Paleozoic metamorphic terranes. The overlying Tres Pasos Formation represents filling of the basin with a shoaling-upward sequence, capped by the deltaic strata of the Upper Cretaceous to Early Paleocene Dorotea Formation. The increased amount of volcanic lithics in the Tres Pasos and Dorotea formations highlight the introduction of an additional volcanic-arc source terrane.

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Apatite (U-Th)/He ages distributed in the Upper Cretaceous to Lower Tertiary Magallanes foreland basin deposits indicate Late Miocene (10-5 Ma) regional exhumation through shallow crustal temperatures < ~40°C along the eastern edge of the southern Patagonian fold-thrust belt. Accelerated Miocene exhumation may be attributed to a variety of events, including thrust-related unroofing and erosional denudation.

LATE JURASSIC RIFTING AND BACKARC BASIN DEVELOPMENT (ROCAS VERDES BASIN)

The Mesozoic-Cenozoic orogenic cycle in the southern Patagonian Andes was initiated during an extensional phase associated with the breakup of Gondwana in the Middle to Late Jurassic (Bruhn et al., 1978; Gust et al., 1985; Pankhurst et al., 2000; Fildani and Hessler, 2005; Calderón et al., 2007; Fig. 1). The sedimentary sequence preserved in the Andean fold-thrust belt reflects both the early extensional phase of basin evolution and the subsequent contractile foreland basin phase associated with Andean orogenesis. In the latest Jurassic, extension associated with the initial breakup of southern Gondwana (Bruhn, et al., 1978; Gust, et al., 1985; Pankurst, et al., 2000) culminated in the development of the Rocas Verdes Basin (Katz, 1963; Dalziel and Cortés, 1972; Dalziel et al., 1974; Suárez, 1979; Dalziel, 1981). The initial continental rift basin evolved into a backarc basin floored by quasi-oceanic crust represented by the Sarmiento and Tortuga ophiolites, which have oceanic ridge basalt affinities (Fig. 2; Allen, 1982, 1983; Stern, 1980; Alabaster and Storey, 1990). Ophiolitic rocks exposed in the Cordillera Sarmiento (Sarmiento Complex) represent the northernmost obducted remains of the floor of this backarc basin, and constitute, together with the Tobífera and Zapata formations, the main tectono-stratigraphic units of the northern remnant of the Rocas Verdes Basin (Figs. 1 and 3; Calderón et al, 2007, and references therein). U-Pb ages from Calderón et al. (2007) suggest that the rifting phase of the Rocas Verdes Basin occurred between 152 and 142 Ma and was associated with bimodal volcanism. The Tobífera Formation is a volcanic-sedimentary succession that unconformably overlies the Paleozoic metamorphic complexes of the crystalline basement (Allen, 1982; Wilson, 1991; Fildani and Hessler, 2005; Calderón et al., 2007). The succession is composed of silicic pyroclastic rocks (mostly tuffaceous deposits) with interbedded black shale, calcareous layers, and contemporaneous shallow silicic intrusions. Samples from the Sarmiento Ophiolite Complex yielded an age of ~150 Ma, whereas two samples of silicic pyroclastic rocks of the Tobífera Formation are 148 and 142 Ma, indicating contemporaneous bimodal volcanism (Calderón et al., 2007). Field mapping identified pillow basalts of the Sarmiento Ophiolite interbedded with tuffaceous beds interpreted as Tobífera Formation (Fildani and Hessler, 2005; Calderón et al., 2007).

To the east, the Tobifera Formation overlies and fills structurally-partitioned, attenuated continental crust. In the Ultima Esperanza District (Fig. 3), the Tobífera Formation is overlain by the shale-dominated Zapata Formation (Lower Cretaceous), which filled the structurally-partitioned Rocas Verdes Basin with a thick drape (>600 m) of shale (with local accumulation of siltstone, marly shale, and fine sandstone) (Wilson, 1991; Fildani and Hessler, 2005). These sediments were mainly derived from local basement uplifts with additional contribution from a juvenile volcanic arc to the west (Fildani and Hessler, 2005). Recent work suggests that the development of a juvenile arc batholith was coeval with the latest Jurassic rhyolitic volcanism represented by the Tobífera Formation (Hérve et al., 2007).

In Tierra del Fuego the basin fill overlies the Tortuga Ophiolite and consists of the Upper Jurassic and Lower Cretaceous volcaniclastic sedimentary rocks (Yahgan Formation), primarily derived from the nascent arc to the west (Fig. 2; Kranck, 1932; Katz and Watters, 1966; Suárez and Pettigrew, 1976; Winn and Dott, 1979). Suárez and Pettigrew (1976) suggested that the Yahgan Formation further south is potentially coeval with the Zapata Formation of the Ultima Esperanza District (Fildani and Hessler, 2005). The northern limit of the Rocas Verdes Basin is interpreted to extend to approximately 51°S, and the basin widened southward (Dalziel and Cortés, 1972; Calderón et al., 2007).

