Marine and Petroleum Geology 41 (2013) 48–61

Contents lists available at SciVerse ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Erosion at inception of deep-sea channels

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ARTICLE INFO

Article history:
Received 19 October 2011
Received in revised form
9 March 2012
Accepted 12 March 2012
Available online 30 March 2012

Keywords:
Deep-sea channels
Incipient channel
Erosional template
Deep-water
Hierarchy

ABSTRACT

We present a general model for channel inception and evolution in the deep sea by integrating observations from two complementary datasets: (1) high-resolution multibeam bathymetry and chirp sub-bottom profiles of the Lucia Chica channel system on the seafloor offshore central California, and (2) the well-exposed channelized strata of the Tres Pasos Formation in southern Chile. The Lucia Chica channel system shows laterally offset, sub-parallel channels that evolved across a similar gradient, but display different architecture, reflecting the influence of channel maturity and intrinsic cyclicity of channel formation. The stratigraphically oldest channel is narrower with well-developed levees while the younger channelized features are broader and bounded by low-relief levees or no levees at all.

The high-resolution Lucia Chica dataset is integrated with detailed field observations of channel axis-to-margin sedimentary facies relationships and the stratigraphic context afforded from depositional-dip continuity in outcrops of the Tres Pasos Formation. Numerous channels from the outcrop belt are characterized by initial erosional stages.

By combining these two datasets with numerical analysis, experimental work, and previous interpretations of additional outcropping strata and seafloor examples, we hypothesize that an initial erosional template extending into a basin is a pre-requisite for creation of channels in deep-sea environments.

1. Introduction

Submarine channel inception, herein referring to the early establishment of a channel-form traversed by turbidity currents on the seafloor, and subsequent channel development in deep-sea environments has been an important research focus during the last few decades (e.g., Bouma et al., 1985; Weimer and Link, 1991; Weimer et al., 1994; Stow and Mayall, 2000; Gardner and Borer, 2000; Weimer et al., 2000; Mutti et al., 2003; Posamentier and Kolla, 2003; Wynn et al., 2007; Hubbard et al., 2011). Submarine channels serve as important conduits for terrigenous material across continental margins to the deep oceans (Allen, 2008), are a geohazard for seafloor infrastructure planning and construction (Paull et al., 2003; Xu, 2010), and their sedimentary fill frequently comprises significant hydrocarbon reservoirs in ancient strata (Stow and Mayall, 2000; Pettingill and Weimer, 2002; Mayall et al., 2006). Understanding the evolutionary processes of channels is important for predictions of their individual occurrence and morphology, as well as stacking patterns of multiple channels over time in sedimentary basins.

Recent physical experiments have raised questions regarding the relative contributions of erosional and depositional processes to sediment-gravity-flow confinement and leveed-channel evolution (e.g., Parsons et al., 2002; Baas et al., 2004; Rowland et al., 2010a). However, experiments are not able to capture all possible controls and conditions of natural settings. In this paper, we expand on insights from experiments with observations drawn from the modern seafloor and exceptional exposures of channel complexes in outcrops of sedimentary rocks. Based on these observations, we hypothesize that an initial, likely brief, purely erosional phase of channel development is necessary to focus turbidity currents and subsequently promote construction of aggrading banks.

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doi:10.1016/j.marpetgeo.2012.03.006

High-resolution acoustically obtained seafloor and subsurface images have provided unprecedented perspectives of channel-dominated seascapes across continental slopes and depositional fans to their distal termini (e.g., Damuth et al., 1983; Twichell et al., 1992). Zones where sediment-laden gravity flows evolve from generally confined to unconfined conditions are favorable locations in which to study channel inception and evolution. Such zones have been observed at the Shepard Meander on Monterey Fan, where an incipient channel is interpreted to be developing along a train of cyclic steps (Fildani et al., 2006), and at the channel-lobe transition (Mutti and Normark, 1987; Wynn et al., 2002). These zones have been related to flow acceleration ($\partial U/\partial t$ where U is flow velocity) and variable sediment deposition rates, resulting from abrupt changes in gravity flow parameters (e.g., Garcia and Parker, 1989), but also hydraulic jumps, which are associated with erosion and sediment bypass into the basin (Garcia and Parker, 1989; Kostic and Parker, 2006). On the other hand, the high-resolution acoustic data of such flow-transition zones only capture static morphologies on the seafloor, providing limited insights into longer-term channel evolution (e.g., Jegou et al., 2008). Even very recent seafloor imaging of flow transition zones have thus far failed to capture low-relief geomorphic features, including nascent channels (e.g., Jegou et al., 2008; Migeon et al., 2010).

In this study, we attempt to isolate the processes at earliest channel creation related to turbidity currents (sediment-laden density currents) by using complementary datasets, including the highest resolution geophysical and outcrop data available. We considered the high-resolution multibeam bathymetric data (1 m lateral resolution) and chirp subsurface profiles (11 cm vertical resolution) of the Lucia Chica channel system, on the seafloor offshore central California (Maier et al., 2011, 2012), along with Cretaceous deep-sea slope channel deposits from the Tres Pasos Formation of the Magallanes Basin, southern Chile. We avoid consideration of channel inception due to non-turbidity-current-related mass-wasting and mass-flow processes, which have been discussed at length by other researchers (Shepard, 1963, 1973; Normark and Carlson, 2003; Piper and Normark, 2009; among others). We concentrate on inception of channels due to avulsion along the slope or past the slope-to-basin-plain transition where post-avulsion flow allows channels to extend across a previously unchannelized area.

We propose that channels traversed by turbidity currents are commonly erosional at inception; hence aggradational confinement at the inception of deep-water channels is less probable. An initial erosional phase is necessary to focus turbidity currents and create a high-velocity core closely bounded by the lower-velocity marginal regions necessary for lateral deposition and levee development (cf. Mohrig and Buttles, 2007), which evolve into the aggrading systems commonly described in seismically resolved deep-water datasets (cf. Pirmez and Imran, 2003). The inception of deep-water channels via erosion has profound implications for connectivity at reservoir scale allowing spatial predictions of amalgamation zones (prone to better reservoir connectivity) in buried deep-water systems.

1.1. The issue of scale

Turbidite channels have been documented from seafloor, outcrop, and subsurface data (Normark, 1970; Mutti and Ricci Lucchi, 1972; Mutti and Normark, 1987, 1991; Clark and Pickering, 1996; Weimer et al., 2000; Mayall et al., 2006; Hodgson et al., 2011; McHargue et al., 2011; among others). Differences between scales of observation, data type, and geomorphic versus stratigraphic expression have led to confusion in classifying channels and their fill (Fig. 1; Mutti and Normark, 1987), particularly where a significant range in temporal and spatial scale exists. For instance, Normark (1978) defined two types of channels on modern submarine fans: large leveed channels and smaller, commonly un-leveed, channels as lobe distributaries. We now know that the large, leveed channels are long-lived and can be filled with strata representing the deposits of numerous smaller-scale, un-leveed channels: the cumulative effect of erosive and depositional processes throughout their history (e.g., Mayall et al., 2006; Gee et al., 2007; Di Celma et al., 2011; Hodgson et al., 2011). Forward modeling approaches (McHargue et al., 2011; Sylvester et al., 2011) have also shown that the time represented by the basal surfaces of large leveed systems can be long relative to the smaller, commonly un-leveed, distributary channels first recognized by Normark et al. (1979). These basal surfaces of large leveed systems are time transgressive, never fully existing on the seascape at any one time (e.g., Sylvester et al., 2011). Despite different forward stratigraphic modeling approaches, McHargue et al. (2011) and Sylvester et al. (2011) addressed the issue of a highly diachronous and amalgamated erosional surface in a deep-marine environment, a topic already debated in the shallow marine depositional systems (e.g., Strong and Paola, 2008).

