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Importance of predecessor basin history on the sedimentary fill of a retroarc foreland basin: provenance analysis of the Cretaceous Magallanes basin, Chile (50–52°S)

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ABSTRACT

An integrated provenance analysis of the Upper Cretaceous Magallanes retroarc foreland basin of southern Chile (50°30′–52°S) provides new constraints on source area evolution, regional patterns of sediment dispersal and depositional age. Over 450 new single-grain detrital-zircon U-Pb ages, which are integrated with sandstone petrographic and mudstone geochemical data, provide a comprehensive detrital record of the northern Magallanes foreland basin-filling succession (>4000-m-thick). Prominent peaks in detrital-zircon age distribution among the Punta Barrosa, Cerro Toro, Tres Pasos and Dorotea Formations indicate that the incorporation and exhumation of Upper Jurassic igneous rocks (*ca*. 147–155 Ma) into the Andean fold-thrust belt was established in the Santonian (*ca*. 85 Ma) and was a significant source of detritus to the basin by the Maastrichtian (*ca*. 70 Ma). Sandstone compositional trends indicate an increase in volcanic and volcaniclastic grains upward through the basin fill corroborating the interpretation of an unroofing sequence. Detrital-zircon ages indicate that the Magallanes foredeep received young arc-derived detritus throughout its *ca*. 20 m.y. filling history, constraining the timing of basin-filling phases previously based only on biostratigraphy. Additionally, spatial patterns of detrital-zircon ages in the Tres Pasos and Dorotea Formations support interpretations that they are genetically linked depositional systems, thus demonstrating the utility of provenance indicators for evaluating stratigraphic relationships of diachronous lithostratigraphic units. This integrated provenance dataset highlights how the sedimentary fill of the Magallanes basin is unique among other retroarc foreland basins and from the well-studied Andean foreland basins farther north, which is attributed to nature of the predecessor rift and backarc basin.

INTRODUCTION

A retroarc foreland basin is defined as an elongate trough that forms between a linear contractional orogenic belt, associated with an active arc, and a stable craton (DeCelles & Giles, 1996). The sedimentary fills of foreland basins have long been used to infer the palaeogeography and evolution of the adjacent, and dynamically linked, orogenic belt (e.g. Dickinson & Suczek, 1979; Schwab, 1986; Jordan *et al*., 1988; Jordan, 1995). The >7000-km-long Andean Cordillera of South America has been an important natural laboratory for addressing questions regarding the development and structural evolution of foreland fold-thrust belts (e.g. Jordan & Allmendinger, 1986; Ramos, 1988; Horton & DeCelles, 1997; Kley *et al*., 1999; Horton *et al*., 2002; DeCelles *et al*., 2007). However, the evolution of the Patagonian segment of the Andean orogenic belt (48–53°S), especially during Mesozoic initiation, is not as well constrained as segments farther north. Investigation of the sedimentary fill of the Upper Cretaceous Magallanes retroarc foreland basin provides an opportunity to evaluate >20 m.y. tectonic history of the orogenic belt. The improved temporal constraints on tectonic deformation in the source area also provide important contextual knowledge for understanding well-documented stratigraphic patterns.

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The Magallanes foredeep succession is the result of long-lived basin subsidence coupled with an abundant sediment supply, which produced an exceptionally complete basin fill (Fildani *et al*., 2009). The >4000-m-thick sedimentary succession is preserved near the eastern limit of the present-day Andean fold-thrust belt of the Ultima

Esperanza District, Chile (Fig. 1). The Mesozoic history of this region is characterized by a complex basin inversion from an early extensional phase (Rocas Verdes backarc basin) to a subsequent contractile phase (Magallanes retroarc foreland basin) associated with Andean orogenesis (Wilson, 1991; Fildani & Hessler, 2005). As a result of inherited attenuated crust associated with early extension, the Magallanes retroarc foreland basin floor subsided to $\sim$2000 m water depth (Natland *et al.*, 1974) and was filled by a significant thickness ($>$4000 m) of deep-marine sediments that are now exposed along the eastern margin of the Andean belt (Katz, 1963; Cortés, 1964; Natland *et al.*, 1974; Wilson, 1991). The focus of this study is the Upper Cretaceous (*ca*. 92–70 Ma) strata exposed in the northern part of the Magallanes basin (50°30′–52°S) (Figs 1 and 2). This succession accounts for accommodation related to initial bathymetric relief and much of the flexural subsidence in the evolving foreland.

The composition of foreland fold-thrust belts, especially during initiation, is significantly influenced by the nature of the preceding tectonic regime. Effects on basin configuration and foredeep subsidence patterns from the predecessor rift and backarc Rocas Verdes basin have been discussed by previous workers (Dott *et al.*, 1982; Wilson, 1991; Fildani & Hessler, 2005; Hubbard *et al.*, 2008; Romans *et al.*, 2009), but a detailed account of timing of emplacement and denudation of distinct geologic terranes in the fold-thrust belt during Turonian–Maastrichtian basin evolution has been lacking. The results of the integrated provenance analysis presented here afford an opportunity to examine basin-scale stratigraphic patterns with an enhanced understanding of source area evolution and regional sediment dispersal patterns.

GEOLOGIC FRAMEWORK

Late Jurassic rifting and backarc basin development

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). This rifting is recorded in the predominately silicic volcanic units of the El Quemado, Ibañez and Tobífera Formations (Figs 1 and 2) (Wilson, 1991; Féraud *et al.*, 1999; Pankhurst *et al.*, 2000, 2003; Calderón *et al.*, 2007). A backarc basin developed as a result of continued extension by the latest Jurassic to Early Cretaceous (Dalziel & Cortés, 1972; Dalziel *et al.*, 1974, 1981; Suárez, 1979; Fildani & Hessler, 2005; Calderón *et al.*, 2007). This basin (Rocas Verdes basin) was floored by quasi-oceanic crust represented by the mafic Sarmiento and Tortuga ophiolites, which have oceanic ridge basalt affinities (Fig. 1) (Allen, 1982, 1983; Stern, 1980; Alabaster & Storey, 1990; Calderón *et al.*, 2007). The continental arc system that developed along the western margin of southern South America in the Mesozoic is represented by igneous rocks of the Southern Patagonian Batholith (SPB), which dominates the southern Andean Cordillera between 40 and 56°S ($>$1700 km) (Fig. 1) (Stern & Stroup, 1982). Recent work suggests that juvenile arc batholith development is coeval with the latest Jurassic rhyolitic volcanism (Hérvé *et al.*, 2007). U–Pb ages from Calderón *et al.* (2007) confirmed that volcanism and rifting occurred at least between 152 and 142 Ma.

The Lower Cretaceous shale-dominated Zapata Formation conformably overlies the Tobífera Formation in the study area (Wilson, 1991) and records sediment-starved conditions for a minimum of 25 m.y., possibly reflecting a position in an isolated sub-basin (e.g. between inherited horst blocks) within the Rocas Verdes basin (Figs 1 and 2) (Fildani & Hessler, 2005). The Rocas Verdes basin was wider in the south and its northern limit is interpreted to be approximately 51°S (Katz, 1964; Dalziel & Cortés, 1972; Dalziel *et al.*, 1974; Wilson, 1991).

Late Cretaceous Magallanes retroarc foreland basin

The transition from the Late Jurassic–Early Cretaceous extensional Rocas Verdes backarc basin (Tobífera and Zapata Formations) to the Late Cretaceous contractile Magallanes retroarc foreland basin is suggested to be initiated as a result of increased spreading rates of the South Atlantic Ocean and corresponding increased subduction rates along the Pacific margin (Rabinowitz & La Brecque, 1979; Dalziel, 1986; Ramos, 1988). Crustal shortening led to the closure of the Rocas Verdes basin, development of the Andean fold-thrust belt, and associated foreland subsidence eastward of the active volcanic arc (Bruhn & Dalziel, 1977; Dott *et al.*, 1982; Wilson, 1991). Although detailed palaeogeographic reconstructions of the Rocas Verdes basin are hindered by structural overprinting as a result of fold-thrust belt shortening (Fildani & 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 (Katz, 1963).

Turbidites of the Upper Cretaceous Punta Barrosa Formation mark the onset of coarse-grained sedimentation, and thus foreland fold-thrust belt activity, in the northern Magallanes basin (Wilson, 1991; Fildani & Hessler, 2005). The timing of this onset, originally interpreted to be *ca*. 120–95 Ma based on limited biostratigraphic control (Cortés, 1964), was revised to a younger age (not older than 92 Ma) based on detrital-zircon ages (Fildani *et al.*, 2003). The Punta Barrosa Formation sediment has been interpreted to be derived from a mixed source containing arc-derived rocks and older metamorphic basement rocks (Fildani & Hessler, 2005).

