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Along-strike variability of back-arc basin collapse and the initiation of sedimentation in the Magallanes foreland basin, southernmost Andes (53–54.5°S)

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[1] The Patagonian Andes record the Cretaceous demise of the quasi-oceanic Rocas Verdes back-arc basin and formation of the Magallanes foreland basin. For >500 km along the strike of the mountains, this tectonic transition is marked by a sandstone-mudstone package that records the beginning of turbiditic sand deposition and fan growth. Sandstone modal analyses and U-Pb detrital zircon spectra show changes in rock composition and provenance across the transition on a basin-wide scale, indicating it has tectonic significance and is related to orogenic uplift and the progressive evolution of the Andean fold-thrust belt. Spatial variations in transition zone characteristics indicate the foreland basin's central and southern sectors were fed by different sources and probably record separate fans. At Bahía Brookes, on Tierra del Fuego, foreland basin sedimentation began at least after 88–89 Ma, and possibly after ~85 Ma, several million years after it did ~700 km away at the northern end of the basin. This event coincided with increased arc volcanism and the partial obduction of the basaltic Rocas Verdes basin floor onto continental crust. By 81–80 Ma, conglomerate deposition and increased compositional and provenance complexity, including the abundance of metamorphic lithic fragments, indicate that the obducted basaltic floor first became emergent and was eroding. The results suggest that the beginning of turbidite sedimentation in the Magallanes foreland basin and the progressive incorporation and exhumation of deeply buried rocks in the Andean fold-thrust belt, occurred later in southern Patagonia than in the north by a few million years.

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1. Introduction

[2] This paper presents the results of a chronostratigraphic and provenance study of rock successions that record the closure and tectonic inversion of an extensional back-arc basin and the formation of a successor foreland basin in the Patagonian Andes (Figure 1). During the mid-Late Jurassic, extension formed the Rocas Verdes back-arc basin [*Pankhurst et al.*, 2000; *Fildani and Hessler*, 2005; *Calderón et al.*, 2007], which was floored by basaltic crust with midocean ridge affinities [*Dalziel et al.*, 1974; *Stern*, 1980; *Allen*, 1982] and filled with up to 4 km of mud-dominated marine sediment [*Dott et al.*, 1982; *Wilson*, 1991; *Fildani and Hessler*, 2005]. By the end of the Early Cretaceous the back-arc basin was in compression and closing, and the Magallanes fold-thrust belt first began to form [*Fildani and Hessler*, 2005; *Fosdick et al.*, 2011]. By ~92 Ma, a few million years after shortening began, turbidite sedimentation in the Magallanes foreland basin (Figure 1) had initiated [*Fildani et al.*, 2003]. Here, we report on the timing, paleogeography, and stratigraphic evolution of this transition in three areas of southernmost Chile: Seno Otway, Peninsula Brunswick, and Bahía Brookes (Figures 2 and 3). These sites allowed us to evaluate spatial variations in the composition, provenance, and age of Magallanes foreland basin sediments, and in the kinematic history of the Magallanes fold-thrust belt (Figure 1) for >500 km along the strike of the orogen.

[3] Historically, little detailed information has been collected from the three study areas because access is difficult, their structure is complex, and because the strata, which are dominated by mudstone, are difficult to separate in the field. Most of what we know about sediment dispersal patterns and depositional environments in the early Magallanes basin, and its links to hinterland uplift, has been derived from exposures in Ultima Esperanza (UE, Figure 1) at the

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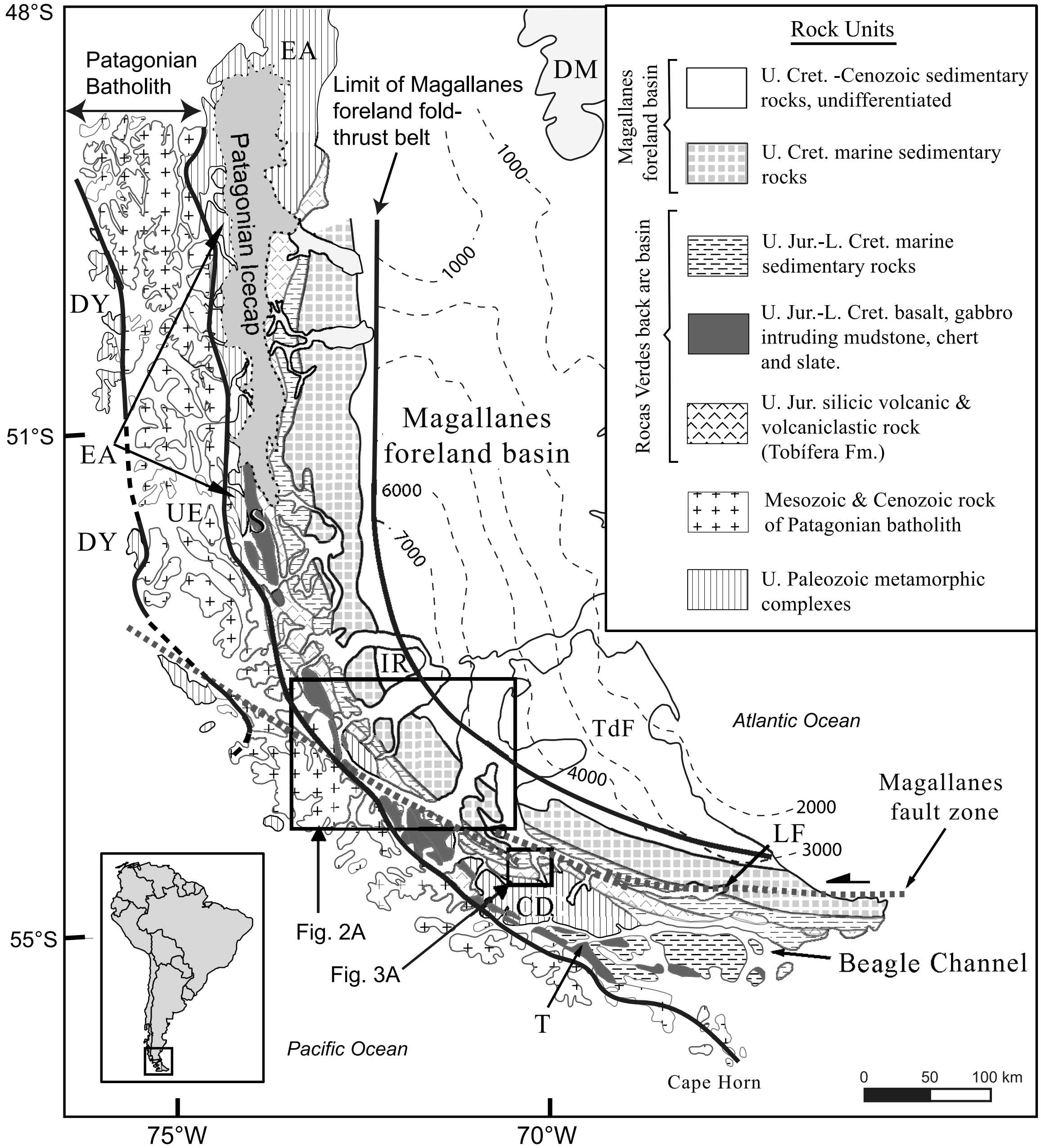

Figure 1. Simplified map of the southernmost Andes showing tectonostratigraphic provinces, modified from *Fildani and Hessler* [2005]. Contours (thin dashed lines) show thickness of sediment on top of Jurassic volcanic rocks (in meters) after *Biddle et al.* [1986]. Metamorphic complexes include Cordillera Darwin (CD), Duque de York (DY), the Deseado Massif (DM), and the Eastern Andean metamorphic complex (EA). Ophiolitic suites include the Sarmiento (S) and Tortuga (T) complexes. UE, Ultima Esperanza; IR, Isla Riesco; TdF, Tierra del Fuego; LF, Lago Fagnano.

northern end of the basin (51.5°S) [*Wilson*, 1991; *Fildani and Hessler*, 2005; *Calderón et al.*, 2007; *Romans et al.*, 2011; *Fosdick et al.*, 2011] and in Argentina at its southeastern end (54.5°S) [*Olivero and Martinioni*, 2001; *Olivero and Malumián*, 2008]. The paucity of data from the central sectors has hindered efforts to evaluate spatial and temporal trends in basin evolution.

[4] To help remedy this problem, we report field observations, petrographic data, sandstone modal analyses, Rare Earth Element (REE) geochemistry of mudstones, and U-Pb detrital zircon geochronology from Seno Otway (Figure 2) to Tierra del Fuego (Figure 3) for the following purposes: (1) to determine spatial and temporal trends in rock composition and provenance during the transition from Rocas Verdes back-arc basin to Magallanes foreland basin (2) to test models of sediment transport and depositional setting, and (3) to determine the timing and kinematics of the Magallanes fold-thrust belt along the strike of the mountain belt. We document the vertical changes in facies and provenance that mark the beginning of turbidite sedimen-

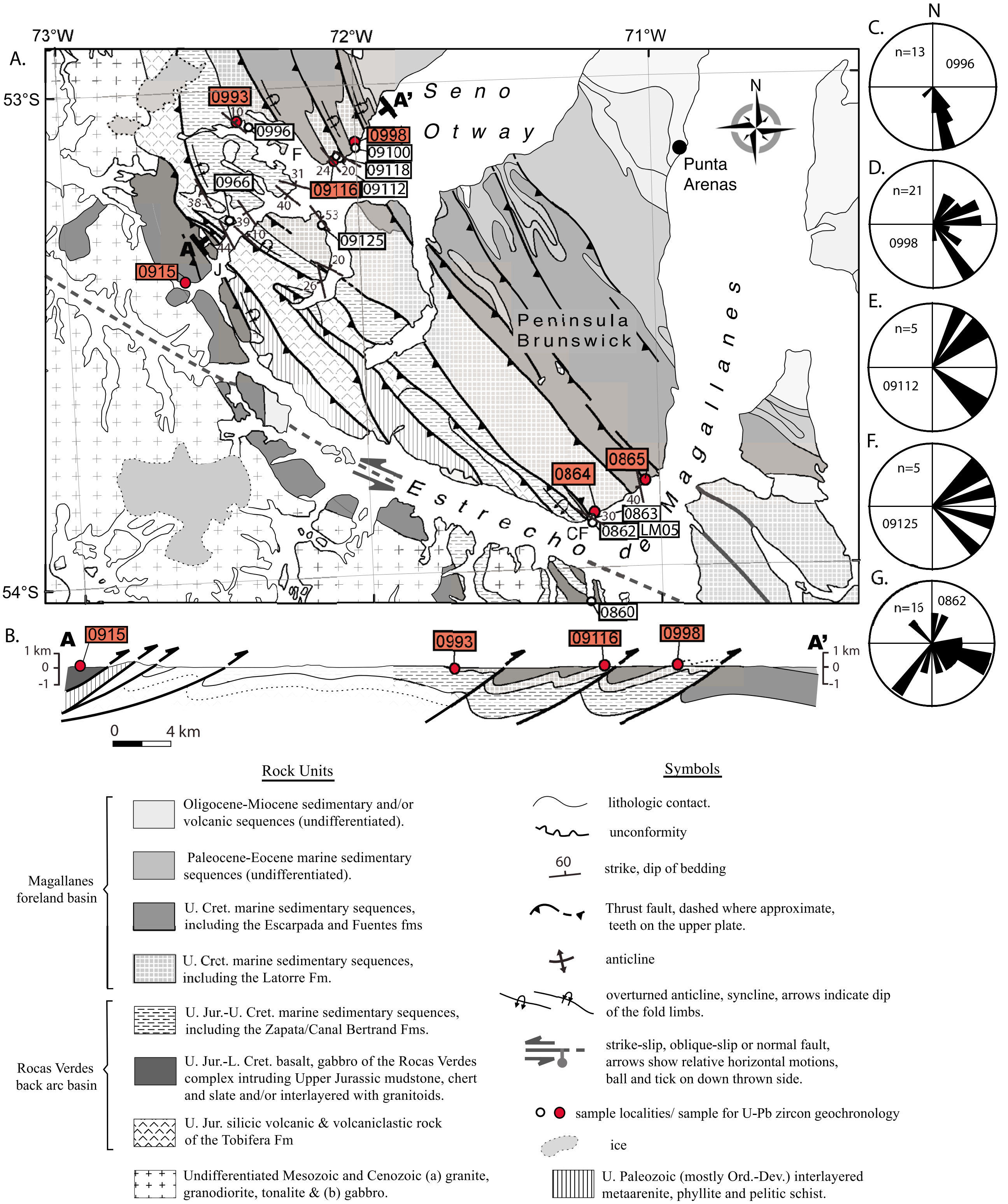

Figure 2. (a) Geologic map of Seno Otway, Peninsula Brunswick constructed from data collected in this study and data from *SERNAGEOMIN* [2002]. Unit names for Cretaceous sedimentary strata are from *Castelli et al.* [1993] and *Mpodozis et al.* [2007]. White dots and boxes show localities and samples. Shaded dots and boxes show U-Pb zircon ages from this study. (b) Cross section A-A′. Rose diagrams showing paleocurrent data from sites (c) 0996, (d) 0998, (e) 09112, (f) 09125, and (g) 0862. F, Fiordo Fanny; CF, Cabo Froward; J, Canál Jerónimo.

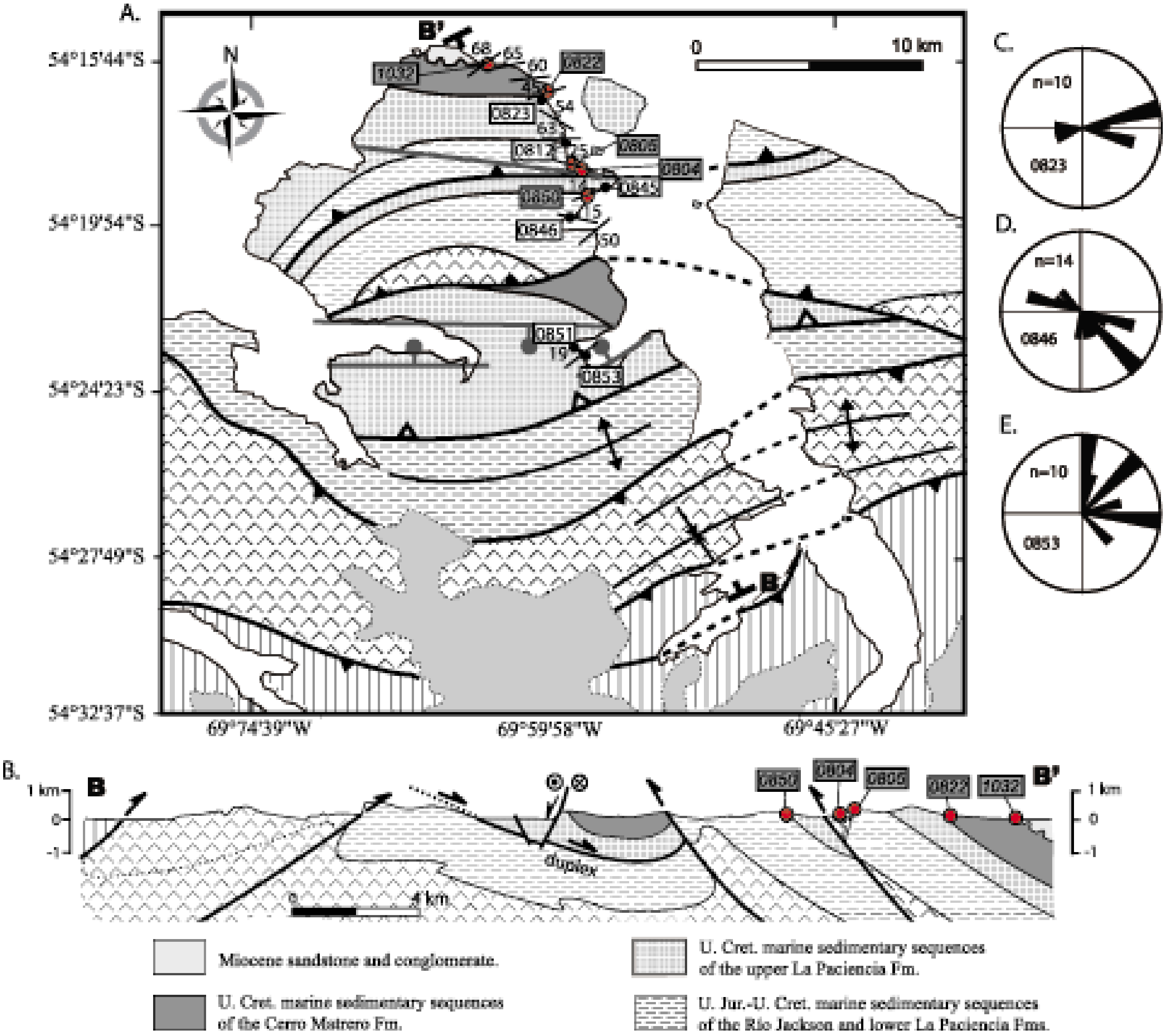

Figure 3. (a) Geologic map of Bahía Brookes constructed from data collected in this study and data from *SERNAGEOMIN* [2002] and unpublished maps of the Empresa Nacionál del Petróleo (2006). Note division of La Paciencia Formation into upper and lower members. Black lines with white teeth indicate bedding-parallel thrusts. Other symbols same as in Figure 2. (b) Cross section B-B′. Rose diagrams of paleocurrent data from sites (c) 0823, (d) 0846, and (e) 0853. Black dots and white boxes show sample localities. Gray boxes with italic text show geochronology samples.

