The Stratigraphic Record of Submarine-Channel Evolution

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ABSTRACT

Submarine-channel systems record basin-margin sediment dispersal and can host significant natural resources. We review the facies architecture (i.e., facies heterogeneity and stacking patterns) of outcropping submarine-channel systems, focusing on the Cretaceous Tres Pasos Formation, Magallanes basin, southern Chile. The fundamental building block of submarine-channel systems is the channel-fill architectural element. A channel fill comprises thick-bedded turbidite sandstone deposited in the deepest segment of the bounding channel surface (i.e., the thalweg), which transitions laterally to thin-bedded heterolithic deposits in the margins.

Submarine-channel fills stack to form composite channel systems, which commonly exhibit an evolution from early channel incision and lateral migration to late-stage aggradation. The incising-to-aggrading trajectory of a submarine-channel system is likely influenced by adjustments toward an equilibrium gradient that is established and maintained by feedbacks between the slope and overriding sediment-gravity flows. A steep slope will promote swift flows that are erosive; a more gradual gradient will promote sluggish flows that aggrade sediment. A combination of these two processes brings the channel floor closer to an equilibrium gradient. Changes in sediment-gravity-flow properties driven by allogenic controls, such as eustatic sea-level change, have also been linked to the incising-to-aggrading trajectory of channel systems. We illustrate the evolution of channel systems with a surface-based stratigraphic forward model. The model allows us to visualize the three-dimensional (3D) stacking patterns of channel systems, which control heterogeneity and sand body connectivity in channelized hydrocarbon reservoirs. Future research opportunities include the interpretation of stratigraphic products integrated with direct monitoring of turbidity currents, physical experiments, and numerical modeling to understand the 3D facies architecture and stratigraphic evolution of channel systems.

INTRODUCTION

Submarine channels are conduits for sediment-gravity flows that sculpt continental margins as they carry terrigenous sediment to the deep sea (Piper and Normark, 2001). Sediment-gravity flows are mixtures of sediment and water in which the sediment component pulls interstitial water down slope under the influence of gravity (Bagnold, 1962; Middleton and Hampton, 1973). Submarine channels are important components of deep-sea fans, which comprise canyon, channel, levee-and-distal-overbank, and depositional-lobe architectural elements (Mutti and Normark, 1987; Normark et al., 1993; Piper and Normark, 2001; Posamentier and Kolla, 2003). Submarine canyons transition to U-shaped, lower-relief channels with levee-and-distal-overbank deposits across the slope and rise of continental margins. Channels can extend across the seafloor for hundreds to thousands of kilometers (Covault et al., 2011; 2012), and their deposits can host significant hydrocarbon resources (Mayall et al., 2006).

Submarine-channel evolution is a result of the interaction between the seafloor within and around the channel, and overriding sediment-gravity flows. Sediment-gravity flows have rarely been directly observed in the ocean (Talling et al., 2015). However, recent monitoring data record the hourly to annual interaction between submarine channels and sediment-gravity flows (e.g., Zeng et al., 1991; Xu et al., 2004; Paull et al., 2010; Conway et al., 2012; Cooper et al., 2013; Sumner and Paull, 2014; Talling et al., 2015; Hughes Clarke, 2016). These data underscore the short-term transience of seafloor geomorphology and multi-phase bed reworking, local deposition, and bypass of sediment-gravity flows active during channel initiation, maintenance, and filling (e.g., Covault et al., 2014). Furthermore, insights from monitoring have inspired reinterpretation of outcropping sedimentary rocks (e.g., Fildani et al., 2013; Hubbard et al., 2014; Postma et al., 2014; Bain and Hubbard, 2016; Pemberton et al., 2016). Missing from the short-term record of monitoring is a longer-term perspective, which is afforded by outcropping and subsurface stratigraphic successions (e.g., Deptuck et al., 2003; Hubbard et al., 2014).

Here we summarize the facies architecture and stratigraphic evolution of outcropping submarine-channel systems. Many outcropping channel fills exhibit a common facies architecture of thick-bedded sandstone deposited in the deepest segment of the bounding channel surface (i.e., the thalweg) that transitions laterally to thin-bedded heterolithic deposits in the margins (Beaubouef et al., 1999; Pyles et al., 2010; Hubbard et al., 2014). Channel fills are also associated with scour surfaces draped by variable mudstone-rich units (Barton et al., 2010; Alpak et al., 2013; Macauley and Hubbard, 2013).