Persistent subsidence coupled with abundant sediment supply as a result of denudation of the active arc and fold-thrust belt during the Late Cretaceous is recorded by the deep-water conglomeratic Cerro Toro Formation and over-

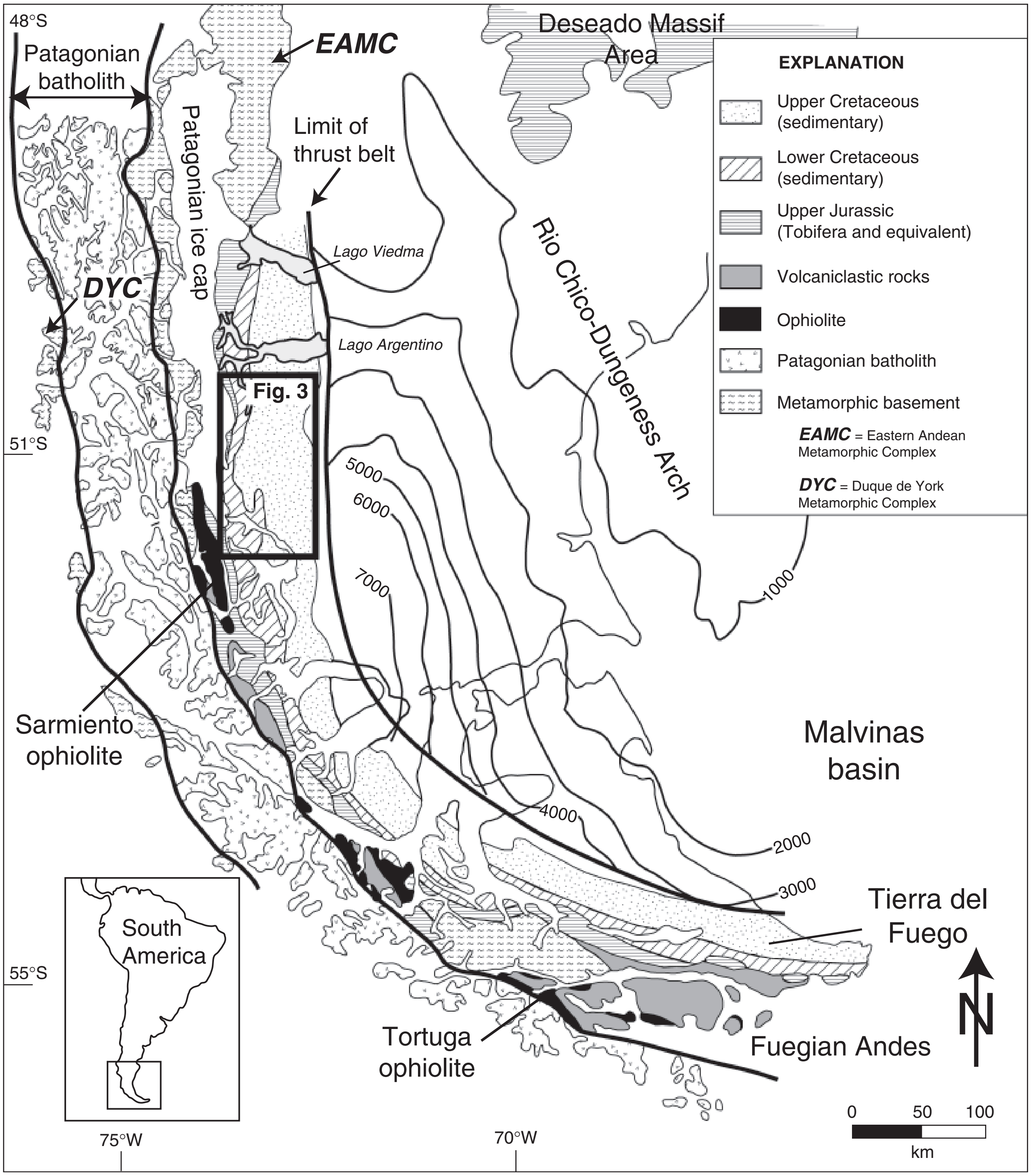

Fig. 1. Simplified geologic map of southern South America (from Fildani & Hessler, 2005; originally adapted from Biddle *et al*., 1986; Wilson, 1991; Thomson *et al*., 2001). Structure contour (in meters) on top of Jurassic Tobífera Formation (from Biddle *et al*., 1986). Study area (Ultima Esperanza District) denoted by rectangle (Fig. 3).

lying slope and deltaic systems of the Tres Pasos and Dorotea Formations, respectively (Figs 2 and 3) (Katz, 1963; Scott, 1966; Natland, 1974; Biddle *et al*., 1986; Wilson, 1991). Palaeocurrent data for the Punta Barrosa, Cerro Toro and Tres Pasos Formations indicate south to SE sediment dispersal (i.e. parallel to trend of fold-thrust belt), reflecting foreland subsidence patterns (Fig. 3) (Cortés, 1964; Scott, 1966; Smith, 1977; Winn & Dott, 1979; Fildani & Hessler, 2005; Shultz *et al*., 2005; Crane & Lowe, 2008; Hubbard *et al*., 2008; Armitage *et al*., 2009; Romans *et al*., 2009).

Cratonward (eastward) migration of the fold-thrust belt continued into the Cenozoic, which uplifted the Upper Cretaceous strata into its present position (Figs 1 and 3) (Biddle *et al*., 1986; Wilson, 1991; Ramos, 1996; Coutand *et al*., 1999; Ghiglione & Ramos, 2005). Compressional deformation generally decreases eastward and up section: the Punta Bar-

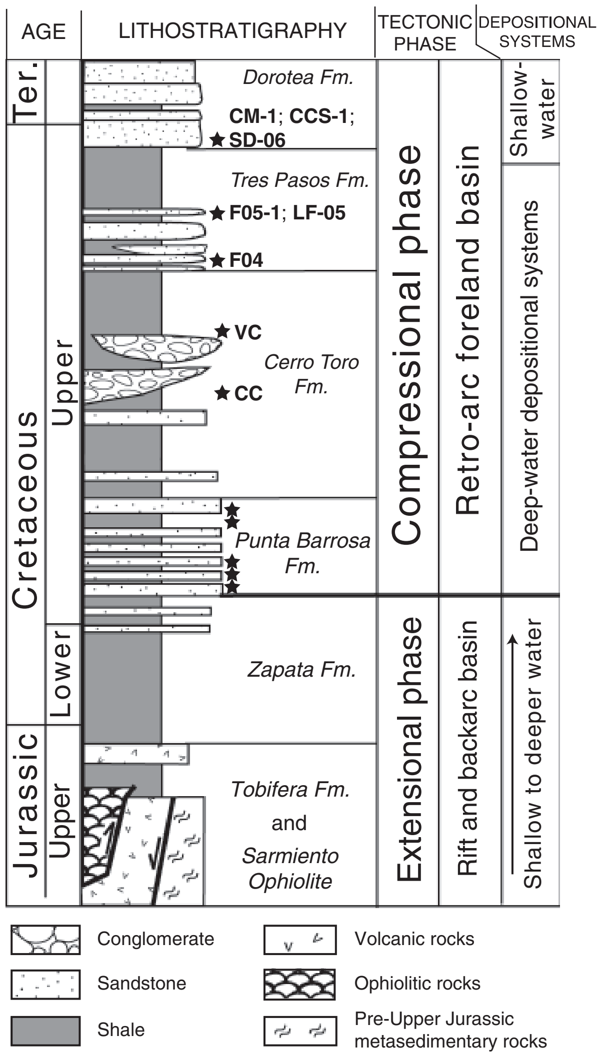

Fig. 2. Generalized stratigraphic column for the Magallanes basin in Ultima Esperanza District, southern Chile, showing approximate position of detrital-zircon samples (stars) used in this study. Major lithostratigraphic formations are associated with tectonic phases and basin types. The normal fault depicted in the Upper Jurassic section represents the extensional phase. The reverse fault depicted reflects interpreted inversion during subsequent compressional phase. Punta Barrosa Formation samples from Fildani *et al.* (2003); see Table 1 for sample names. Column modified from Fildani & Hessler (2005); originally adapted from Wilson (1991).

rosa and Cerro Toro Formations exhibit complex folding and faulting in some places, whereas the Tres Pasos and Dorotea Formations generally dip eastward into the subsurface along a north–south trending homocline (Fig. 3) (Katz, 1963; Winslow, 1982; Wilson, 1991; Shultz *et al.*, 2005).

METHODOLOGY

Detrital-zircon geochronology

This study relies primarily on detrital-zircon age analysis, which is supplemented by sandstone and mudstone compositional information. Single-grain detrital-zircon geochronology is an effective tool for addressing various geologic problems, including (1) constraining depositional age where biostratigraphy is poor and/or other dateable material is unavailable (e.g. Fildani *et al.*, 2003; Surpless *et al.*, 2006), (2) reconstructing general palaeogeographic (or more detailed palaeodrainage) patterns of sediment dispersal systems (e.g. DeGraaff-Surpless *et al.*, 2002; Link *et al.*, 2005; Weislogel *et al.*, 2006; Lease *et al.*, 2007; Dickinson & Gehrels, 2008) and (3) evaluating evolution of sediment source areas and associated tectonic implications (e.g. Gehrels & Dickinson, 1995; Stewart *et al.*, 2001; Sears & Price, 2003; Barbeau *et al.*, 2005). In many cases, all of these aspects can be evaluated with a single dataset.

Previous work has shown that the detrital record might contain biases associated with differential transport and deposition (e.g. Smith & Gehrels, 1994; Fedo *et al.*, 2003; DeGraaff-Surpless *et al.*, 2006). These inherent uncertainties can be minimized somewhat by sampling a broad range of depositional units within the sediment dispersal system. The samples for this study, and for the previous studies with which they are integrated, were collected in conjunction with detailed studies of sedimentology and stratigraphic architecture (Fildani & Hessler, 2005; Shultz *et al.*, 2005; Shultz & Hubbard, 2005; Crane & Lowe, 2008; Hubbard *et al.*, 2008; Armitage *et al.*, 2009; Covault *et al.*, 2009; Romans *et al.*, 2009). These studies provide information about depositional systems evolution, basin-scale stratigraphic organization and palaeocurrent patterns.

For this study, uranium–lead (U–Pb) ages for detrital zircons were obtained using the Sensitive High-Resolution Ion Microprobe-Reverse Geometry (SHRIMP-RG) at the Stanford University-USGS Micro-analytical Center. Detrital zircons were extracted from eight medium-grained sandstone samples (3–5 kg) collected from the Cerro Toro, Tres Pasos and Dorotea Formations (Figs 2 and 3; Table 1). The stratigraphic distribution of sampling is considered adequate because, although the basin-filling sequence is $\sim$4000 m thick, only $\sim$25–35% of that thickness is sandstone or coarser. Details of mineral separation procedures, grain treatment and documentation follow those of DeGraaff-Surpless *et al.* (2002).

