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HIGH-RELIEF SLOPE CLINOFORM DEVELOPMENT: INSIGHTS FROM OUTCROP, MAGALLANES BASIN, CHILE

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ABSTRACT: The Cretaceous–Paleogene Tres Pasos and Dorotea formations of the Magallanes Basin, Chile record the filling of a deep-water foreland setting. Slope clinoforms with at least 700–900 m relief (compacted) prograded southward along the foredeep axis, which was oriented parallel to the adjacent Patagonian Andes. Fluvial- and wave-influenced deltaic deposits of the Dorotea Formation represent the upper, flat portions of the sigmoidal slope profiles. The paleo-shelf edge is estimated where shelf sandstones pinch-out basinward. Mudstone, siltstone, and a notable paucity of sandstone characterize upper slope strata. Further down-slope, conduits are evidenced by sedimentary bodies associated with cross-stratified or normally graded sandy conglomerate and local mudstone rip-up clasts, interpreted to indicate that considerable sediment bypassed the slope. Turbiditic sandstones and mass-transport deposits of the Tres Pasos Formation characterize the lower to base of slope setting.

Numerous examples of slope clinoforms have been recognized in the rock record, with the majority characterized by 200–500 m of estimated paleo-relief. Higher relief examples include those mapped in outcrop from the Magallanes Basin documented here, and comparable clinoforms from the subsurface Cretaceous Brookian succession of the North Slope, Alaska. In the Magallanes Basin, numerous factors contributed to the development of high-relief clinoforms, including generation of substantial basin margin relief, the absence of mobile substrata, adequate sediment supply, and the elongate basin shape. The slope that built and maintained the relatively smooth clinoform profile was narrow, and thus, sediment that was transported across the shelf was focused as it passed into deeper water. In general, the development of slope clinoforms, including high-relief examples like those of the Magallanes Basin, is facilitated when the rate of sediment input onto the slope is higher than the rate at which rugose slope topography is generated from mass wasting or substrata remobilization.

INTRODUCTION

Understanding depositional processes on continental slopes and the stratigraphic architecture of slope deposits has been facilitated, in part, by exploration for hydrocarbons (e.g., Hedberg 1970; Payton 1977; Ross et al. 1994; Prather et al. 1998; Beaubouef and Friedman 2000; Mayall et al. 2006). Advances in data acquisition have improved our ability to resolve the morphology and preserved architecture in slope systems, including seismic-reflection surveying (e.g., Kolla et al. 2001; Posamentier and Kolla 2003; Saller et al. 2004) and a variety of techniques developed to sample and image the modern seafloor with increasingly optimized resolution (e.g., Smith et al. 2005; Paull et al. 2005; Normark et al. 2009).

Clinoform geometry is common to strata of numerous depositional settings (Mitchum et al. 1977) and has perhaps been most frequently recognized in deltaic deposits (Fig. 1; e.g., Berg 1982; Alexander et al. 1991; Pirmez et al. 1998). Distinctive from delta-front features are clinoforms with hundreds to thousands of meters relief that are formed on continental margins (e.g., Uchupi and Emery 1967; Steckler et al. 1999; Walford et al. 2005; Xie et al. 2008) and observed in ancient slope strata (e.g., McMillen 1991; Pinous et al. 2001; Bullimore et al. 2005; Carvajal and Steel 2006; Pyles and Slatt 2007; Houseknecht et al. 2009). These high-relief clinoforms have been called "shelf-margin clinoforms" (Steel et al. 2000) and we refer to them as slope clinoforms herein (Fig. 1). Although Rich (1951) defined a clinoform as only the steep foreset slope portion of a sigmoidal surface, more recent studies have utilized the term to describe the entire sigmoidal surface including the relatively shallowly dipping topset and bottomset.

Insight about the geometry and architecture of slope sedimentary bodies from high-resolution seismic-reflection data has fostered the reinterpretation of high-quality outcrops around the globe. Features such as sinuous channels, levee complexes, ponded slope fans and mass-transport deposits are now commonly interpreted from successions of outcropping slope deposits (e.g., Abreu et al. 2003; Gardner et al. 2003; Martinsen et al. 2003; Shultz and Hubbard 2005; Pyles 2008).

Large-scale features such as slope clinoforms have proved to be more difficult to recognize in outcrop, despite exceptional preservation in numerous subsurface datasets. This largely originates from the scale of the features and their primarily fine-grained composition. Exceptions include slope clinothem complexes of the Eocene of Spitsbergen (~ 300 m relief; Helland-Hansen 1992; Steel et al. 2000) and the Eocene of the Ainsa Basin, Spain (~ 300 m relief; Dreyer et al. 1999), amongst others. Much larger slope systems have been inferred from limited outcrop exposures, based largely on the stratigraphic distribution of sandstone-dominated sedimentary bodies and vertical changes in gravity-flow deposit character (e.g., Schwarz and Arnott 2007; Romans et al. 2009). For the purpose of this study, we arbitrarily define the cut-off between high- and low-relief slope clinoforms to be 500 m. Most

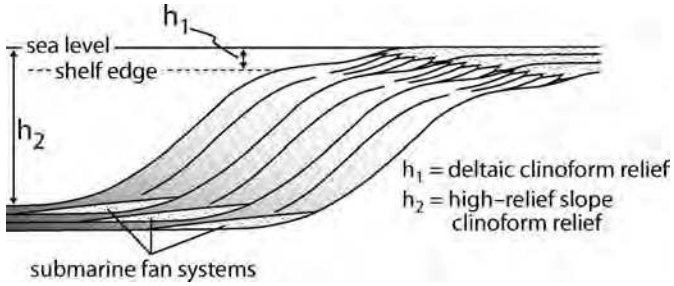

FIG. 1.—Differentiation of deltaic and high-relief slope clinoforms in this study. Deltaic clinoforms are largely constructed landward of the shelf break whereas slope clinoforms represent margin growth into bathyal water depths. As a result, slope clinoforms are characterized by much higher relief than deltaic clinoforms. The height of h_1 is typically < 100 m whereas h_2 can be > 2000 m high.

documented examples of slope clinoforms are characterized by < 500 m relief (not accounting for compaction in ancient examples), whereas the examples documented in this study have > 700 m of interpreted relief.

When identified in outcrop, slope clinoforms constitute an important opportunity to examine and deduce sedimentary processes in the context of a significant portion of an ancient basin margin. Consequently, much of our understanding of these features comes from extensive examination of the Eocene of Spitsbergen (e.g., Plink-Björklund et al. 2001; Johannessen and Steel 2005). The relief on Spitsbergen slope clinoforms ranges from 100–300 m (Plink-Björklund et al. 2001), largely controlled by accommodation in the piggy-back or small foredeep setting in which they were constructed (Blythe and Kleinspehn 1978; Steel et al. 1985). High-relief clinoforms and their associated strata are less well defined and understood (Donovan 2003; Houseknecht et al. 2009). In this paper, we demonstrate complex stratigraphic architecture in the outcropping Cretaceous–Paleogene Tres Pasos and Dorotea formations (Magallanes Basin, Chile) that resulted from multiple phases of sediment bypass and accumulation in a basin with initial shelf to base-of-slope relief of at least 700–900 m. The objectives of this study are to characterize the stratigraphic architecture of shelf to base of slope relief in Magallanes Basin strata, document variation in facies along a high-relief clinoform in the context of the depositional system, and provide insight on the controlling factors for high-relief slope clinoform development. Characterization of the seismic-scale outcrop with detailed facies analysis provides insight into the controls on the evolution of dynamic margins across which sediments are transported and distributed, and contributes to the refinement of hydrocarbon exploration and development models for the slope setting.

Tres Pasos and Dorotea Formations

The Tres Pasos Formation is part of a 5–6 km thick succession of sediment gravity-flow-dominated units deposited in the Magallanes retroarc foreland basin, which formed in response to the development of the Andean fold-thrust belt in southern South America (Fig. 2; Katz 1963). The elongate basin filled axially from the north, with sediment dispersal parallel to the adjacent fold-thrust belt (Smith 1977; Macellari et al. 1989; Shultz et al. 2005). The Tres Pasos Formation is ca. 1500–2000 m thick, and records upwards shallowing from basinal deposits of the underlying Cerro Toro Formation (1000–2000 m water depth; Natland et al. 1974) into shallow-marine and marginal-marine deposits of the overlying Dorotea Formation (Fig. 2; Macellari et al. 1989; Covault et al. 2009).

The Tres Pasos Formation is exposed in the Andean foothills along a $>$ 100 km north–south oriented, eastward-dipping outcrop belt in the Ultima Esperanza District of Chile (Fig. 2). The formation was first described as a suprafan lobe (cf. Normark 1970) in the region of Laguna Figueroa (Fig. 2 for location; Smith 1977), and eventually as a complex slope depositional system over its entire regional extent by Shultz et al. (2005). The formation exposure is discontinuous, related to glacial erosion of the Patagonian landscape. Following reconnaissance mapping and initial sedimentological analysis by Shultz et al. (2005), Shultz and Hubbard (2005) documented slope minibasin fill at El Chingue Bluff, located at the northern end of the area of interest for this study (Fig. 3). Romans et al. (2009) characterized tabular and channel depositional elements at Cerro Divisadero, which exhibits the northernmost, and most proximal, outcrops of the formation (Fig. 2). Armitage et al. (2009) have further examined complex mass-transport and turbidite interstratification at Sierra Contreras, a mountain located between El Chingue Bluff and Cerro Divisidero (Fig. 2). The upper part of the slope system and the overlying shallow-marine strata of the Dorotea Formation are difficult to access; Macellari et al. (1989) loosely characterized the Dorotea Formation at Sierra Dorotea as shallow marine, genetically linking it with underlying fine-grained slope deposits of the Tres Pasos Formation. At Cerro Escondido (Fig. 2), Covault et al. (2009) described and interpreted a large-scale shelf-edge delta complex with evidence for slope instability, including extensive mass wasting.

This study focuses on the southern end of Cerro Cazador, Cerro Sol, and Sierra Dorotea as far south as Chorillo Tres Pasos (Figs. 2, 3). The area has been assessed by Smith (1977) and Shultz et al. (2005), but never in a significant amount of detail. Each of these studies has focused on the thick ($\sim$ 350 m) sandstone succession locally preserved near the lithostratigraphic base of the Tres Pasos Formation. In contrast, the focus of this paper is the genetic stratigraphic delineation of the full slope succession, incorporating the entire Tres Pasos Formation and the overlying, prominent sandstone ridges of the Dorotea Formation (Fig. 3).

METHODOLOGY

The dataset was acquired through field and satellite-image mapping grounded with extensive measured stratigraphic sections. The > 500 km^2 study area was selected because the entire stratigraphic succession from the uppermost Cerro Toro Formation through to the Dorotea Formation is preserved along an outcrop belt $\sim$ 35 km long. Small-offset reverse faults ($<$ 10 m) and associated structures are present locally, however these perturbances are mappable and do not impede regional stratigraphic correlations.