Subsurface and outcropping channel systems form a composite record of stacked channel fills, recording an evolution from early channel incision and lateral migration to late-stage aggradation (Peakall et al., 2000; Deptuck et al., 2003; Hodgson et al., 2011; Sylvester et al., 2011). We illustrate the incising-to-aggrading trajectory of a channel system in a 3D surface-based stratigraphic forward model. The model records the 3D stacking patterns of a channel system, which is a principal control on fluid flow behavior during hydrocarbon production (e.g., Larue and Hovadik, 2006; Stright, 2006; Labourdette, 2007; Stewart et al., 2008; Funk et al., 2012; Alpak et al., 2013). We review the implications of channel-system stratigraphic evolution for channelized reservoir heterogeneity, connectivity, and performance. We also highlight opportunities for research on submarine-channel architecture and evolution.

SUBMARINE-CHANNEL FACIES

Sediment-gravity flows modify channels by erosion and deposition, and in the long term this results in the migration of the active channel floor and the preservation of deposits in its wake (Sylvester et al., 2011). Turbidites and debrites are end members of the spectrum of sediment-gravity-flow deposits. Turbidites are deposited by turbidity currents, in which sand and mud are suspended by the upward component of fluid turbulence; debrites are deposited by debris flows, in which large grains and gravel are supported by a cohesive matrix of interstitial fluid and mud with finite yield strength (Middleton and Hampton, 1973). Channel deposits commonly exhibit the following facies that represent a spectrum of submarine mass-movement processes (Mutti and Normark, 1987; Clark and Pickering, 1996; Campion et al., 2000; Sullivan et al., 2000; Barton et al., 2010; Hubbard et al., 2009, 2014) (Fig. 1):

