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OUTCROP EXPRESSION OF A CONTINENTAL-MARGIN-SCALE SHELF-EDGE DELTA FROM THE CRETACEOUS MAGALLANES BASIN, CHILE

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ABSTRACT: **Shelf-edge deltas are the primary agents of sediment delivery to deeper-water slope and basin-plain depositional environments, and they represent significant targets for hydrocarbon exploration. Subsurface shelf-edge deltas from passive margins have been extensively studied with seismic-reflection data, and only recently have outcrop analogs been documented (e.g., smaller-scale shelf-and-slope systems in the Eocene Central Basin, Spitsbergen, and the Cretaceous Western Interior Seaway, North America). This study characterizes stratigraphic architecture and interprets depositional processes of outcropping deep-water upper-slope and deltaic strata of the Tres Pasos and Dorotea formations of the Late Cretaceous Magallanes foreland basin, southern Chile. The Dorotea delta system at Cerro Escondido is the topset element of an unstable, continental-margin-scale clinoform. Topset-to-basin-floor relief was on the order of two kilometers as a result of inherited tectonic relief from a precursor extensional-basin phase combined with the effects of thrust loading and foreland flexure. The superbly exposed Cerro Escondido outcrop exhibits a depositional-strike perspective of ~ 300 m of shelf-edge delta deposits, including two generally upward-coarsening lithofacies successions (each succession up to ~ 200 m of measured thickness). Lithofacies successions are composed of upward-shoaling lithofacies associations, including prodelta turbidites overlain by thick wave-reworked delta-front, or shoreface, sandstones and subaqueous delta-plain distributary-channel and interdistributary deposits. Successions at Cerro Escondido are distinctively different from upward-shoaling deposits documented in other outcrop-based studies: they include thicker, coarser-grained delta-plain and delta-front strata and relatively coarse-grained prodelta turbidites in pockets of shelf-edge accommodation created as a result of mass wasting. Conditions inherent to the relatively unstable, continental-margin-scale, linked Dorotea shelf and Tres Pasos slope facilitated the development of successions at Cerro Escondido. Therefore, outcrops at Cerro Escondido provide unique insights into shelf-edge architecture and development, which can be applied to models of continental-margin evolution.**

INTRODUCTION

Shelf-edge deltaic sedimentation is the primary mechanism by which continental margins prograde and sedimentary basins fill (e.g., Morton and Suter 1996; Muto and Steel 2002; Porębski and Steel 2003; Steel et al. 2003). The stratigraphic architecture of shelf-edge deltas, therefore, forms the basic building blocks of progradational continental margins and provides insight into sediment delivery across margins to deeper water (Cummings and Arnott 2005). Shelf-edge deltas can also be prolific hydrocarbon reservoirs (Sydow and Roberts 1994; Hart et al. 1996; Meckel 2003). Seminal studies of shelf-edge stratigraphic architecture and development were seismic-reflection-based analyses of the Neogene continental margin in the Gulf of Mexico (e.g., Berg 1982; Winker and Edwards 1983; Suter and Berryhill 1985). Berg (1982) synthesized seismic-reflection-based observations of Neogene Mississippi deltas, which comprise delta-plain, delta-front, and prodelta acoustic facies (see fig. 3 of Berg 1982). Mayall et al. (1992) supplemented seismic-reflection data with local wireline-log and drill-core information in order to study Pliocene Mississippi shelf-edge deltas and documented thick, but laterally restricted, sections of very fine- and fine-grained sandstone turbidites in prodelta environments, which had not been documented in modern deltas.

Outcrops provide greater resolution of two- or three-dimensional stratigraphic architecture. There are few outcrop examples of continental-margin shelf-edge deposits in foreland basins because they are commonly partially subducted or uplifted and eroded as a result of deformation (Ingersoll and Graham 1983). Only recently have outcrop analogs been documented, predominantly from foreland or piggyback basins underlain by continental crust of normal thickness and filled by relatively small-scale shelf-and-slope systems (e.g., the Eocene Central Basin, Spitsbergen, and the Cretaceous Western Interior Basin, Wyoming; Steel et al. 2000; Mellere et al. 2002; Plink-Björklund and Steel 2005; Carvajal and Steel 2006; Pyles and Slatt 2000, 2007; Uroza and Steel 2008). Regressive shelf-edge deltaic units from Spitsbergen are several meters to tens of meters thick and exhibit delta-plain, delta-front, and prodelta deposits similar to those interpreted by Berg (1982) (see fig. 3 of Plink-Björklund and Steel 2005; and fig. 12 of Uroza and Steel 2008). The Eocene Central Basin, however, exhibits shelf-and-slope clinoform amplitudes on the order of hundreds of meters (Steel et al. 2000; Mellere et al. 2002; Plink-Björklund and Steel 2005; Uroza and Steel 2008). "Clinoform" can be used to

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describe sigmoidally shaped surfaces across a range of spatial scales; however, we use "clinoform" to refer to the sigmoidal shape of an entire shelf-and-slope system (Johannessen and Steel 2005).

Shelf-edge stratigraphic architecture and development associated with relatively unstable, large-scale shelf-and-slope systems in foreland basins are understudied. Conditions inherent to these shelf-and-slope systems likely facilitate the development of unique shelf-edge stratigraphic architecture relative to passive margins with extensive sediment-routing systems linking source areas to ocean basins (e.g., Neogene Gulf of Mexico margin) and smaller shelf-and-slope systems in foreland or piggyback basins underlain by continental crust of normal thickness (e.g., Eocene clinothems on Spitsbergen). Conditions include: (1) short sediment-transport distances from adjacent hinterland source areas, which deliver large volumes of coarse-grained sediment to the coast and adjacent shelf; (2) high subsidence rates and common mass wasting off the shelf associated with rapid and voluminous coarse-grained deltaic sedimentation; (3) large accommodation in the deep water beyond the shelf; and (4) large waves reaching the shelf edge as a result of less restricted fetch across the sea surface and propensity for tsunami and storm generation in the open sea (Coleman 1981; Coleman et al. 1983; Ingersoll and Graham 1983; Winker and Edwards 1983; Milliman and Syvitski 1992; Nittrouer and Wright 1994; Ross et al. 1994; Wright and Nittrouer 1995; Porębski and Steel 2003; Swenson et al. 2005; Nittrouer et al. 2007; Yoshida et al. 2007; Shanmugam 2008). These conditions result in a number of processes, many of them involving subaqueous sediment instabilities and the delivery and reworking of relatively coarse-grained sediment, that differ from passive margins with extensive sediment-routing systems and relatively stable, small-scale shelf-and-slope systems. These processes likely facilitate the deposition of thicker, coarser-grained delta-plain and delta-front strata and relatively coarse-grained prodelta turbidites in pockets of shelf-edge accommodation created as a result of mass wasting.

The superbly exposed Cerro Escondido outcrop exhibits the transition from the uppermost Tres Pasos Formation (deep-water upper-slope turbidites and mass-transport deposits; Katz 1963; Shultz et al. 2005; Romans et al. 2008b; Armitage et al. 2009) to the Dorotea Formation (shallow-water shelfal and deltaic deposits; Katz 1963) in the Magallanes foreland basin (Figs. 1, 2). The stratigraphic thickness from base-of-slope deposits at nearby Cerro Divisadero (Tres Pasos Formation) to deltaic topset strata at Cerro Escondido (Dorotea Formation) is measured to be greater than one kilometer, which, considering regional stratigraphic correlation (Macellari et al. 1989) and compaction, suggests water depth as great as two kilometers (Romans et al. 2008a; Romans et al. 2008b) (Fig. 3). This stratigraphic thickness, and inferred water depth, is considerably larger than shelf-and-slope systems documented in previous outcrop-based studies (e.g., shelf-and-slope clinoforms of the Eocene Central Basin, Spitsbergen, and the Cretaceous Lewis Shale in the Western Interior Basin, Wyoming; Steel et al. 2000; Mellere et al. 2002; Plink-Björklund and Steel 2005; Carvajal and Steel 2006; Pyles and Slatt 2000, 2007; Uroza and Steel 2008), and similar to larger-scale continental margins. The Dorotea delta system at Cerro Escondido is represented by a significant thickness (> 300 m) of two shelf-edge lithofacies succes-

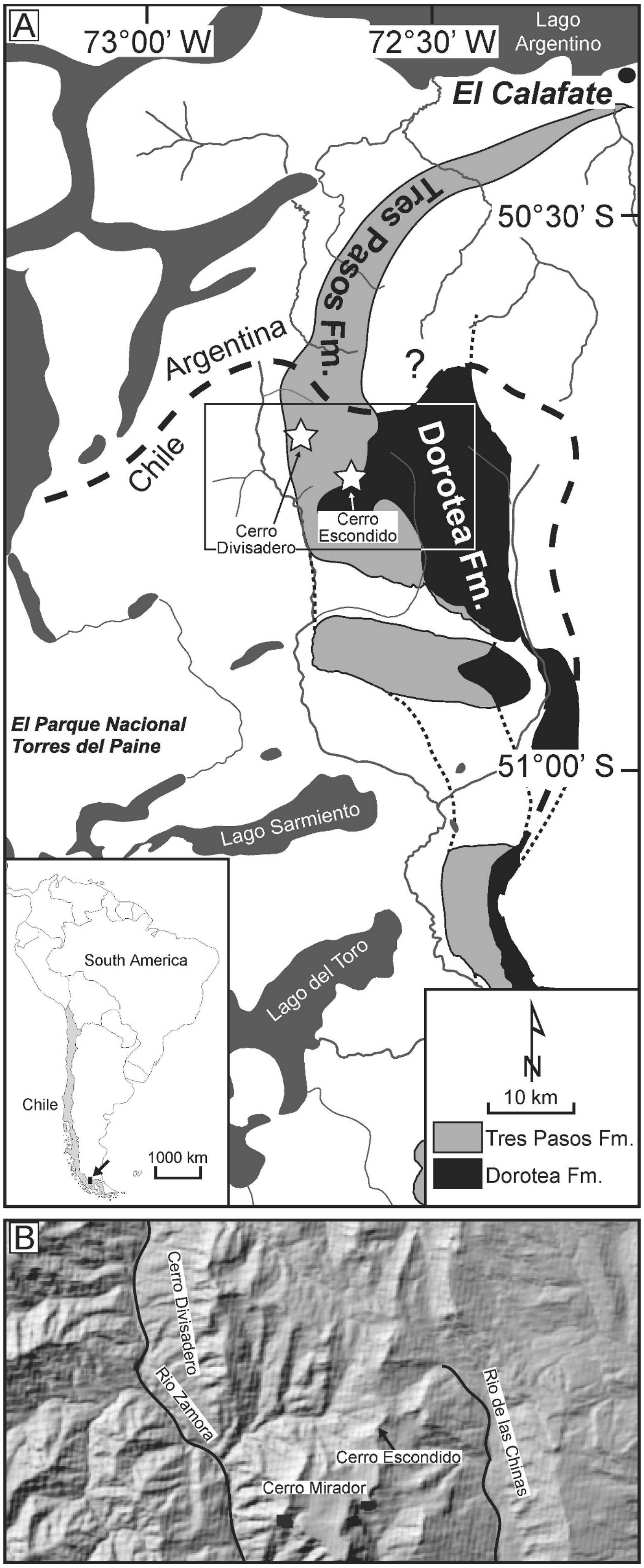

FIG. 1.— Location map of the Upper Cretaceous Tres Pasos and Dorotea formations of the Magallanes Basin, southern Chile. **A)** Regional geography of the Ultima Esperanza District of southern Chile and El Calafate area of Argentina. Tres Pasos and Dorotea formations are shaded in gray and black, respectively.