Satellite imagery superposed onto topography was used to identify and map key stratigraphic surfaces in 3-D space (Fig. 3). The large-scale exposure was interpreted by tracing thick (5–20 m), resistant layers

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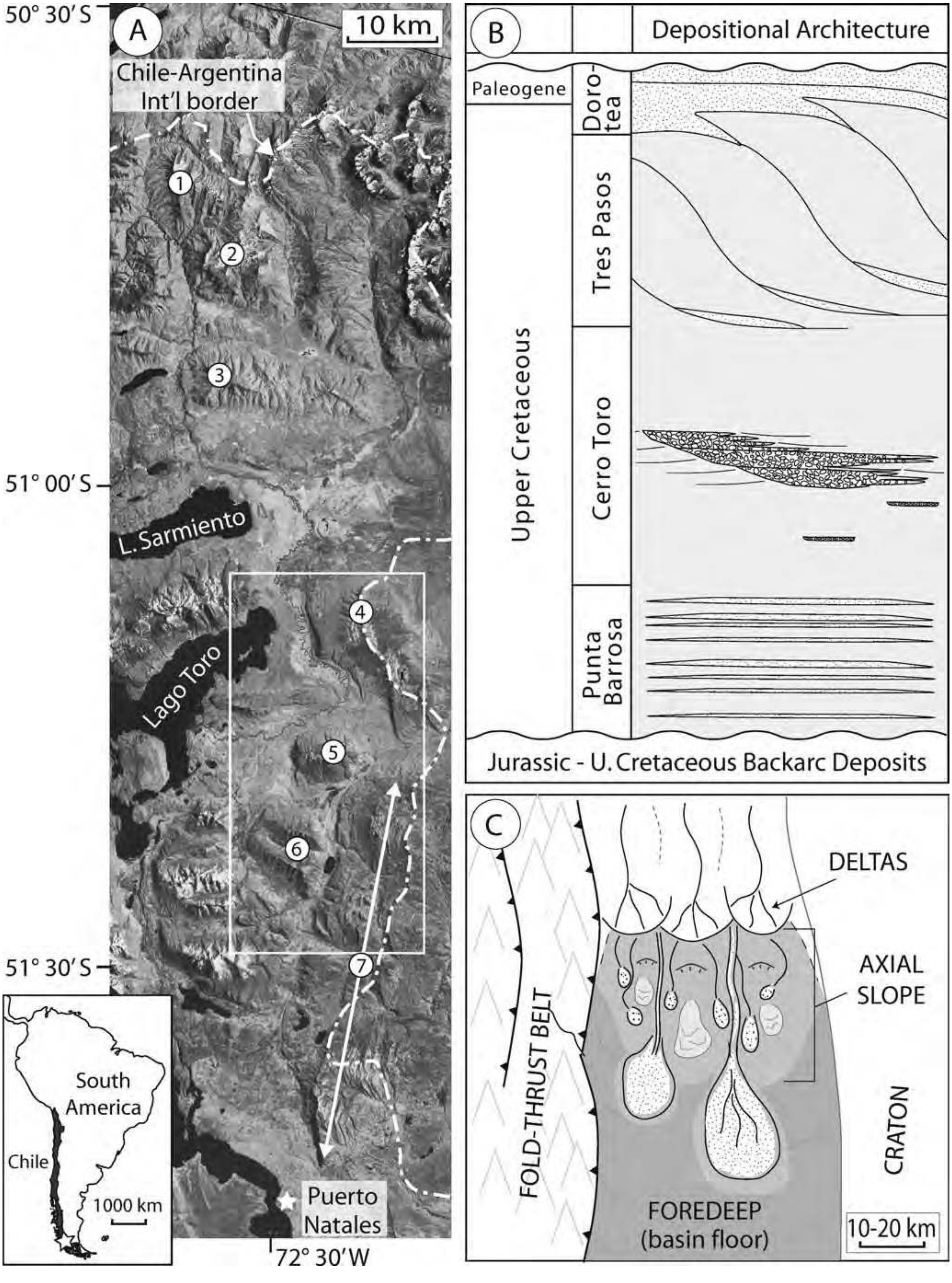
FIG. 2.—Overview of study area. **A)** Regional satellite image showing distribution of main outcrops of the Tres Pasos and Dorotea formations: (1) Cerro Divisidero, (2) Cerro Escondido, (3) Sierra Contreras, (4) Cerro Cazador, (5) Cerro Solitario, (6) Cerro Jorge Montt, (7) Sierra Dorotea. White rectangle defines the specific area of interest for this study. Inset map shows the location of the study area at the southern end of South America, denoted with a star. **B)** Stratigraphic column for the Magallanes foreland basin showing simplified depositional architecture of the main lithostratigraphic units. The Punta Barrosa and Cerro Toro formations were deposited at bathyal water depths; the Tres Pasos and Dorotea formations record the filling of the deep-water seaway (modified from Fildani et al. 2009; based on Fildani et al. 2003; Hubbard et al. 2008; Romans et al. 2009). **C)** Simplified Cretaceous paleogeographic reconstruction of the Magallanes foreland basin showing a southward propagating slope filling the basin axially, parallel to the Andean orogenic front to the west (modified from Fildani et al. 2009).


50° 30′ S
A
10 km
Chile-Argentina Int'l border
1
2
3
51° 00′ S
L. Sarmiento
Lago Toro
4
5
6
7
51° 30′ S
South America
Chile
1000 km
Puerto Natales
72° 30′W
B
Depositional Architecture
Paleogene
Dorotea
Tres Pasos
Upper Cretaceous
Cerro Toro
Punta Barrosa
Jurassic - U. Cretaceous Backarc Deposits
C
DELTAS
AXIAL SLOPE
FOLD-THRUST BELT
CRATON
FOREDEEP (basin floor)
10-20 km

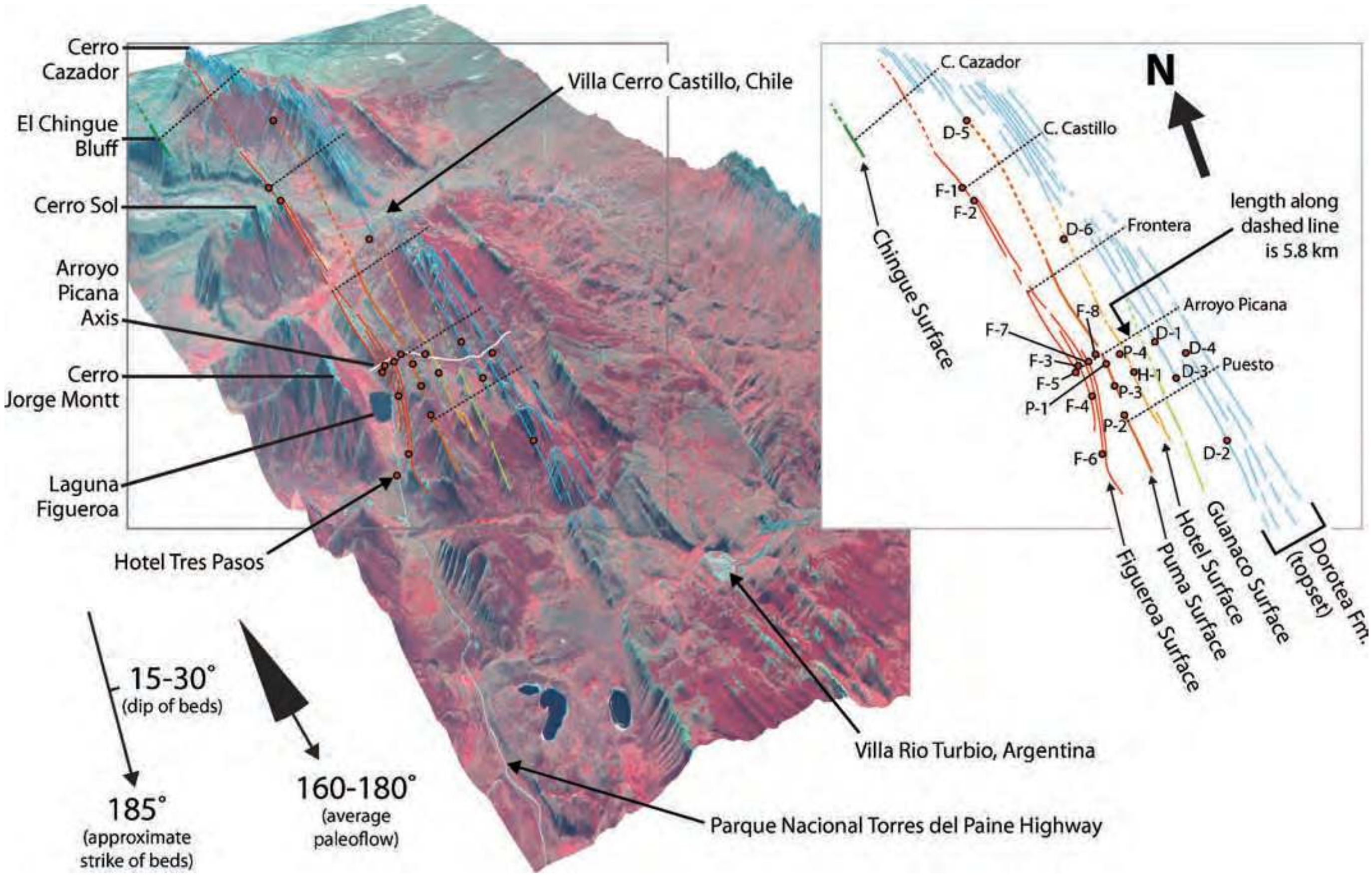


FIG. 3.—Perspective image of satellite imagery draped on topography (exaggerated 3 times) across the 500 km^2 study area highlighting the nature of the outcrop belt and field locations discussed in the paper. Paleoflow was near due south during deposition of the units studied, roughly aligned with the present day structural orientation of the strata. Therefore resistant outcrop ridges are correlated along a depositional dip profile. At right is a line-drawing trace highlighting stratigraphic surfaces in the area. Significant surfaces traced over long distances are labeled. The overall stratigraphic architecture is interpreted to represent a high-relief slope clinoform system prograding southward, with a depositional dip cross-section shown in Figure 4.

exposed as prominent ledges in the satellite data, in much the same way that a seismic-reflection section is interpreted (Mitchum et al. 1977). Importantly, the surfaces, as described in this study, are primarily characterized by the immediately overlying facies, which define the mapped ridges. These layers were traced along lengths from 10 to 35 km and facies variation along individual stratigraphic surfaces was documented with measured sections. Bed tracing in the field fostered correlation across glacially carved areas where units have been eroded. Thick exposures of mudstone–siltstone-dominated strata locally are sparse due to vegetative cover in the study area.

STRATAL SURFACES AND ASSOCIATED SEDIMENTARY PACKAGES

Four widely correlated stratigraphic surfaces are mapped in the study area (Fig. 3). From lowest stratigraphic position to highest, these are hereafter referred to as: (1) Chingue, (2) Figueroa, (3) Puma, and (4) Hotel (Fig. 3). A fifth surface, Guanaco, is mapped in satellite data but has not been studied in detail yet (Fig. 3). These surfaces bound thick successions of strata dominantly consisting of siltstone and shale, with interbedded sandstone packages up to 25 m in thickness. The north–south orientation of the outcrop belt is ideal for mapping stratigraphic architecture and understanding depositional processes for two primary reasons: (1) paleocurrent measurements indicate southward flow was prevalent (this study; Smith 1977; Shultz et al. 2005; Shultz and Hubbard 2005), suggesting that outcrops in the study area are oriented roughly parallel to depositional dip; and (2) on average, beds strike between 175–195° dipping 15–30° to the east (Fig. 3). The perspective image and accompanying line-drawing trace shown in Figure 3 highlight the stratigraphic architecture in depositional dip profile. Depositional strike outcrop exposures are discontinuously exposed along transects 4–6 km in length, associated with east–west drainages across Sierra Dorotea, including Arroyo Picana (Fig. 3).

The Chingue, Figueroa, Puma, and Hotel surfaces are defined over most of their length by relatively resistant ridges of outcrop within thick siltstone and shale deposits (Fig. 3). These surfaces are interpreted here as ancient slope profiles (Fig. 4; e.g., Rich 1951; Van Siclen 1959). In the most northerly position, the oldest Chingue surface is associated largely with fine-grained deposits, punctuated with thick (60 m) sandstone bodies that accumulated in local accommodation on the slope (Shultz and Hubbard 2005). The Figueroa, Puma, and Hotel surfaces are more continuously exposed, characterized by extensive coarse-grained deposits.