LATE CRETACEOUS MAGALLANES FORELAND BASIN

The transition from the Late Jurassic-Early Cretaceous extensional Rocas Verdes backarc basin (Tobífera and Zapata formations) to the Cretaceous contractile Magallanes retroarc foreland basin was generally coincident with faster spreading rates of the South Atlantic Ocean and increased subduction along the Pacific margin (Rabinowitz and La Brecque, 1979; Dalziel, 1986; Ramos, 1988). The spreading rates along the Pacific ridges accelerated in the Neocomian (Bartolini and Larson, 2001) and, combined with increased activity of the Atlantic ridges, possibly caused the early Rocas Verdes Basin to evolve into a closing backarc basin (cf., Sea of Japan) in the Early Cretaceous (Fildani and Hessler, 2005). Crustal shortening led to the ultimate closure of the Rocas Verdes Basin, development of the Andean fold-thrust belt, and associated foreland subsidence eastward of the active volcanic arc (Suárez and Pettigrew, 1976; Wilson, 1991; Fildani and Hessler, 2005). Although detailed paleogeographic reconstructions of the Rocas Verdes Basin are hindered by structural overprinting as a result of fold-thrust belt shortening (Suárez and Pettigrew, 1976; Wilson, 1991; Fildani and

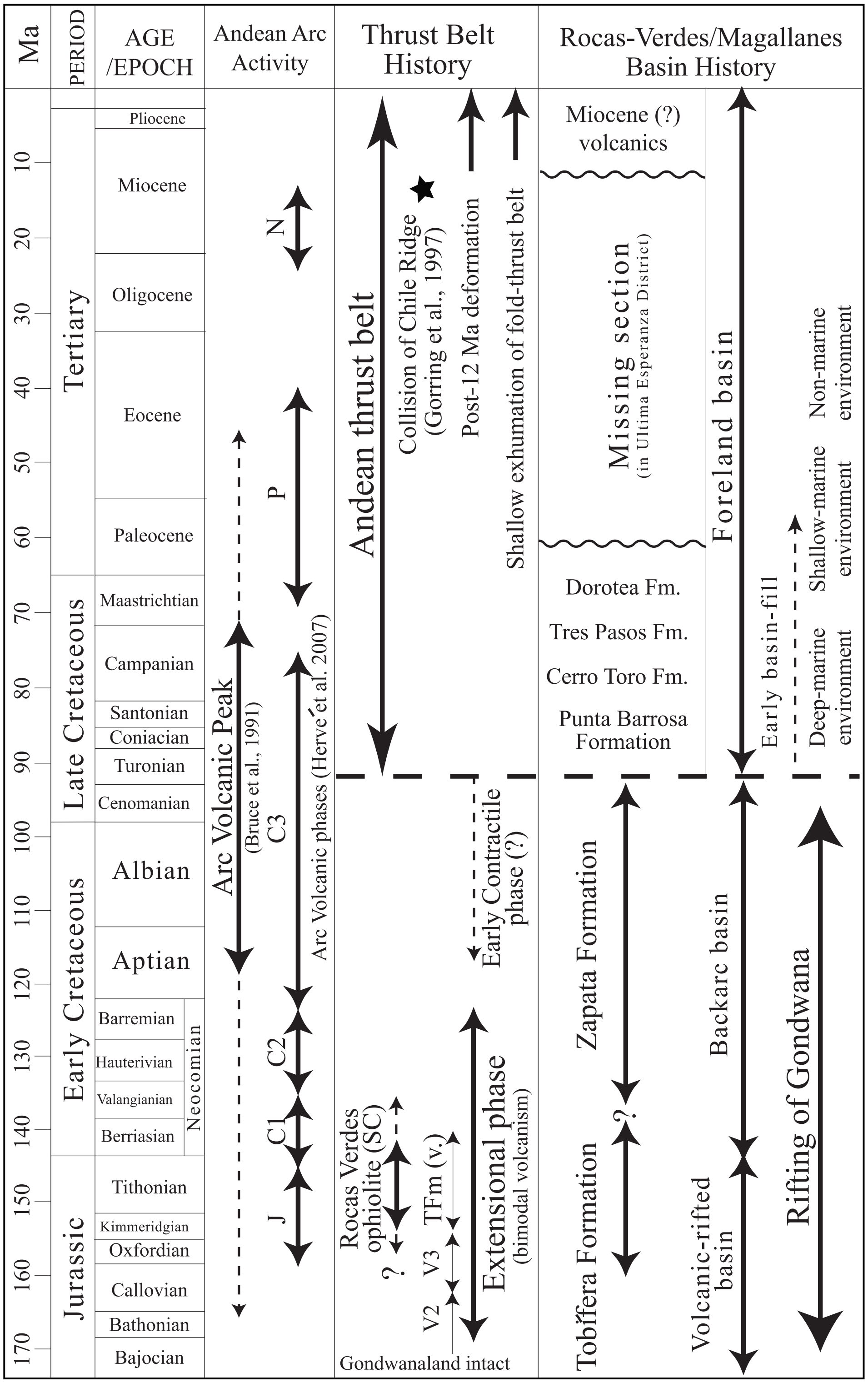

Figure 1. Summary diagram for the main tectonic events of southern South America reporting details of basin transition from backarc (Rocas Verdes Basin) to foreland (Magallanes Basin) (Fildani et al., 2003; Fildani and Hessler, 2005), tectonic setting of Gondwana margin, and onset of Patagonian Andean uplift. V2 and V3 – peak volcanic activity for early Gondwana extension (reported from Punkhurst et al., 2000). Tobifera Formation and Sarmiento Complex ages from Calderón et al. (2007). Arc plutonic peak activity is from Bruce et al. (1991). Volcanic phases from Patagonian Batholiths (J, C1, C2, C3, P, N) are from Hervé et al. (2007). The Chile Ridge collided with the South American place ca. 14-13 Ma at the latitude of the Ultima Esperanza District (Gorring et al., 1997). The timing of post-12 Ma shortening in the fold-thrust belt is based on the broad folding of Miocene and Pliocene volcanic rocks in the eastern exposures of the fold-thrust belt (Ramos, 2005). Additional age constraints of the Torres del Paine intrusive complex (Halpern, 1973; Michael, 1983; and Michel et al., 2007) define the minimum age of the pre-intrusion fabric in the Upper Cretaceous sedimentary rocks (e.g., Skarmeta and Castelli, 1997). Low-temperature thermochronology suggests Late Miocene exhumation of the fold-thrust belt (Fosdick et al., 2006). Diagram modified from Fildani et al., (2003).