Following Mutti and Normark (1987), based on three-dimensional seafloor mapping, a channel is here defined as an expression of negative relief produced by submarine mass movement, and represents a long-term pathway for sediment transport across the seafloor. More specifically, an incipient channel, as defined by Fildani and Normark (2004) based again on seafloor mapping techniques, is a net-erosional channel-form initiated by a series of scours that establish a discontinuous thalweg (Fig. 2A,B). Although incipient channels are ephemeral because of subsequent entrenchment and erosion of the channel (see discussion in Fildani et al., 2006), they have been documented in the subsurface and, thus, can be preserved in the stratigraphic record under certain circumstances (Armitage et al., 2012, Fig. 2C,D).

Classifying channels across data types (i.e., planform bathymetry versus cross-sectional outcrop), while ultimately providing the most complete view, is limited by the inherent disparities of perspectives. Understanding that outcrops provide a more detailed cross-sectional perspective of channels relative to seafloor remote sensing, Mutti and Normark (1987) helped reconcile the definition of the channel “container” (rigorously defined from three-dimensional seafloor mapping) with outcropping channel “fill”. Subsequent outcrop studies have shown that channel-filling strata can exhibit a variety of architectures, from amalgamated sandstone beds interpreted to have been deposited from high-density turbidity currents to heterolithic thin beds above channel floors commonly interpreted to represent deposition from low-density tails of bypassing turbidity currents, with varying degrees of levee development (e.g., Mutti and Normark, 1987; Clark and Pickering, 1996; Campion et al., 2000; Hubbard et al., 2010; McHargue et al., 2011). Typically, what can be observed in outcrop (i.e., fill of a single channel; Fig. 1, also see Fig. 1 of McHargue et al., 2011) is below the resolution of conventional bathymetric data.

The integration of larger-scale seafloor and smaller-scale outcrop observations has proven invaluable toward our understanding of deep-water depositional systems (Bouma et al., 1985; Mutti and Normark, 1987, 1991; Weimer and Link, 1991; Normark et al., 1993; Morris and Normark, 2000; among others). However, there are still differences in scale of observation and data type/resolution that obfuscate a unifying concept of a “channel” (Normark et al., 1993). To address the issue of scale, while making the most out of all available data, we use the following hierarchical scheme: deep-water channel systems are constructed through stacking of fundamental building blocks, or channel elements, each of which record a phase of channel surface creation (erosion) followed by channel filling (deposition) to produce a sedimentary

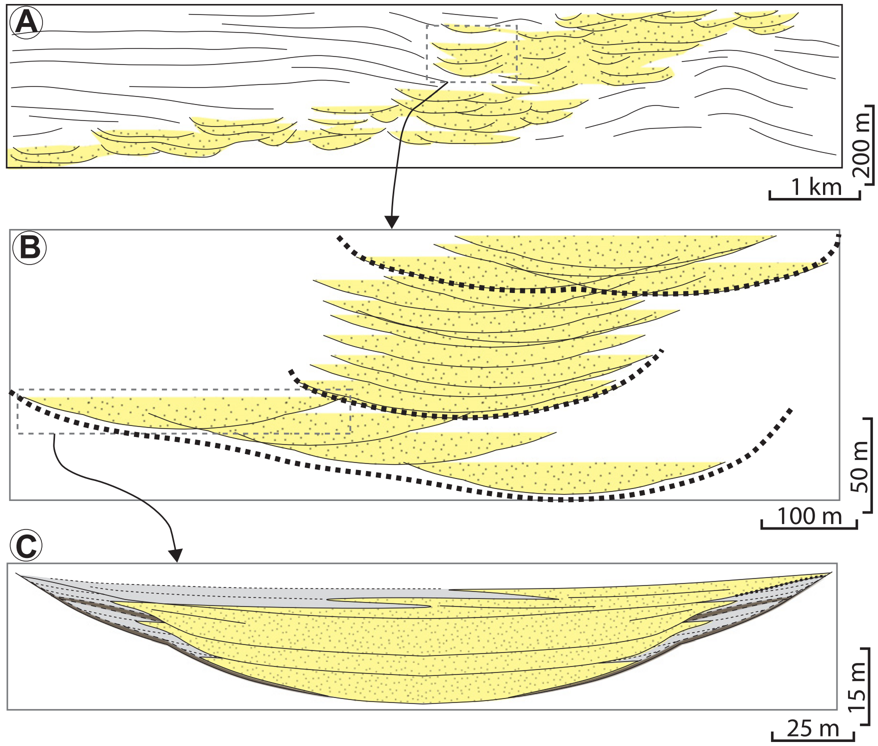

Figure 1. Multiple scales of channel-form features observed in deep-water strata. The stratal relationships documented are highly sensitive to the dataset assessed. (A) Cross-sectional overview of a channel-levee complex traced from a seismic reflection profile (seismic image originally presented in Hubbard et al. (2009)). Distinctive channel forms are hundreds of meters to over a kilometer in width and tens of meters thick. (B) Detailed cross section of channel strata interpreted to be bound by inner levees (adapted from Macauley and Hubbard, 2012). The thick, dark dashed lines separate packages of similar channel elements, with regards to stacking behavior; these lines represent distinct surfaces at a scale that is often observable in seismic reflection datasets (see channel-form surfaces traced in Part A). The lower composite channel-form comprises channel elements that systematically step to the left. The middle composite channel-form comprises channel elements that are largely vertically stacked. The upper composite channel-form comprises more variably stacked channel elements. (C) A fundamental channel element based on outcrops of the Cretaceous Tres Pasos Formation. Channel elements like these are a focus of this study, and are observed to be erosively bound (vertically and laterally) with other, similar channel elements.

body with channel-form geometry in cross section (Fig. 1; e.g., Campion et al., 2000; Gardner and Borer, 2000; Schwarz and Arnott, 2007; Kane et al., 2009; McHargue et al., 2011; among others). Channel elements cluster and stack to form composite features, or complexes, with qualitatively similar channel-form geometry, but at a larger scale (Fig. 1; e.g., Mayall et al., 2006; Di Celma et al., 2011; Hodgson et al., 2011; Macauley and Hubbard, this volume). Individual channel elements are typically observed in high-quality outcrops and are below the resolution of conventional seismic-reflection data. Conversely, channel complexes are commonly the smallest channel-form resolvable in seismic-reflection data and represent the composite expression of long-lived fluctuations in sedimentary processes, including compounding cycles of erosion and deposition (e.g., McHargue et al., 2011).

We propose that it is the sedimentological and stratigraphic information preserved within channel elements (Fig. 1C), or at the sub-element scale, that records the processes at channel inception – specifically the dominantly erosional phase. Moreover, element- and finer-scale observations are fundamentally important to reconciling the inherent, scale-related gaps in our understanding of channel evolution.

2. Observations and interpretations

2.1. Channels in seismic: Lucia Chica system

2.1.1. Dataset

Recent Autonomous Underwater Vehicle (AUV) investigation of the Lucia Chica channel system resulted in high-resolution imaging of uniquely preserved low-relief channels and incipient channel morphologies at near outcrop scale (Maier et al., 2011, 2012). The AUV dataset includes >70 km^2 of multibeam bathymetry with 1 m lateral resolution and >560 km of chirp subsurface profiles with 11 cm vertical resolution.

2.1.2. Observations

The AUV dataset reveals adjacent channels and scour features fed by a single, up-slope channel (Fig. 3). This feeder channel has a thalweg continuous into Channel 4, but it is disconnected from the adjacent Channels 1, 2, and 3 on the seafloor (for details see Maier et al., 2011). With channel relief defined as the difference in elevation between the thalweg and levee crest (Maier et al., 2011), the feeder channel shows diminishing relief, from over 20 m relief to less than 10 m relief in less than 2 km, as it transitions into Channel 4 (Fig. 3).

Seafloor morphologies and architectural style differ between adjacent channels. The channels were formed on the same background seafloor slope; gradient varies minimally between channels with differing morphology and architecture (Fig. 3; Maier et al., 2011). Channel 1 is characterized by a series of depressions on the seafloor related to its burial (Fig. 3). Channel 2 is narrower and has well-developed sinuosity, relief, and asymmetric levees (Fig. 3 and Fig. 4A,B) (see Maier et al., 2012). Channel 3 is wider, with correspondingly lower relief and sinuosity; it shows changes in width down current from avulsion points, incipient scours, and has localized small, symmetric levees (Fig. 3). Channel 4 widens down dip, from an aspect ratio (width:relief) of ∼20 to ∼50, coincident with trains of scours on the channel floor (Fig. 3 and Fig. 4C–G).

