GEOCHRONOLOGY AND STRATIGRAPHIC ARCHITECTURE OF A DEEP-WATER SYSTEM DURING THE EARLY PHASES OF THE MAGALLANES–AUSTRAL BASIN, PATAGONIA: DIACHRONOUS INITIATION OF A RETROARC FORELAND BASIN

Matthew A. Malkowski¹, Glenn R. Sharman², Stephan A. Graham¹, and Andrea Fildani³

¹Geological and Environmental Sciences, Stanford University, Stanford, CA 94305
²ConocoPhilips, Houston, TX
³StatOil, Austin, TX

ABSTRACT
The Magallanes–Austral Basin (MAB) is preserved along a >1000 kilometer north–south trending outcrop belt in the southern Patagonia region of Argentina and Chile. The stratigraphic evolution of the MAB has been well documented in the Chilean sector of the basin, however its along-strike counterpart in Argentina is poorly constrained. We present new stratigraphic and geochronologic analyses of the early basin fill (Aptian–Turonian) from the Argentine sector (49–51°S) of the MAB to document spatial variability in stratigraphy and timing of deposition during the initial stages of basin evolution. The initiation of the MAB is marked by the transition from mud to coarse-clastic deposition, as represented by the consistent presence of sandstone beds > ~20 cm thick. These sandy facies are interpreted to represent turbidity current deposition in a submarine fan system. This study documents that such facies are present as far north as El Chalten, Argentina (~49°S), indicating that facies-equivalent rocks can be traced along-strike for at least 5 degrees of latitude, based on correlation with strata as far south as the Cordillera Darwin (~54°S). Eight new U-Pb zircon ages from ash beds, reveal an overall southward younging trend in the initiation of coarse clastic deposition. Inferred depositional ages range from ~115 Ma in the northernmost study area to 92 Ma and 89 Ma (maximum depositional ages) in the central and southern sectors, respectively. The apparent diachronous delivery of coarse detritus into the basin may reflect 1) gradual southward progradation of a deep-water fan system from a northerly point source or 2) orogen-parallel variations in the timing and magnitude of thrust-belt deformation and erosion that provided more local sources for sediment delivery.
INTRODUCTION

The initial depositional history of retroarc foreland basins (hereafter “retroforelands”) is often difficult to preserve given their extended susceptibility to fold and thrust belt deformation and erosion. This is also complicated by the notion that the early stratigraphic evolution of retroforelands may depend significantly on pre-existing tectonic conditions. For instance, successor foreland basins that develop over attenuated oceanic crust are more prone to enhanced tectonic subsidence that results in a sediment-supply-limited condition and an initially under-filled basin. On the other hand, collision retro-forelands that evolve on continental crust will more quickly result in accommodation-limited conditions and an over-filled basin. With continued thrust-belt development, sediment-supply increases and even under-filled successor retro-forelands may eventually transition from axially drained deep-water basins to more transversely drained shallow- and non-marine depositional systems. In either case, the difficulties of preserving the early fill of a retroforeland basin leave relatively few opportunities to document their early stratigraphic evolution. One of these exceptions has been documented in the Magallanes Basin of southern Chile, where a succession of deep-marine stratigraphy preserves the transition from a pre-existing back-arc rift basin into a retroarc foreland basin system (Wilson, 1991; Fildani and Hessler, 2005).

The Upper Cretaceous Magallanes–Austral Basin (MAB) of southern Patagonia is an example of a successor retro-foreland that, for much its extent, originated as a deep-water and relatively sediment-starved basin. The MAB is preserved along a nearly continuous (>1000 kilometer) north–south trending outcrop belt of Cretaceous–Paleogene stratigraphy in the foothills of the southernmost Andes (Figure 1). These rocks record a complete > 4 kilometer-thick succession of deep-water stratigraphic architecture from submarine fans to prograding slope clinoforms (Wilson, 1991; Hubbard et al., 2010; Romans et al., 2011). Consequently, the Magallanes Basin sector in Chile has received a great deal of attention over the past fifteen years. Despite this, our understanding of the regional distribution of facies and timing of deposition during the early evolution of the MAB remains poorly constrained, especially in the northern (Argentine) sector of the basin. In the Chilean (or, Magallanes) sector of the MAB, the early depositional history is represented primarily by deep-water sediment gravity flow deposits, which have been interpreted as being deposited in a lobe or fan setting (Wilson, 1991; Fildani and Hessler, 2005). Northward (along-strike) variations in this deep-water, early-fill phase of the
basin have not been documented despite their relevance to the early tectonic evolution of this foreland basin system.

To better resolve the timing of deposition and stratigraphic evolution of the early fill of the MAB, this study presents new U-Pb zircon geochronology as well as detailed sedimentologic and stratigraphic data from the northern (Austral) sector of the MAB in Argentina (Figure 1). Combined with previous studies, this work documents the basin-scale distribution and variability in the timing of deposition and depositional facies during the early stages of the MAB. Results reveal a diachronous (southward-younging) initiation of deposition by sediment gravity flows along one or more deep-water fan systems from as far north as El Chalten (~49°S) to at least as far south as the Cordillera Darwin (~55°S).

GEOLOGIC BACKGROUND

Basin Evolution

The Jurassic–Neogene basin evolution of southern Patagonia consists of a two-phase history, which includes an older backarc rift phase (the Rocas Verdes Basin) and a successive retroarc foreland basin (Magallanes–Austral Basin) (Figure 2). The southern Patagonian Andes region of South America originated in a Jurassic – Early Cretaceous backarc extensional setting (the Rocas Verdes Basin) associated with the break-up of Gondwana (Katz, 1963; Dalziel et al., 1974; De Wit and Stern, 1981; Biddle, 1986). Lithospheric extension is recorded through bimodal volcanism including basalt and gabbro of the Sarmiento ophiolitic complex and widespread silicic volcanism of the El Quemado, Ibañez, and Tobífera Formations of western Patagonia (Figure 1) (Saunders et al., 1979; Pankhurst et al., 2000; Calderón et al., 2007). The resulting syn-rift Rocas Verdes Basin was filled by volcaniclastic units associated with the silicic volcanics mentioned above, as well as black shale of the Rio Mayer and Zapata Formations in Argentina and Chile, respectively (Wilson, 1991; Fildani and Hessler, 2005).

The transition from backarc extension to compression and subsequent foreland basin development is well documented in the Ultima Esperanza District of Chile and is represented by the onset of deep-marine deposition of the Punta Barrosa Formation (Wilson, 1991; Fildani et al., 2003; Fildani and Hessler, 2005) (Figure 2). The presence of inherited transitional crust related to the early extensional phase allowed for prolonged deep-water sedimentation (Romans et al., 2010). Continued evolution of the foreland basin resulted in a deep-marine axial channel belt that
delivered sediment from north to south, as recorded by the Cerro Toro Formation (Winn and Dott, 1979; Crane and Lowe, 2008; Hubbard et al., 2008; Jobe et al., 2010). This, in turn, is overlain by the Tres Pasos Formation, which reflects southward progradation of the deep-marine slope (Schultz et al., 2005; Armitage et al., 2009; Romans et al., 2009). Finally, deep-marine facies transition upward to shallow- and marginal-marine deposits of the uppermost Cretaceous Dorotea Formation (Covault et al., 2009; Schwartz and Graham, 2014). Stratigraphy representing the transition from a backarc rift basin to a retroarc foreland basin is not well constrained in the Argentine sector of the basin, which crop out in the regions surrounding Lago Argentino and Lago Viedma (Figures 1 and 2). The following section includes descriptions of stratigraphy that is inferred to reflect this transition in the northern, central, and southern sectors of the basin.