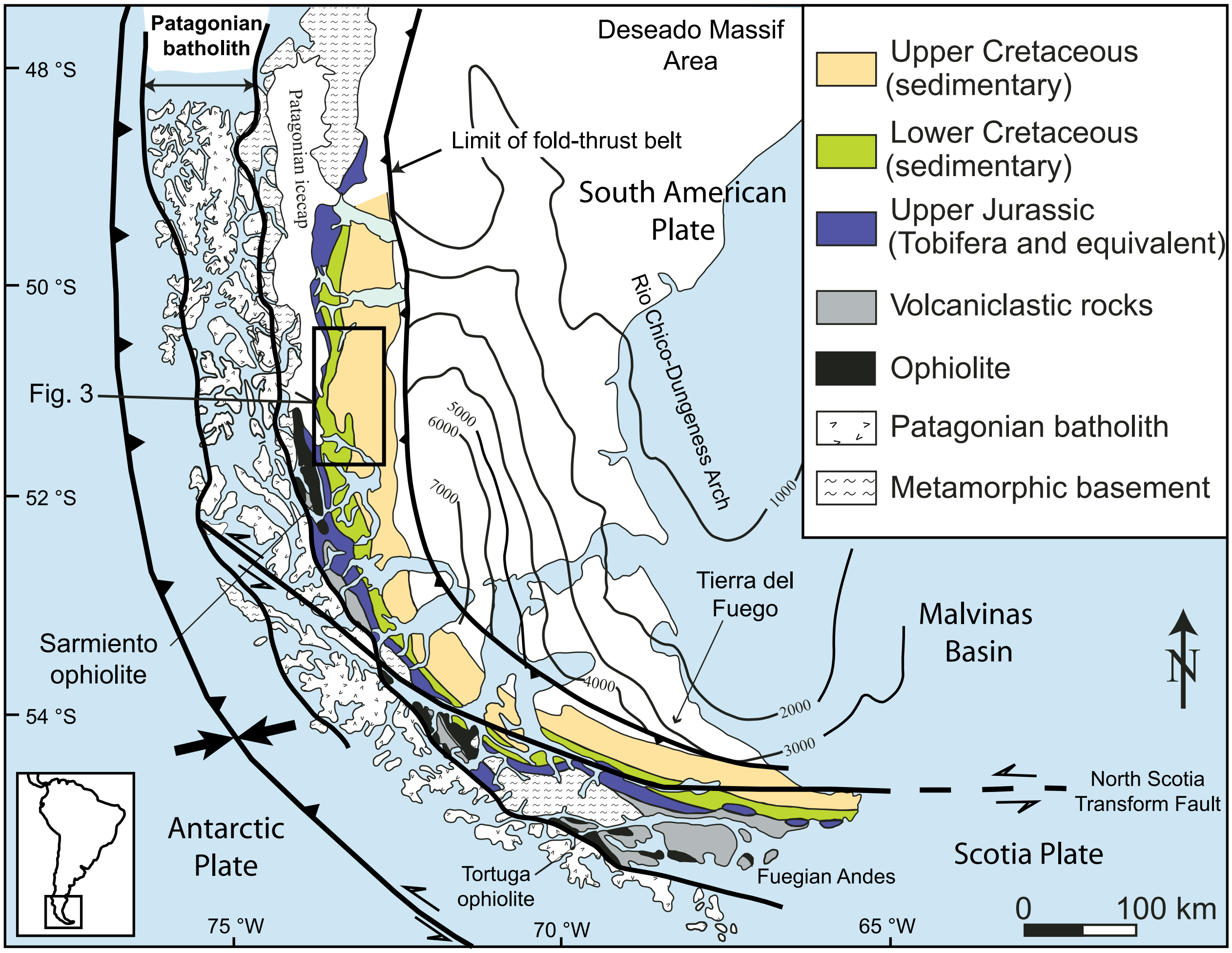

Figure 2. Simplified tectonic map of South America adapted from Fildani and Hessler (2005) (compiled and modified after Wilson, 1991, and Thomson et al., 2001). Basin structure contours, after Fildani and Hessler (2005), define the top of the Jurassic volcanic rocks (from Biddle et al., 1986, integrated with Galeazzi, 1998). Box shows location of study area in Figure 3 (Ultima Esperanza District).

Hessler, 2005), previous work has shown that basin geometry during the backarc phase had a significant influence on sediment distribution and dispersal patterns during the succeeding foreland basin phase (Wilson, 1991; Fildani and Hessler, 2005; Crane and Lowe, 2008; Hubbard et al., 2008).

Fildani and Hessler (2005) hypothesized that initial inversion of the Rocas Verdes Basin occurred during deposition of the upper Zapata Formation, and that a well-established compressional phase was coincident with deposition of turbidites of the overlying Upper Cretaceous Punta Barrosa Formation (Wilson, 1991; Fildani et al., 2003; Fildani and Hessler, 2005). This formation marks the onset of coarse-grained sedimentation, related to encroaching foreland fold-thrust belt activity in the Ultima Esperanza District (Fig. 3), at ~92 Ma (Fildani, et al., 2003). The Punta Barrosa Formation was derived from mixed sources including the juvenile volcanic arc and metamorphic basement complexes exposed during early uplift in the Andean belt (Fildani and Hessler, 2005).

The deep-water conglomeratic Cerro Toro Formation and overlying slope and deltaic systems of the Tres Pasos and Dorotea formations record persistent subsidence coupled with sedimentation resulting from denudation of an active arc and fold-thrust belt during the Late Cretaceous (Katz, 1963; Scott, 1966; Natland, 1974; Biddle et al., 1986; Wilson, 1991; Fildani and Hessler, 2005; Romans, 2008). The Upper Cretaceous Cerro Toro Formation represents the climax of deep-water sedimentation in the Magallanes Basin and was deposited at depths up to 2000 m (Natland et al., 1974). Conglomerate-filled channel systems developed along much of the length of the axial foredeep (Winn and Dott, 1979; Hubbard et al., 2008), punctuating the shale-dominated succession. The entire thickness of the formation ranges from ~1000 m in a proximal setting (Crane, 2004) to ~2500 m in more distal stretches of the axial channel belt (Hubbard, 2006) Petrographic data from the Cerro Toro Formation sampled at the Silla Syncline (terminology of Crane and Lowe, 2008) suggests that the western margin of the basin in the north could have been progressively isolated from the Andean arc by uplifted thrust sheets, and that much of the sediment was derived from Paleozoic terranes along the Andean front (Crane and Lowe, 2008).