Turbidite-dominated strata deposited at the lower to base of slope are characteristic along the southward dipping Chingue, Figueroa, Puma, and Hotel surfaces at the base of the stratigraphic section where the surfaces flatten (Figs. 3, 4). Sandstone-rich sedimentary bodies at the base of the Chingue, Figueroa, and Puma surfaces locally represent the lithostratigraphic base of the Tres Pasos Formation (Fig. 2; Katz 1963). To the north, associated strata transition into deltaic and shallow-marine units in the up-dip, most proximal position of the studied strata (Figs. 3, 4). Lithostratigraphically these units are part of the Dorotea Formation

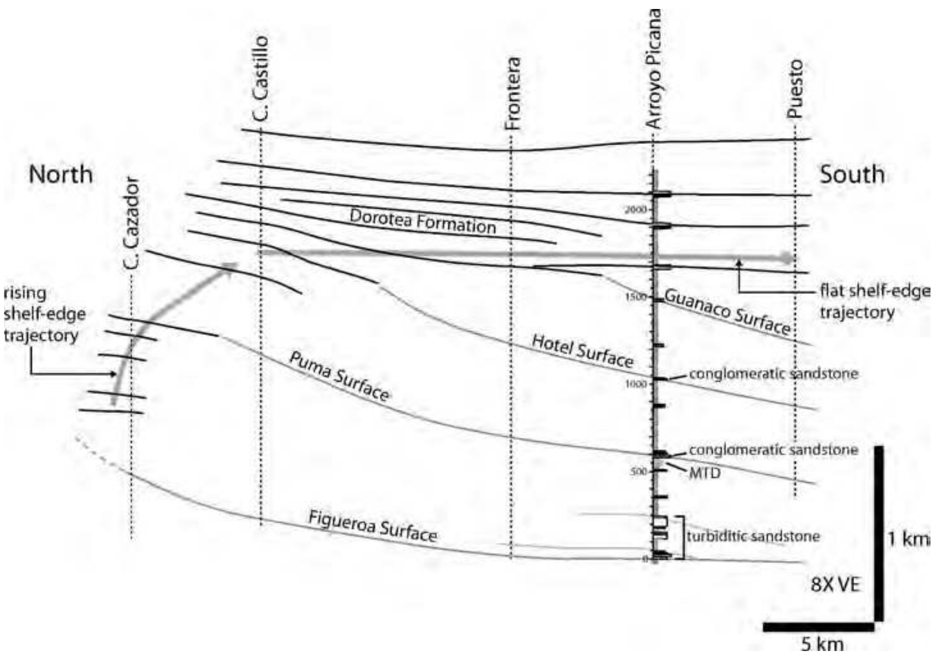


FIG. 4.—Dip-oriented cross-section through the Tres Pasos and Dorotea formations showing the clinoform architecture present. Locations of each of the vertical profiles (C. Cazador, C. Castillo, Frontera, Arroyo Picana, and Puesto) are tied to Figure 3. A composite measured section through the entire slope succession along Arroyo Picana shows the lithologic character of the depositional system. The traced ridges of the Dorotea Formation from satellite data (Fig. 3) form the basis for the correlations shown; trends in shelf-edge trajectory are apparent.

(Fig. 2; Katz 1963). Therefore, the southward offset stacking of the Chingue, Figueroa, Puma, and Hotel surfaces records basinward accretion of a slope system that axially filled the north–south oriented Magallanes Basin.

The Figueroa, Puma, and Hotel surfaces and their overlying stratal packages are described and interpreted below in order to record sedimentological differences amongst, and changes along, the mapped slope profiles. Due to more complete exposure and accessibility, the Figueroa surface and overlying stratal package is more thoroughly discussed. The overlying Dorotea Formation also is briefly described in order to give a more complete context for the slope system.

Figueroa Interval
Description

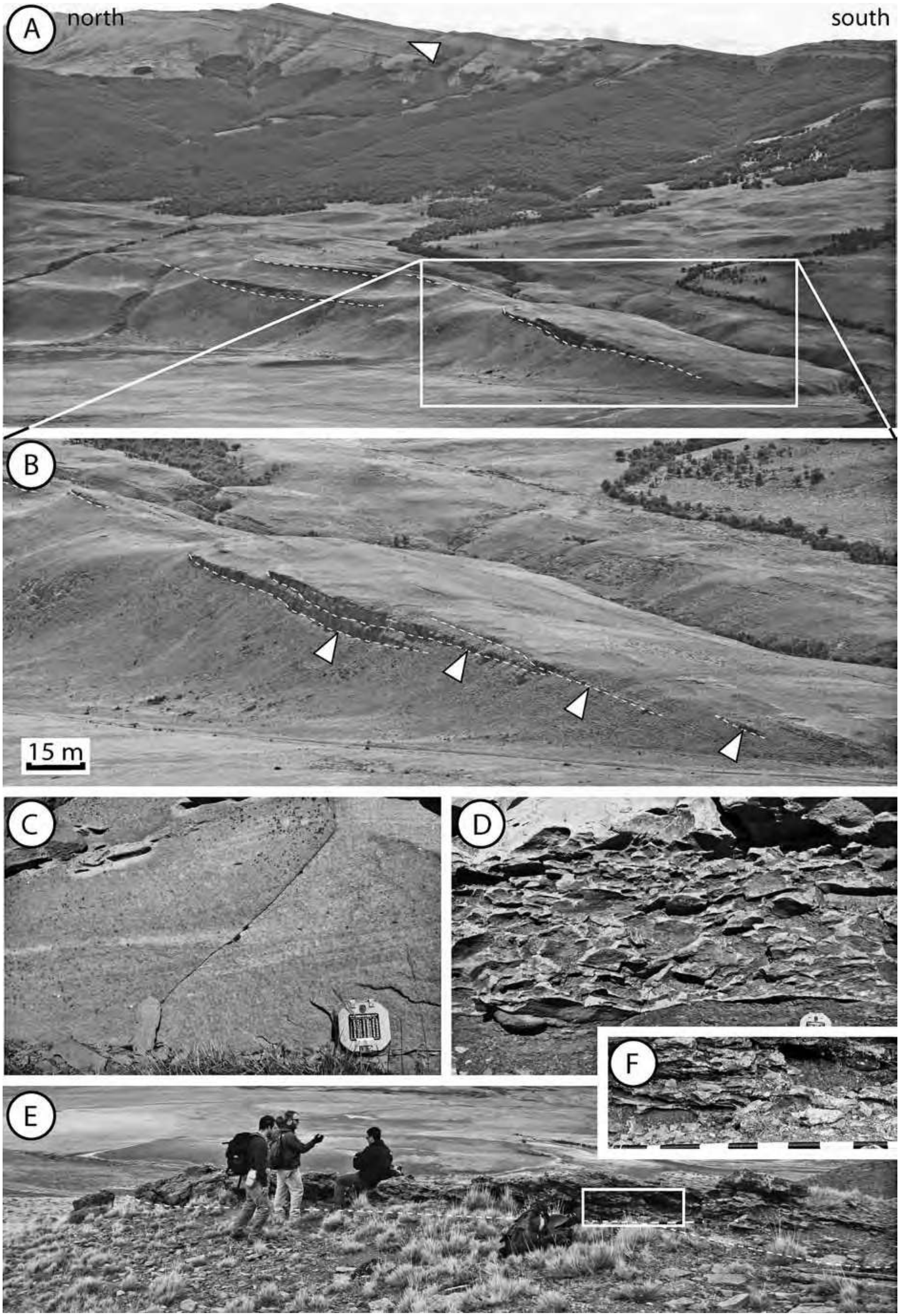
Deposits on the mapped proximal reaches of the Figueroa surface are characterized by extensive mudstone, with sandstone and/or mudstone conglomerate units up to 8 m thick (locations F-1 and F-2; Figs. 3, 5). Sandstone locally comprises lenticular bodies that stack offset of one another (Fig. 5A,B). The sandstone lenses consist of turbiditic beds of normally graded medium- to coarse-grained sandstone with variable amounts of very coarse sand grains, granules, and sub-angular to sub-rounded mudstone clasts up to 10 cm in diameter (Fig. 5C, D). Large-scale cross stratification (up to 80 cm thick) and planar lamination are common (Fig. 5C). Locally, lenticular erosive surfaces (up to 2 m of relief) are filled primarily with mudstone clasts (Fig. 5E).

Approximately 12–14 km down the depositional system at the location of Arroyo Picana (location F-3; Fig. 3), sandstone bodies 18–24 m thick dominate the stratigraphic interval (Fig. 6A–E). These bodies typically are separated by 20–40 m of interbedded mudstone, siltstone, and fine-grained sandstone, although they are amalgamated in some localities (Fig. 6A). The sandstone bodies are 200–450 m wide, have channel-form geometries, and typically are laterally offset from one another. They internally comprise smaller channel-form units 6–8 m thick, with basal surfaces often overlain by siltstone layers up to 80 cm thick (Fig. 6E). Amalgamated, normally graded sandstone beds and an overall upward decrease in amalgamation are notable through the bodies (Fig. 6B). Sandstone beds commonly are structureless and/or planar laminated and characterized by undulous bases. Strata adjacent to the sedimentary bodies consist dominantly of thinly interbedded siltstone and mudstone, with an increase in the proportion of sandstone in the upper parts of these intervals notable (Fig. 6A–C). Fine-grained chaotically bedded deposits commonly are present underlying the sandstone bodies (Fig. 6F).

Two to three kilometers down depositional dip (south) from Arroyo Picana in the vicinity of location F-4 above Laguna Figueroa (Fig. 3), a stratigraphic succession nearly 350 m thick is present consisting primarily of sandstone ($> 70\%$ sandstone). This sandstone package consists of amalgamated turbiditic beds present within channel-form sedimentary units 6–10 m in thickness, commonly separated by discontinuous mudstone beds up to 80 cm thick (Fig. 7). Collectively, these units comprise larger channel-form sandstone bodies 15–20 m thick on average (Fig. 7A–E). Limited outcrop exposure of these sedimentary bodies typically prevents recognition of both lateral margins. Where observed, margins are characterized by the transition from amalgamated to non-amalgamated sandstone beds, and complete pinch out over < 25 m (Fig. 7A–E).

At the most distal position studied along the Figueroa surface, more tabular sandstone bodies are observed (locations F-5 and F-6; Fig. 3). Thicknesses of these laterally persistent composite bodies are variable along their lengths from 2 to 12 m (Fig. 8). Lower contacts are scoured and, internally, the sedimentary bodies consist of amalgamated, thick-bedded sandstone, with higher degrees of amalgamation notable where packages are thickest (Fig. 8A, B). These sandstone-dominated bodies incise interbedded sandstone, siltstone, and mudstone (Fig. 8). Sandstone beds within the interbedded facies are normally graded from medium- to fine-grained, characteristically structureless, and capped with planar and ripple cross stratification. They typically are 15–90 cm thick, variably amalgamated, and laterally continuous over at least hundreds of meters along strike. Mudstone beds are concordant and interlaminated with siltstone or very fine-grained sandstone. Sole marks, including tools and flute casts, are oriented 160–180°.

Overlying the thick sandstone package above the Figueroa surface is a package of mostly poorly exposed fine-grained-dominated strata up to 300–400 m thick (Fig. 4). Sandstone bodies up to 20 m in thickness are present, with channel-form geometries apparent from outcrops oriented along depositional strike (Fig. 9A–C). Fine-grained facies lateral to these sandstone units typically are poorly exposed (Fig. 9C). In some instances,


A
north
south
B
15 m
C
D
E
F

well exposed chaotically bedded units are notable between sandstone bodies (Fig. 9D).

The key characteristics of the Figueroa surface and interval, as described above, are summarized in Figure 10.

Interpretation

Proximal deposits on the Figueroa surface largely record erosion and sediment bypassing on the slope (F-1 and F-2; Figs. 3, 10). Traction-structured sandstone and the thin, channelized sandstone bodies support this interpretation; conduits filled only with locally derived mudstone clasts also provide evidence that highly energetic erosive flows were bypassing the area (cf. Mutti and Normark 1987). Offset sandstone bodies are attributed to stacked channels or deep scour fills in conduits on the slope.