tation in the Magallanes foreland basin in each area. In southern Tierra del Fuego the transition lies within what has been mapped previously as La Paciencia Formation and appears younger than it is in Ultima Esperanza by a few million years. Lithofacies associations, rock compositions, and sediment provenance also are different in the study areas than they are in northern Patagonia. The mud-dominated fill of the Rocas Verdes basin is sandier and thicker than in Ultima Esperanza, allowing us to obtain the first sandstone modal analyses from these units. On Tierra del Fuego mudstones are less primitive and sandstones show a greater degree of compositional diversification up section than in any other area. The compositions show that Paleozoic metamorphic rocks and the basaltic floor of Rocas Verdes basin contributed much less to the early Magallanes foreland basin on Tierra del Fuego, possibly because they were more deeply buried there than farther north. Paleoflow patterns within the central and southern parts of the Magallanes basin also show a greater diversity of fan environments compared to Ultima Esperanza. Despite these differences, the data support interpretations [*Fildani and Hessler*, 2005; *Romans et al.*, 2011; *Fosdick et al.*, 2011] that the onset of turbidite sedimentation in the Magallanes basin represents an evolution in the Magallanes fold-thrust belt related to the obduction of Rocas Verdes basaltic crust. Abrupt changes in sandstone provenance and the appearance of cobble conglomerates at 81–80 Ma mark another period of rapid fold-thrust belt growth. The data suggest that the onset of turbidite sedimentation in the Magallanes basin and the progressive uplift and emergence of both deeply buried

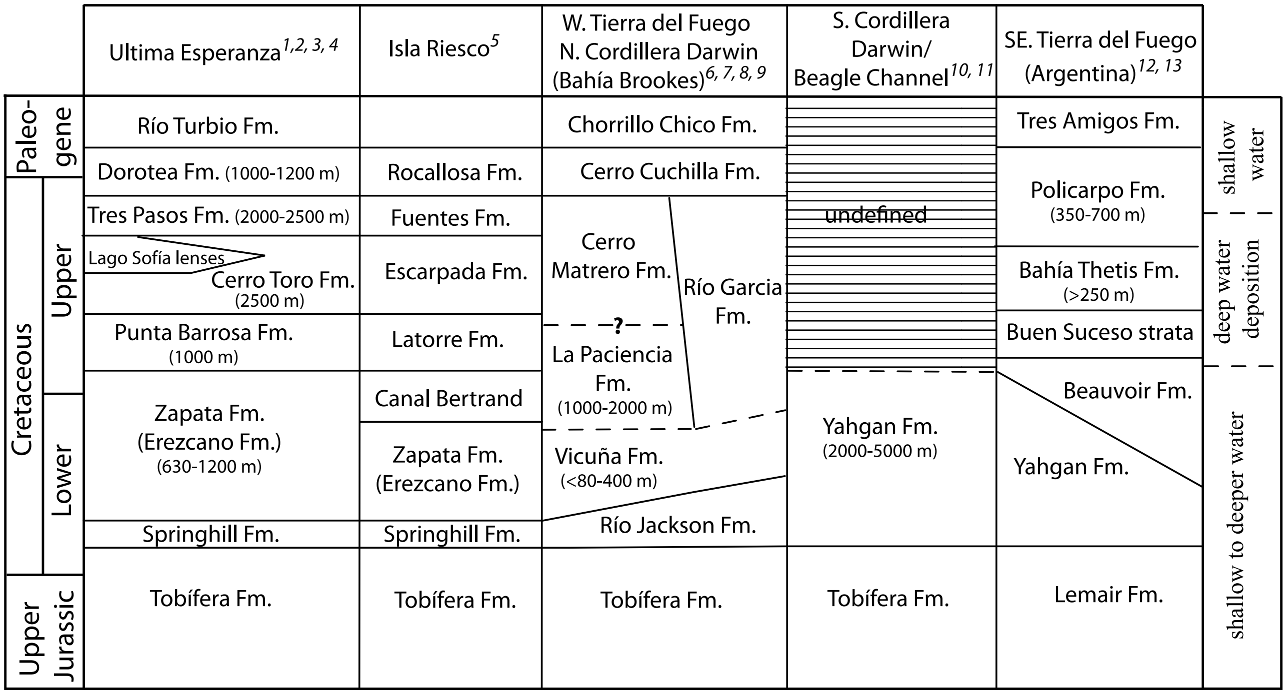

Figure 4. Simplified stratigraphic correlations for Upper Jurassic–Lower Paleogene rock units of the Rocas Verdes and Magallanes basins in Chile and Argentina. Age ranges are approximate. Data sources: 1, *Cortés* [1964]; 2, *Wilson* [1991]; 3, *Fildani and Hessler* [2005]; 4, *Hubbard et al.* [2008]; 5, *Castelli et al.* [1993] and *Mpodozis et al.* [2007]; 6, *Cortés and Valenzuela* [1960]; 7, *Alvarez-Marrón et al.* [1993]; 8, *Klepeis* [1994]; 9, *Rojas and Mpodozis* [2006]; 10, *Winn* [1978]; 11, *Suárez et al.* [1985]; 12, *Olivero and Martinioni* [2001]; 13, *Olivero and Malumián* [2008].

Upper Jurassic igneous rocks and the basaltic floor of the Rocas Verdes basin all were diachronous within the Patagonian Andes.

2. Geologic Setting and Previous Work

2.1. Patagonian Batholith and Metamorphic Complexes

[5] The Patagonian batholith records ~150 Myr of subduction-related magmatism that began during the period 157–145 Ma [*Bruce et al.*, 1991; *Hervé et al.*, 2007]. The batholith intrudes deformed turbidites of the Eastern Andes metamorphic complex (EA, Figure 1), which originally were deposited on a late Paleozoic passive margin [*Hervé et al.*, 2003]. The schistose core of the Cordillera Darwin (CD, Figure 1) metamorphic complex on Tierra del Fuego appear to be composed of similar Paleozoic turbidites [*Hervé et al.*, 2008, 2010]. This complex includes Cretaceous upper amphibolite facies (P = 7–12 kbar) metamorphic mineral assemblages [*Nelson et al.*, 1980; *Kohn et al.*, 1993; *Maloney et al.*, 2011]. Both the schistose core and younger Jurassic-Cretaceous rocks that surround it are intruded by three igneous suites, including granitic dikes of the Late Jurassic Darwin suite, basaltic dikes of the Rocas Verdes basin floor, and granitic plutons of the Late Cretaceous Beagle suite [*Nelson et al.*, 1980; *Hervé et al.*, 1981; 2010; *Kohn et al.*, 1995; *Klepeis et al.*, 2010]. West of the Patagonian batholith metamorphic complexes record tectonic accretion during Triassic-Jurassic subduction [*Hervé et al.*, 2008]. Blueschist facies assemblages of the Diego de Almagro complex indicate Cretaceous (~150 Ma) subduction [*Hervé and Fanning*, 2003].

2.2. Rocas Verdes Basin

[6] During the mid-late Jurassic, southern South America experienced extension and volcanism associated with Gondwana breakup [*Dalziel*, 1981; *Pankhurst et al.*, 2000]. The volcanism began with the eruption of rhyolitic ignimbrites of the Upper Jurassic Tobífera Formation [*Natland et al.*, 1974; *Gust et al.*, 1985; *Hanson and Wilson*, 1991; *Pankhurst et al.*, 2003]. By the Early Cretaceous, basaltic volcanism and extension behind a coeval volcanic arc had formed the quasi-oceanic Rocas Verdes back-arc basin [*Dalziel et al.*, 1974; *Stern*, 1980; *Allen*, 1982; *Suárez et al.*, 1985; *Alabaster and Storey*, 1990]. Deformed remnants of this floor now form the Sarmiento and Tortuga ophiolitic complexes (Figure 1) [*Suárez and Pettigrew*, 1976; *Stern*, 1980; *Calderón et al.*, 2007].

[7] The sedimentary fill of the Rocas Verdes basin is dominated by Lower Cretaceous mudstones that overlie the Tobífera Formation. The names and characteristics of these rocks differ in the various sectors of Patagonia (Figure 4). In Ultima Esperanza (UE, Figure 1), they comprise the Zapata (Erezcano) Formation, which is composed mostly of 630–1200 m of dark mudstone interbedded with thin siltstone and rare limestone [*Wilson*, 1991; *Fildani and Hessler*, 2005; *Calderón et al.*, 2007]. In this region the unit contains little sandstone except near its top where fine- to medium-grained sandstone layers form part of a ~150 m thick transition zone into the overlying Punta Barrosa Formation [*Fildani and*

Hessler, 2005; *Calderón et al.*, 2007]. Farther south, on Isla Riesco (IR, Figure 1), *Castelli et al.* [1993] and *Mpodozis et al.* [2007] reported a succession of volcaniclastic breccias and lavas interbedded with turbidites named the Canal Bertrand Formation (Figure 4) that is younger than the Zapata Formation and older than the Punta Barrosa Formation. East of the cordillera, in the subsurface, the Upper Jurassic Springhill Sandstone lies between the Tobífera and the Zapata formations [*Natland et al.*, 1974; *Biddle et al.*, 1986]. This unit is a transgressive sequence related to deepening as the Rocas Verdes back-arc basin opened, which allowed the deposition of thick muds to the west [*Biddle et al.*, 1986; *Wilson*, 1991].

[8] On Tierra del Fuego, the Hauterivian-Aptian Río Jackson Formation and lower part of the Aptian-Albian Vicuña Formation (Figure 4) record shallow-water deposition on top of the Tobífera Formation [*Cortés and Valenzuela*, 1960]. The former unit is ~400 m thick [*Klepeis*, 1994]. The Vicuña Formation is ~400 m thick in central Tierra del Fuego and thins to <80 m southward [*Cortés and Valenzuela*, 1960]. The Río García (central Tierra del Fuego) and La Paciencia (southern Tierra del Fuego) formations (Figure 4) represent deep-water depositional systems [*Cortés and Valenzuela*, 1960]. In Argentina, the late Albian to basal Cenomanian Beauvoir Formation is similar to La Paciencia Formation [*Olivero and Malumián*, 2008]. The 2000–5000 m thick Yahgan Formation [*Katz and Watters*, 1966; *Suárez et al.*, 1985; *Olivero and Martinioni*, 2001] records marine deposition adjacent to a volcanic arc [*Winn*, 1978; *Suárez et al.*, 1985] until the early Middle Cretaceous [*Barbeau et al.*, 2009b].

2.3. Magallanes Foreland Basin

[9] In Ultima Esperanza, the beginning of sedimentation in the Magallanes foreland basin (Figure 1) is marked by the deposition of deep-water (1000–2000 m) sandstone turbidites of the Punta Barrosa Formation [*Natland et al.*, 1974; *Biddle et al.*, 1986; *Wilson*, 1991; *Fildani and Hessler*, 2005]. Detrital zircon spectra suggest that this unit spans the interval 92–85 Ma [*Fildani et al.*, 2003; *Romans et al.*, 2010]. In this same region, ~2000 m of mud-rich turbidites of the 86–80 Ma Cerro Toro Formation (Figure 4) lie conformably on top of the Punta Barrosa Formation and represent the apex of deep marine sedimentation in the Magallanes basin [*Fildani et al.*, 2009; *Romans et al.*, 2011]. The upper part includes 1200 m of conglomerates, including the Lago Sofía member (Figure 4), which represent filled submarine channel systems [*Scott*, 1966; *Natland et al.*, 1974; *Winn and Dott*, 1979; *Hubbard et al.*, 2008; *Bernhardt et al.*, 2011]. Continued deposition filled the Magallanes basin and resulted in slope systems of the Campanian–early Maastrichtian Tres Pasos Formation [*Biddle et al.*, 1986; *Romans et al.*, 2010]. Deposition of the Maastrichtian-Danian Dorotea Formation and overlying units represents a change to shallow-marine and deltaic facies [*Covault et al.*, 2009].

[10] To the south of Ultima Esperanza (Figure 2), the stratigraphy of the still poorly known Cretaceous strata at Seno Skyring and Seno Otway was first studied by *Castelli et al.* [1993], *Farfán* [1994], and, more recently, by *Mpodozis et al.* [2007]. These latter authors completed a stratigraphic and sedimentological study of the Seno Skyring region where they obtained U-Pb ages of detrital zircons that permitted them to describe early Late Cretaceous units accumulated during the first stages of Magallanes foreland basin development, including the Latorre and Escarpada formations (Figure 4). In this paper, we use these names informally for similar sequences exposed at Seno Otway as a way to distinguish them from Cretaceous units on Tierra del Fuego and until a more in-depth stratigraphy of Seno Otway and Peninsula Brunswick can be completed. In Argentina (Tierra del Fuego), deep water sedimentary successions in the Magallanes foreland basin include the Santonian–lower Campanian Buen Suceso strata and the >250 m thick Upper Campanian Bahía Thetis Formation [*Olivero and Malumián*, 2008]. The latter unit represents deep water channel-levee deposits, including conglomerates. A change to shallow-marine and deltaic facies is recorded in the overlying Maastrichtian-Danian Policarpo and Upper Paleocene Tres Amigos formations [*Olivero and Malumián*, 2008].

[11] In western Tierra del Fuego and northern Cordillera Darwin, the surface locations of the successions marking the initiation of sandstone turbidite sedimentation in the Magallanes basin are poorly known. Overlying La Paciencia Formation is the Campanian Cerro Matrero Formation [*Cortés and Valenzuela*, 1960]. North of Cordillera Darwin, this unit is 1500–2000 m thick, grades laterally (northward) into thick volcaniclastic sandstone turbidites, volcanic agglomerates, and conglomerates of the Río García Formation [*Cortés and Valenzuela*, 1960]. These characteristics suggest it records stages similar to those of the upper Cerro Toro and Tres Pasos (Escarpada and Fuentes) formations. *Olivero and Malumián* [2008] interpreted the lower part of the Policarpo Formation in Argentina to be correlative with the upper part of the Cerro Matrero Formation. Overlying these units are Maastrichtian-Paleocene successions that represent shallow submarine delta systems [*Cortés and Valenzuela*, 1960].

2.4. Magallanes Fold-Thrust Belt

[12] Cretaceous-Neogene crustal shortening closed the Rocas Verdes basin and created the Magallanes fold-thrust belt, which represents the southernmost sector of the Andean fold-thrust belt (Figure 1). The first thrust sheets to form placed the basaltic basin floor onto adjacent South American continental crust [*Dalziel et al.*, 1974; *Nelson et al.*, 1980; *Fildani and Hessler*, 2005; *Calderón et al.*, 2007; *Klepeis et al.*, 2010]. In Ultima Esperanza, the presence of fine- to medium-grained sandstone layers and geochemical data suggest contraction began prior to ~92 Ma during deposition of the upper Zapata Formation [*Fildani and Hessler*, 2005]. This interpretation is supported by a U-Pb zircon age from volcanic ash in the Zapata–Punta Barrosa transition zone, which indicates that the thrust belt had formed by ~101 Ma [*Fosdick et al.*, 2011]. Near the Beagle Channel (55°S), obduction occurred prior to ~86 Ma [*Klepeis et al.*, 2010]. A subsequent stage of out-of-sequence thrusting, culminating in the Paleogene, is recorded in the part of the Magallanes fold-thrust belt now exposed in Cordillera Darwin [*Klepeis*, 1994; *Rojas and Mpodozis*, 2006; *Klepeis et al.*, 2010]. This latter period coincided with an interval of rapid uplift and exhumation of metamorphic basement [*Nelson*, 1982; *Kohn et al.*, 1995]

and a lateral expansion of thrust faulting into the foreland on Tierra del Fuego, terminating in the Eocene [*Alvarez-Marrón et al.*, 1993; *Ghiglione and Ramos*, 2005; *Barbeau et al.*, 2009a; *Gombosi et al.*, 2009].

2.5. Strike-Slip Faulting

[13] The South American–Scotia transform initiated as contraction declined and a regime of sinistral strike-slip and transtensional faulting began during the late Oligocene or early Neogene [*Cunningham*, 1993; *Klepeis and Austin*, 1997; *Lodolo et al.*, 2003; *Gombosi et al.*, 2009]. Segments of this plate boundary parallel the western Straits of Magellan and the Seno Almirantazgo–Lago Fagnano lineament on Tierra del Fuego.

