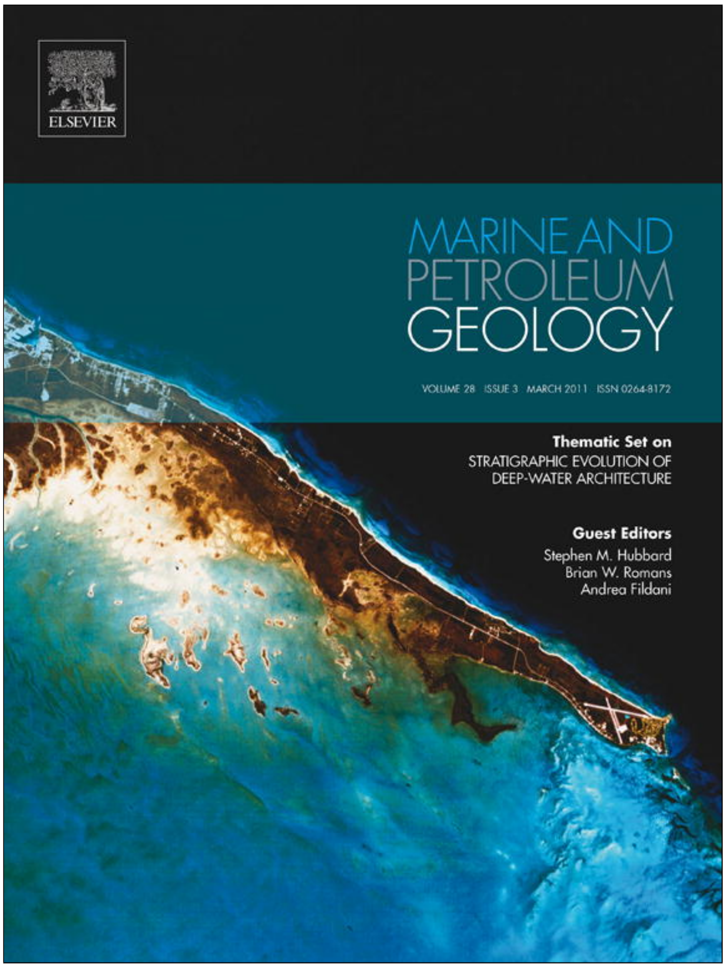
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STRATIGRAPHIC EVOLUTION OF DEEP-WATER ARCHITECTURE
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Evolution of deep-water stratigraphic architecture, Magallanes Basin, Chile

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ABSTRACT

The ˜4000 m thick and ∼20 Myr deep-water sedimentary fill of the Upper Cretaceous Magallanes Basin was deposited in three major phases, each with contrasting stratigraphic architecture: (1) the oldest deep-water formation (Punta Barrosa Formation) comprises tabular to slightly lenticular packages of interbedded sandy turbidites, slurry-flow deposits, and siltstone that are interpreted to record lobe deposition in an unconfined to weakly ponded setting; (2) the overlying, 2500 m thick and shale-dominated Cerro Toro Formation includes a succession of stacked conglomeratic and sandstone channel-fill deposits with associated finer-grained overbank deposits interpreted to record deposition in a foredeep-axial channel-levee system; (3) the final phase of deep-water sedimentation is characterized by sandstone-rich successions of highly variable thickness and cross-sectional geometry and mudstone-rich mass transport deposits (MTDs) that are interpreted to record deposition at the base-of-slope and lower slope segments of a prograding delta-fed slope system. The deep-water formations are capped by shallow-marine and deltaic deposits of the Dorotea Formation.

These architectural changes are associated with the combined influences of tectonically driven changes and intrinsic evolution, including: (1) the variability of amount and type of source material, (2) variations in basin shape through time, and (3) evolution of the fill as a function of prograding systems filling the deep-water accommodation. While the expression of these controls in the stratigraphic architecture of other deep-water successions might differ in detail, the controls themselves are common to all deep-water basins. Information about source material and basin shape is contained within the detrital record and, when integrated and analyzed within the context of stratigraphic patterns, attains a more robust linkage of processes to products than stratigraphic characterization alone.

1. Introduction

The filling patterns of sedimentary basins record a complex interaction of sedimentary and tectonic processes spanning many orders of spatial and temporal magnitude (mm to 1000 s km; seconds to 10 s Myr). Long-term (>10^6 yr) and large-scale (>10^5 km^3) basin-fill patterns are commonly evaluated with extensive field mapping or subsurface datasets that combine regional stratigraphy from seismic-reflection data and lithologic and age information from boreholes (e.g., Williams et al., 1998; Galloway et al., 2000; Hadler-Jacobsen et al., 2005; Martinsen et al., 2005; Gardner et al., 2008). The terminal segment of basin-margin sedimentary systems are commonly represented by deep-water turbidites and, as such, preserve relatively complete records of sedimentation, with evidence for variability of external controls in source areas or other segments of the dispersal system (e.g., Normark and Piper, 1991; Einsele et al., 1996; Mutti et al., 2003; Allen, 2008; Covault et al., 2007; Romans et al., 2009a). Documentation of extensive deep-water outcrop belts over the past decade has led to improved understanding of turbidite system architectures and their evolution through time (Gardner et al., 2003, 2008; Mutti et al., 2003; Hodgson et al., 2006; Pickering and Bayliss, 2009; Flint et al., 2011; Khan and Arnott, 2011; Kane and Hodgson, 2011; Pyles et al., 2011; Tinterri and Muzzi-Magalhaes, 2011).

The first conceptual models of stacking patterns and evolution of turbidite architectures were derived from outcrops in the Apennines of Italy (e.g., Mutti and Ricci Lucchi, 1972, 1975). These depositional models were followed by a decade of discovery in terms of recognition and interpretation of deep-water stratigraphic relationships in outcrops (e.g., Walker, 1975; Mutti, 1977; Winn and Dott, 1979). In the mean time, exploration of the ocean-floor

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fostered the understanding of submarine canyons and channels, which provided sediment during the latest Pleistocene, and occasionally Holocene, to the largest detrital accumulations on Earth (e.g., Shepard, 1948; Gorsline and Emery, 1959; Shepard and Dill, 1966Piper and Normark, 1969; Normark, 1970; Piper, 1970). The study of deep-water stratigraphic architecture significantly advanced as depositional models derived from the investigation of outcropping turbidite systems and ocean-floor submarine fans were integrated (Normark, 1978; Walker, 1978; Nilsen, 1980; Mutti and Normark, 1987, 1991; Normark et al., 1993). However, the very insights that make studies of seafloor fans useful (i.e., high-resolution seafloor morphology, sediment-routing system context, etc.) do not extend far (i.e., Myr) into the geologic past. Moreover, the complete filling pattern of a deep-water sedimentary basin, including a transition to shallow-water depositional environments, can only be investigated in a preserved ancient succession.

Few outcropping deep-water successions combine diverse facies architecture, substantial thickness (~4000 m), prolonged duration of basin filling (20 Myr), and exceptional preservation of stratigraphic relationships as does the sedimentary fill of the Magallanes Basin in southern Chile (e.g., Shultz et al., 2005; Fildani et al., 2007, 2009; Crane and Lowe, 2008; Hubbard et al., 2008; Romans et al., 2009b). Magallanes Basin outcrops are notable for a couple key features: (1) continuous depositional-dip 2-D outcrop panels for ~100 km, with local 3-D exposures; and (2) contrasting styles of deep-water architecture, from unconfined or weakly confined turbidite systems in a "detached" deep-marine basin, though more confined channelized systems (slope-valley and channel-levee complexes), to progradational, failure-dominated slope systems with channels traversing locally complex topography and depositing sand in minibasins and at the bases of slopes. This variability in stratigraphic architecture was driven by factors including the supply and dominant caliber and composition of sediment (i.e., which reflect changes in provenance and/or staging area) and evolution of basin shape (cf. Nelson and Kulm, 1973; Kolla and Coumes, 1987; Normark, 1985; Stow et al., 1985; Mutti and Normark, 1987; Jervey, 1988; Kolla and Macurda, 1988; Wetzel, 1993; Reading and Richards, 1994; Piper and Normark, 2001; Gagnon and Waldron, 2011). We postulate that tectonic processes had a profound influence on how the stratigraphic architecture in the Magallanes Basin changed over time. Tectonism directly influences basinal characteristics (e.g., spatial and temporal patterns of subsidence, basin margin relief, etc.) in addition to source area characteristics (e.g., sediment composition, regional dispersal patterns, availability and rates of supply, etc.) (Dickinson, 1974; Busby and Ingersoll, 1995). The long-held notion that stratigraphy has an intrinsic organization continues to drive stratigraphic research (e.g., Paola et al., 2009). However, an evaluation of stratigraphic patterns without information of, or assuming negligible, tectonic forcings might lead to erroneous interpretations of natural stratigraphic products.

The primary objective of this paper is to present the evolution of stratigraphic architecture within the context of regional patterns and long-term evolution in the Magallanes Basin. This paper represents a synthesis of stratigraphic studies from the past decade, combined with insights from studies on the tectonic evolution of the southern Andean Cordillera (e.g., Wilson, 1991; Fildani et al., 2003; Fildani and Hessler, 2005; Romans et al., 2010; Fosdick et al., in press). Information about the availability and type of detritus delivered to the basin, when integrated and analyzed within the context of stratigraphic patterns, attains a more robust linkage of processes to products than stratigraphic characterization alone.

2. Tectonic and stratigraphic context

The Magallanes Basin is a retroarc foreland basin (Dalziel, 1981; Wilson, 1991: Fildani and Hessler, 2005) and the sedimentary sequence preserved in the Andean fold-thrust belt reflects the early extensional phase of basin evolution and the subsequent contractile phase with progressive uplift associated with Andean orogenesis (Figs. 1 and 2). Compression associated with the onset of the Andean orogeny resulted in uplift along the western basin margin and concurrent foreland subsidence (Wilson, 1991: Fildani and Hessler, 2005; Romans et al., 2010).

2.1. Study area

This study focuses on strata exposed in the Patagonian Andes in Ultima Esperanza District of southern Chile (50°S–52°S), between the town of Puerto Natales, Chile, in the south and the Chile-Argentina border, in the north (Fig. 1). The regional strike of outcropping Cretaceous strata in this region is approximately oriented north-south reflecting its association with the uplifting Andean orogenic belt (Fig. 1). Older basin-filling units are located in the more structurally deformed westernmost part of the region whereas the youngest are exposed in lesser-deformed eastward-dipping homoclinal structures at the present eastern limit of the Andean fold-thrust belt.

This synthesis is focused on the Upper Cretaceous strata that represent the deep-water basin (Punta Barrosa and Cerro Toro Formations) and exhibit evidence for a transition from deposition in deep-water slope to deltaic depositional environments (Tres Pasos and Dorotea Formations). This study does not address the overlying Paleogene non-marine strata (Fig. 2; e.g., Malumian et al., 2000). The onset of deep-water sedimentation is marked by unconfined turbidites of the Punta Barrosa Formation (Fildani et al., 2003, 2009). Conglomerate-filled turbidite channel-levee systems within the overall shale-dominated Cerro Toro Formation developed along the length of the axial foredeep (Winn and Dott, 1979; Hubbard et al., 2008). The final turbidite phase of basin-filling is represented by the prograding slope systems of the Tres Pasos Formation, which eventually filled the deep-water basin (Smith, 1977; Shultz et al., 2005; Romans et al., 2009b; Hubbard et al., 2010). Finally, the Magallanes Basin in Ultima Esperanza District is capped by shelf and shelf-edge deltaic sequences of the Dorotea Formation (Arbe and Hechem, 1985; Macellari et al., 1989; Covault et al., 2009; Fildani et al., 2009; Hubbard et al., 2010).