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Border between Argentina and Chile is a dashed black line. Rivers are gray lines. Lakes are gray polygons. Box is location of Part B. Cerro Divisadero (Romans et al. 2008b) and Cerro Escondido (this study) locations are white stars. Modified from Romans et al. (2008b). Inset: South America with location of Part A indicated with an arrow pointing to a black rectangle. **B)** DEM of study area with rivers and mountains referred to in "Study area: Cerro Escondido."

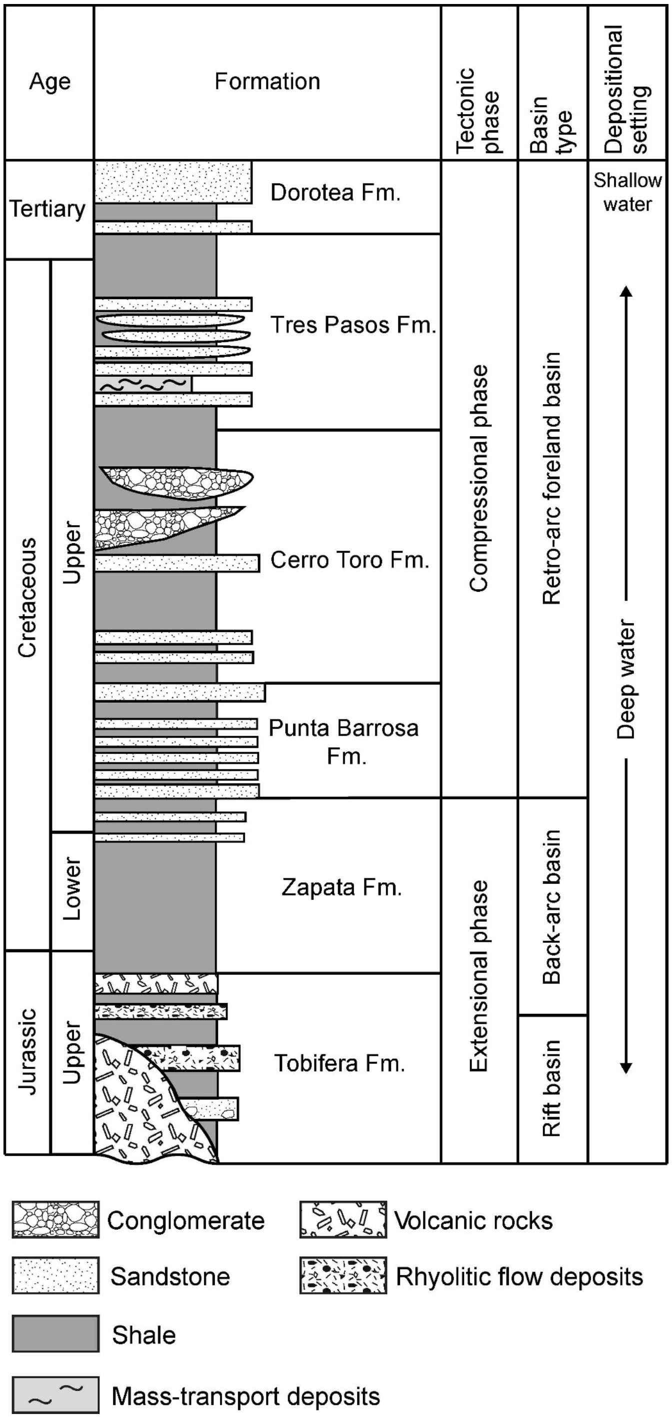

FIG. 2.— Generalized stratigraphic column (not representative of thickness) with lithostratigraphy related to major tectonic events and basin settings. The upper Tres Pasos and lower Dorotea formations are the focus of this study. Modified from Wilson (1991) and Fildani and Hessler (2005).

sions. These successions are distinctively different from upward-shoaling deposits documented in other outcrop-based studies and, therefore, provide unique insights into shelf-edge delta stratigraphic architecture and development associated with an unstable, large-scale shelf-and-slope system.

TECTONIC AND STRATIGRAPHIC CONTEXT

Magallanes Basin Foredeep

The Late Cretaceous Magallanes Basin foredeep was an elongate trough oriented subparallel to the southern Andean arc and associated fold-and-thrust belt. Axial facies of the basin are exposed in the foothills of the Andean Cordillera (Fig. 1). Preceding foreland basin development, the oceanic Rocas Verdes back-arc basin developed during the latest Jurassic and Early Cretaceous as a result of rifting associated with the disintegration of Gondwana (Dalziel 1981; Wilson 1991; Fildani et al. in press b) (Fig. 2). Volcaniclastic sedimentary rocks and rhyolitic volcanic rocks of the Jurassic Tobífera Formation, and thin-bedded deep-water, basinal mudstone of the Lower Cretaceous Zapata Formation were deposited in the back-arc setting (Wilson 1991; Fildani and Hessler 2005) (Figs. 2, 3). The transition from the extensional Rocas Verdes Basin to the compressional Magallanes foreland basin is recorded by the deep-marine Upper Cretaceous Punta Barrosa Formation (Wilson 1991; Fildani and Hessler 2005) (Figs. 2, 3). Deep-marine sediment-gravity-flow deposits accumulated in the Magallanes Basin foredeep during Late Cretaceous deposition of the Punta Barrosa, Cerro Toro, and Tres Pasos formations (Fildani et al. 2003; Romans 2008; Fildani et al. in press b) (Figs. 2, 3). Upward shallowing in the foredeep is recorded by the Upper Cretaceous shallow-marine and deltaic strata of the Dorotea Formation, which is the focus of this study (Figs. 2, 3).

Dorotea–Tres Pasos Shelf-and-Slope System

The Upper Cretaceous Dorotea and Tres Pasos formations are exposed across > 100 km of the foothills of the southern Andean fold-and-thrust belt (Shultz et al. 2005) (Fig. 1). They represent southward progradation of a linked shelf-and-slope system, the Dorotea–Tres Pasos shelf-and-slope system, along the Magallanes foredeep axis (Smith 1977; Macellari et al. 1989; Shultz et al. 2005; Romans et al. 2008b) (Fig. 3). Macellari et al. (1989) interpreted the Upper Cretaceous Dorotea and Tres Pasos formations, and coeval formations in Argentina, as shelf and slope elements of a large-scale regressive siliciclastic wedge, which received a relatively large volume of sediment from nearby hinterland source areas (cf. sequence 1 of fig. 2 of Macellari et al. 1989; see also fig. 4 of Riccardi 1988; Shultz et al. 2005; Romans 2008; Romans et al. 2008b; Armitage et al. 2009; Fildani et al. in press a) (Fig. 3). Detailed work on the stratigraphic architecture of the Tres Pasos Formation by Shultz et al. (2005), Romans et al. (2008b), and Armitage et al. (2009) highlighted the dominance of slope mass-wasting processes. An ~ 1500-m-thick section exposed in the Ultima Esperanza District of southern Chile exhibits sandstone-rich, base-of-slope to lower-slope turbidites and mudstone-rich mass-transport deposits at Cerro Divisadero (~ 600 m thick; Romans et al. 2008b) (Fig. 3) overlain by mudstone-rich strata of upper-slope affinity (~ 600 m thick; Romans et al. 2008a) (Fig. 3), capped by predominantly deltaic strata at Cerro Escondido (~ 300 m thick; Fig. 3), which is the focus of this study. Although direct measures of paleobathymetry are unavailable in the Dorotea and Tres Pasos formations, the underlying Cerro Toro Formation was identified as bathyal water deposits (1000–2000 m) by Natland et al. (1974), and the Dorotea–Tres Pasos shelf-and-slope succession is as much as 1500 m thick from base-of-slope deposits to deltaic topset strata (compacted thickness; Hubbard et al. 2008; Romans et al. 2008a, Romans et al. 2008b; Fildani et al. in press a) (Fig. 3). Therefore, water depths as great as two kilometers are conservatively estimated for the Dorotea–Tres Pasos shelf-and-slope clinoform (see also regional stratigraphic correlation of Macellari et al. 1989) (Fig. 3). The Magallanes Basin inherited attenuated continental crust from the predecessor Rocas Verdes back-arc basin (Fildani and Hessler 2005). Romans et al. (2008b) noted that the attenuated continental crust, combined with the effects of thrust loading

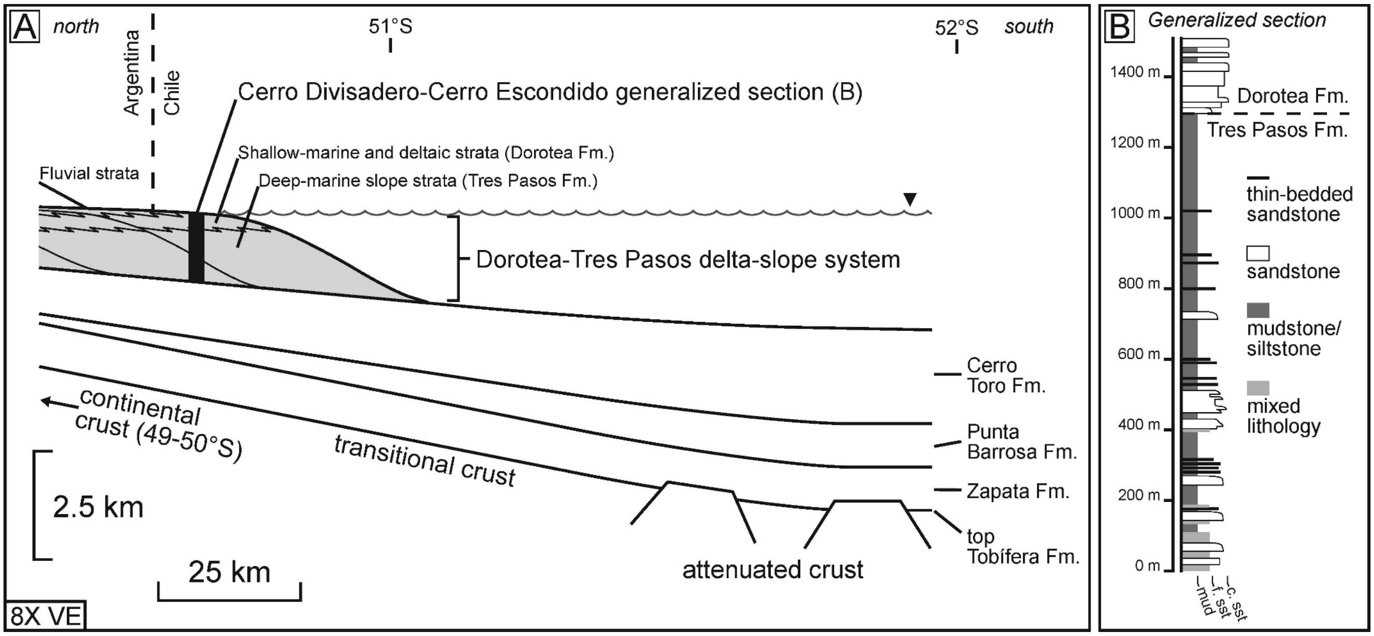

FIG. 3.— Regional stratigraphic framework for the Magallanes foredeep (and predecessor Rocas Verdes back-arc basin), with emphasis on the Dorotea–Tres Pasos shelf-and-slope system. **A)** Simplified north-to-south cross section through the Magallanes foredeep. Tobífera and Zapata formations were deposited in the back-arc setting. Top Tobífera Formation surface gradient is from Biddle et al. (1986). Thicknesses of Zapata, Punta Barrosa, and Cerro Toro formations are from Katz (1963), Riccardi (1988), Fildani and Hessler (2005), and Crane and Lowe (2008). Southward-prograding Dorotea–Tres Pasos shelf-and-slope system (gray) thickness and dominantly regressive character are from Riccardi (1988), Macellari et al. (1989), Shultz et al. (2005), Romans et al. (2008a), Romans et al. (2008b), and this study. Bold black line is location of Cerro Divisadero-to-Cerro Escondido generalized section in Part B. **B)** Cerro Divisadero-to-Cerro Escondido generalized section (modified from Romans et al. 2008a).

and foreland flexure, contributed to a Magallanes Basin shelf-to-basin-floor profile comparable in bathymetric relief to large-scale continental margins during Late Cretaceous deposition of the Tres Pasos and Dorotea formations (see also Biddle et al. 1986; Wilson 1991; Fildani and Hessler 2005; and Fildani et al. in press a) (Fig. 3).