3. Facies and Sedimentary Architecture

[14] Five main lithofacies associations occur in the Lower and Upper Cretaceous sections of the central and southern Magallanes basin. Historically, a hierarchical facies architecture approach to depositional systems, such as that proposed by *Miall* [1985] for fluvial settings, has been applied to many depositional environments, including submarine fans [e.g., *Pickering et al.*, 1995; *Hickson and Lowe*, 2002; *Anderson et al.*, 2006]. In this approach, the repetition of architectural elements, vertical changes in bed thickness, and sand-mud ratios typically are interpreted to reflect autocyclic process related to lobe growth and abandonment on fans. A potential problem is that the identification of trends in bed thickness and sand-mud ratios is subjective [*Murray et al.*, 1996] and some recent work [*Schlager*, 2010] raises questions about the presence of ordered hierarchy in stratigraphy. Nevertheless, subdividing strata in this way is useful for discriminating basic stratigraphic elements from their composite features [e.g., *Romans et al.*, 2011]. Thus, we apply the approach of *Hickson and Lowe* [2002] to describe facies and stratigraphic relationships at scales ranging from centimeters to thousands of meters and to compare facies and stratigraphy between study areas.

3.1. Southern Magallanes Basin

[15] At the northern end of Bahía Brookes (Figure 3) two north dipping back thrusts uplift the Cretaceous section. Within a few hundred meters of the southern back thrust, mudstones of the Río Jackson and La Paciencia formations display a slaty cleavage and tight northeast vergent folds, probably acquired during displacement on the nearby fault. However, north of this narrow zone the rocks are undeformed except for tilting and the minor effects of late Tertiary strike-slip faults. In the hanging wall of the northernmost back thrust, transitions through the Río Jackson, La Paciencia, and Cerro Matrero formations are well exposed. Here, and in the thrust sheet to the south, we obtained measured sections of these units (Figure 5). Other than the two back thrusts, no structural duplication occurs in these areas.

[16] On the basis of the five lithofacies associations, we divided the section at Bahía Brookes into four parts: a ~300 m thick Río Jackson Formation, a 1400 m thick lower member of La Paciencia Formation, a 600 m thick upper member of La Paciencia Formation, and a ~1400 m thick Cerro Matrero Formation (Figure 5). The thickness of the latter unit is a minimum because its top is an angular unconformity, above which are Miocene sandstone and conglomerate. The subdivision of La Paciencia Formation, documented here for the first time, reflects a vertical change in facies that marks the beginning of sandstone turbidite sedimentation in the southern part of the Magallanes foreland basin. This transition occurs over at least several tens of meters (discontinuous exposure precludes a more exact measure) and may be roughly similar to the one found in the Ultima Esperanza district by *Fildani and Hessler* [2005]. These exposures provide the first measure of the thickness (~1700 m) of the mud-dominated fill of the Rocas Verdes basin in northern Cordillera Darwin and confirm that it is sandier and thicker than in Ultima Esperanza.

3.1.1. Río Jackson and La Paciencia Formations

[17] The Río Jackson Formation consists of 4–6 cm thick couplets of black mudstone and orange-weathered, very fine-grained sandstone and siltstone (Figure 6a) that define *lithofacies association 1.* The sandstones are horizontally laminated and cross laminated at the millimeter scale. Sand to mud ratios are approximately constant (20:80–25:75). Climbing ripples and small horizontal *Planolites* and *Palaeophycus* burrows are present. These features, which are consistent with previous descriptions of the Río Jackson Formation [*Cortés and Valenzuela*, 1960; *Klepeis*, 1994], appear to reflect repetitive turbidite deposition of Bouma divisions Tb or Tc [*Bouma*, 1962] with interbedded pelitic division Te.

[18] The lower 1400 m of La Paciencia Formation consists of 7–15 cm thick mudstone beds, some of which contain <1–3 cm thick horizons of fine-grained, white to orange colored very fine sandstone or siltstone (Bouma divisions Tc and Td). These features define *lithofacies association 2* (Figure 6b). The sand horizons exhibit loading structures, *Planolites* and *Zoophycus* bioturbation, and millimeter-scale horizontal and cross laminations. Micritic calcareous lenses interbedded with mudstone represent the remains of limestone beds. Sand to mud ratios typically are ~10:90 but range from 5:95 to 15:85. Some lithofacies 1 sandstone-mudstone couplets occur near the base of the unit (Figure 5a). The relative abundance of fine sandstone in this unit, which represents the mud-dominated fill of the Rocas Verdes basin, contrasts with Ultima Esperanza where the Zapata Formation has little sandstone except at its top [*Fildani and Hessler*, 2005; *Calderón et al.*, 2007].

[19] The upper 600 m of La Paciencia Formation is defined by the appearance of two types of turbiditic sandstone that are absent in the lower La Paciencia Formation (Figure 5). *Lithofacies association 3a* includes thick (tens of centimeters) beds of very fine to medium-grained sandstone that occur at the top of fining-upward sequences above conglomerates. Poorly sorted beds contain granules and pebbles of lithofacies 2 mudstone. The sandstones and mudstones form thickening- or thinning-upward packages meters to tens of meters thick (Figure 5b). The bases of beds, some with sole marks, commonly are nonerosional or have tens of centimeters of relief from the scouring of underlying mudstones. Beds are tabular and lenticular at the meter scale. Sedimentary structures, include planar cross bedding up to 20 cm high, parallel laminations and, more rarely, dish structures. *Lithofacies association 3b* (Figures 6c and 6d) includes 1–10 m thick cyclic packages of flaser to wavy bedded, fine- to medium-grained sandstone inter-

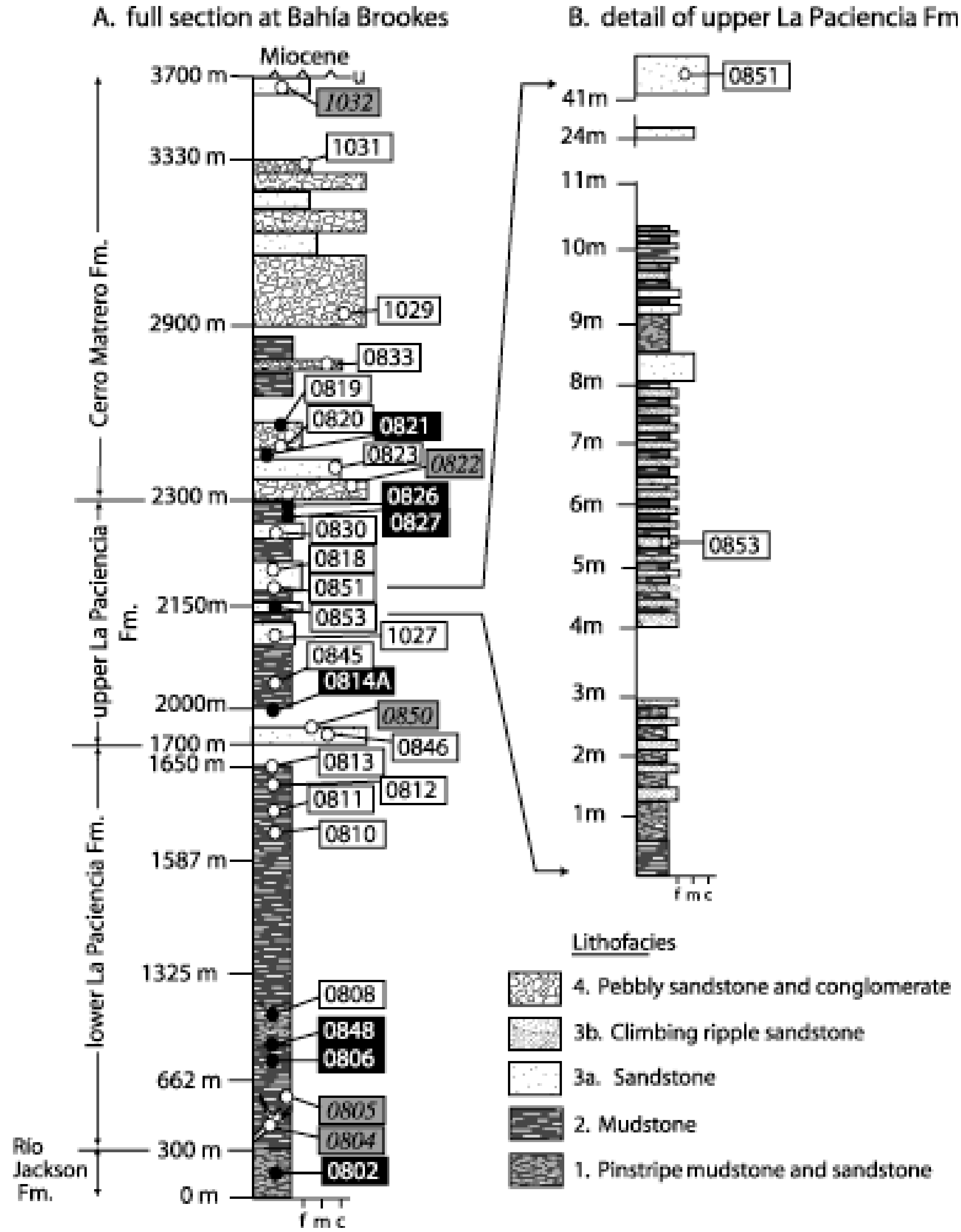

Figure 5. (a) Measured stratigraphic section, Bahía Brookes, Tierra del Fuego. Boxes and dots show relative location of analyzed samples. Black dots and black boxes are samples analyzed for REE mudstone geochemistry. White dots and white boxes are sandstone modal analyses. Black dots and white boxes were analyzed for both REE and modal analyses. Gray boxes with italic numbers show geochronology samples. (b) Detail of stratigraphy within upper La Paciencia Formation.

bedded with lithofacies 2 mudstone and lithofacies 3a sandstone. Sand-mud ratios range from 90:10 to 60:40. Rare convolute laminations occur in the sands and *Skolithos* burrows are present.

[20] The lithofacies associations of the lower La Paciencia Formation suggest an origin characterized by hemipelagic sedimentation interrupted by the periodic deposition of low density turbidity currents. A general upward trend of decreasing repetitive turbidite deposition to primarily hemipelagic mud accumulation (Figure 5a) indicates deepening during deposition in the Rocas Verdes basin. This deepening may have resulted from either a eustatic or a tectonic cause. The lithofacies associations of the upper La Paciencia Formation reflect the deposition of proximal high energy massive sands in high density turbidity currents (S3 of *Lowe* [1982]) alternating with the deposition of finer grained sand in thinner, low density turbidity currents (Bouma divisions Tb and Tc [*Bouma*, 1962]). These latter features may reflect

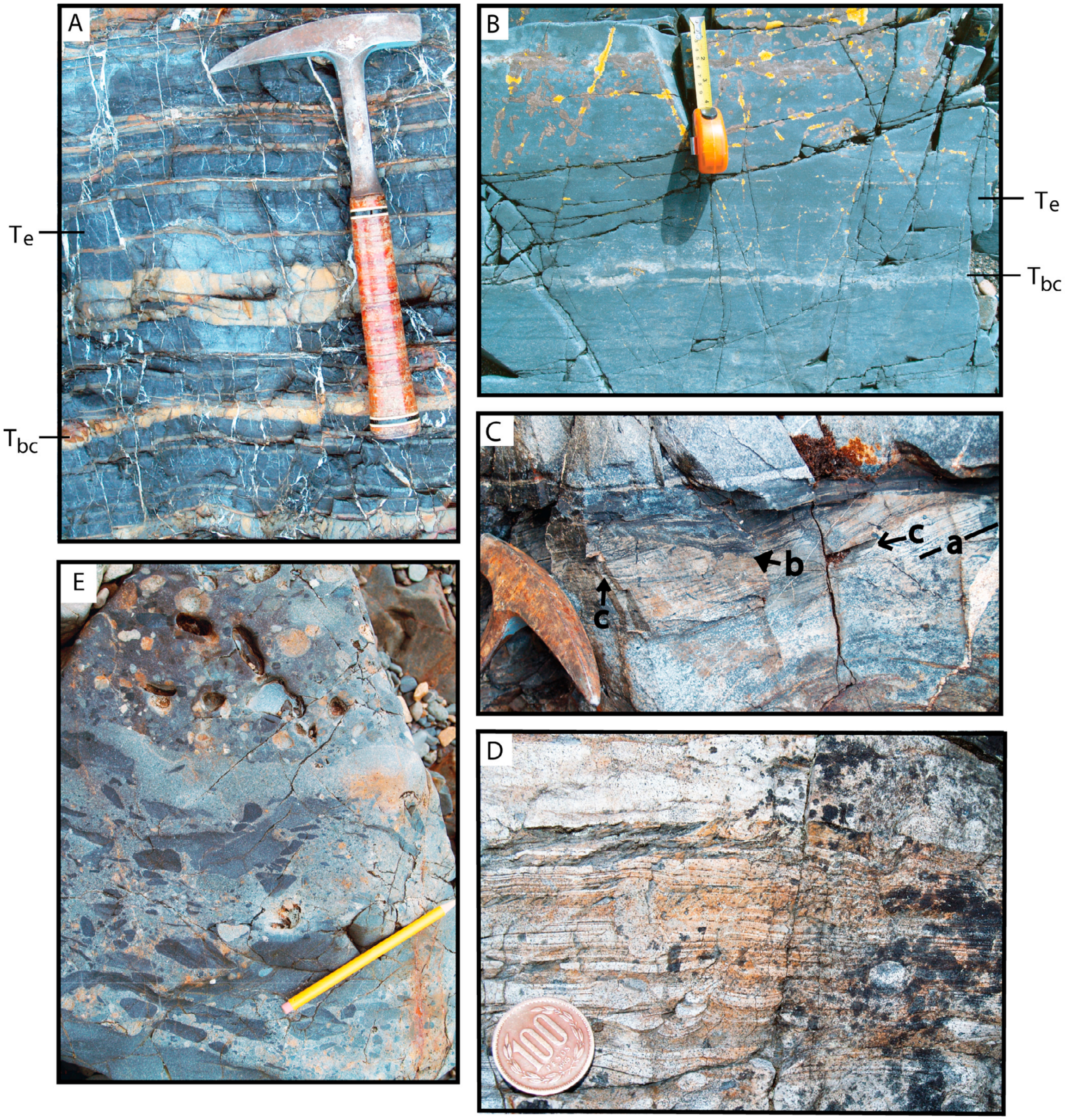

Figure 6. (a) Lithofacies 1 T_b and T_c (sand layers) interbedded with T_e (mud layers) from the Río Jackson Formation. (b) Lithofacies 2 mudstones, lower La Paciencia Formation. Light colored horizons are thin, very fine-grained sand horizons. Tape is 10 cm. (c) Medium-grained lithofacies 3a sandstone capped by fine sand, upper La Paciencia Formation: planar cross beds (point a), burrows (point b), and cross laminations (point c). Sequence is capped by mudstone (lithofacies 2). (d) Thinly interbedded horizons of planar and cross-laminated sand (lithofacies 3b) and mudstone, disrupted by *Skolithos* burrows, upper La Paciencia Formation. Coin diameter is 2 cm. (e) Intraformational clasts in basal conglomerate, Cerro Matrero Formation. Pencil is 15 cm long.

a regime transitional from the outer fan lobe to basin settings [*Mutti et al.*, 1999]. Because these lithofacies represent the beginning of turbiditic sand deposition on a fan lobe, they mark the onset of fan growth in the Magallanes foreland basin.

3.1.2. Cerro Matrero Formation

[21] We define the base of the Cerro Matrero Formation as the first appearance (i.e., stratigraphically lowest) conglomerate horizon (*lithofacies association 4*). These horizons have not been described previously in the southern Magallanes basin. This criterion is notably different than that used to identify the base of the Cerro Toro Formation in Ultima Esperanza. Unlike the Cerro Matrero, the bottom of the Cerro Toro is composed mostly of dark mudstone with no coarse grained beds [*Katz*, 1963; *Romans et al.*, 2011], and cobble conglomerates do not appear until the middle of the section (e.g., the Lago Sofía lenses; Figure 4). The occurrence of cobble conglomerates in the Cerro Matrero For-

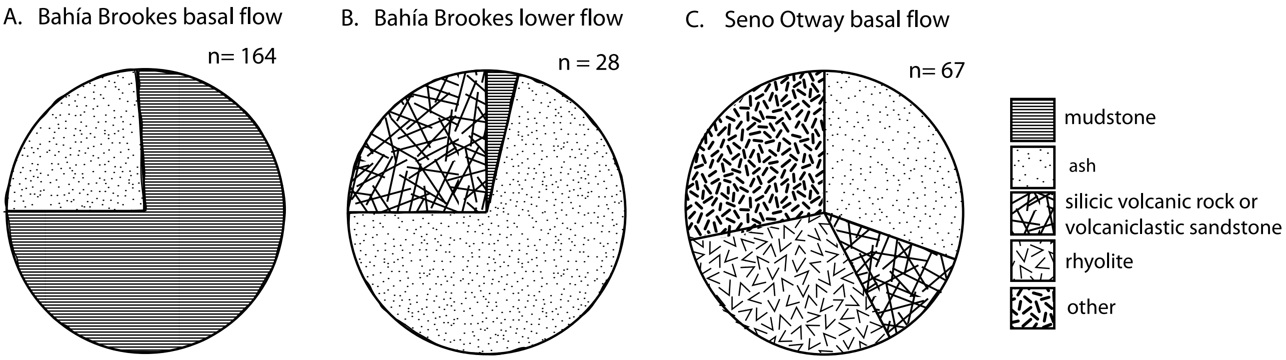

Figure 7. (a) Clast composition in the basal (0.5 m) conglomerate of Cerro Matrero Formation, Bahía Brookes. (b) Clast composition in conglomerate 5 m above those in Figure 7a. (c) Clast composition in basal conglomerate of Escarpada Formation, Seno Otway.

mation, and similar ones at the base of the Escarpada Formation (Section 3.2.3), suggests that a period of rapid uplift and erosion occurred earlier in southern and central sectors of the Magallanes basin than in the north. We discuss the significance of this result further in section 7.3.