Sandstone bodies at Arroyo Picana (F-3; Figs. 3, 10) are interpreted as incised channel complexes with thin overbank packages fringing upper channel margins that are located in a lower slope position. The channel complexes comprise smaller channel elements (cf. Campion et al. 2000) locally separated by basal mudstone drapes that record sediment bypass associated with large, energetic flows (Fig. 6E). Offset stacking of the channel complexes is hypothesized to be related to avulsions instigated by channel back filling (cf. Kolla 2007). Mass-transport deposits (MTD) record slope instability and may have contributed to the focusing of flow and establishment of conduits (Hackbarth and Shew 1994; Armitage et al. 2009).

Sandstone bodies at Laguna Figueroa (F-4) are interpreted as stacked submarine channel complexes in a lower-slope to base of slope position (Figs. 3, 10). Compared to channel elements located 2–3 km upstream at Arroyo Picana, the channels at Laguna Figueroa are less incised and show aggradational marginal–overbank deposits (Fig. 7A, B). The marked increase in sand:shale ratio within a vertical section from Arroyo Picana to Laguna Figueroa (from ~ 30% to ~ 70%) corresponds to a vertical coalescing of channel complexes downstream (Fig. 7C–F). The high sandstone proportion within channel bodies from axis to margin suggests that they filled via emplacement of large, high-concentration sediment gravity flows that decelerated rapidly as a result of a reduction in slope (Lowe 1982). The shale- and siltstone-dominated units that drape channel-element bases record deposition from tails of bypassing turbidity currents (Fig. 7F; cf. Mutti and Normark 1987)

Relatively distal sedimentary units along the Figueroa surface record the waning of low- to moderately erosive turbulent gravity flows in a relatively unconfined region at the base of slope or proximal basin floor. Sedimentary structures are consistent with deposition from low- and high-density turbidity current processes (cf. Bouma 1962; Lowe 1982). Variably thick packages of sandstone beds characterized by the highest degree of amalgamation where sandstone is thickest have characteristics of both sheet and channel sedimentary bodies and likely represent a transitional architecture between these two end members (Fig. 8; e.g., Grecula et al. 2003). Similar composite sedimentary body architectures have been observed in submarine fan deposits, and may record deposition in proximity to the channel-lobe transition (Mutti and Normark 1987; Wynn et al. 2002). The sheet deposits are overlain by channel elements in the base of slope position as a result of forestepping of the depositional system (cf. Mutti and Normark 1987; Booth et al. 2003).

Puma and Hotel Intervals

Description

Deposits associated with the Puma and Hotel intervals are locally characterized by relatively coarse-grained material and evidence for extensive scouring (Fig. 11). In a relatively proximal position (P-1; Figs. 3, 10), conglomeratic facies are common in sedimentary bodies up to 12 m thick and at least 100 m wide on the Puma Surface (complete width not measurable due to limited outcrop exposure; Fig. 11A, B). The Hotel surface is defined by a resistant ridge 8–12 m thick, consisting of very coarse-grained pebbly sandstone grading upward into fine- to medium-grained sandstone (Figs. 3, 11C). On both surfaces, facies are dominated by traction structures at the bases of sedimentary units and thick-bedded, normally graded sandstone beds upwards (Fig. 11). Sandstone of the Hotel surface pinches out paleo-landward towards the north, as observed in the satellite data (Fig. 3). In a more distal position on the Puma Surface (P-2; Figs. 3, 10), sandstone bodies up to 16 m thick consist of thick-bedded turbidites with extensive sub-angular mudstone rip-up clasts (Fig. 11D, E).

Overlying the Puma and Hotel surfaces are thick packages (up to 500 m) of siltstone and mudstone, with fine-grained mass-transport deposits also present (Fig. 4). Channel-form sedimentary bodies up to 5 m in thickness are rare, composed of interbedded mudstone, siltstone, and fine-grained sandstone units up to 20 cm thick (Fig. 12).

Interpretation

Sandstone and pebbly sandstone of the Puma and Hotel surfaces record extensive bypass and erosion on the slope. In the upper slope position, the up dip continuation of the surfaces is subtly exposed, with its position locally emphasized by variations in surface vegetation (Fig. 3). Shale-dominated strata directly beneath the Dorotea Formation topset supports the interpretation of extensive sediment bypass on the upper slope (Fig. 3). Covault et al. (2009) documented a conduit with tens of meters of erosional relief in proximity to the Tres Pasos–Dorotea contact to the north at Cerro Escondido (Fig. 2), which they attributed to mass-wasting on the shelf edge; however, none have been recognized in the study area, possibly due to a lack of extensive outcrop exposures oriented along depositional strike. It is possible that these features are out of the plane of the outcrop. The northward pinch out of sandstone along the Puma and Hotel surfaces corresponds to a shift along the depositional profiles from bypass to dominantly deposition. Traction-structured conglomeratic units in relatively proximal positions along the paleo-slope surfaces and more distal, depositional sandstone units support this interpretation (Fig. 11).

Dorotea Formation

Description

An interfingering relationship between sandstone units of the Dorotea Formation and underlying fine-grained strata of the upper Tres Pasos Formation is apparent from bed tracing on satellite imagery (Fig. 3); these facies relationships are guided by mapping of southward, or basinward, terminating coarse-grained units in the lowermost Dorotea Formation. Due to vegetative cover in the area of this facies transition, details are often difficult to discern, although overall southward stacking

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FIG. 5.—Sedimentological characteristics of up dip, proximal deposits along the Figueroa surface. **A, B)** Offset sandy channel deposits within a dominantly mudstone–siltstone interval, interpreted to have been deposited in a middle slope position (outcrop F-1; Fig. 3). The arrow in part A shows the location of resistant, sandy beds of the Dorotea Formation. **C–E)** Evidence for bypass in a lower-middle slope position along the Figueroa surface, including **C)** cross-stratified sandstone and **D)** mudstone intraclast conglomerate lags (outcrop F-2). **E)** Channel conduit, with base demarcated by dashed line, filled with > 60% mudstone clasts (outcrop F-2). **F)** Close-up of channel fill from area defined in rectangle in Part E, with abundant mudstone clasts.

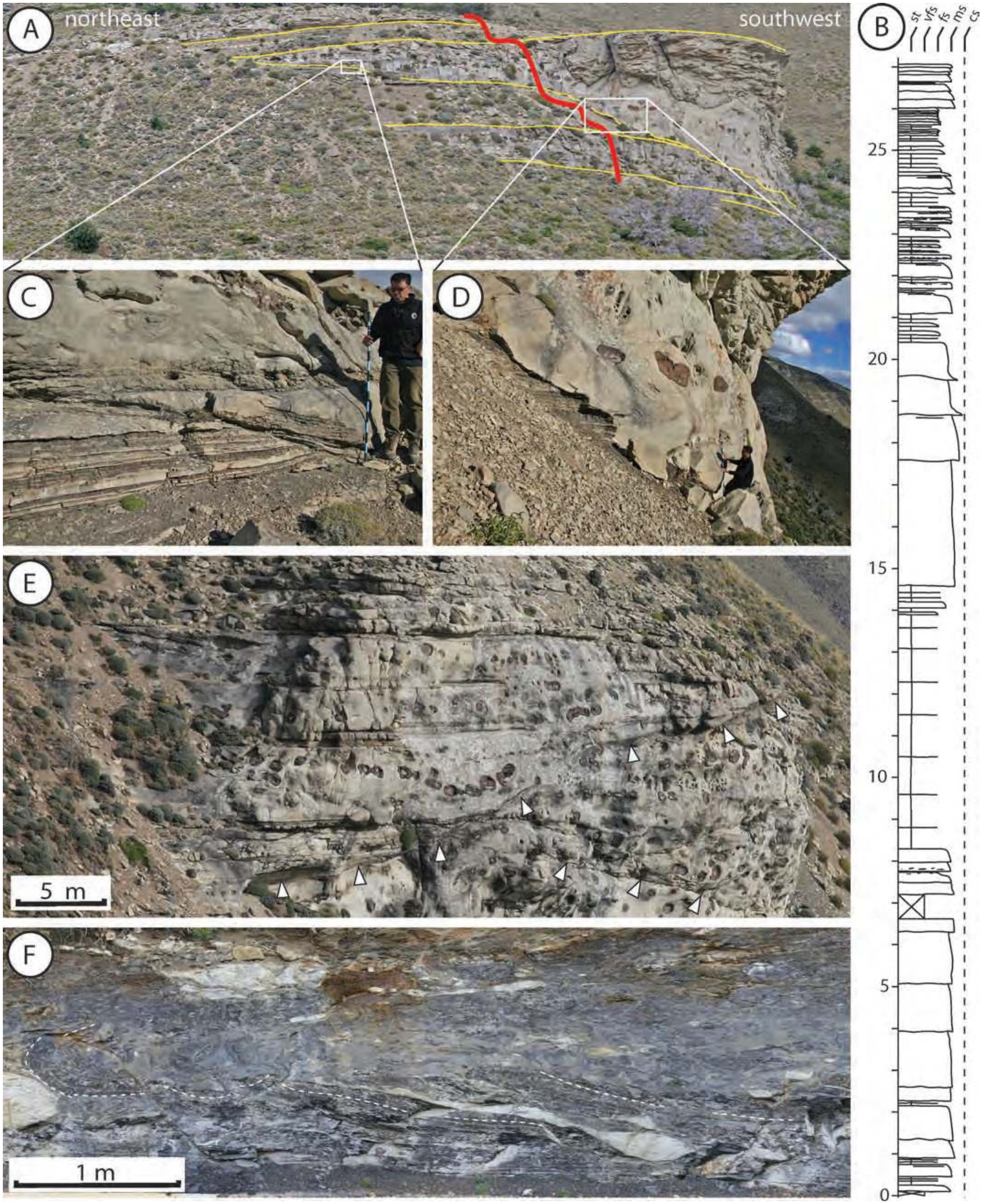

FIG. 6.—Sedimentological characteristics of Figueroa surface at location F-3 (Fig. 3). **A)** Deeply incised channel complex showing multiple phases of incision and back-fill by massive, high-density turbidity-current deposits. **B)** Measured section through the channel fill, with location highlighted with bold line in Part A. **C)** An

is apparent (Fig. 3). Locally, hummocky cross-stratified sandstone is present within otherwise muddy strata in the upper part of the Tres Pasos Formation (Fig. 13A).

The Dorotea Formation in the vicinity of Arroyo Picana is characterized by various sandstone facies that comprise the widespread outcrop ridges mapped in satellite data (Fig. 3). Twenty meters of medium- to coarse-grained trough cross-stratified sandstone are present at D-1 (Figs. 3, 13B, C). Trough cross stratification also dominates a 50 m interval of primarily medium-grained sandstone with local granules at D-2 (Figs. 3, 13D, E), associated with locally abundant *Skolithos*. Swaley- to planar-stratified coarse-grained sandstone with very coarse sandstone grains occurs at D-3 (Fig. 13F). Rare *Shaubcyclindrichnus* and *Skolithos* are present in this swaley cross-stratified sandstone (Fig. 13G). The ridge present at D-4 is composed of fine-grained sandstone (Fig. 13H, I). This sandstone is nearly completely bioturbated, with vestigial cross stratification locally preserved (Fig. 13I). Trace fossils present include *Arenicolites*, *Cylindrichnus*, *Helminthopsis*, *Phycosiphon*, *Planolites*, *Cosmorhaphe*, *Shaubcylindrichnus*, *Skolithos*, *Thalassinoides*, and *Teichichnus*.