**Punta Barrosa Formation**

**Nomenclature**

MAB outcrops extend for hundreds of kilometers in the north-south direction and span two countries (Figure 1). Consequently, many stratigraphic units that are roughly age and/or facies equivalent have been assigned to different formation names, depending on region (Figure 2). The usage of the “Punta Barrosa Formation” has been previously restricted only to the Chilean sector of the basin (Magallanes Basin) in the Ultima Esperanza District, and to our knowledge has not been assigned to any stratigraphy from the Argentine basin sector (Austral Basin). For the purposes of this study, we informally extend the Punta Barrosa Formation nomenclature to refer to stratigraphy that represents the first consistent appearance of coarse-clastic deposition (e.g., medium-grained sandstone) associated with turbiditic, deep-water (?) facies, as defined by previous workers (e.g., Wilson, 1991; Fildani et al., 2003; Fildani and Hessler, 2005). Most notably, this nomenclature expansion includes the Austral basin where it has been previously mapped and referred to as undifferentiated units of the Cerro Toro Formation (near Lago Argentino) (Arbe and Hechem, 1984) and in some cases the Rio Mayer formation (near Lago Viedma) (Kosmal and Spikermann, 2001). South of the Ultima Experanza district of Chile, near the Cordillera Darwin, the Punta Barrosa facies equivalent rocks are referred to as the Latorre and/or Upper La Paciencia Formations (Figure 2).
**Austral Basin, Argentina**

In Austral Basin, there are considerable variations in facies of early coarse clastic deposition. Deep-marine deposition has been documented in outcrops near Lago Argentino (Arbe and Hechem, 1984). However, here these strata are described as undifferentiated units of the Cerro Toro Formation. Nevertheless these outcrops were recognized as early basin fill deposits of Cenomanian–Turonian age and interpreted as low- and high-density turbidites with a southward paleoflow (Arbe and Hechem, 1984). North of Lago Argentino, age-equivalent strata consist of shallow- to non-marine deposits of the Lago Viedma (cf., Arbe, 2002) and Mata Amarilla (cf., Varela et al., 2013) Formations (Figure 2). However, near Lago Viedma and north, these formations are underlain by deltaic and fluvial facies of the Albian aged Piedra Clavada Formation (Poiré, 2002). Although fluvial and shallow-marine deposits appear as the dominant facies early in the evolution of the northern sector of the basin, the northern extent of deep-water facies is unconstrained.

**Ultima Esperanza District, Chile**

In the Ultima Esperanza district of Chile, the onset of foreland basin sedimentation is recorded by the Punta Barrosa Formation, which generally consists of packages of interbedded sandstone and mudstone and has an overall estimated thickness of about 1 kilometer (Wilson, 1991; Fildani et al., 2003). Wilson (1991) describes the transition from the underlying Zapata Formation to the Punta Barrosa Formation as being marked by the “abrupt” consistent presence of medium-grained sandstone beds that range from 30 to 100 cm in thickness; however Fildani and Hessler (2005) suggest that the contact is more subtle and consists of a ~150-m-thick transition zone within which a precise boundary cannot be placed. The transitional stratigraphy between the underlying Zapata Formation and the Punta Barrosa has a reported radiometric age of 101 ± 1.1 Ma (Fosdick et al., 2011). Detrital zircon ages from multiple sandstone units within the Punta Barrosa Formation suggest an overall maximum depositional age of ~92 Ma (Fildani et al., 2003). Detrital zircon age determinations are slightly younger than previous interpretations of a late Albian to Cenomanian age based on a sparse ammonite assemblage (Cortes, 1964).

The Punta Barrosa Formation has been interpreted to primarily reflect high- and low-density turbidity current deposits in a “fan-like” depositional setting within the axis of a constricted foreland basin trough (Wilson, 1991; Fildani and Hessler, 2005; Romans et al.,
Paleocurrent measurements of groove and flute casts from throughout the Punta Barrosa Formation consistently result in south to southeast paleoflow suggesting that sediment dispersal was parallel to the axis of the foreland basin (Cortes, 1964; Wilson, 1991; Fildani and Hessler, 2005).

**Cordillera Darwin, Chile**

South of Ultima Esperanza, Punta Barrosa Formation facies equivalents have been documented as far south as the Cordillera Darwin (53-54°S) in Chile (Figure 1) (McAtamney et al., 2011). Here, these units are referred to as the Latorre (Seno Otway and Peninsula Brunswick) and Upper La Paciencia Formations (Bahia Brooks). Estimated minimum formational thicknesses range from 600 to 800 meters, but may be as thick as 1200 meters at Peninsula Brunswick (McAtamney et al., 2011). These strata generally consist of interbedded fine- to medium-grained sandstone and mudstone with occurrences of coarse-grained sandstone to pebble conglomerate. Beds show a range of tabular to lenticular geometries and are described as upward thinning and fining packages, which are 10’s of meters thick (McAtamney et al., 2011). Deposits from all three locations in this part of the basin have been interpreted as a result of both high- and low-density turbidity currents in a submarine lobe system during “fan growth” into the Magallanes Basin (McAtamney et al., 2011).

Similar to the Ultima Esperanza area, these strata lie above thick successions of thin-bedded mudstone and mark the initial appearance of continuous, coarse-clastic (medium-grained sandstone to pebble conglomerate) deposition. Consequently they are also interpreted as the onset of foreland basin sedimentation in this portion of the Magallanes Basin (Mpodozis et al., 2007; McAtamney et al., 2011). Maximum depositional ages determined from detrital zircon age populations are estimated to be as old as 89 Ma, but may be as young as 85 Ma (McAtamney et al., 2011).

**METHODOLOGY**

New U-Pb ash ages, stratigraphic sections, and sedimentologic descriptions of the Punta Barrosa Formation primarily come from three locations in the Austral Basin. The furthest north is a ~50 meter section exposed along the Loma de las Pizarres (LDLP) ridge within the Parque Nacional los Glaciares near the town of El Chalten, Argentina (Figure 3). The second is a nearly
continuous ~200 meter section that is located along the shoreline on the southern side of the Magallanes Peninsula and is herein referred to as the Magallanes Peninsula (MP) section (Figure 4). The third and southernmost location in the study area includes a continuous ~300 meter section along the shoreline of the southwest shore of Brazo Sur (Lago Argentino) and will herein be referred to as the Brazo Sur (BS) section (Figure 4). Figure 5 shows examples of the outcrop expression of each of these three localities.

This study also highlights the presence of two additional outcrops that may record the onset (or at least early stages) of consistent sandstone deposition, which occur in the Zona Centro region of Argentina (Figure 4). Data obtained from these locations includes general observations of lithology, bedding characteristics, and architecture as well as paleocurrent measurements, photopan interpretations, and sample collection. One of these exposures consists of a ~100-meter section located on Ea. Los Hermanos (ELH) near the southern short of Lago Viedma and the other is a ~20 meter section located just south of Rio Guanaco (RG). These locations/sections are herein referred to as the ELH and RG sections, respectively.

Eight ash samples were collected throughout the study area from the five previously mentioned study locations (Figures 3 and 4). Additionally, a detrital zircon sample was collected from LDLP outcrop near the base of the section. Data from this sample allows for constraining the maximum age of deposition and provides important provenance considerations. Zircon separates were obtained from each sample for U-Pb geochronology following standard heavy mineral separation procedures. Analyses by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) were conducted at the Arizona Laserchron Center.

**FACIES AND ARCHITECTURE**

Measured stratigraphic sections document centimeter- to decimeter-scale features that include grain size, bed thickness, sedimentary structures, and bedding geometries. These sections were then divided into lithofacies or third order architectural elements (Ghosh and Lowe, 1993; Lowe and Ghosh, 2004), which correspond to groups of beds with similar characteristics, most notably grain size and bed thickness in this case (Figure 6). The following descriptions of lithofacies are the result of combined observations and interpretations from all three of the outcrop locations in the study area. Detailed stratigraphic sections from each location as well as the interpreted distribution of lithofacies are shown in Figures 7, 8, and 9.
Lithofacies (Third Order Architectural Elements)

Measured stratigraphy of Punta Barrosa Formation from the Argentine sector of the basin can be subdivided into 5 basic lithofacies (Figure 6, Table 1): (1) thick-bedded sandstone and conglomerate, (2) thick-bedded sandstone and minor mudstone, (3) medium-bedded sandstone and mudstone, (4) thin-bedded sandstone and mudstone, and (5) thin-bedded siltstone and mudstone (Figure 6). Beds from all lithofacies are interpreted as individual sedimentation units resulting from sediment gravity flow deposits, including turbidity currents, debris flows, and transitional (or hybrid) flows (c.f., Haughton et al., 2009). Internal divisions of low- and high-density sediment gravity flow deposits correspond to those assigned by Bouma (1962) and Lowe (1982), respectively.