[22] The basal conglomerate layer (Figures 5a and 6e) is characterized by granule to cobble-sized conglomerates that occur at the base of ~2 m thick fining-up sequences capped by lithofacies 3a sandstones. Because of the limited lateral exposure, the bounding surfaces were not observed and, therefore, the extent of erosion of underlying units that accompanied deposition of the conglomerates is unclear. Clasts are well rounded to subrounded, have a wide range of platy to spherical shapes, are both matrix (sand) and clast supported, and polymictic in composition. Although reverse grading was observed, coarse-tail grading is most common and some clasts are imbricated. Basal clast compositions consist mostly of lithofacies 2 ripped-up mudstone clasts and volcanic ash (Figure 7a). Conglomerate horizons high up in the section also exhibit clasts composed of silicic volcanic rock and volcaniclastic sandstone (Figure 7b). Lithofacies 4 represents high energy deposition from gravelly high density turbidity currents [*Lowe*, 1982] within fan channels [*Mutti et al.*, 1999]. The amalgamated sandstones containing ripped-up intraformational mudstone clasts, scours, and cut and fill deposits are similar to the fan channel-lobe transitional regions summarized by *Mutti and Normark* [1991].

3.2. Central Magallanes Basin

[23] At Seno Otway, rocks that once formed the basaltic floor and sedimentary fill of the Rocas Verdes basin are tectonically interleaved with Paleozoic basement phyllites (Figure 2). Below these slices, rocks of the Tobífera, Zapata, Canal Bertrand, Latorre and Escarpada formations [*Mpodozis et al.*, 2007] are uplifted and imbricated by a series of northeast vergent thrust faults. We obtained measured sections (Figures 8a–8c) of units within and north of Fiordo Fanny at Seno Otway (F, Figure 2) and along the shores of southern Peninsula Brunswick.

3.2.1. Zapata and Canal Bertrand Formations

[24] The Zapata Formation at Seno Otway contains lithofacies associations similar to those found in the lower 1400 m of La Paciencia Formation at Bahía Brookes. This unit (Figure 8b) comprises lithofacies 2 mudstone, representing hemipelagic sedimentation interrupted by the periodic deposition of low density turbidity currents in the Rocas Verdes basin. The abundance of the turbidites increases up-section. These observations are consistent with those reported by *Castelli et al.* [1993] and *Mpodozis et al.* [2007] for the Canal Bertrand Formation, which predates the onset of sedimentation in the Magallanes foreland basin.

[25] The combined thickness of the Zapata/Canal Bertrand formations at Seno Otway is difficult to estimate due to the effects of faulting, folding, and a slaty cleavage. Along Canál Jerónimo (J, Figure 2) the section allows a maximum thickness of 1500 m (Figure 8b). At site 0966 (Figure 2), >1000 m of black mudstone, slate and fine volcaniclastic sandstone of these units lie conformably on top of the Tobífera Formation. Northeast of this thrust slice, where folding is at a minimum, these units have a combined thickness of at least 900 m. Along the southern shore of Peninsula Brunswick (Figure 2), rocks of the Zapata Formation are isoclinally folded, precluding reliable thickness measurements [see also *Farfán*, 1994]. To the northeast, where the folding is less intense, the unit is at least 500 m thick.

[26] Our observations indicate that the Zapata Formation in these areas is thicker and sandier than it is in the Ultima Esperanza region where sandstone is rare except in a ~150 m thick transition zone below the Punta Barrosa Formation contact [*Fildani and Hessler*, 2005; *Calderón et al.*, 2007]. The relative abundance of fine-grained sand horizons in the upper Zapata/Canal Bertrand formations at Seno Otway also is consistent with previous interpretations [*Fildani and Hessler*, 2005; *Romans et al.*, 2010; *Fosdick et al.*, 2011] that the Magallanes fold-thrust belt began to form during the last stages of deep-water deposition in the Rocas Verdes basin.

3.2.2. Latorre Formation

[27] The stratigraphic transition into the Latorre Formation is exposed near site LM05 on Peninsula Brunswick (Figure 8a) and at site 0993 in Seno Otway (Figure 8b). Although a disjunctive cleavage is present in some mudstone layers, sandstone horizons lack cleavage and preserve delicate sedimentary structures. Open folds warp the section but do not thicken it significantly. At Seno Otway, the Latorre Formation has a minimum thickness of 600–700 m.

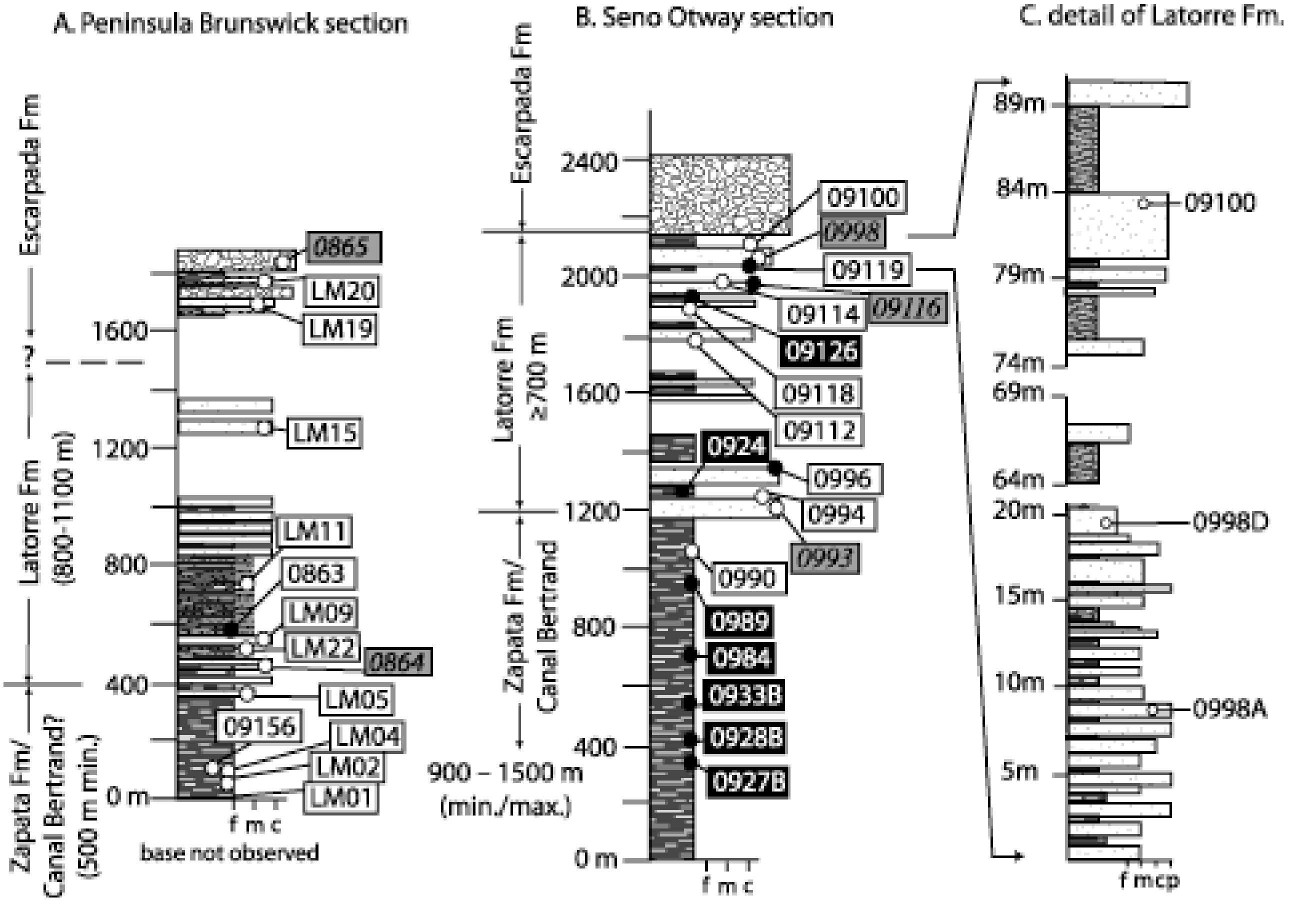

Figure 8. Measured stratigraphic sections at (a) Peninsula Brunswick and (b) Seno Otway. Zapata and Canal Bertrand formations are not distinguished. (c) Detail of stratigraphy within upper Latorre Formation. Symbols same as in Figure 5.

On Peninsula Brunswick, it is at least 800 m thick and may be up to 1100 m thick, although these conclusions are tentative.

[28] The stratigraphic transition from the mudstone and fine-grained turbidites of the Zapata and Canal Bertrand formations into the thicker and coarser-grained turbidite sequences of the overlying Latorre Formation [*Mpodozis et al.*, 2007] marks the beginning of sedimentation in the central Magallanes foreland basin. At Seno Otway, the base of this transition zone (site 0993) includes an 80 cm thick fine to medium-grained sandstone bed that occurs at the bottom of a 1.5 m thick succession of interbedded sandstones and mudstones (Figure 9a). The basal sandstone horizons (Figure 9b) are part of meter to tens of meter thick packages of fining-upwards, thinning upwards units (Figure 8c) composed of fining-upward lithofacies 3a pebbly to medium-grained sandstone layers and lithofacies 2 mudstones. Like the upper La Paciencia Formation on Tierra del Fuego, lithofacies 2 mudstones are abundant in the Latorre Formation although most of the unit consists of lithofacies 3a and 3b sandstone. Upward increases in sand to mud ratios and bed thicknesses occur over an interval of <100 m at the top of the unit (Figure 8c). We interpret this sequence to reflect the beginning of turbiditic sand deposition on a fan lobe as fan growth in the Magallanes foreland basin began.

3.2.3. Escarpada Formation

[29] We defined the base of the Escarpada Formation as the stratigraphically lowest cobble conglomerate horizon (*lithofacies association 4*) at both Seno Otway and on Peninsula Brunswick (Figure 8). This definition is similar to that of *Mpodozis et al.* [2007] who first defined this unit at Isla Escarpada in Seno Skyring north of Seno Otway. The base of this unit is most similar to that of the Cerro Matrero Formation on Tierra del Fuego and dissimilar to the basal Cerro Toro Formation where there is a notable lack of coarse grained beds [*Katz*, 1963; *Romans et al.*, 2011]. Like the Cerro Matrero, the base of the Escarpada contains cobble-sized conglomerates (lithofacies 4) at the bottom of ~2 m thick fining-up successions capped by lithofacies 3a sandstones. This association represents deposition from high-density turbidity currents [*Lowe*, 1982] in fan channels.

[30] Apart from the general similarities between the basal conglomerate horizons of Escarpada and Cerro Matrero formations, there also are some key differences. Clast compositions are more diverse at Seno Otway (Figure 7c) than those at Bahía Brookes (Figures 7a and 7b). At Bahía Brookes, the clasts have compositions suggesting they were derived mainly from Rocas Verdes basin deposits (i.e., its basaltic floor and sedimentary cover) as well as from an active arc. In contrast, those of the Escarpada Formation at Seno Otway are richer in Upper Jurassic igneous rocks and

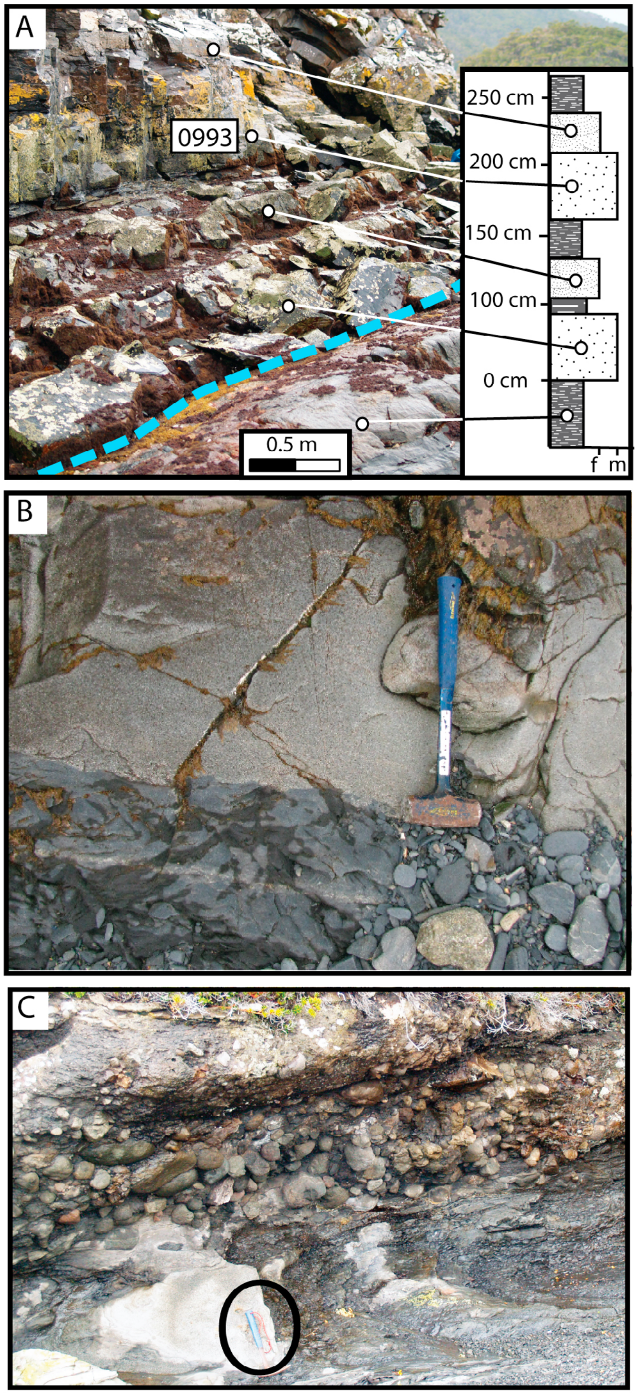

Figure 9. (a) Photograph and measured section of the base (blue line) of the Latorre Formation at Seno Otway. Locality of sample 0993 shown. The basal sandstone is 80 cm thick and exhibits centimeters of scour into the underlying mudstone. Approximately two meters above the contact are amalgamated beds of sandstone (lithofacies 3a) and flaser-bedded sandstone of lithofacies 3b. (b) Lithofacies 3a structureless sandstone sharply overlying lithofacies 2 mudstone, base of Latorre Formation, Peninsula Brunswick. (c) Basal conglomerate of Escarpada Formation (Seno Otway) composed of well-rounded polymictic clasts. Hammer (circled) is 32 cm.

the other units that predate opening of the Rocas Verdes back-arc basin. Both of these conclusions are supported further by sandstone provenance and detrital zircon data (discussed in section 7.3).

[31] Clast shapes also are different in the two regions. At Bahía Brookes, they are angular to subrounded and platy to subspherical whereas at Seno Otway they are all well rounded and spherical to highly spherical. Some conglomerate horizons in the latter region also have densely packed, imbricated round pebble horizons (Figure 9c). These basal clasts exhibit a complex history that, unlike the Bahía Brookes exposures, includes an antecedent period in "upstream" fluvial drainage or another site of reworking during transport, prior to deposition on the fan. The data indicate that clast compositions and shapes vary both regionally and stratigraphically across the central and southern parts of the Magallanes basin [*McAtamney*, 2010]. Although the occurrence of cobble conglomerates in both areas indicate periods of significant uplift and erosion, their characteristics suggest they were derived from different sources and record different fan environments.

4. Paleocurrents

[32] The abundance of cross bedding and cross laminations within sandstones that form part of the upper La Paciencia and Latorre formations allowed us to obtain paleocurrent data from Seno Otway, Peninsula Brunswick, and Bahía Brookes (Figures 2c–2g and 3c–3e). In all cases we removed the regional tilt of the beds caused by thrust faulting to obtain restored paleocurrent directions. The data indicate that sediment dispersal patterns in the central Magallanes basin were complex. All localities record multiple flow directions, including transport parallel to, oblique to, and across the axis of the orogen. Defining flow directions relative to the trend of the orogen in each place allowed us to account for the regional effect of the Patagonian orocline, which involves a gradual change in trend from north-south near Ultima Esperanza to nearly east-west on Tierra del Fuego.