Interpretation

The pinch out of sandstone ridges southward, or basinward, defines the contact between the Dorotea Formation (sandstone dominant) and upper Tres Pasos Formation (mudstone dominant), recording the transition from proximal shoreline-deltaic sandstones to shelf and more distal upper slope mudstones. The shelf–slope break is interpreted for depositional profiles in the vicinity of these facies transitions, also characterized by the down-system shift from flat-lying to more steeply dipping clinoform surfaces (cf. Donovan 2003; Bullimore et al. 2005). Hummocky cross-stratified sandstone beds within stratal packages otherwise dominated by mudstone in the upper portion of the Tres Pasos Formation suggests that, at least locally, the shelf–slope break is not defined by a sharp lithologic transition, showing the limitation of this assumption (Fig. 13A).

Sandstone ridges dominated by trough cross stratification are interpreted as the deposits of distributary channels and mouth bars. Swaley cross-stratified sandstone units represent wave or storm reworked delta front deposits (cf. Bhattacharya and Walker 1992; Gani and Bhattacharya 2007). The trace fossils largely record deposit- and filter-feeding behaviors that are consistent with the *Skolithos* and *Cruziana* ichnofacies, commonly associated with ancient deltaic environments (Gingras et al. 1998; MacEachern et al. 2005). In alignment with analysis and interpretation of the Dorotea Formation in other localities (Macellari et al. 1989; Covault et al. 2009), the examined deposits are interpreted to have been deposited in fluvial- and wave-influenced shelf-edge delta and shelf settings.

Stratigraphic Evolution of the Slope System

The smooth slope profiles and their overlying strata record punctuated periods of extensive sediment bypass and erosion on the upper and middle slope, and deposition of sediment gravity flows at the lower slope to base of slope. The oldest surface mapped in detail, Figueroa, and its overlying strata, are characterized by evidence for bypass including erosional surfaces overlain by mudstone clast conglomerate and fine-grained-dominated facies in up-dip positions, and apparently coeval, progressively thicker sandstone-rich units down dip (Figs. 3, 5–7, 10). The lower slope to base of slope position, defined by facies changes and the apparent geometrical shift to relatively flat bottomset strata, is characterized by fine-grained mass-transport deposits overlain by sandstone-dominated tabular (i.e., sheet) and channel depositional elements (Fig. 10). The paleo-shelf edge for the Figueroa surface is not preserved in the outcrop belt, although the overlying siltstone-dominated strata roughly correlate to an aggradational shelf-edge trajectory (Figs. 4, 10). The near vertical shelf-edge trajectory in the Figueroa interval, associated with significant and prolonged deposition and storage on the shelf and considerably less deposition basinward, was a likely mechanism for building and maintaining the high relief of the slope system.

A shift towards flattening of the shelf-edge trajectory between C. Cazador and Frontera reflects shoreline progradation associated with prolonged dominance of sediment supply over creation of accommodation (Jervey 1988; Steel et al. 2008; Carvajal and Steel 2009). Slope strata associated with the flat shelf-edge trajectory is punctuated by periods of bypass and erosion across the upper and middle slope, linked to the Puma and Hotel surfaces (Figs. 3, 4; cf. Johannessen and Steel 2005; Uroza and Steel 2008). Channel-form bodies composed of gravelly material and extensive mudstone-clast conglomeratic units in the interpreted lower-middle to lower slope position support an interpretation of bypass on the upper slope, as does the paucity of coarse-grained material within the upper Tres Pasos Formation in an up dip position to the north. Bypass on the slope and deposition of coarse-grained material on the Puma and Hotel surfaces reflect pulses of coarse-grained sediment supply to the deep basin as a result of enhanced across-shelf sediment flux and/or falling sea-level conditions (cf. Posamentier et al. 1991; Carvajal and Steel 2009; Fig. 11).

DISCUSSION

Regional Paleogeographic Considerations

Recent work by Romans et al. (2010) proposes that Magallanes Basin architecture, and in particular basin margin relief, was strongly controlled by the inherited tectonic fabric of the region. Underlying attenuated crust combined with the load from uplifted, rifted, and remnant oceanic crust induced substantial subsidence southward from the current Chile–Argentina border in the vicinity of Cerro Divisadero (Fig. 2) during the Late Cretaceous (Fildani and Hessler 2005; Fildani et al. 2009; Romans et al. 2009). As the basin filled southward, the initial slope was steep and unstable, recorded by the presence of extensive mass-transport and ponded sandstone deposits in the Tres Pasos Formation from Cerro Divisidero to the Sierra Contreras (Fig. 2; Shultz et al. 2005; Armitage et al. 2009; Covault et al. 2009; Romans et al. 2009). The topographic complexity observed on slopes is largely the result of mass wasting and slope readjustment, which is reflected by the ponding of sands in local accommodation (cf. Steffens et al. 2003). Paleobathymetric relief, from shelf-edge to basin floor, is difficult to measure from northern exposures of the Tres Pasos Formation. The stratigraphic thickness between sandstone packages at the base of the Tres Pasos Formation and the overlying shallow marine deposits of the Dorotea Formation is ~ 1300 m (Covault et al. 2009), giving a rough indication of the relief on the paleo-slope surface (cf. Rich 1951). A composite measured section from the base of the Tres Pasos Formation to the base of the Dorotea Formation (estimated shelf break) along Arroyo Picana in the study area is 1660 m thick (Fig. 4).

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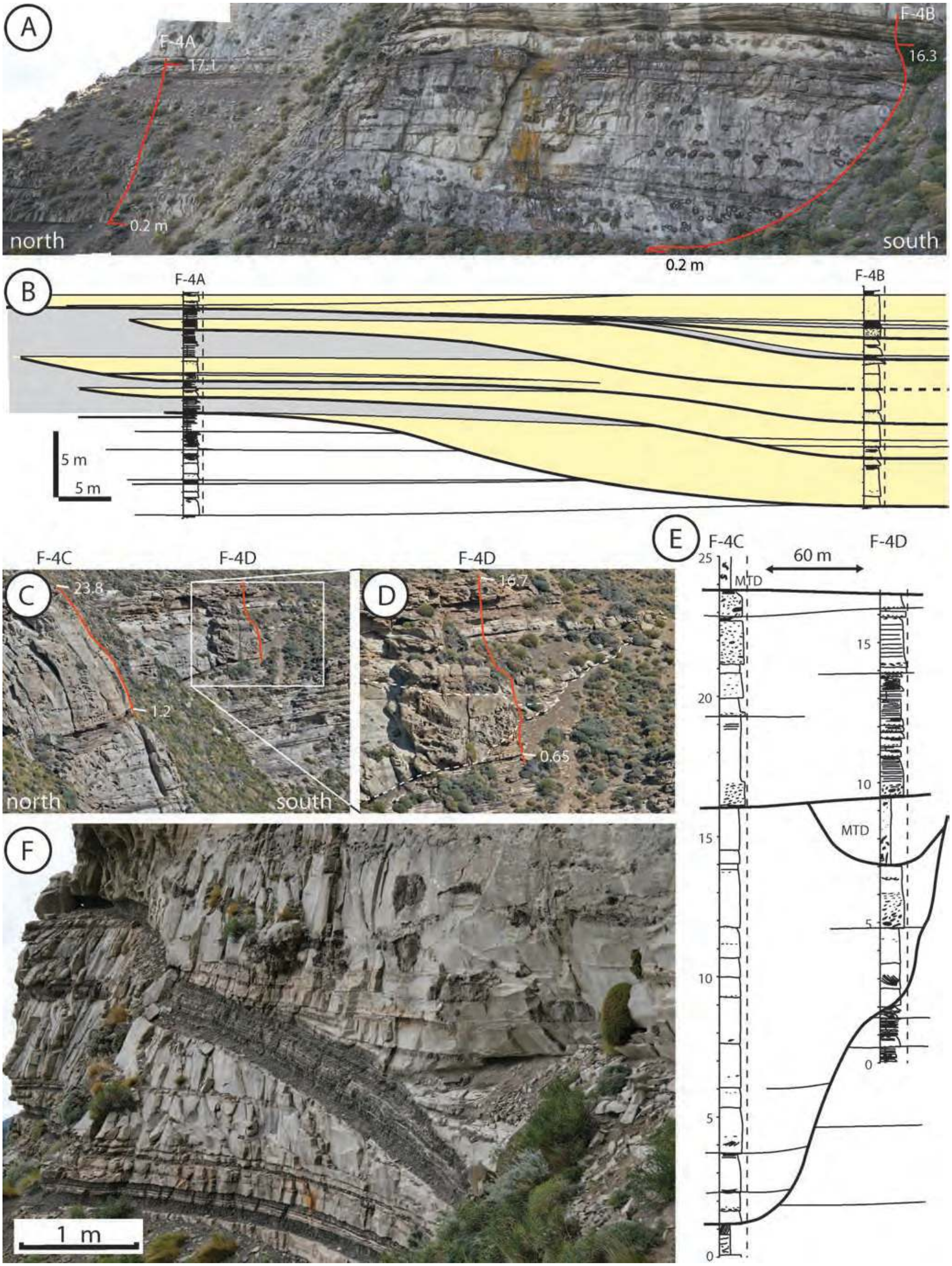
increase in sandstone bed abundance associated with the upper, relatively flat marginal strata is attributed to sediment spilling over the channel banks. **D)** Close-up of the stepped channel margin, recording plucking of cohesive blocks of fine-grained strata during channel incision. **E)** The internal architecture of the channel complex is characterized by amalgamated, smaller channel bodies on the order of 6–8 m thick. Variably shale-draped channel bases are highlighted with arrows. **F)** Mass-transport deposits are common beneath channel bodies in the area of Arroyo Picana.


A
F-4A
17.1
0.2 m
north
F-4B
16.3
south
0.2 m
B
F-4A
F-4B
5 m
5 m
C
F-4C
F-4D
23.8
1.2
north
south
D
F-4D
16.7
0.65
E
F-4C
F-4D
60 m
MTD
MTD
F
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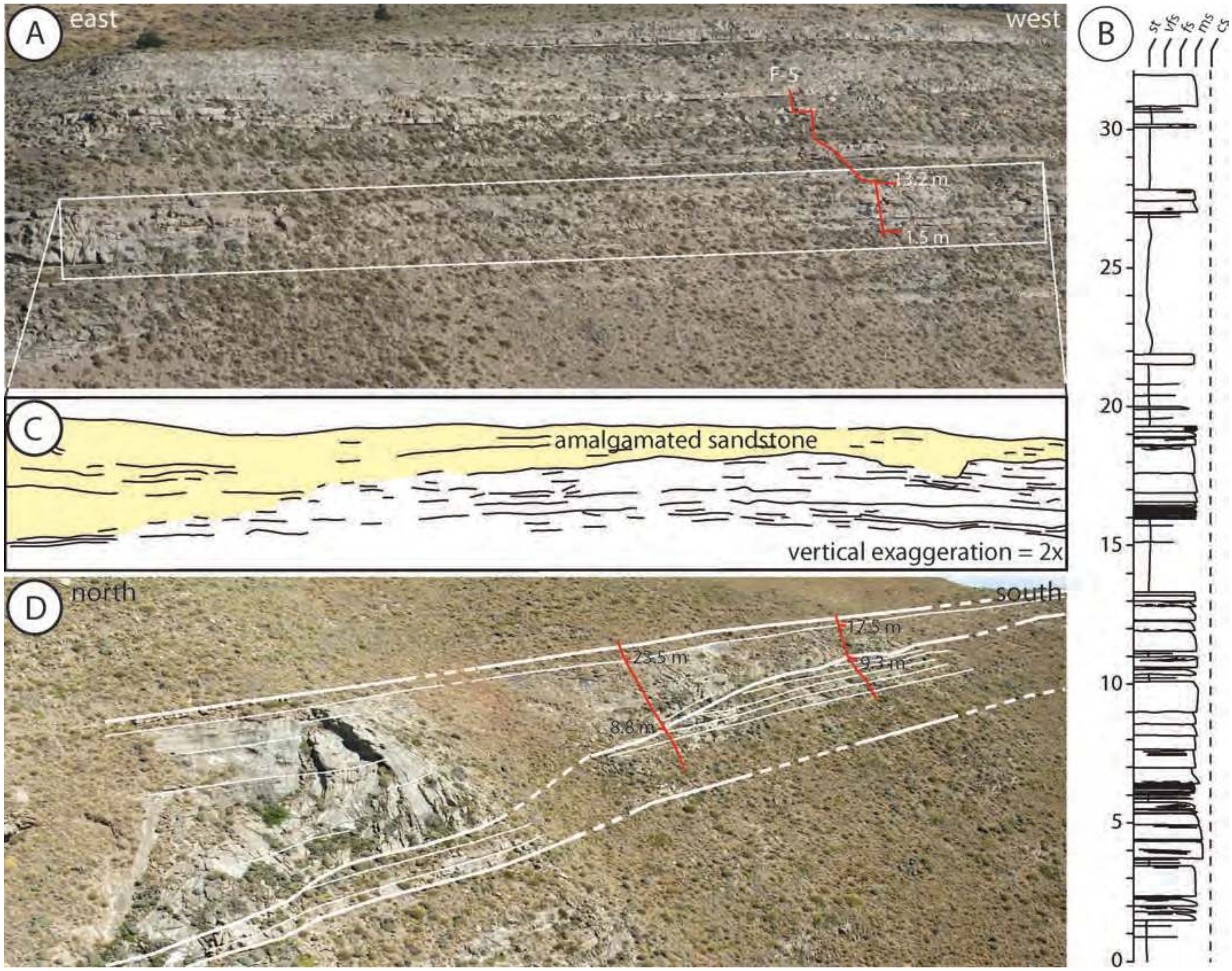