**LF-1: Thick-bedded sandstone and conglomerate (IIItsc)**

**Description** – Deposits of thick-bedded medium-grained sandstone to gravel-sized clast-supported conglomerate are the coarsest facies observed in the Punta Barrosa Formation and are only observed within one interval at the Brazo Sur location (Figures 8 and 9). Individual beds are up to 5 meters thick, but commonly range from .5 to 1.5 meters thick. Bedding geometries are often irregular and lenticular as basal scour and amalgamation are common (Figure 10A). Sedimentation units are typically normally graded and occasionally exhibit planar laminations (Tb), but are otherwise structureless (S3/Ta). Additional features include dish and pillar dewatering structures, flute casts, grooves, and tool marks. Although rarely preserved in these units, mudstone and siltstone intervals are up to 5 to 10 centimeters thick and occasionally contain sand-filled burrows (*Thalassinoides*).

**Interpretation** – Massive (structureless) sandstone intervals that are abundant in the lower portions of beds represent S3 divisions (Lowe, 1982). Water escape structures reflect density instabilities of trapped fluids due to rapid deposition of waning flows. Planar laminated beds are interpreted as high-velocity Tb divisions of low-density turbidity currents (Bouma, 1962). Lenticular bedding geometries, the abundance of amalgamated beds, basal scour, and the presence of conglomerate suggest that these deposits represent laterally confined flows, which we interpret as indicating a channel-like depositional setting.

At Brazo Sur, two additional stratigraphic sections (BS-2 and BS-3) were measured through this interval to compare lateral trends in facies (Figure 9). Although the angle of bedding
and lack of continuous lateral exposure make it difficult to correlate these sections, at least one surface along the base of LF-1 can be traced along the outcrop. Locally, this surface commonly shows down-stepping (toward the west-southwest) into underlying beds (Figure 10B). Furthermore, in sections BS-2 and BS-3, lithofacies 1 is nearly double the thickness (~34 meters) compared with that of BS-1 (18 meters) (Figure 9). We interpret the down-stepping and lateral thickness changes as additional evidence for the presence of a confined distributary system.

**LF-2: Thick-bedded sandstone and minor mudstone (IIIts)**

**Description** – Thick beds of fine- to coarse-grained sandstone with minor mudstone are present within all three measured sections (Figure 6). Bed thicknesses range from 25 to 200 cm, but are typically 40 to 120 cm thick. Bedding geometries are mostly even (tabular) and occasionally irregular (undulose) at the base. Amalgamation of sandstone units is common, however basal scour and erosion are rare. Sandstone beds are most commonly massive (S3/Ta), normally graded, and contain dish and/or pillar structures. Planar laminations (Tb) and mudstone rip-up clasts are common while ripple cross-laminations (Tc) are rare. Where preserved, mudstone portions of sedimentation units are less than 10 cm thick, appear massive, and are occasionally bioturbated.

**Interpretation** – Lithofacies 2 is interpreted to reflect rapid deposition of mostly high-density turbidity currents in an unconfined setting. Amalgamation of sandstone beds, mudstone rip-up clasts, and infrequent preservation of mudstone horizons suggest that flows were energetic enough to remove finer-grained caps of previous flows, but unable to maintain suspension of sand. Conditions of collapsing flows (rapid deposition) are supported by the pervasive abundance of dewatering structures (dishes and pillars). An unconfined to weakly-confined depositional setting is interpreted as a result of beds being laterally continuous and showing mostly even thicknesses at the extent of the outcrop. We interpret the rapid deceleration and collapse of these flows to reflect a channel-to-lobe transitional setting.

**LF-3: Medium-bedded sandstone and mudstone (IIImsm)**

**Description** – Lithofacies 3 consists of medium-bedded, fine- to medium-grained sandstone and mudstone and represents the overall most abundant lithofacies. Individual beds are generally 30 to 80 cm thick, but range from 20 to 120 cm thick, and usually consist of tabular
geometries with rare occurrences of uneven thicknesses or lenticularity (Figures 6 and 10C). Tabular beds can be traced laterally for the entire extent of the outcrop, up to 250 meters in some cases (Figure 5B). Nearly all sedimentation units are normally graded and have a massive sandstone interval (Ta) at the base and a mudstone/siltstone upper interval (Td). Sandstone beds are rarely amalgamated. Current-structured intervals such as planar laminations (Tb) and ripple cross laminations (Tc) are also common (Figure 10D). Other common structures/features include dish and pillar structures, mudstone-rip up clasts and occasional sole marks (flutes and grooves) at the base of beds. The mudstone portions (Td) of beds are typically silty and massive, and rarely show exhibit horizons of strictly claystone (Te). Trace fossils are common within this lithofacies and most commonly include *Thalassinoides* and *Ophiomorpha* as well as fewer instances of *Spyrophyton*, *Scolicia*, and *Skolithos*.

Another important characteristic of this lithofacies is the presence of argillaceous (mud-rich) sandstone beds with varying concentrations of mud that occur at discrete intervals within a bed (Figure 11). These beds typically contain cleaner (mud-poor) sandstone intervals at the base that abruptly transition upward into more mud-rich sandstone divisions with dewatering pillars and mudstone rip-up clasts. It is also common for argillaceous units to exhibit one or more current-structured intervals (e.g., planar laminations and/or ripple cross-laminations).

**Interpretation** – Lithofacies 3 is interpreted to reflect the deposition of sediment gravity flow deposits in an unconfined setting. Modes of deposition include low-density turbidity currents, transitional flows, and debris flows. Clean (mud-poor) sandstone beds commonly exhibit one or more divisions (Ta-d) of low-density turbidites (Bouma, 1962). Argillaceous sandstone beds with discrete intervals of varying mud-content are interpreted as “hybrid event beds” (cf., Haughton et al., 2009). Instances where sandstone beds appear mud-rich throughout and do not show transitions in mud content (except for mudstone caps) are interpreted as debris flow deposits. In all cases, the abundance of tabular bedding geometries and preservation of mudstone divisions indicates that these flows were generally non-erosive and unconfined. Similar facies characteristics have been described in the Magallanes basin sector by previous workers and interpreted as lobes (a.k.a., sheets or splays) along a fan setting (Wilson, 1991; Fildani, 2007; Romans et al., 2011).
**LF-4: Thin-bedded sandstone and mudstone (IIIsm)**

*Description* – Lithofacies 4 consists of thin beds of mudstone, fine-grained sandstone, and rare medium-grained sandstone. Individual beds are most commonly 5 to 20 centimeters thick, but can be up to 40 cm thick (Figures 6 and 10E). Beds are tabular and typically exhibit even thicknesses at the scale of the outcrop. Massive basal divisions, planar laminations, and ripple cross laminations are all common in sandstone units. In many instances, near-complete and continuous low-density turbidite divisions (Ta-Td) are preserved (Bouma, 1962). Mudstone units are usually massive and contain burrows. In addition to bed thickness and grain size, these units are most distinguishable from lithofacies 3 and 5 in that they contain abundant current structures (planar laminations and ripple cross-laminations) and are typically 40 to 60 per cent mudstone.

*Interpretation* – Thin-bedded sandstone and mudstone facies are interpreted as deposits of low-density turbidity currents in an unconfined setting. The abundance of current structures and overall thin-bedded nature of these units suggests deposition under waning flow conditions in a relatively distal or off-axis depositional setting (e.g., outer fan, crevasse splay, or levee-overbank). The general lack of any scour features and tabular, laterally extensive bedding geometries is interpreted to reflect relatively low-energy flows that were unconfined. In some instances, LF-4 likely corresponds to off-axis deposition such as levee-overbank settings; whereas in other cases these facies simply reflect the distal run-out of flows. See below for more discussion on depositional setting interpretations.

**LF-5: Thin-bedded mudstone (IIIm)**

*Description* – Thinly-interbedded mudstone facies are primarily mudstone and siltstone, but occasionally include grain sizes up to fine-grained sandstone. Beds are commonly 2 to 15 centimeters thick and have even, tabular geometries. Sedimentation units are normally graded when they contain enough grain size variation and are otherwise massive. This lithofacies differs from LF-4 in that, overall, it is finer grained (only occasional beds of very fine- to fine-grained sandstone) and consists of thinner beds that rarely exceed 20 cm (Figure 10F). Bioturbation is abundant as nearly all of the mudstone and siltstone units within this lithofacies contain trace fossils, which commonly include *Scolicia*, *Cosmorhaphe*, and *Chondrites*. 
**Interpretation** – Similar to Lithofacies 4, we interpret thin-bedded mudstone and occasional fine-grained sandstone to reflect deposition of low-density turbidity currents in a relatively distal or off-axis depositional setting such as a lower fan, basin plain, or along a slope. The majority of these units are interpreted to result from sediment fall-out from suspension, as they are typically massive or normally graded. Thick (>5 m) intervals of LF-5 are present at least once in all three sections and likely represent a relatively quiescent time and/or position in the depositional setting of this system.