At four locations from up-dip to down-dip, Channel 4 bifurcates into “arms” characterized by less continuous morphologies, lower

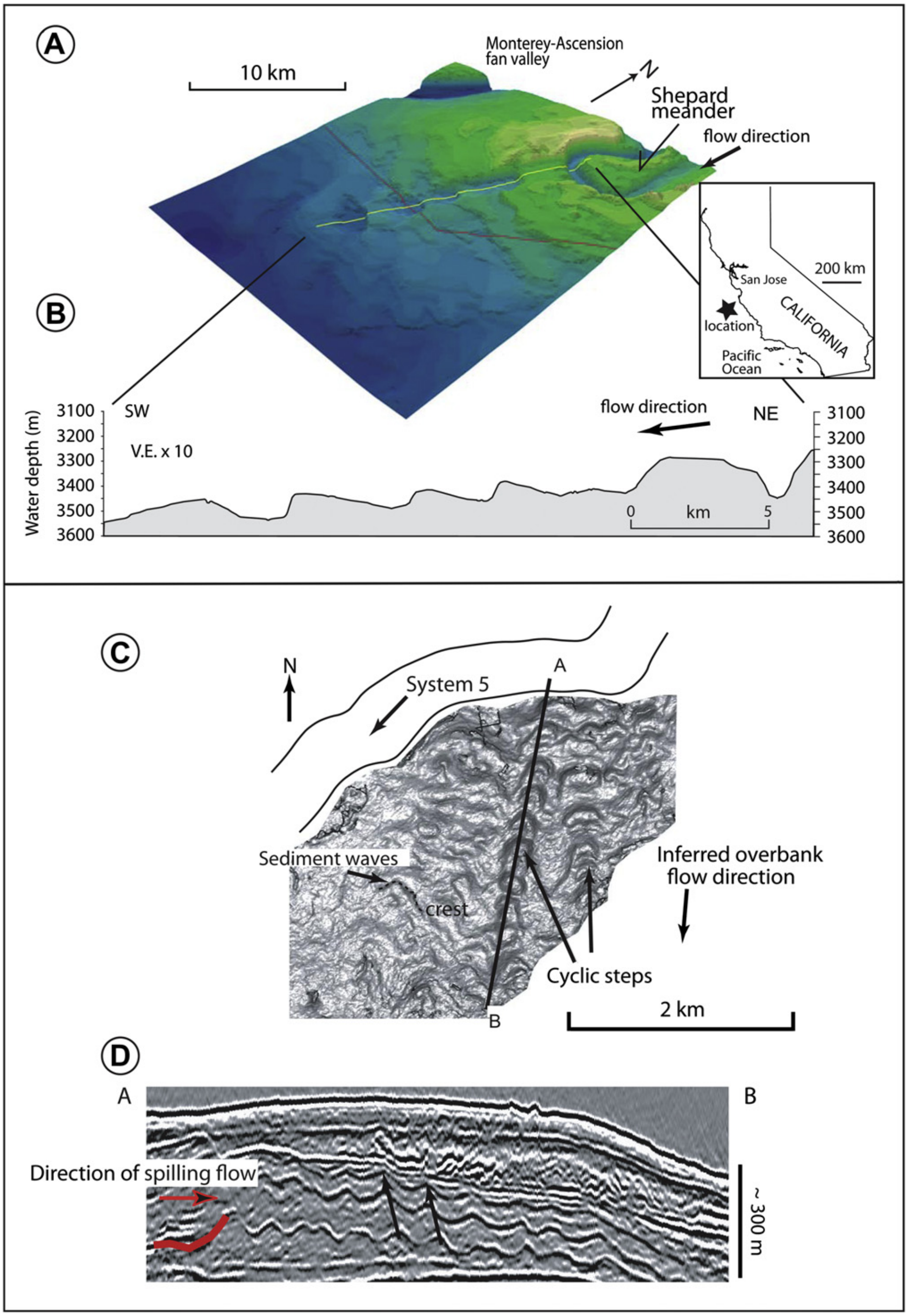

Figure 2. A. Shaded relief image of the Monterey East scour-train, associated with overspill on the Shepard Meander, constructed from multibeam bathymetric data (modified from Fildani et al., 2006). The discontinuous channel floor character of Monterey East is apparent, attributed to cyclic-step erosion. Note that the solid red line demarcates the location of a seismic reflection profile presented in Fildani and Normark (2004). B. Axial bathymetric profile constructed from multibeam data along the Monterey East train of scours (yellow line Fig. 2A) (modified from Fildani et al., 2006). C. Surface rendering of cyclic steps obtained form a 3D seismic volume offshore West Africa (modified from Armitage et al., 2012). The cyclic steps dissect a sediment wave field located on the outside bend of the mapped system 5 (see Armitage et al., in press for details). D. Seismic reflection profile showing the interpreted cyclic step crests and their up-slope migration.

relief, greater width, lower levees, and truncated reflections. Arms 4b and 4c have discontinuous thalwegs. Both arms (4b and 4c) of channel 4 have developed trains of cyclic scours (Fig. 3 and Fig. 4B,C). Channel 4 arm c displays a planform morphology intermediate between a discontinuous train of scours and a continuous channel thalweg (Fig. 3 and Fig. 4F). In chirp profile cross section, the arm is erosional and do not have associated levee morphologies (Fig. 4F–G).

2.1.3. Channel evolution

The Lucia Chica channel system allows interpretation of deep-water channel inception because: (1) the dataset exhibits

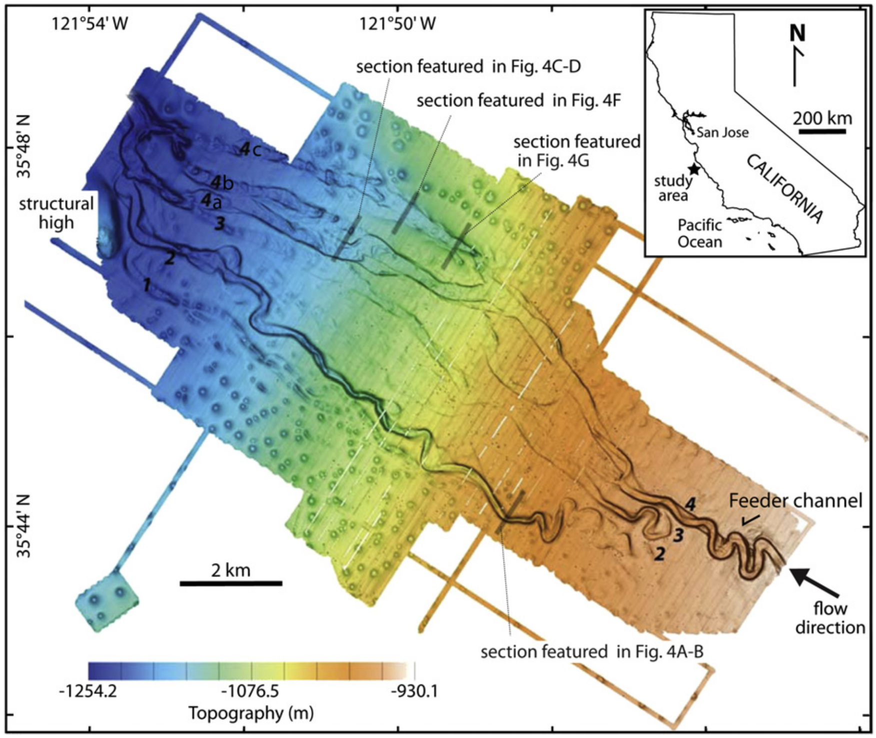

Figure 3. Multibeam bathymetry of the Lucia Chica channel system acquired with the Monterey Bay Aquarium Research Institute's (MBARI) Autonomous Underwater Vehicle (AUV). The inset map shows the approximate location of the dataset off the Pacific Coast of California. The channels of interest are numbered based on relative age, with 1 the oldest and 4 the youngest (modified from Maier et al., 2011).