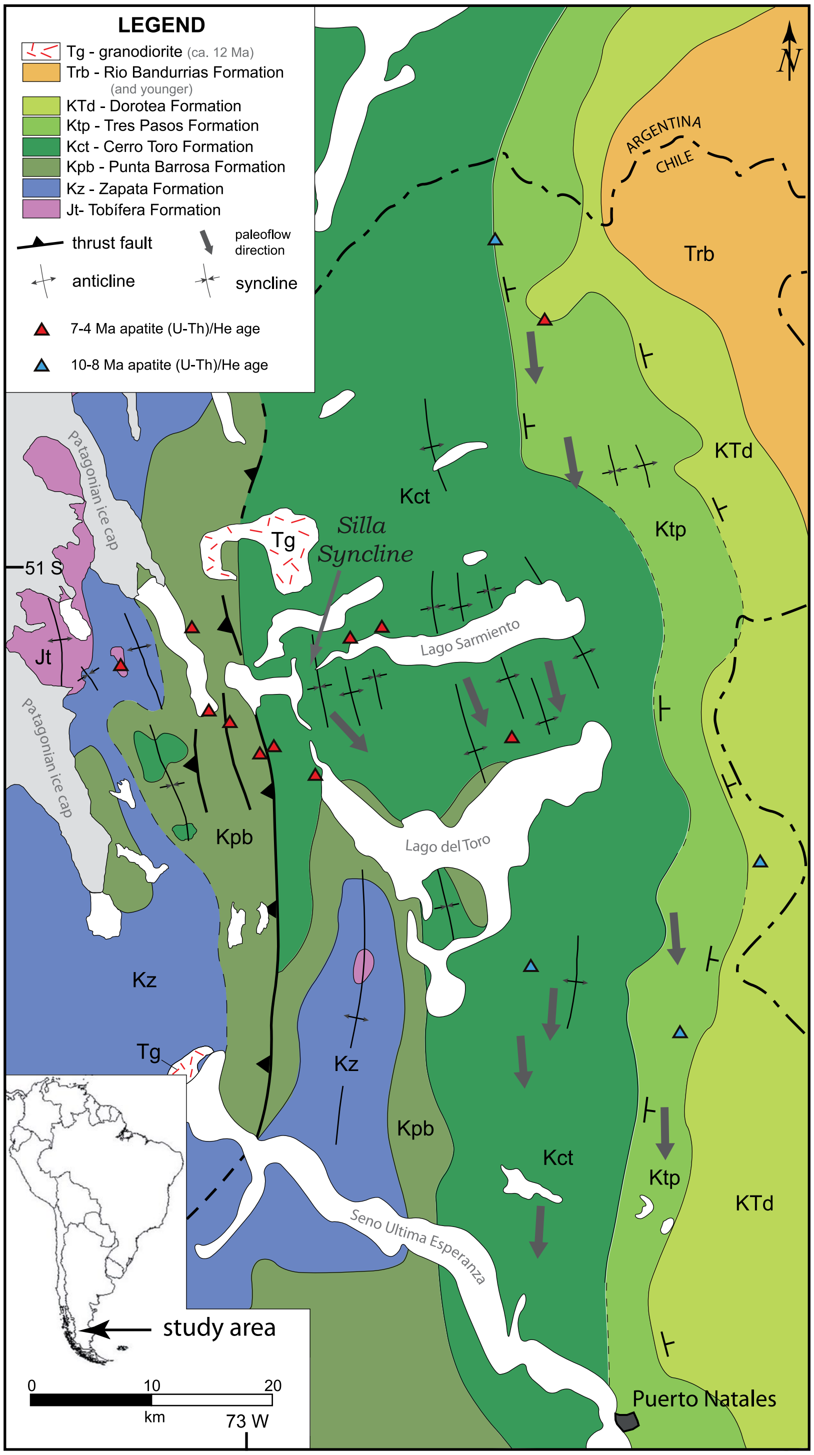

Figure 3. Generalized geologic map of the Ultima Esperanza District showing the distribution of Jurassic through Lower Cretaceous rocks of the Rocas Verdes Basin and volcanic and Upper Cretaceous Magallanes foreland basin deposits (geology modified from Wilson (1983), Altenberger et al. (2003), and Fildani and Hessler (2005), with additional mapping by the authors). Sample locations are shown for all petrographic, geochemical, and thermochronologic analyses.

The overlying Tres Pasos Formation, deposited during the Late Cretaceous, represents shoaling upward in the Magallanes Basin (Smith, 1977; Wilson, 1991; Shultz et al., 2005). The Tres Pasos Formation preserves a well-developed slope succession dominated in its lower part by mudstone-rich mass wasting deposits punctuated by lenticular sandstone successions (Shultz et al., 2005) and shallows upward into the overlying deltaic and shallow-marine deposits of the Dorotea Formation. Ultimately, the deltaic systems of the Dorotea Formation and linked slope systems recorded in deposits of the Tres Pasos Formation prograded southward, filling the foredeep during the latest Cretaceous (Romans, 2008).

Paleocurrent data for the Punta Barrosa, Cerro Toro, and Tres Pasos formations indicate south to southeast sediment dispersal (i.e., parallel to trend of fold-thrust belt), reflecting foreland subsidence patterns (Scott, 1966; Smith, 1977; Winn and Dott, 1979; Fildani and Hessler, 2005; Shultz et al., 2005; Crane and Lowe, 2008; Hubbard et al., 2008; Romans, 2008).