**Outcrop Descriptions**

*Loma de las Pizarres (LDLP) Section*

Stratigraphy from the LDLP outcrop is represented here by a ~50 meter section of sandstone and mudstone, however these rocks lie conformably above >100 meters of brittle mudstone that gradually transitions upward into the more sand-rich units captured by the section shown in this study. Here, only 3 of the 5 lithofacies are identified. In order of abundance, these include LF2 - 57%, LF3 - 24%, and LF5 - 19%. At least four lobe elements are interpreted from the LDLP section with an average thickness of 9.3 meters and a range of 5.5 meters up to 18 meters. Lobe elements are separated by 2 to 6 meter thick inter-element intervals of LF-5 or by poorly exposed intervals that usually correspond to mudstone dominated units.

*Magallanes Peninsula (MP) Section*

The base of the MP section is determined locally by the exposure of some medium-bedded sandstone and mudstone units because the contact with the underlying Rio Mayer mudstone is not exposed here. The upper bound of the section corresponds to a disruption in stratigraphic continuity as a result of vegetation cover and faulting. In order of proportional abundance the MP section consists of the following four lithofacies: LF3 - 46%, LF5 - 25%, LF2 - 16%, LF4 - 13%. Approximately 10 lobe elements are interpreted from this section. On average, lobe elements are 9.9 meters thick and range from 6 to 20.5 meters thick. Inter-element intervals consist of sections of LF4, LF5, and/or cover that range from 1 to 33 meters thick. Similar to the LDLP section, covered intervals most commonly correspond to mud-dominated facies and are interpreted as such.
**Brazo Sur (BS) Section**

The Punta Barrosa Formation at the southern end of Brazo Sur preserves at least 300 meters of continuous stratigraphic section and, to our knowledge, also represents the most complete documented section of Punta Barrosa facies equivalent rocks. For descriptive purposes only, this section is informally divided into lower, middle, and upper sections. These are not intended to correspond to upper and lower Punta Barrosa divisions that have been described in the Ultima Esperanza district in Chile (Wilson, 1991; Fildani and Hessler, 2005). All 5 lithofacies are present at this location and consist mostly of LF3 (40%) and LF4 (31%). Sandstone injectites (clastic dikes) are common throughout the entire BS-1 section, but are especially abundant in the upper 50 meters of the upper interval.

The lower section is at least 120 meters thick (Figure 6) and primarily consists of tabular beds of mudstone and fine- to medium-grained sandstone (LF4, LF3, and LF2) (Figure 8). Eight lobe elements have been identified within the lower interval and range in thickness from 7 to 22 meters. This section also contains ~90% of the hybrid event beds identified from the entire BS-1 section. The middle section of BS-1 consists of approximately 70 meters of very thin- to thin-bedded mudstone, siltstone, and very fine- to fine-grained sandstone (LF4 and LF5). Initially this interval fines upward (increasing mudstone/sandstone ratio) and then gradually shifts back to a slightly upward coarsening trend with increasing proportions of sandstone beds (Figure 8).

Lastly, the upper unit of the Punta Barrosa Formation at Brazo Sur is represented in the upper 110 meters of the stratigraphic section (Figure 8). All lithofacies are present in this interval and there is a marked change in the style of deposition. Overall, amalgamation is much more common, especially in the lower 30 meters of the interval, and bedding geometries are commonly lenticular or uneven. Also, finer-grained lithofacies (most notably LF4) are more bioturbated, pervasively ripple cross-laminated and often consist of intervals of repetitive thicknesses (see Figure 10E for example). LF4 intervals are up to 15 meters thick, whereas in the lower section they do not exceed 5 meters when separating thick intervals of LF2 and LF3.

**Estancia Los Hermanos (ELH) Section**

In addition to the measured stratigraphic sections described above, additional outcrops within the Zona Centro region record some important variations in depositional context within the Austral basin sector (Figure 4). Most notably, the outcrop near Estancia Los Hermanos
(ELH), located near the southern shore of Lago Viedma, exposes an approximately 100-meter section of mostly thin-bedded sandstone and mudstone with packages of thicker bedded sandstone (Figure 12). This exposure is oriented north-south and based on previous documentation of a dominantly south-directed paleoflow throughout the basin (Wilson, 1991; Fildani and Hessler, 2005; this study) we infer the north end of the outcrop to be up-dip (depositionally) relative to the southern end. Chaotically bedded units are common within mudstone-dominated intervals and to a lesser extent are observed in the sand-prone facies as well. Sandstone packages are coherent at the north end of the outcrop and transition to a more chaotic expression at the southern end. These sandstone beds show an apparent on-lapping relationship with the underlying surface (Figure 12). At least three northward-dipping (antithetic) normal faults are observed and cross-cut both mudstone- and sandstone-dominated facies (Figure 12). Although some sandstone units are off-set, faults terminate up-section within the sandier facies until they are healed by an overlying continuous set of beds. We also highlight the presence of imbricated (thrust-faulted) sandstone beds that appear to be duplexed in at least two locations along the outcrop (Figure 12). Although precise fault-orientation measurements were not collected, fault-imbricated sandstone beds appear to be verging generally toward the north.

**Paleocurrents**

A total of 321 paleocurrent measurements were collected from the study area. The majority (approximately two-thirds) of the measurements come from sole marks (tool marks, grooves, flute casts, etc.) and the remainder are ripple cross laminations. In nearly all cases, tool marks were accompanied by flute casts, which provided the unidirectional component of the flow. Ripple laminations were only considered if the plane of that lamination could be observed. All data were rotated to correct for bedding using Stereonet® (Allmendinger et al., 2013; Cardozo and Allmendinger, 2013). Much of this dataset (n = 267) is from the MP and BS outcrops (Figures 4, 7, and 8). The remaining 56 measurements were collected from the RG outcrop near the Rio Guanaco in the Zona Centro region (Figure 4). All of the paleocurrent determinations reveal a consistent south-southwest to south-southeast direction of flow, which is similar to previous studies of outcrops to the south, in the Ultima Esperanza District of Chile (Wilson, 1991; Fildani and Hessler, 2005).
Interpretation of Depositional Environments

Deep-marine fan system

We interpret the overall depositional setting for the LDLP, BS, and MP measured sections to represent a deep-marine fan system. This is consistent with previous workers’ interpretations of facies equivalent units from the Magallanes basin sector in Chile (Wilson, 1991; Fildani and Hessler, 2005; McAtamney et al., 2011). Bathyal (1000-2000 m) water depths have been determined from biostratigraphic assemblages in the Magallanes Basin (Natland et al., 1974). For the purposes of this study, a submarine fan “system” includes both confined and unconfined elements, which from distal to proximal consist of: basin plain, lower fan, mid fan, and upper fan (Ricci Lucchi, 1975; Normark, 1978) (Figure 13). Furthermore, similar to other deep-water fan models, this synthesis also includes the interpretation of lobes as smaller scale features that are typically associated with the middle to lower fan region (Ricci Lucchi, 1975; Mutti, 1977; Walker 1978; Howell and Normak, 1982). Lobe definitions and characteristics are discussed later.

Thin-bedded, fine-grained units of lithofacies 4 and 5 are interpreted as off-axis deposits in a lower fan to basin plain setting (e.g., Mutti and Ricci Lucchi, 1975; Mutti et al., 1978; Howell and Normark, 1982). Overall, LF-3 is the most abundant and we interpret these facies to represent lobes in a mid to lower fan depositional setting. Thicker bedded, and more amalgamated units of lithofacies 2 correspond more closely to mid to upper fan regions where flows are losing confinement and rapidly collapsing. The coarse-grained units of LF-1 are present only in the upper part of the section at Brazo Sur and we interpret these facies to represent confined deposits in the upper fan region, or at least in the vicinity of the channel-lobe transition zone (Mutti and Ricci Lucchi, 1975; Mutti et al., 1978, Howell and Normark, 1982; Wynn et al., 2002).