unparalleled, high-resolution perspectives of the seafloor and shallow subsurface; and (2) the lateral juxtaposition of channels across the seafloor and shut-down of the entire system preserved the incipient (nascent) erosional channel forms. Because of the high-resolution datasets, individual channels are interpreted as channel elements. By mapping the stratigraphic packages defined by levees it is possible to clearly demonstrate by superposition that channels are stratigraphically younger from Channels 1 to 4 and bounded by avulsions (Maier et al., 2011). Wedge-shaped packages of closely spaced, seismic reflections that flank the channels are interpreted to be inter-bedded levee deposits (Fig. 4A–D). These wedge-shaped packages show a pattern of superposition from northeast to southwest; that is, Channel 4 appears to superpose Channel 3, which superposes Channel 2, which superposes Channel 1 (Maier et al., 2011). Thus, the Lucia Chica channel system shows sub-parallel channels that evolved across a similar gradient, but display different architecture, reflecting the influence of channel maturity and intrinsic cyclicity of channel formation.

Channels have discontinuous thalwegs in map view during initial development (e.g., arms of Channels 3 and 4) related to scouring at erosional channel inception. The up-dip portion of Channel 4 shows more "mature" channel geometries with relatively well formed levees and benches (e.g., Paull et al., 2010; Maier et al., 2012). Deposition of levees, channel narrowing, development of sinuosity, levee aggradation, and increasing channel relief are interpreted to occur as channels evolve. Adjacent to Channel 3, discontinuous, linear scours are present, which are interpreted to be megaflutes (Fig. 3). Morphologies in the down-dip portion of Channel 4 (arms 4b and 4c; Fig. 4) show immature architecture and initial trains of scours, interpreted to have been sculpted by turbidity currents (i.e., cyclic steps of Kostic and Parker, 2006; Fildani et al., 2006; Kostic, 2011), which likely carved an incipient channel (*sensu* Fildani and Normark, 2004) into underlying deposits. With repeated flows, these scoured areas coalesced, resulting in development of a more continuous channel thalweg as seen in Channel 4a (Fig. 3).

Subsequent aggradational levee development is preserved in the architectures of older channels. Channel 2 is narrower and has well-developed levee relief, and asymmetric levees that are interpreted to record punctuated migration of the channel thalweg through time (Maier et al., 2012) (Fig. 4A,B). With repeated flows, the muddier, top portions of the flows are interpreted to have been stripped from the main flow, facilitating additional levee growth and enhancing channel confinement (e.g., Normark and Piper, 1991).

2.2. *Channels in outcrop: Tres Pasos formation*

2.2.1. *Dataset*

The Tres Pasos Formation consists of outcropping slope strata that were deposited as the Magallanes retroarc foreland basin filled during the Late Cretaceous–Paleogene (Shultz et al., 2005; Hubbard et al., 2010; Romans et al., 2011). The area of interest for this study consists of a 300 m-thick and 2.5 km-long package of channel strata, associated with deposits at a lower-slope to toe-of-slope position at Laguna Figueroa (Figs. 5 and 6). Channel units are exposed in a series of gullies eroded along the entire length of the outcrop belt, offering local three-dimensional exposures (Fig. 5). The channels and their fill are captured in >3 km of stratigraphic section measured at cm-scale resolution, with hundreds of paleoflow measurements ($n = 738$), and detailed high-resolution photomosaics of outcrop faces. Thousands of global positioning system waypoints (accuracy < 1 m) were acquired to map significant stratigraphic surfaces in three dimensions. Two prominent sandstone-rich units, each 100–130 m thick, comprise a complex arrangement of stacked

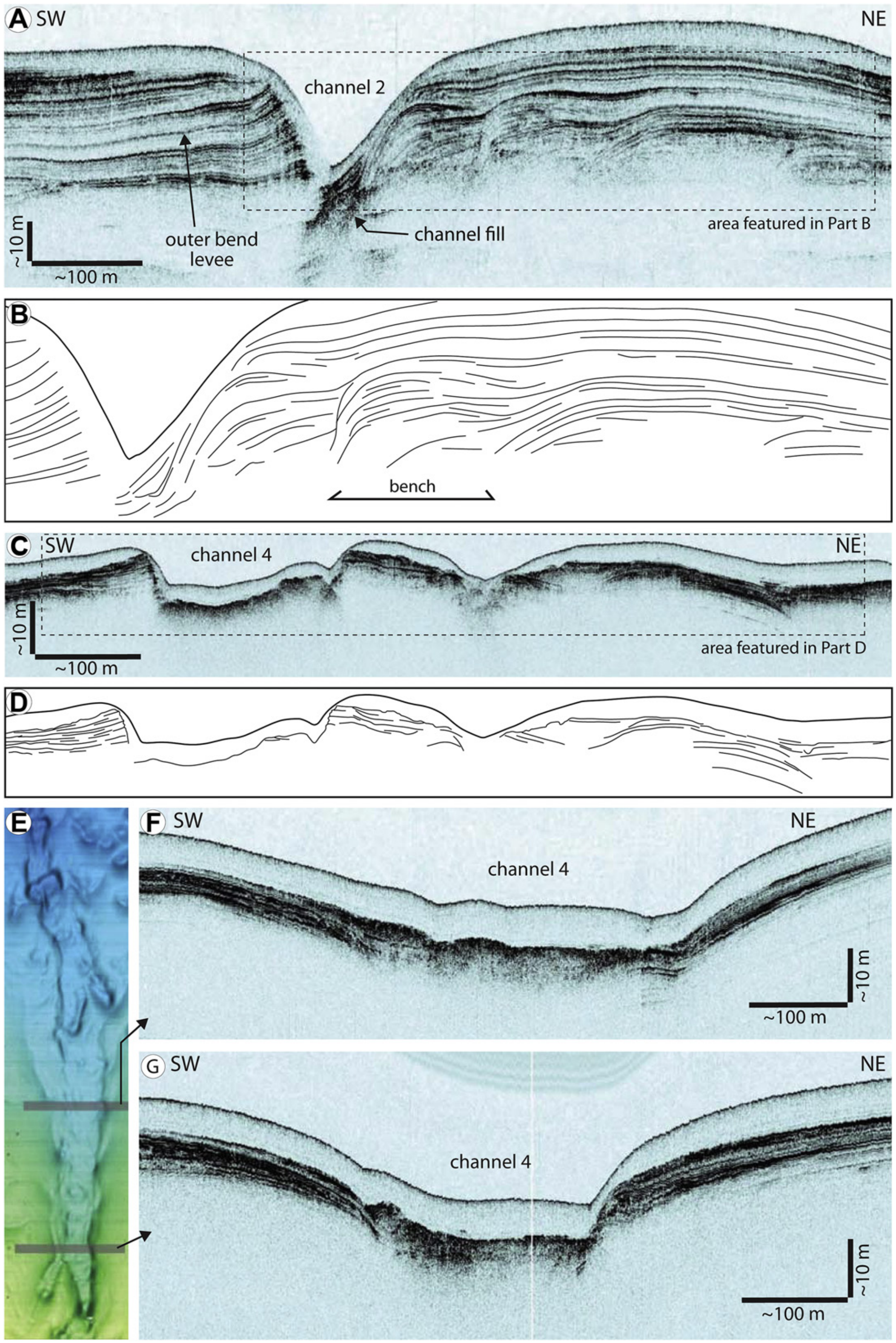

Figure 4. Chirp subsurface profiles from the Lucia Chica channel system showing more mature (A)–(B) and incipient (C)–(G) channel features. The flow direction is into the plane for each profile. (A) Channel 2. Sinuous Channel 2 has asymmetric levees resulting from punctuated migration (Maier et al., 2012). (B) Traced reflections from profile in (A). (C) Continuous Channel 4 and arm 4b. Channel 4 (left) has small levees and channel fill that produces an irregular top surface and diffuse reflectivity indicative of erosion and coarser-grained deposits. The adjacent scour (4b to the right) is an erosional feature that truncates surrounding reflections. Both channel and arm have lower relief than Channel 2. (D) Traced reflections from profile in (C). (E) Multibeam bathymetric image of the Channel 4c arm with morphology intermediate between a discontinuous train of scours and a continuous channel. Locations of profiles in F–G are indicated. (F) More distal cross section of (E). This incipient channel is wider than Channel 4 in (G) but also associated with sediments that produce diffuse reflectivity and an irregular top surface, indicating coarser-grained deposits and potential erosion. (G) More proximal cross section of (E). Levees are not imaged adjacent to the incipient channel feature.