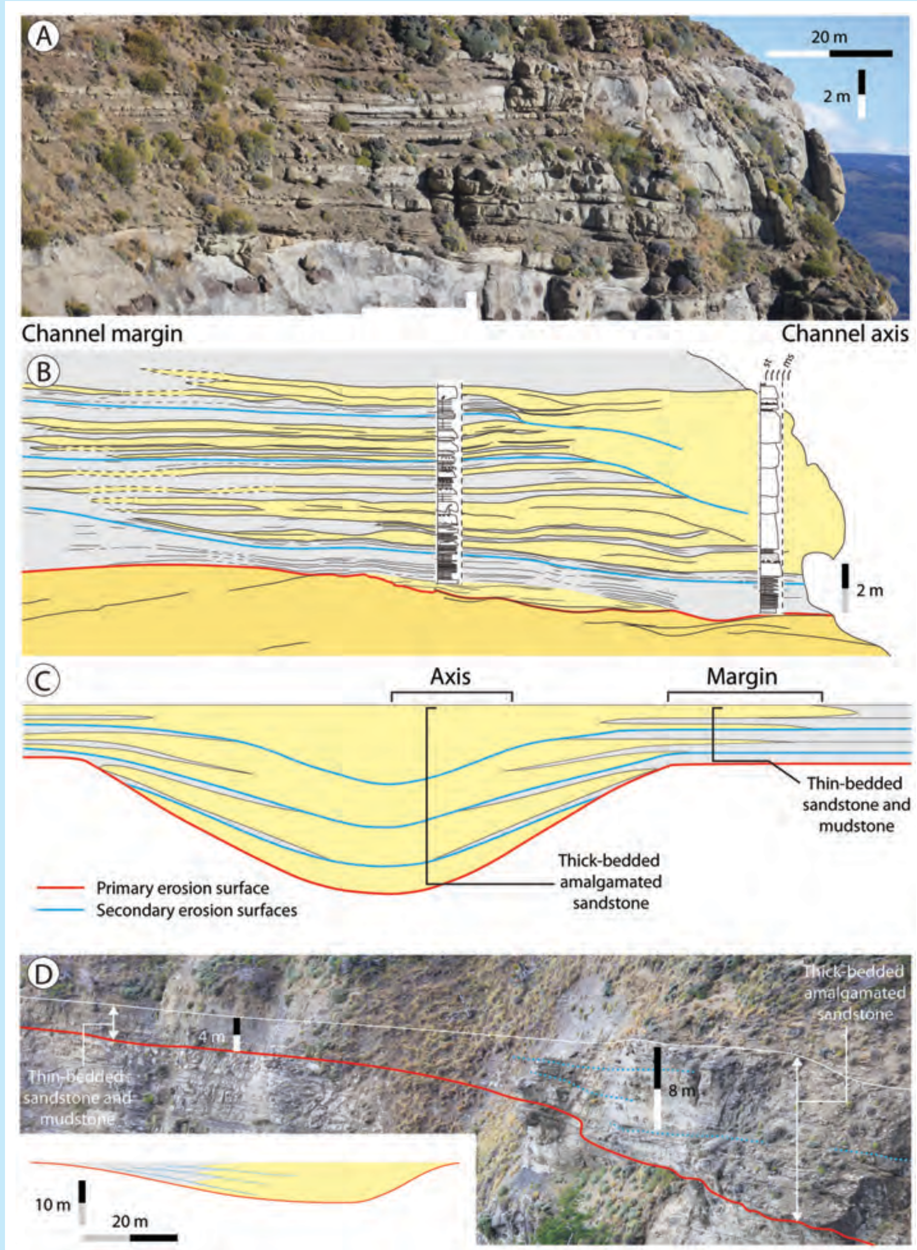

Figure 1: Submarine-channel facies of the Cretaceous Tres Pasos Formation, Magallanes basin, southern Chile. (A-B) Photograph and line-drawing trace of channel axis to margin facies associations. Yellow is sand-rich; gray is mud-rich lithology. (C) Schematic cross section of a channel-fill architectural element (Sullivan et al., 2000). (D) Photograph and schematic cross section of asymmetric channel fill in the Tres Pasos Formation (Reimchen et al., 2016).

1) thick-bedded, amalgamated sandstone and/or sand-matrix conglomerate deposited from the collapse of high-density turbidity currents (suspended load) and through tractional reworking of sediment (bed load);

2) thin, interbedded sandstone and mudstone deposited from low-density turbidity currents;

3) stratified mudstone deposited from dilute, low-density turbidity currents and the subsequent suspension sedimentation of mud between turbidity currents;

4) ungraded sandstone and/or conglomerate with a muddy matrix, deposited from debris flows; and

5) contorted (overturned and/or offset stratification) heterolithic units deposited from slumps and/or slides.