Pb/U ratios were calibrated with reference to standard zircon R33 (R33 standard age of 419 Ma from a quartz diorite of the Braintree Complex, Vermont; Black *et al.*, 2004). We analysed *ca.* 60 grains for each of the eight samples, with the exception of one sample (F04; Table 1), achieving 95% confidence of finding at least one grain from every population that makes up at least 5% of the total sample population (Dodson *et al.*, 1988; Gehrels, 2000; DeGraaff-Surpless *et al.*, 2002). Multiple samples represent each lithostratigraphic formation analysed, thus increasing the total number of dated grains per formation to at least 120, which satisfies suggestions from recent work regarding statistical validity (Vermeesch, 2004). All reported ages and errors were calculated using the Squid data-reduction tool (Ludwig, 2000). Samples yielding ages <1000 Ma

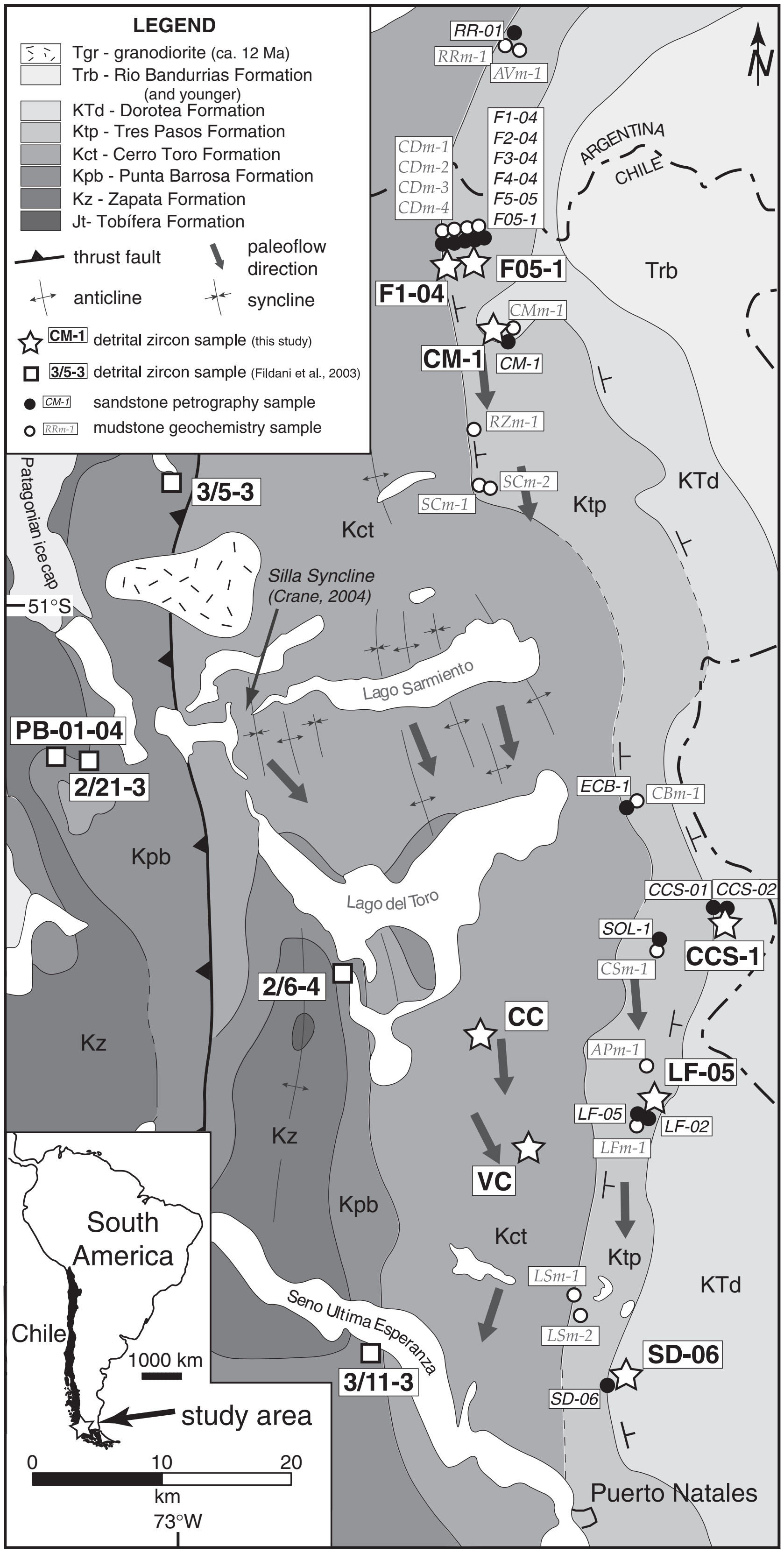

Fig. 3. Geologic map of Ultima Esperanza District showing locations for all detrital-zircon samples and for sandstone and mudstone samples for the Tres Pasos and Dorotea Formations. Cerro Toro Formation sandstone petrographic and mudstone geochemical data cited in text from Crane (2004) are from Silla Syncline outcrop locations. Refer to Fildani & Hessler (2005) for details regarding Zapata and Punta Barrosa Formation sample locations. Geologic map modified from Wilson (1991).

were corrected for common Pb using calculated ^{207}Pb, and were determined by the ^{206}Pb/^{238}U ratio, whereas those > 1000 Ma were corrected for common Pb using measured ^{204}Pb, and the ^{207}Pb/^{206}Pb ratio was used to determine the age. Age data are plotted as histograms with superimposed relative probability curves using Isoplot/Ex (Ludwig, 2003). All values are tabulated in the Supporting information.

Table 1. Magallanes basin detrital zircon samples used in this study

Formation (sample#)	Location	Stratigraphic position	#grains dated	Reference
Dorotea (KTd)				
SD-06	Sierra Dorotea	Lithostratigraphic base	60	This study
CCS-1	Cerro Cazador (south)	Lithostratigraphic base	59	This study
CM-1	Cerro Mirador	Lithostratigraphic base	60	This study
Tres Pasos (Ktp)				
LF-05	Laguna Figueroa	Upper part of sandstone-rich section	61	This study
F05-1	Cerro Divisadero	Upper part of sandstone-rich section	60	This study
F04	Cerro Divisadero	Lithostratigraphic base	40	This study
Cerro Toro (Kct)				
VC	Ventana Creek	Directly above conglomerate member	60	This study
CC	Cerro Castillo	Directly below conglomerate member	60	This study
Punta Barrosa (Kpb)				
3/11-3	Seno Ultima Esperanza	Uppermost sandstone-rich section	50	Fildani *et al.* (2003)
PB 01-04	Cerro Ferrier	Lower Punta Barrosa	28	Fildani *et al.* (2003)
3/5-3	Lago Dickson	Lower Punta Barrosa	60	Fildani *et al.* (2003)
2/6-4	La Peninsula	Uppermost sandstone-rich section	29	Fildani *et al.* (2003)
2/21-3	Refugio Pingo	Lower Punta Barrosa	53	Fildani *et al.* (2003)

Refer to Fig. 3 for map of samples.

Table 2. Proportions of detrital framework grains for Upper Cretaceous Tres Pasos and Dorotea formations in Ultima Esperanza District, southern Chile

Sample	Formation	Location	Q	F	L	Qm	F	Lt	Qp	Lv	Ls
RR-01	Tres Pasos (Alta Vista)	Rio Roca	23	22	55	19	22	59	8	88	5
F1-04	Tres Pasos	Cerro Divisadero	28	23	49	26	23	51	4	81	15
F2-04	Tres Pasos	Cerro Divisadero	23	21	56	21	21	58	5	86	9
F3-04	Tres Pasos	Cerro Divisadero	28	25	47	24	25	51	8	74	18
F4-04	Tres Pasos	Cerro Divisadero	25	18	57	23	18	59	3	82	15
F5-04	Tres Pasos	Cerro Divisadero	20	27	53	20	27	53	0	84	16
F05-1	Tres Pasos	Cerro Divisadero	23	27	50	22	27	52	3	89	8
CM-1	Dorotea	Cerro Mirador	25	18	57	24	18	58	2	91	7
ECB-1	Tres Pasos	El Chingue Bluff	28	24	48	26	24	50	3	91	6
CCS-01	Dorotea	Cerro Cazador south	14	20	66	12	20	68	2	91	7
CCS-02	Dorotea	Cerro Cazador south	34	15	51	31	15	54	6	92	2
SOL-1	Tres Pasos	Cerro Solitario	24	27	49	21	27	52	6	88	6
LF-05	Tres Pasos	Laguna Figueroa	12	34	54	10	34	56	4	91	5
LF-02	Tres Pasos	Laguna Figueroa	23	22	56	19	22	60	7	85	8
SD-01	Dorotea	Sierra Dorotea	21	37	42	18	37	45	7	89	4

Q, quartz; F, feldspar; L, lithic fragments; Qm, monocrystalline quartz; Lt, lithic fragments including polycrystalline quartz; Qp, polycrystalline quartz; Lv, volcanic lithic fragments; Ls, sedimentary and metasedimentary lithic fragments.
Samples are ordered generally north to south. See Fig. 3 for map of sample locations and refer to Each sample consists of 400 counts. See Fig. 6 for QFL and QmFLt ternary plots.

Sandstone composition and mudstone geochemistry

Modal composition for 15 sandstone samples (11 from the Tres Pasos Formation and four from the Dorotea Formation) was determined using the Gazzi–Dickinson point-counting method (e.g. Graham *et al.*, 1976; Ingersoll *et al.*, 1984) (Fig. 3; Table 2). Four hundred total points were counted on each thin section, then normalized to quartz–feldspar–lithic (QFL) parameters and plotted on ternary diagrams using provenance fields defined by Dickinson (1985). These data are integrated with sandstone compositional data from the underlying Punta Barrosa (26 samples; Fildani & Hessler, 2005) and Cerro Toro (18 samples; Crane, 2004) Formations, as presented in Fildani *et al.* (2008), and supplemented here with published data from Smith (1977) and Valenzuela (2006).