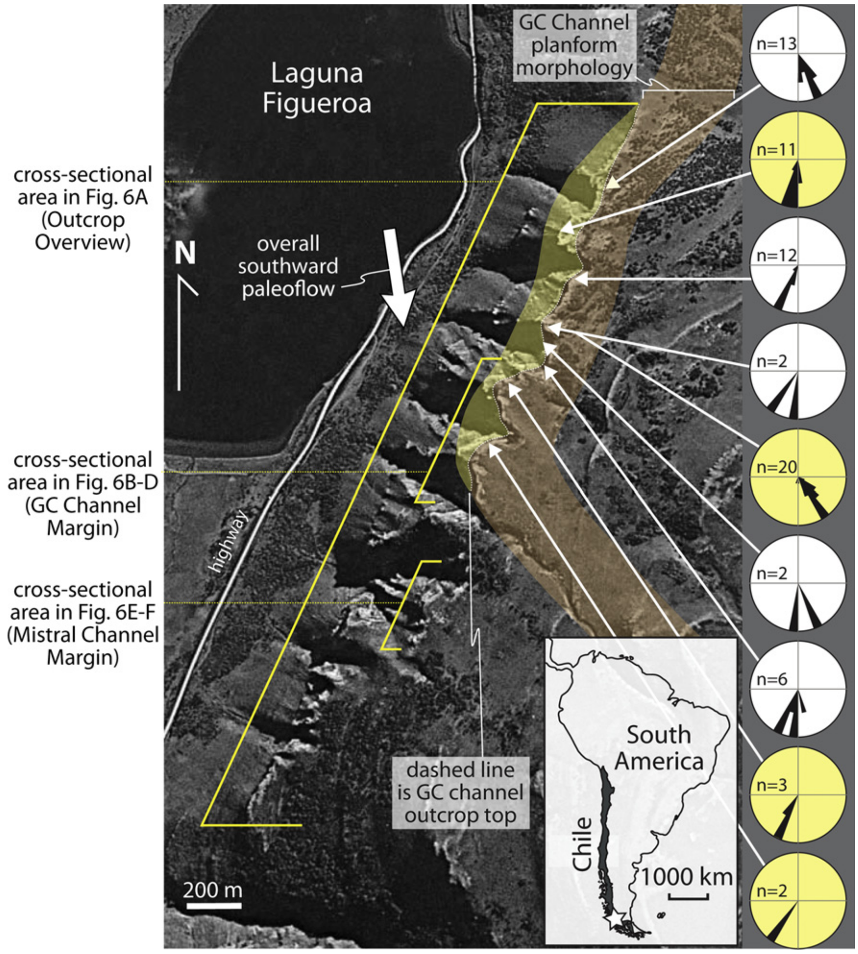

Figure 5. Planform overview of the Chilean study area, featuring Cretaceous slope outcrops of the Tres Pasos Formation. The mapped morphology of a single slope channel element, "GC Channel", is shown. Paleocurrent data derived from sole marks and current ripples were measured from axial sandstone beds (white circles) and thinly inter-bedded channel margin units (yellow circles). Inset map of South America including the location of the study area, demarcated by a white star.

channel-form sedimentary bodies; these units are separated by a fine-grained mass-transport-deposit-dominated interval (Fig. 6A). The lower of these two units is the focus of analysis by Macauley and Hubbard (2012) whereas this study emphasizes aspects of the upper stratal units.

2.2.2. Observations

Channels are erosionally juxtaposed against one another, with erosional relief of channel margins equal to the thickness of the channel fill in some instances (i.e., up to ∼25 m; Fig. 7B–D). Channel bases are draped by interbedded/interlaminated siltstone and very fine-grained sandstone units (Hubbard et al., 2010). Channel fill is dominated by amalgamated to non-amalgamated thick-bedded sandstone, although packages of thinly inter-bedded sandstone and mudstone locally are preserved at channel margins, within the conduit (i.e., not in an overbank position) (Fig. 1C and Fig. 6). These margin facies generally are associated with upward-coarsening of grain size and upward- thickening of beds (Macauley and Hubbard, 2012).

2.2.3. Channel evolution

The Tres Pasos Formation contains evidence of initial phases of slope channel incision, represented by deeply scoured basal surfaces (Fig. 6E–F) and silty drape deposits that are interpreted to originate from the tails of largely bypassing erosive turbidity currents (Hubbard et al., 2010). Subsequent gravity currents appear to have been primarily contained within the channel; Fig. 6D shows the margin of the sedimentary fill of a channel, which comprises thin-bedded, heterolithic facies (cf. Sullivan et al., 2004; Macauley and Hubbard, 2012). These heterolithic facies, interpreted as margin, are present within the channel cut (Fig. 1C). Overall, outcropping channel characteristics are broadly consistent with the results of recent experimental work that concluded that the emplacement of an erosional template is required to propagate channels basinward in submarine environments (Rowland et al., 2010a). Because of the scale of channels discernable in outcrops (∼300 m wide and ∼10–15 m thick, on average; McHargue et al., 2011) and the nature of their erosive margins (e.g., Fig. 6), it is not surprising that many workers interpret early channel evolution dominated by erosional processes in the field (Clark and Pickering, 1996; Elliot, 2000; Sullivan et al., 2004; Eggenhuisen et al., 2011; among others). The high-resolution information gathered from the channels of the Tres Pasos Formation is directly comparable (scale-wise) to the Lucia Chica dataset. Each individual channel master-erosion could be interpreted as a channel element. The hetero-lithic margin facies (thin bedded silt and mud deposits) present within the channel erosional surface and interpreted as channel margins could be similar in composition to the remnants preserved in Lucia Chica (bench of Channel 2 Fig. 4A; described in Maier et al., 2012).

