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Sediment transfer and deposition in slope channels: Deciphering the record of enigmatic deep-sea processes from outcrop

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ABSTRACT

The processes within deep-sea sediment-routing systems are difficult to directly monitor. Therefore, we rely on other means to decipher the sequence and relative magnitude of the events related to erosion, sediment bypass, and deposition within channels that crosscut the seascape, and in particular, continental slopes. In this analysis, we examine the nature of slope channel fill in outcrop (Cretaceous Tres Pasos Formation, southern Chile) in order to evaluate the geological evidence of the full channel cycle, from inception to terminal infill with sediment, and we attempt to provide insight into the enigmatic deep-sea processes that are critical for a comprehensive understanding of Earth surface dynamics.

In the stratigraphic record, slope channel fills are typically represented by sandstone- or conglomerate-dominated deposits that define channelform sedimentary bodies tens of meters thick and hundreds of meters across. Despite the prevalence of coarse-grained sediment, key information is recorded in the fine-grained deposits locally preserved within the channelform bodies, as well as a breadth of scours or internal channelform stratal surfaces. These characteristics preserve the record of protracted sedimentary bypass and erosion. In many instances, the life of a slope channel is dominated by sedimentary bypass, and the stratigraphic record is biased by the products of shorter-lived channel filling and abandonment.

INTRODUCTION

Channels on the continental slope and other high-relief basin margins are important conduits for sediment transfer from non- and shallow-marine environments to deep-water basin-floor settings. As such, they feed the greatest accumulations of detritus on the modern seafloor at the ends of continent-draining, sediment-routing systems, and their deposits hold a wealth of proxy information about past climate and other perturbations to Earth systems (e.g., Clift and Gaedicke, 2002). Moreover, the transfer of nutrients, pollutants, and organic carbon to the deep sea by the flows that traverse these conduits influences marine biota, including fisheries valuable to human communities, and the global inventory of carbon on Earth's surface (Lyons et al., 2002; Syvitski et al., 2005; Galy et al., 2008). Submarine channel deposits can also be hosts for significant oil and gas resources (Samuel et al., 2003; de Ruig and Hubbard, 2006; Mayall et al., 2006; Kane et al., 2013). The history of deep-water sediment dispersal and channel filling recorded in sedimentary rocks has the potential to reveal the relative tempo of processes and associated conveyance of sediment across seascapes. This is significant, as up to this point, direct monitoring of coarse-grained sediment transport in our oceans is extremely difficult, and therefore poorly constrained.

Slope channel deposits preserve a variable record of sediment transfer across ancient basin margins. Sandstone-dominated channel fill tends to bias the stratigraphic record toward the preservation of channel-filling processes at the expense of the record of potentially long-lived sediment bypass. Heterolithic intra-channel fill is characteristic of numerous slope systems (e.g., Sullivan et al., 2000; Hodgson et al., 2011; Pyles et al., 2010). We hypothesize that in these heterolithic intrachannel fill deposits, a more complete record of sediment transfer is preserved, thereby revealing a more complete perspective of channelized deep-water sedimentation, from inception to terminal infill. That is, the stratigraphic architecture described and sedimentary processes interpreted from these heterolithic deposits will shed light on the history of a channel as a conduit for submarine sediment dispersal relative to merely accommodating the deposition of sand. Furthermore, multiscale insights from the stratigraphic evidence of channelization are necessary to improve recent efforts to quantify sediment transfer and deposition within a mass-balance framework (e.g., Paola and Martin, 2012).

In this study, we consider deep-water channel strata of the Cretaceous Tres Pasos Formation that crop out in the Magallanes Basin of Chilean Patagonia. These outcrops provide three-dimensional exposure at a range of scales, including scales typically characterized only in seismic-reflection data sets (up to kilometer scale spatially, hundreds of meters stratigraphically), as well as the bed and finer scales that are common to outcrops. With this perspective, fine-scale facies information can be placed within the framework of channel architecture, which allows examination of the relative contributions of different sedimentary processes in the history of channelization.

The Tres Pasos Formation channel segment of interest developed along an intraslope point on the Cretaceous basin-margin profile, i.e., downdip of canyons and updip of turbidite depositional environments characteristic of the base of slope (Hubbard et al., 2010). Therefore, this point is transitional with regards to erosion-dominated processes upslope and deposition-dominated processes on the basin floor. This paleoslope position led to preservation of deposits that provide an inclusive perspective of channel-fill components, recording widespread evidence for erosion, sediment bypass, and deposition. We provide recognition criteria for these fundamental stratigraphic components, and we assess their broad applicability to slope channels for a range of submarine settings. Finally, we consider the temporal significance of submarine channel fill, and we hypothesize on the relative longevity recorded by the fundamental stratigraphic components.

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Slope Channel Fill

Slope channels and their deposits have been the focus of extensive research over the past two decades (e.g., Clark et al., 1992; Peakall et al., 2000; Gardner et al., 2003; Posamentier and Kolla, 2003; Sylvester et al., 2011; Kane et al., 2013), largely in response to challenges in exploration and development of deep-water reservoirs on continental margins (e.g., Samuel et al., 2003; Mayall et al., 2006). Opportunities to study these deep-water geomorphic and stratigraphic features on the seafloor and in the subsurface have historically been limited because of the inherent difficulty in directly or remotely accessing modern seascapes. Unlike flow within rivers on Earth's surface, large turbulent currents that transport significant volumes of coarse-grained material across continental slopes have rarely been monitored, with the exception of indirect means such as seafloor cable breaks (Piper et al., 1988). Technological advances in high-resolution seafloor imaging and three-dimensional seismic-reflection data acquisition have resulted in unparalleled perspectives of deep-water channel systems (e.g., Pirmez et al., 2000; Babonneau et al., 2002; Deptuck et al., 2003; Normark et al., 2009; Labourdette and Bez, 2010; Dalla Valle and Gamberi, 2011; Maier et al., 2011; Paull et al., 2013). These advances have provided insights into submarine-channel architecture (e.g., leveed channels, stratigraphically complicated slope-valley turbidite systems, and complexes of nested channels), and inspired reevaluation of slope channel units that crop out in mountain belts around the world (Gardner et al., 2003; Beaubouef, 2004; Campion et al., 2005; Kane et al., 2007; Crane and Lowe, 2008; Hodgson et al., 2011; Gamberi et al., 2013).

Conduits on slopes or within slope strata are considered at multiple physical scales (Fig. 1). Channelform features mapped in three-dimensional seismic volumes range from hundreds to thousands of meters across and tens to hundreds of meters thick (e.g., Morris and Normark, 2000; Samuel et al., 2003; Mayall et al., 2006; Porter et al., 2006; Cross et al., 2009; Jobe et al., 2011; Janocko et al., 2013). The largest of these represent composite features that consist of numerous smaller channelform bodies (e.g., Gardner and Borer, 2000; Campion et al., 2005; Schwarz and Arnott, 2007; Hubbard et al., 2009; Di Celma et al., 2011). These smaller channelform bodies are considered herein as slope channel fills, which are most commonly observed in outcrop or high-resolution subsurface data (Fig. 1). Slope channels are typically less than 400 m wide and less than 30 m thick (Fig. 1; McHargue et al., 2011). The fill of these relatively small-scale conduits, or fundamental slope channels, is the focus of this study.

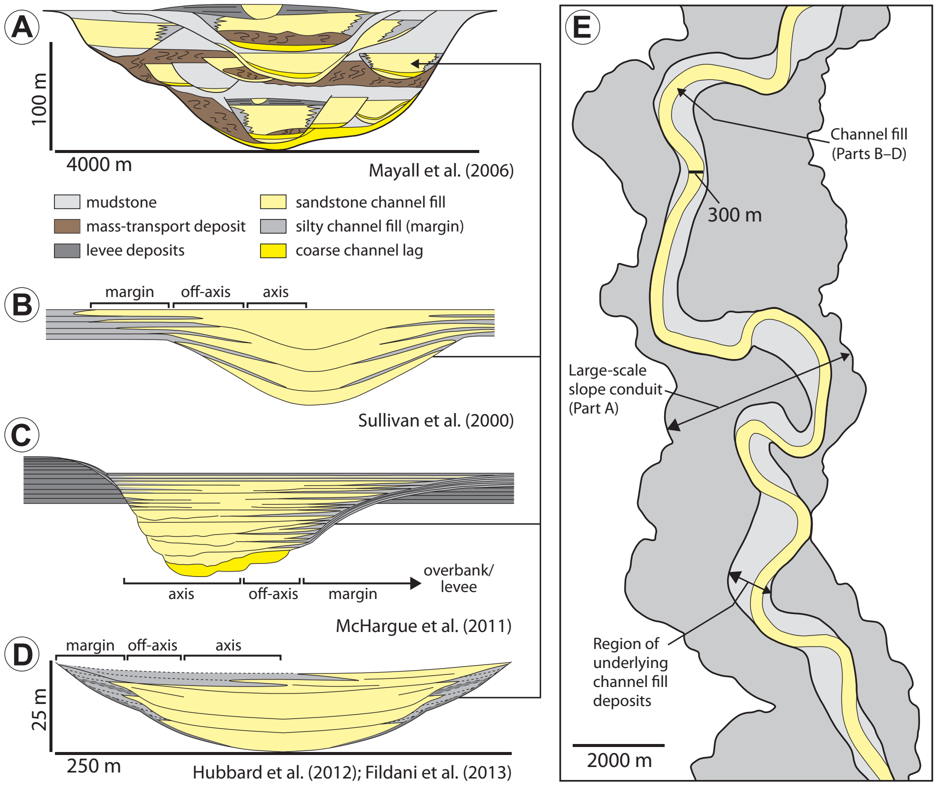

Figure 1. Two-dimensional schematic cross sections and map of channelform sedimentary bodies common in slope strata, emphasizing a broad range of scales. (A) Channelforms greater than 1000 m across and 50 m thick generally represent composite features, composed of numerous smaller channelform bodies, as well as voluminous deposits attributed to submarine mass wasting. These large-scale features are commonly observed in seismic-reflection data. (B–D) Examples of smaller channelforms, generally less than 300 m wide and 30 m thick. These features stratigraphically stack within the larger channelforms, as in part A, yet are commonly difficult to resolve in seismic-reflection data. They are most commonly documented in outcrop. (E) Planform view of channelforms traced from a three-dimensional seismic-reflection volume (modified from Deptuck et al., 2003).

STUDY CONTEXT AND METHODOLOGY

The Magallanes retroarc foreland basin (known as the Austral basin in Argentina) formed in response to Andean uplift during the Late Cretaceous (Biddle et al., 1986; Wilson, 1991; Fildani and Hessler, 2005; Fosdick et al., 2011). Deep-water conditions persisted in the basin for 20 m.y., attributed to a backarc basin heritage (Rocas Verdes basin) and the formation of underlying attenuated continental crust (Romans et al., 2010). The deep-water basin was eventually filled axially, from north to south, by a prograding clinoform system that linked slope turbidite systems of the Tres Pasos Formation to coeval shelf-edge deltaic strata of the lithostratigraphically overlying Dorotea Formation (Hubbard et al., 2010). The strata of interest in this study are interpreted to have been deposited at an intraslope slope position along a high-relief (>900 m) clinoform that formed as the bathyal Magallanes foreland basin filled (Hubbard et al., 2010; Romans et al., 2011).