[33] The paleoflow patterns at Seno Otway and Bahía Brookes contrast with paleocurrent measurements from the Punta Barrosa [*Fildani and Hessler*, 2005] and the Cerro Toro formations in Ultima Esperanza [*Winn and Dott*, 1979; *Hubbard et al.*, 2008] where paleoflow was parallel to the axis of the basin (a southerly direction in that region). These observations are important because they indicate increased complexity of sediment dispersal patterns from north to southeast within the Magallanes basin, a pattern that is expected on submarine fans due to construction and abandonment of lobes [*Mutti and Normark*, 1991].

5. Provenance

5.1. Methods

[34] Sandstone modal analyses (Figures 11a and 11b) provide information that can be used to infer tectonic setting and contributing source rock lithologies [*Johnsson*, 1993, and references therein]. We identified and counted a minimum of 300 framework grains in 38 sandstones (relative stratigraphic positions shown in Figures 5 and 8). Grains included (1) monocrystalline and polycrystalline quartz

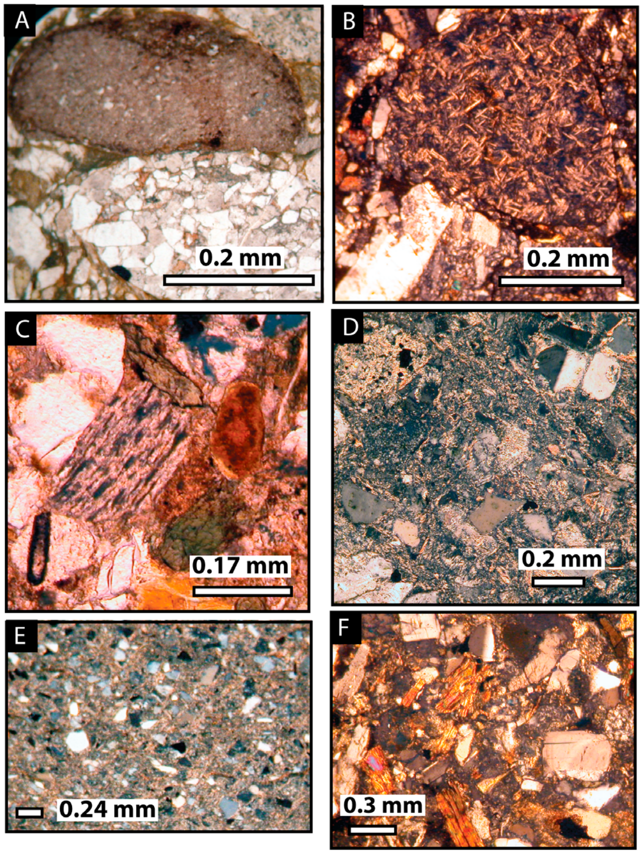

Figure 10. (a) Sedimentary lithic grains, mudstone (top) and sandstone (bottom). (b) Volcanic lithic grain with numerous tiny feldspar lathes. (c) Low to medium grade metamorphic lithic grain. (d) Matrix of clay from degraded lithic fragments. (e) Sandy mudstone. (f) Chlorite-rich sandstone. Magnification for all photos 10× except for Figure 10f (4×).

and chert, (2) feldspar, (3) sedimentary lithic fragments, (4) volcanic lithic fragments, (5) metamorphic lithic fragments, (6) cement and matrix type and abundance, and (7) accessory minerals (Table S1 and Data Set S1).[1] Figure 10 shows examples of the lithic fragments. *Dorsey* [1988] described the pitfalls of using a subjective classification of foliation intensity to identify metamorphic lithic fragments. To avoid potential bias we adopted her approach of "blind" sample identification during point counting. Isolated euhedral feldspar lathes surrounded by matrix and not encased within other grains were counted as feldspar.

[35] We used standard quartz-feldspar-lithic fragment (QFL) and metamorphic-volcanic-sedimentary lithic fragment (Lm, Lv, Ls) ternary diagrams (Figures 11a and 11b), and the provenance fields of *Dickinson* [1985] and *Dickinson and Suczek* [1979], to compare sandstone compositions from the central and southern Magallanes basin to those of *Crane* [2004] and *Fildani and Hessler* [2005] from Ultima Esperanza. Typically the abundance of quartz makes this grain type less useful in provenance determination than feldspar and lithic fragment types. Although, *Dickinson and Suczek* [1979] showed that distinguishing feldspar composition can be useful for discriminating arc-derived sediment, we present total feldspar data because distinguishing these compositions rarely was possible due to alteration. Nevertheless, cathode luminescence images confirmed the paucity of potassium feldspar and the relative abundance of plagioclase. Lithic fragments were especially useful because they represent a direct relationship with eroding bedrock lithologies and they allowed us to establish trends. Volcanic lithic fragments were identified by the presence of lathe networks and microlitic textures in feldspar-rich grains [*Ingersoll et al.*, 1984; *Suczek and Ingersoll*, 1985] (e.g., Figure 10b). Plutonic grains that show feldspar encased within a larger polycrystalline grain were not observed.

[36] Mudstone geochemistry provided additional information on source areas, such as mafic terranes, that typically yield detritus finer than sand. In Ultima Esperanza, *Fildani and Hessler* [2005] developed an innovative approach that used shale geochemistry as a comparative provenance indicator in units dominated by mudstone, including the Zapata and Punta Barrosa formations. These authors showed that shales from the Zapata and Punta Barrosa formations in Ultima Esperanza have significantly different geochemical signatures and that these can be demonstrated by a comparison of chondrite-normalized REE abundances. For comparison, we applied this same approach using mudstones from our study areas. Fifteen Rare Earth Elements (Figures 11c and 11d and Data Set S2) in twenty two samples were analyzed with an inductively coupled plasma mass spectrometer (ICP-MS) at the Washington State University Geoanalytical Laboratory using established methods [*Lichte et al.*, 1987; *Jarvis*, 1988; *Longerich et al.*, 1990].

5.2. Sandstones

[37] The 38 sandstones analyzed range from $Q_1F_{97}L_2$ to $Q_{41}F_{45}L_{14}$ and are all arkoses and arkosic wackes in composition. The data show three major trends, which are common to both the central and southern Rocas Verdes and Magallanes basins.

[38] The first trend occurs in rocks representing the sedimentary fill of the Rocas Verdes basin. These data are significant because they are first analyses obtained from units representing the northern flank of the back-arc basin. In the Río Jackson, lower La Paciencia, and Zapata/Canal Bertrand formations, QFL ratios are all similar and show relatively simple distributions that cluster in the 'basement uplift' field (Figure 11a). This basement was igneous rather than metamorphic because metamorphic clasts are rare to absent. Lithic fragments mostly are recycled sediments (mudstones and siltstones) with a contribution of volcanic fragments (Figure 11b). All three units contain abundant pristine feldspar clasts. These data, therefore, indicate that an active volcanic arc was adjacent to the Rocas Verdes basin in all areas. This arc, and the basin's own sedimentary fill, were among the most important sources for all three units.

[39] A second major trend is a diversification in sandstone source regions upward across the transitions that mark the beginning of turbidite sedimentation in the Magallanes foreland basin. This pattern occurs in both the central and southern regions. In contrast to the fine-grained sands in the

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[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/tc/2010tc002826. Other auxiliary material files are in the HTML.

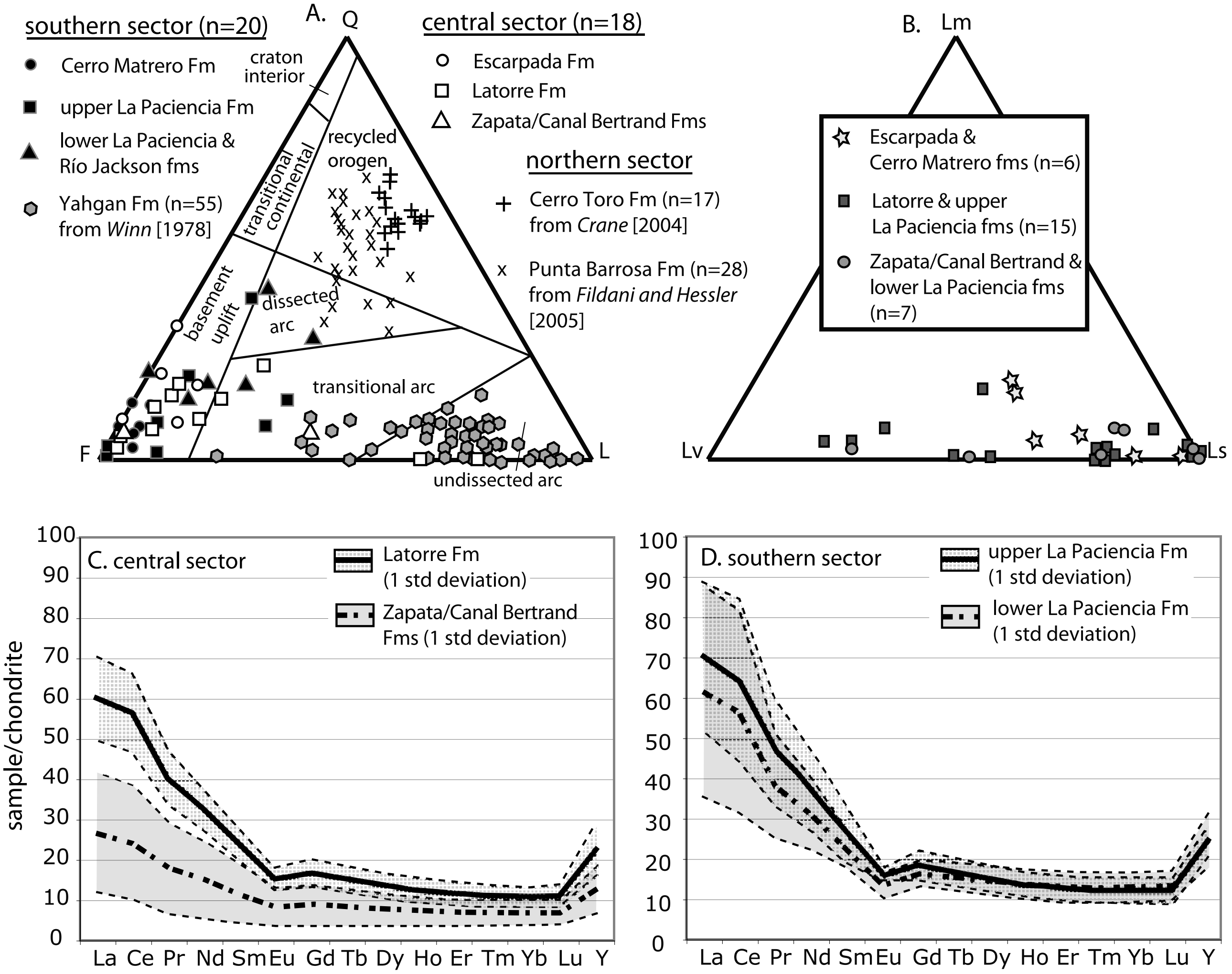

Figure 11. (a) Ternary plot showing total quartz (Q), feldspar (F), and lithic fragments (L). Note all sandstones from the Zapata/Canal Bertrand and lower La Paciencia formations plot in the uplifted basement field whereas those from the Latorre, upper La Paciencia, Escarpada, and Cerro Matrero formations also plot in the transitional and dissected arc fields of *Dickinson and Suczek* [1979]. (b) Ternary plot of volcanic lithic (Lv), metamorphic lithic (Lm), and sedimentary lithic (Ls) components. Note that sandstones from the upper La Paciencia and Cerro Matrero show much greater lithic compositional variation than those of the lower La Paciencia Formation. Lm, Lv, and Ls ternary plot showing the trend in lithic grain composition from samples that are stratigraphically well constrained. Diagram shows that an increase in compositional diversity occurs up-section from the lower to the upper La Paciencia Formation at Bahía Brookes. (c) Fractionation diagrams for Rare Earth Elements (REE) in mudstones. At Seno Otway (Figure 11c), average REE abundances for samples from the Latorre Formation are distinct from average REE abundances for those from the Zapata/Canal Bertrand formations by one standard deviation (Data Set S1). (d) In contrast, at Bahía Brookes the REE abundance patterns for the upper and lower La Paciencia formations are indistinguishable. The vertical scale at left represents chondrite normalized values (sample/chondrite) (method of *Boynton* [1984]).

Rocas Verdes deposits, sandstones from the Latorre and upper La Paciencia formations exhibit much greater compositional variations in the QFL diagram (Figure 11a). The latter rocks plot in the uplifted basement, transitional arc, and dissected arc fields (Figure 11a) and show much greater variation in lithic fragment composition, notably in the appearance of low grade metamorphic grains (Figures 10c and 11b), than the underlying units. On the basis of the abundance of feldspar, sedimentary, and volcanic lithic fragments, and the appearance of the metamorphic lithic fragments, the provenance of the first deposits of the Magallanes basin is interpreted to be a volcanic arc with sedimentary cover, including clasts from sedimentary units of the Rocas Verdes basin. The fact that this pattern occurs hundreds of kilometers apart in both the central and southern parts of the basin indicates that the change in provenance was a basin-wide event. Nevertheless, there is a pronounced difference in the composition of sandstones from the Latorre and upper La Paciencia formations compared to those from the Punta Barrosa Formation (Figure 11a), suggesting that different source regions fed the central and southern sectors of the Magallanes basin.

[40] A third pattern is another increase in the diversity of sediment source regions up section across the Latorre-Escarpada and the upper La Paciencia–Cerro Matrero boundaries in the central and southern parts of the Magallanes basin, respectively. The abundance of metamorphic lithics, including detrital chlorite grains, increases abruptly across the contact in each place (Figure 11b). The compositional trends suggest a period of unroofing and erosion in the source area coincides with the top of the Latorre and upper La Paciencia formations in both areas, respectively. These boundaries, thus, mark a period of significant growth of the Magallanes fold-thrust belt.

[41] In addition to these three trends, which are common to all areas studied, several differences in sandstone provenance exist between the central and southern regions. At Bahía Brookes, rocks of the Magallanes foreland basin show a greater abundance of lithic clasts, including more metamorphic lithic clasts, than they do in the central part of the basin. The transition from the upper La Paciencia into the Cerro Matrero Formation also shows a higher degree of diversification than the transition from the Latorre into the Escarpada Formation. These patterns suggest that sediment source regions were different in the two regions and that there may have been a greater degree of uplift and erosion in the south than in the north.

5.3. Mudstones

[42] Mudstone geochemistry, like the sandstone analyses (Section 5.2), reveal differences in provenance between the central and southern Magallanes basin. Eleven samples of mudstone from Seno Otway and Peninsula Brunswick show that the Zapata/Canal Bertrand and Latorre formations are characterized by significantly (1σ) different REE signatures. These differences are illustrated best using chondrite-normalized REE abundances. With one exception (sample 0996C from several meters above the base of the Latorre Formation), mudstones from the Zapata/Canal Bertrand formations display a lower overall REE abundance than those from the Latorre Formation (Figure 11c). In addition, the Zapata/Canal Bertrand mudstones show less fractionation between light (La-Eu) and heavy (Gd-Y) REE compared to the Latorre Formation, indicating that the former are more primitive (mafic). Both units display negative Eu anomalies, suggesting a relatively low abundance of plagioclase and feldspar-bearing lithoclasts [*McLennan et al.*, 1993]. These patterns are similar to those obtained for the Zapata and Punta Barrosa formations by *Fildani and Hessler* [2005] in Ultima Esperanza, suggesting that mudstone source regions in the central Magallanes basin are similar to those observed in the northern part of the basin.

[43] In contrast to Seno Otway, eleven samples of mudstone from Bahía Brookes show that rocks from all units have nearly identical REE signatures (Figure 11d). All units show similar degrees of fractionation between light (La-Eu) and heavy (Gd-Y) REE and display similar strong negative Eu anomalies. The Rocas Verdes basin deposits (lower La Paciencia Formation) may show slightly less fractionation between light (La-Eu) and heavy (Gd-Y) REE than overlying mudstones, suggesting it is slightly more primitive. However, all mudstones at Bahía Brookes are significantly less primitive than those from Seno Otway. These contrasting patterns suggest significant differences in provenance for rocks of both basins along the strike of the mountain range. They also suggest that rocks of both basins at Bahía Brookes, unlike those in the central sector, were derived from similar sources and/or that Rocas Verdes basin rocks at Brookes were recycled during deposition of the first foreland basin sediments.