Mudstone geochemistry is valuable in provenance analysis because: (1) it addresses sediment source areas that typically yield detritus finer than sand (e.g. mafic terranes) and (2) is thought to represent a better average mix of regional source areas (McLennan *et al.*, 1993). As a result, these potentially significant contributors to the basin fill may be underrepresented in either detrital-zircon or sandstone-petrographic analyses. Compared to major and trace elements, the geochemical signature of rare earth elements (REE) from the clay-sized fraction is not significantly affected during erosion, sedimentation and diagenesis, thus representing a better average source composition (Table 3; Fleet, 1984; Bhatia, 1985; McLennan, 1989). A plot of chondrite-normalized (Boynton, 1984) REE abundances is the most effective summary with respect to provenance. Sixteen mudstone samples were collected from various locations within the uppermost Cerro Toro Formation (i.e. shales directly underlying the lithostratigraphic base of the Tres Pasos Formation) and within the Tres Pasos Formation (Fig. 3). Each sample was analysed for major, trace and REE using standard XRF and ICP-MS techniques (refer to the Supporting information for elemental analysis methods).

in Fig. 5. These composite plots show detrital-zircon age results grouped according to the four lithostratigraphic formations of the Magallanes foreland basin succession (Punta Barrosa Formation data from Fildani *et al.*, 2003). The Cerro Toro, Tres Pasos and Dorotea Formations all contain populations of zircons slightly older or nearly equal to inferred depositional ages, which were originally based on biostratigraphic data from Natland *et al.* (1974) and later Macellari (1988) (Fig. 5A–C).

A 90–100 Ma age population is dominant in the Punta Barrosa, Tres Pasos and Dorotea Formations (Fig. 5A, B and D). The dominant population in the Cerro Toro Formation is 140–145 Ma; however, the overall detrital-zircon signature for ages < 200 Ma is more broadly distributed than the other formations (Fig. 5C). The Dorotea Formation age spectrum contains a nearly equal secondary mode at 145–155 Ma (Fig. 5A). This population is also present in the Tres Pasos Formation as a secondary mode, although it is not as proportionally significant (Fig. 5B).

PROVENANCE DATA

Detrital-zircon age populations for Cerro Toro, Tres Pasos and Dorotea Formations

Detrital-zircon age data for grains < 600 Ma for the Cerro Toro, Tres Pasos and Dorotea Formations are shown by sample in Fig. 4. Although each sample does include zircons > 600 Ma, they are few and unclustered, and thus not discussed here (see Supporting information for tables of all ages). The cluster of age populations < 200 Ma is the most obvious, and a secondary population is observed in most of the samples at *ca*. 270–300 Ma (Fig. 4).

The majority (~60%) of detrital zircons in this dataset are younger than 200 Ma and therefore shown separately

Petrography of Tres Pasos and Dorotea sandstones

The bulk of sandstone petrographic data reported here (11 of 15 samples) are from the Tres Pasos Formation with the remaining from the overlying Dorotea Formation (Table 2). Samples from north of the Chile–Argentina border at Rio Roca southward to Sierra Dorotea near Puerto Natales, Chile, were analysed from a > 125-km-long transect parallel to depositional dip (Fig. 3). The proportion of sandstone to shale in the Tres Pasos Formation varies significantly along this trend but is generally ~20–40%. The basal Dorotea Formation is > 90% sandstone.

Table 3. Results of rare earth element (REE) analysis for Tres Pasos Formation shales

Sample	REE in ppm (parts per million)													
	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
RRm-1	28.20	70.71	7.50	28.37	5.84	1.62	5.24	0.87	5.29	1.07	3.11	0.47	2.91	0.46
AVm-1	26.33	60.12	6.51	24.25	5.18	1.16	4.41	0.74	4.59	0.98	2.87	0.44	2.86	0.47
CDm-1	26.67	63.12	7.27	27.86	5.71	1.20	4.90	0.79	4.90	1.02	2.94	0.45	2.88	0.46
CDm-2	23.38	51.30	5.97	22.67	4.67	0.95	3.91	0.65	4.16	0.88	2.57	0.39	2.63	0.42
CDm-3	26.01	56.65	7.00	27.72	6.29	1.43	5.85	0.97	5.80	1.14	3.19	0.47	3.01	0.47
CDm-4	20.46	46.47	6.16	25.66	6.30	1.55	6.16	1.01	5.95	1.11	2.86	0.39	2.35	0.36
CMm-1	29.20	64.36	7.49	28.33	5.79	1.20	4.85	0.81	5.09	1.03	2.96	0.45	2.88	0.46
RZm-1	19.93	53.62	5.15	20.50	4.52	1.06	4.20	0.68	4.10	0.83	2.32	0.34	2.17	0.35
SCm-1	19.82	47.00	5.36	20.82	4.64	1.15	4.22	0.70	4.31	0.85	2.44	0.36	2.29	0.36
SCm-2	21.82	53.76	5.89	23.20	5.24	1.16	5.03	0.83	5.15	1.05	3.02	0.44	2.85	0.45
CBm-1	22.55	53.35	5.69	21.87	4.89	1.14	4.56	0.77	4.83	1.00	2.80	0.42	2.67	0.42
CSm-1	23.29	60.67	5.88	22.20	4.96	1.01	4.35	0.77	4.82	0.97	2.73	0.42	2.64	0.42
APm-1	35.69	80.06	10.34	46.69	8.00	2.42	7.12	1.01	5.62	1.17	3.08	0.41	2.43	0.41
LFm-1	21.60	44.18	5.28	20.65	4.42	1.09	4.11	0.67	4.01	0.81	2.22	0.32	2.05	0.34
LSm-1	20.24	49.77	5.18	19.66	4.37	0.86	3.60	0.64	4.09	0.86	2.59	0.40	2.64	0.44
LSm-2	12.13	32.26	3.63	14.07	3.47	0.86	3.17	0.56	3.49	0.72	2.09	0.32	2.05	0.34

Analyses done at Washington State GeoAnalytical Laboratory. Refer to Fig. 3 for map of sample locations; refer to Fig. 7 for chondrite-normalized curves. See Supporting information for analytical methods.

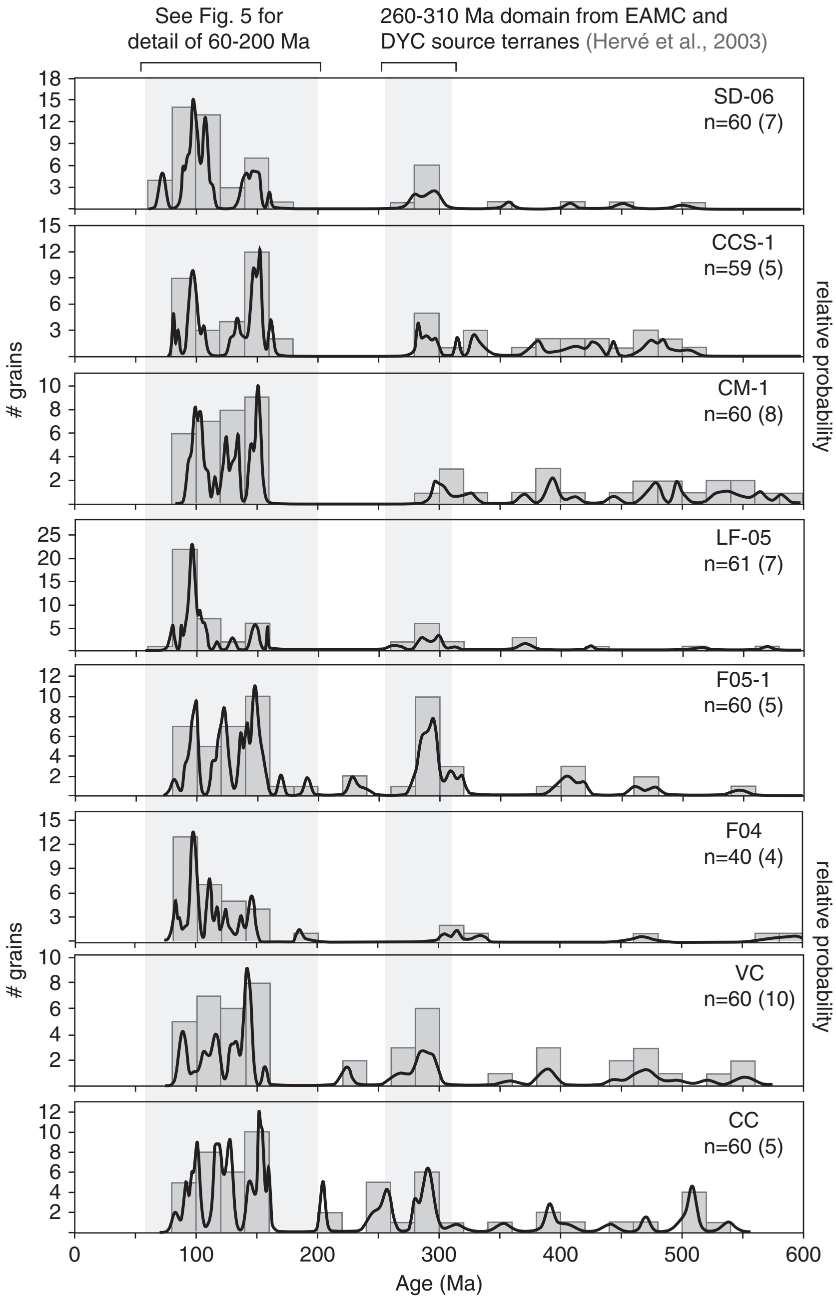

Fig. 4. Histograms and probability plots of detrital-zircon ages for eight sandstone samples from the Cerro Toro (CC, VC), Tres Pasos (F04, F05-1, LF-05) and Dorotea Formations (CM-1, CCS-1, SD-06) reported in this study. Lower case 'n' refers to total number of grains dated; number in parentheses refers to number of grains > 600 Ma and not shown in plot. Plots are organized stratigraphically by formation (oldest at bottom) and then within formations they are organized north-to-south (north below south). Highlighted age domain 260–310 Ma corresponds to detrital-zircon age data of Hervé *et al.* (2003) for Palaeozoic metamorphic source terranes (EAMC, Eastern Andean metamorphic complex; DYC, Duque de York metamorphic complex). See Fig. 5 for expanded view of ages younger than 200 Ma. Refer to Table 1 for sample information, Fig. 2 for stratigraphic distribution of samples, and Fig. 3 for geographic distribution of samples and location of EAMC and DYC terranes. See Supporting information for table of all ages and errors.