The Upper Cretaceous Tres Pasos Formation consists of 300 m of slope channel strata in the vicinity of Laguna Figueroa, Ultima Esperanza District, southern Chile (Fig. 2; Katz, 1963; Smith, 1977). The deposits of at least 25 slope channels are present at Laguna Figueroa, separated into two distinct packages of sandstone-dominated strata (Fig. 2C). The lower of these was studied in detail by Macauley and Hubbard (2013). The analysis of a single channel fill, the "GC channel," which is present in the upper stratal package, provides the basis for this study

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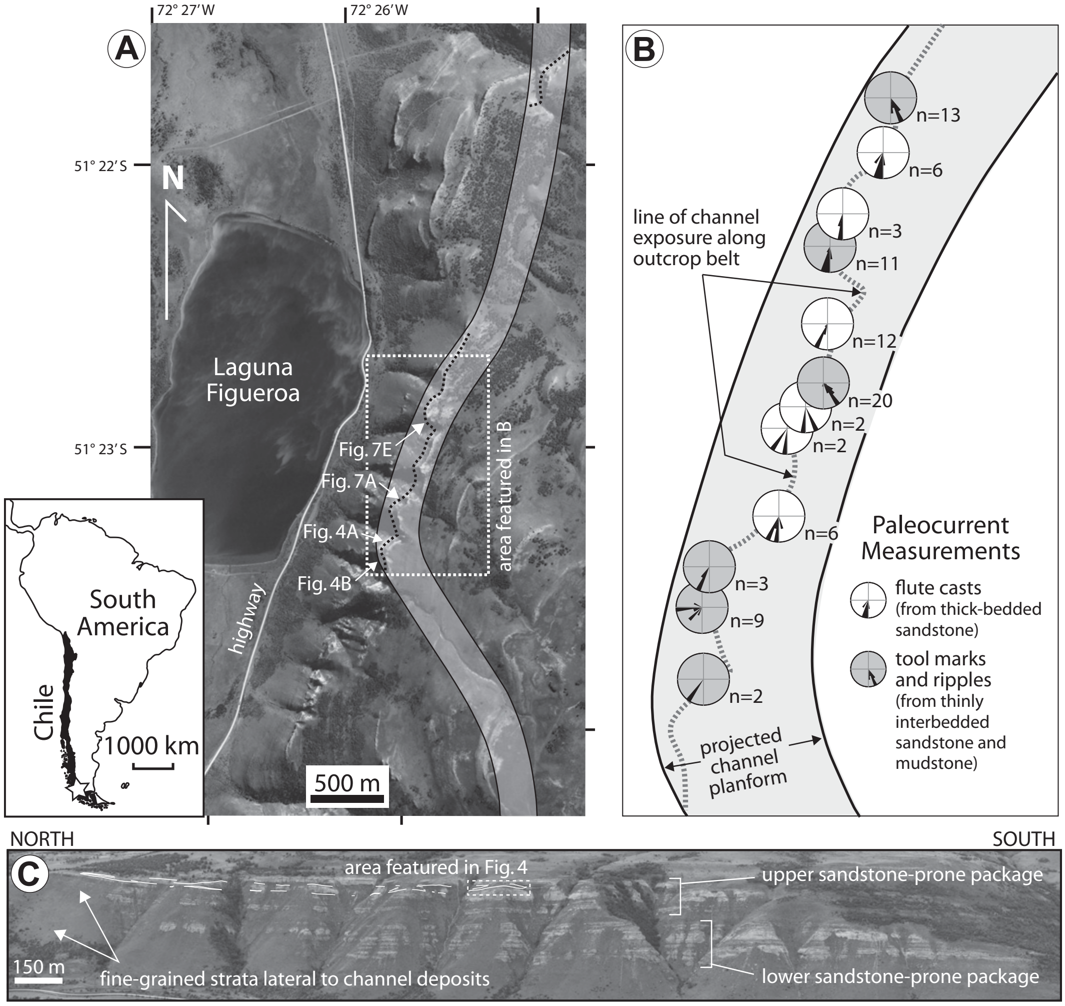

Figure 2. Study area overview. (A) Satellite image of the Tres Pasos Formation outcrop belt adjacent to Laguna Figueroa, with the mapped outline of GC channel fill. Inset map provides the location of the study area in southern Chile. (B) Close-up perspective of area highlighted in white box in part A, showing the outline of GC channel and summarizing paleocurrent data, which generally indicate southward flow. (C) Photomosaic of the outcrop belt, with the GC channel fill highlighted near the top of the exposure (the dotted black line in part A corresponds to the outcrop intersection of the GC channel deposit). Note that a dip-oriented perspective is exposed, which yields numerous three-dimensional views of the channel along the 1.5-km-long transect.

(Fig. 2). GC is an acronym for "Gabriela Channel," after Chilean Nobel Prize laureate Gabriela Mistral, who wrote a collection of poems while visiting the area of Laguna Figueroa (Mistral, 1922). The GC channel fill is best exposed in a series of gullies along a 1.5-km-long outcrop transect (Fig. 2); two- and three-dimensional exposures of channel deposits were documented with diferential GPS surveying, photomosaics, and bed-scale sedimentological analysis.

The complex of channels that includes GC channel is up to 110 m thick (Fig. 2C). GC channel deposits are incised into, and locally incised by, other similar channel bodies within this complex (Fildani et al., 2013). The entire, composite sandstone-prone sedimentary body is laterally encased by poorly exposed (vegetated), mudstone-prone turbidites (Fig. 2C). The aggradation of channel fills within the complex suggests that these out-of-channel turbidites are levee deposits (Macauley and Hubbard, 2013; cf. Deptuck et al., 2003; Kane and Hodgson, 2011).

OUTCROP CHARACTERISTICS

Sedimentary Facies

We describe the fill of Tres Pasos Formation slope channels according to a hierarchy of stratigraphy in which no a priori interpretive descriptors are appended to components at any hierarchical level, and which is open ended at the largest scale (cf. the tenets of the fluvial hierarchy of Miall, 1985; the deep-water hierarchy of Ghosh and Lowe, 1993; and Hickson and Lowe, 2002). Beds, sedimentation units, and component sedimentary structures are the fundamental order of observation. Sedimentation units are interpreted to represent deposition from a single sediment gravity flow (e.g., a turbidity current or a debris flow). Internal divisions within sedimentation units rely upon descriptive characteristics outlined by Bouma (1962) and Lowe (1982). Grouped beds and their interpreted sedimentation units of similar affinity constitute the next order of observation, i.e., facies, which are the basic mappable components of the channelform sedimentary body. Facies are described and interpreted next.

Mudstone-Prone Facies

Mudstone-prone facies include sedimentation units that are 1–10 cm thick and characterized by sharp basal contacts (Fig. 3A). Individual sedimentation units are normally graded, from very fine– and fine-grained sandstone to siltstone and mudstone. Proportionally, the siltstone and mudstone components represent >70% of each sedimentation unit (Fig. 3A). Physical sedimentary structures dominantly consist of current ripples (Bouma T_c division) in sandstone layers through silty planar lamination upward (Bouma T_{d-e} divisions). The facies is typically <20 cm thick; however, it is up to 100 cm thick locally. Mudstone-prone facies are interpreted to preserve the deposits of dilute, low-density turbidity currents, as well as the subsequent suspension sedi-

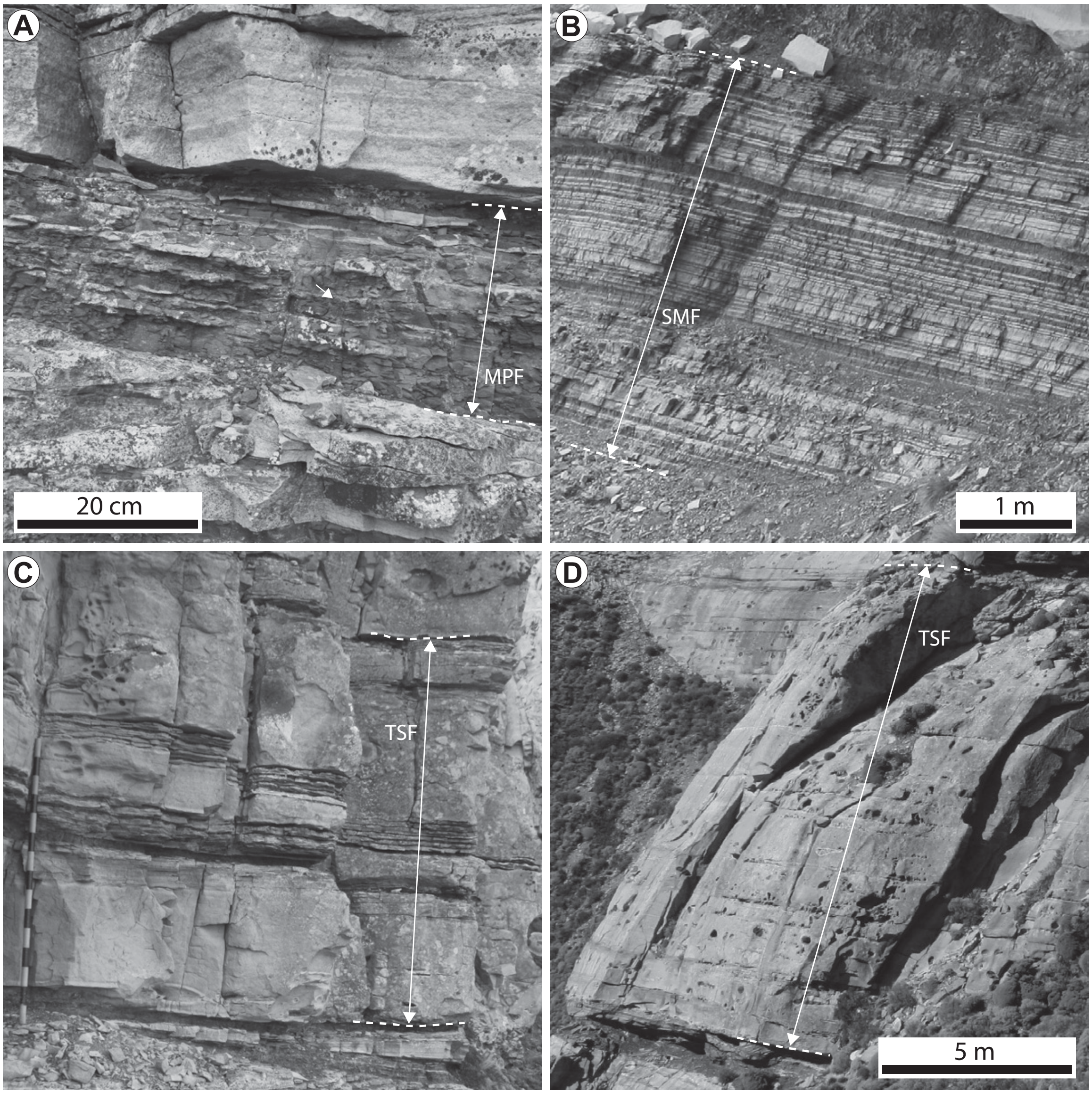

Figure 3. Facies of the GC channel fill. (A) Mudstone-prone facies (MPF). (B) Thinly interbedded sandstone and mudstone facies (SMF). (C) Thick-bedded sandstone facies (TSF). Jacob staff marked with 10 cm increments. (D) Thick-bedded sandstone bound by amalgamation surfaces (TSF).

mentation of fine-grained material that accumulated between turbulent transport events (Bouma, 1962).

Thinly Interbedded Sandstone and Mudstone Facies

Sandstone and mudstone facies constitute beds that are 5–30 cm thick (Fig. 3B). Individual sedimentation units are characterized by sharp and commonly undulating basal contacts overlain by fine-grained, and rarely medium-grained, sandstone. The sandstone is 4–15 cm thick and normally grades upward into siltstone and mudstone. The sandstone component typically makes up the majority of the thickness of each sedimentation unit (Fig. 3B). Sandstone is dominated by planar or ripple lamination (Bouma T_{b-c}), and the overlying fine-grained material is either laminated or massive (Bouma T_{d-e}). The facies is up to 12 m thick. Overall, it is interpreted to record deposition from low-density turbidity currents (Bouma, 1962).

Thick-Bedded Sandstone Facies

Sandstone sedimentation units 25–400 cm thick are characterized by sharp bases that are commonly undulatory (<1 m relief; Figs. 3C and 3D). The units are normally graded, with very coarse-grained sand- to pebble-sized clasts locally preserved in the strata within 50 cm of basal bed contacts. Upward, the sedimentation units transition from medium- to fine-grained sandstone, and, locally, a siltstone cap is preserved. Nearly the entire thickness of each sedimentation unit is composed of sandstone (Figs. 3C and 3D). Sandstone is largely massive appearing (Bouma T_a), with planar and/or ripple lamination (Bouma T_{b-c}) sometimes preserved in the upper 50 cm of sedimentation units. Diffuse internal stratification within the thick sandstone is locally apparent. Both angular and rounded mudstone clasts are locally significant, typically present overlying bed bases, ranging from 0.1 to 1 m in diameter. These mudstone clast conglomerates are rarely associated with low- to highangle planar to wavy cross-stratification (i.e., T_t of Lowe, 1982). Thick-bedded sandstone facies sedimentation units stack up to 24 m thick (Fig. 3D). The units can be either in erosional contact (amalgamated; Fig. 3D), or separated by thin (<10 cm) beds of mudstone (Fig. 3C). The thick sandstone sedimentation units are typically flat lying across the extent of the studied strata, with differential erosion imparted by subsequent turbidity currents, resulting in bed thickness variation. A lack of grain-size contrast across many amalgamated bed contacts limits a more thorough analysis of their continuity in three dimensions. Thick-bedded sandstone facies are attributed to the collapse of high-density turbidity currents, and bed-load traction reworking of sediment beneath high-energy turbulent gravity flows (cf. Lowe, 1982). Recent work has also hypothesized that massive sandstone and diffuse internal stratification could be attributable to internal hydraulic jumps within turbidity currents (Postma et al., 2009). The locally preserved planar and ripple laminations in the upper sections of sedimentation units are interpreted to represent traction sedimentation during a final stage of low-density turbidity current deposition (cf. Lowe, 1982).

Stratal Surfaces

The slope channel fill in the Tres Pasos Formation is dominated by recurring stratal surfaces that can be correlated and mapped at lateral scales of tens to hundreds of meters (Figs. 4 and 5).