2.2. Pre-Andean tectonic context: Jurassic-Early Cretaceous extension

The basin configuration and compositional characteristics of the sedimentary fill of the predecessor Jurassic-Early Cretaceous (~160–100 Ma) extensional basin system (Fildani and Hessler, 2005; Calderón et al., 2007) had a significant influence on the tectonic evolution of the Magallanes foreland basin (Romans et al., 2010) and, thus, the long-term stratigraphic evolution of turbidite system architecture. In the Jurassic, extension associated with the initial breakup of southern Gondwana resulted in predominantly silicic rift-related volcanism as recorded by the Tobífera Formation (Fig. 2; Bruhn et al., 1978; Gust et al., 1985; Pankhurst et al., 2000; Calderón et al., 2007). Extension culminated in the development of an oceanic backarc basin referred to as the Rocas Verdes Basin (Dalziel et al., 1974; Suarez, 1979; Dalziel, 1981). Ophiolitic rocks exposed in the Cordillera Sarmiento, south and west of Parque Nacional Torres del Paine, represent the obducted remnants of the floor of this backarc basin (Wilson, 1991; Fildani and Hessler, 2005; Calderón et al., 2007).

The Lower Cretaceous Zapata Formation is dominated by shale with rare thin sandstone beds and is interpreted to have blanketed the Rocas Verdes Basin (Fig. 2; Fildani and Hessler, 2005). The Zapata Formation mudstone is dark gray to black with disseminated pyrite

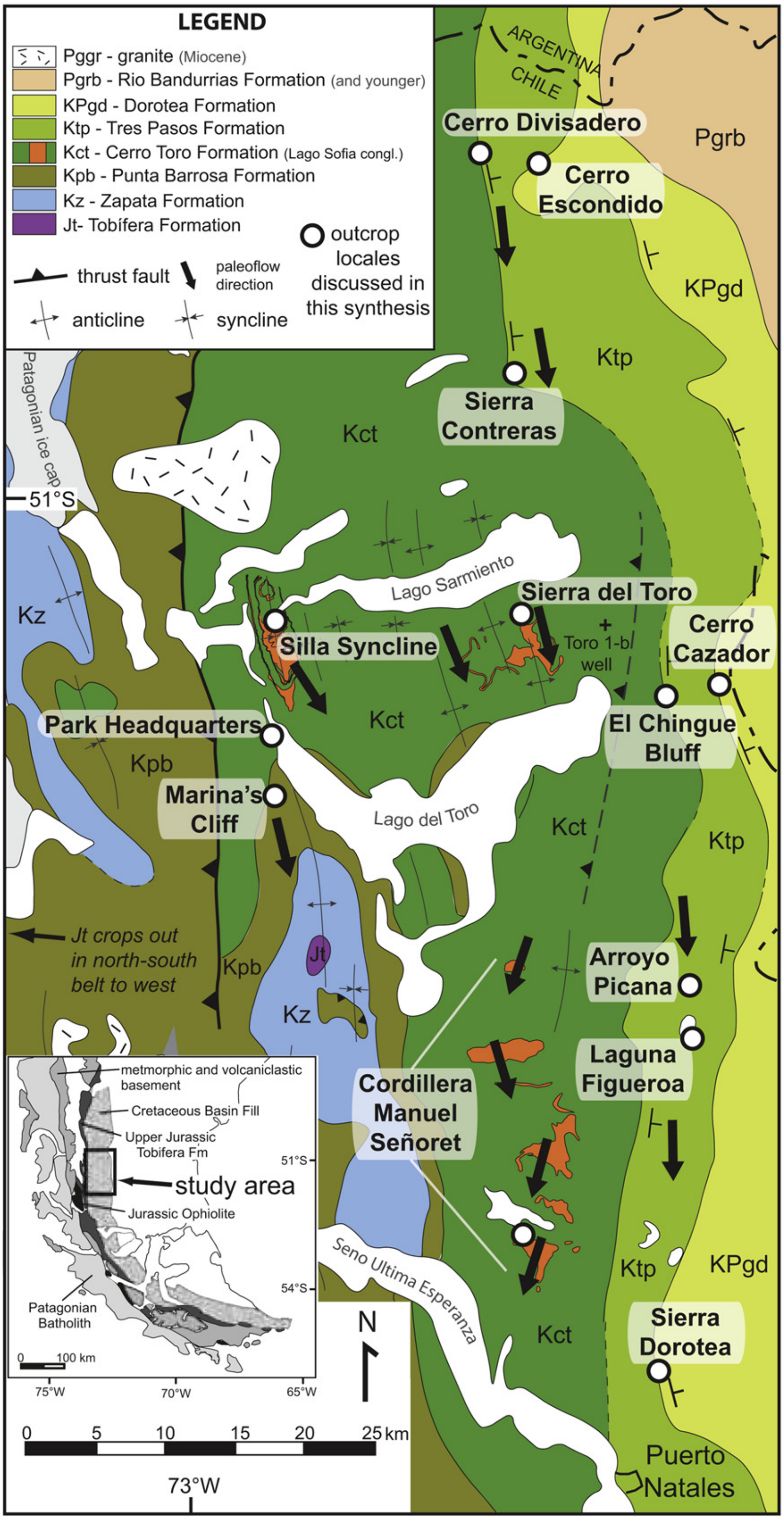

Fig. 1. Simplified geologic map of Ultima Esperanza District, southern Chile, showing the major lithostratigraphic units of the Cretaceous Magallanes Basin. The dominant paleocurrent direction for the three deep-water formations (Punta Barrosa, Cerro Toro, and Tres Pasos) is south to southeast, which was parallel to the Andean orogenic belt during the Late Cretaceous. Formations are younger and progressively less structurally deformed to the east. The Jurassic Tobífera Formation, which is discussed at length in text, crops out in a north-south belt to west of area depicted here. Outcrop locations that are discussed in text are highlighted. Geologic map adapted from Wilson (1991) and Fosdick et al. (in press). Paleocurrent summary arrows derived from several hundred to thousands of measurements for each formation; see text for specific references. Refer to Fig. 2 for a generalized stratigraphic column.

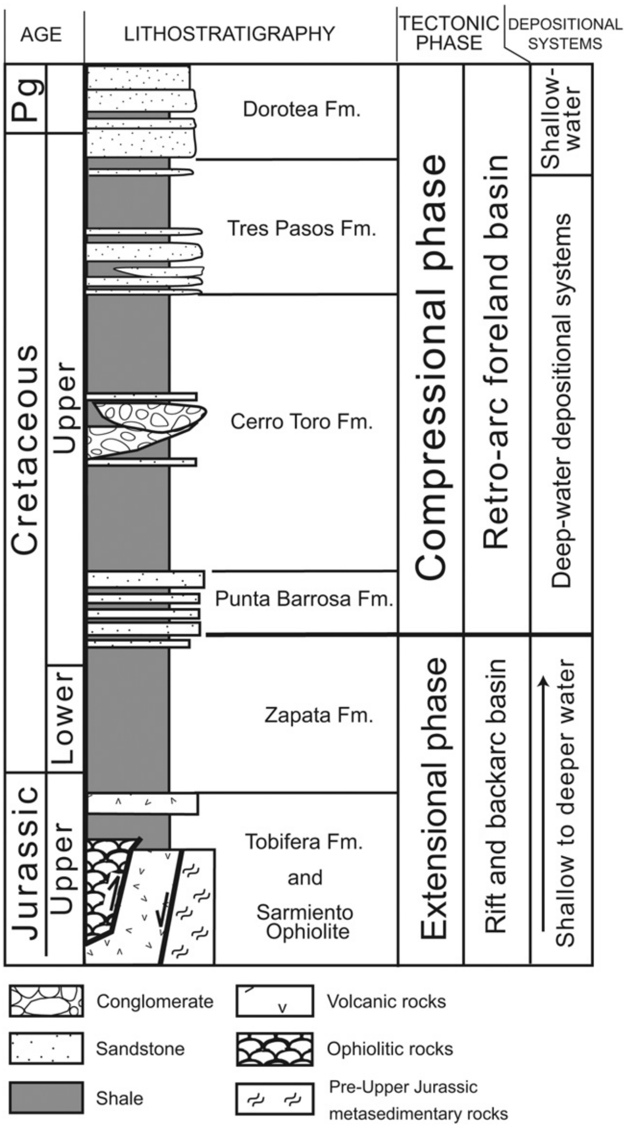

Fig. 2. Generalized stratigraphic column for the Magallanes Basin in Ultima Esperanza District, southern Chile. Major lithostratigraphic formations are associated with tectonic phases and basin types. Modified from Romans et al. (2010); originally adapted from Fildani and Hessler (2005) and Wilson (1991).

indicative of a persistent and partially anoxic depositional environment (Fildani and Hessler, 2005). The well-bedded nature of the shale sequence, with notable lack of sedimentary structures, suggests that the basin was closed and relatively starved of clastic sediment. The recognition of Zapata Formation strata conformably overlying the pillow basalt of the Sarmiento Ophiolite at the Peninsula Taraba indicates that these beds were deposited at a water depth of at least 2500 m suggesting a very deep and restricted basin for a time span of ~40–50 Myr (Fildani and Hessler, 2005; Calderón et al., 2007). The transition between the Zapata Formation and the overlying Punta Barrosa is gradual and manifested by a recurrence of thin-bedded sandstone interstratified with the typical Zapata mudstone (Fildani and Hessler, 2005).

2.3. Deformation, uplift, and Exhumation history of the Magallanes Basin

Knowledge of the structural evolution of the Patagonian fold-thrust belt is essential for understanding the basinal stratigraphic evolution because: (1) the fold-thrust belt was the primary source of sediment delivered to the basin; and (2) one of the principle subsidence mechanisms was loading from thrust sheets. Spatial and temporal variations of sediment supply and basin accommodation are, in many cases, closely tied to the tectonic evolution of the orogenic belt. Here, we summarize the existing literature on the timing and style of deformation to better understand concurrent basin evolution.

Following the onset of fold-thrust belt development in Ultima Esperanza District ~92–100 Ma (Fildani et al., 2003; Fosdick et al., in press), orogenic shortening continued throughout the Late Cretaceous and Paleogene as the eastward-migrating thrust front progressively incorporated foreland basin deposits into the orogenic belt (e.g., Wilson, 1991). Fosdick et al. (in press) document at least 30 km of Cenomanian-Miocene shortening across the fold-thrust belt. A significant proportion of this retroforeland convergence occurred during Coniacian development of a structural duplex within the volcanogenic Tobífera Formation, synchronous with deep-water foredeep deposition. Deformation and uplift of the Upper Cretaceous deep-water Magallanes Basin occurred during subsequent phases of Paleogene retroforeland shortening (Fosdick et al., in press).