Outcrops of the Cretaceous Tres Pasos Formation, Magallanes basin, southern

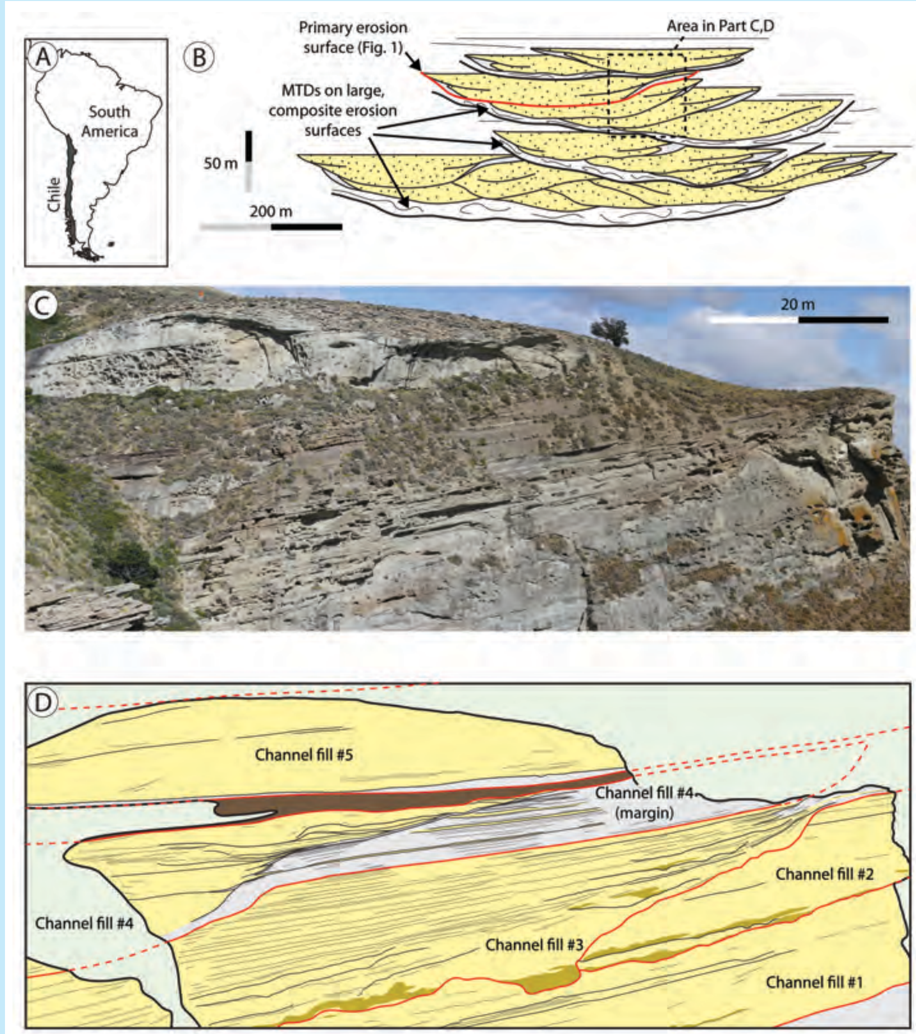

Figure 2: Stacking patterns of submarine-channel fills of the Cretaceous Tres Pasos Formation, Magallanes basin, southern Chile. (A) Location map. (B) Interpretive cross section of incising-to-aggrading stacking patterns of submarine-channel fills of the Tres Pasos Formation. Yellow is sand-rich; gray is mud-rich lithology. (C-D) Photograph and line-drawing trace of stacked submarine-channel fills.

Chile, record excellent examples of these submarine-channel facies and their spatial distribution (Macauley and Hubbard, 2013; Hubbard et al., 2014) (Figs. 1 and 2). The Magallanes basin is a retroarc foreland basin that formed in response to Andean uplift during the Late Cretaceous (Fosdick et al., 2011). Deep-water conditions persisted in the basin as a result of a backarc basin heritage (Rocas Verdes basin) and the formation of underlying attenuated continental crust (Fildani and Hessler, 2005; Romans et al., 2010). The deep-water basin was eventually filled axially from north to south by a prograding shelf-margin clinoform system that linked slope turbidite systems to shelf-edge deltaic strata (Hubbard et al., 2010). Channel fills summarized here are interpreted to have been deposited 25-30 km from the paleoshelf edge in 1000-1500 m of water (Hubbard et al., 2010).

Submarine-channel facies of the Tres Pasos Formation are confined by two key scales of stratigraphic surface that can be correlated and mapped for tens to hundreds of meters (Fig. 1). Hubbard et al. (2014) documented a primary channel surface (250-300 m wide; <24 m of relief), which is sometimes characterized by a notched, or stepped, cross-sectional profile. This surface defines a channel fill, or channel architectural element (e.g., Sullivan et al., 2000; Mayall et al., 2006; McHargue et al., 2011) (Figs. 1 and 2). The primary channel surface is interpreted to have been created as a result of incision of the seafloor by a series of high-energy turbidity currents (e.g., Elliott, 2000; Fildani et al., 2013). The notched cross-sectional profile might indicate that the processes of channel formation involved multiple phases of erosion to different depths (Hubbard et al., 2014). Secondary surfaces are smaller (200-250 m wide; <6 m relief) and locally truncate beds within the channel fill.

In the Tres Pasos Formation, thick-bedded sandstone (facies 1, above) was deposited in the thalweg (Fig. 1). The sandstone transitions laterally to finer-grained deposits (facies 2-5) in the channel margins (Fig. 1). The turbidity currents that deposited thick-bedded sandstone (facies 1) in the thalweg did not always deposit sand directly against the erosive edges of the primary channel surface (Fig. 1). The deposits of the upper, more dilute and fine-grained portions of the turbidity currents (facies 2) onlap or drape the primary or secondary channel surfaces in the channel margins (Fig. 1). Instability of thin-bedded facies on channel margins can result in slump and/or slide deposits (facies 5). The fine-grained channel-margin deposits contain an order of magnitude more numerous sedimentation units, which individually represent deposition from a single turbidity-current event (Hubbard et al., 2014). Therefore, the channel margins contain a more complete record of turbidite deposition and downstream sediment dispersal. Hubbard et al. (2014) interpreted the origins of channel-margin turbidites to be deposition from the tails of bypassed turbidity currents and/or the marginal equivalents of subsequently eroded turbidites deposited in the thalweg. Hubbard et al. (2014) used these stratigraphic observations to demonstrate the protracted nature of submarine channels, showing evidence for numerous incision, sediment bypass, and depositional events during a channel lifecycle.