Tres Pasos and Dorotea sandstone can generally be classified as feldspathic litharenite (cf. Folk, 1980). Framework sand grains include angular monocrystalline quartz and feldspar grains (typically plagioclase, twinned or untwinned). In some samples, feldspar grains have a high degree of alteration (calcite replacement) making specific identification, and thus comparison among samples, difficult. Potassium feldspar is rare and only a few microcline grains were observed. An abundance of volcanic and volcaniclastic rock fragments are recognized in every sample and outweigh the proportion of other lithic fragments (Table 2). Volcanic lithic grains are altered to various degrees by partial or total recrystallization, compounding the difficulty in systematically differentiating framework components.

Modal results are normalized and compared on QFL ternary plots with tectonic fields of Dickinson (1985) (Fig. 6). Because there is no observable difference between the Tres Pasos and Dorotea sandstones within a QFL framework, they are plotted together. The mean composition is within the *transitional arc* field in both QFL and monocrystalline quartz–feldspar–total lithics (QmFLt) plots (Fig. 6). Petrographic analyses by Smith (1977) are slightly more quartz-rich and plot in the *dissected arc* to *mixed* fields of the QFL diagram. Results from the Punta Barrosa Formation (Fildani & Hessler, 2005)

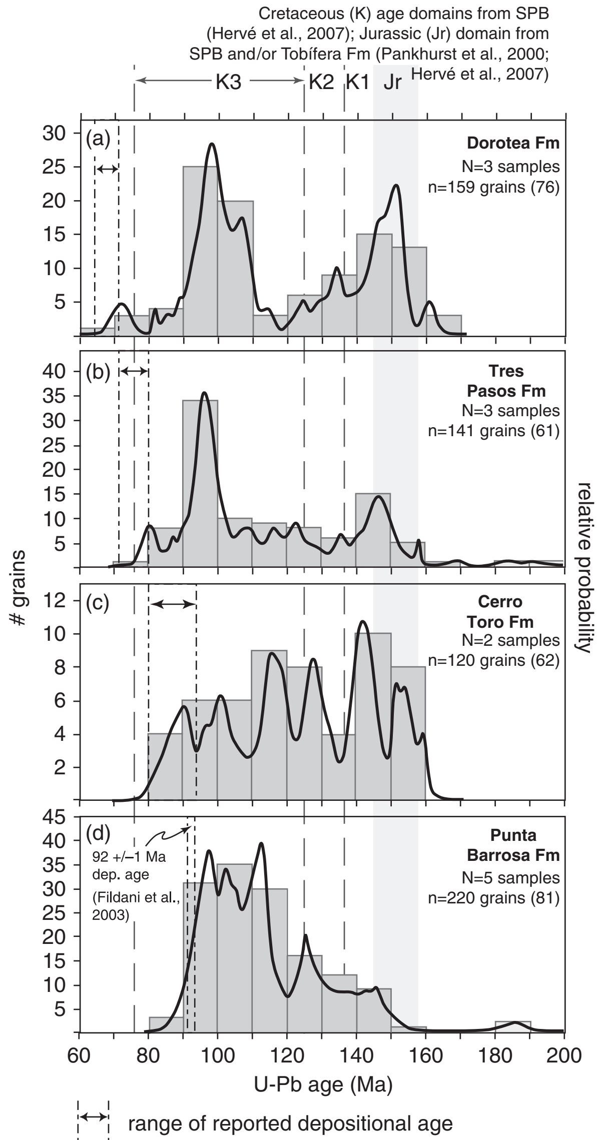

Fig. 5. Composite histograms and probability plots for detrital zircons younger than 200 Ma grouped by lithostratigraphic formation and in stratigraphic order from bottom top. Upper case 'N' refers to number of samples; lower case 'n' refers to total number of grains dated; number in parentheses refers to total number of grains >200 Ma and not shown in plot. Punta Barrosa Formation data replotted from Fildani *et al.* (2003). Jurassic domain (Jr) from Pankhurst *et al.* (2000) and Hérvé *et al.* (2007); Cretaceous domains (K1, K2 and K3) within Southern Patagonian Batholith (SPB) from Hérvé *et al.* (2007). Depositional age ranges for the Cerro Toro, Tres Pasos and Dorotea Formations from Macellari (1988); depositional age range for the Punta Barrosa Formation from Fildani *et al.* (2003). See Fig. 4 for plots by sample. Refer to Table 1 for sample information and Supporting information for table of all ages and errors.

and the Cerro Toro Formation (Crane, 2004) are shown in Fig. 6 for comparison.

Geochemical signature of Tres Pasos shale

The Tres Pasos shale REE abundances plot in the same general region as the underlying Punta Barrosa (Fildani & Hessler, 2005) and Cerro Toro Formations (Crane, 2004). The three formations are plotted together (in 'Magallanes basin shales' field) in Fig. 7 and compared with Zapata Formation shale, potential source terrane data (Fildani & Hessler, 2005), and with the North American shale composite data (Gromet *et al.*, 1984). These data indicate that the Magallanes basin shales: (1) do not vary significantly among the three lithostratigraphic formations and (2) are slightly more mafic than typical shales.

POTENTIAL SOURCE TERRANES

Fildani & Hessler (2005) and Fildani *et al.* (2003) collected data and compiled an extensive review for the potential source areas exposed along the Andean belt. These data are herein integrated with recent absolute ages published for the Patagonian Batholith (Hérvé *et al.*, 2007) and the early formations of the basin fill (Calderón *et al.*, 2007). Sedimentological studies of the Magallanes basin spanning five decades establishes a robust palaeocurrent dataset indicating a south to SE direction of sediment transport for all formations of the stratigraphic interval of interest (Fig. 3) (e.g. Katz, 1963; Scott, 1966; Smith, 1977; Winn & Dott, 1979; Dott *et al.*, 1982; Wilson, 1991; Fildani & Hessler, 2005; Shultz *et al.*, 2005; Crane & Lowe, 2008; Hubbard *et al.*, 2008; Armitage *et al.*, 2009; Romans *et al.*, 2009). Potential unique source areas to the south of Ultima Esperanza are therefore precluded as contributors to the basin fill [e.g. Beagle and Darwin granites (Nelson *et al.*, 1980); Antarctic Peninsula Batholith (Thomson & Pankhurst, 1983; Millar *et al.*, 2002)]. The Argentine craton, to the east of Ultima Esperanza, is interpreted to have been a broad depositional platform that accumulated mostly muddy sediment during the Late Cretaceous (Biddle *et al.*, 1986) and is also ruled out as a significant source of sediment.

The western and northwestern terranes of the Andean orogenic belt have been interpreted to be important source areas for the Magallanes basin during the Cretaceous (Wilson, 1991; Fildani *et al.*, 2003; Fildani & Hessler, 2005; Calderón *et al.*, 2007). Specific sediment source terranes reviewed here include: (1) pre-Upper Jurassic metamorphic complexes, (2) Upper Jurassic rift-related silicic volcanic rocks (Tobífera Formation and equivalents), (3) Upper Jurassic mafic rocks (Sarmiento Ophiolite) and (4) the Jurassic to Tertiary continental arc (SPB).

Pre-upper Jurassic metamorphic complexes

Several metamorphic complexes ranging in age from Late Devonian to Early Jurassic have been recognized in southern South America (Fig. 1) (e.g. Hervé, 1988; Faúndez *et al.*, 2002). The most relevant as potential source areas for the Magallanes basin are (1) the Eastern Andean Metamorphic Complex (EAMC), which is present on the eastern flank of the modern Patagonian Andes north of 51°S and the Staines Complex, interpreted as the southern extension

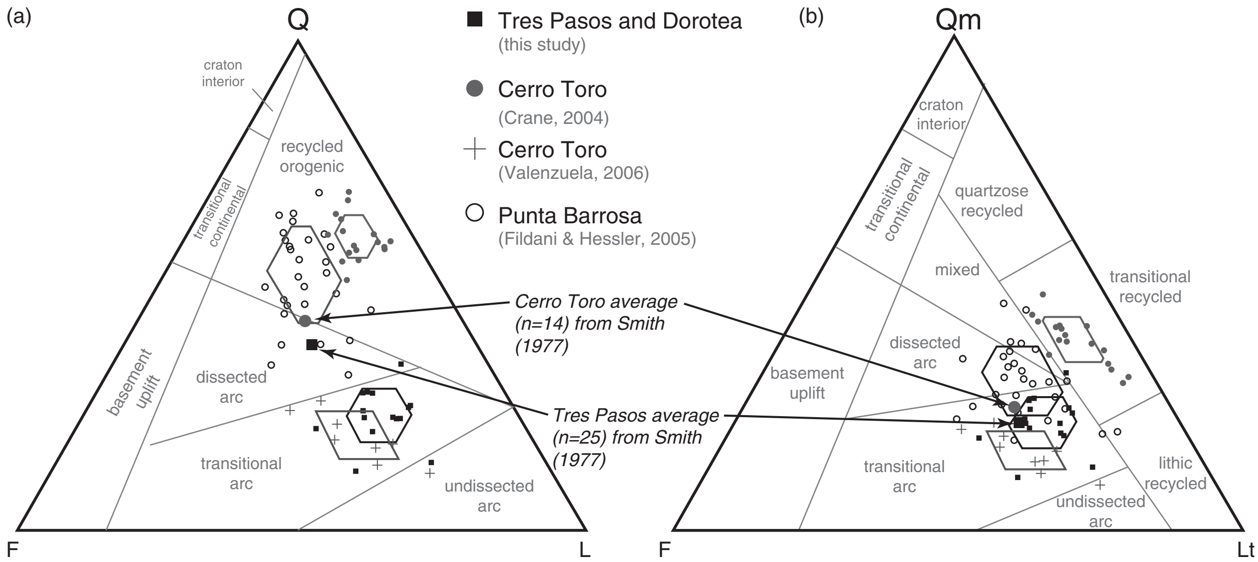

Fig. 6. (A) quartz-feldspar-lithics (QFL) and (B) monocrystalline quartz-feldspar-total lithics (QmFLt) ternary plots for Magallanes basin sandstones. Tres Pasos and Dorotea sandstones from this study; Punta Barrosa Formation from Fildani & Hessler (2005); Cerro Toro Formation from Crane (2004) and Valenzuela (2006). Additional average values from Smith (1977). Tectonic fields from Dickinson (1985). Polygons represent 1σ standard deviation. Refer to Table 2 for data.