FIG. 8.—Sedimentological characteristics of deposits in the distal portion of stratigraphic horizons within the thick turbiditic packages at the base of the Figueroa surface (outcrops F-5 and F-6; Fig. 3). **A)** Tabular interbedded turbiditic sandstone and siltstone at outcrop F-5, with amalgamated sandstone beds that vary in thickness from 2–12 m. These lenticular beds are architecturally intermediate between channels and sheets; an individual sheet is highlighted along section F-5 between 1.5 and 13.2 m. **B)** Measured section at F-5. See Part A for section location. **C)** Line-drawing trace showing basal relief on lenticular sheet element outlined in Part A. **D)** Outcrop at F-6 showing that the channel-form element varies considerably in thickness yet the composite sandstone-dominated sedimentary body that it is part of is more tabular.

A large portion of the Tres Pasos–Dorotea outcrop belt has been removed by erosion between the Sierra Contreras and Cerro Cazador (Fig. 2). The Chingue and Figueroa surfaces mapped in this study show the continued basinward accretion of slope deposits from Cerro Cazador to Sierra Dorotea (Figs. 3, 4). The development of high relief slope clinoforms is indicative of periods of bypass and erosion. Mass-transport deposits are much less prevalent in the southern part of the outcrop belt, although the recognition of MTDs is difficult as vegetation is much more extensive than in outcrops exposed in the northern part of the Ultima Esperanza District (Fig. 2; Armitage et al. 2009). Only the lower portion of the Chingue surface is preserved in the outcrop belt; however, the Figueroa surface can be traced for nearly 25 km from Cerro Cazador to the eastern shore of Laguna Figueroa (Fig. 3). Thin channel sandstones up dip (Fig. 5A, B), a paucity of ponded slope sandstones, and the thick sandstone package at the base of slope (Figs. 3, 4) are consistent with slopes characterized by smooth profiles (Prather 2003). Despite the fact that the Figueroa surface cannot be mapped to a shelf edge in the Dorotea Formation due to outcrop erosion, an estimation of original

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FIG. 7.—Sedimentological characteristics of deposits in the medial portion of stratigraphic horizons within the thick turbiditic packages at the base of the Figueroa surface (location F-4; Fig. 3). **A)** Photo and **B)** cross-section of aggradational channels at the margin of a channel complex up to 18 m thick. The lateral transition from amalgamated channel sandstone beds to non-amalgamated marginal units takes place across < 50 m. The locations of measured sections in Part B are highlighted in Part A. **C)** Overview, **D)** close-up, and **E)** cross-section showing the dramatic change in facies laterally from channel axis to margin. Note that section locations in Part E are highlighted in Part C. **F)** Amalgamated channel elements (each typically 6–8 m thick) with mudstone beds up to 80 cm thick draping channel bases, recording the bypassing of turbulent gravity-flows.

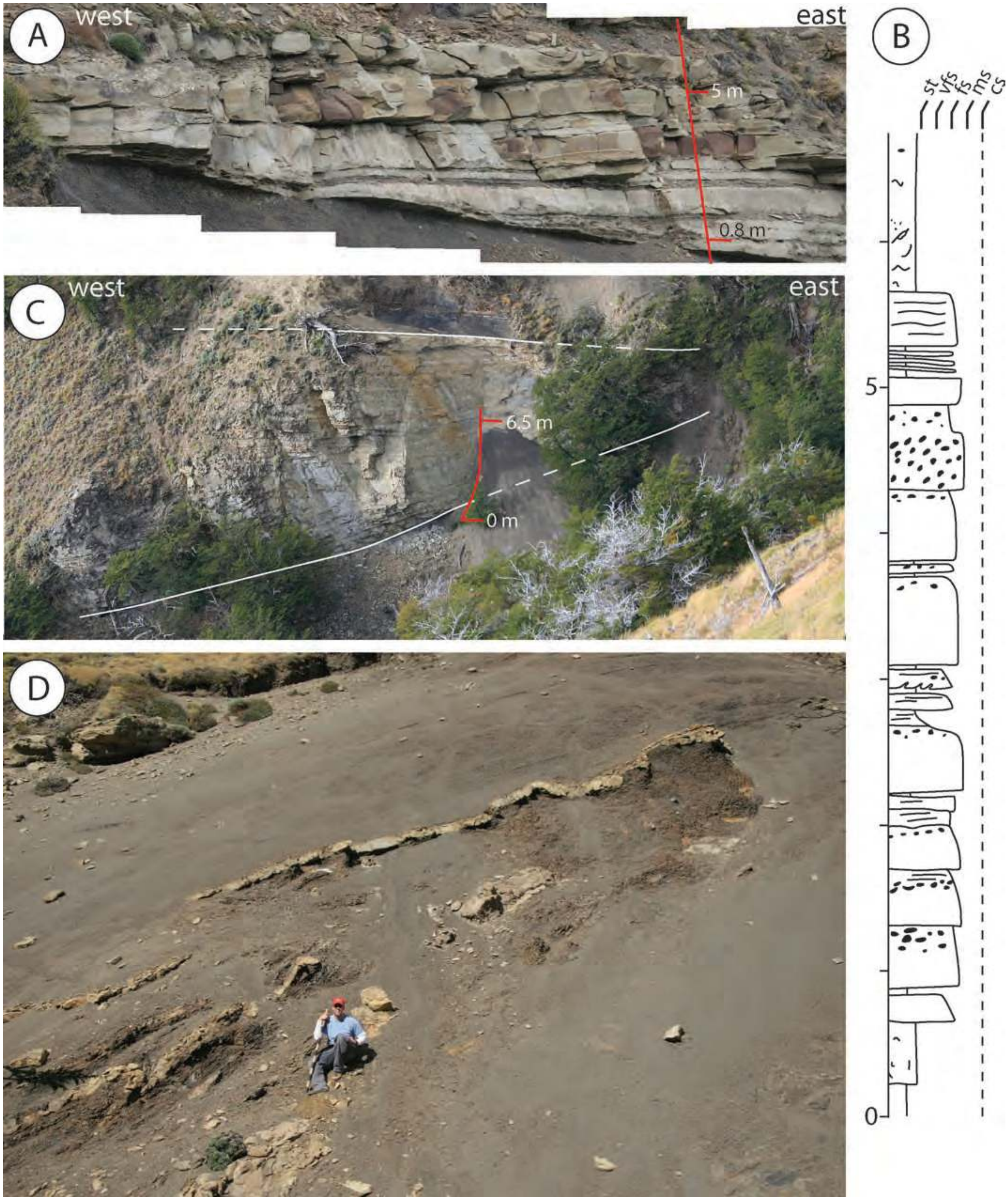

FIG. 9.—Sedimentological characteristics of strata overlying the sandy package on the Figueroa surface (250–600 m, Arroyo Picana Section; Fig. 4). **A)** Sandstone beds on-lapping channel margin with corresponding measured section delineated by vertical line in **B**. Location F-7, Figure 3. **C)** Sandstone-filled channel at Location F-8, Figure 3. **D)** Overturned bedding in mass transport deposit stratigraphically above channel in Part C.

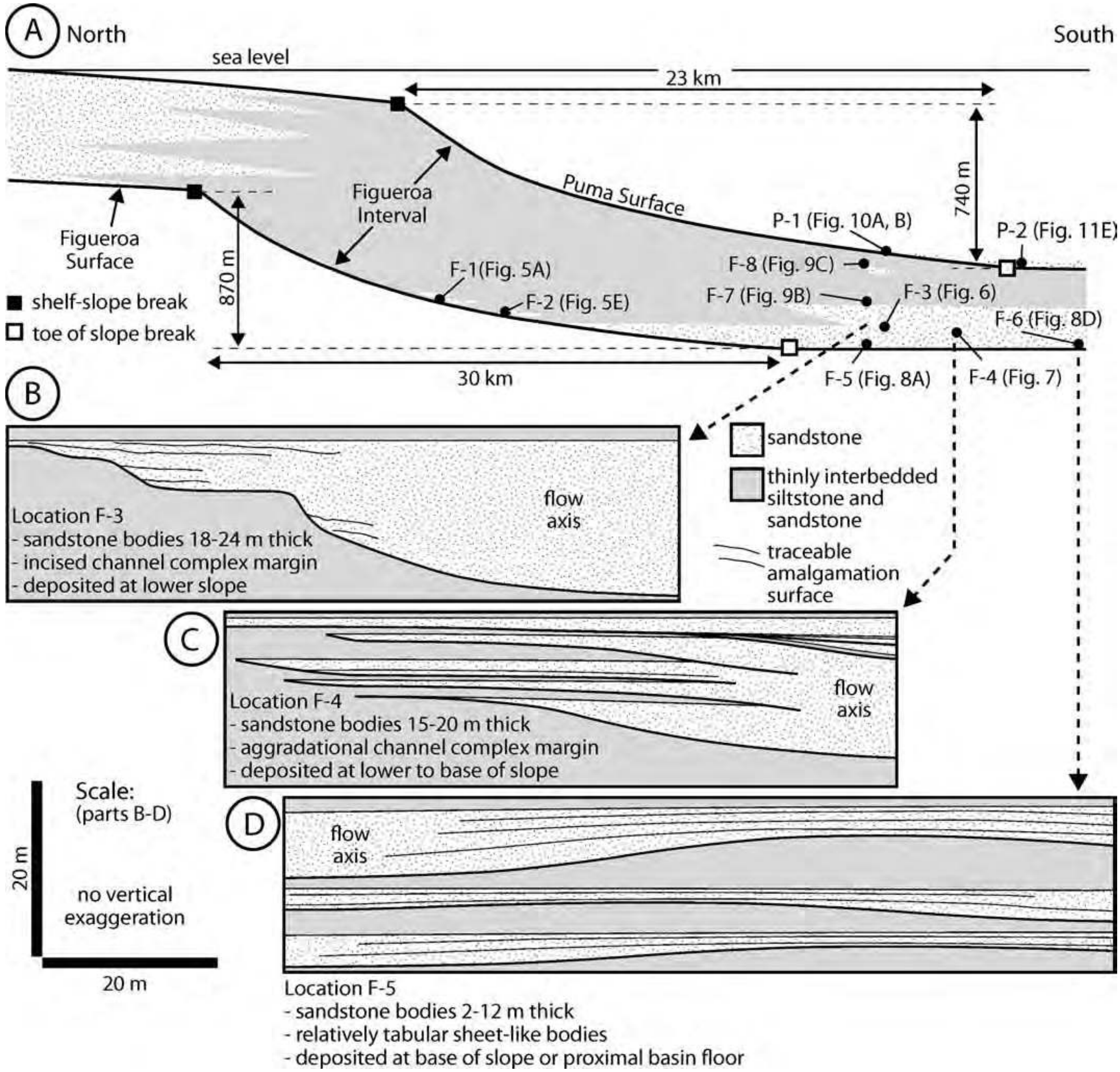

FIG. 10.—Schematic overview of **A)** Figueroa surface, Figueroa interval, and Puma surface, as well as **B–D)** sandstone bodies at the lower to base of slope transition along the Figueroa surface. Sandstone body geometries and sedimentary characteristics record the transition from erosional and confined to depositional and more unconfined flows down-slope.

relief on the slope surface is attained by measuring the vertical thickness from the base of the lowermost sandstone in a base of slope position (near Arroyo Picana; Fig. 3) to the up dip limit of the base of the Dorotea Formation exposed on Cerro Cazador (Figs. 10, 14A). The vertical thickness is 870 m, with an along-basin length of the slope surface measured at $\sim$ 30 km (minimum estimation) and the paleo-slope angle calculated at 1.7° (Fig. 14).