Sinuous channel fills commonly exhibit sandstone-rich facies in outer

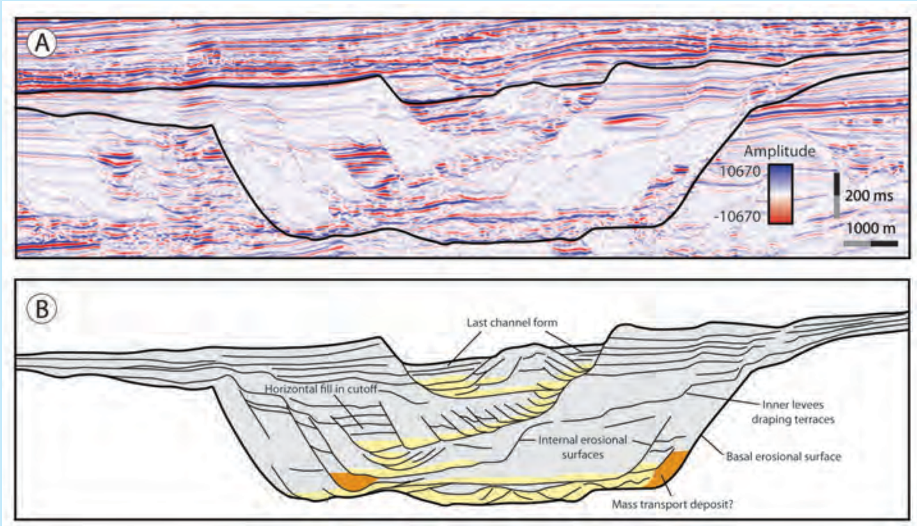

Figure 3: (A) High-resolution (~80 Hz) seismic-reflection profile across submarine-channel system CLS3 of the Indus Fan (Deptuck et al., 2003; Sylvester et al., 2011). (B) Interpretive line-drawing of the channel-levee system shown in (A), illustrating the change from laterally to vertically stacked channel deposits. Yellow is sand-rich; gray is mud-rich lithology.

bends and finer-grained facies in inner bends (Fig. 1D) (Abreu et al., 2003; Campion et al., 2005; Pyles et al., 2010; Reimchen et al., 2016). This variability of facies across a strike-oriented cross section of a channel fill, or facies asymmetry, is likely a result of elevated shear stresses along outer bends (Jobe et al., 2010; Pyles et al., 2010): sediment gravity flows have the highest velocities close to the outer bank (Straub et al., 2008; Peakall and Sumner, 2015). The degree of facies asymmetry probably correlates with the morphological asymmetry, which is a function of sinuosity and curvature. Straight channel segments and inflection points between channel bends tend to have more symmetric facies patterns than bend apices (Reimchen et al., 2016).

Researchers have recently suggested that turbidite facies in outcrop can be associated with internal hydraulic jumps in a supercritical turbidity current overriding cyclic steps (Postma et al., 2014; Postma and Cartigny, 2014). Supercritical turbidity currents are defined by the densimetric Froude number, $\mathbf{Fr_d}$, exceeding unity ($\mathbf{Fr_d} = U/\sqrt{g'h}$, where U is velocity, g' is reduced gravitational acceleration, and h is depth of a current). Cyclic steps are long-wave (the ratio of wavelength to height is >>1), upstream-migrating bedforms, commonly with asymmetrical waveforms in cross section, which develop in regions with high gradients and slope breaks that promote repeated internal hydraulic jumps in an overriding turbidity current (Kostic, 2011). These bedforms have been documented in field-scale observations combined with morphodynamic modeling (e.g., Fildani et al., 2006; Kostic, 2011; Covault et al., 2014), physical experiments (e.g., Spinewine et al., 2009), direct monitoring of turbidity currents (e.g., Hughes Clarke, 2016), and recently in outcrops (Postma et al., 2014). These features might play a significant role in the development of stratigraphic architecture and facies distribution within relatively high-gradient channels. However, most outcrops are limited in scale compared to the size of cyclic steps (up to ~10^3 m wavelength; ~10^2 m height; Symons et al., 2016), and facies-based recognition remains a challenge.

SUBMARINE-CHANNEL STRATIGRAPHIC EVOLUTION

The stratigraphic evolution of submarine channels generally includes the creation of a large-scale, composite, erosional bounding surface (i.e., valley) as a result of incision and lateral migration of the active channel floor during early channel-system evolution, followed by stacking and aggradation of leveed channels during later evolution (Deptuck et al., 2003; 2007; Posamentier, 2003; Mayall et al., 2006; Hodgson et al., 2011; McHargue et al., 2011; Sylvester et al., 2011; Janocko et al., 2013; Bain and Hubbard, 2016) (Figs. 2 and 3). In outcrop, these large-scale composite surfaces are commonly associated with deposits of debris flows, slumps, and/or slides (facies 4 and 5) (Hodgson et al., 2011; Macauley and Hubbard, 2013).

A relatively high rate of incision of the active channel floor can result in a complex architecture at the base of the channel system, in which erosional remnants of sandstone-dominated channel fills are preserved on the valley side; these remnants usually originate as meander-bend cutoffs (Sylvester et al., 2011; Sylvester and Covault, 2016). This early phase of channel evolution is poorly understood because the preserved stratigraphic record is commonly fragmented or completely absent as a result of subsequent erosion (Sylvester and Covault, 2016).