An important exception to the aforementioned association of LF4 occurs in the interval that is stratigraphically above the section of LF1 at Brazo Sur. Here, the LF4 interval is laterally equivalent to coarse-grained, amalgamated units of LF1 (Figure 9), which suggests that they more likely represent overbank or levee deposits rather than a distal fan setting. Thus the presence of repetitiously thin-bedded, low-density turbidites in LF4 that are laterally equivalent to high-density turbidites of LF1 reflects processes of flow-stripping whereby flows can overspill confining margins and portions still within the channel rapidly decelerate and collapse due to
loss of sediment load and/or loss of confinement (Piper and Normark, 1983). Given this transition in depositional setting, the sandstone intervals of LF2 and LF3 that are present above the LF1 interval at Brazo Sur more likely represent overbank (crevasse) splays rather than mid-to upper fan lobe associations. These interpretations imply that, at least at Brazo Sur, the Punta Barrosa Formation represents an overall progradational system.

**Slope**

The section of stratigraphy exposed at ELH is interpreted to represent a depositional setting along a deep-water slope system. This interpretation is based primarily on the evidence for antithetic growth faulting as well as the abundance of mass transport deposits. Syn-depositional extension (growth faulting) along antithetic normal faults is best preserved in the lowermost sandstone package and is indicated by: 1) increasing overall thickness of the sandstone package toward the fault; 2) onlapping geometry of sandstone beds along the northern, footwall side of the fault; and 3) the fact that lower sandstone beds are off-set within the sandstone package while upper beds are continuous across both sides suggesting healing of the fault. These observations and interpretations are consistent with, and similar to, younger slope systems documented in the Tres Pasos Formation along El Chingue Bluff in the Chilean sector of the basin (Shultz and Hubbard, 2005). Additional evidence for the interpretation of a slope setting is provided by the abundance of contorted and chaotically bedded units, which we interpret as mass transport deposits (MTDs) (e.g., Shipp et al., 2011).

**U-Pb Zircon Geochronology - Samples and Results**

A summary of sample locations and interpreted ages is available in Table 2. Age data from each sample is shown in Figure 15. Results from samples LH158, RG163, LP60, LTA87, and MP94 yield MSWD values that are outside the lower bounds of 95% confidence, which suggests that uncertainties in the ages are being over-estimated (Mahon, 1996). We attribute this to 1) low U concentrations in several of the analyses, which yield higher 6/8 uncertainties, and 2) overdispersion factors added into the data reduction process to more conservatively account for greater analytical scatter that is inherent when using lower precision techniques such LA-ICPMS. Thus given the precision limits of LA-ICPMS and the fact that all U-Pb ages within each sample’s calculated age overlap within 2-sigma error, there is no statistical justification for
the exclusion of data to obtain “better-fit” MSWD values. Uncertainties for each sample age discussed in the text and shown in Table 2 and Figure 15 are expressed at 95% confidence (~2σ).

Sample LP60 comes from the northernmost study area and was collected from a mudstone interval approximately 20 meters below the base of the LDLP measured section. It yields an interpreted age of 115.1 ± 1.9 Ma (2σ), which is consistent with previous biostratigraphic age constraints that suggest an Aptian–Albian age for these rocks (Kosmal and Spikermann, 2001).

Samples LH158, RG163, and CH06 were all collected from the “Zona Centro” region, between Lago Viedma and Lago Argentino. Sample LH158 was collected from near the base of the ELH section (Figure 12) and yields an interpreted age of 100.3 ± 3.7 Ma. RG163 was collected just below the base of a relatively short (~20 meter) section of sandstone and mudstone, which is internally coherent, but regionally folded and faulted. It has an interpreted age of 92.3 ± 2.3 Ma and it should be noted that the interpretation of this result warrants caution given that the limited outcrop extent and tectonic deformation make it difficult to determine the depositional facies and stratigraphic context of the section it was collected from. Sample CH06 was collected from Cerro Horqueta near the northern shore of Lago Argentino and yields an interpreted age of 95.7 ± 1.2 Ma.

Two ash samples (MP48 and MP94) were collected from the Magallanes Peninsula and yield interpreted ages of 96.8 ± 1.3 and 95.6 ± 1.9 Ma, respectively. Sample MP48 was collected from a roadcut exposure of interbedded sandstone and mudstone. Sample MP94 was collected within the context of the measured section from the Magallanes Peninsula (Figure 7). Finally, samples LTA84 and LTA87 were both collected in the context of the measured stratigraphy at the southern end of Brazo Sur (Figure 8). Sample LTA84 comes from lower in the section and yields an interpreted age of 98.1 ± 1.5 Ma. Sample LTA87 was collected near the middle of the section and yields an interpreted age 97.5 ± 2.9 Ma.

Results of a U-Pb detrital zircon ages (n = 96) from sample LP33 are shown as a histogram plot and probability density functions in Figure 15B. Age populations reveal one primary peak at ca. 110 Ma, and additional, subordinate peaks at 130, 143, 270, and 520 Ma. Given that there is a continuous range of ages between 105 and 135 Ma, a maximum depositional age was interpreted by calculating a weighted man average of the of the youngest peak age population, which in this case includes 39 ages between ~105 to 120 Ma. This yields an
interpreted MDA of 110.2 ± 1.7 Ma. When accounting for 95% confidence (~2σ) limits on the uncertainties the MDA interpreted for sample LP33 is only slightly younger (~2 Ma) than the interpreted depositional age of sample LP60. This result comes as no surprise given that LP60 was collected ~20 meters lower in the section.

DISCUSSION

Lobe Dimensions

Implementing a hierarchical framework for the division of stratigraphic successions has proven to be a useful and valid approach to better understanding the architecture of turbidite systems (Mutti and Normark, 1987; 1991; Normark et al., 1993; Ghosh and Lowe, 1993). Prelat et al (2009) established a hierarchical division for submarine lobes from the Karoo Basin that emphasizes thickness, lithofacies, and grain sizes of composite stratal units. Much of the nomenclature used by Prelat et al (2009) is adopted in this study, however some important modifications are made. We define the most basic architectural unit (“bed”) as referring to individual depositional events (e.g., sedimentation units). However, in contrast to lobes of the Karoo Basin the vast majority of beds that are affiliated with lobe facies in this study have preserved mudstone caps. Thus the application of the term “lobe element” as described by Prelat et al (2009) is probably not appropriate for these rocks. Instead, we define a lobe element as a set of genetically related beds (typically 8 or more) that are bound by “inter-element” intervals of thin-bedded mudstone and sandstone, which are at least 0.5 meters thick. The usage of lobe element in this study is more similar to the term “lobe” used by Prelat and others (2009). Figure 14 shows an example of how this architecture is translated to the outcrop at Brazo Sur. In general, the hierarchy used here is closely matched with lithofacies divisions such that LF-2 and LF-3 correspond to lobe elements and LF-4 and LF-5 are generally associated with inter-element intervals.

Thrust faulting and folding of the Punta Barrosa Formation limits the temporal, and especially the lateral, continuity of outcrops. Nevertheless, sections representing submarine lobe facies from this study and from the Chilean sector of the basin are well exposed and show vertically stacked packages of beds, which can be interpreted and subdivided into lobes or lobe elements. Prelat and others (2010) compiled morphological data from six different lobe systems to compare intrinsic and extrinsic relationships of lobe dimensions. Their dataset demonstrated
that two general groups characterize the dimensions of lobe deposits: confined and unconfined. Confinement, in this case, refers to basins with steeper gradients perpendicular (or oblique) to flow directions than those parallel, which includes irregular sea-floor topography (Prelat et al., 2010). A comparison of the vertical dimensions of lobe elements from our study with their data set allows for a first-order approximation of the dimensions of lobes that record the early phases of deposition in the MAB.

Figure 16 shows a comparison of lobe element thickness from each of the three sections presented in this study as well as those documented in the Ultima Esperanza District of Chile (Fildani and Hessler, 2005). Maximum lobe element thicknesses range from 18 to 22 meters and the average from each section/area ranges from 9.3 to 12.5 meters. Plotting this data on fields determined by Prelat et al. (2010) suggests that lobe element widths could range anywhere from ~2.5 kilometers (confined system) up to 20 kilometers (unconfined system).

Overall, lithofacies 3, 4, and 5 constitute the vast majority of Punta Barrosa equivalent outcrops and each of these facies are characterized by commonly having beds with mudstone intervals (Bouma Td and Te intervals). We interpret this as an indication that once flows reached a fan setting they were able to sufficiently expand laterally and deposit mud from suspension settling. Consequently, these flows were probably not confined by basin margins or local sea floor topography, except those associated with more amalgamated lithofacies (LF1 and LF2).