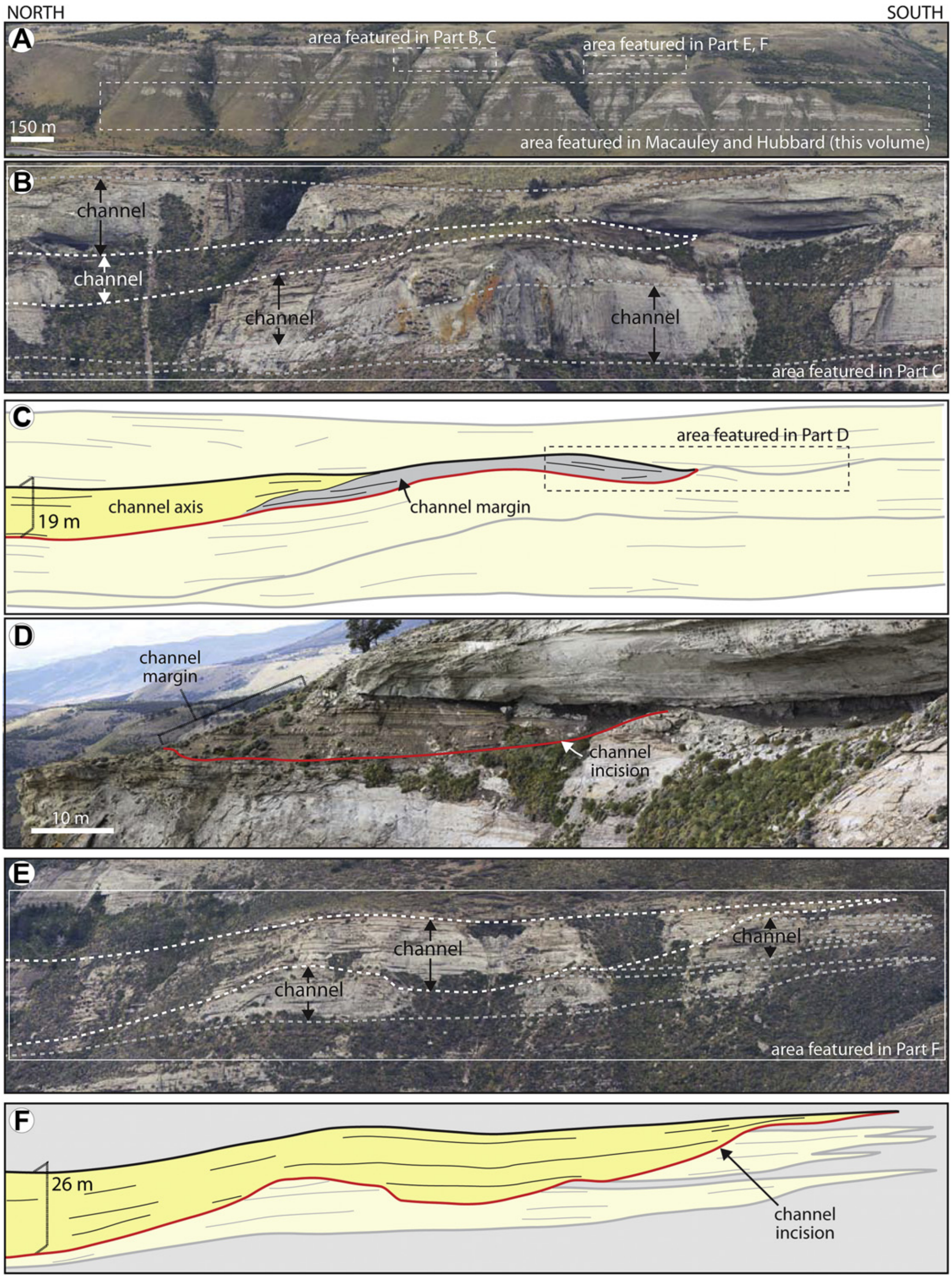

Figure 6. (A) Photomosaic of the Laguna Figueroa outcrop belt with areas shown in detail in (B) through (F), as well as area of interest of Macauley and Hubbard (2012), highlighted. (B) Detailed photo and (C) line-drawing trace of the transition from axial sandstone to thinly inter-bedded marginal deposits of the GC channel. (D) The edge of the GC channel, with fine-grained marginal facies onlapping the erosional contact. (E) Overview and (F) line-drawing trace of nested channel elements at the southern edge of the channel complex.

3. Discussion

3.1. Erosion at channel inception

We hypothesize that channels formed by turbidity currents are generally created as a result of a brief, early evolutionary phase dominated by erosional cutting into substrate. This initial period of erosion is followed by aggradation, which preserves the channel-form geometry and evolution into the stratigraphic record. We envision a time-step evolution (Fig. 7) where after an initial erosional phase and channel establishment, turbidity currents are able to construct aggrading levees. We have documented this evolutionary model from a seismic perspective with the Lucia Chica channel system integrated with outcrop observations from the well-exposed

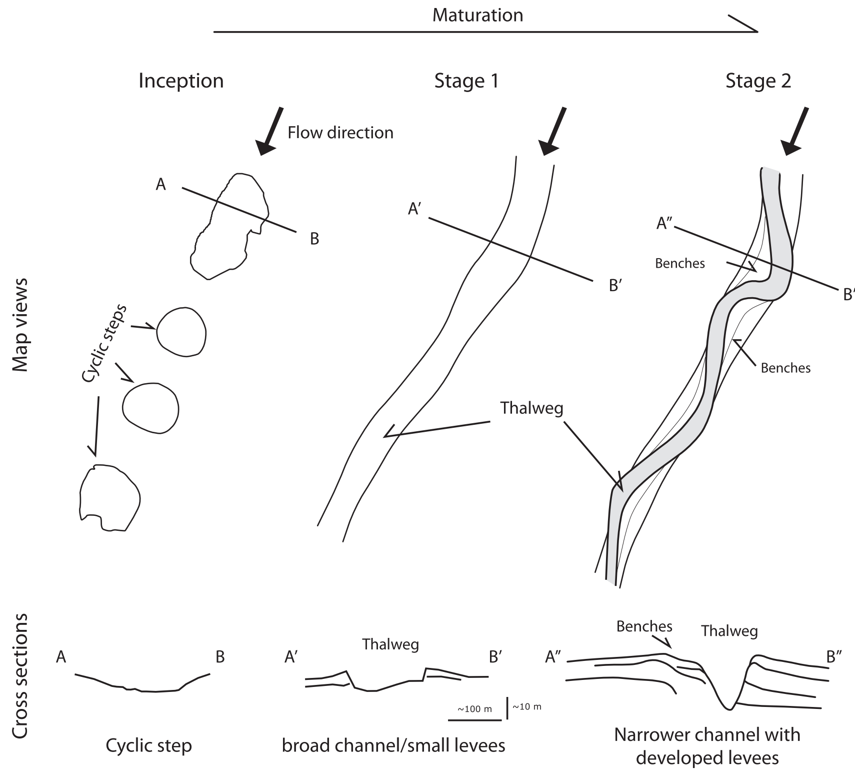

Figure 7. Simplified sketch diagram showing the proposed time-step channel evolution of slope channels. After an initial erosional phase and channel establishment, turbidity currents are able to construct aggrading levees and evolve into a channel-levee system. The initial erosional template could be supplied by net-erosional cyclic steps.

Tres Pasos Formation. What follows is the extension of these ideas into an experimental, numerical, and conceptual framework.

3.2. Insights from experimental work

With the assumption that no channel or channel-like form exists on the seafloor before it is traversed by a fully turbulent flow, a situation analogous to a flow entering a still tank onto a sloping planar surface from a point source, initial channel confinement has been attributed to (1) net erosion (as we observe from geologic evidence) or (2) net deposition (i.e., levee aggradation). To explore the latter, Rowland et al. (2010a) tested flow conditions ranging from subcritical to supercritical in a series of experiments aimed at determining if net-depositional currents were capable of generating self-confining leveed channels. These experiments failed to produce depositional architectures that either confined the experimental density currents or exhibited the potential to develop into confining leveed channels. A review of prior experimental and numerical studies aimed at generating leveed channel systems by Rowland et al. (2010a) revealed that levee development along channels conveying turbidity currents was only reliably observed in experiments where a significant portion of the flow was already confined by 1) an existing leveed channel (Mohrig and Buttles, 2007; Straub and Mohrig, 2008; Straub et al., 2008; Kane et al., 2010) or 2) by a channel eroded into the seafloor such that a limited fraction of the current spilled out of the channel and onto the adjacent seafloor (Bradford and Katopodes, 1999; Huang et al., 2007). In the absence of channel confinement, experimental work predicts that turbidity currents traversing a featureless seafloor will deposit sediment in lobes or sheet-like features without well-developed levees (Rowland et al., 2010a). Within net-depositional lobe/sheet complexes, however, localized erosion has been widely observed (Mutti and Normark, 1987; Elliot, 2000) and attributed to abrupt changes in current dynamics such as hydraulic jumps that occur as flow transition upon exiting from a confined point source and/or at a break in slope (Mutti and Normark, 1987, 1991). The scours produced by hydraulic jumps can hypothetically coalesce into a channel (Fig. 2; Fildani et al., 2006; Armitage et al., in press), and established confinement promotes erosion at the base of turbidity currents as a result of increased shear stress imposed on the substrate – a channel is born.