As the incision rate decreases, the preservation potential of channel deposits increases, but channels tend to erode into previously deposited sediment. This stage is characterized by limited incision or aggradation but significant lateral migration of channels; the resulting stratigraphy consists of numerous erosional channel remnants that usually fill the valley floor from one side to the other and there is only one continuous channel thread that can be seen and mapped across the area of interest (Figs. 2 and 3).

Following the early phases of incision and lateral migration, aggradation of the channel floor and bounding levees at the top of the channel system promotes greater preservation and results in more continuous and vertically connected sandstone-rich facies bounded by finer-grained deposits (Kane and Hodgson, 2011; Sylvester et al., 2011; McHargue et al., 2011; Janocko et al., 2013; Macauley and Hubbard, 2013) (Figs. 2 and 3). Submarine channel aggradation rates are usually much higher than those observed in fluvial systems (Peakall et al.,

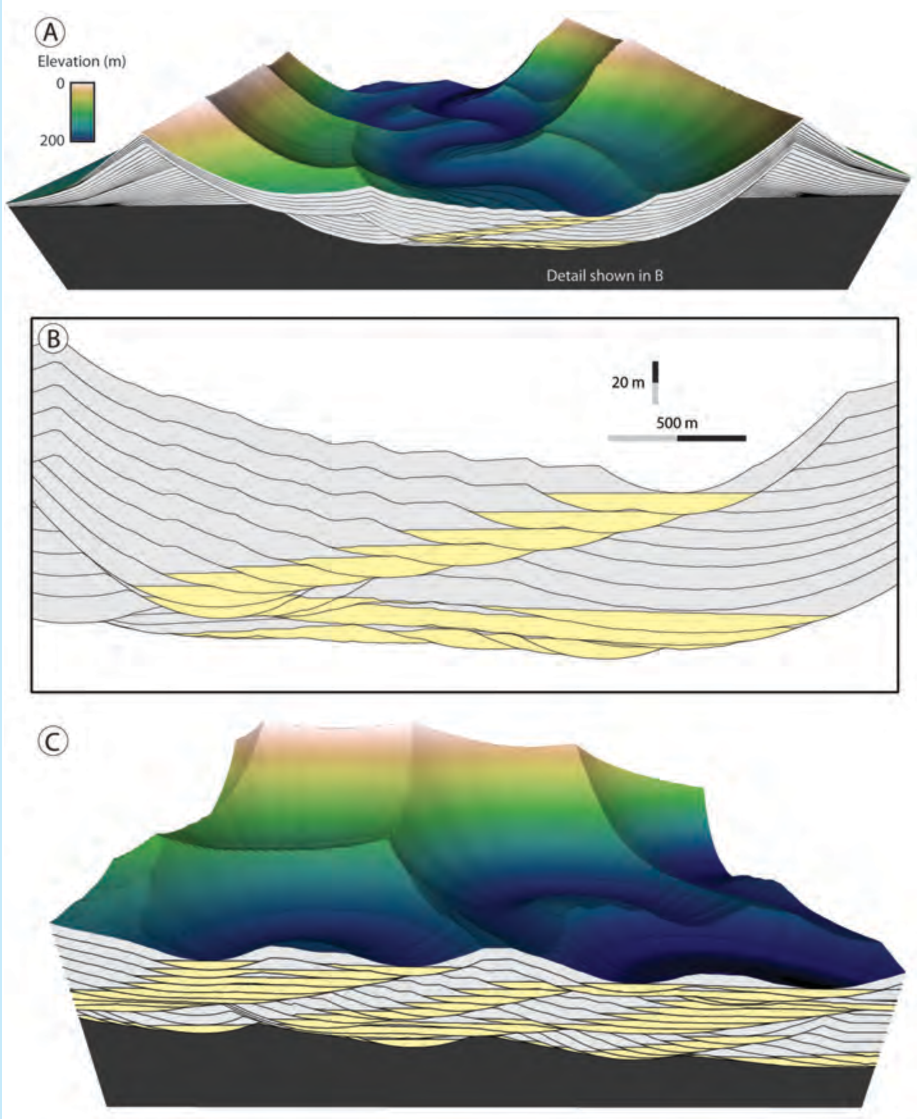

Figure 4: (A) Surface-based stratigraphic forward model of the incising-to-aggrading trajectory of a channel system (Sylvester and Covault, 2016). Bed-scale lithological variability is not represented. (B) Detailed depositional-strike-oriented cross section. Yellow is sand-rich; gray is mud-rich lithology. (C) Depositional-dip cross section.