Modal results for sandstone composition of the Punta Barrosa, Cerro Toro and Tres Pasos formations are normalized and compared on quartz-feldspar-lithic (QFL and QmFLt) ternary plots with tectonic fields from Dickinson (1985) (Fig. 4). The mean composition of the Punta Barrosa Formation sandstone is within the recycled orogen field with few samples located in the dissected arc field. Fildani and Hessler (2005), using different provenance tools, concluded that the Punta Barrosa Formation was derived from mixed sources including the juvenile volcanic arc and metamorphic basement complexes exposed during early uplift of the Andean belt (Figs. 2 and 3). The Cerro Toro petrographic and geochemical data are restricted to samples from the outcrops of the Silla Syncline (Fig. 3; Crane, 2004). Here, modal sandstone-composition determinations place the Cerro Toro Formation distinctly within the recycled orogen domain of Dickinson (1985). Sandstones of the Tres Pasos and Dorotea formations are classified as feldspathic litharenites (cf., Folk, 1980) (Romans, 2008). The mean composition is within the transitional arc field in both quartz-feldspar-lithics (QFL) and monocrystalline quartz-feldspar-total lithics (QmFLt) plots (Fig. 4). Petrographic analyses by Smith (1977) are slightly more quartz-rich and plot in the dissected arc to mixed fields of the QFL diagram.