**Deposition of Hybrid Event Beds**

Although turbidity currents are interpreted to be the primary mode of deposition for the stratigraphy documented in this study, there are some notable exceptions particularly with regard to hybrid event beds. A comprehensive assessment of the detailed sedimentology associated with these deposits is outside the scope of this study. However we emphasize their presence and abundance because outcrops along Brazo Sur and the Magallanes Peninsula exhibit excellent exposures of transitional flow deposits that may be on par with several other well-known locations such as the Ross Sandstone Formation in Ireland and the Karoo basin in South Africa (Haughton et al., 2009; Hodgson, 2009). Depositional models for end-member sediment gravity flows and their deposits (e.g., debrites and turbidites) have been available for decades, however the characterization of hybrid flows and their deposits (e.g., “slurries” or “hybrid event beds”) is still a work in progress. Recent efforts to constrain the origin and significance of
transitional flow processes and the resulting hybrid beds highlight the complexities and challenges associated with these deposits (Lowe and Guy, 2000; Haughton et al., 2003; 2009). Hybrid event beds can be difficult to identify in outcrop because they often require fresh, clean exposure as mud-content is difficult to see. Similar to turbidity current deposits, there is also a range of vertical profiles that may be expressed in outcrop where only portions of the idealized profiles are preserved.

The interpretation of a depositional setting for rocks of this study was based primarily on bedding geometries, grain size, and sedimentary structures and independent of the distribution and characteristics of the identified hybrid beds. Thus, the observations and interpretations may offer insight into the depositional context of transitional flows. A few key observations from this study include: (1) hybrid beds are interbedded with turbidites and debrites, (2) the most abundant vertical facies profile consists of H1, followed by H3, and then capped by an H5 division (Haughton et al., 2009), (3) upward transitions in mud/clay content within beds are typically abrupt and rarely gradational (4) hybrid beds are most common in the lower portions of the sections at both Brazo Sur and the Magallanes Peninsula, but do occur sporadically throughout each section, and (5) hybrid beds are most abundant in facies associated with lobe deposits.

Haughton et al. (2009) noted that hybrid beds are common in the initiation stages of distal portions of fan systems with inherited out-of-grade (over-steepened) slope profiles that can be attributed to changes in flow scale, active tectonics, and/or continued substrate deformation. Stratigraphy at Brazo Sur and the Magallanes Peninsula show that transitional flow deposits are most abundant in the lower portions of the sections (Figures 7 and 8). Thus if the indication of hybrid beds is in fact related to up-dip slope profiles it follows that the early evolution of the basin likely included out-of-grade slopes that were inherited from the predecessor Rocas Verdes backarc basin phase or due to reactivated thrust faults associated with the advancement of a fold and thrust belt. Additionally, the underlying mud-dominated Zapata/Rio Mayer Formations may also have served as a source for additional mud being incorporated into the flow causing downslope bulking and transitional flow behavior. In either case, this interpretation implies that the initial delivery of coarse clastic detritus into the MAB involved sediment gravity flows over out-of-grade slopes that progressively evolved to a more graded profile and decreasing the abundance of transitional flow processes over time. Additional, independent evidence for over-
steepened slope profiles is provided by the presence of multiple mass transport deposits that make up the section at ELH (Figure 12).

**Basin-scale variations**

Along strike comparisons of outcrops representing the Punta Barrosa and facies equivalent units are somewhat limited by the fact that observations from each of the geographic basin sectors (north, central, and south) have been described by different authors. There also seems to be a considerable amount of variation in the continuity of sections as well as the level of detail used to describe each section. For example, exposures in the Ultima Esperanza District of Chile, largely consist of folded and faulted discontinuous outcrops which preclude the ability to measure continuous stratigraphic sections thicker than ~60 meters (Fildani and Hessler, 2005). Additionally, facies equivalent units documented in the southern sector of the basin near the Peninsula Brunswick, are presented as cumulative sections up to 100’s of meters thick and do not show bed-scale characteristics, as this was outside the scope of their study (McAtamney et al., 2011).

Nevertheless, there are several notable similarities in the lithology, sedimentology and stratigraphic architecture of the Punta Barrosa Formation between Austral and UE basin sectors: 1) Predominant grain sizes consist of mudstone to fine- to medium-grained sandstone; 2) Bedding geometries are mostly tabular at the extent of the outcrop; 3) Interpreted modes of deposition include low- and high-density sediment gravity flows (Wilson, 1991) as well as hybrid event beds, and occasional debris flows (Fildani and Hessler, 2005). Although these study areas share several commonalities, some differences/changes are also noted, such as: 1) units in the upper section at Brazo Sur contain gravel (granule) conglomerates, which is coarser than any of the facies documented to the south (although conglomerate is also described in the southern sector), 2) based on stratigraphic sections from Fildani and Hessler (2005), evidence for bioturbation is much more abundant in outcrops from this study area, and 3) the amalgamation of beds (most notably from the upper section at BS) is more common in the northern sector. These similarities and differences between units in the Austral sector and UE District of Chile can be attributed to an interpretation that the Punta Barrosa Formation in both locations represents the same overall deep-water fan depositional setting; however, outcrops in the Austral basin sector
are likely in a more proximal setting and thus reflect more amalgamation, thicker beds, and coarser grain sizes.

Comparisons between the Punta Barrosa Formation and facies equivalent rocks in the Austral sector and the southern sector are somewhat limited because the strata from the Cordillera Darwin and Seno Otway have not yet been documented in similar detail. General descriptions by McAtamney et al (2011) record similar facies and are also interpreted to reflect deposition on a submarine fan. Similarly, sandstone beds are described as being in meter to 10s of meter thick packages, which may be similar in scale to the lobe facies described in this study. However, in contrast to a consistent southward paleoflow pattern documented in the Ultima Esperanza District as well as this study, paleocurrent data from southern basin sector suggests a wider range of sediment dispersal patterns including northeast, east, southeast, and southwest (McAtamney et al., 2011).

Abundant along-strike (north-south) exposures offer excellent opportunities for improved basin constraint and the north-south distribution of facies; However spatial constraint in the east-west direction is much more limited. Subsurface data from the Toro-1B well drilled in the Ultima Esperanza District of Chile suggests that the Punta Formation pinches out laterally toward the east within a distance of ~40 kilometers (Figure 4) (Katz, 1963). Depending on the location of the pinch-out, deposits of the Punta Barrosa Formation may only extend laterally for ~80–100 kilometers. Consequently the MAB is described as originating as a narrow, elongate trough oriented parallel to the strike of the orogenic belt (Wilson, 1991), and that the paleocurrents and geometries of depositional “bodies” indicates that this trough was ~100 km wide (Fildani and Hessler, 2005; Fildani et al., 2009; Romans et al., 2011). A comparison of lobe thicknesses from the Punta Barrosa Formation in this study with other systems (Prelat et al., 2010) suggests that individual lobes may range from ~2.5 km in a confined system up to widths of ~20 km for an unconfined system (Figure 16). In either case, despite being commonly identified as a narrow basin, the overall geometry of the MAB was likely sufficient for accommodating the spatial capacity of sediment gravity flows into the basin. Thus, these flows were probably not being confined by the basin margins.
U-Pb Geochronology

Ashes – Timing of Deposition

New zircon U-Pb ages from ash beds reveal some important trends about the early fill of the MAB. Figure 17 shows a plot of radiometric age constraints relative to location from throughout the basin, which includes maximum depositional ages interpreted from detrital zircon geochronology by previous workers (Fildani et al., 2003; McAtamney et al., 2011). An overall southward younging trend is shown by the assembly of interpreted depositional ages of units representing the onset of coarse clastic deposition.