2000; Sylvester et al., 2011; Jobe et al., in press).

We illustrate the incising-to-aggrading trajectory of channel systems in a surface-based stratigraphic forward model that is inspired by a kinematic model of river meandering (Fig. 4). The model is based on an implementation of the Howard and Knutson (1984) meandering channel model, a computationally simple and fast approach for generating sinuous channel centerlines with realistic shapes. Using an approach similar to that of Finnegan and Dietrich (2011), we track along-channel slope variability; this increases the complexity of the model as cutoff-related knickpoints cause re-incisions (Sylvester and Covault, 2016). For the generation of topographic and stratigraphic surfaces, we use three simple steps for each centerline: 1) channel-base erosion; 2) channel-filling sand deposition; and 3) overbank mud deposition (Sylvester et al., 2011; Sylvester and Covault, 2016). The resulting surface-based model captures large-scale submarine-channel architecture, but bed-scale lithological variability is not represented (Fig. 4).

The commonly observed incising-to-aggrading trajectory of a channel system is likely influenced by both autogenic and allogenic controls. The similarities in stratigraphic evolution and resulting facies architecture of submarine-channel systems suggest common processes in different continental-margin settings (Deptuck et al., 2003; McHargue et al., 2011). The incising-to-aggrading trajectory might reflect adjustments toward an equilibrium state, in which sediment is transported through a channel with minimum incision or aggradation of the seafloor (Pirmez et al., 2000; Hodgson et al., 2011; McHargue et al., 2011; Janocko et al., 2013). Equilibrium is established and maintained by feedbacks between the slope and overriding sediment-gravity flows: a steep slope will promote swift flows that are erosive; a more gradual gradient will promote sluggish flows that aggrade sediment (Kneller, 2003; Ferry et al., 2005). A combination of these two processes brings the channel floor closer to an equilibrium gradient. For example, a channel on the steeper, down-dip side of an anticline will undergo upstream-propagating incision until equilibrium is achieved. Knickpoints probably play an important role in submarine channel incision (Heiniö and Davies, 2007; Sylvester and Covault, 2016). Channel segments affected by ongoing subsidence are likely to respond with deposition. Steep submarine slopes are commonly related to incision of erosional surfaces during early channel evolution (Ferry et al., 2005). The transition from laterally stacked and cutoff channel deposits at the base of the system to more continuous and aggradational channel and overbank deposits at the top might also be related to levee deposition across a reduced slope as a result of grading the slope to an equilibrium profile (Peakall et al., 2000; Pirmez et al., 2000; Hodgson et al., 2011; McHargue et al., 2011).

Changes in sediment-gravity-flow properties driven by allogenic controls, such as eustatic sea-level change, have also been linked to the incising-to-aggrading trajectory (Pirmez et al., 2000; Posamentier and Kolla, 2003; Piper and Normark, 2001; Deptuck et al., 2003; Kneller, 2003; Ferry et al.,

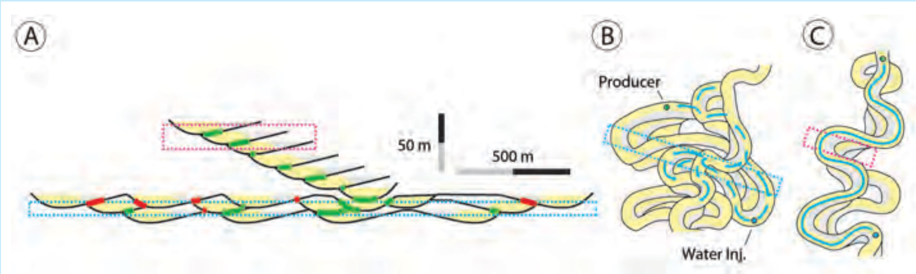

Figure 5: Hypothetical submarine-channel-system facies architecture (i.e., facies heterogeneity and stacking patterns) inspired by outcrop (Figs. 1 and 2) and stratigraphic forward model (Fig. 4) and potential fluid flow behavior during hydrocarbon production. (A) Cross section of incising-to-aggrading trajectory of a submarine-channel system. Yellow is sand-rich; gray is mud-rich lithology. Green lines indicate sand body connectivity. Red lines indicate baffles or barriers between sand bodies in cross section. Approximate locations of B and C are blue and pink dashed boxes, respectively. (B) Lower zone of cutoff and eroded channel deposits. Downstream continuity of sand-rich facies is likely oversimplified. Water injector well (Water Inj.) is a blue dot. Producer well is a green dot. (C) Upper zone of more continuous and vertically connected sandstone-rich facies. See text for explanation.