The sub-Andean belt at this latitude consists of several structural domains with contrasting styles of deformation (Wilson, 1991; Fildani and Hessler, 2005; Calderón et al., 2007; Fosdick et al., in press). Deformation along the western margin of the Cretaceous foreland basin has been accommodated by both thick- and thin-skinned thrust faults and related folding (Fosdick et al., in press; following early work from Wilson, 1991; Fildani and Hessler, 2005) and the presence of a regional north-south trending cleavage in the uppermost Cretaceous foreland basin strata (e.g., Wilson, 1991). Reactivation of inherited rift structures associated with Late Jurassic extension across the Rocas Verdes Basin exhibit a strong control on the location of subsequent thrust faulting (Fosdick et al., in press). The Punta Barrosa Formation exhibits greenschist facies metamorphism, indicating a depositional and/or tectonic burial and heating to > 100 °C (Fildani and Hessler, 2005). Tectonic burial of pre-foreland basin rocks, specifically the meta-rhyolites of the Tobífera Formation, reached metamorphic conditions of up to 7 kb (350 °C), suggesting regional high-pressure, low-temperature regional metamorphism (Calderón et al., 2007; Hervé et al., 2004; Galaz et al., 2005). This metamorphic event, although poorly dated, is consistent with tectonic thrusting and duplex formation during early stages of foreland sedimentation. Farther east of the main fold-thrust belt, the upper Cerro Toro Formation and overlying formations lack this metamorphic overprint and high degree of deformation and instead exhibit broad folding and minor faulting (Fig. 1) (Wilson, 1991). In their easternmost exposures, the Tres Pasos and Dorotea Formations dip eastward into the subsurface along an approximately north-south trending homocline (Katz, 1963; Wilson, 1991). Seismic-reflection imaging suggests deep-seated thrust faults are responsible for the Miocene regional uplift of the fold-thrust belt (Harambour, 2002; Fosdick et al., in press).

3. Facies and sedimentary architecture of the Magallanes Basin fill

3.1. Subdividing deep-water strata

Although the concept of a hierarchical organization of sedimentary strata is alluded to in early literature (e.g., Barrell, 1917), it wasn't until Campbell (1967) and subsequently Vail et al. (1977), that a methodology for subdividing strata in a hierarchical fashion was presented as a workflow. Work by Jackson (1975), Brookfield (1977), Kocurek (1981), Allen (1983) and Miall (1985) emphasized

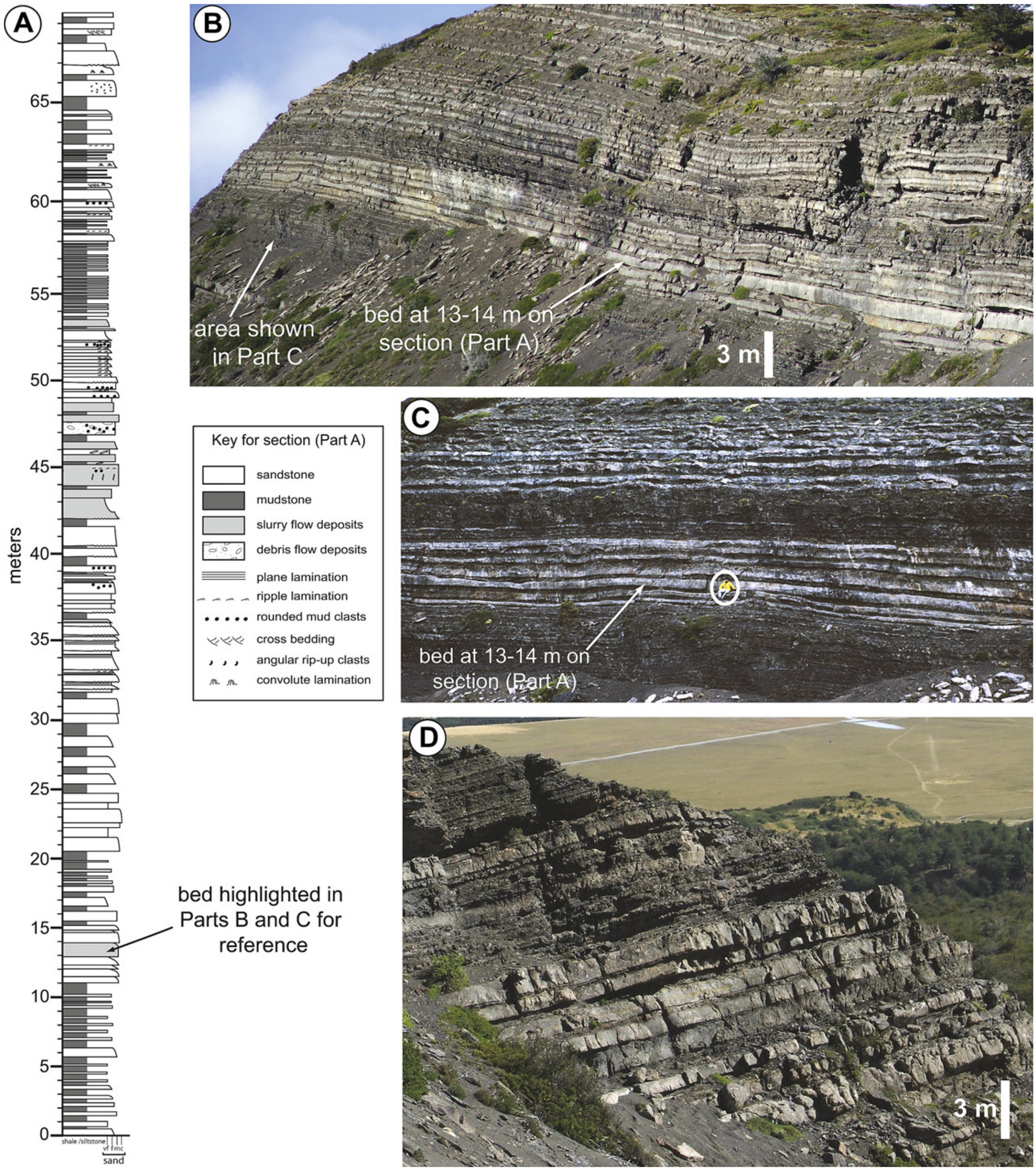

Fig. 3. Punta Barrosa Formation at 'Marina's Cliff' outcrop (Fildani et al., 2007, 2009). (A) Composite measured section showing representative stacking pattern of the informally defined upper Punta Barrosa Formation (terminology of Wilson, 1991). (B) Photograph of 'Marina's Cliff highlighting tabular architecture and stratigraphic packaging, including lower part of composite section shown in Part A. A prominent bed at 13–14 m on section is shown for reference. (C) Photograph showing interbedded nature of sandstone and siltstone deposits. Note person for scale. (D) Additional photograph of bed-scale features of the Punta Barrosa Formation.

the relationship of process to a hierarchy of geomorphologic bodies for non-marine strata. The first usage of a hierarchical framework specifically for turbidite successions was presented by Mutti and Normark (1987), who employed an element-based approach to turbidite systems in an attempt to evaluate seafloor and outcrop observations (see also Mutti and Normark, 1991; Normark et al., 1993). Ghosh and Lowe (1993) developed a widely used turbidite hierarchy predominantly based on 1-D criteria useful for characterizing core or limited outcrops. Pickering et al. (1995) applied an architectural element approach to the 2-D and 3-D expression of deep-water architectural bodies. The convention of characterizing 2-D cross sections of channel-form and sheet-like sedimentary bodies within a hierarchy originated from petroleum-related research in the 1990s and appeared in the literature soon thereafter (Beaubouef et al., 2000; Campion et al., 2000; Gardner and Borer, 2000; Grecula et al., 2003; Schwarz and Arnott, 2007; Prelat et al., 2009; McHargue et al., 2011). Architectural elements in this approach typically cluster with similar elements collectively making up a complex (e.g., channel elements and channel complexes). Although recent work questions the presence of ordered hierarchy in stratigraphy (e.g., Schlager, 2009), subdividing strata in this manner is a useful method for discriminating fundamental building blocks from composite features. Furthermore, it provides a mechanism for classification and comparison of sedimentary bodies that vary in scale and/or character.

3.2. Punta Barrosa Formation

The Punta Barrosa Formation is the oldest formation in the Magallanes Basin deep-water succession (~92–85 Ma) and records the onset of turbiditic sedimentation in the retroarc foreland basin system (Fig. 2; Fildani and Hessler, 2005; Romans et al., 2010). The Punta Barrosa is the westernmost formation and, as a result of its proximity to the Andean orogenic belt, is pervasively thrust-faulted and folded along much of the outcrop belt. Nevertheless, several outcrops of the informally defined upper Punta Barrosa Formation (terminology of Wilson, 1991) display sufficient lateral continuity to assess stratigraphic architecture (Fig. 1). The thickness of the Punta Barrosa Formation decreases eastward; sandstones are nearly absent in the Toro 1-b well drilled ~50 km east of the outcrops of the Cerro Ferrier, where Wilson (1991) estimated the formation to be no more than 1000 m thick, indicating an eastward thinning and likely pinch out of the unit. Later fieldwork illustrated the presence of repeated sections of Punta Barrosa at the top of Cerro Ferrier, which suggested that this estimate might be a liberal one (Fildani and Hessler, 2005). The transition from the underlying Zapata Formation to the basal Punta Barrosa Formation is marked by a more consistent presence of thin- to medium- bedded, medium-grained sandstone and a decrease in thick mudstone sections. The Punta Barrosa Formation comprises a lower section dominated by shale and siltstone that changes upwards into interbedded packages of sandstone, muddy sandstone and siltstone. Paleocurrents and general shape of the depositional bodies indicate that the depositional system was confined to a ~100 km wide trough oriented parallel to the strike of the orogenic belt (Fildani and Hessler, 2005; Fildani et al., 2009).

Select high-quality exposures provide insights into the formation-scale stratigraphy, as well as access to detailed bed-scale sedimentologic processes. Despite variable degrees of tectonic deformation along the outcrop belt, locally it is possible to document vertical stacking patterns, including coarsening- and thickening-upward successions in the upper Punta Barrosa Formation (Fig. 3). Laterally continuous outcrops of well-preserved, discrete sandstone packages ranging from 10 to 15 m thick have recently been exposed as a consequence of Park Highway construction (Fig. 3). The facies within these sandstone packages are composed of very fine- to medium-grained structureless sandstone containing rare debris flow deposits (Fig. 4D). Several locations contain an abundance of slurry-flow deposits (Fig. 4B and C) (cf. Lowe and Guy, 2000), alternating with successions of finer-grained units of thin-bedded turbidites (i.e., T_b, T_c, and T_d Bouma divisions sensu Bouma, 1962), siltstone, and shale (Fig. 4A).

The overall architecture of the Punta Barrosa Formation is characterized by tabular beds and bedsets with very minor (<1 m of relief) to no erosion (Figs. 3 and 4D). The main architectural element present are sheets, associated with relatively unconfined flows, attributed to fan-like composite lobes (cf. Fildani et al., 2007; Prelat et al., 2009). A composite section constructed from the Marina's Cliff outcrop provides a general representation of the stratigraphic style and stacking pattern of the gravity flow deposits (Fig. 3). The transition with the overlying Cerro Toro Formation is marked by the presence of dark Cerro Toro mudstone and notable absence of coarse-grained beds (Katz, 1963).