At the latitude of El Chalten (~49°S) consistent deposition of medium- to thick-bedded sandstone (beds 1–2 meters thick) began as early as ca. 115 Ma, which is chronologically associated with the shale-dominated Rio Mayer Formation. Deposition of sandstone along a deep-water slope is preserved by stratigraphy at ELH and occurs at ~100 Ma at this latitude. Based on interpretations of the LDLP outcrop, the relative age and deposition setting at ELH suggests southward progradation of this deep-water system during Albian time. The other two samples collected from Zona Centro, RG163 and CH06, were collected from outcrops that regionally seemed to correspond to the initial consistent appearance of sandstone deposition, however additional work is needed in order to more confidently place these samples into depositional context. Sample RG163 plots slightly off-trend from the other data, which may be due to either a lack of stratigraphic and depositional context or the presence of isoclinal folding in the sample area. Data from these samples provides valuable relative age constraint from the formations they were collected and may indicate that a deep-water basin was present in this area at least through Cenomanian time. Deposition of a deep-water fan system was well-established at the latitude of Lago Argentino by no later than middle Cenomanian time. U-Pb ash ages from the BS and MP study areas range from 95.6 to 98.1 Ma. The majority of facies at these locations suggest deposition along a middle to lower fan setting and in the upper section of the BS section facies indicate progradation of the system to an upper fan setting (Figure 13). The youngest age interpreted from the southern portion of the Austral sector predates maximum depositional ages of the Punta Barrosa Formation in the Magallanes sector by approximately 3 My.
**Detrital zircon provenance**

U-Pb detrital zircon ages from sample LP33 help constrain the maximum timing of deposition as well as sediment sources for these sandstone deposits. The interpreted MDA for this unit is 110.2 ± 1.3, which is compatible with sample LP60 given their relative stratigraphic positions. Approximately 64% of the ages are between 100 and 150 Ma and are represented in the primary peak at ca. 110 Ma and subordinate peaks at 130 and 143 Ma. Arc magmatism begins at ca. 150 Ma and is more or less continuous through the Cretaceous but has been described as occurring in episodes of peak magmatism at 144–137, 136–127, and 126–75 Ma (Hervé et al., 2007). Regardless of these intervals, based on detrital zircon signatures, the Cretaceous arc appears to be the primary source of detritus during the initial appearance of consistent sandstone deposition at LDLP. Additional, secondary peaks at ca. 270 and 520 Ma correspond closely to detrital signatures observed in the East Andean Metamorphic Complex (EAMC) (Hervé et al., 2003) and are thus likely sourced by exhumation and recycling of the EAMC during early the depositional history of the MAB.

**Foreland Basin Initiation**

The Magallanes–Austral Basin and its predecessor Rocas Verdes Basin represent a long-lived (>150 My) and dynamic history of tectonism. Thus, a clear determination of the relationships between tectonics, basin evolution, and sedimentation may not be straight-forward. For example, the onset of a foreland basin would not be reflected by increased subsidence or accommodation space because a deep-water basin had already been established by extension and thermal subsidence during the backarc phase of the basin. However, given that the later stages (Lower Cretaceous) of the RVB are represented by up to 1 kilometer (check reference) of carbonate and mud deposition, the abrupt appearance of coarse clastic deposition is likely the result of a relatively rapid increase in sediment supply. We interpret this to correspond to increasing rates of uplift and erosion as a result of thrust belt development. This rationale, combined with provenance constraints, is consistent with previous workers’ interpretations for the representation of a well-developed foreland basin. The onset of foreland basin sedimentation in the well-constrained Magallanes Basin sector is marked by the appearance of consistent (deep-water) coarse clastic deposition (following the a period of dominantly fine-grained sedimentation), and we suggest that similar facies in the Austral Basin sector represent the same.
Varela et al. (2012) suggest that the onset of shortening in the Austral Basin is recorded by west to east progradation of fluvial-estuarine deposits of the Mata Amarilla Formation (Figure 2), which begins at ~100 Ma based on an interbedded tuff age of 96.2 ± 0.7 Ma collected from the middle Mata Amarilla Formation. From this, they concluded that the initiation of the foreland basin was synchronous between the Austral basin sector and the Magallanes Basin sector, citing the reported 101 Ma age of the Zapata–Punta Barrosa transition zone (Fosdick et al., 2011). Our results depart from the conclusions of Varela and others (2012) and suggest a revised model whereby the onset of coarse clastic deposition and foreland basin development is diachronously initiated from as far north as El Chalten, Argentina (~49°S) to as far south as the Cordillera Darwin in Chile (~54°S). We favor a revised interpretation because it accounts for the timing and distribution of facies highlighted in this study and is consistent with how previous models document this transition in the Chilean sector. Furthermore, the Mata Amarilla Formation locally overlies Albian-aged fluvial-deltaic deposits of the Piedra Clavada Formation (Riccardi et al., 1986; Poiré, 2002; Archangelsky et al., 2008), which to our knowledge remains relatively unconstrained in terms of provenance and tectonic setting. Also, the type location for the Mata Amarilla Formation crops out ~100 kilometers east of El Chalten whereas directly east of El Chalten is a thick (~1000 meter) succession of Cenomanian aged shallow-marine strata described as the Lago Viedma Formation (Arbe 2002). Thus, if the Mata Amarilla Formation represents foreland basin initiation, it is not clear how this interpretation accounts for the tectonic association of coarse clastic deposition in age equivalent strata of the Lago Viedma Formation as well as the older Piedra Clavada Formation. Lastly, results from this work suggest the presence of deep-water basin throughout the Cenomanian in the Zona Centro region, which makes it depositionally unfeasible to have roughly age-equivalent west-to-east prograding shallow to non-marine strata located to the east of the study area.

**Paleogeographic Implications**

Based on the interpretations from this study, submarine fan facies can be traced from as far south as the Cordillera Darwin in Chile to as far north as El Chalten, Argentina. Prior to this study, such facies were mapped only as far north as Lago Argentino (Figure 1) (Arbe and Hechem, 1984). Additionally, we report new evidence for the existence of slope facies, which have not been previously documented for the early depositional history of the MAB. New
constraints on the distribution of these facies as well as the timing of deposition provide a better understanding of the paleogeography and initial basin fill during the early stages of the MAB (Figure 18).

The southward younging trend observed in the initiation of coarse clastic deposition can be explained by one of the following scenarios: 1) The MAB originated with a strong longitudinal sediment dispersal system for a northern point source and the protracted appearance of sandstone is a result of this sediment dispersal system prograding southward. 2) Alternatively, the detritus for these deep-water fan systems is derived from local sources and there is a southward appearance/onset of sediment supply over time. One way to accommodate this is through increased uplift (and erosion) migrating southward possibly in response to along-strike (north to south) maturation of a fold and thrust belt. At present, data and observations from the Austral basin sector (this study) and UE district of the Magallanes sector favor the former model based on the spatial and temporal distribution of facies as well as a consistent south-directed paleocurrent evidence. Although it is beyond the scope of this study, one approach to resolving the feasibility of each of these models would be to compare provenance signatures between each of these outcrops as well as expected contributions from potential source areas.

**Late Aptian–Albian (115-100 Ma)**

In the northern sector of the basin (~49°S), the Aptian–Albian (as well as Cenomanian) time interval corresponds to an overall transition from rift-sag subsidence to retroarc deformation and foreland basin development. Consequently there are also complexities in the range of depositional settings documented in different locations at this latitude. This study highlights the presence of high- and low-density turbidites interpreted as being deposited in an unconfined deep-marine environment. Based on U-Pb zircon geochronology these deposits are late Aptian in age. Near Tres Lagos, approximately 100 kilometers east of El Chalten, early Albian (Riccardi et al., 1986; Archangelsky et al., 2008) fluvial-deltaic sequences have been identified as the Piedra Clavada Formation (Poiré et al., 2002). The tectonic context, provenance, and spatial extent of both the turbiditic sandstone units from this study as well as the Piedra Clavada Formation remain largely unconstrained, making it difficult to assess the stratigraphic relationships between these two seemingly disparate units. Based on the data available at this time we suggest that the
deposition of deep-water turbidites documented in the Rio Mayer Formation (this study) not only pre-dates deposition of the Piedra Clavada Formation, but is also sufficiently distal to accommodate significant differences in depositional settings (e.g., fluvial deltaic vs. deep-water fan).