Study Area: Cerro Escondido

Cerro Escondido is located ~ 8 km south of the border between Argentina and Chile, and 6 km east of Cerro Divisadero (Romans et al. 2008b) (Figs. 1, 4). The Tres Pasos and Dorotea formations are exposed here across broad and open anticlines and synclines. The Cerro Escondido study area is located on the west-dipping limb of an anticline between the Rio de las Chinas and Rio Zamora. Cerro Mirador forms the east-dipping limb of the syncline west of Cerro Escondido (Fig. 4). Strata of the Dorotea delta system are > 300 m thick, and exposed across > 800 m of outcrop oriented approximately perpendicular to depositional dip (Fig. 4).

Paleocurrent indicators are limited at Cerro Escondido as a result of the lack of three-dimensional exposure of cross stratification and bedding planes. Nonetheless, paleocurrent indicators include north-to-south-oriented tool marks in thick sandstone beds near the base of the stratigraphic section. Prominent scour surfaces near the middle of the section support a depositional-strike outcrop perspective, which indicates a north-to-south, foredeep-axial paleocurrent direction (Fig. 4). Abundant paleocurrent data for the Dorotea–Tres Pasos shelf-and-slope system from previous studies also emphasize north-to-south sediment dispersal throughout the basin, i.e., parallel to the trend of the southern Andean fold-and-thrust belt and Magallanes foredeep axis (Smith 1977; Macellari et al. 1989; Shultz et al. 2005; Romans et al. 2008b) (Fig. 3). These data supplement the limited paleocurrent indicators at Cerro Escondido and suggest that the outcrop affords a depositional-strike perspective of the Dorotea delta system.

STRATIGRAPHIC ARCHITECTURE OF CERRO ESCONDIDO

Architectural-Element Method

This study employs an architectural-element hierarchy in which no *a priori* interpretive descriptors are appended to architectural elements at any level in the hierarchy, and which is open-ended at the largest scale (cf. the tenets of the fluvial architectural-element hierarchy of Miall 1985; and the deep-water architectural-element hierarchy of Ghosh and Lowe 1993; and Hickson and Lowe 2002). In this hierarchy, individual sedimentation units and component sedimentary structures are the fundamental order of observation. It is difficult to identify sedimentation units in amalgamated trough and swaly cross-stratified sandstone beds, and in thick mudstone beds. Grouped sedimentation units of similar affinity constitute the next order of observation, i.e., lithofacies, which are the basic mappable components of a dataset (Table 1). Regularly recurring groups of genetically related lithofacies, which have some environmental significance, represent the next larger order of observation (lithofacies associations; Collinson 1969). The largest order of observation is the lithofacies succession, which is a stack of progressively changing lithofacies and their associations (Walker 1992). Walker (1992) suggested that lithofacies successions are comparable to parasequences of Van Wagoner et al. (1990), which are relatively conformable successions of genetically related bedsets bounded by flooding surfaces; however, Walker (1992) also noted that the concept of lithofacies successions is broader than that of parasequences.

Two stratigraphic sections were recorded at Cerro Escondido at 10-cm-scale resolution, an eastern section (295 m thick) and a western section (197 m thick; Fig. 4). The sections show similar stratigraphic architecture across the > 800-m-wide outcrop (Fig. 4). However, the eastern section documents the upper Tres Pasos Formation (from 0 to 99 m in the eastern section; Fig. 4) and sedimentary fill of prominent scours (from 103 to 157 m in the eastern section; Fig. 4), and the western section

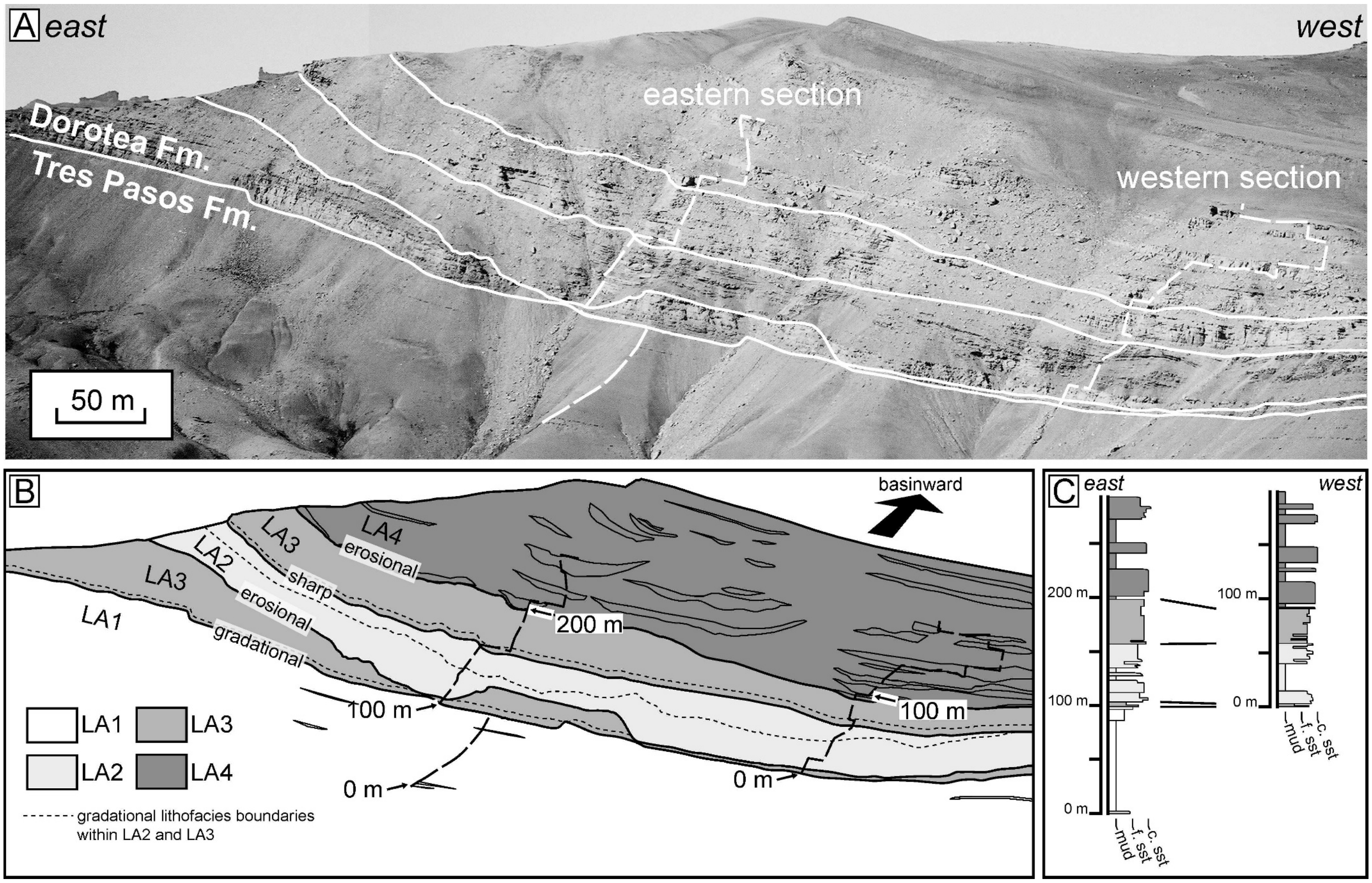

FIG. 4.— Cerro Escondido stratigraphic architecture. **A)** Photo of Cerro Escondido. Lithofacies association boundaries are approximately horizontal white lines. Stratigraphic section locations are approximately vertical dashed white lines. **B)** Simplified line drawing of Cerro Escondido. Lithofacies associations are shaded. Contacts between associations are characterized. Distinctive lithofacies boundaries within LA2 and LA3 are dashed black lines. Stratigraphic section locations are approximately vertical dashed black lines. Thin solid black lines in LA4 are lenticular, trough cross-stratified sandstone bodies (L6). **C)** Generalized eastern and western stratigraphic sections. Association shading corresponds with Part B.

documents deposits adjacent to the scours (from 15 to 40 m in the western section; Fig. 4). Seven lithofacies are identified (Table 1; Figs. 5, 6). They are grouped into four lithofacies associations, described and interpreted below (Figs. 7–10), which compose two generally upward-coarsening lithofacies successions, each < 200 m thick (Figs. 4, 11).

Lithofacies Association 1: Mudstone Punctuated by Lenticular Sandstone Bodies

Description.—Lithofacies Association 1 (LA1) is observed in the lower 100 m of the eastern Escondido section and consists predominantly of thick mudstone lithofacies with local, lenticular sandstone bodies (i.e., stacks of Lithofacies 1 [L1]; Table 1; Figs. 4, 5A, 7). Mudstone sections were measured to be < 45 m thick. They are punctuated by medium-grained sandstone bodies presented below and include local centimeter-thick siltstone and very fine-grained sandstone units. The top 13 m of the association (i.e., from 86 to 99 m in the eastern section; Fig. 7) is predominantly very fine-grained sandstone, and the top meter of the association is extensively bioturbated.

Lenticular, < 1-m-thick, fine- to medium-grained sandstone bodies are laterally discontinuous (i.e., pinch out across tens of meters) and include normally graded, traction-structured (i.e., planar and local poorly defined ripple and wavy laminae) units (Fig. 7). Units include organic detritus and shell fragments. The top 23 m of the association (i.e., from 76 to 99 m in the eastern section; Figs. 4, 7) exhibits more sandstone bodies. The top 6 m of the association exhibits relatively tabular sandstone bodies, which include poorly sorted, wavy-laminated units. Wavy laminae are approximately symmetrical with amplitudes of ~ 1 cm and wavelengths of < 10 cm (Fig. 7). The top of the association is an approximately even, parallel contact defined by the first hummocky cross-stratified sandstone unit of Association 3 (Figs. 4, 7).