3.3. Cerro Toro Formation

The Santonian-Campanian (86–80 Ma) Cerro Toro Formation is present in an elongate, north-south oriented outcrop belt at least 150 km in length, extending from the Chile–Argentina border in the north of the study area to Cerro Rotonda in the south (Fig. 1; Scott, 1966; Hubbard et al., 2008). Structurally, the outcrop belt is characterized by broad folds producing exposures on limbs of anticlines and synclines with minor faulting over most of its extent. Natland et al. (1974) interpreted paleobathymetry based on microfossil assemblages between 1000 and 2000 m for the deposits. The ~2500 m thick formation is shale dominated overall but punctuated with a package of conglomeratic strata > 400 m thick (Fig. 2; Katz, 1963; Scott, 1966; Winn and Dott, 1979; Hubbard et al., 2008; Crane and Lowe, 2008). This conglomeratic unit, informally called the "Lago Sofia Member" by Winn and Dott (1979), is in the middle of the formation stratigraphically and pinches out to the east and west. The east-west width of the conglomeratic belt ranges from 3 to 8 km. In the vicinity of Sierra del Toro, the conglomeratic unit separates into at least two mappable outcrop belts; one oriented approximately north-south and parallel to the basin axis and the other approximately north-northwest to south-southeast, which crops out in Parque Naciónal Torres del Paine at the Silla Syncline locality (Figs. 1 and 5; Scott, 1966; Winn and Dott, 1979; Sohn et al., 2002; Beaubouef, 2004; Crane and Lowe, 2008; Hubbard et al., 2008; Bernhardt et al., 2011).

Extensive field measurements have demonstrated that paleoflow was oriented southward, roughly aligned with the foredeep axis, with the Silla Syncline conglomeratic belt representing a tributary to a basin axial channel belt (Fig. 1; Scott, 1966; Winn and Dott, 1979; Sohn et al., 2002; Crane and Lowe, 2008; Hubbard et al., 2008). The main facies of the channel belt include: (1) sandy-matrix conglomerate deposited largely by traction (Figs. 2 and 4G,H normally graded muddy-matrix conglomeratic units where grain support was a result of a combination of turbulence (Fig. 4F; i.e., mechanisms proposed by Lowe, 1982) and cohesion, (3) chaotic slump, slide and debris flow deposits (Fig. 4J), and (4) thin- to thick-bedded turbidites (Fig. 4E,K; Winn and Dott, 1977, 1979; Crane and Lowe, 2008; Hubbard et al., 2008). Fine-grained facies laterally adjacent to the conglomeratic trends consist of thin-bedded, very fine- to fine-grained turbidites and laminated siltstone. Hubbard et al. (2008) interpreted these facies as overbank deposits in the area of Cordillera Manuel Senoret (Fig. 4A,E). In the Silla Syncline outcrops, these units have been interpreted as genetically related overbank deposits (Winn and Dott, 1979; Beaubouef, 2004; Campion et al., 2011) or slope deposits subsequently incised by channel processes associated with emplacement of the conglomeratic beds (Coleman, 2000; Crane and Lowe, 2008). Recognition of individual channel elements in the Cerro Toro Formation is complicated by amalgamation of sedimentary bodies and the vast scale across which they are exposed in the outcrop belt. Individual coarse-grained channel-fill complexes are most commonly 40–80 m thick and 4–8 km wide in the axial channel belt (Fig. 5) (Hubbard et al., 2008). High-resolution physical correlation of strata between the axial channel belt (Fig. 5C) and the tributary channel system exposed at the Silla Syncline (Fig. 5B) locality is not possible. Smaller channel complexes delineated at the Silla Syncline, 30 m thick by 500–1500 m wide (Beaubouef, 2004), are suggestive of downstream, and tributary versus axial, variability in channel expression in the depositional system (Fig. 5).

From north to south, or paleogeographically proximal to distal, an increase in amalgamation of channel bodies is notable. At Silla Syncline, three major channel complex sets have been mapped, up to

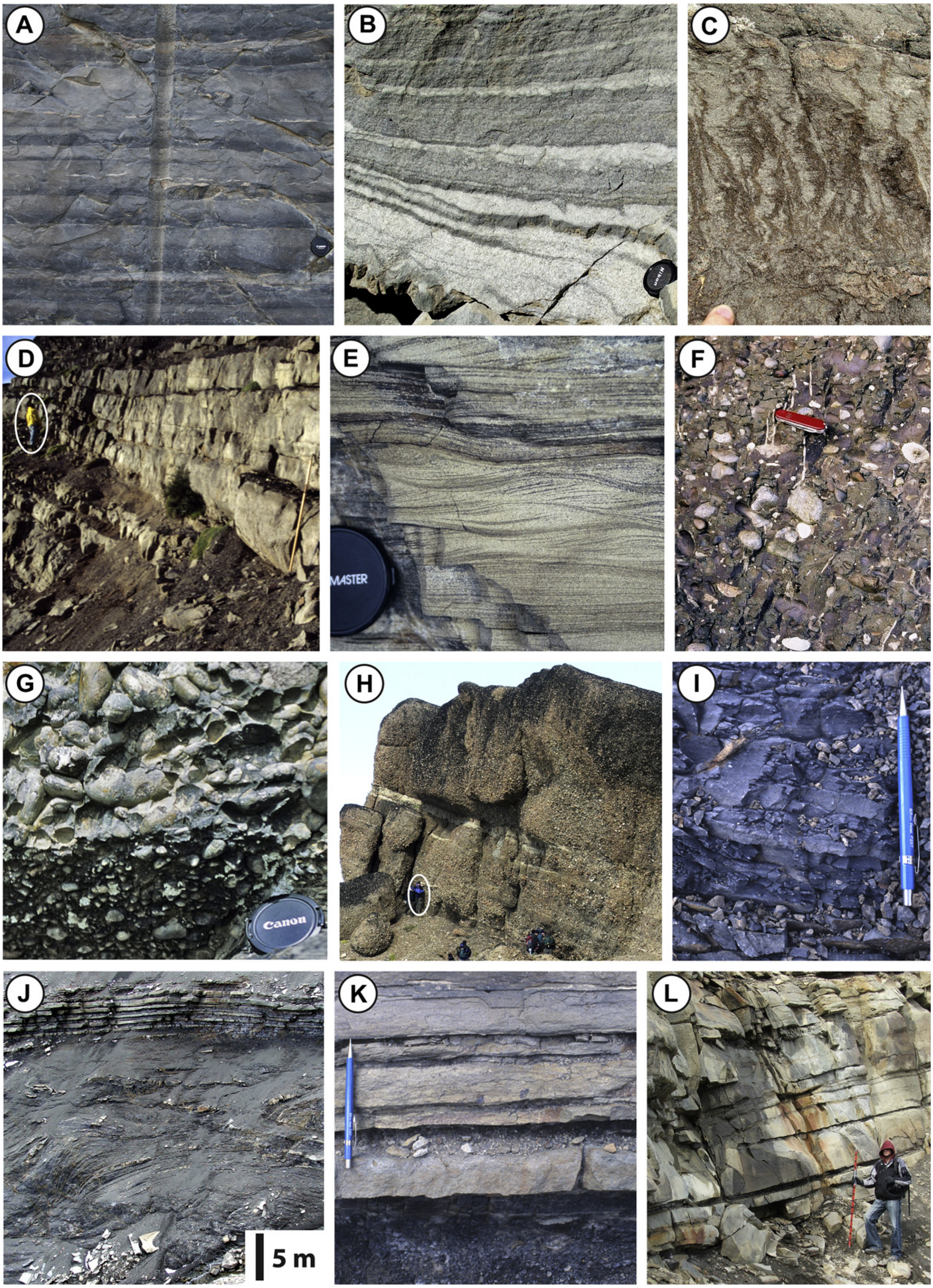

Fig. 4. Compilation of photographs showing common deep-water facies observed in Magallanes Basin formations. (A) Interbedded shale and turbiditic siltstone, Punta Barrosa Formation. (B) Micro-banded slurry-flow deposits, Punta Barrosa Formation. (C) Water escape structures (pillars) in slurry-flow deposits of the Punta Barrosa Formation. (D) Medium- to thick-bedded, normally graded medium-grained sandstone, Punta Barrosa Formation. (E) Plane- to ripple-laminated, very fine- to fine-grained sandstone, Cerro Toro Formation. (F) Mudstone-rich, matrix-supported conglomerate; this example also showing Glossifungites ichnofacies, Cerro Toro Formation. (G) Clast-supported conglomerate,

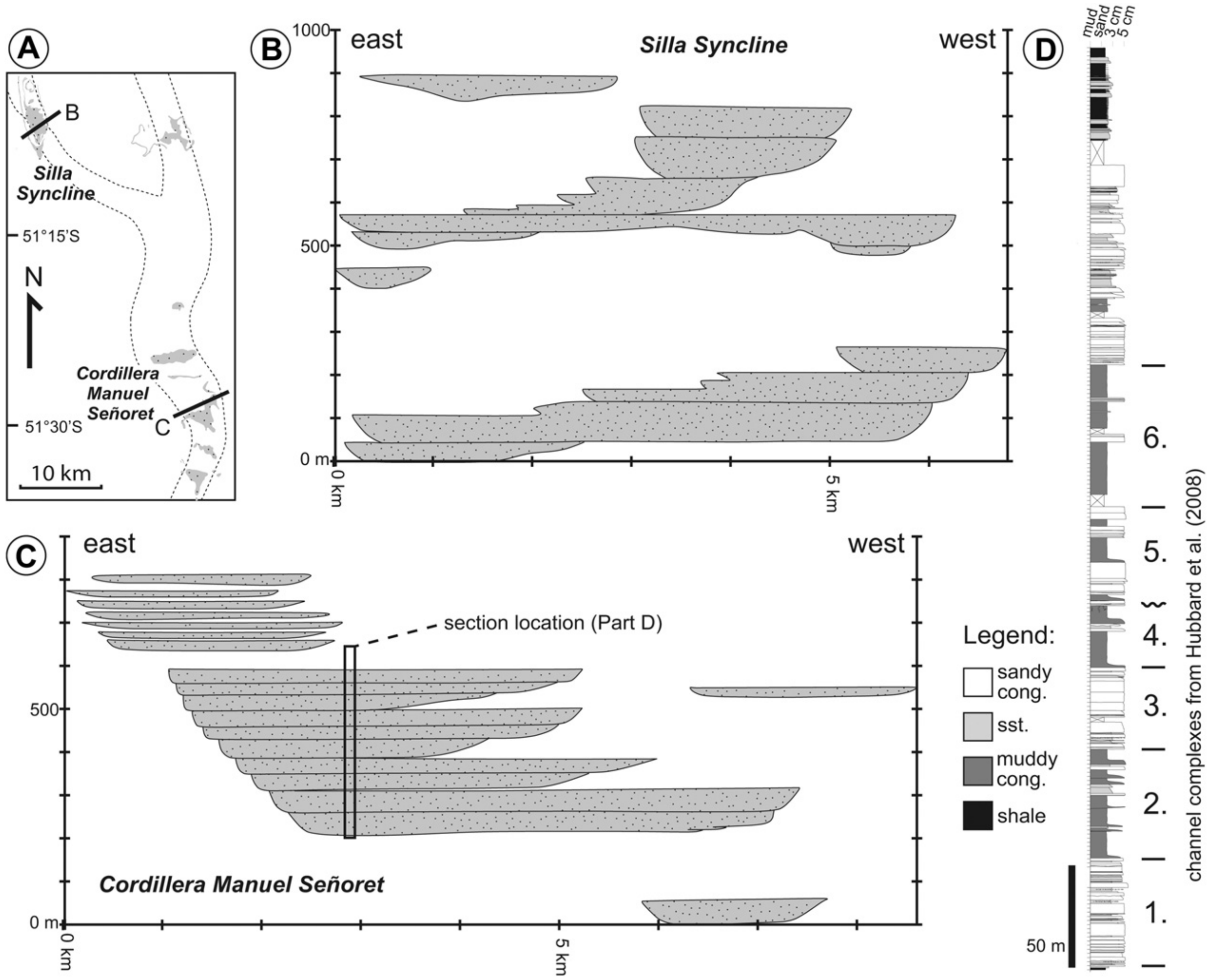

Fig. 5. (A) Paleogeographic outline of the axial channel belt (dashed lines) mapped in the Cerro Toro Formation (modified from Hubbard and Shultz, 2008). Paleoflow was from north to south. Location of conglomeratic outcrops indicated with shaded areas. (B) Schematic stratigraphic cross-section showing architecture of channel bodies in the Cerro Toro Formation at the Silla Syncline locality. Note that the shaded areas include thick-bedded gravity flow deposits, including sandstone, sandstone matrix conglomerate, mudstone matrix conglomerate, and mudstone-dominated mass-transport deposits. See part A for orientation of cross section; paleoflow was into the plane of the page (modified from Crane, 2004; Bernhardt et al., 2011). (C) Schematic stratigraphic cross-section showing architecture of channel bodies in the Cerro Toro Formation at Cordillera Manuel Senoret. See part A for orientation of cross section; paleoflow was into the plane of the page (constructed from data presented in Hubbard and Shultz, 2008; Hubbard et al., 2008, 2009; Fildani et al., 2009). (D) Representative measured section through the stack of conglomeratic channel complexes at Cordillera Manuel Senoret (Hubbard et al., 2008).