Primary Channelform Surface

The most recognizable surface associated with a channelform sedimentary body is the one that defines its base and sides (Fig. 4). For the GC channel, this primary surface separates the channel fill from genetically unrelated strata, including older channel-fill deposits. The basal channelform surface is estimated to be 250–300 m wide and is characterized by up to 24 m of relief (concave upward); it can be traced along the entire length of the outcrop belt examined, or ~1.5 km. This surface is generally smooth, but it can be characterized by local notches, or steps, along its margins (Fig. 4).

Secondary, Internal Channelform Surfaces

Secondary surfaces that truncate beds are present within the channel fill, and they are estimated to be 200–250 m wide and characterized by 3–6 m of erosional relief (concave upward; Fig. 5). These surfaces are typically only preserved locally and cannot be traced more than a few hundred meters downdip, along the channel. The secondary surfaces are generally smooth. These secondary channelform surfaces formed within, and are typically aligned or subaligned with, the underlying and larger, primary channelform surface. An intrachannel sedimentary body defined and separated by these surfaces has been referred to as a "storey" by other workers (e.g., Sprague et al., 2005; Campion et al., 2005; Pyles et al., 2010), based on previous analyses of similar intrachannel stratal hierarchical patterns within fluvial strata (Friend et al., 1979).

Channel Planform

The GC channel deposit is exposed over 1.5 km adjacent to Laguna Figueroa, with modern erosional gullies providing local three-dimensional perspectives (Fig. 2B). The channel intersects the outcrop at a highly oblique angle, such that only the right bank of the channelform,

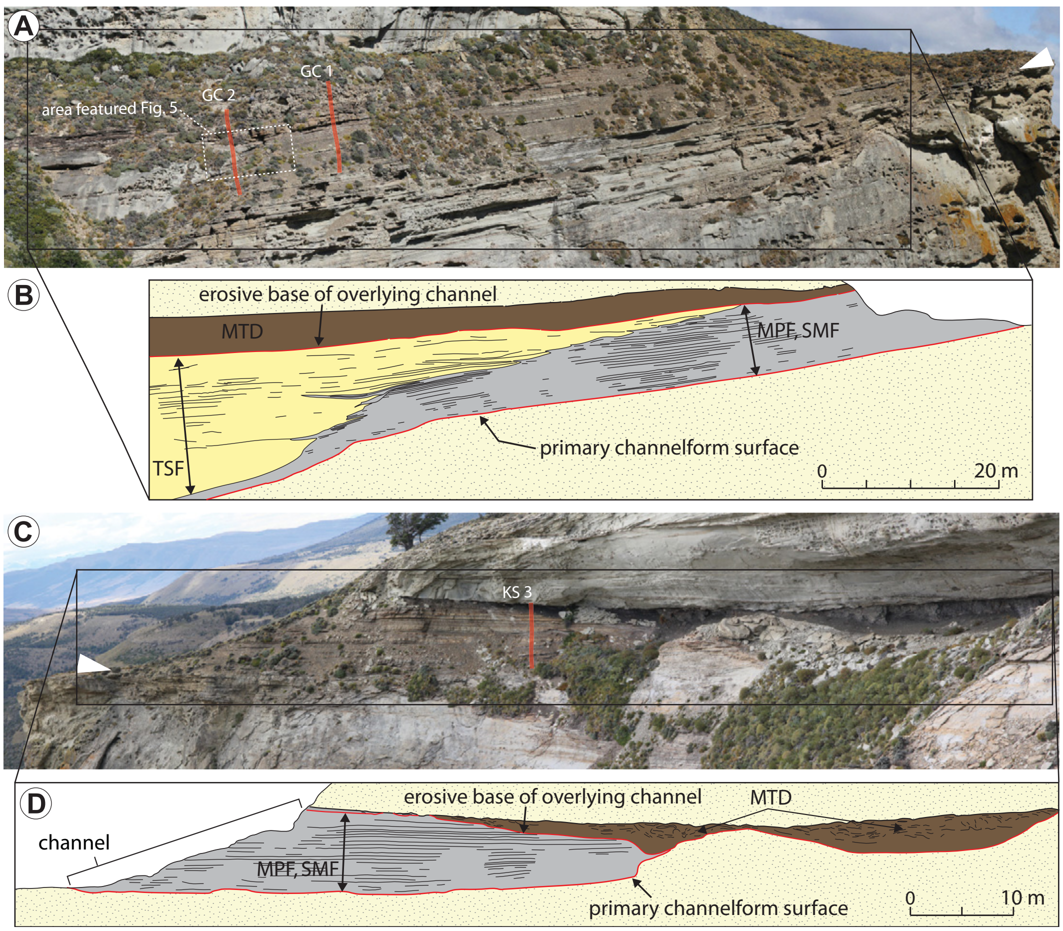

Figure 4. Basal surface and intrachannel facies distributions of the GC channel fill. (A) Sandstone-dominated channel axis deposits (TSF) transitioning to more heterolithic facies (SMF and MPF) toward the channel edge. (B) Line-drawing trace of main stratigraphic features of section in part A. Note the presence of overlying mass-transport deposits (MTD). (C) Pinch-out of channel showing heterolithic channel margin facies (SMF and MPF) onlapping onto the channel edge. (D) Line drawing trace of main stratigraphic features in part C. Photo locations are shown on Figure 2A.

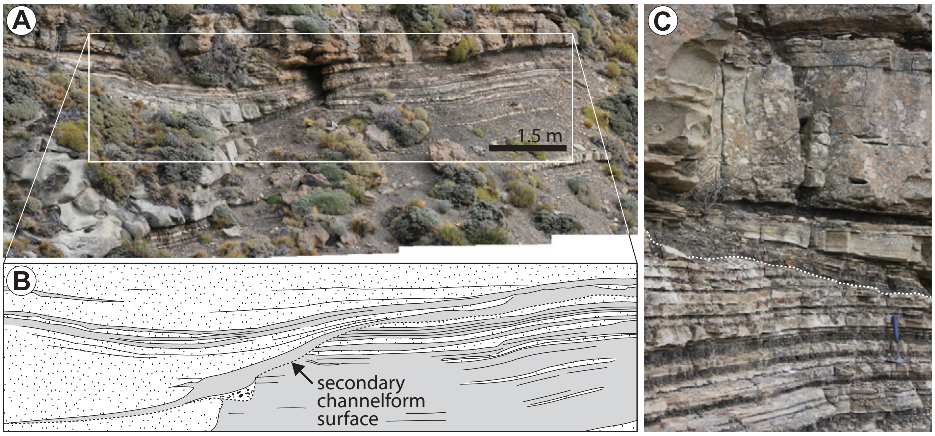

Figure 5. Secondary, internal channelform surfaces. (A) Erosional contact between a portion of the sandstone-dominated channel axis at left and the heterolithic channel margin to the right of the photo. (B) Line-drawing trace of area highlighted in part A; note the siltstone drape on top of the erosional surface (demarcated by dashed black line). See location of photo in Figure 4A. (C) Draped internal channelform surface, defined by white dashed line. Location is section KS 7 (Fig. 6B).

through to its axis, is exposed (Fig. 6). The outcrop transects an outer bend of the low-sinuosity channel (sinuosity ratio = 1.1 over entire 5.5-km-long outcrop; Fig. 2), as mapped from facies relationships (i.e., axial through marginal transitions), decimeter-scale-resolution global positioning system (GPS) surveying of the channel edge, and paleocurrent measurements taken from sole marks and ripples (Figs. 2B and 6). The full channel width (300 m) is estimated from the aforementioned direct observations of the GC channel deposit, combined with observations of other channel bodies in the Laguna Figueroa outcrop belt (Macauley and Hubbard, 2013), and supported with geometrical data sets derived from outcrop and subsurface strata (McHargue et al., 2011). The projected low sinuosity of the GC channel fill leads to a simplified channel reconstruction that is near symmetrical in strike-oriented cross section (Fig. 1D).

RECORD OF CHANNEL PROCESSES

The facies and stratal surfaces identified in the Tres Pasos Formation constitute predictable channel fill, both in a vertical stratigraphic sense and from axis to margin (Figs. 1 and 6). From the aforementioned fundamental observations, a series of channel-forming and channel-filling gravity flow processes are deduced.

Erosional Turbidity Currents that Sculpt the Channel Base

The primary channelform surface is interpreted to have been created through incision of the seafloor by a series of high-energy, turbulent gravity flows (cf. Elliott, 2000; Fildani et al., 2013). The notched, or stepped, profile may indicate that the process of channel formation involved multiple phases of erosion to different depths (Fig. 7). Alternatively, the notched profile may have been created as a result of different degrees of scour, controlled by variable resistance to erosion by underlying deposits. Coarse-grained sediment is generally not preserved directly overlying the primary channelform surface. A thin-bedded unit, typically <2 m thick, locally drapes the channel base (Figs. 7A and 7C). This drape deposit largely consists of mudstone-prone and thinly interbedded sandstone and mudstone facies. The drape is preferentially preserved beneath the outer margins of the channel, such that it is completely absent or significantly reduced in thickness over the central third of the cross-sectional channel width (Fig. 6). Such drape units are attributed, in part, to deposition from the low-density tails of the largely bypassing turbidity currents that eroded the channel (cf. Mutti and Normark, 1987). Locally, rip-up clasts are present within drape units (Fig. 7C). Instability of thin-bedded facies on channel margins is interpreted to have resulted in mass wasting and the local accumulation of slump blocks at the base of the channel; alternatively, thin-bedded facies could have been plucked from channel margins by energetic gravity flows and deposited at the base of the channel. The variety of facies observed just above the basal erosion surface, associated with multiple erosion surfaces (Fig. 7C), suggests that the channel was a dynamic environment impacted by numerous, varied currents and processes, long before it was infilled with sand.

Erosional Turbidity Currents that Sculpted and Bypassed the Intrachannel Environment

Substantial erosion within the channel is recorded by the secondary, internal channelform surfaces (Fig. 5). The surfaces are commonly draped with fine-grained, largely mudstone-prone facies (Figs. 3A and 5), which is also a common constituent of the drapes deposited directly overlying the channel base (Figs. 4 and 7C). The origin of these facies is considered to be the dilute tails of turbidity currents that: (1) largely bypassed the channel environment (cf. Mutti and Normark, 1987); or (2) deposited sand only in the axial portions of the channel (Figs. 8A–8B). This drape is typically not present in the channel axis setting, because it has been eroded by subsequent flows (Fig. 5; Barton et al., 2010). Internal channelform surface drapes attributed to bypassing currents that are preserved in the channel margin setting are distinguished from the other thin-bedded facies because they are much finer grained overall, typically lacking appreciable sandstone (Fig. 6C).

Depositional Turbidity Currents

Volumetrically, the thick-bedded sandstone facies dominates the channel fill from axis to margin (Fig. 6). Individual turbidites are up to 4 m thick and amalgamated in the central portion of the channel fill. They are notably more tapered and less amalgamated toward the edges and top of the channel fill (Fig. 8A). Where the beds taper at the edges of the channel, they are characterized by more traction structures, including cross-bedding and planar stratification (Figs. 3A and 8C). In these locations, the erosive bases of sandstone beds are cut into fine-grained units of thinly interbedded sandstone and mudstone facies (Fig. 8). Erosion and entrainment of relatively fine-grained interbeds into turbulent currents might have been responsible for enrichment of mudstone clasts within thick-bedded sandstone in off-channel-axis positions (Figs. 6C and 8D).