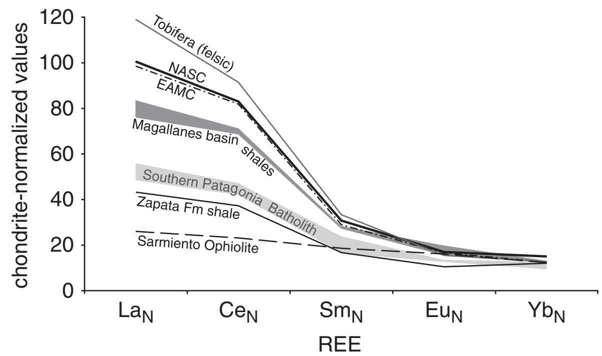

Fig. 7. Fractionation diagram for select rare earth elements (REE) abundances in Magallanes basin shales compared with Zapata Formation shale, possible source terranes from the Andean Cordillera, and NASC (North American shale composite). Magallanes Basin shales field combines Punta Barrosa Formation ($n = 12$ samples; Fildani & Hessler, 2005), Cerro Toro Formation ($n = 9$ samples; Crane, 2004) and Tres Pasos Formation ($n = 15$ samples; this study; see Table 3). Zapata Formation and source terrane data summarized in Fildani & Hessler (2005). *Y*-axis represents chondrite-normalized values; chondrite values from Boynton (1984). EAMC, Eastern Andean metamorphic complex.

of EAMC south of 51°S, and (2) an areally smaller complex, the Duque de York Complex (DYC), preserved on the western side of the SPB (Fig. 1). Depositional age of the protolith for the EAMC and Staines complex is no older than *ca*. 250 Ma (Hervé *et al*., 2003). The DYC has a depositional age of *ca*. 275 Ma (Hervé *et al*., 2003) and consists largely of metasedimentary rocks (Forsythe *et al*., 1981). U–Pb dating of detrital zircons by Hervé *et al*. (2003) of the EAMC and DYC indicate a dominant age population of *ca*. 260–310 Ma that is common to both complexes.

Jurassic rift-related volcanic rocks

Jurassic volcanic rocks unconformably overlie or are in fault contact with the metamorphic complexes discussed above and consist of rhyolitic and andesitic ignimbrite, lava and tuff (Gust *et al*., 1985; Wilson, 1991). Geochronological studies of the Tobífera Formation and its equivalents by Pankhurst *et al*. (2000) show that volcanism spanned a total of *ca*. 35 m.y. and occurred in three distinct phases: (1) 188–178 Ma, (2) 172–162 Ma and (3) 157–153 Ma. The youngest phase represents a westward shift in volcanism as rifting of Gondwana continued; it is the most voluminous with respect to its potential as a source of sediment for the Magallanes basin (Fig. 1) (Pankhurst *et al*., 2000; Calderón *et al*. 2007). Recent work by Hérvé *et al*. (2007) suggests that this youngest phase of rift volcanism is concurrent with development of arc magmatism occurring from 157 to 145 Ma.

Jurassic ophiolite sequences

The Sarmiento ophiolite complex is the northernmost preserved segment of the Rocas Verdes backarc basin crust (Fig. 1). It consists of nearly 3000 m of dominantly mafic intrusive and extrusive igneous rocks (Allen, 1982) with ages from 143 to 137 Ma (Stern *et al*., 1992). Although this age range is observed in the detrital-zircon record (Fig. 5), crystallization age alone is insufficient for identification, because of similar age grains from the SPB (Hérvé *et al*., 2007) and the general lack of zircons in mafic rocks.

Upper Jurassic to Tertiary continental arc

The continental arc system that developed along the western margin of southern South America in the Mesozoic is represented by igneous rocks of the Southern Patagonian Batholith (SPB) (Fig. 1). The SPB, which is composed of granodiorite and tonalite with some localized gabbro, dominates the southern Andean Cordillera extending from 40 to 56°S (> 1700 km) (Stern & Stroup, 1982). The initial geochronological studies on the SPB showed that magmatism spanned from 165 to 11 Ma, with a peak between 120 and 70 Ma (Bruce *et al.*, 1991). More recent U–Pb dating of SPB zircons by Hérvé *et al.* (2007) refine the oldest ages and thus the onset of arc magmatism to *ca.* 157–145 Ma. This age population, however, is from a bimodal igneous body (leucogranite and gabbro) that overlaps in age with the extensive rhyolitic volcanism associated with the Tobífera Formation (Hérvé *et al.*, 2007).

DETRITAL COMPOSITION OF THE MAGALLANES BASIN

Punta Barrosa Formation

The Punta Barrosa Formation sediment has been interpreted to be derived from a mixed source containing arc-derived rocks and older metamorphic basement rocks (Fildani & Hessler, 2005). Detrital-zircon age results show that > 40% of the dated grains are from a 25 m.y. period of arc activity (*ca.* 115–90 Ma) (Fig. 5D). The bulk of the remainder of the sediment is interpreted to be sourced from pre-rift (i.e. Palaeozoic to earliest Mesozoic) metamorphic complexes that were uplifted during the early Andean orogeny (Fildani & Hessler, 2005). Sandstone petrography indicates a blend of *transitional-dissected arc* and mixed sources (Fig. 6); mudstone geochemical signature (Fig. 7) was interpreted as a metamorphic source with additional input from the Sarmiento (see Table 2 of Fildani & Hessler, 2005).

Cerro Toro Formation

The source for the Cerro Toro Formation sediment has been interpreted as a mix of volcanic/volcaniclastic and metamorphic detritus, which is generally similar to the underlying Punta Barrosa Formation (Fildani *et al.*, 2008). At the Silla Syncline outcrop, Crane (2004) documented decreasing volcanic and volcaniclastic input through the stratigraphic succession and a sandstone petrographic signature clearly within the *recycled orogen* QFL field (Fig. 6). Additionally, an assessment of conglomerate clast composition from the Silla Syncline indicates an abundance of metamorphic material (Crane, 2004). Sandstone petrographic data from the main axial conglomerate belt, however, plot within the *transitional arc* domain (Valenzuela, 2006) suggesting a possible local palaeogeographic bias in the Silla Syncline data. Clast count data from conglomerate members in the axial belt, which indicate a high proportion of rhyolitic and felsic igneous clasts with subordinate proportions of metasedimentary (e.g. quartizite) and other rocks, seems to support that interpretation (Valenzuela, 2006).

The REE pattern is comparable to the Punta Barrosa Formation, which suggests Jurassic ophiolitic rocks and/or intermediate volcanic rocks from the arc were a component of the source of sediment (Fig. 7). Relative to the Punta Barrosa, the detrital-zircon age results for the Cerro Toro suggest continued input from the Cretaceous arc (Fig. 5C) and a similar abundance of Palaeozoic grains (310–260 Ma) interpreted to be sourced from the metamorphic complexes (Fig. 4). Notably, the appearance of grains *ca.* 160–145 Ma indicates that Upper Jurassic rocks started contributing detritus to the basin during Cerro Toro Formation deposition.

Tres Pasos and Dorotea Formations

The provenance signature of the Tres Pasos and overlying Dorotea Formations are presented together because of their genetic association with respect to depositional system development at regional scales (hundreds of km) (Macellari *et al.*, 1989; Covault *et al.*, 2009). Sandstone petrographic data reported here indicate that Tres Pasos and Dorotea sandstones are rich in volcanic/volcaniclastic lithic grains and plot within the *transitional arc* QFL fields (Table 2; Fig. 6). Sandstone petrographic data from the Tres Pasos, Dorotea, and coeval units to the north in Argentina (~50°S) compiled by Macellari *et al.* (1989) (including work on the Tres Pasos by Smith, 1977) are somewhat consistent with results of this study; their composite QFL results are slightly more quartz-rich and plot within the *mixed* and *dissected arc* fields. Tres Pasos REE patterns indicate that the source area for the shales is very similar to both the Punta Barrosa and Cerro Toro Formations, which is slightly more mafic than typical shale (Fig. 7).

Detrital-zircon age results reveal a small population of grains *ca.* 80 Ma present in the Tres Pasos Formation (Fig. 5B). This population is younger than the depositional age of the underlying Cerro Toro Formation, which helps constrain maximum depositional age. The dominant age population is *ca.* 100–90 Ma, which is common to both the older Punta Barrosa Formation and the overlying Dorotea Formation (Fig. 5). A secondary age population in the Tres Pasos (*ca.* 155–145 Ma) indicates incorporation of Upper Jurassic grains (Fig. 5B). The detrital-zircon age signature for the Dorotea Formation shows an increased proportion of Upper Jurassic ages and also contains a small population of grains that constrain maximum depositional age to be *ca.* 70 Ma. Similar to the older depositional formations, the Palaeozoic detrital zircons are interpreted to be derived from the metamorphic basement (Fig. 4).

This integrated provenance dataset suggests a mixed source area for the Tres Pasos and Dorotea Formations: (1) Upper Jurassic rift volcanic rocks (157–145 Ma), (2) significant component of Cretaceous arc material (110–90 Ma), (3) minor component of younger, and nearly contemporaneous, arc material and (4) Palaeozoic metamorphic basement.