250 m thick and 3 km wide (Fig. 5B) (Beaubouef, 2004; Crane and Lowe, 2008). Each of the coarse-grained units is separated by a succession of fine-grained strata up to 150 m thick. At Sierra del Toro, Jobe et al. (2009) has similarly mapped three major coarse-grained channel-form bodies in the Cerro Toro Formation, attributing them to deposition in the main, north-south trending axial channel belt. The widest channel complex mapped by Jobe et al. (2009) is nearly 6 km across. At Cordillera Manuel Senoret, individual channel complexes are difficult to discern because the entire conglomeratic succession is amalgamated, up to 600 m thick. A sinuous channel belt was mapped in the area, and analysis of the interstratified inner margin of a bend at Cerro Mocho led Hubbard et al. (2008) to interpret a 40–80 m thickness for individual channel-form bodies (Fig. 5C). Individual bodies are dominated by either traction-structured sandy-matrix conglomerate (Fig. 4GH) or graded, muddy-matrix conglomerate (Fig. 4F); individual complex boundaries are sometimes characterized by the *Glossifungites* ichnofacies, with trace fossils interpreted to have been excavated and filled during extended periods of gravel starvation in the basin (Fig. 4F) (Hubbard and Shultz, 2008). The overall conglomeratic channel complex set fill is asymmetric, characterized by 400 m of stacked conglomerate at the outer bend and interstratified conglomerate, sandstone and fine-grained overbank packages at the inner bend (Fig. 5C). Overall, the width of channel complexes narrows upwards and downstream, from 6 to 7 km to 3–5 km (Hubbard et al., 2008).

3.4. Tres Pasos Formation

The lithostratigraphic base of the Tres Pasos Formation is defined as the first significant sandstone overlying the shale-dominated uppermost Cerro Toro Formation (Fig. 2; Katz, 1963; Smith, 1977). The Tres Pasos outcrop belt is characterized by eastward-dipping ridges in the south and slightly more complex structures (e.g., local reverse faults and associated folding) in the

Cerro Toro Formation. (H) Clast-supported, traction structure-dominated conglomerate, Cerro Toro Formation. (I) Massive to faintly laminated siltstone, Tres Pasos Formation. (J) Discordant, chaotically deformed strata including mudstone-rich debris-flow deposits; note overlying concordant thin-bedded sandstone facies, Tres Pasos Formation. (K) Thin-bedded, fine-grained sandstone; commonly normally graded and including Bouma turbidite divisions; this facies typically interbedded with laminated siltstone, Tres Pasos Formation. (L) Medium- to thick-bedded, medium-grained sandstone; commonly normally graded and including mudstone intraclasts, Tres Pasos Formation.

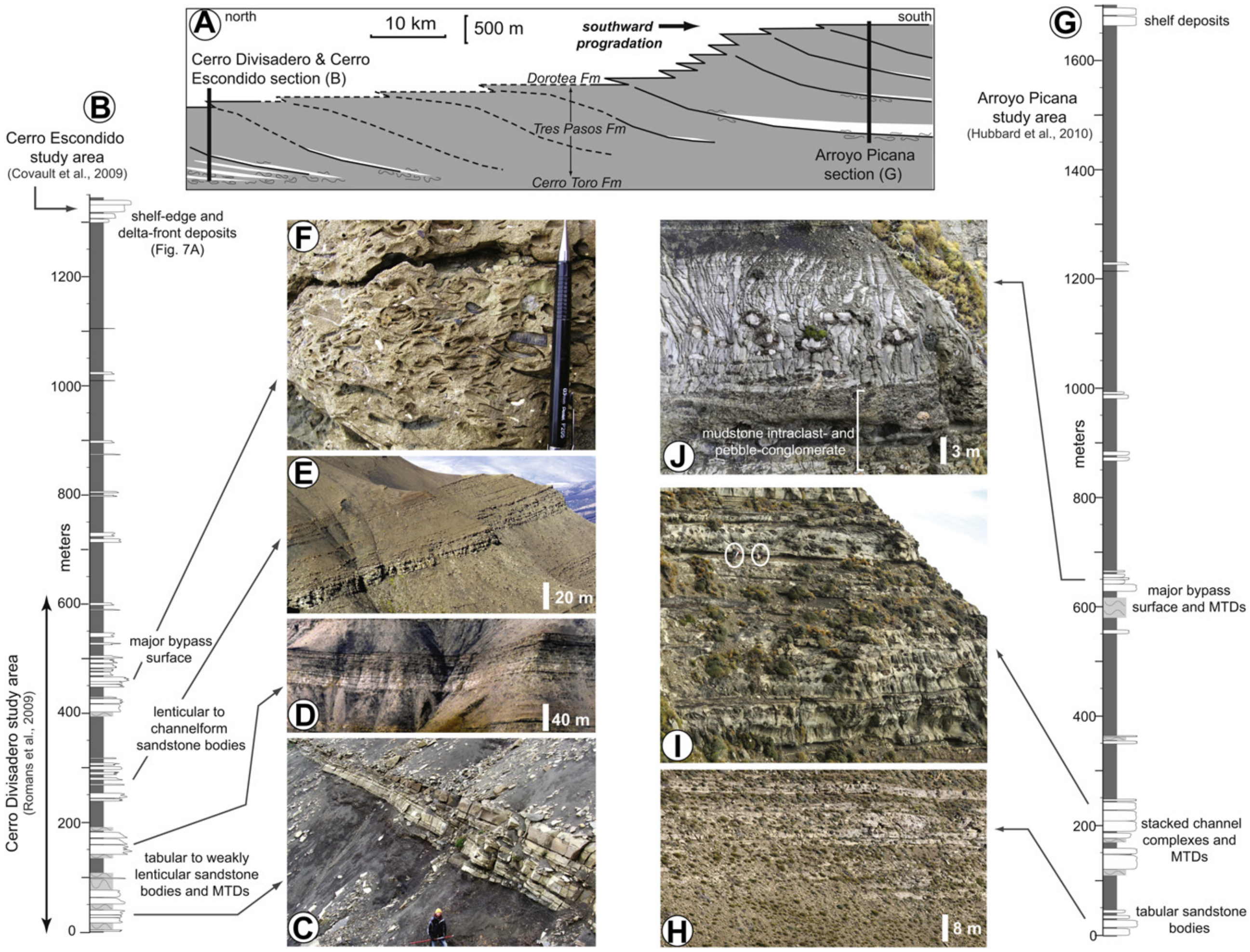

Fig. 6. Summary of sandstone-dominated sedimentary body architectures documented in the Tres Pasos Formation. (A) Schematic regional stratigraphic cross section of the Tres Pasos Formation in Ultima Esperanza District showing generalized relationship of Cerro Divisadero/Escondido section in the north (part B) and Arroyo Picana section in the south (part G). Slope architecture dashed where not precisely mapped. (B) Simplified stratigraphic column of the Tres Pasos Formation at Cerro Divisadero and Cerro Escondido locations. Representative sandstone body architecture for this area shown in (C), (D), (E), and (F). (G) Simplified stratigraphic column of the Tres Pasos Formation at Arroyo Picana locations. Representative sandstone body architecture for this area shown in (H), (I), and (J). See Fig. 7 for examples of stratigraphic architecture in the lowermost Dorotea Formation. Refer to Fig. 1 for outcrop locations.

north (Fig. 1). Biostratigraphic information from Natland et al. (1974) and Macellari (1988) indicates a depositional age of ~70–80 Ma (Campanian), which is consistent with detrital-zircon ages recently reported by Romans et al. (2010). Abundant paleocurrent data from numerous locations across the study area indicate south to south-southeast dispersal (Smith, 1977; Shultz et al., 2005; Shultz and Hubbard, 2005; Romans et al., 2009b; Armitage et al., 2009; Hubbard et al., 2010). The Tres Pasos Formation ranges from 1200 to 1500 m thick and can be subdivided into a lower part characterized by lenticular to tabular sandstone-rich packages of variable thickness (10–200 m) intercalated with mudstone-rich mass transport deposits, and a dominantly finer-grained upper part characterized by concordant siltstone punctuated by relatively thin (<10 m) and discontinuous coarser-grained deposits (Fig. 6A,B,G). The facies and architecture of the lower part of the Tres Pasos Formation vary significantly along the trend of the 100 km-long outcrop belt (Shultz et al., 2005).

Sandstone-rich sedimentary bodies include structureless sandstone (Fig. 4L; high-density turbidity current deposits S_3 *sensu* Lowe, 1982), intrabasinal mudstone-clast conglomerates, and various finer-grained turbidite facies (Fig. 4I and K; e.g., Bouma divisions). The sandstone bodies exhibit a highly variable internal architecture, including complex cut-and-fill features and lateral changes in degree of amalgamation (Shultz et al., 2005; Romans et al., 2009b; Hubbard et al., 2010). Mudstone-dominated mass transport deposits of varying sizes (5–30 m thick) typically contain mud-matrix debris flow deposits mixed with slide and slump blocks of variable sizes and are present between sandstone packages (Fig. 4J; Armitage et al., 2009). The upper part of the Tres Pasos Formation is dominated by turbiditic mudstone and siltstone (Fig. 4I), hemipelagic mudstone, and sparse scours filled with coarser-grained sandstone and pebbles.

The Tres Pasos Formation is interpreted as a large-scale progradational slope system (Fig. 6A; Romans et al., 2009b; Hubbard et al., 2010). In the northern outcrops, from Cerro Divisadero south to the Sierra Contreras (Fig. 1), high-resolution shelf-to-basin correlations are hampered by locally complex structural deformation and lack of data. However, based on stacking patterns at Cerro Divisadero and Cerro Escondido, combined with correlations from Riccardi (1988), Macellari et al. (1989), and Shultz et al. (2005), Romans et al. (2009b) estimated slopes >20 km in dip length with water depths of at least 1500 m from the stratigraphic thickness of compacted base-of-slope to deltaic topset strata (Fig. 6AB) (see also Covault et al., 2009). The southern outcrops, from El Chingue Bluff south to the

Laguna Figueroa area (Fig. 1), reveal the scale of the slope systems with more certainty; Hubbard et al. (2010) document shelf-edge to toe-of-slope lengths of 25–30 km and water depths up to 900 m from compacted sedimentary rocks (Fig. 6A). The transition from the uppermost Tres Pasos Formation shale to the overlying Dorotea Formation sandstone is conformable across the length of the outcrop belt (Figs. 6 and 7)(Covault et al., 2009; Hubbard et al., 2010).