The Cerro Toro Formation recycled orogen domain differs strikingly from the other formations characterized within the arc domains (Fig. 4).

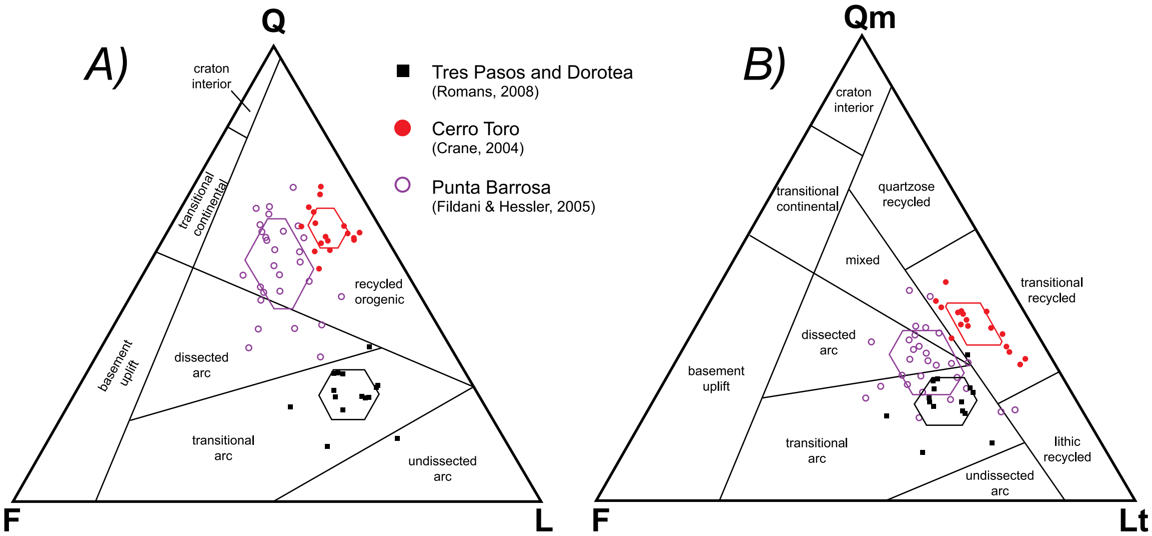

Figure 4. (A) quartz-feldspar-lithics (QFL) and (B) monocrystalline quartz-feldspar-total lithics (QmFLt) ternary plots for Magallanes Basin sandstones. Tres Pasos and Dorotea sandstones from this study; Punta Barrosa Formation from Fildani and Hessler (2005); Cerro Toro Formation from Crane (2004). Tectonic fields from Dickinson (1985). Polygons represent 1σ range for each of the three variables.

Crane (2004) concluded that the Cerro Toro Formation at the Silla Syncline represents a diminished arc source and enhanced metamorphic source relative to the underlying Punta Barrosa Formation.

Petrographic data from the main axial conglomerate belt of the Cerro Torro (Valenzuela, 2006) plots more similarly to the Punta Barrosa, Tres Pasos, and Dorotea sandstones shown in Figure 4. Detailed work on the conglomerates reported predominantly felsic, mostly porphorytic rhyolites, diorites, and granitoid clasts; less common are basalts, gabbros, quartz-arenites, radiolarian cherts, schists, and rare mylonites (Valenzuela, 2006). Valenzuela (2006) suggested the Tobífera Formation, the Patagonian batholith, the Sarmiento ophiolite, and the metamorphic basement as the possible source terranes. These results reinforce the hypothesis that provenance difference for the Cerro Toro Formation could very well be a function of paleogeography. The Silla Syncline may represent a tributary to the main axial channel belt tapping into a local drainage partially isolated from arc sources, while the axial belt of the Cerro Toro Formation received detritus from a more connected and extensive dispersal system. This hypothesis has been proposed by previous workers (e.g., Crane and Lowe, 2008; Hubbard et al., 2008). The increased amount of volcanic and volcaniclastic lithics in the Tres Pasos and Dorotea formations relative to underlying formations (Fig. 4) is consistent with the introduction of an additional volcanic source terrane.

Shale rare-earth-element (REE) abundances generally provide the best average-provenance indicators (McLennan, 1989; McLennan et al., 1993). REE have long been considered appropriate provenance indicators because of their tendency to be transferred almost completely from weathered parent rocks to sedimentary systems (McLennan, 1989; McLennan et al., 1993; and references herein). Shales from the Rocas Verdes Basin (Zapata Formation) have REE signatures that are significantly less fractionated than those from the foreland basin units (Punta Barrosa, Cerro Toro, and Tres Pasos formations) (Fig. 5). The Tres Pasos Formation shale REE patterns reflect a similar mass fractionation as the underlying Punta Barrosa Formation and Cerro Toro Formation shales (Fig. 5; Fildani and Hessler, 2005; Crane, 2004). In general, these REE patterns indicate that the source area for the foreland basin shales is less mafic than for the predecessor backarc basin Zapata Formation (Fildani and Hessler, 2005).