Depositional Processes and Environment.—Thick mudstone lithofacies reflect settling of hemipelagic mud out of suspension (Stow and Piper 1984) and deposition of mud-rich, low-density turbidity currents (Lowe 1982). Sandstone bodies reflect deposition of fine- and medium-grained sand from low-density turbidity currents (Bouma 1962). The fine- and medium-sized grains of the sandstone bodies could be entirely supported in turbidity currents by fluid turbulence (Lowe 1982). Overriding turbidity currents worked beds into traction structures (Lowe 1982). Poor sorting of tabular sandstone bodies near the top of the association suggests that turbidity currents were unable to significantly grain-size fractionate their rapidly deposited sediment load, and reflects relatively limited sediment-transport distance (Lowe 1982; Sylvester 2001). Wavy laminae reflect subtle wave- and current-reworking processes. Wavy laminae associated with turbidites have been documented in prodelta deposits of Pleistocene shelf-edge deltas of the northern Gulf of Mexico (Morton and Suter 1996), storm-influenced prodelta turbidites of the Late Cretaceous lower Kenilworth Member of the Blackhawk Formation, Book Cliffs, Utah (Pattison 2005), and wave-influenced prodelta

TABLE 1.—*Lithofacies (L) at Cerro Escondido. sst, sandstone; fs, fine-grained sandstone; ms, medium-grained sandstone; cs, coarse-grained sandstone. It is difficult to identify sedimentation units in trough and swaly cross-stratified sandstone sections and in thick mudstone sections. Turbidite divisions are from Bouma (1962) and Lowe (1982).*

Lithofacies	Lithology and Bedding Style	Grading and Sorting	Thicknesses	Basal Bounding Surfaces	Lithologic Accessories	Physical Structures	Turbidite Divisions	Trace Fossils and Bioturbation	Depositional Processes
L1	Mudstone w/ local, thin-bedded sst	sst is normally graded from ms base to fs top; mod. to well sorted	Mudstone sections are < 45 m; local sst units are < 1 m; max. lithofacies thickness is ~ 45 m	Mudstone beds are even, parallel; sst units are sharp; sole marks rare	sst includes fine organic detritus, which define laminae; local mudstone clasts (< 1 cm diameter) and shell fragments	sst exhibits planar laminae; local ripple and wavy laminae	T_{a-e} (T_b most common in sst; T_{d-e} common in mudstone)	Locally extensively bioturbated	Mudstone from settling of hemipelagic mud out of suspension and low-density turbidity currents; sst from low-density turbidity currents
L2	Amalgamated, thick-bedded sst w/ mudstone laminae or beds	sst is massive to normally graded from ms base to fs top; well sorted	sst units are < 3.5 m; stacks of amalgamated sst units are < 12 m; mudstone beds are < 5 m; max. lithofacies thickness is ~ 30 m	sst units are even and parallel to undulating; commonly amalgamated; sole marks rare; mudstone beds are even, parallel	sst includes shell fragments; organic detritus and mudstone clasts define laminae (< 1 cm diameter)	sst exhibits planar laminae; local ripple laminae and low-angle cross stratification	S_3 (T_{b-e}, S_1 locally present)	Rare	sst from high-density turbidity currents; mudstone from suspension settling and low-density turbidity currents
L3	Thin-bedded sst	Normally graded from ms base to fs top w/ mudstone lamina cap; poorly to mod. sorted	< 1-m-thick sandstone units interbedded with mudstone; max. lithofacies thickness is ~ 20 m	Even and parallel to undulating; sole marks rare	Organic detritus define laminae	Planar and wavy laminae	T_{a-c} (T_{d-e} common in mudstone laminae)	Rare	Predominantly low-density turbidity currents
L4	Interbedded hummocky cross-stratified sst (HCS) and normally graded sst	HCS is ungraded fs and ms; normally graded sst from ms base to fs top; mod. to well sorted	HCS units are < 1 m; stacks of amalgamated HCS units are < 2 m; stacks of normally graded sst units are < 1 m; max. lithofacies thickness is ~ 10 m	Even, parallel	Organic detritus	HCS	N/A	HCS locally extensively bioturbated; normally graded sst extensively bioturbated	HCS from storm wave-generated oscillatory currents; normally graded sst from low-density turbidity currents
L5	Amalgamated swaley cross-stratified sst (SCS)	Ungraded fs and ms; well sorted	< 10-m-thick stacks of amalgamated SCS units; max. lithofacies thickness is ~ 35 m	Even, parallel	Organic detritus and local shell fragments	SCS	None	Locally extensively bioturbated	Combined oscillatory and unidirectional currents
L6	Trough cross-stratified sst (TCS)	Subtly normally graded cs w/ outsized granules/ pebbles at base	< 25-m-thick lenticular sst bodies; max. lithofacies thickness is ~ 25 m	Even and parallel to undulating	Abundant organic detritus	TCS	None	*Skolithos*; *Diplocraterion*	Fluvial current bed load
L7	Carbonaceous mudstone	Mudstone; local cs to siltstone beds and laminae	< 25-m-thick mudstone sections; max. lithofacies thickness is ~ 25 m	Even, parallel	Abundant organic detritus	Local planar and ripple laminae	None	Rare; not recognized	Suspension settling and fluvial currents

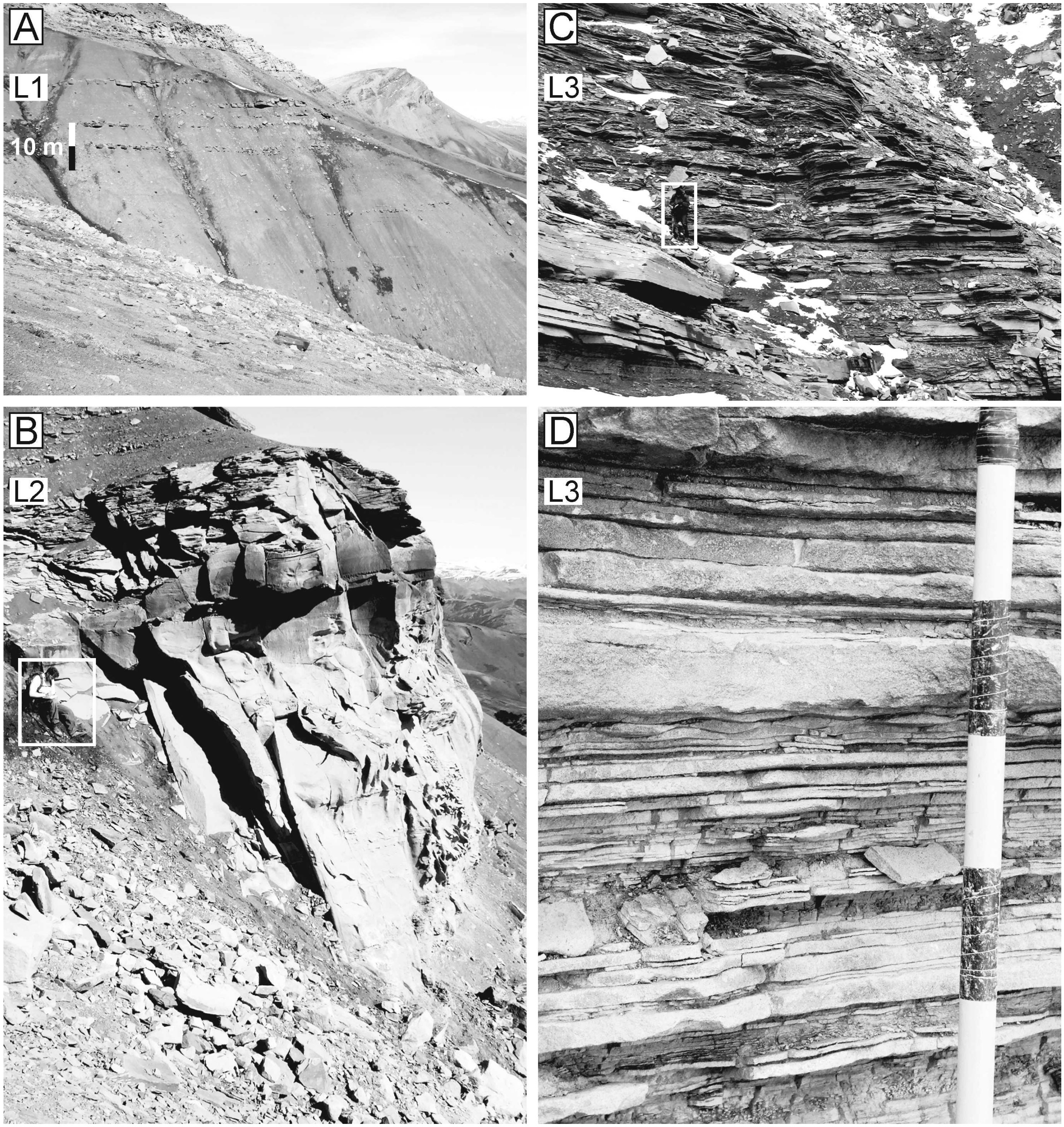

FIG. 5.— Lithofacies 1, 2, and 3 photos. **A)** Lithofacies 1 (L1): mudstone with local, thin-bedded sandstone. **B)** Lithofacies 2 (L2): amalgamated, thick-bedded sandstone with local mudstone beds. Person for scale. **C)** Lithofacies 3 (L3): thin-bedded sandstone. Person for scale. **D)** Bed-scale photo of L3 thin-bedded sandstone with mudstone laminae. Jacob's staff for scale (black and white sections are 10 cm thick). See Table 1 for lithofacies details.

turbidites of the Pennsylvanian Minturn Formation, Colorado (Lamb et al. 2008).

The crude upward coarsening of the association (i.e., the top 23 m of the association exhibits more sandstone bodies) reflects a basinward advance of depositional environments from a relatively distal to proximal prodelta, or upper-slope, environment (Bhattacharya and Walker 1992). Relatively fine-grained prodelta stratigraphic architecture is consistent with general delta models, which advocate that coarse-grained deposits are restricted to delta-plain and delta-front environments (e.g., Scruton 1960; Coleman 1981; Berg 1982; Bhattacharya and Walker 1992).