The overlying Puma surface, dominated by facies recording extensive bypass along much of the mapped slope profile, is traced along depositional dip for nearly 23 km. Thick deposits of sandstone are absent along the majority of the surface. The base of slope was taken at location P-3 (Fig. 3) and the coeval slope break at D-5 (Fig. 3); the measured vertical stratigraphic thickness between these two levels is approximately 740 m (Figs. 10, 14A). Given these dimensions, the calculated angle of slope on the Puma surface is 1.8° (Fig. 14A).

The point on the Hotel surface depositional profile that represents the break at the base of slope has not been identified in the field or interpreted from stratigraphic analysis of satellite and field data (Fig. 3). Deposits of the Tres Pasos and Dorotea formations have not been extensively studied south of the study area. The Tres Pasos Formation outcrop trend plunges into the subsurface beneath the town of Puerto Natales (Fig. 2). The Dorotea Formation is well-exposed directly south of

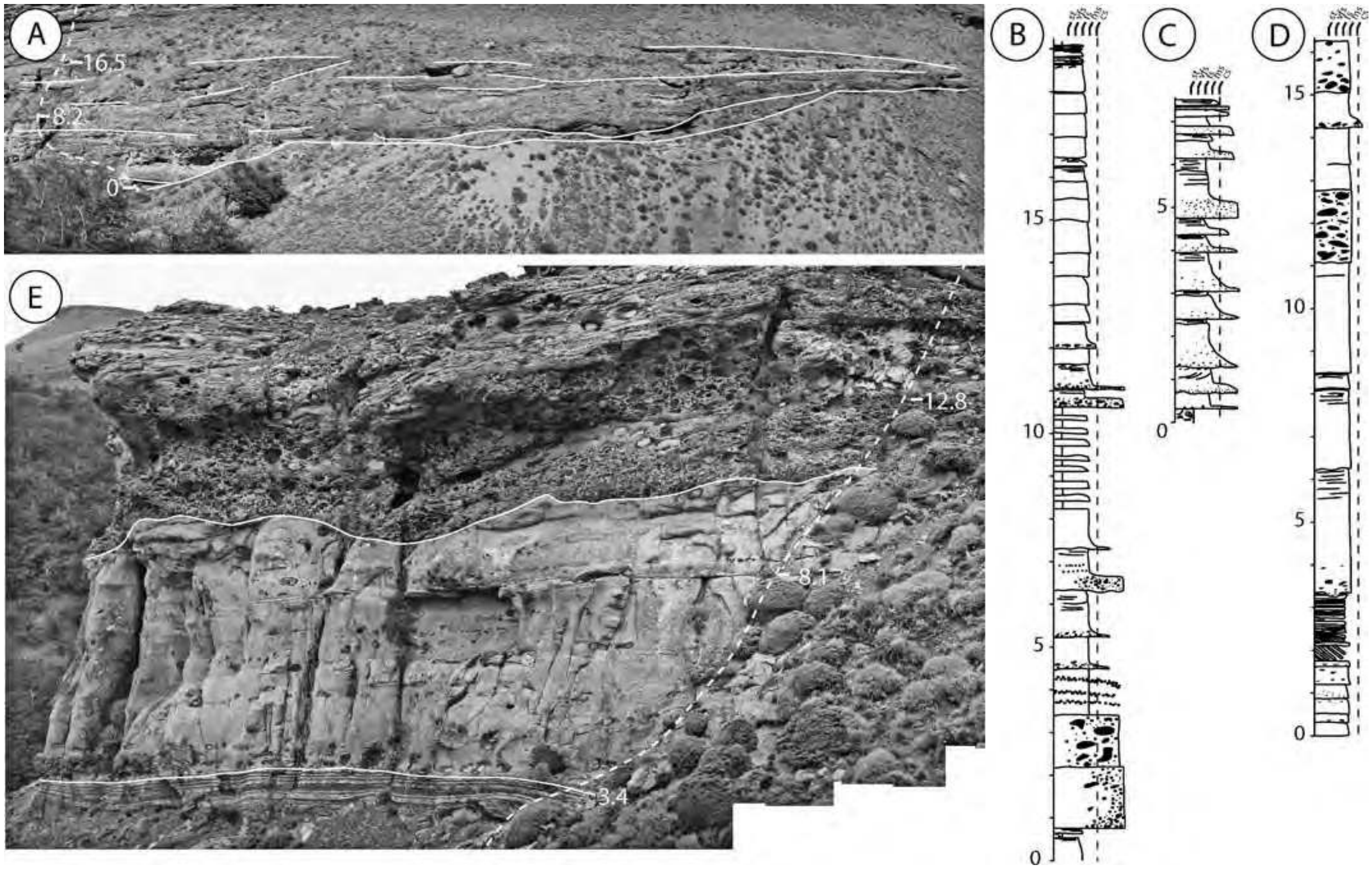

FIG. 11.—Sedimentological characteristics of coarse-grained facies on the Puma and Hotel surfaces. **A)** Channel-form sedimentary body and **B)** corresponding measured section documenting conglomeratic bypass facies at outcrop P-1. Location of the measured section is highlighted by the dashed white line in Part A. **C)** Measured section exhibiting conglomeratic deposits on the Hotel surface at location H-1 (Fig. 3). **D)** Measured section and **E)** outcrop overview at P-2, located approximately 7–8 km down-slope from outcrop shown in Part A. At this locality, thick-bedded massive sandstone beds are overlain by a thick succession dominated by mudstone intraclast conglomerate, recording extensive erosion up dip. Location of the measured section in Part D is highlighted by dashed white line in Part E.

the study area; however, cliff outcrops are difficult to access and, thus far, have not been studied in detail.

Controls on Clinoform Development

Continental slopes have broadly been defined within the realm of two end-member scenarios: graded, where erosional and depositional processes are in equilibrium over geological time scales, and ungraded, where they are not (Hedberg 1970; Ross et al. 1994). Slope architectures are more ordered and systematic in the former case, such as that demonstrated for the Tres Pasos–Dorotea system in the Magallanes Basin, or considerably more complex in depositional profile in the latter.

Controls on continental margin sedimentation and deep-water depositional system development are numerous, with tectonic setting established as an important factor (Mutti 1985; Mutti and Normark 1987). Consideration of various parameters that influence slope architecture, and in particular clinoform development, that are closely aligned with tectonic setting sheds insight into the complexity of a slope profile that can be expected for a given region. These include: (1) basin margin relief; (2) controls on the development of rugose slope surface profiles; and (3) basin shape and sedimentary input.

Basin Margin Relief

The stratigraphic architecture of slope deposits can be influenced to a certain degree by the relief on the slope, or paleo-slope (Hadler-Jacobsen et al. 2005; Steel et al. 2008). High-relief margins are prone to phases of bypass on the upper slope and, therefore, detached base of slope bodies are characteristic (cf. Mutti 1985). These high-relief margins also tend to develop oversteepened, out of grade upper slopes that are commonly unstable, characterized by extensive mass wasting (Hedberg 1970; Ross et al. 1994; Saller et al. 2004). Smaller scale margins, including some slope clinoform systems, are characterized by the absence, or poor development of, base of slope sandstone accumulations where interpreted relief was < 200 m (e.g., Helland-Hansen 1992; Plink-Björklund et al. 2001). Thicker base of slope sandstone deposits are more typical of higher-relief examples (McMillen 1991; Pyles and Slatt 2007).

Slope clinoforms with > 500 m relief (not considering compaction in ancient examples) have been recognized or interpreted from foreland basin, passive margin, and extensional settings (e.g., Uchupi and Emery 1967; McMillen 1991; Fulthorpe and Austin 1998; Hansen and Kamp 2002; Scott et al. 2004; this study). Overall, relatively few examples have been documented in detail, with the geologic record biased towards the preservation of smaller examples (Fig. 14; e.g., Plink-Björklund et al. 2001; Pinous et al. 2001; Johannessen and Steel 2005; Pyles and Slatt 2007). Because of this paucity of high-relief slope clinoforms, scale is often directly cited or implied as the primary control on clinoform development (e.g., Hadler-Jacobsen et al. 2005).

High-relief slope clinoform development in foreland settings is restricted to those basins with a geologic history that facilitated development of particularly deep bathymetric conditions. The Cretaceous

FIG. 12.—**A)** Scours filled with non-amalgamated turbiditic strata within the fine-grained wedge of sediment between the Puma and Hotel surfaces (outcrop P-4; Fig. 3). **B)** Measured section through the scour fill shown in Part A.

clinoforms in the Brookian succession, Alaska, which are up to 2 km thick, built into the rapidly subsiding Collville Trough (Fig. 14; Houseknecht et al. 2009). The back-arc heritage of the Magallanes Basin resulted in anomalously deep bathymetric conditions in the retro-arc foreland setting, providing the continental margin scale-relief over which the Tres Pasos–Dorotea slope system built (Covault et al. 2009; Fildani et al. 2009; Romans et al. 2010).

The recognition of slope clinothems ranging from 100s to 1000s of meters thick in the geologic record demonstrates that basin margin relief, on its own, does not control their development (Fig. 14).

Slope Rugosity

Many high-relief slopes are associated with salt or shale diapirism (e.g., NW Gulf of Mexico, offshore Angola, offshore Nigeria), and the link between mobile substrata and out-of-grade slopes is well established (e.g., Prather et al. 1998; Beaubouef and Friedmann 2000; Steffens et al. 2003; Adeogba et al. 2005). These systems are characterized by highly rugose slope surfaces, and the development of minibasins leads to the accumulation of variably distributed turbidite sandstone bodies (e.g., Prather et al. 1998; Adeogba et al. 2005). Because of the topographically irregular slope surfaces characteristic of these systems, and the syndepositional modification of the slope in cases such as intraslope salt-withdrawal depocenters, well-ordered clinoform systems are not typically documented from these settings. Slopes characterized by smooth clinoform profiles, however, can be associated with high-relief slopes of major continental margins, such as on the eastern seaboard of the United States, where extensive mobile substrata are not present (Uchupi and Emery 1967; Fulthorpe and Austin 1998).

Basin Shape and Sedimentary Input

In theory, if the rate of sediment input outpaces the rate of slope denudation and deformation, then a smooth slope profile will be maintained. Despite significant sediment input from rivers in numerous instances, continental margins like the Gulf of Mexico (East Breaks) and West Africa do not receive sediment at a high enough rate to achieve smooth slope profiles. This is particularly true of the two aforementioned margins where mobile substrata, often driven by sediment loading, contribute to the development of substantial topographic rugosity. In contrast, the eastern seaboard of the United States receives enough fine-grained sediment to outpace nominal topographic development.