Recent experiments (Yu, 2011; Cantelli et al., 2011), following the work of Yu et al. (2006), have produced small isolated leveed channels on the distal portions of what they describe as "fan complexes." A fundamental requirement for such channel formation appears to be the dramatic thinning and splitting of an unconfined turbidity current (Yu et al., 2006; Yu, 2011; Cantelli et al., 2011). Whereas these channel systems appear important in controlling deposition across these "tank scale fan complexes", there is little to suggest that these channels have the capacity to recapture the master flow and provide channelized confinement of currents across unchannelized portions of the seafloor and into deeper water settings.

Rowland et al. (2010b) experimentally investigated the morphodynamics of subaqueous levee formation at a river mouth and successfully extended levees into a tank "basin". In these experiments lateral deposition and levee formation occurred in relatively quiescent lateral zones bounding the main flow. Sediment delivery to these zones was driven by strong lateral shear zones along the margin of the debouching flow. Due to limited density contrast between the sediment-laden current and the receiving waters, flow expansion upon unconfinement was limited. In contrast to these experiments on debouching fluvial effluents, suddenly unconfined turbidity currents rapidly spread laterally and lack quiescent lateral zones into which focused deposition needed for levees may develop (Rowland et al., 2010a). The disparity between deep sea and subaerial initiation of channels is likely a problem of density contrast. Lesser density contrast between ambient fluid and sediment-laden underflows in the deep sea may require erosion to replenish the sediment plume, offset water entrainment, and maintain flow momentum (Parker et al., 1986). With this in mind, deep-sea channels might be better analogs for channels forming on planetary bodies where there is comparable density contrast between sediment-laden underflows and the ambient fluid (c.f., Rowland et al., 2010a).

3.3. Numerical modeling

Surprisingly little work has been done using numerical models to describe channel inception. Imran et al. (1998) and Bradford and Katopodes (1999) have investigated this phenomenon and employed models that are effectively expanded versions of the one-dimensional, layer-averaged model of turbidity currents proposed by Parker et al. (1986). Both studies have shown that laterally bounding deposits (levees) can be constructed without erosion. Yet, the model of Imran et al. (1998) shows that initial lateral deposits were often strongly flared outwards, finally reaching near-parallel morphologies after 1500–2000 m down-dip of the entry point under optimum channelization conditions. The length scale and width of these lateral deposits is inconsistent with the morphologies present in the Lucia Chica system, where levees are near parallel within tens of meters of the avulsion site and strong outward flaring is not observed. The model of Bradford and Katopodes (1999) shows that levees can aggrade with near-parallel morphology almost instantly, but each subsequent channel was truncated with a depositional mound 40–80 m down-flow of the inlet. If we assume that erosive flows follow this initial period of aggradation, then the channel relief will increase, and the depositional mound will pose an even more daunting obstacle to overcome for any subsequent flow.

More recently, Hall et al. (2008) investigated channel inception using a Navier-Stokes-based stability analysis, finding that a base flow velocity boundary layer thinner than the base concentration profile was required to promote instability and produce evenly spaced submarine channels. This destabilizing effect leads to increased erosion at the trough (intended as a depression on the surface the flow is traversing) primarily due to increased shear stress caused by counter-clockwise rotating secondary flow cells, concurrent with decreased erosion at the channel margins (Hall et al., 2008). It should be noted that this analysis requires an initial perturbation and does not rely upon the slope traversed by the turbidity current, but does provide the framework for progressive instabilities leading to channel formation.

Undoubtedly, confinement plays a significant role in channel inception and elongation. Yet, to our knowledge, no studies have specifically addressed this key issue. Kane et al. (2008) have shown that flows with increased vertical confinement, defined as the ratio of levee height to flow height, prefer bypass to aggradation while flows with low vertical confinement are strongly aggradational, and prefer to deposit within the channel axis rather than upon the levees. Relating these results to channel inception is problematic as Kane et al. (2008) focused upon channel meandering rather than channel inception, but we can still glean important information from this study. Specifically, vertical confinement promotes non-aggradational flow conditions. Imran et al. (1998) and Bradford and Katopodes (1999) have modeled increases in vertical confinement through the construction of aggradational levees. However, this process is slow as the bed concurrently aggrades, and the resulting levee and channel morphologies are not consistent with observations made in the Lucia Chica system (Maier et al., 2011), as discussed above, nor with previous work from Gee et al. (2007).

In light of this, an easier way to increase vertical confinement is by erosion. If a channel begins with an erosional pit, as suggested by the scour train on the Monterey Fan (Fig. 2) as well as the scours present in Lucia Chica (Figs. 3 and 4), then the initial slope traversed by the flow, even at short length scales, will be increased down the slip face of the step. Using scaling analysis, Traer et al. (2012) have shown that the driving force provided by down-slope gravity on the suspended sediments dominates the momentum budget of the one-dimensional, layer-averaged model of turbidity currents. The initial increase in slope will promote flow acceleration, which will in turn lead to an increase in bed-shear stress and erosion (e.g., Smith and McLean, 1977; Garcia and Parker, 1993). Concurrent levee aggradation at the flanks of the erosional channel may occur. The resulting channel-levee morphologies might be more realistic than those previously proposed if we add an initial erosive phase to the model. Future experimental and numerical work dealing with the effects of flow confinement on erosion and deposition would serve to address this key issue in channel inception.

3.4. Conceptual model

While the effects of flow confinement on channel inception have not been adequately investigated, we can attempt such an analysis through a thought experiment. If we adopt a layer-averaged model of flow through a channel much wider than it is deep so that cross-channel flow is negligible (after Parker et al., 1986), we can write the conservation of fluid mass as:

$$\partial hw/\partial t + \partial Uhw/\partial x = e_w Uw \qquad \text{(X1)}$$

where h is flow height, U is layer-averaged flow velocity, w is flow width (defined as the width of the confining container, or “pipe”), e_w is a dimensionless coefficient of clear-water entrainment (e.g., Parker et al., 1987), t is time, and x is down-flow distance. If we further assume that flows are steady, we can re-write Equation (X1):

$$\partial U/\partial x = (e_w Uw - Uw\,\partial h/\partial x - Uh\,\partial w/\partial x)/hw \qquad \text{(X2)}$$

We concern ourselves here with the fluid mass balance as changes in sediment mass will not have a profound impact on flow dimensions given that the flows considered are dilute (Parker et al., 1986). Additionally, we will only deal with the momentum balance qualitatively as the coupling of these two equations (three if we were to additionally consider the turbulent kinetic energy balance) becomes mathematically complex, unnecessarily so for the purposes of this simple thought experiment. As flow approaches an erosional pit, some flow on the flanks of the scour will follow the increased slope and join the flow traversing the axis of the scour. This can be thought of as a decrease in flow width *within* the scour. Analysis of Equation (X2) shows that a decrease in flow width ($\partial w/\partial x < 0$) will lead to flow acceleration. Further analysis of Equation (X2) shows that an increase in flow height will decelerate the flow. As the width decreases, the flow will certainly increase in height to accommodate the changing confinement geometry. Yet the flow traversing the increased slope will accelerate and as it accelerates, will preferentially thin – a result of the momentum budget. Therefore, it is not unreasonable to assume that *within* the scour the decreasing flow width will be accompanied by a negligible change in flow height as the current accelerates. However, should the flow height grow rapidly through flow convergence, the top portions of the flow would likely spill over the confining container (levee or otherwise). This may, or may not decelerate the flow as such a model fails to account for flow stripping (*sensu* Piper and Normark, 1983) or overbank flow collapse. Peakall et al. (2000) suggested that strongly stratified flows can lose much of the overriding, more dilute suspension cloud without significant effect on the downstream velocity, further suggesting that any increase in flow height caused by decreasing flow width would not adversely affect flow acceleration predicted by Equation (X2). As flow accelerates due to an increase in lateral confinement, the bed-shear stress would increase and promote erosive flow conditions, analogous to the results presented by Hall et al. (2008). It should be noted that such a thought experiment is not intended to be definitive. It is presented here speculatively as a potential course for future research to resolve this critical issue of the effect of confinement on flow evolution.