The turbidity currents that are interpreted to have deposited the thick-bedded sandstone facies in the channel apparently did not deposit sand directly against the erosive edges of the primary channelform surface. Instead, the sandy portions of the flows were underfit relative to the full channel width, and deposits of the upper, more dilute and fine-grained-sediment–bearing portions of the turbidity currents lapped onto or draped the edges of the channel (Figs. 4C, 6C, and 8A). The deposits of these upper portions of flows are interpreted to be the dominant constituent of thinly interbedded sandstone

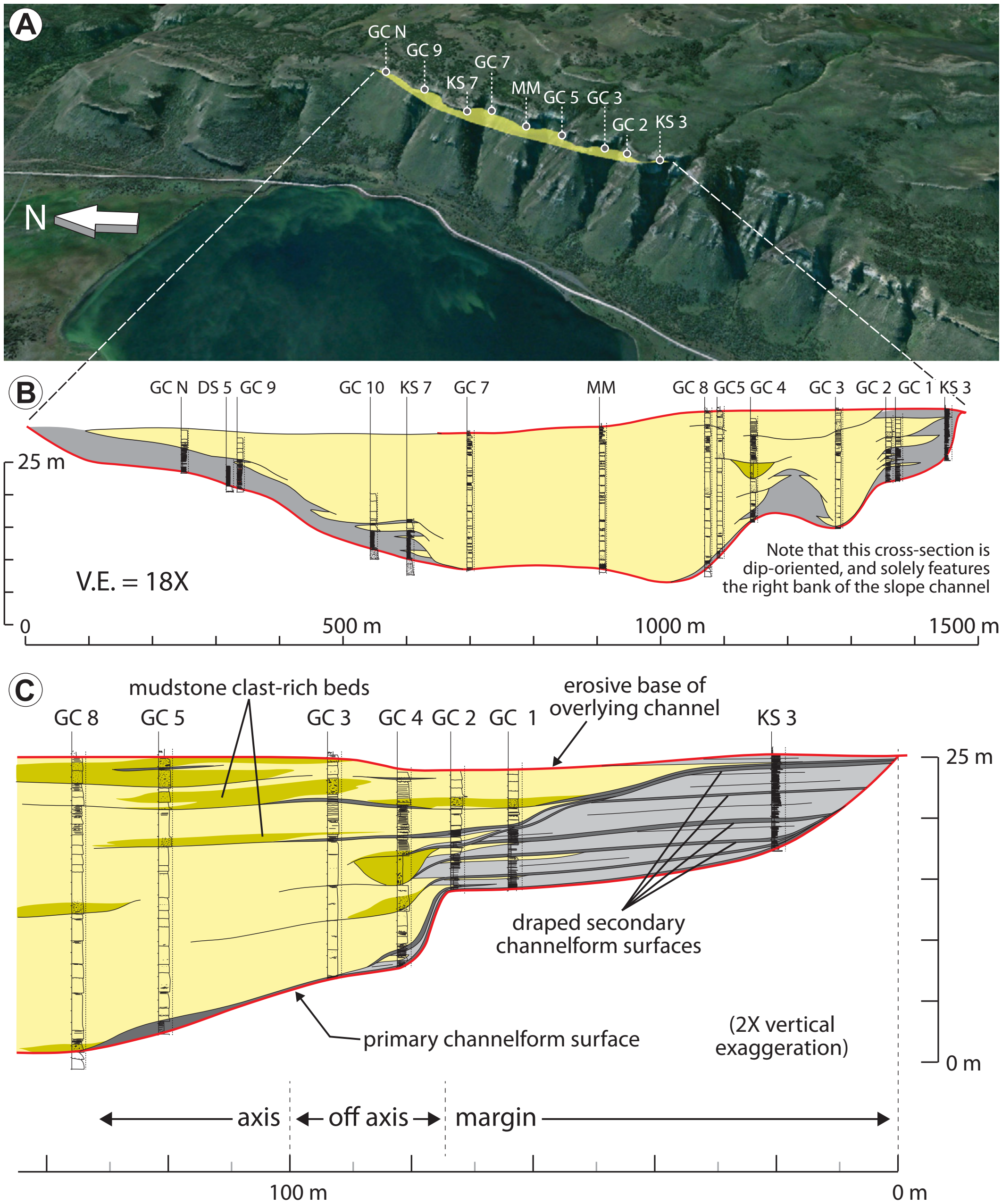

Figure 6. Overview of the GC channel fill. (A) Oblique view of satellite image draped onto a digital elevation model of the study area showing the position of GC channel in the outcrop belt. Note that paleoflow was southward. (B) Cross section constructed with measured stratigraphic sections taken along the length of the outcrop belt, with six section locations shown for reference in part A. Only the right edge of the channel is exposed along an outer bend of the low-sinuosity feature. (C) Detailed reconstruction of the channel in cross section showing intrachannel stratigraphic relationships from the axis through to the margin. Red line in parts B and C denote erosional surfaces. V.E.—vertical exaggeration.

and mudstone facies–prone sedimentary bodies, 6–15 m thick and up to 80 m wide, located between the primary channelform surface edges and sandstone-dominated axial fill (Figs. 6B and 6C). These are considered as "channel margin" deposits. These deposits are notably characterized by flat stratal geometry, and they are present within the channel, and not in an overbank position. Therefore, we do not interpret them to be levee units (cf. Piper and Normark, 1983; Hubscher et al., 1997; Kane and Hodgson, 2011). The composite channel margin sedimentary body is restricted in lateral extent (<80 m, limited by accommodation within the channel), which also distinguishes it from levee units (cf. Deptuck et al., 2003).

Representative end-member channel margin section KS 3 is characterized by evidence for 147 turbidite sedimentation units, whereas representative end-member channel axis section GC 8 includes only 27 units (Fig. 9). Stratigraphic relationships indicate that some thick sandstone-prone turbidites within the channel axis can thin dramatically at the channel margin (Figs. 8A and 8B); however, there is evidence for significantly more sediment gravity flow events documented within the record of channel margin facies, with more than five times more sedimentation units. Additional marginal turbidites, which do not correlate into the channel axis, are commonly truncated by the secondary, internal channelform surfaces (Fig. 5). These additional beds could represent either deposition from the tails of bypassed gravity flows and/or the marginal equivalent of a subsequently eroded axial turbidite. Although a significant proportion of the channel fill consists of sandstone-prone axial deposits, these units record a relative paucity of turbidity-current events. Rather, the channel margin stratigraphic record better honors the history of channelized erosion, bypass, and deposition.

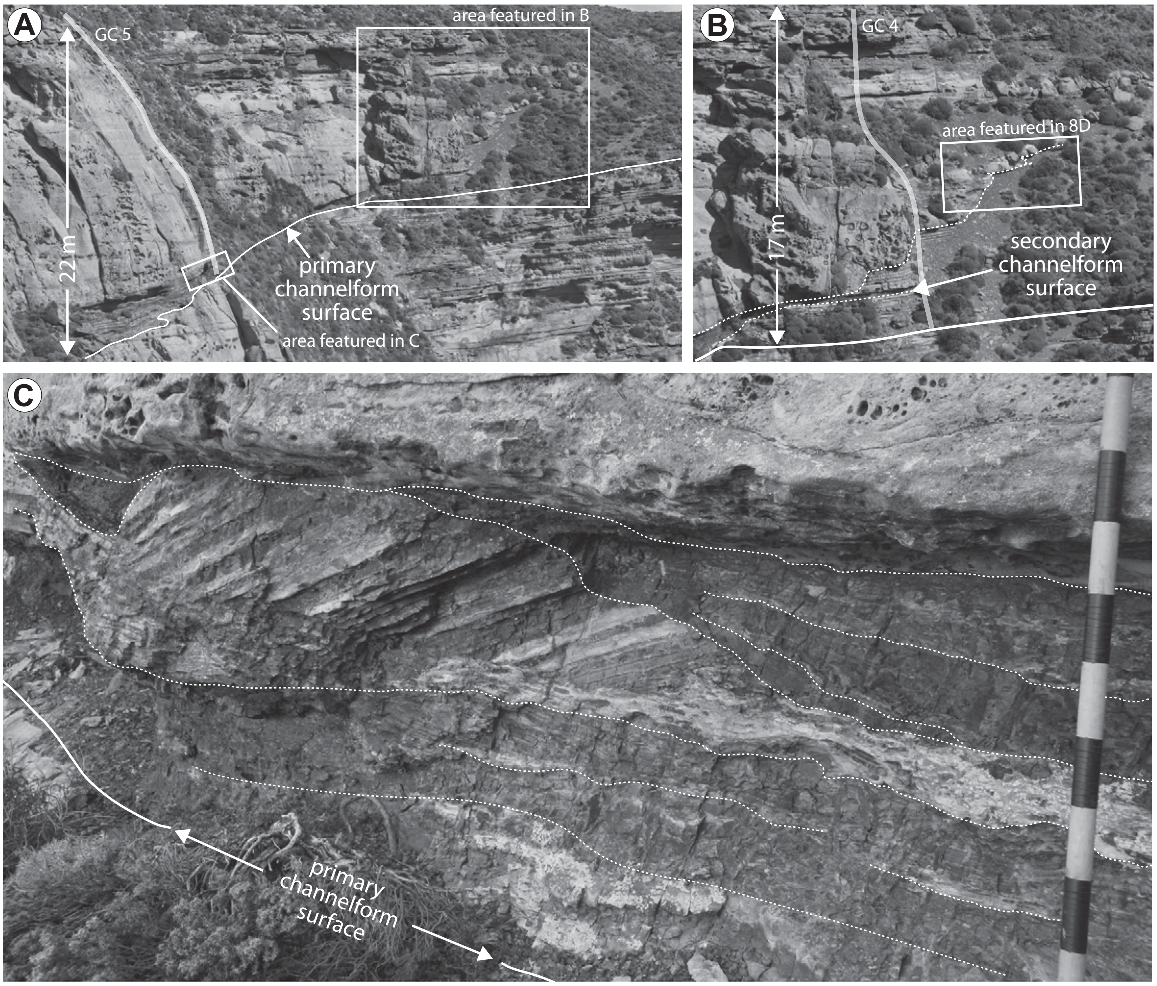

Figure 7. Detailed sedimentological characteristics of the GC channel at section locations GC4 and GC5 (Fig. 6). (A–B) Channel axis through margin transition. (C) Facies that overlie, or drape, the primary channelform surface. Numerous erosion, bypass, and mass-wasting events are often recorded in these deposits, with intradrape surfaces demarcated by white dashed lines. Location shown in part A.

Terrestrially derived organic material is locally abundant, typically at the tops of beds in both channel axis and margin units. Abundant organic material in the axis is restricted to the upper portion of the channel fill, likely related to the increased preservation of turbidite caps where this material is concentrated. The increased abundance of this detritus in the thinly interbedded marginal deposits may indicate that the final phase of channel infill was associated with increased deposition of organic debris across the entire channel setting. A trace fossil suite, consisting dominantly of robust and abundant *Ophiomorpha* in sandstone and *Thalassinoides* in mudstone, is also locally unique to these deposits (Hubbard et al., 2012). The trace fossil suite is likely closely linked to unique depositional conditions (cf. Callow et al., 2013); surface grazing structures are absent, and only opportunistic, deeply penetrating burrowers were suited to occupy deeper, better-oxygenated tiers within the substrate (i.e., thicker basal turbidite divisions).

CHANNEL EVOLUTIONARY MODEL

We interpret two broad phases of channel evolution from the GC channel and its fill. The first phase is associated with net-erosional processes and channel inception (cf. Fildani and Normark, 2004; Fildani et al., 2013), and a long-lived period of sediment bypass, recorded by the primary channelform surface and immediately overlying, draping mudstone-prone and thinly interbedded facies (Figs. 10A–10B). As proposed earlier herein, the primary channelform surface is interpreted to have been created by erosional turbidity currents. Draping thin beds are interpreted to reflect deposition from the fine-grained tails of largely bypassing currents or currents that deposited sand only in the channel axis setting (Fig. 8B). This phase of channel evolution likely represents a protracted period, as evidenced by the relief of the primary channelform surface and the large number of gravity flow events evident in the overlying drape (Fig. 7C). However, the presumed lengthy period over which a channel was primarily a sediment bypass conduit is poorly reflected by the meager preserved thickness or volume of sedimentary rock within the channel in general, and more specifically, within the basal drape (cf. Macdonald et al., 2011; Stevenson et al., 2013). The significance of sediment bypass might be best reflected by the amount of sediment present downstream of the GC channel fill segment studied. Correlations of downdip strata to GC channel have not been made; however, the sandstone-rich outcrop belt extends for greater than 20 km basinward,

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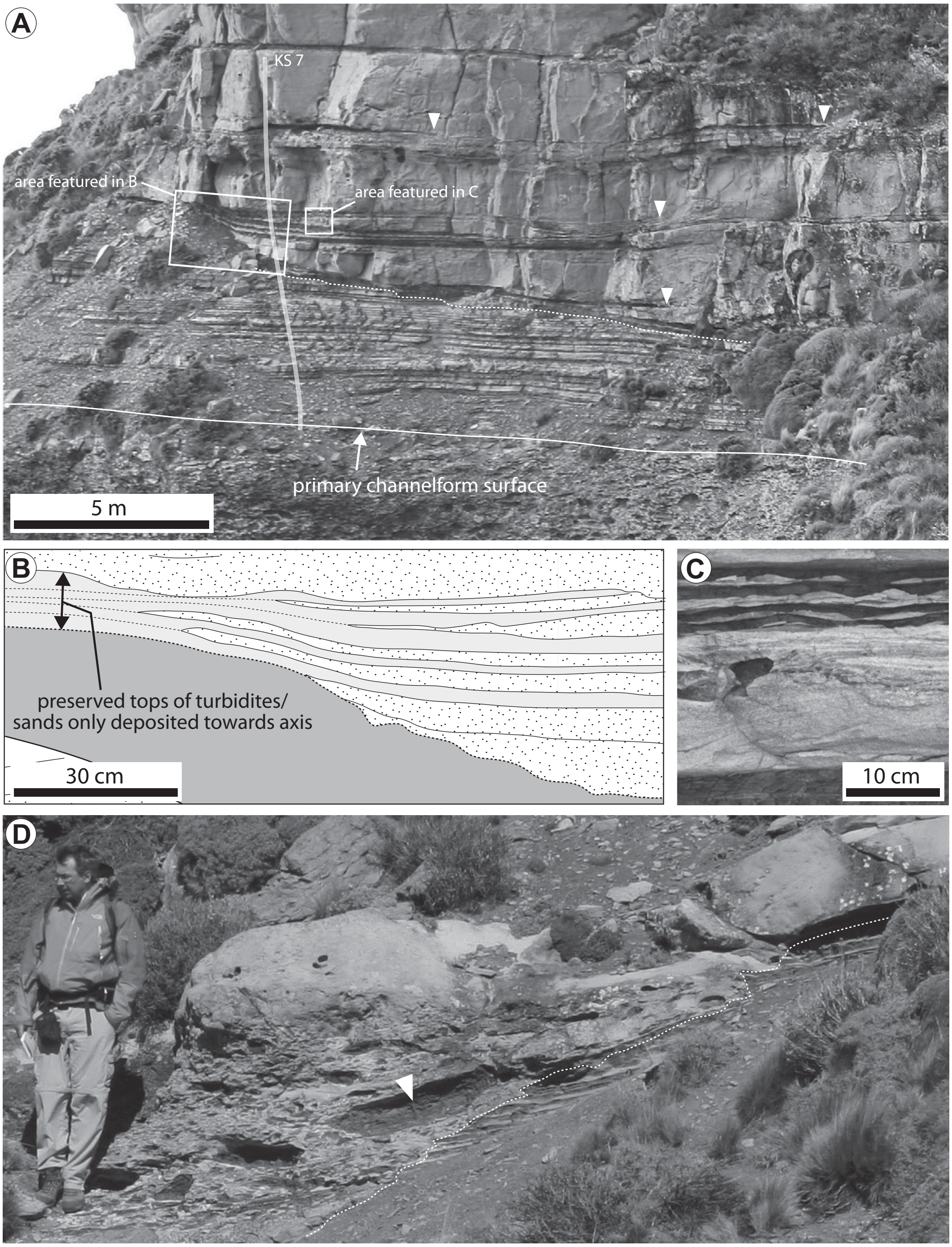