6. U-Pb Zircon Crystallization Ages

6.1. Methods

[44] The analysis of detrital zircon grains from nine samples (Figures 12 and 13) allowed us to evaluate depositional ages and the provenance of Rocas Verdes basin and Magallanes basin sediments. Two igneous crystallization ages (Figure 14) from intrusive rock also helped us determine the timing of magmatic pulses that predate and accompanied foreland basin sedimentation. All concentrates were prepared at the University of Arizona Laserchron Geochronological Laboratory (auxiliary material). For detrital zircon analyses, 80–100 randomly selected zircon crystals (with one exception where zircon yield was lower) were analyzed to identify the main age groups present. The data (Figures 12 and 13 and Data Set S2) were filtered according to precision (10% cutoff) and discordance (30% cutoff) using the algorithms of *Ludwig* [2003]. Relative probability age curves were constructed by calculating a normal distribution for each analysis based on the reported age and uncertainty, summing the probability distributions of all acceptable analyses into a single curve, and, if normalized, dividing the area under the curve by the number of analyses. The 'UnMix' algorithm in Isoplot v.3.70 [*Ludwig*, 2008] looks for the number of separate age components (i.e., peaks on probability distributions) in a mixture of ages. It then takes the youngest of these to be a reliable estimate of the youngest age component in the sample. The geological timescale follows the IUGS-ICS (http://www.stratigraphy.org/cheu.pdf).

6.2. Samples and Results

6.2.1. Seno Otway

[45] Sample 0993 is a lithic arkosic wacke from the base of the Latorre Formation (Figures 2 and 8). The analysis of 99 grains yielded a detrital age distribution that can be unmixed into several distinctive populations (Figure 12c). The dominant group (n = 64) lies in the range 103–135 Ma and yielded a youngest unmixed component at 106.5 ± 2.0 Ma (MSWD = 0.64). Several subordinate peaks occur within the ranges 130–160 Ma, 220–300 Ma, 343–417 Ma, and 477–540 Ma. A few Proterozoic grains (>800 Ma) also occur. The youngest unmixed component indicates that rocks overlying the Latorre and Escarpada formations at this site must be younger than ~104 Ma.

[46] Sample 09116 is a mica-rich lithic arkosic wacke from the upper third of the Latorre Formation (Figure 2). The analysis of 45 grains yielded a dominant peak (n = 41) in the range 78–133 Ma and a youngest unmixed component at 84.2 ± 1.2 Ma (MSWD = 0.62) (Figure 12b). A small number of Cambrian and Precambrian grains also occur. The youngest unmixed component indicates that the over-

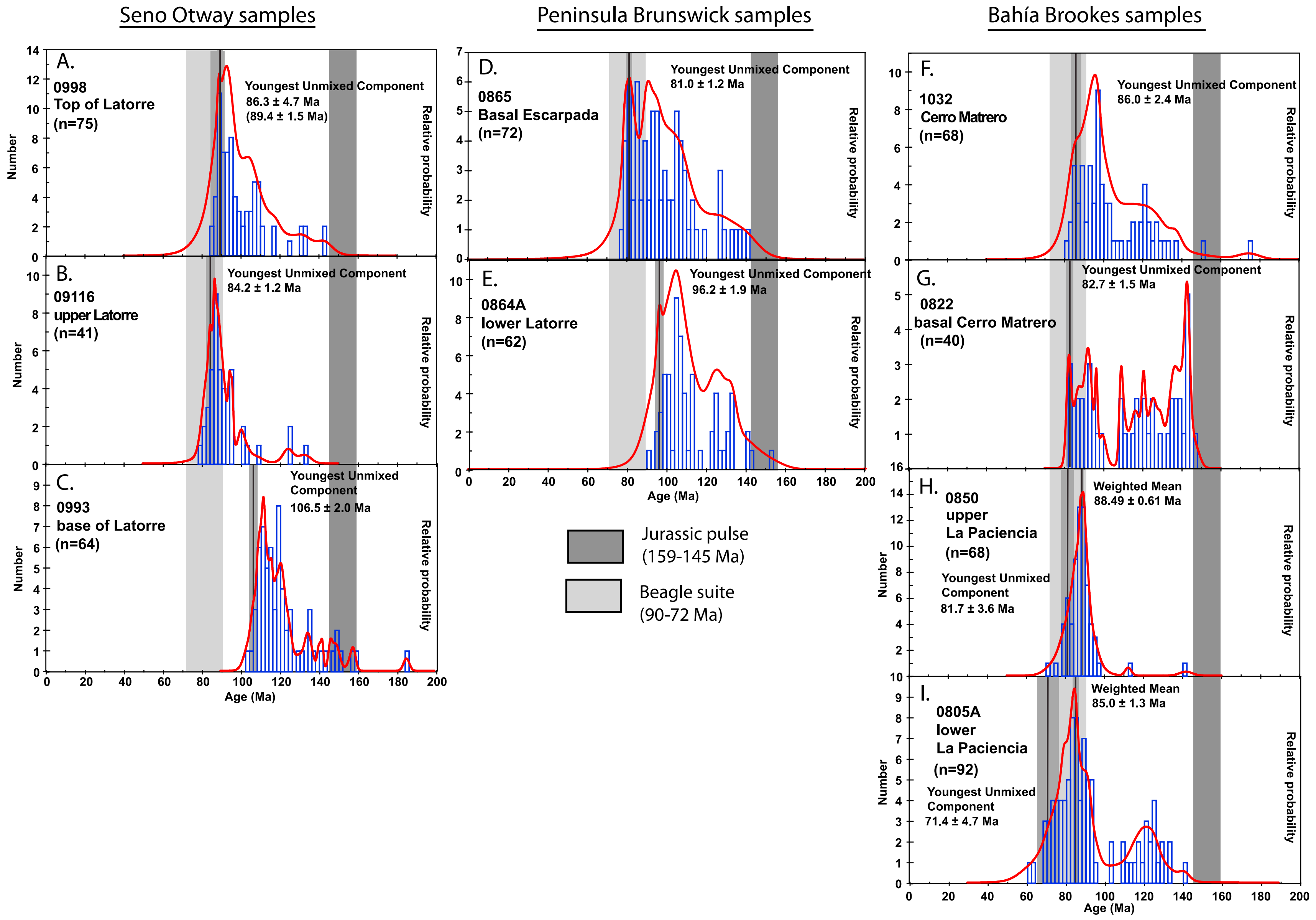

Figure 12. (a–i) Relative probability spectra for Mesozoic populations of detrital zircon from Bahía Brookes, Peninsula Brunswick and Seno Otway. Age histograms show total amount of concordant ages per sample with cumulative probability curve. Mesozoic ages are enlarged to show dominant ages and associated uncertainties.

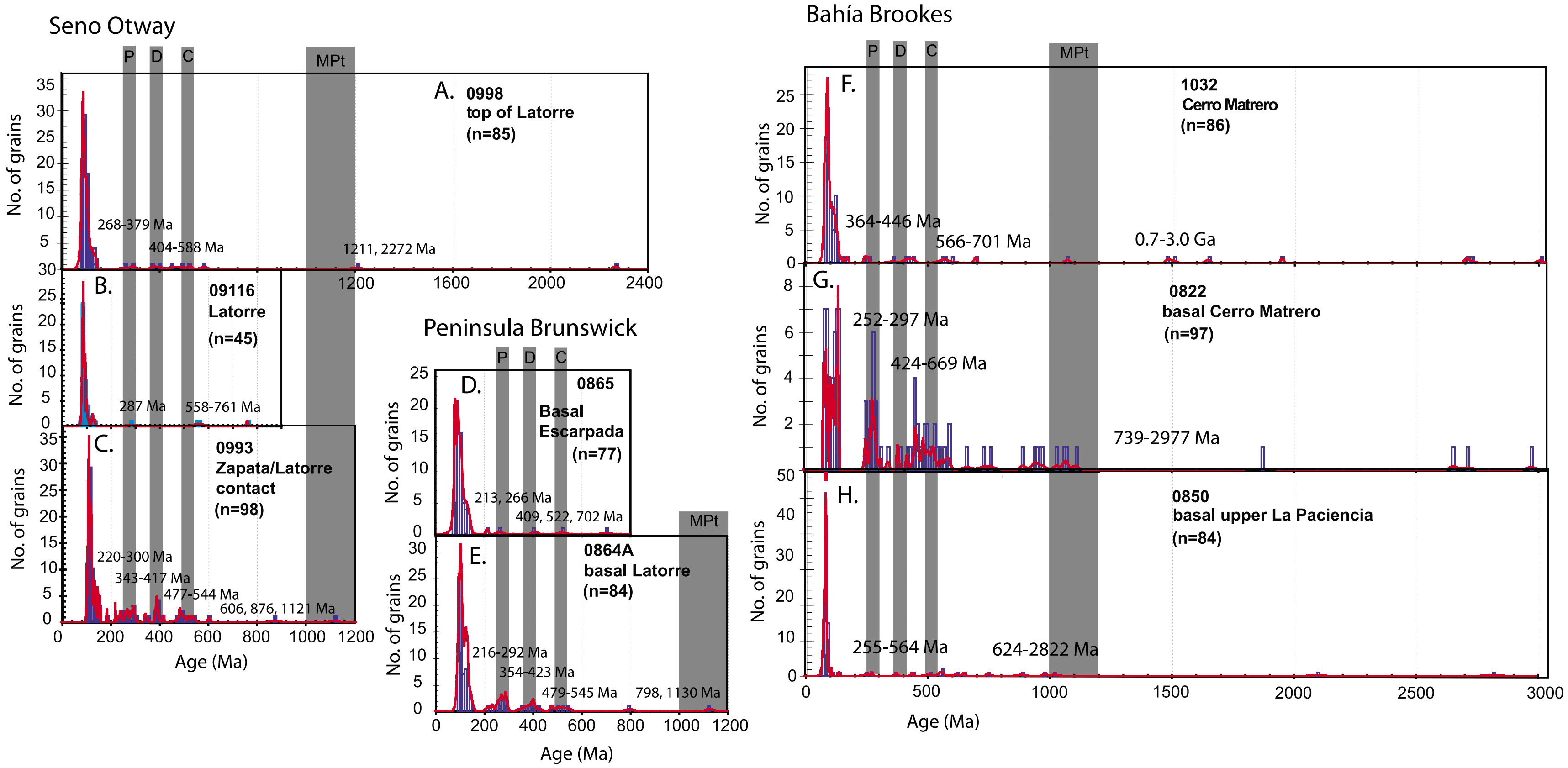

Figure 13. Detrital zircon relative probability spectra for samples (numbers shown in upper left of plots) collected from (a–c) Seno Otway, (d, e) Peninsula Brunswick, and (f–h) Bahía Brookes. Samples are the same as those shown in Figure 11. The plots emphasize the contributions of pre-Mesozoic metamorphic complexes to sediment in units of the upper Zapata/Canal Bertrand formations and equivalents of the Punta Barrosa and lower Cerro Toro formations. Note that no zircon older than ~142 Ma was recovered from sample 0805A, reflecting an increase in population complexity up-section. Age histograms show total amount of concordant ages per sample with cumulative probability curve.

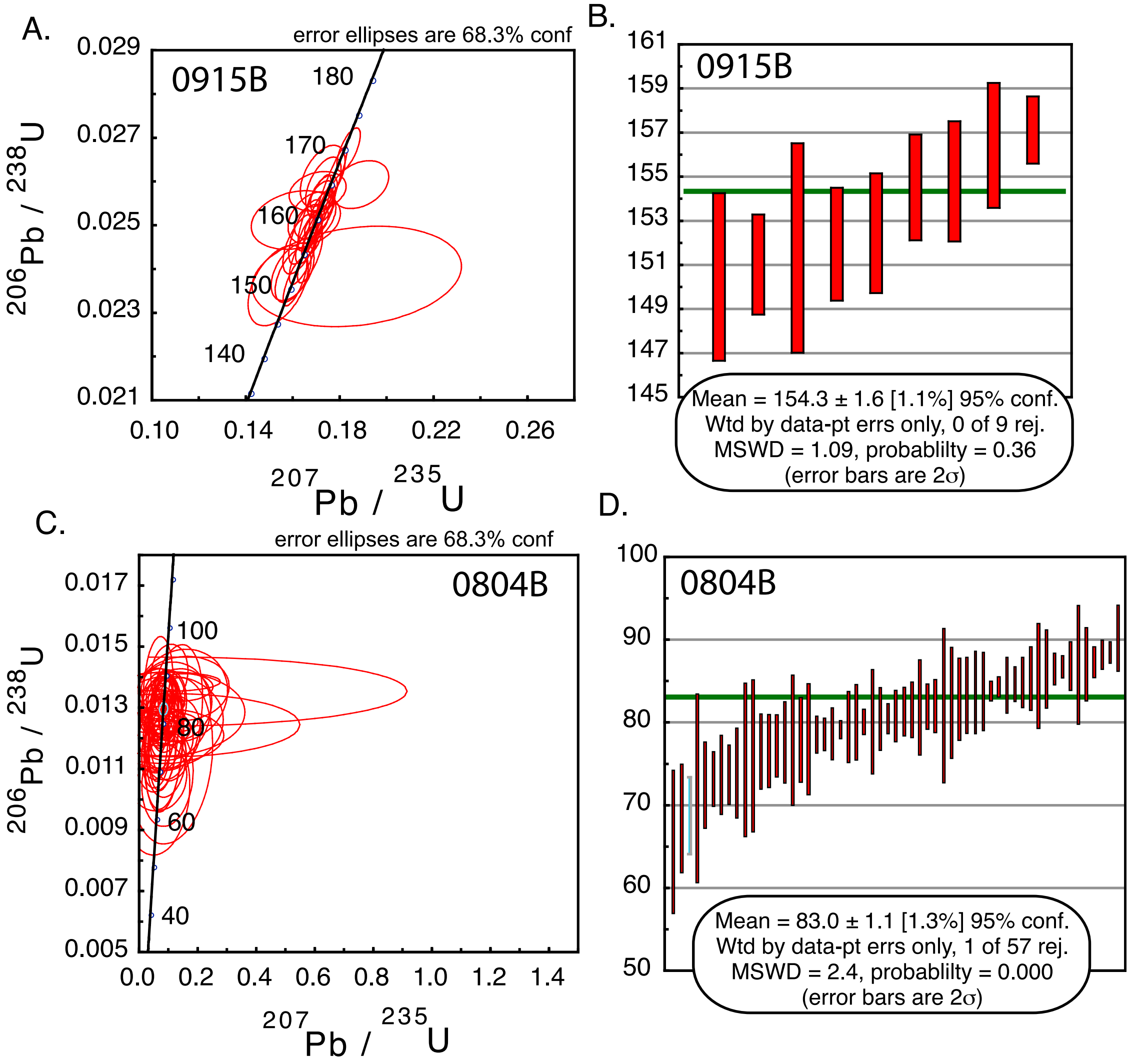

Figure 14. U-Pb isotopic data on zircon from two samples of igneous dikes. (a) Concordia plot and (b) calculated mean with errors reported at the 2σ level for sample 0915 from Seno Otway (sample location in Figure 2). (c) Concordia plot and (d) calculated mean with errors reported at the 2σ level for sample 0804B from Bahía Brookes (sample location in Figure 3).

lying rocks of the Latorre and Escarpada formations at this site must be younger than ~83 Ma.

[47] Sample 0998D (Figure 2) is a lithic arkosic wacke from top of the Latorre Formation, several meters below its contact with the Escarpada. The analysis of 85 grains yielded a dominant peak (n = 75) in the range 84–112 Ma and a youngest unmixed component at 89.4 ± 1.5 Ma (MSWD = 0.983) (Figure 12a). The youngest five grains provided an unmixed component at 86.3 ± 4.7 Ma (with MSWD = 0.033). Several subordinate peaks occur within the ranges 130–144 Ma and 400–588 Ma. Two Proterozoic grains (>1.2 Ga) also were obtained from the sample. An evaluation of the youngest unmixed component suggests that the overlying rocks of the Escarpada Formation are at least younger than ~88 Ma.

[48] Sample 0915B (Figure 3) is a plagiogranite dike that intrudes a host of interlayered olivine-bearing gabbro and massive basalt that form part of the suite of rocks interpreted to represent the mafic floor of the Rocas Verdes basin [cf. *Calderón et al.*, 2007]. An analysis of 28 zircon grains (Figure 14a) provided an average age of 159.9 ± 1.7 Ma (MSWD = 4.1) for the dike. A weighted average of the youngest component (n = 9 grains) yielded 154.3 ± 1.6 Ma (MSWD = 1.09) (Figure 14b), which we take to be the best estimate of the igneous crystallization age. Two grains yielded older Precambrian and Paleozoic cores. The average crystallization age confirms that the plagiogranite dike intruded during the opening of the Rocas Verdes basin. The plagiogranite forms a part of a bimodal mafic-felsic magmatic suite [cf. *Calderón et al.*, 2007] that was emplaced during the early stages of rifting.