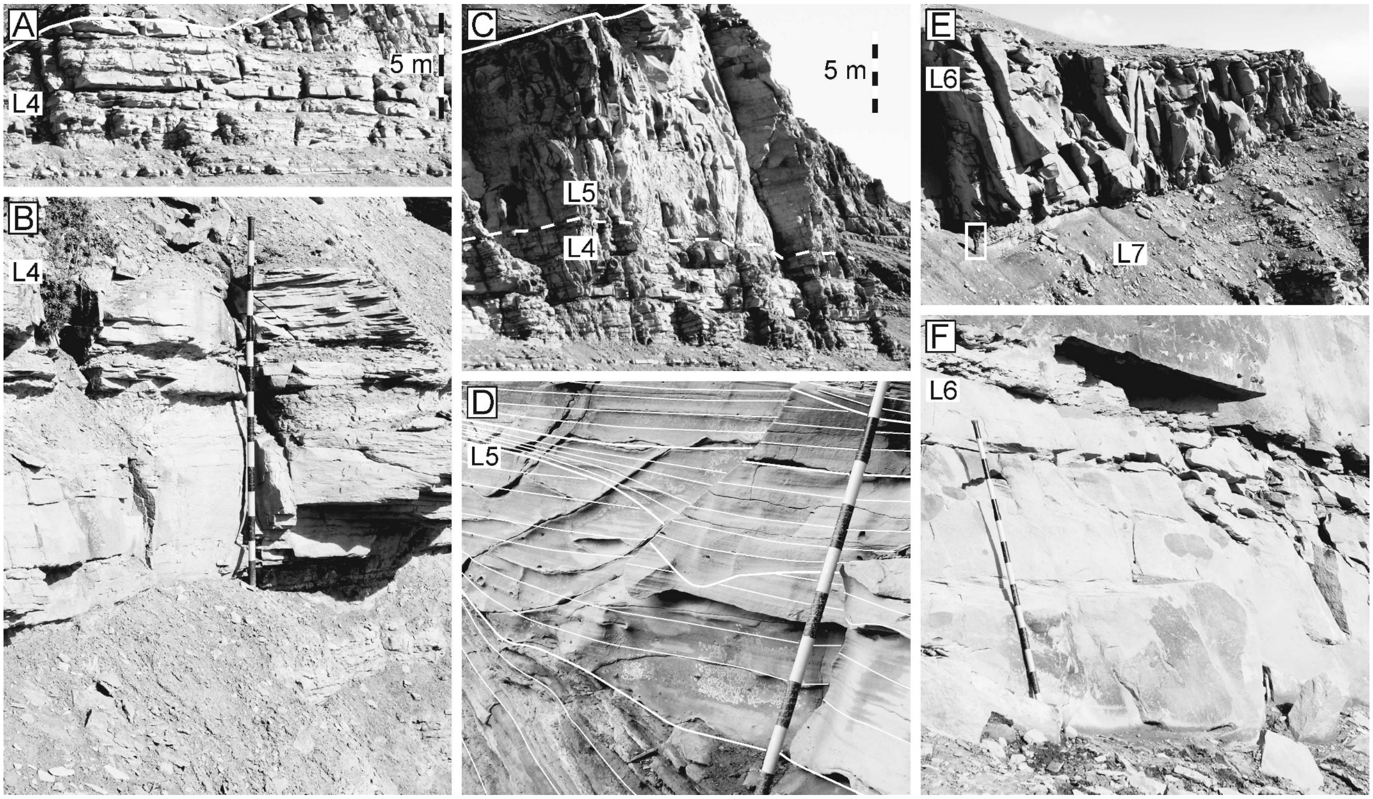

FIG. 6.—Lithofacies 4, 5, 6, and 7 photos. **A)** Lithofacies 4 (L4): interbedded hummocky cross-stratified sandstone and normally graded sandstone. Solid white line is a lithofacies association boundary. **B)** Bed-scale photo of a L4 hummocky cross-stratified bed bounded by bioturbated normally graded sandstone beds. Jacob's staff for scale (black and white sections are 10 cm thick). **C)** Lithofacies 5 (L5): amalgamated swaly cross-stratified sandstone. Boundary between L4 and L5 is a dashed white line. Solid white line is a lithofacies association boundary. **D)** Bed-scale photo of an L5 swaly cross-stratified bed. Stratification highlighted by white lines. Jacob's staff for scale. **E)** Lithofacies 6 and 7: trough cross-stratified sandstone (L6) and carbonaceous mudstone (L7). Person for scale. **F)** Bed-scale photo of the base of a L6 trough cross-stratified sandstone body. Jacob's staff for scale. See Table 1 for lithofacies details.

Coleman (1981) noted that when a fluvial effluent debouches into a receiving basin, without confinement provided by a subaqueous conduit, its momentum is dissipated by the interaction of the river water with the ambient seawater. The result is deceleration of the effluent and deposition of its sediment load. These processes facilitate the progressive seaward decrease in the concentration and grain size of sediment transported by the effluent.

Lithofacies Association 2: Amalgamated, Thick Sandstone Units and Mudstone Overlain by Thinner Sandstone Units

Description.—Lithofacies Association 2 (LA2) is ~ 50 m thick and consists of nearly equal thicknesses of amalgamated, thick sandstone units separated by mudstone beds (Lithofacies 2 [L2]; Table 1; Figs. 4, 5B, 8) and several-centimeters-thick sandstone units interbedded with

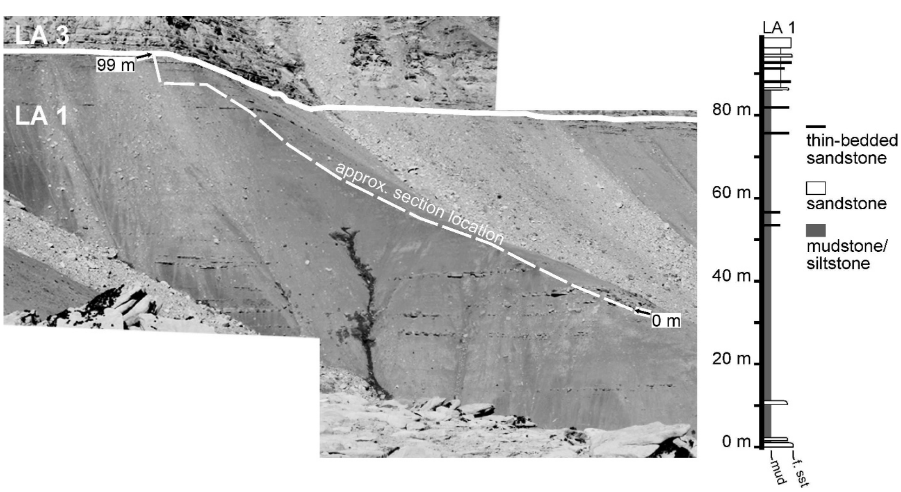

FIG. 7.—Lithofacies Association 1 (LA1): mudstone punctuated by lenticular sandstone bodies (stacks of L1). Left: annotated photo. Section location is identified by an approximately vertical dashed white line. Boundary between LA1 and LA3 is an approximately horizontal bold white line. Right: generalized LA1 section (0 to 99 m in the eastern Escondido section).

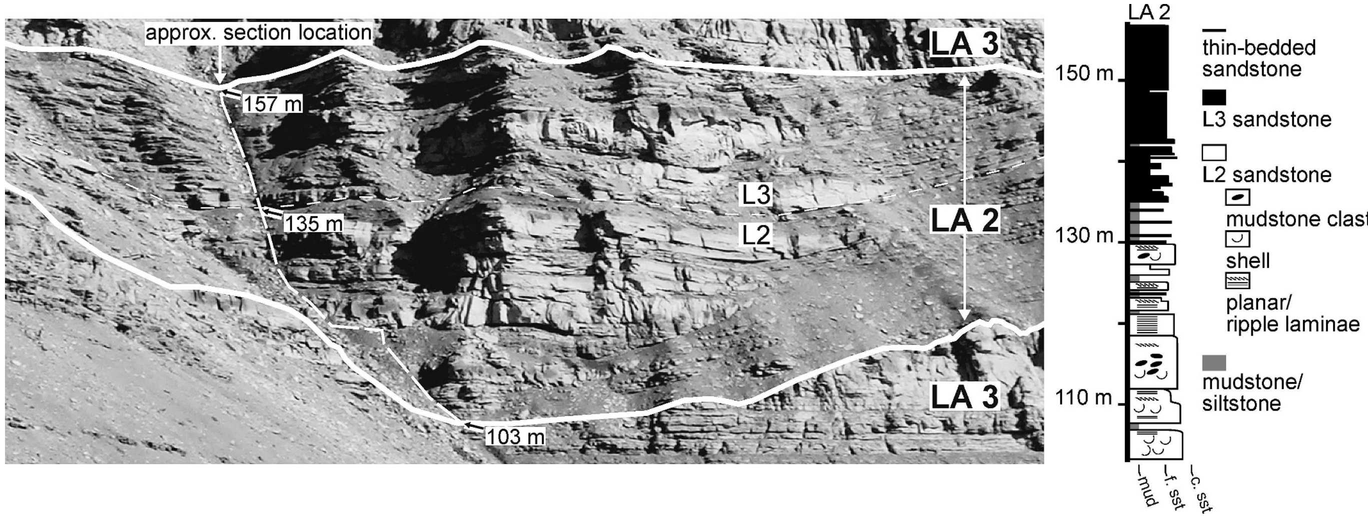

FIG. 8.—Lithofacies Association 2 (LA2): amalgamated, thick sandstone units and mudstone overlain by thinner sandstone units (L2 overlain by L3). Left: annotated photo. Section location is identified by an approximately vertical dashed white line. Boundaries between LA2 and LA3 are approximately horizontal bold white lines. The base of LA2 is an outcrop-wide erosional surface. The top of LA2 is an approximately even, parallel contact defined by the first hummocky cross-stratified sandstone unit of LA3. L2–L3 boundary is an approximately horizontal thin dashed white line. Right: generalized LA2 section (103 to 157 m in the eastern Escondido section).

mudstone laminae or beds (Lithofacies 3 [L3]; Table 1; Figs. 4, 5C, 5D, 8). Association 2 fills prominent scours. The basal ~ 30 m of the association is composed of Lithofacies 2 (Figs. 5B, 8). Amalgamated sedimentation units of Lithofacies 2 are < 12 m thick, well-sorted, massive and normally graded, traction-structured (i.e., planar laminae and local low-angle cross stratification), and composed predominantly of medium-grained sandstone (Figs. 5B, 8). Units include organic detritus and shell fragments, and lack burrows. Intervening mudstone beds are < 5 m thick, and include several-centimeters-thick siltstone and fine- and medium-grained sandstone units (Fig. 8).

The top ~ 20 m of the association is composed of Lithofacies 3 (Figs. 5C, 5D, 8). The transition from lithofacies 2 to 3 is gradational (Figs. 4, 8). Sedimentation units of Lithofacies 3 are poorly sorted, normally graded, locally traction-structured (i.e., planar and wavy laminae) fine- and medium-grained sandstone beds capped by mudstone laminae (Figs. 5C, 5D, 8). Units include organic detritus and lack burrows. Local mudstone beds are < 30 cm thick (Figs. 5C, 5D, 8). Lithofacies 3 includes local amalgamated, meter-thick sandstone units; however, they are less common than in Lithofacies 2 (Fig. 8). The upper few meters of Lithofacies 3 exhibit more wavy laminae, which are similar to the uppermost wavy laminae of Association 1. The base of the association is an outcrop-wide erosional surface, which cuts into hummocky and swaly cross-stratified sandstone of Association 3. The erosional surface and immediately overlying strata do not exhibit

FIG. 9.—Lithofacies Association 3 (LA3): hummocky, overlain by swaly, cross-stratified sandstone (L4 overlain by L5). Left: annotated photo. Section location is identified by an approximately vertical dashed white line. Boundary between LA2 and LA3 is an approximately horizontal bold white line. The contact between LA2 and LA3 is relatively sharp. Boundary between L4 and L5 is an approximately horizontal thin dashed white line. Right: generalized LA3 section (0 to 24 m near the western Escondido section).

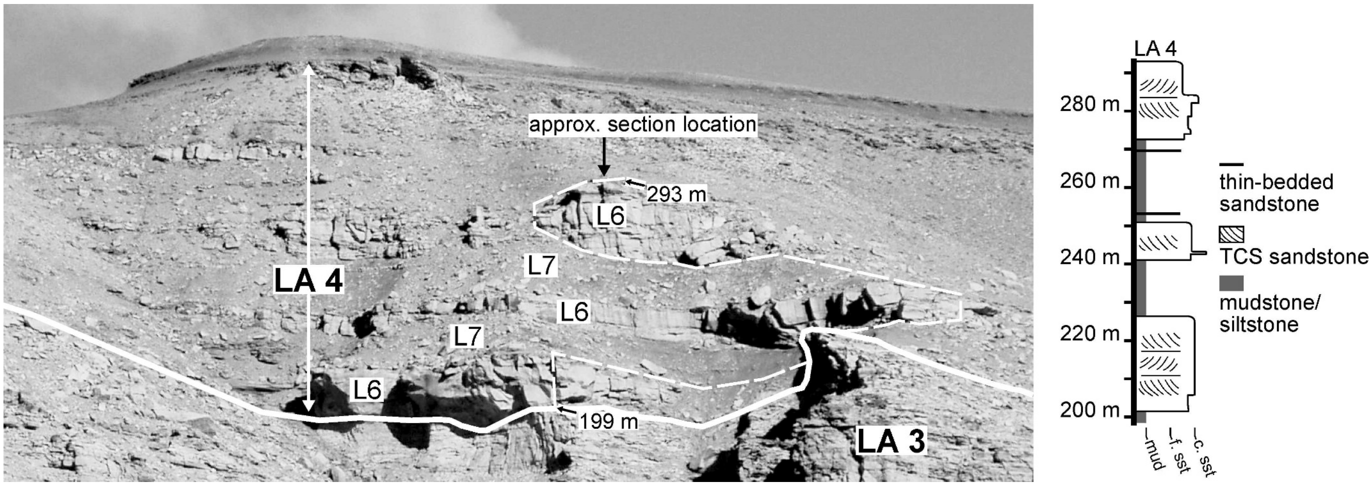

FIG. 10.—Lithofacies Association 4 (LA4): lenticular, trough cross-stratified sandstone bodies encased in carbonaceous mudstone (L6 and L7). Left: annotated photo. Section location is identified by sinuous, vertically climbing dashed white line. Boundary between LA3 and LA4 is an approximately horizontal bold white line. The contact between LA3 and LA4 is an outcrop-wide erosional surface. Right: generalized LA4 section (199 to 293 m in the eastern Escondido section). Trough cross sets of L6 locally exhibit a herringbone-like alternating inclination between beds.

glauconite, paleosols, *Glossifungites* ichnofacies, wave ripples, or relatively coarse-grained lag deposits. The top of the association is an approximately even, parallel contact defined by the first hummocky cross-stratified sandstone unit of Association 3 (Figs. 4, 8).