Figure 8. Detailed sedimentological characteristics of the transition from channel axis to margin deposits. (A) The coarsening-upward stratigraphic package characteristic of an off-axis to margin position within the channel. (B) Line drawing trace showing turbidites with sand deposited only toward the channel axis, and their muddy caps extending into the channel margin setting (to the left). Location of beds is indicated in part A. (C) Evidence for traction transport of sediments at the point where sands pinch out marginward, including cross-stratification in thick sandstone beds. Location is shown in part A. (D) Enrichment of mudstone intraclasts at erosional contact (dashed white line) between thick-bedded sandstone and heterolithic margin facies. Location is shown in Figure 7B.

until the strata plunge into the subsurface (Hubbard et al., 2010).

The second broad phase of GC channel evolution is associated with a greater occurrence of sand deposition from presumably highly stratified turbidity currents (Figs. 10C–10F). Turbidity-current stratification is implied from the rapid, lateral intrachannel transition from sand-sized to finer-grained facies despite a limited amount of interpreted relief on the channel base between the axis and margin (Fig. 10). Multiple erosion events led to the development of progressively higher-aspect-ratio (width:relief) secondary channelform surfaces, which modified the channel base morphology and resulted in complex channel-fill architecture (Fig. 11; cf. Pyles et al., 2010). The aspect ratio of the channel changes as accommodation is filled more rapidly in the axis relative to the margins as the channel evolves (number 2, Fig. 11). As the channel fills, the resultant aspect ratio of space available for subsequent flows to pass increases (number 3, Fig. 11); this change results in the upward bed thickening in channel margin successions (Fig. 6). The development of notches in the primary channelform surface is largely coincident with overlying marginward terminations of intrachannel sandstones, suggesting a possible influence on the fill history of the channel (Figs. 4A–4B and 6B–6C). In combination, these factors result in the characteristic distribution of thick-bedded sandstone facies in the channel axis and mudstone-prone and thinly

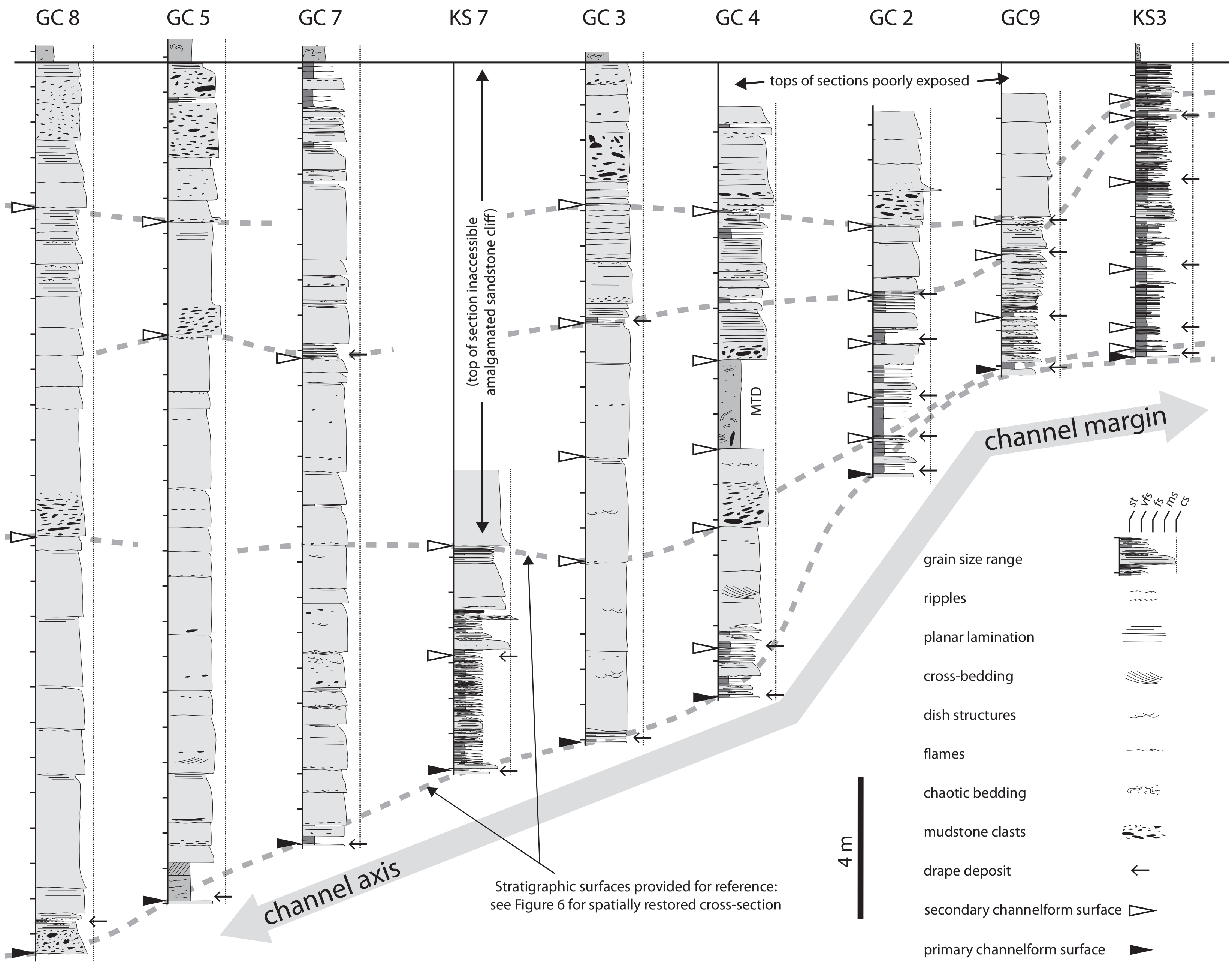

Figure 9. Representative measured stratigraphic sections through the GC channel fill, from the axis to the margin. The record of turbidity currents that passed through the conduit is more complete toward the channel margins: 27 turbidites are present in the axis section of GC 8, whereas 147 turbidites are present in the margin section of KS3. See Figures 6B–6C for a detailed cross section through these strata. Grain size abbreviations are: st—silt; vfs—very fine-grained sand; fs—fine-grained sands; ms—medium-grained sand; cs—coarse-grained sand.

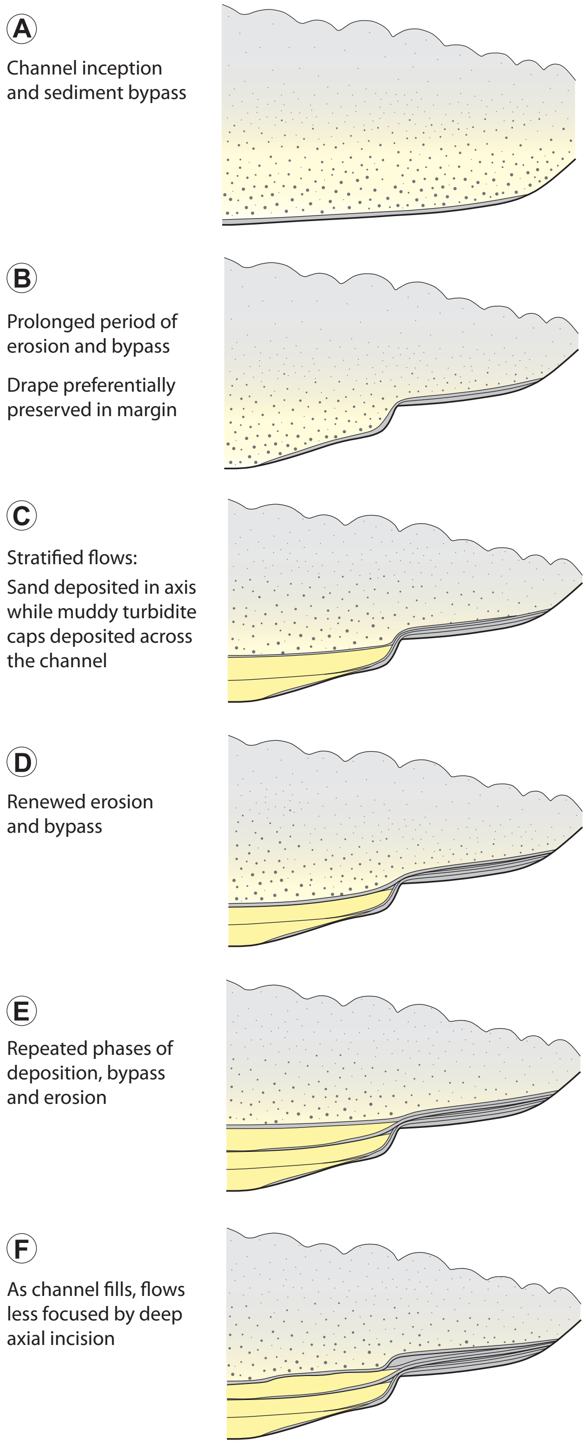

Figure 10. Schematic evolution of the GC channel, focused on the axis to margin transition.

interbedded facies in the channel margin setting (Figs. 6 and 11). The channel margin deposits likely accumulated on a terrace within the channel, and might be attributed to overbank flow at the secondary channelform surface level (i.e., intrachannel; Fig. 10; cf. Gamberi and Marani, 2007; Normark et al., 2009; Maier et al., 2013).

Evidence for scour and bypassing turbidity currents is prevalent in the fill of GC channel (Figs. 10C–10F). This is especially apparent from the primary channelform surface, which defines the channel base. This surface is likely highly composite in nature—the result of innumerable incision, bypass, and depositional events associated with turbidity currents, as well as channel-wall failure. The secondary, intrachannel surfaces are probably also the result of composite incision, reworking, and, less commonly deposition, as evidenced by the record of scours and heterolithic thin beds of channel margin and drape deposits. Evidence for point bar lateral accretion, such as large-scale inclined stratification or widespread upward grain-size fining (cf. Allen, 1970), is absent in the outcropping channel fill.

In the context of eroding and bypassing turbidity-current processes, the disparity of sedimentation unit counts between axis and margin deposits sheds light onto the true nature of deep-water channels as conduits for sediment bypass, as opposed to a common petroleum industry bias of channels as accommodation for deposition of sand (Fig. 9). These insights underscore the role of the GC channel in basin-margin stratigraphic evolution: The channel was a long-lived conduit for sediment dispersal to deeper-water depositional sites. That is not to say that the GC channel was devoid of sand deposition; clearly, sandstone constitutes the majority of channel fill. However, the history of channelized sedimentary processes was dominated by protracted sediment reworking and bypass.

DISCUSSION: TOWARD A COMPREHENSIVE UNDERSTANDING OF SUBMARINE CHANNELS

The GC channel fill records a complex history of incision and bypass of turbidity currents across the Magallanes Basin slope. The heterolithic, mudstone-prone and thinly interbedded sandstone and mudstone facies (Fig. 3), as well as associated scours of multiple scales, are the temporally most significant stratigraphic record of channelization processes. Contrary to the implication of the most obvious depositional feature of the GC channel fill (i.e., axis deposits composed of thick-bedded sandstone facies), the role of the channel was not predominantly accommodation for sand deposition during its history. The life span of the GC channel was dominated by repeated sedimentary processes of bed reworking and erosion, sediment bypass, deposition of numerous turbidites, many of which were subsequently removed by erosion, and deposition of fine-grained tails of bypassing turbidity currents.