TIMING AND STYLE OF DEFORMATION IN THE MAGALLANES BASIN

Deposition in the Magallanes foreland basin was concurrent with Late Cretaceous through Tertiary regional shortening and cratonward (eastward) migration of the fold-thrust belt (Biddle et al., 1986; Wilson, 1991; Ramos, 1989; Coutand et al., 1999; Ghiglione and Ramos, 2005). The dissected Upper Cretaceous and Tertiary strata were uplifted and exposed in their present position along the sub-Andean fold-thrust belt (Figs. 2 and 3). Although a precise history of this deformation is still unclear in the Ultima Esperanza region, at least three distinct phases of contractile deformation have occurred in the Magallanes Basin and are broadly categorized here as Late Cretaceous, Oligocene, and post-Miocene episodes (e.g., Coutand et al., 1999; Suárez et al., 2000; Altenberger et al., 2003; Ghiglione and Ramos, 2005; Radic et al., 2007). In the southernmost Fuegian Andes (Fig. 2), perhaps up to 300-600 km of orogenic shortening has taken place (Winslow, 1982; Kraemer, 2003), in contrast to substantially less crustal short-

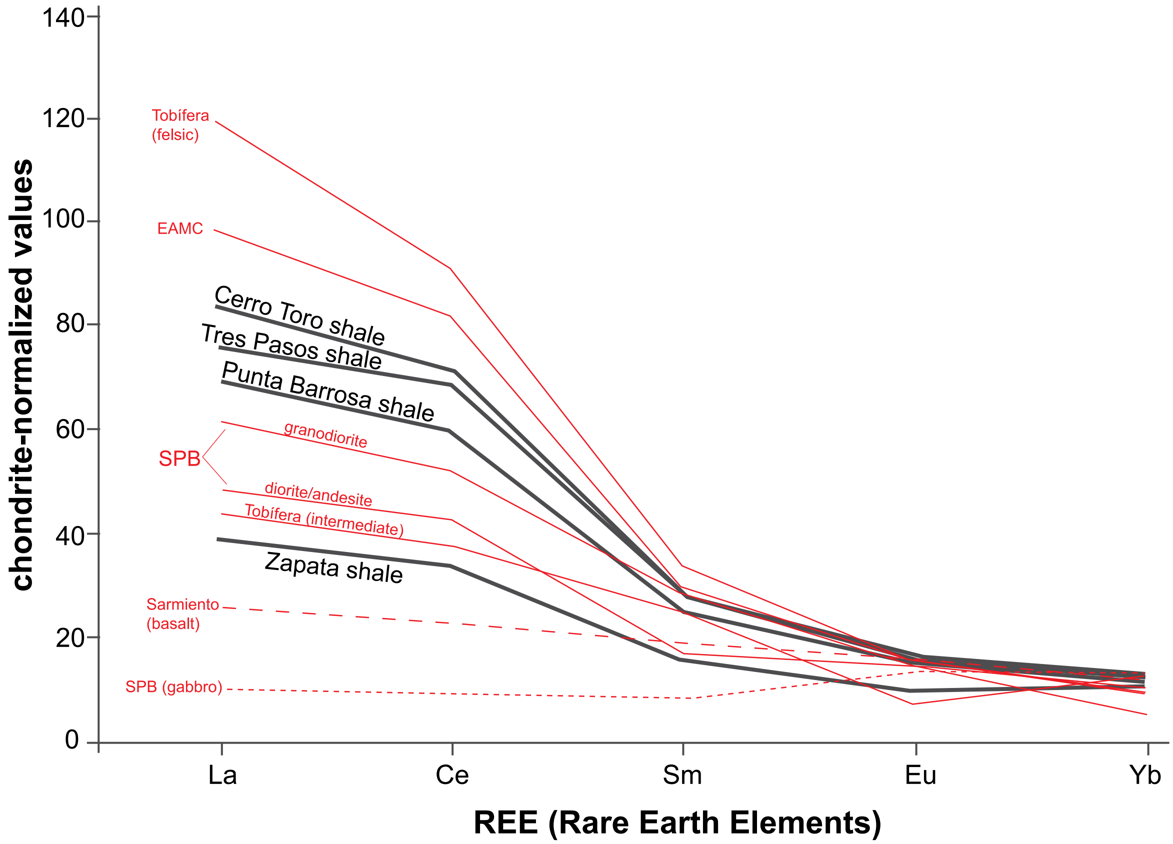

Figure 5. Abundances of selected rare-earth elements (REE) in Magallanes Basin shale, comparing Zapata and Punta Barrosa formations (data from Fildani and Hessler, 2005), Cerro Toro Formation (data from Crane, 2004), and Tres Pasos Formation (this study) versus possible source terranes from the Andean Cordillera. Source terrane data from Fildani and Hessler (2005). Y-axis represents chondrite normalized values from Boynton (1984).

ening in the Ultima Esperanza District (Mpodozis, 2006). Furthermore, major plate reorganization in the Tertiary has contributed to a complex distribution of spatially and temporally variable deformation along this sector of the Patagonian Andes (Cande and Leslie, 1986; Cunningham, 1993; Gorring et al., 1997; Ghiglione and Ramos, 2005; Fig. 2).