DISCUSSION

Cretaceous evolution of the Patagonian Andean fold-thrust belt and arc

The onset of foreland basin sedimentation in Ultima Esperanza is marked by the appearance of coarse-grained turbidites of the Punta Barrosa Formation at *ca*. 92 Ma (Fildani *et al*., 2003). The detrital-zircon record for the Punta Barrosa Formation shows that a significant proportion of relatively young to nearly synchronous arc detritus (*ca*. 115–92 Ma) was delivered to the basin (Fig. 5D). Although overlying formations contain grains younger than 92 Ma, this dominant population persists through the basin fill (Fig. 5A and B). One explanation of this pattern is that the retroarc fold-thrust belt initiated before 92 Ma but had not migrated into the Ultima Esperanza region until that time. Fildani & Hessler (2005) postulated that the upper Zapata Formation may have accumulated in a rift sub-basin within the Rocas Verdes basin largely disconnected from the developing arc, associated fold-thrust belt, and supply of coarse-grained detritus. The closure of the marginal oceanic basin is thought to have initiated in the Aptian–Albian (120–105 Ma), resulting in uplifted horst blocks along reverse faults that would eventually evolve into the fold-thrust belt (Calderón *et al*., 2007; Fildani *et al*., 2008). The temporal gap between initiation of basin closure (120–105 Ma) and onset of foreland basin sedimentation (*ca*. 92 Ma) may represent the time required for the leading (eastward) edge of the overriding fold-thrust belt to migrate to Ultima Esperanza.

Upper Jurassic zircon grains are not present in the Punta Barrosa Formation detrital record (Fig. 5D). The record from the overlying formations, however, clearly indicates that uplift and associated denudation of Upper Jurassic igneous units was occurring by the Santonian (*ca*. 85 Ma) and that these rocks were a significant source of detritus by the Maastrichtian (*ca*. 70 Ma) (Fig. 5). The inability to definitively distinguish a temporal unroofing pattern from a spatial change in source area is recognized; however, the fact that all formations share similar Cretaceous age peaks suggests a drastic shift in dispersal patterns was unlikely. The increased proportion of volcanic lithic grains in the Tres Pasos and Dorotea Formations relative to underlying formations (Fig. 6) is consistent with the introduction of a volcanic source terrane (in addition to the arc) in the hinterland.

The detrital-zircon age results show that a significant part of the Magallanes basin fill is dominated by arc material. Although there are populations of nearly contemporaneous detrital zircons observed in the Tres Pasos and Dorotea Formations, the dominant population is arc-derived material that is *ca*. 20–30 m.y. older than inferred depositional ages (Fig. 5A and B). U–Pb dating over a large region of the SPB by Hérvé *et al*. (2007) does not indicate a clear spatial pattern with respect to age groupings in the arc. Assuming arc magmatism was consistent throughout this period, the reduction in younger arc-derived material (i.e. <90 Ma) during the Tres Pasos and Dorotea deposition might reflect trapping of arc detritus behind the fold-thrust belt front (e.g. in piggy-back basins created by uplift of Upper Jurassic rocks). Although difficult to definitively discriminate, this pattern could also represent geomorphic evolution of drainage patterns of the arc itself (cf. DeGraaff-Surpless *et al*., 2002). Despite the variability among the basinal formations, the record shows that a connection between the arc and the foredeep was maintained throughout the Late Cretaceous. This long-lived connection suggests that the continental arc and coeval retroarc foreland basin were probably not separated by great distances.

The pre-rift Palaeozoic metamorphic basement was also an important contributor of sediment to the Magallanes basin through the entire basin fill. Detrital-zircon age populations reported here demonstrate that the EAMC and DYC were a source of sediment to the foreland basin during the Late Cretaceous (Fig. 4). The EAMC age spectrum includes older populations (*ca*. 500–550 Ma) that are not well represented in the detrital record (Figs 4 and 8), suggesting that the DYC might have been a more significant contributor of detritus to the Magallanes basin. The few Precambrian grains found in the Magallanes detrital record are likely recycled from these Palaeozoic metamorphic complexes (Augustsson *et al*., 2006).

Some interesting insights on arc development and evolution are offered by the detrital record. The dominant age population in the detrital-zircon record (*ca*. 110–95 Ma) reflects arc-related activity but is a much shorter duration compared with the peak of activity determined from the preserved batholith (Bruce *et al*. 1991; Hérvé *et al*. 2007; Fig. 5). In some continental-arc systems, rapid build-up and exhumation of arc material is interpreted to occur during and shortly after periods of high-magmatic flux, or 'flare-ups', which can be *ca*. 10–15 m.y. in duration (Ducea & Barton, 2007).

Sediment dispersal patterns and stratigraphic organization of the Magallanes foredeep

Detrital-zircon age populations that are nearly contemporaneous or slightly older than reported depositional age ranges are recognized in each successive Magallanes basin formation. The Tres Pasos Formation (Fig. 5B) has a small population of grains (*ca*. 80 Ma) younger than the interpreted depositional age of the underlying Cerro Toro Formation (Fig. 5C). A similar pattern is repeated in the overlying Dorotea Formation (*ca*. 73 Ma) (Fig. 5A), indicating that the Magallanes foreland basin continued to receive detritus from arc plutons and/or associated arc volcanic cover throughout its filling history. Detrital-zircon age results from Fildani *et al*. (2003) revised the maximum depositional age of the Punta Barrosa Formation from the previously reported Albian–Cenomanian age to 92 ± 1 Ma (Fig. 5D). The youngest detrital-zircon ages for the Cerro Toro, Tres Pasos and Dorotea Formations are generally consistent with depositional age ranges constrained by regional biostratigraphic data (Macellari, 1988).

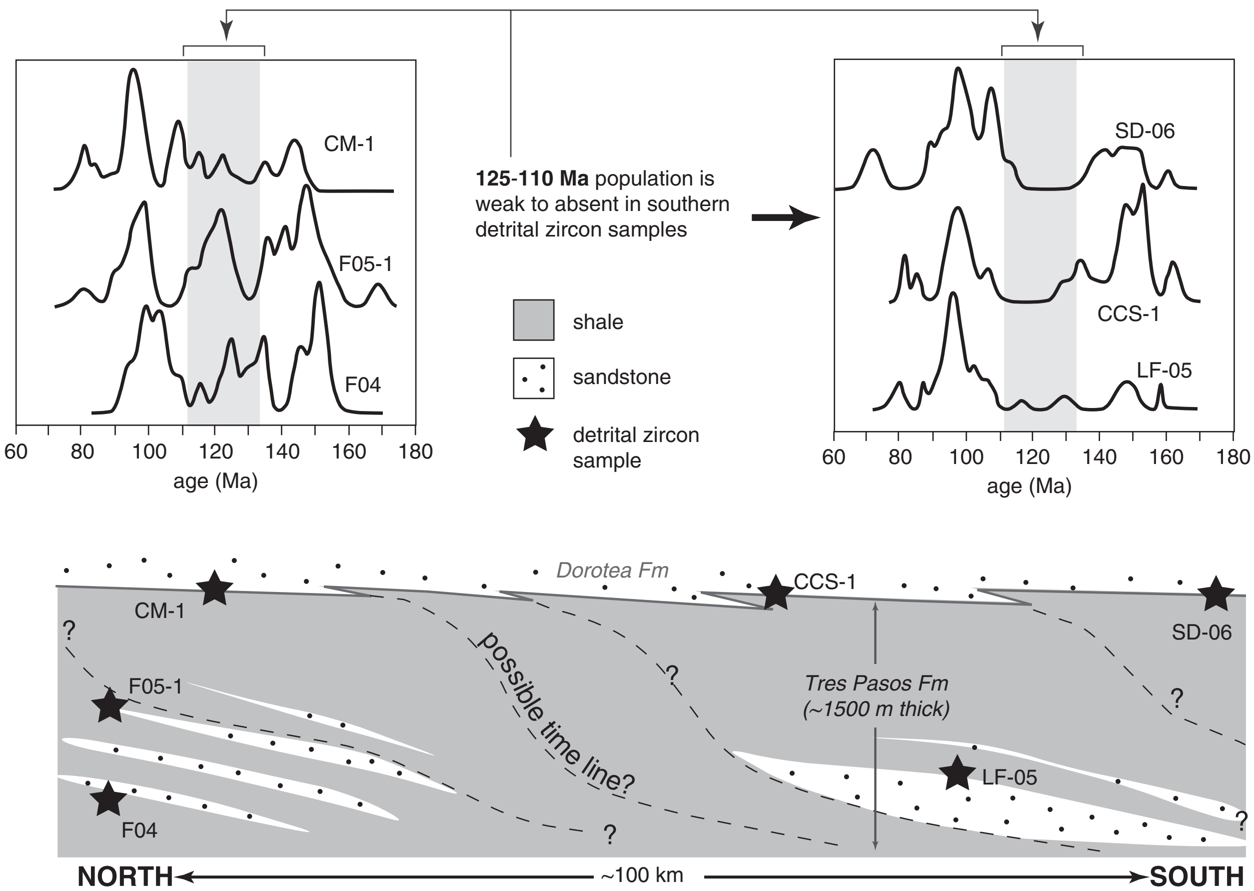

Fig. 8. Schematic stratigraphic cross-section parallel to depositional dip showing Tres Pasos (slope) and Dorotea (deltaic and shallow-marine) Formations. Detrital-zircon age populations for samples in northern vs. southern areas suggest temporal evolution of source area recorded in diachronous strata. General southward-prograding pattern consistent with stratigraphic relationships at regional scales (Macellari *et al*., 1989; Shultz *et al.,* 2005) and at outcrop scale (Covault *et al*., 2009; Romans *et al*., 2009).

The depositional systems of the Magallanes foreland basin in Ultima Esperanza have a strong north-to-south dispersal pattern throughout its filling history (Scott, 1966; Smith, 1977; Winn & Dott, 1979; Dott *et al*., 1982; Fildani & Hessler, 2005; Shultz *et al*., 2005; Crane & Lowe, 2008; Hubbard *et al*., 2008; Romans *et al*., 2009). The transition from deep- to shallow-marine systems is recorded by the Tres Pasos Formation slope strata and the overlying deltaic strata of the Dorotea Formation (Katz, 1963; Macellari *et al*., 1989; Covault *et al*., 2009). Thus, a north–south diachroneity is produced as the result of southward progradation of these sedimentary systems during the latest Cretaceous and earliest Tertiary. The signature of this basin-filling pattern and southward younging of lithostratigraphic units has been interpreted at outcrop scale (Romans *et al*., 2009) and documented at regional scales (several hundreds of km) from biostratigraphic data (e.g. Macellari, 1988). However, the recognition of this stratigraphic architecture at an intermediate scale (*ca*. tens of km) has been enigmatic because individual outcrops are too small and biostratigraphic resolution is too coarse.