The stratigraphic evidence for dynamic sedimentary processes of channel evolution is consistent with observations of submarine channels on the present-day seafloor. Recent analyses of the California Borderland have produced a breadth of high-resolution autonomous underwater vehicle bathymetric data of canyons and channels, providing new insights into the mosaic of low-relief (<10 m) geomorphology inherent to submarine sediment-dispersal systems (e.g., Normark et al., 2009; Paull et al.,

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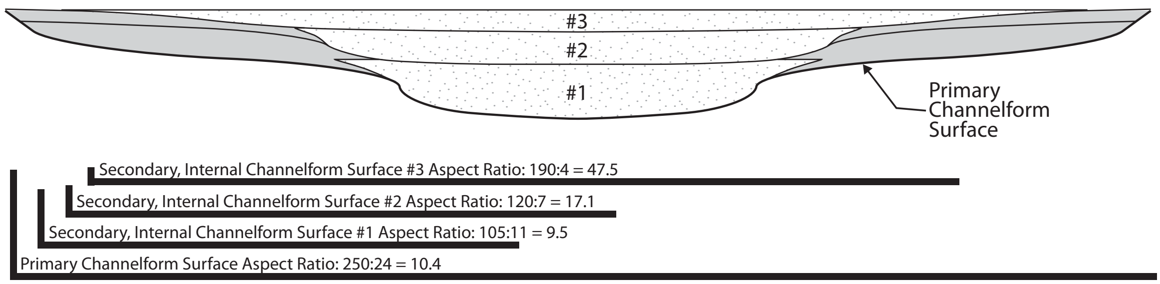

Figure 11. Simplified morphological characteristics of the GC channel fill in strike section, emphasizing the changing aspect ratio of the conduit through its fill history. Within package 1, the thickest beds of the entire channel system are present in the axis. There is some evidence for traction transport, including cross-stratification. Only rare mud clasts are preserved, and internal secondary channelform surface drapes are absent. Within package 2, amalgamated sandstone, with rare mudstone clasts, dominates the channel axis. Mudstone clasts are most abundant in the off-axis setting, and they are also more common upward within the channel axis setting. Internal channelform surface drapes are rarely preserved in the axis to off-axis regions, yet they are common in margin deposits. The fine-grained tops of turbidites are preserved primarily toward the channel margin. Package 3 is characterized by some of the coarsest sandstone in the entire channel (Fig. 8), as well as an abundance of mudstone clasts across the axis to off-axis regions. The fine-grained tops of turbidites are locally preserved in axis and off-axis strata.

2010, 2011; Maier et al., 2011, 2012; Xu et al., 2013). The resolution of seafloor geomorphology revealed in these studies (1 m lateral and 0.3 m vertical; Maier et al., 2011) approaches that of outcropping sedimentary rocks, such as the GC channel deposit. A particularly compelling example of the breadth of channelized geomorphology and sedimentary processes is the Lucia Chica turbidite system, offshore of central California, which shows at least four channels in different developmental stages locked in place on the modern seafloor as a result of punctuated channel initiation, avulsion, and abandonment (Maier et al., 2011, 2013). Low-relief (<10 m) seafloor morphologic features of the Lucia Chica system include multiple terrace-like features within channels, where the seismic-reflection character of the upper terrace reflections indicates heterolithic strata (Fig. 12). The most continuous stratal packages are acoustically transparent, and they suggest widespread draping of fine-grained material that has settled out of suspension through the water column (Fig. 12). Channelform-shaped truncations result in discontinuous sedimentary bodies, which could be interpreted as remnant channel margin deposits; we consider these truncations to be analogous to the secondary, intrachannel surfaces of the GC channel fill (Figs. 5, 6, and 9). Xu et al. (2013) recorded turbidity currents across 14.5 km of the Monterey Canyon floor, offshore central California, during a year of observation. These frequent occurrences of turbidity currents were hypothesized to be fundamentally important mechanisms of sediment transfer down the continental slope (Xu et al., 2013). Repeated bathymetric surveys of submarine canyons and channels further underscore the dynamic nature of channelized geomorphology (e.g., Paull et al., 2010; Conway et al., 2012), and the breadth of sedimentary processes likely active during channel maintenance and evolution, including the inferred dynamic, multiphase processes of bed reworking, local deposition, and bypass of turbidity currents (cf. Pickering et al., 2001; Fildani et al., 2006; Macdonald et al., 2011; Covault et al., 2014).

We postulate that the unfilled channels imaged offshore continental margins are not merely in nascent developmental stages. Rather, these ubiquitous, unfilled, geomorphically complex features that carve Earth's continental margins are in the primes of their existence, with intermittent turbidity currents of a range of magnitudes and recurrence. This is analogous to the breadth of floods and sediment-transport events characteristic of terrestrial fluvial systems (e.g., Wolman and Miller, 1960), reworking the seabed, eroding, locally depositing, re-eroding, and bypassing sediment downslope. These channels of the present-day seafloor are not incipient features, with an inevitable subsequent predominance of sand-rich depositional processes; rather, these features are serving a prominent role as conduits for material dispersal across continental margins.

Our analysis of slope channel-fill outcrops of the Tres Pasos Formation, southern Chile, includes numerous detailed stratigraphic sections, differential GPS surveying of stratal surfaces for visualization and analysis in three dimensions, paleoflow measurements, bed counts, and placement within a robust physical stratigraphic framework, which is interpreted within a depositional process framework vetted by studies of depositional products (e.g., Kuenen and Migliorini, 1950; Bouma, 1962; Middleton and Hampton, 1973; Lowe, 1982; Talling et al., 2012), and from models based on physical theory (e.g., Parker et al., 1986; Straub et al., 2008) and experimentation (e.g., Garcia and Parker, 1991; Kane et al., 2008; Rowland et al., 2010). This stratigraphic analysis reveals a history of channelized sedimentary processes that is complementary to observations and measurements of the modern seafloor: the GC channel outcrop provides a unique preservation of heterolithic intrachannel facies, which reveal insights into the longevity of sediment bypass across the Magallanes Basin slope. Bathymetrically imaged, open-slope channels on the modern seafloor have been interpreted to reflect predominant bypassing and bed reworking by turbidity currents during periods of increased terrigenous sediment supply. This phase of channel maintenance likely represents the majority of time recorded in the GC channel stratigraphic record. Improved models of slope channel formation and history constrained by the deposits and surfaces that are observable in the stratigraphic record should be integrated with ongoing efforts to quantify mass balance at the scale of sedimentary systems (e.g., Paola and Martin, 2012). From analysis of the GC channel fill, integrated with observations and measurements of the modern seafloor, the ancient stratigraphic record informs the meaning of channelized seafloor geomorphology and vice versa. Direct monitoring of coarse-grained sediment transfer in the deep-sea remains extremely difficult, and highly limited, to date. An integrated approach to deciphering channelized sedimentary processes, drawing on modern and ancient analogs, provides a more complete understanding of fundamental submarine sediment-routing processes.

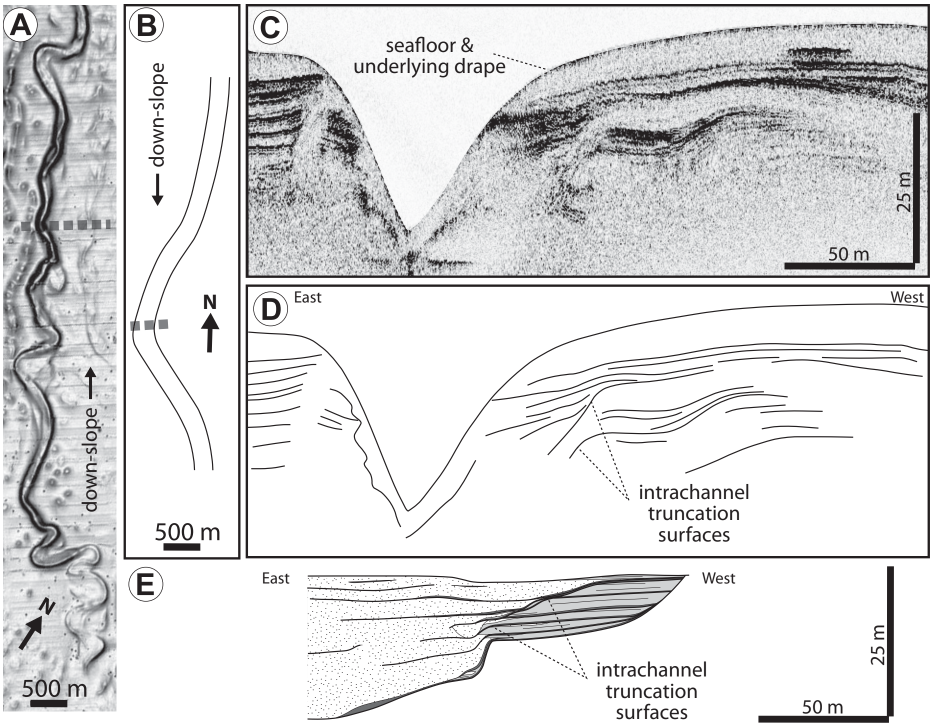

Figure 12. Comparison of the GC channel fill with the Lucia Chica channel system ("Channel 2"), offshore California (California data modified from Maier et al., 2012). (A) Multibeam bathymetry data (dip-attribute image) taken from an autonomous underwater vehicle, highlighting the Lucia Chica Channel. (B) Planform image of the GC channel deposit presented at the same scale as Lucia Chica Channel in part A, highlighting similarity in scale and sinuosity (redrawn from Fig. 2A). (C) Chirp (compressed high-intensity radar pulse) profile and (D) corresponding line-drawing trace through the Lucia Chica Channel, highlighting features comparable to those observed in the GC channel outcrop, including internal channelform (erosion) surfaces. Location is demarcated by thick dashed line in part A. (E) GC channel-fill cross section presented at the same scale as Lucia Chica Channel 2 in parts C and D, highlighting similarity in scale and internal stratigraphic architecture (simplified from Fig. 6C). Approximate location is demarcated by thick dashed line in part B.

CONCLUSIONS

The Cretaceous Tres Pasos Formation of southern Chile (Magallanes Basin) contains segments of a sediment-routing system that facilitated transfer of material to the deep sea. Despite the prevalence of sandstone within the outcropping slope channel fills, the local preservation of fine-grained facies (i.e., thin-bedded turbidites) and numerous internal erosion surfaces suggest a history of protracted erosion and sediment bypass, which preceded the terminal filling of the channels with coarse-grained detritus. These interpretations, based on careful observation and comparison with seafloor data, emphasize that a primary function of deep-sea channels that traverse the seascape is sediment transfer, as opposed to a primary role as a locus of deposition. These insights from the ancient record inform our understanding of: (1) deep-sea sediment transfer, which is inherently limited by our inability to monitor large gravity flows; and (2) reservoir distribution and internal heterogeneity from prolific continental margin petroleum provinces around the world.

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REFERENCES CITED

Allen, J.R.L., 1970, Studies in fluviatile sedimentation: A comparison of fining-upwards cyclothems, with special reference to coarse-member composition and interpretation: Journal of Sedimentary Petrology, v. 40, p. 298–323.

Babonneau, N., Savoye, B., Cremer, M., and Klein, B., 2002, Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan: Marine and Petroleum Geology, v. 19, p. 445–467, doi:10.1016/S0264-8172(02)00009-0.

Barton, M., O'Byrne, C., Pirmez, C., Prather, B., van der Vlugt, F., Alpak, F.O., and Sylvester, Z., 2010, Turbidite channel architecture: Recognizing and quantifying the distribution of channel base drapes using core and dipmeter data, *in* Pöppelreiter, M., Garcia-Carballido, C., and Kraaijveld, M.A., eds., Dipmeter and Borehole Image Log Technology: American Association of Petroleum Geologists Memoir 92, p. 195–210.

Beaubouef, R.T., 2004, Deep-water leveed-channel complexes of the Cerro Toro formation, upper Cretaceous, southern Chile: American Association of Petroleum Geologists Bulletin, v. 88, p. 1471–1500, doi:10.1306/06210403130.

Biddle, K.T., Uliana, M.A., Mitchum, R.M., Jr., Fitzgerald, M.G., and Wright, R.C., 1986, The stratigraphic and structural evolution of the central and eastern Magallanes Basin, southern South America, *in* Allen P.A., and Homewood, P., eds., Foreland Basins. International Association of Sedimentologists Special Publication 8, p. 41–63.

Bouma, A.H., 1962, Sedimentology of Some Flysch Deposits; A Graphic Approach to Facies Interpretation: Amsterdam, Elsevier, 168 p.

Callow, R.H.T., McIlroy, D., Kneller, B., and Dykstra, M., 2013, Ichnology of Late Cretaceous turbidites from the Rosario Formation, Baja California, Mexico: Ichnos, v. 20, p. 1–14, doi:10.1080/10420940.2012.734763.