In the Ultima Esperanza District, the fold-thrust belt consists of several structural domains with contrasting styles of crustal shortening (Wilson, 1991; Fildani and Hessler, 2005; Calderón et al., 2007). In the westernmost exposures (Fig. 3), the Tobífera and Zapata formations are broadly folded and faulted along steep reverse faults. Farther east, compressional deformation of the foreland basin deposits is characterized by intense folding and thrust faulting in the Upper Cretaceous Punta Barrosa and lowermost Cerro Toro formations (Wilson, 1983; Fildani and Hessler, 2005; Fig. 3), in addition to the development of a regional cleavage across all of the uppermost Cretaceous foreland basin strata (e.g., Wilson, 1983). Farther east and distal to the main fold-thrust belt, the upper Cerro Toro and overlying foreland basin formations lack this metamorphic overprint and high degree of deformation and instead exhibit broad folding (Wilson, 1983; Fig. 3). In their easternmost exposures, the Tres Pasos and Dorotea formations dip gently eastward into the subsurface along a north-south trending homocline that extends beneath the undeformed foreland basin system (Katz, 1963; Wilson, 1991; Fildani and Hessler, 2005; Shultz et al., 2005; Fig. 3). Seismic-reflection imaging suggests deep-seated thrust faults may be responsible for the regional uplift of the fold-thrust belt (Soffia et al., 1988; Mpodozis, 2007); however, both the timing and significance of these structures are ambiguous.

Late Paleocene-Early Eocene deformation in the orogen and uplift of the Cretaceous basin is inferred from an erosional unconformity spanning 15 m.y. in the Tertiary foreland basin deposits exposed near the Chile-Argentina border (Malumián et al., 2001). Subsequent Eocene to early Oligocene synorogenic deposition documents eastward propagation of the thrust-front, consistent with the prevailing view of progressive deformation of the foreland basin (e.g., DeCelles and Giles, 1996). Geochronologic data from cross-cutting intrusions provide additional constraints on the timing of deformation in the foreland basin. Altenberger et al. (2003) document a folded 29 Ma gabbroic dike within the tightly folded Punta Barrosa Formation that yields a maximum age of this deformational event. However, it is unclear how much folding and thrust-faulting occurred in the sedimentary succession prior to 29 Ma. Intrusion of the Torres del Paine intrusive complex ca. 13-12 Ma (Halpern, 1973; Michael, 1983; Michel et al., 2007; Fig. 3) clearly postdates the development of the regional foliation and tight folding within the Punta Barrosa and Cerro Toro formations (e.g., Skarmeta and Castelli, 1999), and indicates a hiatus of regional deformation during local magmatic emplacement (Michel et al., 2007). Post-Miocene shortening at this latitude resulted in broad folds and uplift of the eastern margin of the Magallanes Basin, where the overlying Miocene (?) volcanic rocks (Ramos, 1989) of the Sierra de los Baguales have been uplifted and tilted eastward toward the craton (Wilson, 1983; Ramos, 2005).

EXHUMATION OF THE SUB-ANDEAN FOLD-THRUST BELT

Low-temperature thermochronologic dating of Upper Jurassic to Upper Cretaceous strata from the Rocas Verdes and Magallanes basins constrains the recent thermal evolution of the fold-thrust belt through shallow crustal temperatures (closure temperature (Tc) of ~70°C, after Zeitler et al., 1987; Wolf et al., 1996; Farley, 2002). Preliminary apatite (U-Th)/He cooling ages from the Upper Cretaceous Magallanes foreland basin deposits range from ca. 10-4 Ma and are significantly younger than their depositional ages (Fig. 1; Fosdick and Fildani, 2007), indicating that they were subsequently heated to temperatures above the apatite helium partial retention zone (T > 80-40°C) (cf., Farley, 2002). Judging by the total basin thickness (>5 km), most samples were heated to even higher temperatures as a result of depositional burial and tectonic loading by thrust sheets (Fosdick and Fildani, 2007).

In general, the apatite (U-Th)/He data from the Ultima Esperanza District suggest regional exhumation of the Magallanes Basin and fold-thrust belt ca. 10-4 Ma (Figs. 1 and 3). North of this study area, between 44 and 51°S (Fig. 2), fission-track dating in the Patagonian batholith documents accelerated cooling and denudation ca. 30-23 Ma, followed by a 200 km eastward migration of the locus of maximum denudation until 12-8 Ma (Thomson et al., 2001). Thermochronologic findings in the Magallanes Basin are consistent with the general denudation patterns suggested by these fission track studies and document even younger exhumation farther east in the sub-Andean fold-thrust belt (ca. 6-4 Ma) (Fig. 3; Fosdick et al., 2006; Fosdick and Fildani, 2007).

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