Individual sandstone-dominated architectural bodies include channel complexes up to 25 m thick and 450 m wide at a toe of slope position and more laterally extensive sheet-like bodies (typically <10 m thick) more distally along the depositional profile (Fig. 6) (Hubbard et al., 2010). The lower slope position locally includes intraslope minibasin strata consisting of tabular beds interpreted to have filled topography generated through growth faulting (Shultz and Hubbard, 2005; Armitage et al., 2009), and weakly lenticular to sheet-like bodies 20–70 m thick (Fig. 6C–E) (Romans et al., 2009b). Armitage et al. (2009) described fine-grained mass transport complex bodies 10 s–100 s of meters thick and wide, closely associated with sandstone bodies limited in lateral extent by the original topographic development associated with mass transport deposit emplacement. These sandstone elements are typically 10–30 m thick.

3.5. Dorotea Formation

A detailed discussion of the facies and depositional evolution of the Dorotea Formation is not within the objectives of this study, although the context it provides on the final filling of the deep-water Magallanes Basin is significant.

The lithostratigraphic base of the Dorotea Formation is defined as the first prominent sandstone succession above the mudstone-dominated upper Tres Pasos Formation (Fig. 2) (Katz, 1963). The Dorotea Formation is up to 300 m thick and typically crops out as a series of resistant sandstone ridges located east of outcrops of the Tres Pasos Formation (Fig. 1). The Dorotea Formation is dominated by sandstone containing sedimentary structures and biogenic features indicative of shallow-water environments with sparse intervals of pebble conglomerate and local areas consisting of thick sections of siltstone (Macellari et al., 1989; Covault et al., 2009; Hubbard et al., 2010). The depositional age of the Dorotea Formation is 72–65 Ma based on biostratigraphic information (Natland et al., 1974; Macellari, 1988), which is corroborated by detrital-zircon ages (Hervé et al., 2004; Romans et al., 2010). Similar to the underlying and genetically linked Tres Pasos Formation, the Dorotea Formation has been interpreted to have prograded along the Magallanes Basin axis to the south and, thus, is younger southward (Macellari et al., 1989; Hubbard et al., 2010).

The stacking pattern of stratal packages in the Dorotea Formation represent an overall upward-shallowing evolution from outer-shelf and upper-slope deposition at the base to shallow-marine and deltaic deposition and, ultimately, non-marine deposition at the top. This overall regressive pattern was interpreted regionally (10s–100s km) by Macellari et al. (1989) and Hubbard et al. (2010), and from a higher-resolution investigation in the northern part of the Ultima Esperanza District of Chile (Covault et al., 2009). Despite facies and architectural variability at high resolutions, deposits of the lower part of the Dorotea Formation illustrate the progradational nature of this basin- capping unit across the outcrop belt (Fig. 7).

4. Evolution of the Magallanes foreland fold-thrust belt

Analyses of sandstone composition, geochemical signature of shale, and age distribution of detrital zircons provide information about the evolution of the source area, primarily, but not limited to, the southern Andean Cordillera, and its tectonic history (Fildani et al., 2003; Fildani and Hessler, 2005; Romans et al., 2010). Provenance data indicate that the Punta Barrosa Formation was derived from mixed sources, including the contemporaneous volcanic arc and pre-Upper Jurassic metasedimentary basement complexes exposed during early uplift in the Andean belt (Fildani and Hessler, 2005). Provenance data from the Cerro Toro, Tres Pasos, and Dorotea Formations indicate that the Cretaceous Andean arc continued to supply detritus to the basin in addition to the metasedimentary terranes (Romans et al., 2010). Additionally, detrital-zircon age data from all four formations show that material from the Upper Jurassic Tobífera Formation was delivered to the basin starting with deposition of the Cerro Toro Formation and in increasing proportions in overlying formations (Fig. 8) (Romans et al., 2010).

This unroofing signal recorded in the provenance history provides some constraints on the timing of uplift and associated denudation in the sediment source area. The emplacement of Tobífera Formation thrust sheets generally correlates with development of the Cerro Toro Formation conglomeratic axial channel-levee system (Romans et al., 2010). Effects on the basin included: (1) increased subsidence in the foredeep as a result of thrust-sheet emplacement; (2) associated changes in overall basin shape, including an eastward shift and an apparent narrowing of the foredeep axis; and (3) introduction of a new source of detritus, with unique grain-size and compositional character.

5. Discussion

5.1. Evaluating controls on the evolution of deep-water stratigraphic architecture

The formations of the Magallanes Basin exhibit contrasting stratigraphic architectures. The deep-water phase of foreland-basin filling started with deposition of the Punta Barrosa Formation (Fildani and Hessler, 2005). The westernmost Punta Barrosa outcrops in Ultima Esperanza District include the informally defined lower Punta Barrosa Formation, which was deformed as a result of tectonic activity associated with Andean folding and thrusting. However, the upper Punta Barrosa Formation is well preserved and displays a packaging style that includes alternating upward coarsening and thickening turbidites and slurry-flow deposits (Fildani et al., 2007). Composite sandstone-rich bodies compose laterally extensive tabular and slightly lenticular geometries, which imply unconfined to weakly confined depocenters (Fig. 9A). Cessation of sand deposition was followed by the deposition of >1000 m of finer-grained mud- and silt-dominated units through the transition from the Punta Barrosa to Cerro Toro Formation. The Cerro Toro Formation is characterized by evidence for punctuated deposition of >400 m of gravely strata in the basin axis, associated with a major southward-flowing channel-levee system (Fig. 9B). The transition from the Cerro Toro to the overlying Tres Pasos Formation, as preserved in the outcrop belt, is recorded by a >1000 m thick succession of shale and siltstone, which is interpreted to represent another phase of quiescence of coarse-grained deposition. A large-scale progradational slope system, at least 1500 m in relief from toeset-to-topset thicknesses of compacted sedimentary rocks, is represented by deposits of the genetically linked Tres Pasos (toeset and overlying fine-grained slope strata; Fig. 6) and Dorotea (topset strata; Fig. 7) Formations (Fig. 9C) (Covault et al., 2009; Romans et al., 2009b; Hubbard et al., 2010). The southward progradation of the slope system records the final filling of the deep-water foredeep (Fildani et al., 2009; Hubbard et al., 2010). We relate the substantial changes in Magallanes Basin stratigraphic architecture to: (1) changes in sediment source and staging areas with direct impact on sediment caliber, composition, and supply; (2) basin configuration; and (3)

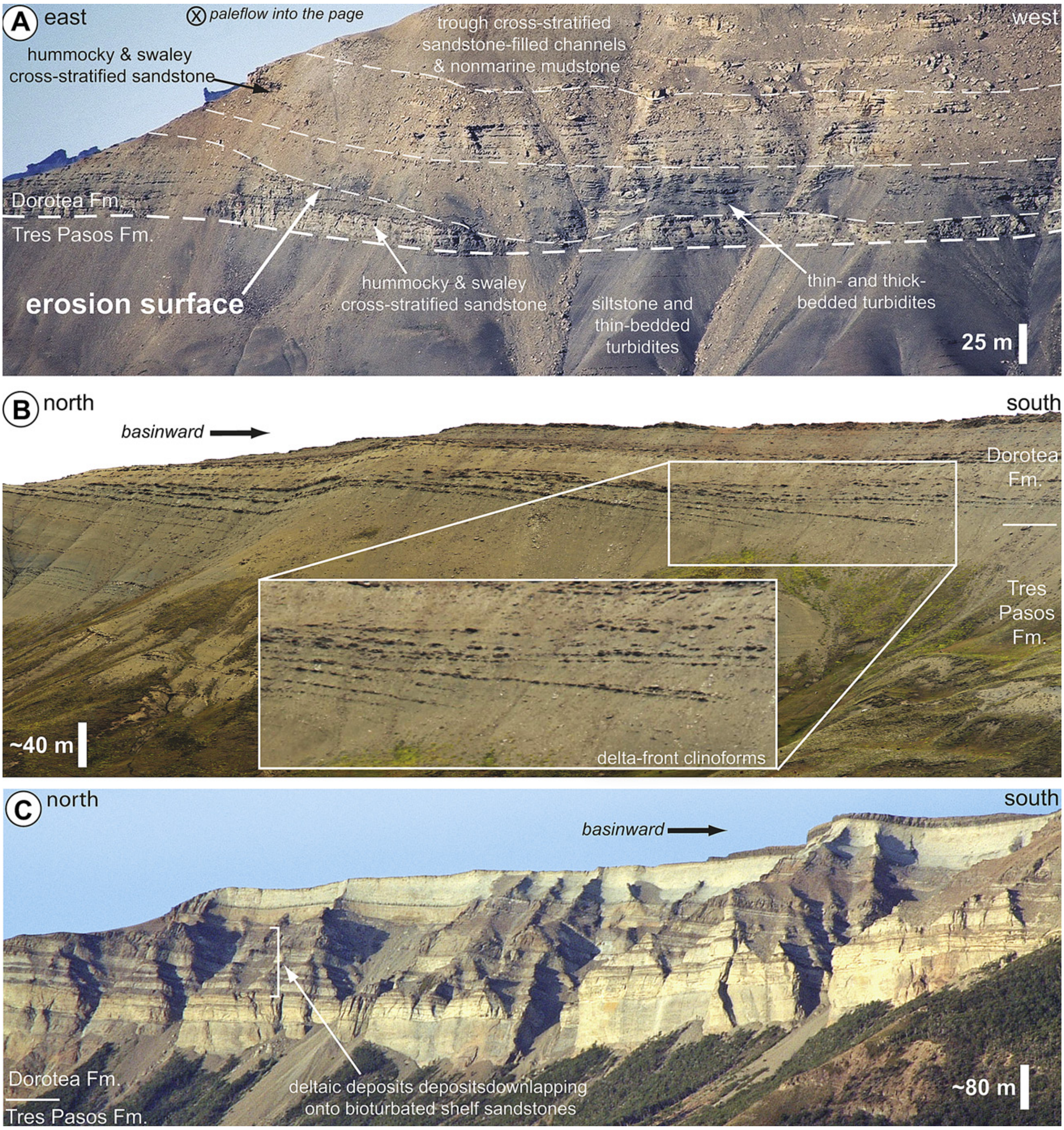

Fig. 7. Examples of stratigraphic architecture observed in the deltaic and shallow-marine Dorotea Formation. (A) Depositional-strike oriented photograph of Cerro Escondido outcrop showing transition from mudstone-dominated upper slope to shelf deposits (Tres Pasos Formation) to hummocky and swaley cross-stratified sandstone of the lowermost Dorotea Formation. A major erosion surface overlain by prodelta turbidite deposits is interpreted to represent a shelf-edge conduit that potentially connected deltaic sources of coarse-grained detritus to depositional systems on the slope and basin floor. Refer to Fig. 6A for regional stratigraphic context. See Covault et al. (2009) for comprehensive presentation of data and discussion of this outcrop. (B) Photograph of the uppermost Tres Pasos Formation and lowermost Dorotea Formation at Cerro Cazador. Sandstone bedsets that dip and pinch out basinward (southward) interpreted as prograding deltaic clinoforms. (C) Photograph of Sierra Dorotea near town of Puerto Natales. Interbedded sandstone and mudstone deposits in middle part of cliff-face exposure are observed dipping basinward (southward) and downlapping onto underlying bioturbated shelf sandstones and also interpreted as prograding deltaic clinoforms. Refer to Fig. 1 for outcrop locations.

destruction of accommodation as a result of progressive basin filling. The tectonic setting had a primary control on these factors, which we closely link to the variability in stratigraphic architecture. While it may be possible to link deep-water stratigraphic patterns to eustatic drivers (e.g., Flint et al., 2011), the lack of sufficiently precise age control combined with uncertainties related to the global sea-level curve discouraged such linkage.