In relatively elongate basins, like the Cretaceous Magallanes and Colville foreland basins, sedimentary input is focused onto relatively narrow reaches of the continental slope. In the case of the Magallanes Basin, the north to south axially filling deep-water trough was likely on the order of 50–100 km wide (Fildani et al. 2009). Limited accommodation for major fluvial–deltaic point-source switching on shelves and for lobe switching associated with fans in narrow foredeep-slope and basin-floor depozones led to a situation where extensive sediment derived from denuding orogenic belts passed over a narrow reach of continental slope. Additionally, it seems likely that numerous small mountainous rivers represented the dominant conduits for sediment supply into the basin, enhancing sediment dispersal across the slope system. Therefore, topography that developed from processes such as growth faulting or mass wasting was inevitably healed leading to graded slope conditions and the development of clinoform geometry over time.

Most settings where high-relief clinoforms have been documented are linked with regular sediment supply sourced from active orogenic belts. Aside from the Cretaceous forelands discussed earlier, the Pliocene to Pleistocene Giant Foresets Formation of the northern Taranaki Basin, New Zealand derives its name from ~ 2200 m thick clinothem packages of which it is composed (Fig. 14; Beggs 1990; Soenandar 1992; Hansen and Kamp 2002; Scott et al. 2004). Sediment derived from the uplifting Southern Alps infilled broad extensional structures, effectively healing topographic relief on the continental slope. Continued sedimentation led to the formation and sustained progradation of high relief slope

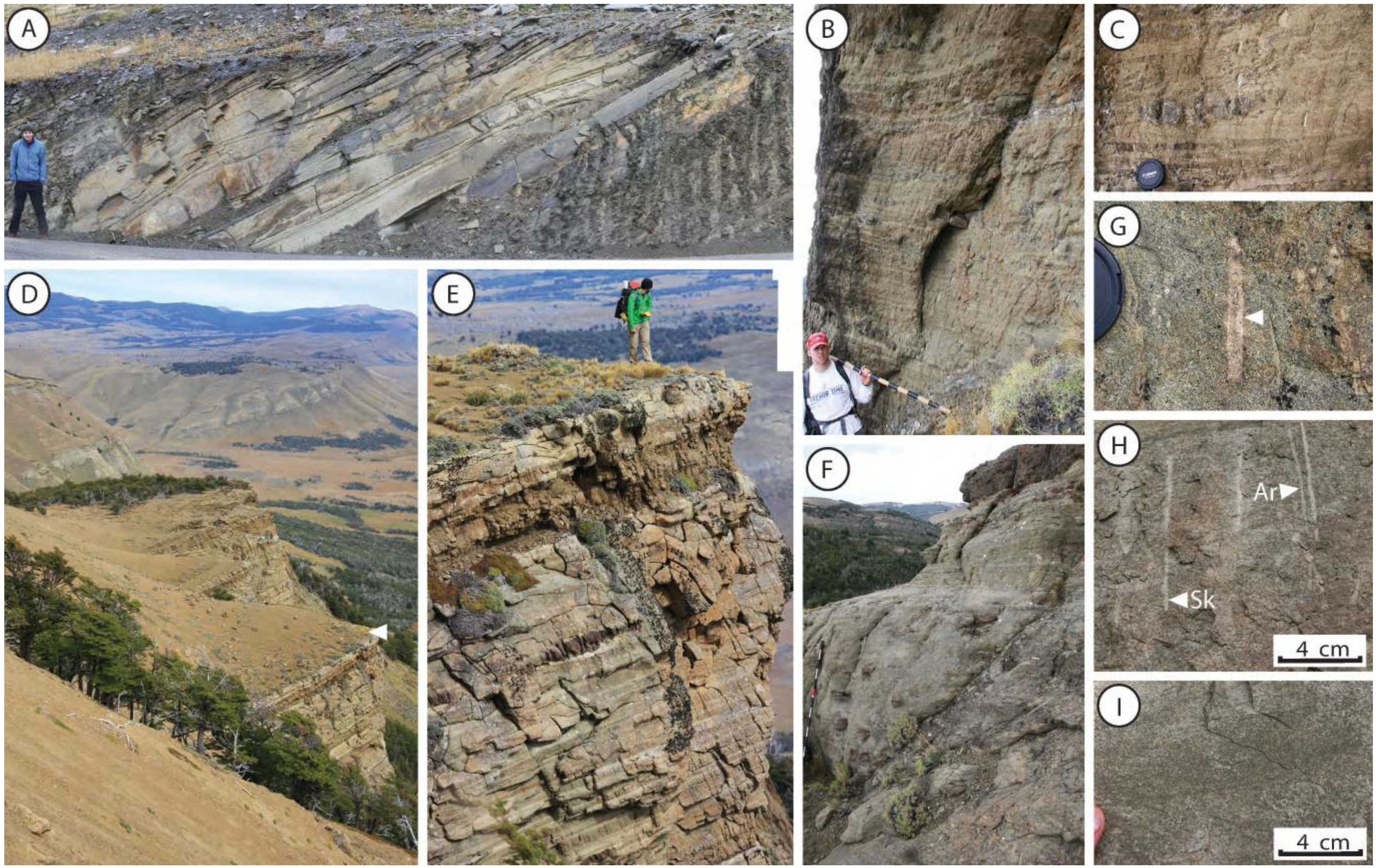

FIG. 13.—Overview of the Dorotea Formation. The ridges of sandstone mapped in satellite data are characterized by various units with features indicative of shallow marine or deltaic sedimentation within the topset of the slope clinoform system. **A)** Hummocky cross-stratification in shelf deposits at outcrop D-6. **B**, **C)** Trough-cross stratified sandstone at outcrop D-1. **D)** Southward view of resistant sandstone ridge from location D-2 (Fig. 3). **E)** Traction-structured marine sandstone. Person for scale in location demarcated by arrow in Part D. **F)** Swaley cross-stratified sandstone with the trace fossil **G)** *Shaubcylindrichnus* at outcrop D-3. **H)** A diverse ichnofossil assemblage is present in sandstones of outcrop D-4, including *Skolithos* (Sk), and *Arenicolites* (Ar). **I)** Vestigial lamination is preserved locally despite extensive bioturbation at outcrop D-4.

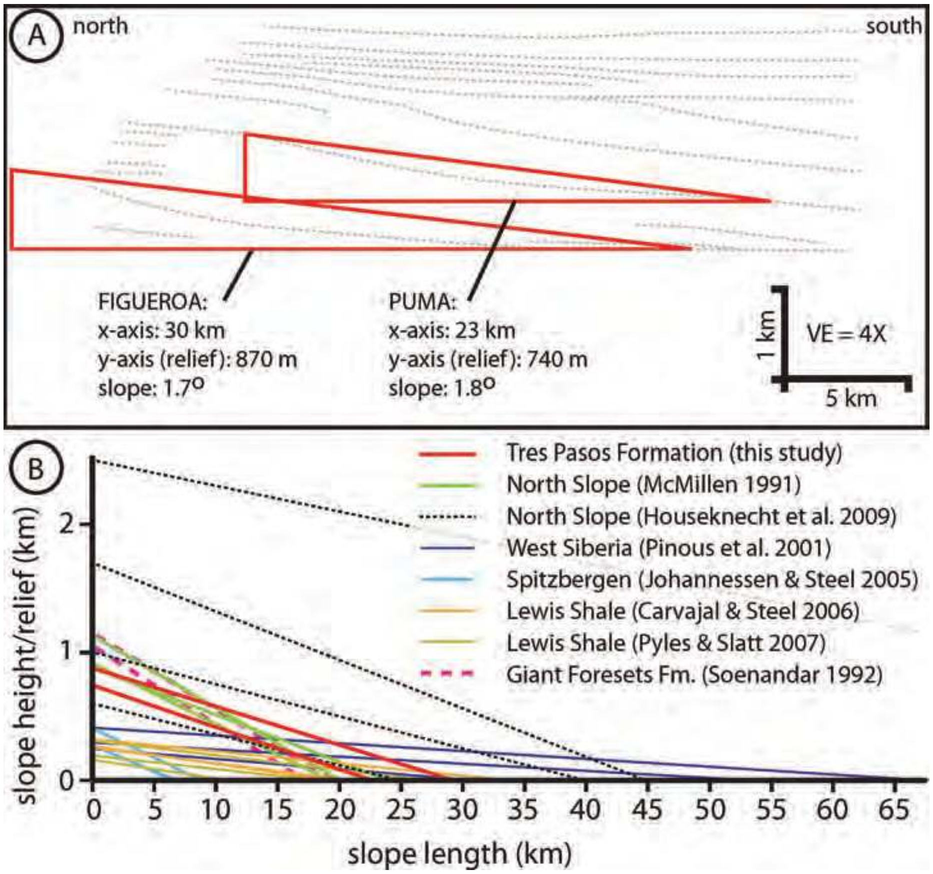

FIG. 14.—Slope clinoform scale and slope analysis. **A)** Simplified cross-section shown in Figure 4, showing shelf-edge and lower to base of slope positions used along the Figueroa and Puma surfaces in order to calculate relief and magnitude of paleoslope. Note that the measured distances on the *x* axis are minimum estimates based on outcrop interpretation of slope breaks. As a result, slope angles calculated are maximum estimates. **B)** Comparison of clinoform lengths and heights from various slope systems. Note that the definition of clinoform established by Rich (1951) is considered in the analysis, where the clinoform consists of the area of steepest slope between the shelf break (his undaform) and the base of slope (his fondoform). Of the slope systems considered, the relief and angle of the clinoforms mapped in the Tres Pasos Formation are most comparable to those of the Cretaceous North Slope, Alaska.

clinoforms north-northwestward across the northern part of the Taranaki Basin (Beggs 1990; Scott et al. 2004).

The combination or interaction of basin margin relief, slope rugosity, basin shape, and sedimentary input controls the stratigraphic architecture preserved in the slope setting. In the Magallanes Basin example, the tectonic setting contributed to the development of (1) a high-relief margin; (2) a source of sediment from the uplifting Andes; and (3) an elongate basin that funneled sediment over a narrow reach of continental slope, facilitating the widespread accretion of sediment and subsequent development of clinoforms. The history of the basin was such that substrata susceptible to mobilization, such as salt, were never deposited. Topography on the paleoslope was modest enough to have been healed by the relatively large volumes of sediment en route to the deep basin, thereby facilitating the development of a smooth slope profile and efficient transfer of sediment across the Magallanes Basin margin.

CONCLUSIONS

Slope clinoforms with at least 700–900 m of relief, measured from compacted stratal thicknesses, filled the Magallanes Basin southward along the foredeep axis during the Late Cretaceous–Paleogene. Individual clinoform surfaces are defined by overlying resistant ridges of coarse-grained strata in outcrop. The upper, flat segments of the depositional profiles (paleo-shelf) consist dominantly of fluvial- and wave-influenced deltaic deposits assigned to the Dorotea Formation. Basinward from the interpreted paleo–shelf break, upper slope deposits are dominated by mudstone and siltstone. Evidence for bypass in the upper to middle slope includes conduits filled with mudstone rip-up clasts and/or sandy conglomerate, often characterized by traction structures that show paleoflow was downslope to the south. The lower to base of slope setting was characterized by turbiditic sandstones and finer grained mass transport deposits of the Tres Pasos Formation, recording deposition at the decrease in slope gradient.

Generation of the high-relief slope clinoforms was facilitated by a number of factors that are associated with the tectonic setting. These include: (1) development of significant basin margin relief; (2) the lack of mobile substrata, resulting in the development of a relatively smooth slope profile and efficient transfer of sediment across the margin; (3) an adequate sediment supply; and (4) basin shape, consisting of an elongate depocenter where a high proportion of the sediment that was input into the basin passed over a narrow reach of slope. The slope setting was inundated by a significant volume of sediment resulting in southward accretion of the high-relief depositional system. The rate of sediment input was consistently higher than the rate of topographic development on the slope and thus, a smooth, sigmoidal profile was maintained.

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