Campion, K.M., Sprague, A.R., and Sullivan, M.D., 2005, Architecture and lithofacies of the Capistrano Formation (Miocene-Pliocene), San Clemente, California: Pacific Section, American Association of Petroleum Geologists Fieldtrip Guidebook 100, 42 p.

Clark, J.D., Kenyon, N.H., and Pickering, K.T., 1992, Quantitative analysis of the geometry of submarine channels: Implications for the classification of submarine fans: Geology, v. 20, p. 633–636, doi:10.1130/0091-7613(1992)020<0633:QAOTGO>2.3.CO;2.

Clift, P., and Gaedicke, C., 2002, Accelerated mass flux to the Arabian Sea during the middle to late Miocene: Geology, v. 30, p. 207–210, doi:10.1130/0091-7613(2002)030<0207:AMFTTA>2.0.CO;2.

Conway, K.W., Vaughn Barrie, J., Picard, K., and Bornhold, B.D., 2012, Submarine channel evolution: Active channels in fjords, British Columbia, Canada: Geo-Marine Letters, v. 32, p. 301–312, doi:10.1007/s00367-012-0280-4.

Covault, J.A., Kostic, S., Paull, C.K., Ryan, H.F., and Fildani, A., 2014, Submarine channel initiation, filling and maintenance from seafloor geomorphology and morphodynamic modeling of cyclic steps: Sedimentology, (in press) doi:10.1111/sed.12084.

Crane, W.H., and Lowe, D.R., 2008, Architecture and evolution of the Paine channel complex, Cerro Toro Formation (Upper Cretaceous), Silla syncline, Magallanes Basin, Chile: Sedimentology, v. 55, p. 979–1009, doi:10.1111/j.1365-3091.2007.00933.x.

Cross, N.E., Cunningham, A., Cook, R.J., Taha, A., Esmaie, E., and El Swidan, N., 2009, Three dimensional seismic geomorphology of a deep-water slope-channel system: The Sequoia field, offshore west Nile Delta, Egypt: American Association of Petroleum Geologists Bulletin, v. 93, p. 1063–1086, doi:10.1306/05040908101.

Dalla Valle, G., and Gamberi, F., 2011, Slope channel formation, evolution and backfilling in a wide shelf, passive continental margin (northeastern Sardinia slope, central Tyrrhenian Sea): Marine Geology, v. 286, p. 95–105, doi:10.1016/j.margeo.2011.06.005.

Deptuck, M.E., Steffens, G.S., Barton, M., and Pirmez, C., 2003, Architecture and evolution of upper fan channel-belts on the Niger Delta slope and in the Arabian Sea: Marine and Petroleum Geology, v. 20, p. 649–676, doi:10.1016/j.marpetgeo.2003.01.004.

de Ruig, M.J., and Hubbard, S.M., 2006, Seismic facies and reservoir characteristics of a deep marine axial channel belt in the Molasse Basin, Puchkirchen Formation, Upper Austria: American Association of Petroleum Geologists Bulletin, v. 90, p. 735–752, doi:10.1306/10210505018.

Di Celma, C.N., Brunt, R.L., Hodgson, D.M., Flint, S.S., and Kavanagh, J.P., 2011, Spatial and temporal evolution of a Permian submarine slope channel-levee system, Karoo Basin, South Africa: Journal of Sedimentary Research, v. 81, p. 579–599, doi:10.2110/jsr.2011.49.

Elliott, T., 2000, Megaflute erosion surfaces and the initiation of turbidite channels: Geology, v. 28, p. 119–122, doi:10.1130/0091-7613(2000)28<119:MESATI>2.0.CO;2.

Fildani, A., and Hessler, A.M., 2005, Stratigraphic record across a retroarc basin inversion: Rocas Verdes–Magallanes Basin, Patagonian Andes: Geological Society of America Bulletin, v. 117, p. 1596–1614, doi:10.1130/B25708.1.

Fildani, A., and Normark, W.R., 2004, Late Quaternary evolution of channel and lobe complexes of the Monterey fan: Marine Geology, v. 206, p. 199–223, doi:10.1016/j.margeo.2004.03.001.

Fildani, A., Normark, W.R., Kostic, S., and Parker, G., 2006, Channel formation by flow stripping: Large-scale scour features along the Monterey East Channel and their relation to sediment waves: Sedimentology, v. 53, p. 1265–1287, doi:10.1111/j.1365-3091.2006.00812.x.

Fildani, A., Hubbard, S.M., Covault, J.A., Maier, K.L., Romans, B.W., Traer, M., and Rowland, J.C., 2013, Erosion at inception of deep-sea channels: Marine and Petroleum Geology, v. 41, p. 48–61, doi:10.1016/j.marpetgeo.2012.03.006.

Fosdick, J.C., Romans, B.W., Fildani, A., Bernhardt, A., Calderon, M., and Graham, S.A., 2011, Kinematic evolution of the Patagonian retroarc fold-and-thrust belt and Magallanes foreland basin, Chile and Argentina, 51°30′S: Geological Society of America Bulletin, v. 123, p. 1679–1698, doi:10.1130/B30242.1.

Friend, P.F., Slater, M.J., and Williams, R.C., 1979, Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain: Journal of the Geological Society of London, v. 136, p. 39–46, doi:10.1144/gsjgs.136.1.0039.

Galy, V., Beyssac, O., France-Lanord, C., and Eglinton, T., 2008, Recycling of graphite during Himalayan erosion: A geological stabilization of carbon in the crust: Science, v. 322, p. 943–945, doi:10.1126/science.1161408.

Gamberi, F., and Marani, M., 2007, Downstream evolution of the Stromboli slope valley (southeastern Tyrrhenian Sea): Marine Geology, v. 243, p. 180–199, doi:10.1016/j.margeo.2007.05.006.

Gamberi, F., Rovere, M., Dykstra, M., Kane, I.A., and Kneller, B.C., 2013, Integrating modern seafloor and outcrop data in the analysis of slope channel architecture and fill: Marine and Petroleum Geology, v. 41, p. 83–103, doi:10.1016/j.marpetgeo.2012.04.002.

Garcia, M., and Parker, G., 1991, Entrainment of sediment into suspension: Journal of Hydraulic Engineering, v. 117, p. 414–435, doi:10.1061/(ASCE)0733-9429(1991)117:4(414).

Gardner, M.H., and Borer, J.M., 2000, Submarine channel architecture along a slope to basin profile, Permian Brushy Canyon Formation, west Texas, *in* Bouma, A.H., and Stone, C.G., eds., Fine-Grained Turbidite Systems: American Association of Petroleum Geologists Memoir 72, p. 195–215.

Gardner, M.H., Borer, J.M., Melick, J.J., Mavilla, N., Dechesne, M., and Wagerle, R.N., 2003, Stratigraphic process-response model for submarine channels and related features from studies of Permian Brushy Canyon outcrops, West Texas: Marine and Petroleum Geology, v. 20, p. 757–787, doi:10.1016/j.marpetgeo.2003.07.004.

Ghosh, B., and Lowe, D.R., 1993, The architecture of deep-water channel complexes, Cretaceous Vanado Sandstone Member, Sacramento Valley, California, *in* Graham, S.A., and Lowe, D.R., eds., Advances in the Sedimentary Geology of the Great Valley Group, Sacramento Valley, California: Pacific Section, Society of Economic Paleontology and Mineralogy Guidebook 73, p. 51–65.

Hickson, T.A., and Lowe, D.R., 2002, Facies architecture of a submarine fan channel-levee complex: The Juniper Ridge Conglomerate, Coalinga, California: Sedimentology, v. 49, p. 335–362, doi:10.1046/j.1365-3091.2002.00447.x.

Hodgson, D.M., DiCelma, C.N., Brunt, R.L., and Flint, S.S., 2011, Submarine slope degradation, aggradation and the stratigraphic evolution of channel-levee systems: Journal of the Geological Society of London, v. 168, p. 625–628, doi:10.1144/0016-76492010-177.

Hubbard, S.M., de Ruig, M.J., and Graham, S.M., 2009, Confined channel-levee complex development in an elongate depocenter: Deep-water Tertiary strata of the Austrian Molasse Basin: Marine and Petroleum Geology, v. 26, p. 85–112, doi:10.1016/j.marpetgeo.2007.11.006.

Hubbard, S.M., Fildani, A., Romans, B.W., Covault, J.A., and McHargue, T.R., 2010, High-relief slope clinoform development; insights from outcrop, Magallanes Basin, Chile: Journal of Sedimentary Research, v. 80, p. 357–375, doi:10.2110/jsr.2010.042.

Hubbard, S.M., MacEachern, J.A., and Bann, K.L., 2012, Slopes, *in* Knaust, D., and Bromley, R.G., eds., Trace Fossils as Indicators of Sedimentary Environments: Amsterdam, Elsevier, Developments in Sedimentology 64, p. 607–642.

Hubscher, C., Spiesz, V., Breitzke, M., and Weber, M.E., 1997, The youngest channel-levee system of the Bengal Fan: Results from digital sediment echosounder data: Marine Geology, v. 21, p. 125–145.

Janocko, M., Nemec, W., Henriksen, S., and Warchol, M., 2013, The diversity of deep-water sinuous channel belts and slope valley-fill complexes: Marine and Petroleum Geology, v. 41, p. 7–34, doi:10.1016/j.marpetgeo.2012.06.012.

Jobe, Z.R., Lowe, D.R., and Uchytil, S.J., 2011, Two fundamentally different types of submarine canyons along the continental margin of Equatorial Guinea: Marine and Petroleum Geology, v. 28, p. 843–860, doi:10.1016/j.marpetgeo.2010.07.012.

Kane, I.A., and Hodgson, D.M., 2011, Sedimentological criteria to differentiate submarine channel levee subenvironments: Exhumed examples from the Rosario Fm. (Upper Cretaceous) of Baja California, Mexico, and the Fort Brown Fm. (Permian), Karoo Basin, S. Africa: Marine and Petroleum Geology, v. 28, p. 807–823, doi:10.1016/j.marpetgeo.2010.05.009.

Kane, I.A., Kneller, B.C., Dykstra, M., Kassem, A., and McCaffrey, W.D., 2007, Anatomy of a submarine channel-levee: An example from Upper Cretaceous slope sediments, Rosario Formation, Baja California, Mexico: Marine and Petroleum Geology, v. 24, p. 540–563, doi:10.1016/j.marpetgeo.2007.01.003.

Kane, I.A., McCaffrey, W.D., and Peakall, J., 2008, Controls on sinuosity evolution within submarine channels: Geology, v. 36, p. 287–290, doi:10.1130/G24588A.1.

Kane, I.A., Mayall, M., and McCaffrey, W.D., eds., 2013, Internal architecture, bedforms and geometry of turbidite channels: Marine and Petroleum Geology, v. 41, Special Issue, p. 1–294.

Katz, H.R., 1963, Revision of Cretaceous stratigraphy in Patagonia Cordillera of Ultima Esperanza, Magallanes Province, Chile: American Association of Petroleum Geologists Bulletin, v. 47, p. 506–524.

Kuenen, Ph.H., and Migliorini, C.I., 1950, Turbidity currents as a cause of graded bedding: The Journal of Geology, v. 58, p. 91–127, doi:10.1086/625710.

Labourdette, R., and Bez, M., 2010, Element migration in turbidite systems: Random or systematic depositional processes?: American Association of Petroleum Geologists Bulletin, v. 94, p. 345–368, doi:10.1306/09010909035.

Lowe, D.R., 1982, Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents: Journal of Sedimentary Petrology, v. 52, p. 279–297.

Lyons, W.B., Nezat, C.A., Carey, A.E., and Hicks, D.M., 2002, Organic carbon fluxes to the ocean from high-standing islands: Geology, v. 30, p. 443–446, doi:10.1130/0091-7613(2002)030<0443:OCFTTO>2.0.CO;2.

Macauley, R.V., and Hubbard, S.M., 2013, Slope channel sedimentary processes and stratigraphic stacking, Cretaceous Tres Pasos Formation slope system, Chilean Patagonia: Marine and Petroleum Geology, v. 41, p. 146–162, doi:10.1016/j.marpetgeo.2012.02.004.

Macdonald, H.A., Wynn, R.B., Huvenne, V.A.I., Peakall, J., Masson, D.G., Weaver, P.P.E., and McPhail, S.D., 2011, New insights into the morphology, fill, and remarkable longevity (>0.2 m.y.) of modern deep-water erosional scours along the northeast Atlantic margin: Geosphere, v. 7, p. 845–867, doi:10.1130/GES00611.1.

Maier, K.L., Fildani, A., Paull, C.K., Graham, S.A., McHargue, T., Caress, D., and McGann, M., 2011, The elusive character of discontinuous deep-water channels: New insights from Lucia Chica channel system, offshore California: Geology, v. 39, p. 327–330, doi:10.1130/G31589.1.