5.1.1. *Influence of sediment supply and staging area characteristics on deep-water architecture*

Fluctuation in sediment caliber is a result of rate and character of sediment supplied from source and staging areas. Temporal control in ancient outcropping systems is typically neither dense enough nor of adequate precision to calculate meaningful rates of sediment accumulation among formations or between geographic areas.

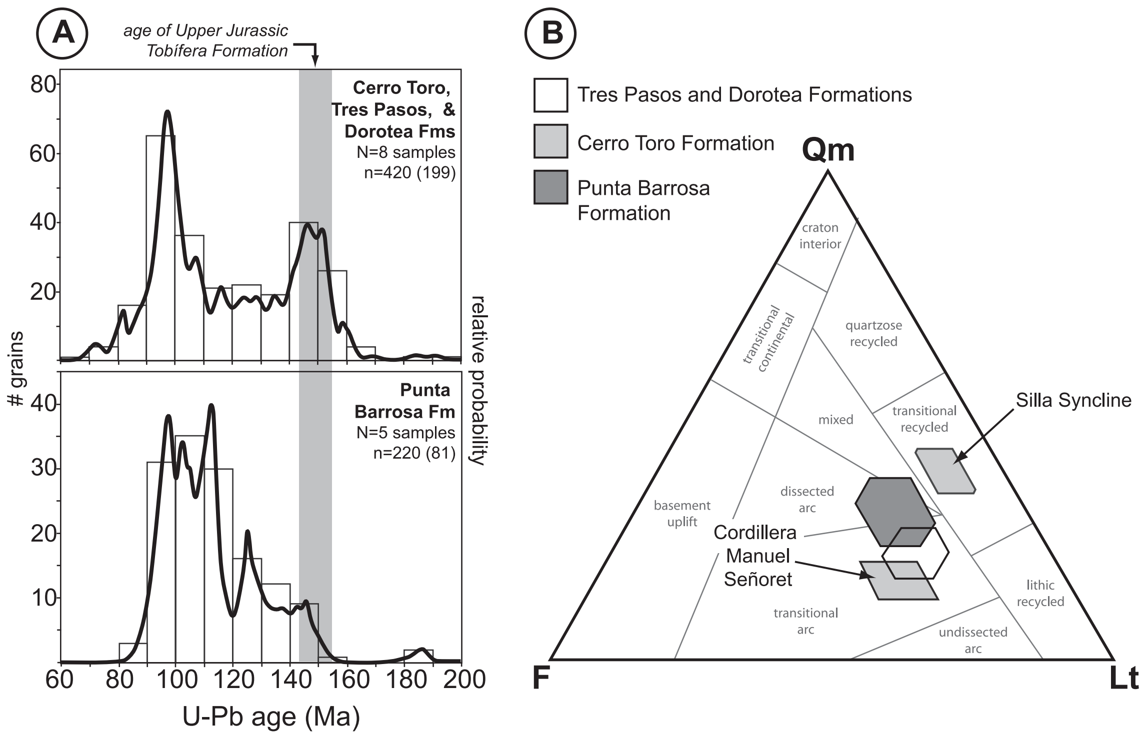

Fig. 8. (A) Composite histograms and probability plots for detrital zircons younger than 200 Ma for Punta Barrosa Formation and for Cerro Toro, Tres Pasos, and Dorotea Formations combined. The latter are grouped together because they each contain a peak in the ca. 145–155 Ma age domain shown in gray (Pankhurst et al., 2000; Hervé et al., 2007), which records the unroofing of the volcanic Upper Jurassic Tobífera Formation. 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 not shown on plot. Punta Barrosa Formation data from Fildani et al. (2003); all other detrital-zircon data from Romans et al. (2010). (B) Monocrystalline quartz-feldspar-total lithics (QmFLt) ternary plot for Upper Cretaceous Magallanes Basin sandstones. Polygons represent 1σ standard deviation. Punta Barrosa Formation data ($n = 28$ samples) from Fildani and Hessler (2005); Cerro Toro Formation data at Silla Syncline locality ($n = 17$ samples) from Crane (2004); Cerro Toro Formation data from Cordillera Manuel Senoret ($n = 9$ samples) from Valenzuela (2006); Tres Pasos and Dorotea Formation samples ($n = 15$ samples) from Romans et al. (2010). Tectonic setting fields from Dickinson (1985). Refer to Romans et al. (2010) for comprehensive presentation and discussion of detrital-zircon age and sandstone composition data.

Mudstone is abundant in all three formations of the Magallanes Basin and makes up most of the basin fill. Therefore, we focus on variability of sandstone and coarser-grained sediment and its association with changes in stratigraphic architecture. The stratigraphic and geographic distribution of coarse-grained sediment in the basin fill is based on the preserved outcrop and, thus, uncertainties related to lack of regional three-dimensionality (e.g., along-strike variability of basin margin) is noted.

The first coarse-grained detritus to reach the basin in this location was the coarse- to medium-grained sandstone of the Punta Barrosa Formation after deposition of the mudstone-rich Zapata Formation. The Punta Barrosa sandstone composition signature reflects a well-developed fold-thrust belt, which Fildani and Hessler (2005) interpreted to have controlled the supply of detritus to the geographically extensive foreland basin.

The most striking pattern regarding grain-size variability is the occurrence of significant thicknesses (hundreds of meters) of amalgamated pebble- to cobble-conglomerate in the Cerro Toro Formation (Fig. 4F–H). Conglomerate is not present in the underlying Punta Barrosa Formation. The timing of a major phase of thrust-sheet emplacement, constrained by detrital-zircon age data (Romans et al., 2010), generally correlates to the development of the Cerro Toro axial channel-levee system (Fig. 8). This episode of uplift in the nearby hinterland was the primary control regarding introduction of pebble- and cobble-sized sediment to the basin (Fig. 9B). However, the distribution of those conglomeratic strata in the basin was influenced by the development of leveed channels. Sediment gravity flows and other mass movements included abundant fine-grained sediment, which promoted flow-stripping processes and levee construction (cf., Piper and Normark, 1983; Normark and Piper, 1991; Manley et al., 1997), which, in turn, promoted long-lived confinement and resultant stacking of conglomeratic channel-fill deposits bounded by mudstone-rich overbank deposits in the basin axis (Fig. 5) (Hubbard et al., 2008).

Conglomerate deposits are generally lacking in the studied outcrops of the overlying Tres Pasos Formation with the exception of a few examples of relatively thin and discontinuous intervals interpreted to record bypass on the upper slope (Hubbard et al., 2010). The lower part of the overlying Dorotea Formation is dominated by sandstone; however, the upper part contains some pebble- to cobble-conglomerate intervals (Covault et al., 2009). Thus, the lack of conglomerate in the Tres Pasos Formation might not be a function of lack of gravel in the sedimentary system as a whole; rather, it might reflect a lack of delivery of this caliber sediment to deep-water settings, which is discussed below.

An additional aspect of sediment supply, and an important control on the dominant grain-size observed in deep-water systems, is the nature of the connection between coastal sediment sources and submarine conduits. This critical zone, commonly termed the "staging area", influences sediment-gravity flow event frequency and magnitude, processes that initiate turbidity currents, and the morphology of feeder canyons (e.g., Normark and Piper, 1991; Reading and Richards, 1994; Martinsen et al., 2005; Piper and Normark, 2009). As a result of significant post-depositional tectonic deformation and extensive cover from the Patagonian ice sheet (Fig. 1), the staging area for the Punta Barrosa is not preserved

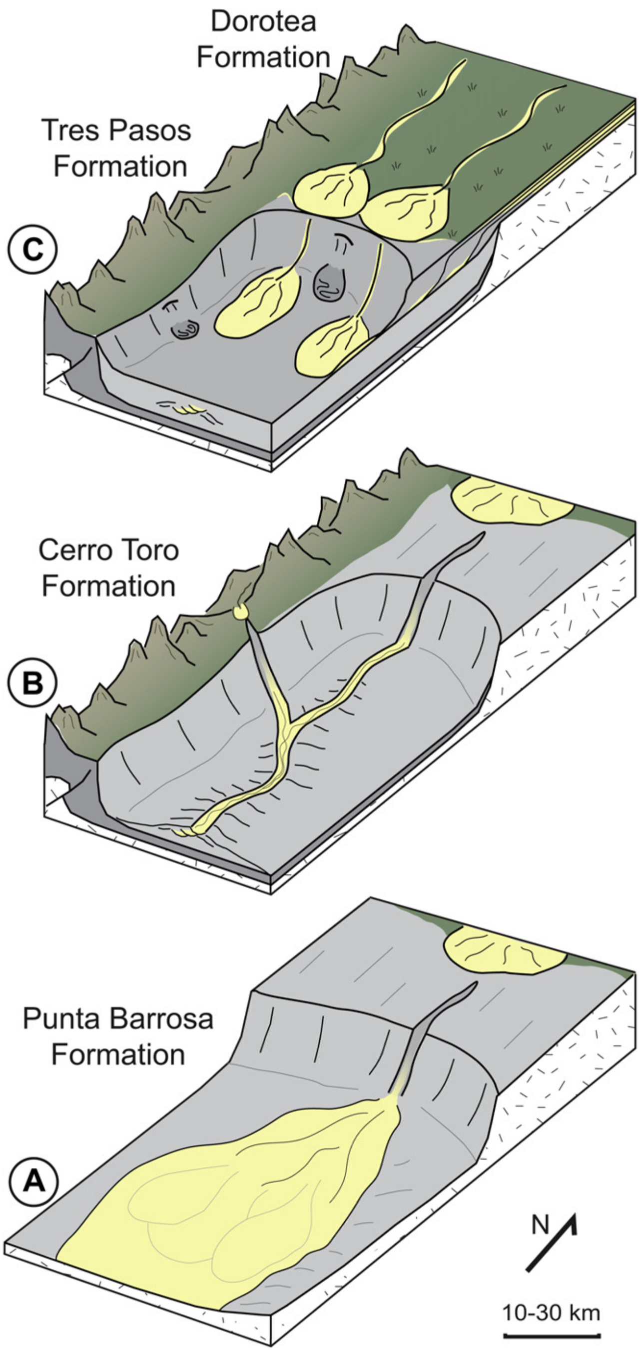

Fig. 9. Schematic block diagrams depicting the dominant style of deep-water deposition and associated architecture in the Magallanes Basin. Position of transition from fully continental crust in north to attenuated crust in south inherited from older Rocas Verdes backarc basin. The nature of the basin margin adjacent to the fold-thrust belt is not preserved as a result of younger deformation and is, therefore, interpretive. (A) The oldest phase of coarse-grained deep-water deposition represented by the Punta Barrosa Formation, which is characterized by tabular to slightly lenticular sandstone bodies interpreted to represent deposition in an unconfined setting (Fig. 3). Eastward thinning and potential pinch out (discussed by Wilson, 1991) suggests potential ponding against forebulge. (B) The Cerro Toro Formation is characterized by a foredeep-axial channel-levee system filled with conglomeratic channel deposits (Figs. 4F–H and 5). Silla Syncline outcrop depicted as major tributary to axial system, which is constrained by paleocurrents (Fig. 1), distinct architectural style (Fig. 5), provenance data (Romans et al., 2010), and has been suggested by previous workers (Crane and Lowe, 2008). Provenance data also indicates timing of thrust-sheet emplacement and associated foredeep subsidence coincident with Cerro Toro deposition. (C) The final phase of deep-water sedimentation is represented by the genetically linked Tres Pasos (slope) and Dorotea (deltaic/shelfal) Formations (Fig. 7). Deep-water accommodation was ultimately filled as the Tres Pasos slope systems prograded southward. See text for further discussion.

in the outcrop record and, thus, it is impossible to directly discriminate effects of staging area characteristics from other external factors on documented patterns.