Depositional Processes and Environment.—Thick, massive divisions of Lithofacies 2 sandstone units reflect deposition as a result of high grain fallout rates from medium-grained high-density turbidity-current suspended loads (Lowe 1982). Scour surfaces, amalgamation, and traction structures reflect ample boundary shear stress imposed on the underlying bed by turbidity currents to erode and rework sediment (Lowe 1982). Mudstone beds likely settled out of suspension from relatively fine-grained buoyant plumes (Stow and Piper 1984; Wright 1977) or were deposited from mud-rich, low-density turbidity currents (cf. mudstone of LA1). Scour-filling, amalgamated, thick sandstone units interbedded with relatively thick mudstone beds reflect punctuated bypass and deposition of large-magnitude turbidity currents during prolonged periods of fine-grained “background” sedimentation in a relatively distal prodelta

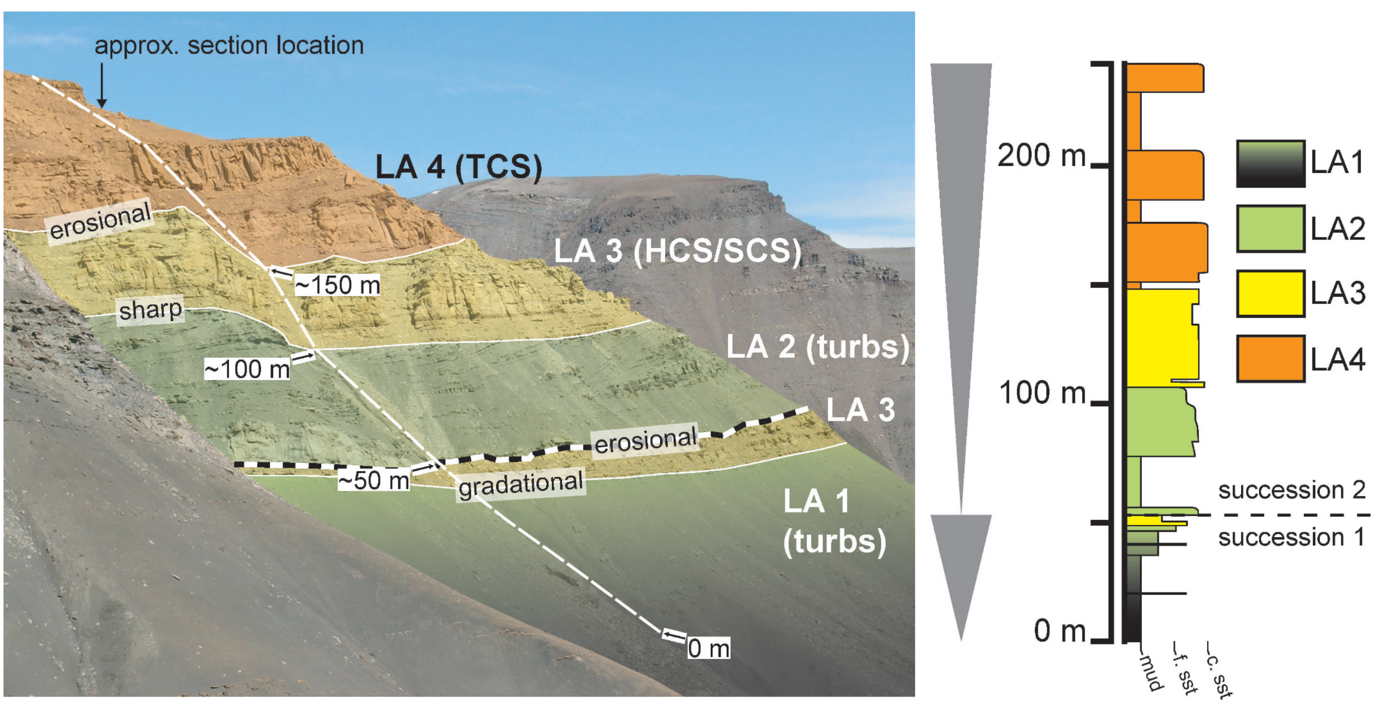

FIG. 11.—Cerro Escondido lithofacies successions. Left: annotated photo. Section location is identified by an approximately vertical dashed white line. Succession boundary is an approximately horizontal dashed black and white line. Lithofacies association boundaries are approximately horizontal thin white lines. The stratigraphic transition from association 1 to 3 in the lower succession is gradational. The top of the lower succession is an outcrop-wide erosional surface. The contact between associations 2 and 3 of the upper succession is relatively sharp. The contact between associations 3 and 4 of the upper succession is an outcrop-wide erosional surface. Right: generalized section (0 to 250 m near the western Escondido section). Upside-down triangles represent upward-shoaling successions 1 and 2.

environment. These large-magnitude turbidity currents were likely efficient at carrying their sediment load basinward (cf. catastrophic turbulent sediment-laden stream flows of flood-dominated river-delta systems discussed by Mutti et al. 1996; Mutti et al. 2003; and Tinterri 2007).

The deposition of relatively thin sandstone units (L3) by low-density turbidity currents is discussed in the interpretation of sandstone bodies of Lithofacies Association 1. Hundreds of relatively poorly sorted, coarse-grained turbidites reflect deposition in a relatively proximal environment, where more frequent, dilute turbidity currents transported and deposited sediment a relatively small distance from the location of initiation. These dilute turbidity currents were relatively inefficient at carrying their sediment load basinward, and reflect processes of flow expansion at a river mouth, followed by rapid gravitational collapse of the sediment load in the absence of substantial traction (cf. normal flood-dominated river-delta processes discussed by Mutti et al. 1996; Mutti et al. 2003; and Tinterri 2007; see also Wright 1977; and Coleman 1981). The prevalence of wavy laminae in the upper few meters of Lithofacies 3 reflects subtle wave- and current-reworking processes (Morton and Suter 1996; Pattison 2005; Lamb et al. 2008). The paucity of burrows in Association 2 indicates that conditions were not hospitable for bottom-dwelling organisms, which is consistent with prodelta flood deposits of the Cretaceous Western Interior Seaway of North America (Bhattacharya and MacEachern 2008).

Association 2 stratigraphic stacking reflects a basinward advance of depositional environments from a relatively distal to proximal prodelta environment (Bhattacharya and Walker 1992). General delta facies models show little evidence of significant sand deposition in prodelta environments (e.g., Bhattacharya and Walker 1992; and references therein). Notwithstanding, seismic-reflection- and limited drill-core- and wireline-log-based studies of Pliocene Mississippi deltas showed that mass-wasting processes created local pockets of accommodation at the shelf edge and upper slope in which very fine- and fine-grained sandstone prodelta turbidites accumulated (Mayall et al. 1992). However, fine-scale details of subsurface Mississippi prodelta turbidite architecture in two or three dimensions are not available and there are few outcrop analogs for prodelta constituents of large-scale deltas and continental margins. Cerro Escondido outcrops provide a unique, two-dimensional perspective of the fine-scale details of relatively coarse-grained prodelta deposits analogous to deltas associated with continental margins.

Lithofacies Association 3: Hummocky, Overlain by Swaly, Cross-Stratified Sandstone

Description.—Lithofacies Association 3 (LA3) is < 45 m thick and consists of interbedded hummocky cross-stratified sandstone units (Lithofacies 4 [L4]; Table 1; Figs. 4, 6A, 6B, 9) overlain by amalgamated swaly cross-stratified sandstone units (Lithofacies 5 [L5]; Table 1; Figs. 4, 6C, 6D, 9). The basal < 10 m of the association is composed of Lithofacies 4 (Figs. 4, 6A, 6B, 9). Hummocky cross-stratified units of lithofacies 4 are < 1 m thick, and composed of fine- to medium-grained sandstone (Figs. 6A, 6B, 9). Units locally exhibit wavy-laminated tops and are progressively more amalgamated up section (Figs. 6A, 6B, 9). Hummocky units are interbedded with several-centimeters-thick, normally graded, locally traction-structured (i.e., planar and wavy laminae) fine- to medium-grained sandstone units (Figs. 6A, 6B, 9). These thin sandstone interbeds are locally bioturbated.

The top ~ 20 to 35 m of the association is composed of Lithofacies 5 (Figs. 4, 6C, 6D, 9). The transition from lithofacies 4 to 5 is gradational (Figs. 4, 9). Amalgamated swaly cross-stratified units of Lithofacies 5 are < 10 m thick, and composed of fine- to medium-grained sandstone (Figs. 6C, 6D, 9). Hummocky and relatively flat stratification are also present. Swaly units include organic detritus and local shell fragments. The base of the association is an approximately even, parallel contact defined by the base of the first hummocky cross-stratified sandstone unit overlying association 1 or 2. The top of the association is an erosional surface overlain by association 2 or 4 (Figs. 4, 9).

Depositional Processes and Environment.—Hummocky cross stratification reflects deposition as a result of large-scale oscillatory currents associated with storm waves (Harms et al. 1975; Dott and Bourgeois 1982; Southard et al. 1990). Hummocky cross stratification typically develops in water shallow enough for wave orbits to become large and fast, but deep enough for waves to remain symmetrical and unidirectional currents weak (Dott and Bourgeois 1982; Dumas and Arnott 2006). Local wavy-laminated tops of hummocky cross-stratified units reflect waning of storm waves (Dott and Bourgeois 1982). Thin, normally graded, bioturbated interbeds are likely turbidites (cf. explanations of thin-bedded turbidite deposition in interpretations of LA1 and LA2; see also Pattison 2005; and Lamb et al. 2008). Preservation of turbidites between hummocky cross-stratified units is likely a result of the punctuated occurrences of the storms that generated the hummocky units (cf. Wheatcroft 2000; Shanmugam 2008).

Swaly cross stratification reflects deposition as a result of combined oscillatory and unidirectional currents (Walker and Plint 1992; Dumas and Arnott 2006). Amalgamated swaly cross-stratified units develop in shallower, more agitated environments relative to hummocky units, where unidirectional currents are stronger (Walker and Plint 1992; Dumas and Arnott 2006). Organic detritus and local shell fragments might have been transported offshore by strong unidirectional currents (e.g., storm-generated, tidal, rip, fluvial, or turbidity currents).

The transition from interbedded hummocky units to amalgamated swaly units reflects a basinward advance of depositional environments from a relatively distal delta-front, or lower shoreface, to more proximal delta-front, or shoreface, environment (Leckie and Walker 1982; Bhattacharya and Walker 1991; Walker and Plint 1992). The maximum thickness (45 m) of Lithofacies Association 3 is one and a half times greater than the maximum thickness of comparable sandstones of the Cretaceous Western Interior Seaway of North America, where they are important analogs for hydrocarbon reservoirs (Walker and Plint 1992; and references therein). Thicker sections of shoreface sandstones were recognized in the larger-scale Pliocene to Pleistocene Orinoco Delta of the Columbus Basin, offshore Trinidad. Their significant thicknesses were attributed to accentuated reworking of rapidly deposited deltaic sediment at the shelf edge by large waves from an open ocean (Wood 2000; Sydow et al. 2003; see also Cummings and Arnott 2005; and Uroza and Steel 2008). Association 3 thickness also reflects enhanced wave reworking of voluminous unconsolidated sediment.