**Cenomanian–Turonian (100-89 Ma)**

Slope facies and architecture of earliest Cenomanian (or lastest Albian) age documented at the ELH outcrop suggests that a southward-facing slope system was present in the Zona Centro region at this time. Ages of deep-water fan deposits in the vicinity of Lago Argentino may range from 93.7 to 100.4 Ma, based on 2σ uncertainties. Any direct relationships between these slope and fan systems, during this time, is difficult to determine, but should not be ruled out as there is a subtle overlap in age and a link between these systems would be consistent with the dominantly south-directed paleocurrents documented in fan facies around Lago Argentino. In the northernmost part of the study area, this time interval corresponds to shallow marine deposition of the Lago Viedma Formation (Arbe, 2002) near Cerro Pyramide (Figure 3) as well as shallow marine and fluvial deposits of the Mata Amarilla Formation (Varela et al., 2012). By the Turonian stage (~92 Ma) the onset of fan deposition likely reaches the Ultima Esperanza District of the Chilean sector of the basin as suggested by detrital zircon maximum depositional ages (Fildani et al., 2003).

**Coniacian (89-85 Ma)**

Based on maximum depositional ages of detrital zircon analyses, consistent deposition of medium-bedded sandstone (e.g., Lattore and upper La Panciencia Formations) near the latitude of Peninsula Brunswick (~54°S) does not begin until at least 89 Ma and possibly not earlier than 85 Ma (McAtamney et al., 2011). This represents the youngest known onset of deep-water fan deposition into the basin. The timing of these deposits corresponds to the early development of the Cerro Toro formation, which includes the evolution of a well-documented sinuous axial channel belt in the Ultima Esperanza District (Hubbard et al., 2008; Bernhardt et al., 2012). Although these units are chronologically correlative, their stratigraphic relationships are not constrained.
SUMMARY AND CONCLUSIONS

Deep-water slope and fan deposits record the early depositional history of the MAB from as far north as El Chalten, Argentina (49° S) to at least as far south as the Cordillera Darwin (55° S). In summary, the stratigraphic architecture of the early fill of the Magallanes–Austral retroarc foreland basin is characterized by sediment gravity flow deposits along a deep-water fan system with facies that range from a confined upper fan setting to distal lower fan and basin plain settings. Interpreted sediment gravity flow processes include turbidity currents, debris flows, and transitional flows, that consistently show south-directed paleoflow. Initial deposition of hybrid beds by transitional flows may indicate the inheritance of out-of-grade slopes during the initiation of the retroforeland. The upper portions of sections are relatively less abundant in hybrid beds suggesting that, over time, the slopes evolved into more graded profiles.

Detailed stratigraphic sections and facies analysis from the Argentine sector of the MAB suggest that this fan system was overall progradational. Although the initial basin geometry may be characterized as a narrow trough, its margins likely did not influence the stratigraphic architecture of the Punta Barrosa formation and facies equivalent rocks. Thus the progradational aspect of this system may have been governed more by sediment supply and source area uplift rather than the basin configuration and accommodation.

New U-Pb zircon geochronology of ash bed deposits reveals a southward younging trend in the onset of coarse clastic deposition into the basin. In the northernmost part of the study area (~49° S) consistent sandstone deposition begins as early as ~115 Ma; whereas in the southern basin sector (~54°) this does not occur earlier than ~89 Ma. This progressive southward younging in the timing of consistent sand delivery into the basin is interpreted to reflect diachronous initiation of the foreland basin. Possible explanations for this trend include gradual southward progradation of deep-water fan system from a northern point-source or a southward increase and/or availability in local (likely westward) sediment supply in response to uplift and erosion associated with the southward migration and development of a fold-and-thrust belt.

ACKNOWLEDGEMENTS

Funding for field research and laboratory analyses was provided by the industrial affiliates of the Stanford Project On Deep-water Depositional Systems (SPODDS) as well as the McGee and Leverson graduate research grants awarded to Malkowski. SPODDS affiliates

We are grateful for the cooperation of the Estancias Nibepo Aike, La Querencia, and Los Hermanos as well as the Parque Nacional Los Glaciares for providing access to these outcrops. This work has benefited tremendously from discussions with Marty Grove, Don Lowe, Theresa Schwartz, Julie Fosdick, and Zach Sickmann as well as field assistance from Corey Steimel. We thank Trevor Dumitru for help and guidance with heavy mineral separation as well as George Gehrels, Mark Pecha, and the Arizona Laserchron staff members for their help with geochronology analyses.
REFERENCES


Allen, R.B., 1982, Geología de la Cordillera Sarmiento, Andes Patagonicos, entre los 51°00' y 52°15' Lat. S, Magallanes, Chile, Bull. 38, 46 pp., Serv. Nac. de Geol. y Minería-Chile, Santiago.


Riccardi et al., 1986


Winn, R.D., and Dott Jr., R.H., 1977, Large-scale traction produced structures in deep-water fan-channel conglomerates in southern Chile: Geology, v. 5, p. 41–44.

Winn, R.D., Dott Jr., R.H., 1979, Deep-water fan-channel conglomerates of Late Cretaceous age, southern Chile. Sedimentology 26, p. 203–228.

Figure 1. Geologic map of southern Patagonia highlighting Jurassic-Cretaceous volcanic and sedimentary rocks associated with Jurassic Rocas Verdes backarc and the Cretaceous retroarc foreland fold-and-thrust belt. Modified from Biddle et al. (1986), Wilson (1991), and Fildani and Hessler (2005).
**Figure 2.** Stratigraphic correlations between age-equivalent units exposed in geographically different portions of the Patagonia fold-and-thrust belt. A) General stratigraphy of the Ultima Esperanza district of southern Chile, modified after Wilson (1991), Fildani and Hessler (2005), and Romans et al. (2010); B) Generalized stratigraphy from the region just north of Lago Argentino in Argentina, modified after Kraemer and Riccardi (1997); and C) Generalized stratigraphy summary of the region just north of Lago Viedma (near El Chalten) in Argentina, modified after Arbe (2002). The dashed line represents the approximate transition from deep to shallow marine facies. See Figure 1 for the approximate locations of each section.
Figure 3. Geologic map of the northernmost study area surrounding El Chalten, Argentina. Modified from Kosmal and Spikermann (2001).
Figure 4. Geologic map of northern Ultima Esperanza District of Chile up to Lago Viedma, Argentina. Modified from Ghiglione et al. (2009).
Figure 5. Photos showing the outcrop character of Punta Barrosa equivalent units in Argentina. A) lower section of stratigraphy from Loma de las Pizarres near El Chalten, B) lower portion of section from the Magallanes Peninsula showing tabular bedding geometries, person circled for scale, and C) Photopan showing nearly the entire outcrop expression at Brazo Sur, yellow dotted line is approximate route where the section was measured (people circled for scale).
Figure 6. Examples of type-sections that represent each of the 5 lithofacies identified in outcrops from this study.
Figure 7. Measured stratigraphic sections from Loma de las Pizarres (A) and the Magallanes Peninsula (B).
Figure 8. Measured stratigraphic section from Brazo Sur. See Figure 5 for photopan of the outcrop.
Figure 9. Lateral correlation of LF1 units from sections measured at Brazo Sur. See Figure 5 for section locations on outcrop.
Figure 10. Examples of bed-scale characteristics A) lenticular beds showing basin scour and amalgamation common in LF1, B) Localized scouring (down-stepping toward the west) of LF1 in the BS-2 section, C) Example of tabular units of interbedded sandstone and mudstone of LF3, D) upper bed shows preservation of Ta-Td Bouma divisions, E) Repetitious beds of thin low-density turbidites characteristic of LF4, and F) bioturbated siltstone and mudstone beds of LF5
Figure 11. Characteristics of hybrid event beds from the Magallanes Peninsula.
Figure 12. Photopan and interpretation of the outcrop near Estancia Los Hermanos (ELH) including the presence of growth faults, mass transport deposits (MTDs), and imbricated sandstone beds.
Figure 13. A) depositional setting diagram for submarine fan systems. B) schematic up-section changes observed at Brazo Sur showing the overall progradational architecture.
Figure 14. Photo and measured section showing the outcrop expression and rationale for the classification of lobe elements.
Figure 15. A) Results of zircon U-Pb geochronology of eight ash samples collected from the Austral basin sector, and B) detrital zircon age spectra from sample LP33 collected from the base of the LDLP section near El Chalten. See text for analytical discussion of results.
**Figure 16.** Plot of lobe dimensions from the Punta Barrosa Formation compared with fields from Prelat et al (2010).

**Figure 17.** A plot of interpreted U-Pb ages (Ma) compared with sample locations (latitude) from ash beds associated with the onset of consistent sandstone deposition in the MAB.

**Figure 18.** Paleogeographic interpretations for the early fill of the MAB based on new results from this study combined with previous workers’ constraints from the Chilean basin sector. See text for explanation.