The staging area for the Cerro Toro Formation, which outcrops in northernmost Ultima Esperanza District and across the international border into Argentina (Fig. 1), is characterized by mudstone-dominated successions and a notable lack of coarse-grained deposits (Scott, 1966; Arbe and Hechem, 1985; Hubbard et al., 2008). This relationship indicates that the proximal part of the Cerro Toro channel system was predominantly a zone of bypass of coarse-grained sediment gravity flows. With regard to the nature of the staging area, the Cerro Toro Formation channels were likely fed by deep, incisional submarine canyons cut into the northern margin of the basin (Fig. 9B). Relatively steep gradients at this location were inherited from a predecessor tectonic configuration and potentially enhanced as a result of thrust-load-induced subsidence (Romans et al., 2010), which would have facilitated the formation of steep submarine conduits and associated transfer of abundant sand- and coarser-caliber sediment into deep water.

In contrast to underlying formations, the staging area during deposition of the Tres Pasos Formation is well preserved. As discussed, the overlying deltaic Dorotea Formation is genetically linked to the slope deposits of the Tres Pasos Formation (Figs. 6 and 7, and 9C) (Hubbard et al., 2010). Although high-resolution correlations of individual slope channel complexes to coeval shelf strata are uncertain, patterns documented in the Dorotea Formation lend insight to potential staging area types. Covault et al. (2009) documented an 800 m wide by up to 30 m deep erosional feature cut into wave- dominated deltaic deposits and filled with turbidites of variable thicknesses interpreted as prodelta deposits (Fig. 7A). This feature is interpreted to have been created by erosion associated with shelf-edge failure and bypass of turbidity currents, some of which likely made it beyond the shelf edge and onto the slope (Covault et al., 2009). Large-scale slope systems, such as the Tres Pasos, commonly are characterized by rapid and voluminous deltaic sedimentation on the shelf and at the shelf edge, which facilitates the creation of major erosional features that can develop into important conduits for sand to deeper water (e.g., the Neogene Gulf of Mexico continental margin; Coleman et al., 1983; Suter and Berryhill, 1985; Mayall et al., 1992; Porębski and Steel, 2003).

5.1.2. *Influence of basin configuration on deep-water architecture*

Variations in Magallanes Basin morphology significantly impacted the general architecture and distribution of depositional systems. Architectural variability in deep-water depositional systems related to changes in basin shape was described in seminal work by Nelson and Kulm (1973) and Normark (1985) and further explored by numerous subsequent workers (e.g., Kolla and Coumes, 1987; Kolla and Macurda, 1988; Mutti and Normark, 1987; Nelson and Maldonado, 1988; Mutti, 1992; Piper and Normark, 2001; Lomas and Joseph, 2004 and papers therein; Fildani and Normark, 2004; Adeogba et al., 2005; Covault and Romans, 2009).

The basin configuration at the time of deposition of the Punta Barrosa Formation is the most difficult to assess because of poor exposures owed to significant post-depositional tectonic deformation (Fosdick et al., in press; Fildani and Hessler, 2005), which precludes discrimination of effects of basin shape. However, the relatively well-preserved outcrops of the informally defined upper Punta Barrosa, with their lateral continuity and tabular to lenticular organization, suggest deposition in a poorly confined to unconfined environment likely associated with submarine fan lobes (Fig. 3; Fig. 9A). Therefore, sediment gravity flows in the early foredeep of the Magallanes Basin likely did not extend to basin margins. This unconfined condition, however, might have changed if topography from forebulge development in the east caused partial ponding of upper Punta Barrosa deposits (Fig. 9A). This is implied by abrupt pinch outs of the upper Punta Barrosa formation to the east (evident in the Toro-1b well to the eastern flank of Sierra del Toro; Wilson, 1991). Additional subsurface evidence suggests that horst and graben structures inherited from the predecessor extensional phase might have influenced the distribution of basinal sedimentation (Fosdick et al., in press).

Subsequent emplacement and propagation of thrust sheets caused the foredeep to narrow and deepen. The sedimentary response to this change in basin shape is reflected in the development of large-scale channel-levee complexes in the Cerro Toro Formation that occupied the axis of the basin (Fig. 9B). Although the absolute width of the basin during Cerro Toro deposition is uncertain, the presence of a 3–8 km wide leveed channel system for >100 km suggests the deep-water part of the foredeep was on the order of 10s of kilometers wide. This estimate is consistent with studies of analogous axial channel- belt systems (e.g., de Ruig and Hubbard, 2006) and with modeling of foredeep subsidence patterns (e.g., Flemings and Jordan, 1989; Jordan, 1995). Additionally, as mentioned above, the position of older graben features might have significantly influenced the position of the Cerro Toro axial channel belt (Fosdick et al., in press).

Sandstone-rich successions of variable architecture and mudstone-rich mass transport deposits of the Tres Pasos Formation accumulated on depositional slope systems that filled the deep-water accommodation as they prograded from north to south (Fig. 9C) (Shultz et al., 2005; Romans et al., 2009b; Hubbard et al., 2010). Paleocurrent data from Tres Pasos slope deposits are similar to underlying formations (i.e., consistently north to south), which indicates that axial foredeep sediment dispersal was maintained during this phase of basin filling. This relatively narrow basin configuration likely resulted in more focused sedimentation at a regional scale and, thus, enhanced accretion of the slope system (Hubbard et al., 2010). In the Magallanes Basin, the shift from a canyon-fed system (Cerro Toro Formation) to a constructional margin (Tres Pasos Formation) was associated with a shift from deep-water deposition of coarse-grained sediment in large-scale channel-levee complexes to smaller channel, lobe, and intraslope minibasin architectural elements (Fig. 9C).

5.1.3. *Variability in architecture as function of basin-filling evolution*

We suggest that the destruction of deep-water accommodation as a result of progressive basin filling was an important control on the architectural variability documented in the Magallanes Basin. The initial bathymetric relief of the foredeep was influenced by attenuated crust (Wilson, 1991; Fildani and Hessler, 2005; Romans et al., 2010), and deposition of the Punta Barrosa Formation was not sufficient to outpace subsidence. These conditions resulted in an underfilled foredeep in which accommodation was approximately maintained. This underfilled, detached, and out-of-grade foredeep margin generally persisted through the deposition of the Cerro Toro Formation, in which a canyon-fed channel-levee system facilitated southward bypass of sediment (Fig. 9).

A change from a generally out-of-grade margin to a more graded, or progradational, margin is reflected by the transition from the Cerro Toro to the Tres Pasos Formation (cf. Hedberg, 1970; Ross et al., 1994; Hadler-Jacobsen et al., 2005; Pyles et al., 2011) (Fig. 9). The early phase of constructional slope development, recorded in the Tres Pasos strata of the northern outcrop belt (Cerro Divisadero to Sierra Contreras), is characterized by significant mass wasting of an unstable slope setting (Shultz et al., 2005; Armitage et al., 2009; Covault et al., 2009). The highly rugose slope profiles that developed imparted a strong influence on sand distribution (e.g., depocenters in ponded minibasins and mass transport deposit-controlled topographic lows; Shultz et al., 2005; Shultz and Hubbard, 2005; Armitage et al., 2009; Romans et al., 2009b). Eventually, a progradational slope system associated with more balanced depositional and degradational processes developed, as documented and discussed by Hubbard et al. (2010) south of Cerro Cazador.

The paucity of conglomerate in the Tres Pasos Formation compared to the underlying Cerro Toro Formation could also be a function of the transition from a high-relief bypass-dominated basin margin to a lower-relief progradational margin. The Cerro Toro Formation was fed by fluvial and deltaic systems that developed to the north and west of Ultima Esperanza District (Arbe and Hechem, 1985; Hubbard et al., 2008). As these systems aggraded in upsystem segments, and also prograded southward, they "healed" the inherited, high-relief basin margin and progradational slope systems developed (Fig. 9). In such dispersal systems, the deltaic and shallow-water segments likely had low regional gradients and, as a result, gravel- and coarser-caliber sediment was rarely delivered to staging areas and beyond to deeper water. Although high-resolution stratigraphic linkages are not sufficiently constrained to rigorously test this hypothesis, provenance data suggests that the source area did not significantly change from the time of Cerro Toro to Tres Pasos deposition (Romans et al., 2010). Furthermore, conglomerate beds are present in the upper part of the Dorotea Formation in some locations, which indicates that the genetically linked Dorotea-Tres Pasos dispersal system consisted of gravel- and coarser-caliber sediment. In other words, the relative lack of conglomerate in the Tres Pasos Formation is probably not a function of the source area having ceased to contribute coarser-caliber sediment to the system; rather, lack of coarser-caliber sediment is likely a function of a constructional staging area with mixed deposition and bypass, in which coarser-grained sediments were sequestered on the shelf.

6. Conclusion

This paper presents a synthesis of the sedimentology, high-resolution facies architecture, regional stratigraphic relationships, and provenance characteristics of the Upper Cretaceous deep-water strata of the Magallanes Basin in the Ultima Esperanza District of southern Chile in order to evaluate the long-term (20 Myr) evolution of stratigraphic patterns. The total basin fill of ~4000 m was deposited in three phases of contrasting stratigraphic architecture: (1) the oldest deep-water formation (Punta Barrosa Formation) comprises tabular to slightly lenticular packages of interbedded sandy turbidites, slurry-flow deposits, and siltstone that are interpreted to record lobe deposition in an unconfined to weakly ponded setting; (2) the overlying, 2500 m thick and shale-dominated Cerro Toro Formation includes a succession of stacked conglomeratic and sandstone channel-fill deposits with associated finer-grained overbank deposits interpreted to record deposition in a foredeep-axial channel-levee system; (3) the final phase of deep-water sedimentation is characterized by sandstone-rich successions of highly variable thickness and cross-sectional geometry and mudstone-rich mass transport deposits (MTDs) that are interpreted to record deposition at the base-of-slope and lower slope segments of a prograding delta-fed slope system. The deep-water formations are capped by shallow-marine and deltaic deposits of the Dorotea Formation.

Interpretations of temporal changes in the type and availability of detritus from the source area (derived from detrital-zircon age and sandstone compositional data) are integrated with the stratigraphic dataset producing a robust framework for assessing controls on sedimentary patterns. The evolution of the stratigraphic architecture is related to: (1) the variability of amount and type of source material, (2) the variations in the basin shape through time, and (3) intrinsic evolution of the fill as a function of prograding systems filling the deep-water accommodation. While the expression of these controls in the stratigraphic architecture of other deep-water successions might differ in detail, the controls themselves are common to all deep-water basins. Information about source material and basin shape is contained within the detrital record and, when integrated and analyzed within the context of stratigraphic patterns, attains a more robust linkage of processes to products than stratigraphic characterization alone.

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