Lithofacies Association 4: Lenticular, Trough Cross-Stratified Sandstone Bodies Encased in Carbonaceous Mudstone

Description.—Lithofacies Association 4 (LA4) is ~ 100 m thick and consists of nearly equal thicknesses of trough cross-stratified sandstone (i.e., Lithofacies 6 [L6]; Table 1; Figs. 4, 6E, 6F, 10) and carbonaceous mudstone (i.e., Lithofacies 7 [L7]; Table 1; Figs. 4, 6E, 10). Trough cross-stratified lithofacies are organized into < 25-m-thick lenticular sandstone bodies, which are composed predominantly of coarse-grained sandstone (Figs. 6E, 6F, 10). The bases of sandstone bodies are scours overlain by local outsized granules and pebbles organized into trough cross sets. Sandstone bodies include abundant organic detritus. The basal sandstone in the eastern Escondido section exhibits *Skolithos* and *Diplocraterion* trace fossils.

Carbonaceous mudstone lithofacies are < 25 m thick and include local several-centimeters-thick, traction-structured (i.e., planar and ripple laminae) siltstone and very fine- to coarse-grained sandstone units

(Figs. 6E, 6F, 10). Peat is present, with local coal material. There are no systematic grain-size trends up section. The base of the association is an outcrop-wide erosional surface, which cuts into hummocky and swaly cross-stratified sandstone of Association 3 (Figs. 4, 10). There are no other outcrop-wide surfaces recognized within the association.

Depositional Processes and Environment.—Thick, lenticular trough cross-stratified sandstone bodies reflect deposition as a result of migration of dunes along and across channels as bed load. *Skolithos* and *Diplocraterion* trace fossils are characteristic of energetic and oxygenated shallow-marine environments (Pemberton et al. 1992). Thick, carbonaceous mudstone lithofacies with local coarser-grained units reflect prolonged, steady deposition of suspended, fine-grained sediment and organic material with punctuated deposition from coarser-grained currents. Lithofacies Association 4 reflects deposition in a subaqueous delta-plain environment (Coleman 1981), where lenticular sandstone bodies compose the fill of distributary channels and carbonaceous mudstone composes the overbank interdistributary regions (Coleman 1969; Miall 1981). The measured thicknesses of Association 4 and distributary-channel-fill Lithofacies 6 are larger than thicknesses advocated in general delta models (e.g., Bhattacharya and Walker 1992; and references therein). However, the maximum thickness and architecture of Association 4 are similar to delta-plain deposits of the Cretaceous Upper Ferron Sandstone Member of the Mancos Shale of the Western Interior Seaway, Utah (Gardner 1993; Moiola et al. 2004). Ferron delta-plain maximum thickness (i.e., ~ 100 m) was attributed to a high rate of sediment supply (Gardner 1993; Moiola et al. 2004). Association 4 thickness also reflects voluminous sediment supply from nearby hinterland source areas (Macellari et al. 1989; Shultz et al. 2005; Romans 2008; Romans et al. 2008b; Fildani et al. in press a); however, differences in basin and stratigraphic settings between the Western Interior epicontinental seaway and the larger-scale Dorotea–Tres Pasos shelf-and-slope system in the Magallanes Basin preclude meaningful comparison of subaqueous delta-plain deposits and their generation mechanisms.

The basal outcrop-wide erosional surface might be an incised valley, which, according to Zaitlin et al. (1994), is a "fluvially eroded, elongate topographic low that is typically larger than a single channel form, and is characterized by an abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at its base" (see also Dalrymple et al. 1994). The erosional character of the basal surface of Association 4 and the juxtaposition of relatively proximal marine distributary-channel and interdistributary deposits over distal delta-front, or shoreface, deposits of Association 3 support this interpretation. Reynolds (1999) also noted that incised-valley fill can be as much as 152 m thick, which is similar to the thickness of Association 4. However, incised-valley formation is commonly attributed to a relative fall of sea level (Van Wagoner et al. 1990), and the limited depositional-strike perspective at Cerro Escondido prevents rigorous assessment of sea-level fluctuations during delta development. Also, Zaitlin et al. (1994) noted that "depositional markers within the deposits of the incised-valley fill will onlap the valley walls"; however, the relatively small outcrop does not clearly exhibit this relationship.

Lithofacies Successions

Strata at Cerro Escondido are organized into two stacked, generally upward-coarsening lithofacies successions (each < 200 m thick; Figs. 4, 11). The lower succession is ~ 100 m thick in the eastern Escondido section (Fig. 4). It includes mudstone of Lithofacies Association 1 overlain by interbedded hummocky cross-stratified sandstone of Association 3. The stratigraphic transition from association 1 to 3 is gradational. The top of the succession is an outcrop-wide erosional surface that truncates hummocky and swaly cross-stratified sandstone of Association 3 (Figs. 4, 11). The erosional surface exhibits up to tens of meters of erosional relief (Fig. 4).

The upper succession overlies the outcrop-wide erosional surface (Figs. 4, 11). It is nearly 200 m thick, and includes sandstone of Lithofacies Association 2 overlain by hummocky and swaly cross-stratified sandstone of Association 3. The contact between associations 2 and 3 is relatively sharp (Figs. 9, 11). The top of the succession is trough cross-stratified sandstone bodies encased in carbonaceous mudstone of Association 4. The contact between associations 3 and 4 is an outcrop-wide erosional surface (Figs. 4, 10, 11).

Interpretation of Lithofacies Successions

The thick lithofacies successions, each < 200 m, record two episodes of progradation of the Dorotea delta system (Fig. 3). Progradation is indicated by upward shoaling of lithofacies associations within successions. The lower succession reflects the transition from a relatively distal prodelta, or upper-slope, environment (represented by LA1) to a proximal delta-front, or shoreface, environment (LA3). The upper succession reflects the transition from a prodelta (LA2) to delta-front, or shoreface, (LA3) to subaqueous delta-plain environment (LA4; Figs. 4, 11). The distinctly different prodelta lithofacies associations 1 and 2 reflect the absence and presence, respectively, of a local pocket of accommodation in which relatively coarse-grained turbidites were deposited, and which might have served as a sediment conduit across the shelf and slope to deeper water. During deposition of the lower succession, no local pocket existed at Cerro Escondido and thick mudstone lithofacies with local, lenticular sandstone bodies were deposited away from the focus of deltaic sedimentation (LA1; Figs. 4, 7). During deposition of the upper succession, local accommodation existed through which sediment gravity flows transported larger volumes of coarser-grained sediment, and created prominent scours in which amalgamated turbidites were deposited (LA2; Figs. 4, 8).

The outcrop-wide erosional surface that separates lithofacies successions is comparable to a flooding surface as defined by Van Wagoner et al. (1990) because it separates younger from older strata above which there is evidence of an abrupt increase in water depth and a landward retreat of depositional environments: hummocky and swaly cross-stratified sandstone of Association 3, which was deposited in a relatively proximal delta-front, or shoreface, environment, is truncated and overlain by Association 2 turbidites, which were deposited in a distal prodelta environment (Fig. 4). The erosional surface and overlying strata do not exhibit direct or indirect evidence of subaerial exposure or shoreline regression (see description of LA2). For examples of evidence of shoreline regression see Posamentier et al. (1992) and Posamentier and Allen (1999).

We interpret that the erosional surface above which the upper lithofacies succession accumulated was created as a result of mass-wasting processes of a delta front in a shelf-edge position. Mass-wasting processes associated with the unstable Dorotea–Tres Pasos shelf-and-slope system have been interpreted by Shultz et al. (2005), Romans et al. (2008b), and Armitage et al. (2009). Passive margins associated with rapid and voluminous deltaic sedimentation also exhibit major erosional features (Porębski and Steel 2003; Lee et al. 1993). Winker and Edwards (1983) suggested that unstable progradational clastic shelf margins, including the Neogene Mississippi and Niger deltas, are dominated by large-scale erosional features that disturb the topset-to-foreset geometry of the margin (see also Shepard 1955; Coleman et al. 1974; Lindsay et al. 1984; Bouma et al. 1991; and Porębski and Steel 2003). McAdoo et al. (2000) documented up to 27% of selected areas of the Gulf of Mexico slope are covered by landslide deposits that failed from headscarps exhibiting tens to hundreds of meters of erosional relief. The late Pleistocene Mississippi Delta exhibits extremely large failure scars up to