6.2.2. Peninsula Brunswick

[49] Sample 0864A (Figure 2) is a lithic arkosic wacke from near the base of the Latorre Formation. The analysis of 84 grains yielded a dominant peak (n = 62) in the range 91–152 Ma and a youngest unmixed component at 96.2 ± 1.9 Ma (MSWD = 0.36) (Figure 12e). Several subordinate peaks occur within the ranges 216–292 Ma, 354–423 and 479–

545 Ma. Two Precambrian grains also were obtained. The youngest unmixed component indicates that the overlying rocks are younger than ~94.3 Ma.

[50] Sample 0865 is a lithic arkosic wacke from the lower part of the Escarpada Formation. The analysis of 77 grains yielded a dominant peak (n = 72) in the range 77–141 Ma and a youngest unmixed component at 81.0 ± 1.2 Ma (MSWD = 0.68) (Figure 12d). Five older zircon grains at ~213, ~266, ~409, ~522, and ~702 Ma also were recovered. The youngest unmixed component indicates that the overlying rocks must be younger than ~79.8 Ma and that the contact between the Latorre and Escarpada formations at this location is slightly older than 81.0 ± 1.2 Ma.

6.2.3. Bahía Brookes

[51] Sample 0805A is from a coarse-grained sandstone layer within a lithofacies 2 mudstone in the bottom part of the lower La Paciencia Formation (Figure 5). The analysis of 92 grains (Figure 12i) yielded a relatively simple detrital zircon spectra with two broad peaks of Mesozoic age. Sixty seven grains form one dominant population (68–96 Ma) with a weighted average of 85.0 ± 1.3 Ma (MSWD = 3.7). A second subordinate peak in the range 102–141 Ma is centered on ~122 Ma. The youngest peak can be unmixed into several components, the youngest of which is 71.4 ± 4.7 Ma (MSWD = 1.02) (Figure 12i). However, this unmixed age appears to be too young for this unit. The paleontological age of the top of La Paciencia Formation, indicated by the presence of *Inoceramus* along the shores of Seno Almirantazgo, is Turonian (93.5–89.3 Ma) (Empresa Nacionál del Petróleo, unpublished data, 2010). It is possible that the large analytical errors associated with the youngest zircon grains (typically about ±5 to ±10 Ma) hide some amount of lead loss. Regardless, the weighted average of the dominant peak indicates, conservatively, that the overlying rocks are younger than ~85 Ma. If the youngest unmixed ages are correct the overlying strata may be even younger.

[52] Sample 0850 is a coarse-grained sandstone from the base of the upper La Paciencia Formation (Figure 3). The analysis of 84 grains yielded a dominant peak (n = 68) with a weighted average of 88.49 ± 0.61 Ma (Figure 12h). This peak can be unmixed into several components, the youngest of which is 81.7 ± 3.6 Ma (MSWD = 0.94) (Figure 12h). Several subordinate peaks occur in the range 255–564 Ma. Like sample 0805, the age of the youngest unmixed component appears young, possibly because the large analytical errors (with some ±4 to ±7 Ma) hide some lead loss. The weighted average of the dominant peak suggests that the overlying rocks are younger than 88–89 Ma. If the youngest unmixed age is correct, the overlying rocks may be as young as ~85 Ma.

[53] Sample 0822 is from a massively bedded, medium-grained lithic arkosic wacke sandstone at the base of the Cerro Matrero Formation (Figure 5a). The analysis of 98 grains yielded a broad spectra of Mesozoic ages (n = 40) in the range 82–145 Ma, a relatively narrow peak in the range 252–297 Ma, and a broad group of ages in the range 424–669 Ma (Figure 12g). Eighteen grains of Precambrian age range form minor peaks in the range 739–2977 Ma. The Mesozoic spectra can be unmixed into several components, with the youngest component at 82.7 ± 1.5 Ma (MSWD = 0.15). This youngest component provides an estimate of the maximum depositional age of the top of the upper La Paciencia Formation at this locality and indicates that the overlying rocks of the Cerro Matrero Formation are younger than ~81 Ma. The broad spectrum of peaks indicates a complex source of mixed provenance.

[54] Sample 1032 is a coarse lithic arkosic wacke sandstone from the middle or middle-lower Cerro Matrero Formation, below the unconformity mapped near the mouth of Bahía Brookes (Figure 5a). The analysis of 86 grains yielded a broad spectra of Mesozoic ages (n = 68) in the range 80–140 Ma (Figure 12f). A dominant peak in the range 80–115 Ma yielded a youngest unmixed component at 86.0 ± 2.4 Ma (MSWD = 0.88). Subordinate peaks occur in the ranges 364–446 Ma and 566–701 Ma. Several Proterozoic and Archean grains also were retrieved. The youngest unmixed component suggests that the overlying rocks are younger than ~83.6 Ma.

[55] Sample 0804 is from a granite dike that intrudes mudstone of the lower La Paciencia Formation (Figure 5a). The analysis of 57 grains yielded no sign of inheritance and provide a weighted average igneous crystallization age of 83.0 ± 1.1 Ma (MSWD = 2.4) (Figures 14c and 14d). This result confirms that the granite belongs to the Cretaceous Beagle suite [*Nelson et al.*, 1980; *Hervé et al.*, 1984; *Klepeis et al.*, 2010]. This locality represents the northernmost known occurrence of granitic rocks of the Beagle suite on Tierra del Fuego.

7. Discussion

7.1. Rocas Verdes Back-Arc Basin

[56] The Zapata/Canal Bertrand, Río Jackson and lower La Paciencia formations all record sediment deposition on the northeastern (present coordinates) flank of the Rocas Verdes back-arc basin. The lithofacies associations in these units suggest slow hemipelagic sedimentation with the periodic influx of fine-grained, low density turbidites. This interpretation is similar to that made by *Fildani and Hessler* [2005] and *Calderón et al.* [2007] who concluded the Zapata Formation in the Ultima Esperanza region (UE, Figure 1) records deep-water (~2500 m) deposition in a sediment-starved basin rather than an outer shelf or slope setting. The trend of decreasing repetitive turbidite deposition (lithofacies association 1) to primarily hemipelagic mud accumulation (lithofacies association 2) observed in the lower La Paciencia Formation (Figure 5a) on Tierra del Fuego indicates deepening during deposition in the Rocas Verdes basin. The cause of this deepening is undetermined and could reflect eustatic and/or tectonic changes.

[57] In addition to depositional setting, the exposures at Bahía Brookes (Figure 3) provide the first measure of the thickness (1700 m) of the muddy fill of the Rocas Verdes basin in northern Cordillera Darwin and confirm that it is nearly twice as thick on Tierra del Fuego than in Ultima Esperanza. This observation is consistent with an asymmetric basin architecture whereby the southern part of the basin was wider, experienced greater subsidence, and accumulated more mud-dominated sediment than its northern end [*Dott et al.*, 1982] (Figure 15a). The asymmetry is important, as discussed in detail below, because of its potential influence on subsequent patterns of sedimentation in the Magallanes foreland basin.

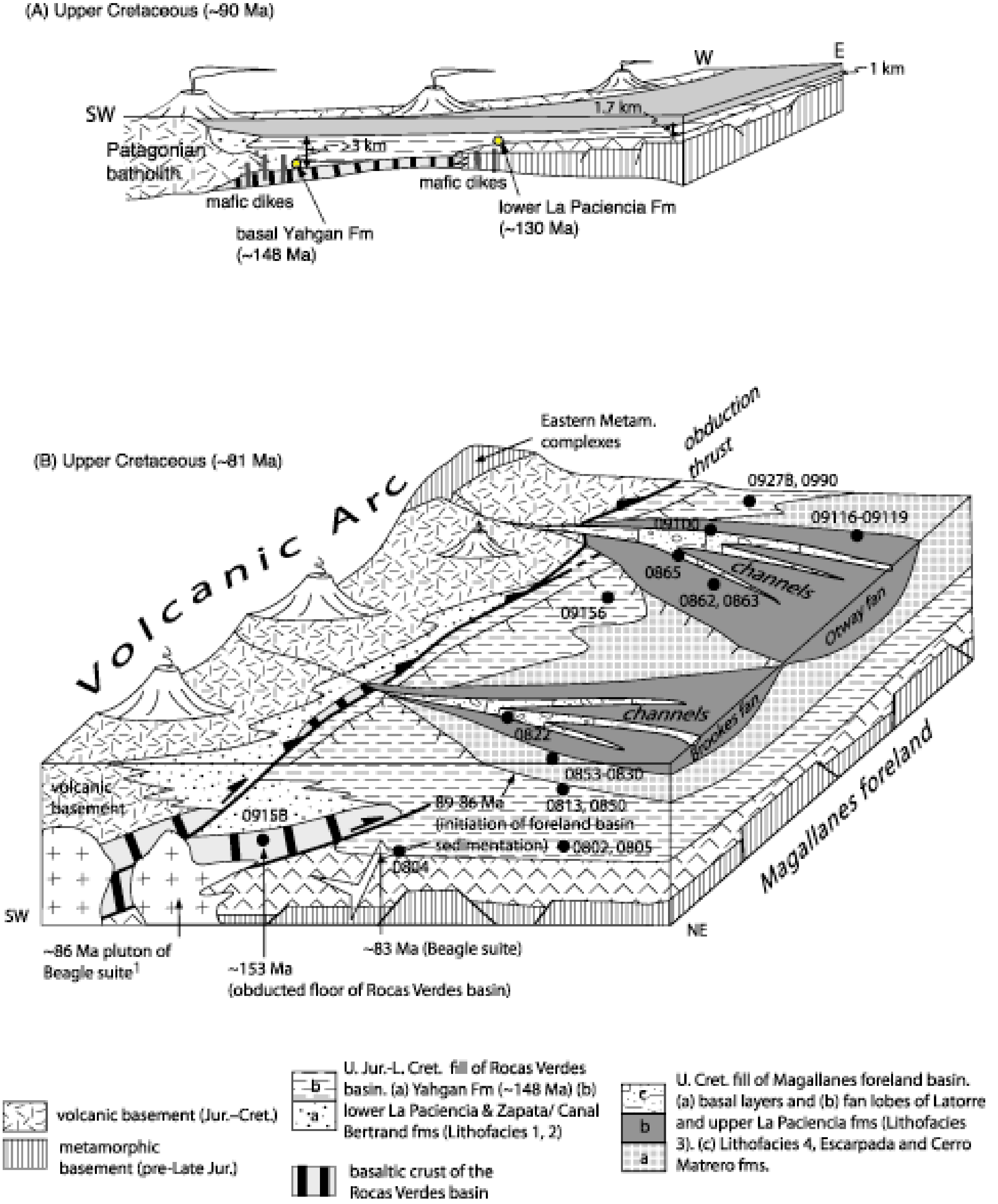

Figure 15. Block diagrams illustrating (a) asymmetric geometry of the Rocas Verdes back-arc basin at its apex (~90 Ma), including an increasing width and thickness of Lower Cretaceous fill to the south and southwest. Age of basal Yahgan Formation is from *Klepeis et al.* [2010]. The ~130 Ma age is from southern Cordillera Darwin [*Hervé et al.*, 2010]. (b) Preferred interpretation of the depositional environment and sediment dispersal pattern in the early Magallanes foreland basin at ~81 Ma, when deposition of basal cobble conglomerates began. Age of thrust that places basaltic floor of the Rocas Verdes basin (obduction) on top of Yahgan and lower La Paciencia formations is from *Klepeis et al.* [2010]. Black dots show relative positions of sample sites. Horizontal distances are not to scale.

[58] As noted in Section 5.2, because sandstone is rare to absent in the Ultima Esperanza region, Figures 11a and 11b show the first modal analyses from units deposited on the northeastern flank of the Rocas Verdes basin. These data are significantly different than those from the Lower Cretaceous Yahgan Formation on Tierra del Fuego, which represents the southwestern flank of the basin. *Barbeau et al.* [2009b] showed that the upper part of this latter unit contains Cretaceous (130–105 Ma) U-Pb zircon age populations, indicating it is coeval with the deposition of at least a part of the Zapata and lower La Paciencia formations. *Winn* [1978] found that 95% of sandstones in the Yahgan Formation consist of volcanic lithic clasts with lesser amounts of plagioclase and small quantities of quartz. These latter rocks, thus, are more lithic rich than we observed and plot within the '*undissected arc*' and '*transitional arc*' fields of a QFL diagram (Figure 11a). Although both data sets indicate the presence of an active volcanic arc south of the Rocas Verdes basin [*Winn*, 1978; *Suárez et al.*, 1985; *Barbeau et al.*, 2009b], the compositional differences may reflect the relative unavailability of deeply buried silicic volcanic rock of the Upper Jurassic Tobífera Formation as a source during the deposition of most of the Zapata/Canal Bertrand and lower La Paciencia formations, or a more proximal position relative to the arc for the Yahgan Formation. The differences also could reflect a partitioning of the Rocas Verdes basin by a horst and graben topography developed during rifting, an interpretation suggested by *Fildani and Hessler* [2005] to explain contrasts between approximately coeval units in Ultima Esperanza versus those on Tierra del Fuego.

[59] In addition to a volcanic arc to the south, some previous workers [e.g., *Winn*, 1978; *Dott et al.*, 1982; *Wilson*, 1991] interpreted cratonic (easterly) sources for the Rocas Verdes basin fill. In contrast, *Fildani and Hessler* [2005] found no indication of easterly sources in Ultima Esperanza. Instead these authors interpreted source terrains composed mostly of ophiolitic crust and volcanic rock of the underlying Upper Jurassic Tobífera Formation. The data from the central and southern sectors of the basin align more with the latter interpretation in the sense that detrital zircon spectra (Figures 12 and 13) reveal a paucity of pre-Mesozoic ages and mudstones do not exhibit the degree of light-to-heavy REE fractionation expected for felsic cratonic sources (Figures 11c and 11d) [cf. *Fildani and Hessler*, 2005]. Metamorphic basement appears to have been buried and not eroding significantly during deposition of the Zapata/Canal Bertrand and lower La Paciencia formations in the south. Instead, the basaltic floor of the basin, its sedimentary cover, and detritus from the volcanic arc and its plagioclase-rich, quartz-poor basement were primary sources. The Upper Jurassic Tobífera Formation also could have contributed some material early in the back-arc basin's history, particularly during deposition of the lower Yahgan Formation [*Klepeis et al.*, 2010]. Thus, although the Rocas Verdes basin may have been locally partitioned, areas characterized by significant proximal cratonic sources, if they existed, have yet to be identified.

7.2. Initiation of Magallanes Foreland Basin Sedimentation

[60] The demise of the Rocas Verdes back-arc basin and the beginning of sedimentation in the Magallanes foreland basin in central and southern Patagonia is marked by the appearance of two types of turbiditic sandstone at the base of the Latorre and upper La Paciencia formations, respectively (Figures 5 and 7). These types, defined in section 3.1.1, record a spectrum of low and high density turbidity current deposition with depositional settings ranging from inner to outer fan lobes (Figure 15b). Because they represent the start of turbiditic sand deposition on a fan lobe, these successions mark the beginning of fan growth in the Magallanes foreland basin (see also Figure 14 of *Fildani and Hessler* [2005]). Sandstone modal analyses (Figures 11a and 11b) confirm our placement of the stratigraphic transitions, which are several tens of meters thick, by showing changes in rock composition and provenance up-section across the tops of these two units. The geochemistry of mudstones from Seno Otway and Peninsula Brunswick (Figure 11c) show similar changes. Detrital-zircon spectra also show increases in population complexity up-section within these units in all areas (Figures 12 and 13). *Mpodozis et al.* [2007] reported similar increases in detrital zircon spectra complexity up section at Seno Skyring. These patterns indicate that the transition zones record an evolution in provenance on a basin-wide scale (i.e., >500 km along the strike of the orogen) and are tectonic in origin.

[61] Although the first sediments of the Magallanes foreland basin show more compositional variation and a greater diversity in sources than the underlying Rocas Verdes basin sediments, the specific characteristics of these changes are spatially variable. In Ultima Esperanza, >40% of the Punta Barrosa Formation was sourced from a volcanic arc that was active during the period 115–90 Ma; with the rest sourced from Paleozoic metamorphic complexes and the basaltic floor of the Rocas Verdes basin [*Fildani et al.*, 2003; *Fildani and Hessler*, 2005]. Sandstones from this region show mixed sources, with most plotting in the *recycled orogen* field, and a few plotting in the *dissected arc* field of a QFL diagram (Figure 11a). In contrast, rocks from Tierra del Fuego show that Paleozoic metamorphic rocks and the basaltic floor of Rocas Verdes basin contributed much less to this unit than farther north. Instead, most of the upper La Paciencia Formation was sourced from a younger (<90 Myr) volcanic arc and recycled sedimentary cover from the underlying sedimentary fill of the Rocas Verdes basin. This interpretation is supported by the detrital zircon age spectra (Figures 12 and 13), the sandstone modal analyses, and the mudstone geochemistry (Figure 11). The data also show that significant differences in unit compositions and provenance exist between Seno Otway and Bahía Brookes. Mudstones in the former region exhibit a geochemical signature that is most similar to that from Ultima Esperanza, but they are dissimilar in their detrital zircon spectra and petrography (Figure 11). These patterns illustrate a southeasterly increase in the degree of complexity in the provenance and composition of the units that record the beginning to turbidite sedimentation within the Magallanes basin.