Detrital-zircon age probability curves for six samples from the Tres Pasos and Dorotea Formations are shown with a schematic stratigraphic cross section oriented parallel to depositional dip (Fig. 8). The detrital-zircon age population of *ca*. 125–110 Ma is present in the northern samples (F04, F05-1 and CM-1) but is weak to absent in the southern samples (CCS-1, LF-05 and SD-06). We interpret this spatial change in provenance to reflect a temporal change in the source area that is recorded in the diachronous lithostratigraphic formations. This is consistent with previous interpretations from Macellari *et al.* (1989) based on petrographic data and mapping. Moreover, this pattern is consistent with younger detrital-zircon ages reported by Hervé *et al.* (2004) for the Dorotea Formation near the town of Puerto Natales (Fig. 2) and from provenance data even further south (Barbeau *et al*., in press). No significant difference is recognized in the sandstone and mudstone composition when subdivided into the same northern and southern regions. A source area change recorded solely in detrital-zircon age data might, therefore, suggest that the change was relatively subtle.

Tectonic inheritance and the sedimentary fill of retroarc foreland basins

The provenance of foreland basins reflects the composition of their dynamically linked fold-thrust belt source areas. Thus, the sedimentary fill of retroarc foreland basins is dominated by detritus recycled from the predecessor geologic terranes that were incorporated into the fold-thrust belt (Dickinson, 1974, 1976). Provenance characteristics of many ancient retroarc foreland basins indicate a fill composed of predominantly recycled sedimentary cover (Jordan, 1995; DeCelles & Giles, 1996). Several unique characteristics distinguish the sedimentary fill of the Magallanes basin from other retroarc foreland successions: (1) unroofing succession of rift-basin-derived detrital zircons, (2) mudstone geochemical signature that is slightly more mafic than composite shale values, (3) abundant arc-derived detrital zircons and (4) thick succession of deep-marine depositional facies. Inversion of the predecessor extensional basin and incorporation of its basement rocks and associated sedimentary fill into the fold-thrust belt are the principal reasons for such differences (Fig. 9).

Detrital-zircon age populations clearly show that older rift-related igneous rocks were incorporated into the fold-thrust belt. Mudstone geochemistry data from all formations (Fig. 7) indicate a component of mafic input to the basin, interpreted as the incorporation of obducted oceanic crust in the fold-thrust belt and/or abundant detritus derived from intermediate arc volcanic rocks. The compositions of retroarc fold-thrust belts that are positioned on continental crust of normal thickness typically lack a significant component of rift and/or mafic igneous rocks (Jordan, 1995; DeCelles & Giles, 1996). For example, the Cretaceous Sevier orogenic belt in North America was largely composed of older passive margin sedimentary rocks (DeCelles & Coogan, 2006). The Cenozoic fill of the foreland basin associated with the Central Andean orogenic belt is dominated by recycled Palaeozoic–Mesozoic sedimentary rocks with a subordinate magmatic-arc source (Horton *et al*., 2002).

The detrital-zircon age results show that the Magallanes basin received young arc-derived material throughout its filling history, which suggests a short transport distance from arc to foredeep. Reactivation of inherited normal faults as high-angle reverse faults during basin inversion (Allen, 1982; Fildani & Hessler, 2005; Calderón *et al*., 2007) could have contributed to the development of a relatively narrow orogenic belt and thus short sediment transport distances. Other retroarc foredeeps are not dominated by young arc detritus, especially for protracted periods, because of sediment storage in piggy-back basins or presence of a major drainage divide that separates a distant arc source. For example, the Cretaceous Sevier fold-thrust belt of North America was characterized by an uplifted plateau and fold-thrust belt with extensive décollement thrust faults, which separated the arc from its contemporaneous foreland basin by as much as 500 km (DeCelles & Coogan, 2006). The style of the Cenozoic Central Andean orogenic belt (~16–24°S) exhibits a similar broad foreland fold-thrust belt region (Horton & DeCelles, 1997; DeCelles & Horton, 2003).

The tectonic inheritance likely provided a setting in which significant basinal subsidence permitted long-lived (> 20 m.y.) deep-marine deposition and accumulation of ~4000 m of largely turbiditic sediment in the Cretaceous Magallanes basin. Retroarc foreland basins that developed on continental crust of normal thickness, even during global highstands in sea level, typically do not have well-developed and substantially thick turbidite fills (Jordan, 1995; DeCelles & Giles, 1996). The long-lived axial sediment dispersal (parallel to the orogenic belt) observed in the Magallanes basinal strata, also reflects this enhanced subsidence.

The inheritance recorded in the sedimentary fill of the Magallanes foredeep thus suggests a basin configuration and evolution comparable, in some aspects, to remnant ocean basins (*sensu* Ingersoll *et al*., 1995), which are characterized by: (1) a shrinking ocean basin, (2) flanked by at least one convergent margin and (3) a basin floor covered

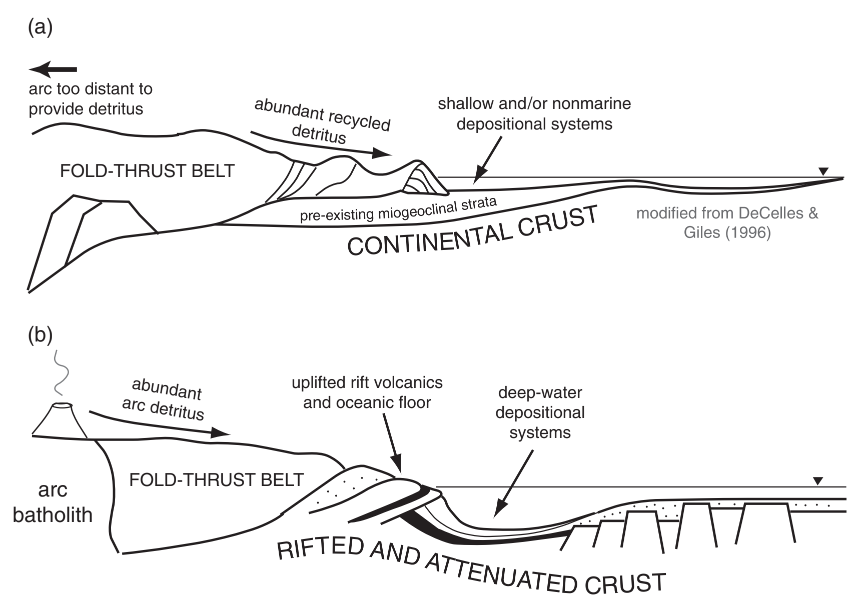

Fig. 9. Schematic tectonic-scale cross sections depicting dominant features of (a) retroarc foreland basin on fully continental crust (adapted from DeCelles & Giles, 1996) and (b) retroarc foreland basin that develops from inversion of predecessor backarc basin (this study). See text for discussion of distinguishing features with respect to make-up of fold-thrust belt, age and compositional trends of basinal detritus, dominant depositional systems and sediment dispersal patterns.

by turbidites derived from an associated suture zone. An important caveat in this comparison is that the predecessor Rocas Verdes backarc basin was not a true oceanic basin at this latitude; rather, it was a relatively narrow (<100 km) marginal basin with rift volcanic rocks and areally limited oceanic crust (Dalziel *et al.*, 1974; Alabaster & Storey, 1990; Wilson, 1991). Consequently, the Late Cretaceous retroarc fold-thrust belt could be considered an uplifted suture zone and the Magallanes basin similar to a nearly closed remnant ocean basin or peripheral foreland basin. However, unlike true remnant ocean basin successions, which are typically significantly deformed or not preserved at all during collision (Ingersoll *et al.*, 1995), the retroarc position and subsequent evolution of the fold-thrust belt during the Cenozoic resulted in exceptional preservation of this unique basin fill.

CONCLUSIONS

More than 450 new single-grain detrital-zircon U-Pb ages from the Cretaceous Magallanes basin reveal a >20 m.y. history of retroarc fold-thrust belt and associated foreland basin development. Comparison of >200 previously published detrital-zircon ages from the Punta Barrosa detrital-zircon record with new dates from the overlying Cerro Toro, Tres Pasos and Dorotea Formations (>4000 m stratigraphic thickness) shows a signature of unroofing in the fold-thrust belt. Increased abundance of Upper Jurassic grains (157–145 Ma) upwards through the basin fill records the uplift and associated denudation of the rift basin-related Tobífera Formation. Unroofing of Upper Jurassic rocks started by the Santonian (*ca.* 85 Ma) and was a significant source of detritus by the Maastrichtian (*ca.* 70 Ma). Sandstone compositional trends also indicate an increase in volcanic and volcaniclastic grains associated with this unroofing pattern and the shale geochemical signature suggests a mafic component interpreted as the uplifted oceanic crust remnant of the predecessor backarc basin (Sarmiento Ophiolite).

Populations of arc-derived detrital zircons that are nearly contemporaneous with reported maximum depositional ages for each formation constrain timing of these significant basin-filling phases. Additionally, a temporal change in source area characteristics is recorded in the detrital-zircon age results from the Tres Pasos and Dorotea Formations, which is consistent with interpretations documenting a large-scale north-south progradational pattern that genetically link the two formations. The results of this integrated study highlight significant differences in provenance characteristics between retroarc foreland basins that develop on continental crust of normal thickness and the Magallanes basin, which developed on rifted crust inherited from a preceding extensional phase.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Mineral Separation Procedure.
Table S1. U-Pb ages and associated errors for sample CC.
Figure S1. Detrital-zircon histograms and probability plots for eight sandstone samples.

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