2005; McHargue et al., 2011; Jobe et al., 2015). For example, diminished sediment supply as a result of gradual shoreline transgression might yield underfit sediment gravity flows that were confined by overdeepened bounding surfaces, preventing flows from overspilling and promoting inner levee and channel aggradation (Deptuck et al., 2012; Janocko et al., 2013; Jobe et al., 2015). More work is needed to better understand the commonly observed shift from incision to aggradation (Jobe et al., in press).

SUBMARINE-CHANNEL RESERVOIR CHARACTERIZATION

Integrated subsurface characterization, modeling, and flow simulation studies have evaluated the effect of facies architecture on channelized reservoir connectivity and performance (Larue and Hovadik, 2006; Stright, 2006; Labourdette, 2007; Stewart et al., 2008; Funk et al., 2012; Alpak et al., 2013). For example, Larue and Hovadik (2006) simulated oil production with water injection in simple 3D geostatistical models of channelized reservoirs. They found that fine-grained facies, such as mud-rich turbidites and debrites draping channel floors, decreased connectivity (Larue and Hovadik, 2006; see also Stright, 2006; Labourdette, 2007; Stewart et al., 2008; Li and Caers, 2011; Alpak et al., 2013). Stewart et al. (2008) performed flow simulations on a model describing the submarine-channel facies architecture of the Miocene-Pliocene Capistrano Formation, southern California, to evaluate the effect of heterogeneity and connectivity on hydrocarbon recovery. Facies architecture represented in these models included the presence of basal high-permeability zones in the center of each channel and lower permeability zones in the margins of channel fills (Stewart et al., 2008). This facies architecture had a significant negative impact on recovery and timing of injected water breakthrough compared to models that did not contain such organized extremes of permeability (Stewart et al., 2008).

Fluid flow behavior during hydrocarbon production is likely to vary according to reservoir architecture that differs as a function of the incising-to-aggrading trajectory of a channel system (Fig. 5). At the base of a channel system, the complex juxtaposition of cutoff and eroded sandstone-rich facies against finer-grained facies results in an abundance of short length-scale heterogeneity (Fig. 5). Within this type of reservoir architecture, connectivity between injector-producer well pairs is likely to be established via multiple remnant channel sand bodies, which has the potential to promote efficient sweep by reducing the organized structure of permeability extremes. At the top of a channel system, injected water might preferentially sweep the more continuous and vertically connected sandstone-rich facies, bypassing oil in thin-bedded heteroltihic deposits (e.g., Stewart et al., 2008) (Fig. 5). Future work should focus on the effect of submarine-channel stratigraphic evolution and facies architecture on fluid flow behavior during hydrocarbon production (cf. Meirovitz et al., 2016).

SUMMARY

Submarine-channel systems are composed of channel fills with thick-bedded turbidite sandstone deposited in the thalweg, thin-bedded heterolithic turbidites in the margin, and scour surfaces draped with turbidite mudstone and/or mudstone-dominated units deposited by debris flows, slumps, and/or slides. Submarine-channel stratigraphic evolution commonly reflects an incising-to-aggrading trajectory that results in a lower zone of cutoff and eroded channel deposits overlain by an upper zone of more continuous and vertically connected sandstone-rich facies. However, channel systems can also be 'frozen' in time at different stages of their evolution (e.g., Janocko et al., 2013). Outcrop characterization and a stratigraphic forward model illustrate the 3D stacking patterns of channel systems. The 3D facies architecture that results from the incising-to-aggrading trajectory of a channel system is viewed as a primary control on reservoir heterogeneity and connectivity.

Future research opportunities include constraining fundamental processes that operate in submarine channels via analysis of stratigraphic products integrated with short-term observations from direct monitoring and physical experiments; this is particularly critical as observing natural flows in the deep sea has proven challenging. The importance of hydraulic jumps, cyclic steps, and knickpoints in submarine-channel evolution are all active research topics. The integration of morphodynamic numerical modeling with outcrop characterization can be employed to evaluate the long-term evolution of bed-scale sedimentary processes and products. Autogenic and allogenic controls on stratigraphic evolution are also active research topics. These controls are important as they determine the stratigraphic evolution and facies architecture of submarine-channel systems, thereby influencing continental-margin sediment dispersal, as well as the heterogeneity and connectivity of channelized reservoirs.

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