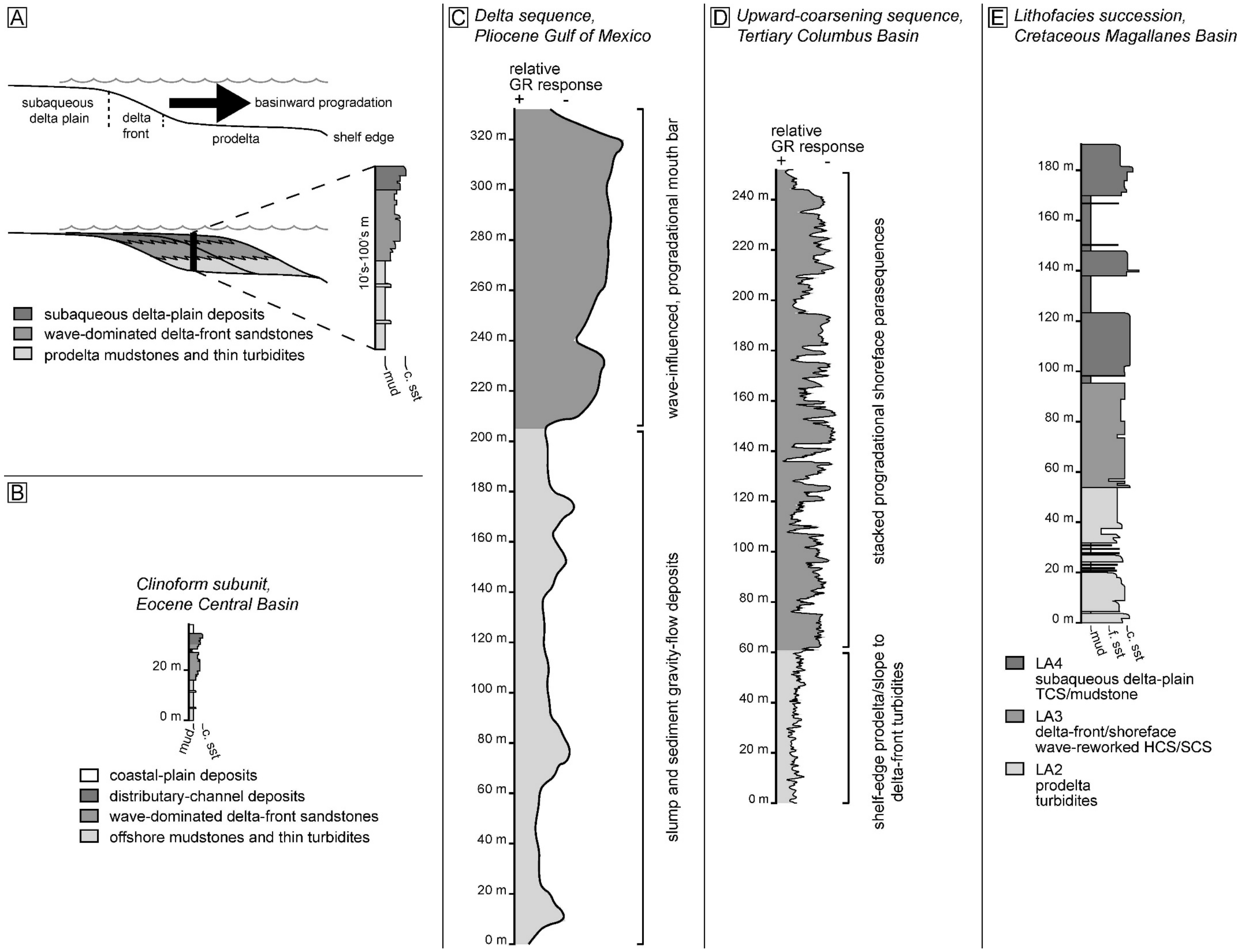

FIG. 12.— Upward-shoaling shelf-edge deposits. **A)** Generalized cross section of delta-plain, delta-front, and prodelta environments (above) and stratigraphic architecture as a result of basinward progradation (below). Generalized section is to the right. Modified from Berg (1982) and Bridge and Demicco (2008). **B)** Grain-size profile of Clinoform 17 subunit 1 of the Eocene Battfjellet Formation of the Central Basin, Spitsbergen. Modified from Uroza and Steel (2008). **C)** Gamma-ray log of a Pliocene Mississippi shelf-edge delta of the Gulf of Mexico. Modified from Mayall et al. (1992). **D)** Gamma-ray log of an upward-coarsening sequence of the Tertiary Orinoco Delta of the Columbus Basin, offshore eastern Trinidad. Modified from Sydow et al. (2003). **E)** Generalized grain-size profile of upper lithofacies succession from the eastern Escondido section (this study).

tens of thousands of square kilometers in area, which can be filled with progradational deposits comparable to stratigraphic architecture at Cerro Escondido (Coleman et al. 1983). Mayall et al. (1992) noted that the higher angle of slope on Neogene shelf-edge deltas of the Gulf of Mexico might result in an almost constant state of sediment instability of the uppermost delta slope (see also Suter and Berryhill 1985). This instability can instigate mass-wasting processes, which create pockets of accommodation at the shelf edge and upper slope in which relatively coarse-grained turbidites can accumulate (Mayall et al. 1992; Porębski and Steel 2003).

The Dorotea delta system at Cerro Escondido is interpreted to have been deposited at or near the shelf edge. Deposition at this location is reflected by the relatively thick lithofacies successions overlying hundreds of meters of mudstone-rich slope deposits of the Tres Pasos Formation (Ingersoll and Graham 1983; Cummings and Arnott 2005; Romans et al. 2008b; Uroza and Steel 2008) (Fig. 3). The presence of scour surfaces and sediment-gravity-flow deposits of Association 2 indicates relatively steep gradients associated with a shelf-edge location (Porębski and Steel 2003; Cummings and Arnott 2005) (Fig. 8). A shelf-edge location is also reflected by the relatively thick sections of wave-reworked hummocky and swaly cross-stratified sandstone (LA3; Porębski and Steel 2003; Cummings and Arnott 2005; Uroza and Steel 2008) (Fig. 9). The scale of the shelf-and-slope clinoform in the Magallanes foredeep (i.e., as great as two kilometers deep) (Fig. 3) prevents a continuous depositional-dip perspective of the Late Cretaceous paleoshelf, slope, and basin plain. This limitation hinders precise identification of the shelf edge and rigorous assessment of sea-level fluctuations during delta development (Steel et al. 2000); however, the Cerro Escondido outcrop provides unique insight into the fine-scale stratigraphic architecture of a relatively large, progradational shelf-edge delta.

DISCUSSION

Comparison to Shelf-Edge Delta Stratigraphic Architectures

Progradational shelf-edge deltas are composed of upward-shoaling deposits, which include delta-plain, delta-front, and prodelta constituents (Fig. 12A). However, the fine-scale stratigraphic architecture and development of shelf-edge deltas and their constituents vary between: (1) relatively stable, small-scale shelf-and-slope systems similar to the Eocene strata outcropping on Spitsbergen; (2) unstable, larger-scale passive margins imaged in seismic-reflection and limited drill-core and wireline-log datasets; and (3) the Dorotea–Tres Pasos shelf-and-slope system of the Late Cretaceous Magallanes Basin of this study (Winker and Edwards 1983; Porębski and Steel 2003) (Fig. 12). Eocene outcrops on Spitsbergen reflect progradation of a small-scale shelf-and-slope system (100 to 350 m clinoform relief; Plink-Björklund et al. 2001) into a foreland or piggyback basin underlain by continental crust of normal thickness (Steel et al. 1985; Blythe and Kleinspehn 1998). Relatively meager volumes of sediment were interpreted as having been supplied from ephemeral mountain streams draining an actively uplifting fold-and-thrust belt (Plink-Björklund et al. 2001; Petter and Steel 2006). Regressive shelf-edge deltaic units from Spitsbergen are several meters to tens of meters thick and generally comprise prodelta mudstones and thin turbidites, overlain by wave-influenced delta-front sandstones, and capped with distributary-channel deposits (Mellere et al. 2002; Plink-Björklund and Steel 2005; Uroza and Steel 2008) (Fig. 12B). The depositional-dip perspective of outcropping shelf-edge deposits on Spitsbergen exhibits a physical connection between distributary-channel deposits and delta-front and prodelta deposits, and a paucity of evidence for major delta collapse and slumping (Plink-Björklund et al. 2001; Mellere et al. 2002).

The Neogene Mississippi and Orinoco river-delta systems fed relatively unstable continental margins with kilometer-scale shelf-to-basin-floor clinoform relief (Winker and Edwards 1983; Wood 2000; Sydow et al. 2003). The rivers transported large volumes of sediment thousands of kilometers from continental interiors and mountain belts to enormous ocean basins (i.e., the Gulf of Mexico and Central Basin, offshore Trinidad; Coleman 1981; Coleman et al. 1983; Winker and Edwards 1983; Wood 2000). Rapid and voluminous deltaic sedimentation resulted in high subsidence rates and common mass wasting at the shelf edge (Coleman et al. 1983; Winker and Edwards 1983; Mayall et al. 1992; Wood 2000; Sydow et al. 2003). Waves reaching the shelves across ocean basins accentuated reworking of deltaic sediment and initiated mass wasting (Wood 2000; Sydow et al. 2003; Shanmugam 2008). These circumstances resulted in sedimentary processes that facilitated the development of distinctively different shelf-edge stratigraphic architecture relative to the Spitsbergen deposits. Hundreds-of-meters-thick Pliocene Mississippi shelf-edge deltas include fluvial- and wave-influenced delta-plain and delta-front deposits, which overlie prodelta sediment-gravity-flow deposits in evacuated pockets of accommodation (Mayall et al. 1992) (Fig. 12C). Wood (2000) and Sydow et al. (2003) documented upward-shoaling deposits up to 300 m thick of the Pliocene to Pleistocene Orinoco shelf-edge delta. The deposits comprise prodelta, or upper-slope, mudstone turbidites overlain by thick sections of relatively coarse-grained wave-reworked shoreface deposits (Sydow et al. 2003) (Fig. 12D).

Inherited tectonic relief and crustal thinning from the predecessor Rocas Verdes back-arc basin contributed to a Magallanes Basin shelf-to-basin-floor profile comparable in bathymetric relief to large-scale continental margins during Late Cretaceous deposition of the Tres Pasos and Dorotea formations. The unstable Dorotea–Tres Pasos shelf-and-slope system received a relatively large volume of sediment from nearby hinterland source areas (Macellari et al. 1989; Shultz et al. 2005; Romans 2008; Romans et al. 2008b; Armitage et al. 2009; Fildani et al. in press a). These characteristics of the Dorotea–Tres Pasos shelf-and-slope system and Late Cretaceous Magallanes Basin contributed to the unique stratigraphic architecture at Cerro Escondido (Fig. 12E). However, shelf-edge stratigraphic architecture at Cerro Escondido shares some characteristics of upward-shoaling deposits of the Neogene Mississippi and Orinoco shelf-edge deltas, which were influenced by conditions inherent to relatively unstable continental margins that filled enormous ocean basins: (1) upward-shoaling shelf-edge deposits of all three settings are hundreds of meters thick; (2) all three shelf-and-slope systems exhibit evidence of mass wasting; (3) Pliocene Mississippi and Cerro Escondido prodelta deposits include stacks of turbidites in local accommodation from erosional surfaces, although, Cerro Escondido turbidites are coarser grained (Mayall et al. 1992); and (4) Pliocene to Pleistocene Orinoco and Cerro Escondido delta-front, or shoreface, sandstone sections are exceptionally thick (Wood 2000; Sydow et al. 2003) (Fig. 12). Subaqueous delta-plain deposits (LA4) and their distributary-channel-fill constituents (L6) at Cerro Escondido are thicker than comparable deposits in either the Eocene Spitsbergen outcrops or the Neogene Mississippi or Orinoco subsurface deltas, which reflects enhanced fluvial sediment supply from nearby hinterland source areas (Fig. 12).

CONCLUSIONS

Subsurface shelf-edge deltas from passive margins have been extensively studied with seismic-reflection data, and only recently have outcrop analogs been documented. However, subsurface studies of large-scale continental margins commonly lack fine-scale details of shelf-edge deposits, and outcrop analogs are predominantly from foreland or piggyback basins underlain by continental crust of normal thickness and filled by relatively small-scale shelf-and-slope systems. Outcrops of the unstable, larger-scale Dorotea–Tres Pasos shelf-and-slope system in the Late Cretaceous Magallanes Basin provide unique insights into shelf-edge stratigraphic architecture and development, which can be applied to models of progradation of continental margins:

1. Existing deltaic facies models show little evidence of significant sand deposition in prodelta environments (e.g., Bhattacharya and Walker 1992; and references therein); however, local accommodation from an erosional surface positioned at the shelf edge, likely created as a result of mass wasting, facilitated the accumulation and preservation of an appreciable thickness of sandstone-rich prodelta turbidites (LA2). The observed turbidite stacking pattern records the increased occurrence of relatively frequent and dilute turbidity currents, such as might have been debouched from a river mouth, and is thus a signal of progradation.
2. The maximum thickness (45 m) of delta-front, or shoreface, sandstones (LA3) is one and a half times greater than the maximum thickness of comparable sandstones of the Cretaceous Western Interior Seaway of North America, where they are important analogs for hydrocarbon reservoirs (Walker and Plint 1992; and references therein). Similar to thicker sections of shoreface sandstones of the Pliocene to Pleistocene Orinoco Delta, Lithofacies Association 3 reflects enhanced wave reworking of voluminous deltaic sediment at the shelf edge.
3. The measured thicknesses of subaqueous delta-plain deposits (LA4) and distributary-channel-fill Lithofacies 6 are larger than thicknesses documented in many other studies of deltaic systems (e.g., Bhattacharya and Walker 1992; and references therein), which reflects enhanced fluvial sediment supply from nearby hinterland source areas.
4. Shelf-edge stratigraphic architecture at Cerro Escondido shares some characteristics of upward-shoaling deposits of Neogene Mississippi and Orinoco shelf-edge deltas, which are influenced by conditions inherent to relatively unstable continental margins that fill enormous ocean basins. However, successions at Cerro Escondido include coarser-grained, thicker subaqueous delta-plain deposits, and coarser-grained prodelta turbidites in evacuated pockets of accommodation. Proximity of the Magallanes foredeep to hinterland source areas also contributed to this unique stratigraphic architecture.

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