Maier, K.L., Fildani, A., McHargue, T.R., Paull, C.K., Graham, S.A., and Caress, D.W., 2012, Punctuated deep-water channel migration: High-resolution subsurface data from the Lucia Chica channel system, offshore California, U.S.A.: Journal of Sedimentary Research, v. 82, p. 1–8, doi:10.2110/jsr.2012.10.

Maier, K.L., Fildani, A., Paull, C.K., McHargue, T.R., Graham, S.A., and Caress, D.W., 2013, Deep-sea channel evolution and stratigraphic architecture from inception to abandonment from high-resolution autonomous underwater vehicle surveys offshore central California: Sedimentology, v. 60, p. 935–960, doi:10.1111/j.1365-3091.2012.01371.x.

Mayall, M., Jones, E., and Casey, M., 2006, Turbidite channel reservoirs—Key elements in facies prediction and effective development: Marine and Petroleum Geology, v. 23, p. 821–841, doi:10.1016/j.marpetgeo.2006.08.001.

McHargue, T., Pyrcz, M.J., Sullivan, M.D., Clark, J., Fildani, A., Romans, B.R., Covault, J.A., Levy, M., Posamentier, H., and Drinkwater, N., 2011, Architecture of turbidite channel systems on the continental slope: Patterns and predictions: Marine and Petroleum Geology, v. 28, p. 728–743, doi:10.1016/j.marpetgeo.2010.07.008.

Miall, A.D., 1985, Architectural-element analysis: A new method of facies analysis applied to fluvial deposits: Earth-Science Reviews, v. 22, p. 261–308, doi:10.1016/0012-8252(85)90001-7.

Middleton, G.V., and Hampton, M.A., 1973, Sediment gravity flows: Mechanics of flow and deposition, *in* Middleton, G.V., and Bouma, A.H., eds., Turbidites and Deep-Water Sedimentation: Los Angeles, Society of Economic Paleontologists and Mineralogists, Short Course Lecture Notes, p. 1–38.

Mistral, G., 1922, Desolación: New York, Instituto de las Españas, 248 p.

Morris, W.R., and Normark, W.R., 2000, Scaling, sedimentology, and geometric criteria for comparing modern and ancient sandy turbidite elements, *in* Weimer, P., Slatt, R.M., Coleman, J., Rosen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J., and Lawrence, D.T., eds., Deep-Water Reservoirs of the World: Houston, Gulf Coast Society–Society for Sedimentary Geology 20th Annual Research Conference, p. 606–628.

Mutti, E., and Normark, W.R., 1987, Comparing examples of modern and ancient turbidite systems: Problems and concepts, *in* Legget, J.K., and Zuffa, G.G., eds., Deep Water Clastic Deposits: Models and Case Histories: London, UK, Graham and Trotman, p. 1–38.

Normark, W.R., Paull, C.K., Caress, D.W., Ussler, W., and Sliter, R., 2009, Fine-scale relief related to late Holocene channel shifting within the floor of the upper Redondo Fan, offshore Southern California: Sedimentology, v. 56, p. 1690–1704, doi:10.1111/j.1365-3091.2009.01052.x.

Paola, C., and Martin, J.M., 2012, Mass-balance effects in depositional systems: Journal of Sedimentary Research, v. 82, p. 435–450, doi:10.2110/jsr.2012.38.

Parker, G., Fukushima, Y., and Pantin, H.M., 1986, Self-accelerating turbidity currents: Journal of Fluid Mechanics, v. 171, p. 619–628, doi:10.1017/S0022112086001404.

Paull, C.K., Ussler, W., Caress, D.W., Lundsten, E., Covault, J.A., Maier, K.L., Xu, J.P., and Augenstein, S., 2010, Origins of large crescent-shaped bed forms within the axial channel of Monterey Canyon, offshore California: Geosphere, v. 6, p. 755–774, doi:10.1130/GES00527.1.

Paull, C.K., Caress, D.W., Ussler, W., Lundsten, E., and Meiner-Johnson, M., 2011, High-resolution bathymetry of the axial channels within Monterey and Soquel Submarine Canyons, offshore central California: Geosphere, v. 7, p. 1077–1101, doi:10.1130/GES00636.1.

Paull, C.K., Caress, D.W., Lundsten, E., Gwiazda, R., Anderson, K., McGann, M., Conrad, J., Edwards, B., and Sumner, E.J., 2013, Anatomy of the La Jolla Submarine Canyon system, offshore southern California: Marine Geology, v. 335, p. 16–34, doi:10.1016/j.margeo.2012.10.003.

Peakall, J., McCaffrey, W., and Kneller, B., 2000, A process model for the evolution, morphology, and architecture of sinuous submarine channels: Journal of Sedimentary Research, v. 70, p. 434–448, doi:10.1306/2DC4091C-0E47-11D7-8643000102C1865D.

Pickering, K.T., Hodgson, D.M., Platzman, E., Clark, J.D., and Stephens, C., 2001, A new type of bedform produced by backfilling processes in a submarine channel, late Miocene, Tabernas–Sorbas Basin, SE Spain: Journal of Sedimentary Research, v. 71, p. 692–704, doi:10.1306/2DC40960-0E47-11D7-8643000102C1865D.

Piper, D.J.W., and Normark, W.R., 1983, Turbidite depositional patterns and flow characteristics, Navy Submarine Fan, California Borderland: Sedimentology, v. 30, p. 681–694, doi:10.1111/j.1365-3091.1983.tb00702.x.

Piper, D.J.W., Shor, A.N., and Hughes Clarke, J.E., 1988, The 1929 “Grand Banks” earthquake, slump, and turbidity current, *in* Clifton, H.E., ed., Sedimentologic Consequence of Convulsive Geologic Events: Geological Society of America Special Paper 229, p. 77–92.

Pirmez, C., Beaubouef, R.T., Friedmann, S.J., and Mohrig, D.C., 2000, Equilibrium profile and baselevel in submarine channels: Examples from late Pleistocene systems and implications for the architecture of deepwater reservoirs, *in* Weimer, P., Slatt, R.M., Coleman, J., Rosen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J., and Lawrence, D.T., eds., Deep-Water Reservoirs of the World: Houston, Gulf Coast Society–Society for Sedimentary Geology 20th Annual Research Conference, p. 782–805.

Porter, M.L., Sprague, A.R.G., Sullivan, M.D., Jennette, R.T., Beaubouef, R.T., Garfield, T.R., Rossen, D., Sickafoose, D.K., Jensen, G.N., Friedmann, S.J., and Mohrig, D.C., 2006, Stratigraphic organization and predictability of mixed coarse- and fine-grained lithofacies successions in a Lower Miocene deep-water slope-channel system, Angola block 15, *in* Harris, P.M., and Weber, L.J., eds., Giant Hydrocarbon Reservoirs of the World: From Rocks to Reservoir Characterization and Modeling: American Association of Petroleum Geologists Memoir 88, p. 281–306.

Posamentier, H.W., and Kolla, V., 2003, Seismic geomorphology and stratigraphy of depositional elements in deep-water settings: Journal of Sedimentary Research, v. 73, p. 367–388, doi:10.1306/111302730367.

Postma, G., Cartigny, M., and Kleverlaan, K., 2009, Structureless, coarse-tail graded Bouma T_a formed by internal hydraulic jump of the turbidity current?: Sedimentary Geology, v. 219, p. 1–6, doi:10.1016/j.sedgeo.2009.05.018.

Pyles, D.R., Jennette, D.C., Tomasso, M., Beaubouef, R.T., and Rossen, C., 2010, Concepts learned from a 3D outcrop of a sinuous slope channel complex: Beacon Channel complex, Brushy Canyon Formation, West Texas, U.S.A.: Journal of Sedimentary Research, v. 80, p. 67–96, doi:10.2110/jsr.2010.009.

Romans, B.W., Fildani, A., Graham, S.A., Hubbard, S.M., and Covault, J.A., 2010, Importance of predecessor basin history on the fill of a retroarc foreland basin: Provenance analysis of the Cretaceous Magallanes Basin, Chile (51–52°): Basin Research, v. 22, p. 640–658, doi:10.1111/j.1365-2117.2009.00443.x.

Romans, B.W., Fildani, A., Hubbard, S.M., Covault, J.A., Fosdick, J.C., and Graham, S.A., 2011, Evolution of deep-water stratigraphic architecture, Magallanes Basin, Chile: Marine and Petroleum Geology, v. 28, p. 612–628, doi:10.1016/j.marpetgeo.2010.05.002.

Rowland, J.C., Hilley, G.E., and Fildani, A., 2010, A test of initiation of submarine leveed channels by deposition alone: Journal of Sedimentary Research, v. 80, p. 710–727, doi:10.2110/jsr.2010.067.

Samuel, A., Kneller, B., Ralan, S., Sharp, A., and Parsons, C., 2003, Prolific deep-marine slope channels of the Nile Delta, Egypt: American Association of Petroleum Geologists Bulletin, v. 87, p. 541–560, doi:10.1306/1105021094.

Schwarz, E., and Arnott, R.W.C., 2007, Anatomy and evolution of a slope-channel-complex set (Neoproterozoic Isaac Formation, Windermere Supergroup, southern Canadian Cordillera): Implications for reservoir characterization: Journal of Sedimentary Research, v. 77, p. 89–109, doi:10.2110/jsr.2007.015.

Smith, C.H.L., 1977, Sedimentology of the Late Cretaceous (Santonian–Maastrichtian) Tres Pasos Formation, Ultima Esperanza District, Southern Chile [M.S. thesis]: Madison, Wisconsin, University of Wisconsin, 129 p.

Sprague, A.R.G., Garfield, T.R., Oulding, F.J., Beaubouef, R.T., Sullivan, M.D., Rossen, C., Campion, K.M., Sickafoose, D.K., Abreu, V., Schellpeper, M.E., Jensen, G.N., Jennette, D.C., Pirmez, C., Dixon, B.T., Ying, D., Ardill, J., Mohrig, D.C., Porter, M.L., Farrell, M.E., and Mellere, D., 2005, Integrated Slope Channel Depositional Models: The Key to Successful Prediction of Reservoir Presence and Quality in Offshore West Africa: Veracruz, CIPM (Mexican College of Oil Engineers) E-Exitep 2005, 13 p.

Stevenson, C.J., Talling, P.J., Wynn, R.B., Masson, D.G., Hunt, J.E., Frenz, M., Akhmetzhanhov, A., and Cronin, B.T., 2013, The flows that left no trace: Very large-volume turbidity currents that bypassed sediment through submarine channels without eroding the sea floor: Marine and Petroleum Geology, v. 41, p. 186–205, doi:10.1016/j.marpetgeo.2012.02.008.

Straub, K.M., Mohrig, D., McIlroy, B., Buttles, J., and Pirmez, C., 2008, Interactions between turbidity currents and topography in aggrading sinuous submarine channels: A laboratory study: Geological Society of America Bulletin, v. 120, p. 368–385, doi:10.1130/B25983.1.

Sullivan, M., Jensen, G., Goulding, F., Jennette, D., Foreman, L., and Stern, D., 2000, Architectural analysis of deep-water outcrops: Implications for exploration and development of the Diana sub-basin, western Gulf of Mexico, *in* Weimer, P., Slatt, R.M., Coleman, J., Rosen, N.C., Nelson, H., Bouma, A.H., Styzen, M.J., and Lawrence, D.T., eds., Deep-Water Reservoirs of the World: Houston, Gulf Coast Society–Society for Sedimentary Geology 20th Annual Research Conference, p. 1010–1031.

Sylvester, Z., Pirmez, C., and Cantelli, A., 2011, A model of submarine channel-levee evolution based on channel trajectories: Implications for stratigraphic architecture: Marine and Petroleum Geology, v. 28, p. 716–727, doi:10.1016/j.marpetgeo.2010.05.012.

Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., and Green, P., 2005, Impact of humans on the flux of terrestrial sediment to the global coastal ocean: Science, v. 308, p. 376–380, doi:10.1126/science.1109454.

Talling, P.J., Masson, D.G., Sumner, E.J., and Maigesini, G., 2012, Subaqueous sediment density flows: Depositional processes and deposit types: Sedimentology, v. 59, p. 1937–2003, doi:10.1111/j.1365-3091.2012.01353.x.

Wilson, T.J., 1991, Transition from back-arc to foreland basin development in southernmost Andes: Stratigraphic record from the Ultima Esperanza District, Chile: Geological Society of America Bulletin, v. 103, p. 98–111, doi:10.1130/0016-7606(1991)103<0098:TFBATF>2.3.CO;2.

Wolman, M.G., and Miller, J.P., 1960, Magnitude and frequency of forces in geomorphic processes: The Journal of Geology, v. 68, p. 54–74, doi:10.1086/626637.

Xu, J.P., Barry, J.P., and Paull, C.K., 2013, Small-scale turbidity currents in a big submarine canyon: Geology, v. 41, p. 143–146, doi:10.1130/G33727.1.

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