[62] Paleocurrent data from measured sections indicate that sediment dispersal patterns were more complex in the south central Magallanes foreland basin than in Ultima Esperanza. In the latter area, flow and sediment transport during deposition of the Punta Barrosa Formation [*Fildani and Hessler*, 2005] generally was south directed in a narrow,

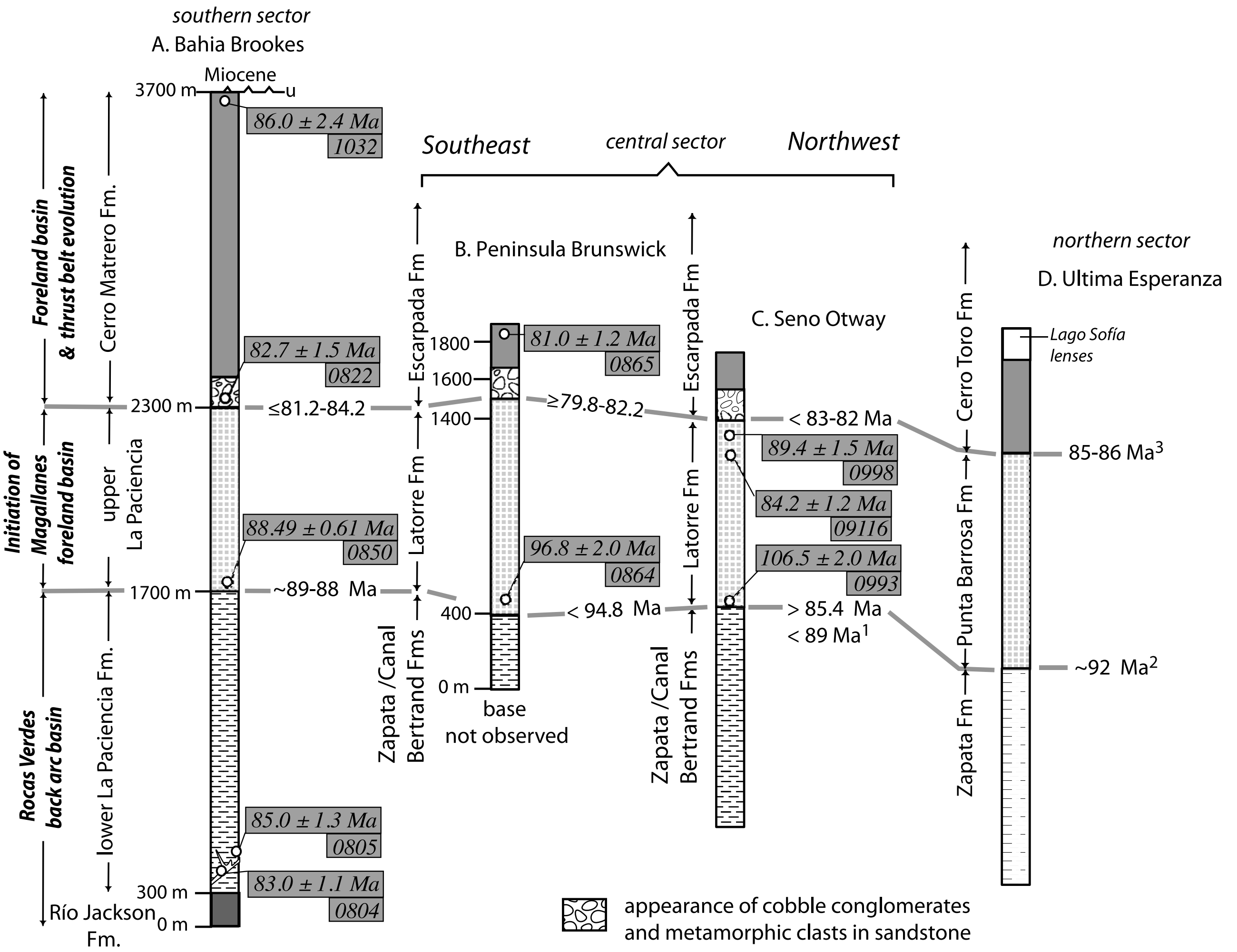

Figure 16. Stratigraphic correlations across the southern, central, and northern sectors of the Magallanes basin and interpreted significance. (a) Bahía Brookes. (b) Peninsula Brunswick. (c) Seno Otway. (d) Ultima Esperanza. Sources are as follows: 1, *Castelli et al.* [1993] and *Mpodozis et al.* [2007]; 2, *Fildani et al.* [2003]; 3, *Romans et al.* [2011].

elongate fan (4–8 km wide by >100 km long) that paralleled the trend of the orogen. Above the Punta Barrosa at this northern locality, the Cerro Toro Formation records an elongate, sinuous submarine fan within the narrow Magallanes foreland basin [*Hubbard et al.*, 2008] where the confinement of flows to a narrow trough by a topographic high to the east resulted in unidirectional paleocurrents to the south and southeast in all deposits [*Bernhardt et al.*, 2011]. In contrast, our measurements show multiple flow directions, including transport parallel to, oblique to, and across the axis of the young orogen (Figures 2 and 3). These differences could reflect either separate fans or a diversity in flow directions that is common in large submarine fans. They suggest either (1) the elongate fan evident in Ultima Esperanza developed later farther south or (2) the Latorre and upper La Paciencia formations record a greater diversity of fan environments (i.e., overbank and lobe) where turbidites, coming from a network of small channels, flowed at high angles relative to other orogen-parallel channel axes. We prefer the second interpretation because of the distinctive submarine channel systems and pronounced differences in rock composition and provenance. We suggest that spatial variability in these elements, plus the increased complexity of sediment dispersal patterns from north to southeast, are best explained by the presence of multiple fans (Figure 15b). In this context, it is possible that any orogen-parallel channels remained underdeveloped because the confining influence of the adjacent basin slopes was not as great in the south where the Rocas Verdes basin was wider [cf. *Hubbard et al.*, 2008; *Bernhardt et al.*, 2011].

[63] In addition to provenance, the detrital zircon age spectra (Figures 12 and 13) allowed us to infer when sedimentation in the central and southern parts of the Magallanes basin began. As with the sandstone compositions, these spectra show increased population complexity and changes in provenance up-section from the bases of the Latorre and upper La Paciencia formations, indicating they are sensitive to the beginning of turbidite sedimentation in the Magallanes foreland basin. The most conservative interpretation of the ages obtained from Bahía Brookes (samples 0805 and 0850) is that on Tierra del Fuego foreland basin sedimentation began after 88–89 Ma (Figure 16a). This estimate is derived from the weighted mean of the dominant peak of ages from sample 0850 (Figure 12h),

which has the lowest analytical errors and is from several meters above the basal turbidites in the transition zone (Figure 16a). However, if the youngest unmixed age from this same sample is correct, then the initiation of turbidite sedimentation on Tierra del Fuego could be even younger, beginning after ~85 Ma.

[64] The <88–89 Ma age of the first sediments deposited into the Magallanes basin on Tierra del Fuego agrees with detrital zircon ages reported by *Mpodozis et al.* [2007], which suggest the base of the Latorre Formation at Seno Skyring also is ~89 Ma or younger. This similarity suggests that foreland basin sedimentation could have initiated approximately simultaneously at these two localities, at least 2–3 Myr after it did in the Ultima Esperanza region. However, if the youngest unmixed ages from Bahía Brookes are correct (samples 0850, 0805), the onset of foreland basin sedimentation on southern Tierra del Fuego may be significantly younger (i.e., after ~85 Ma) than it is in both Seno Skyring (~89 Ma) and in Ultima Esperanza (~92 Ma). These relationships indicate that sedimentation in the Magallanes foreland basin at Bahía Brookes began several millions of years after it did at the northern end of the basin (Figures 16a and 16d). Thus, although we cannot rule out the possibility that the later arrival of turbidites at Bahía Brookes partly reflects its paleogeographic position within the basin, the data point to significant spatial and temporal differences in the evolution of the northern and southern parts of the Magallanes basin.

7.3. Initiation and Growth of the Magallanes Fold-Thrust Belt

[65] The ages of the first faults to form in the Magallanes fold-thrust belt are poorly known. In Ultima Esperanza, *Fildani and Hessler* [2005] used the arrival of the first fine- to medium-grained sandstone horizon and geochemical data to suggest that contraction began during deposition of the uppermost Zapata Formation. *Fosdick et al.* [2011] reported a U-Pb zircon age from volcanic ash in the Zapata–Punta Barrosa transition zone indicating that thrust belt formation was underway by ~101 Ma. *Mpodozis et al.* [2007] also reported tight folds in the Canal Bertrand Formation at Seno Skyring that formed prior to deposition of Latorre Formation that support with this interpretation. In southern Cordillera Darwin, crosscutting relationships between granite plutons and faults indicate that the first thrusts to place the basaltic floor of the Rocas Verdes basin onto continental crust formed prior to ~86 Ma [*Klepeis et al.*, 2010]. In northern Cordillera Darwin, the appearance of thick turbidite sands by 88–89 Ma evince the presence of a well-developed thrust belt by this time. These relationships support flexural subsidence models of the foreland basin [*Biddle et al.*, 1986; *Wilson*, 1991] by suggesting that the onset of turbidite sedimentation coincided with the partial obduction of the Rocas Verdes basaltic floor. They also are consistent with interpretations [*Fildani and Hessler*, 2005; *Romans et al.*, 2010; *Fosdick et al.*, 2011] that the onset of turbidite sedimentation in the Magallanes basin represents an evolution in the fold-thrust belt related to the obduction, implying that contraction began during the last stages of deep-water deposition in the Rocas Verdes basin.

[66] Although fan growth and the arrival of thick turbidites into the Magallanes basin most likely coincided with the obduction of the Rocas Verdes basin floor, the mudstone and sandstone compositions from Bahía Brookes indicate that this basaltic crust initially was not a substantial source of sediment on Tierra del Fuego like it was farther north. At the beginning of the Late Cretaceous, the basaltic floor of the southern Rocas Verdes basin and other older rocks appear to have been deeply buried and mostly unavailable as sources when turbidite sedimentation in the southern sector of the Magallanes basin began. *Klepeis et al.* [2010; Figure 12] showed that when the obduction occurred, the fold-thrust belt was a narrow, ~60 km wide, topographically subdued wedge on the southern side of the Rocas Verdes basin adjacent to the volcanic arc. The provenance data presented here confirm that the basaltic floor and rock units that predate the opening of the Rocas Verdes basin, including metamorphic complexes and the Upper Jurassic Tobífera Formation, experienced little uplift and erosion during the deposition of the Latorre and upper La Paciencia formations.

[67] By 81–80 Ma, the appearance of conglomerate horizons and increased complexity in rock composition and provenance, which is evident in both the sandstone modal analyses and detrital zircon populations, mark the transition into the overlying units of the Magallanes basin (Figure 16). These units (i.e., the Escarpada and Cerro Matrero formations) contain chlorite and mica clasts that are larger and more abundant than those of the underlying formations (Figure 11). Grains of this composition are abundant in the Rocas Verdes ophiolitic rocks exposed south of Tierra del Fuego [*Suárez et al.*, 1985; *Cunningham*, 1994; *Klepeis et al.*, 2010], suggesting that the basaltic floor of the Rocas Verdes basin, which previously did not contribute much to the foreland basin, was emergent and eroding by 81–80 Ma. This result supports the interpretation of *Fildani and Hessler* [2005], who suggested that obducted ophiolitic blocks were among the first components of the fold-thrust belt to be exposed west of the basin. However, in the south this distinctive period of emergence appears to have occurred later than in the south by approximately ten million years, possibly because of the greater thickness of sediment overlying basaltic crust.

[68] The use of the detrital zircon record of the Magallanes basin to infer aspects of the history of the Magallanes fold-thrust belt on Tierra del Fuego, invites comparison with other similar studies conducted in Ultima Esperanza. Using detrital zircon spectra, *Romans et al.* [2010] inferred that thrust sheets uplifting Upper Jurassic igneous rocks of the Tobífera Formation (147–155 Ma) were not emergent and eroding during deposition of the Punta Barrosa Formation. This conclusion is identical to the one we reached for the Latorre and upper La Paciencia formations in the south. *Romans et al.* [2010] also concluded that the Tobífera Formation began to be a significant source of detritus into the Magallanes foreland basin only after ~85 Ma, during development of the Cerro Toro Formation conglomeratic axial channel system (Figure 16d). This latter interpretation also is similar to the one we reached on Tierra del Fuego, except that our detrital zircon spectra indicate that the Cerro Matrero Formation is not as rich in these and the other deeply buried rocks. Rather, the southern sector of the Magallanes foreland basin was receiving sediment derived mostly from rock units at shallower depths at this time,

again possibly because of the thicker fill of the Rocas Verdes basin. Thus, the incorporation and exhumation of the Tobífera Formation into the Magallanes fold-thrust belt appears to have occurred later in southern Patagonia than in the north by a few million years.

[69] This inferred kinematic history, where the uplift and emergence of the Tobífera Formation and other deeply buried rocks occurred later in southern Patagonia than in the north, is consistent with other studies of the Magallanes fold-thrust belt on Tierra del Fuego. *Klepeis et al.* [2010] showed that the small (~60 km wide) size of the thrust belt persisted until the Paleogene when a major period of out-of-sequence thrusting internally thickened, uplifted, and expanded the wedge. This event resulted in the uplift and exhumation of both metamorphic basement and the Upper Jurassic Tobífera Formation in Cordillera Darwin [*Nelson*, 1982; *Kohn et al.*, 1995; *Gombosi et al.*, 2009; *Klepeis et al.*, 2010], which contributed abundant sediment to the Magallanes basin by the middle to late Eocene [*Barbeau et al.*, 2009a]. Our study adds to this picture by revealing the progressive history of thrust belt uplift, growth, and emergence prior to this major Paleogene event.

8. Conclusions

[70] Mud-dominated successions deposited on the northern and eastern flanks of the Rocas Verdes back-arc basin record slow hemipelagic sedimentation with the periodic influx of fine-grained, low density turbidites. The abundance of feldspar clasts and types of lithic fragments indicate that a volcanic arc was located south and west of the basin (present coordinates) throughout the late Jurassic and Cretaceous. The sediments filling the Rocas Verdes basin are nearly twice as thick on Tierra del Fuego (1700 m) than in Ultima Esperanza, reflecting an asymmetry whereby the southern part of the back-arc basin was wider, experienced greater subsidence, and accumulated more sediment than its northern end.

[71] The stratigraphic transitions that mark the tectonic inversion of the Rocas Verdes back-arc basin and the beginning of sedimentation in the Magallanes foreland basin are traceable for at least 700 km along the strike of the Patagonian Andes. Vertical changes in lithofacies associations across transition zones that are at least several tens of meters thick record the beginning of turbiditic sand deposition and fan growth in the nascent foreland basin. In all localities changes in rock composition and provenance occur up-section across these transition zones, indicating that they have tectonic significance and are related to the partial obduction of the basaltic floor of the Rocas Verdes back-arc basin. Nevertheless, the specific characteristics of the transition zones are spatially variable. The first sediments of the Magallanes basin record increasing degrees of complexity in composition and provenance from north to the southeast. On Tierra del Fuego, Paleozoic metamorphic rocks and the basaltic floor of Rocas Verdes back-arc basin contributed much less to this unit than in the north, probably because of the thicker sedimentary fill of the Rocas Verdes basin in the south. On Tierra del Fuego they were sourced mostly from a younger (<90 Myr) volcanic arc and recycled sedimentary fill of the Rocas Verdes basin. The southern Magallanes basin also records a greater diversity of fan environments and more complex sediment dispersal patterns compared to patterns observed farther north, further suggesting the presence of multiple fans.

[72] The onset of turbiditic sand deposition and fan growth in the Magallanes foreland basin began after 88–89 Ma (and possibly after ~85 Ma) at Bahía Brookes on Tierra del Fuego, allowing the onset of foreland basin sedimentation there to be at least 2–3 Myr (and possibly up to 7 Myr) younger that at its northern end. This appearance of thick turbidite sands evinces the presence of a well-developed thrust belt by this time, supporting interpretations that contraction began a few million years earlier. By 81–80 Ma, the appearance of cobble conglomerates and increased complexity in rock composition and provenance indicate that the basaltic floor of the Rocas Verdes basin first became emergent and was eroding during another period of fold-thrust belt growth. The data allow this latter period to have occurred later in southern Patagonia than in the north by ~10 Myr. The data suggest that the onset of sedimentation in the Magallanes foreland basin and the progressive uplift and exhumation of Upper Jurassic igneous rocks of the Tobífera Formation and the basaltic floor of the Rocas Verdes basin all were diachronous within the Patagonian Andes.

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