3.5. Early erosional phase and the role of net-erosional cyclic steps

Early erosional scouring at channel inception has been observed in channels with well-defined constructional banks (McHargue, 1991; Deptuck et al., 2003; Gee et al., 2007; Catterall et al., 2010; Migeon et al., 2010), but the ability to establish the timing and significance of erosion is hindered by the low-resolution of most existing seismic reflection and conventional bathymetric imaging. Deptuck et al. (2003) identified scours on the seafloor as a focusing mechanism of subsequent flows, which facilitated channel complex formation. Gee et al. (2007) identified erosional features (rills) as precursors of channel complexes. An early perturbation of the seafloor is important but it has low-preservation potential and/or its recognition is hindered by subsequent channel evolution. Detailed observations of the outcrops presented here, including (1) channel incisions up to ~25 m deep, (2) evidence for extensive sedimentary bypass, and (3) well-preserved marginal facies (Fig. 6) are consistent with a model of very early erosion and subsequent containment of sediment gravity flows in lieu of appreciable overbank deposition. Confinement of flows may be promoted by incision of remnant marginal facies by subsequent flows (Fig. 1C and Fig. 6B–D). Subsequent aggradation is needed to stabilize and preserve the channel in the rock record.

The idea that an incipient channel is created by net-erosional cyclic steps, heralding development of a full-fledged conduit, is not novel (Kostic and Parker, 2006; Fildani et al., 2006; Kostic, 2011). In the case of the Monterey East incipient channel, a train of scours is interpreted to have developed on the overbank of the Monterey Fan as turbidity currents were stripped off from the main channel and underwent a series of net-erosional hydraulic jumps (cyclic steps; Fildani et al., 2006). This linear feature is an incipient channel and an avulsion “in progress”, whereas the scour fields and incipient channels in the Lucia Chica channel system may evolve into continuous channels in the future, pending capture of sediment gravity flows from the main feeder channel (Fig. 3; Maier et al., 2011). Interestingly, the cyclic steps that formed down-dip of avulsion nodes appear to generally scale with the avulsed conduit; larger steps, with longer wavelengths emanate from larger main channels (Fig. 2). Monterey East (Fig. 2A and B), the subsurface west-Africa example from Armitage et al. (in press) (Fig. 2C and D), and Lucia Chica cyclic steps (Fig. 3) cover a broad range of dimensions (kilometers to hundreds of meters), which suggests a scaling relationship to the up-dip flow. Cyclic steps are increasingly recognized on the modern seafloor and their conditions of formation are not limited to specific locations along fan systems. They form in overbank regions as well as the distal mouths of channels, where physical conditions are ideal (Lamb et al., 2008; Heinio and Davies, 2007, 2009; Normark et al., 2009; Kostic, 2011; Armitage et al., 2012).

This model of channel inception by cyclic step coalescence highlights erosional processes in lieu of confinement by aggradation of levees (Fig. 7); however, it is likely that only the earliest, brief phase of scour is purely erosional, with subsequent channel development characterized by at least some depositional overbank development. Initial erosion produces early relief that allows differentiation of confined lower flow from unconfined upper flow. At that point, any initial deposit outside the eroded new portion could help levees to form and the flow to entrench (Fig. 7). A similar erosional model, derived from outcrop (bed-set to sub-element scale) in an overall aggradational setting, is invoked by Eggenhuisen et al. (2011). Early perturbations on the seafloor (scours) could capture and accelerate turbulent erosive flows in a positive feedback scenario; a channelization threshold is crossed and channel architecture established.

An alternative scenario is that initial deposition is facilitated by pre-existing topography (such as confinement in the negative relief of ‘interlobe’ areas). Based on the results of small-scale experiments, turbidity currents flow to locations of lower gravitational potential energy (Kneller, 1995). Analogous to fluvial channels, deep-water channels are hypothesized to evolve toward graded equilibrium profiles, which are determined by characteristics of turbidity currents and their interactions with bathymetry (Pirmez et al., 2000; Kneller, 2003). We predict that some examples from the seafloor may encourage channel formation by bathymetrically supported confinement (Kneller, 1995, 2003; Kneller and McCaffrey, 1999) and we recognize that irregularities of the seafloor could enhance channelization. Examples of flows at equilibrium with the surrounding environment are documented (Stevenson et al., 2012; and references herein). However, given the prevalence of submarine channel systems, we find it difficult to accept that all channels start by a chance convergence of flow and topography.

3.6. Revisiting the issue of scale

Incipient channel features on the seafloor are recognized across a broad range of scales. The Lucia Chica scour trains described by Maier et al. (2011) are an order of magnitude smaller in length, width and wavelength than those of the Monterey East system reported by Fildani et al. (2006). Moreover, Kostic (2011) highlighted the natural range of these features, reviewing the basic dynamics of turbidity currents and cyclic-step evolution. It is not a surprise that different sizes of bedforms and different sizes of channels manifest in the submarine realm because gravity flow parameters can significantly vary between events, continental margins, and sediment-routing systems. In this paper we stress the importance of a clear definition of a channel: a channel is a single, through-going erosional feature with a continuous thalweg that could be eventually filled by sediment (Fig. 1C). In the Lucia Chica channel system, each channel is separated from a younger channel by an avulsion, fitting the channel-element definition of McHargue et al. (2011) (see references therein).

It is possible that mature channel systems reach a state of equilibrium and the flows traversing them are eventually scaled to the conduit size. This has been postulated by different authors invoking different mechanisms to reach this equilibrium phase that reflects both the flow sizes and run out distances (Kneller, 2003; Prelat et al., 2010; McHargue et al., 2011; Sylvester et al., 2011). McHargue et al. (2011) presented statistics from a proprietary database that indicated a relatively narrow range of channel dimensions (~15 m-thick and 200-300 m-wide elements). Conditions conducive to the development of similar channel morphology may preferentially occur in the lower slope and/or base of slope at a point where flows have been filtered by overbank deposition (Chough and Hesse, 1980), flow stripping (Piper and Normark, 1983; Normark and Piper, 1991), and early deposition (Prelat et al., 2010). The “filtering” process happens along the run out profile of the turbidity currents where, because of bends along the conduit, the natural range of the flow is scaled to a certain thickness (e.g., Skene et al., 2002; Straub and Mohrig, 2008; among others). However, the McHargue et al. (2011) database could be biased to continental-margin settings that are favored by the petroleum-industry exploration and production portfolio, and limited by models and wireline-log interpretations because channel elements commonly are below seismic resolution. Moreover, both McHargue et al. (2011) and Sylvester et al. (2011) carefully crafted their channel elements for specific portions of deep-water slope systems, with well-defined boundary conditions, including highly aggradational (levee-building) systems (Fig. 1A). It is possible, as implied from the breadth of incipient channel features on the present seafloor (i.e., cyclic steps; Kostic, 2011), that channels and their incipient features vary over greater spatial scales.

4. Conclusions

We propose that channels traversed by turbidity currents are erosional at inception. With a channel defined as a single, continuous thalweg along which gravity flows traverse, we envision a time-step evolution where only after an initial erosional phase and channel establishment, are turbidity currents able to construct aggrading levees and evolve into the complex systems observed from numerous deep-water settings.

Acknowledgments

Animated and always constructive discussions with Angela Hessler, Julian Clark, Morgan Sullivan, Bruce Power, Henry Posamentier, and George Hilley helped shape our early ideas. Bill Normark and Emiliano Mutti inspired the authors with their encyclopedic knowledge of the deep-sea systems and their remarkable seminal work. We are grateful we had an opportunity to discuss some of these concepts with them at different stages of our careers. S. Hubbard's work on the Tres Pasos Formation is supported by Chevron Energy Technology Company, Marathon Oil, ConocoPhillips, Talisman Energy Inc., Statoil, and the Natural Sciences and Engineering Research Council of Canada. Fieldwork in Chile was assisted by Ryan Macauley and Sean Fletcher. Funding for Lucia Chica data collection was provided by Chevron Energy Technology Company and the David and Lucile Packard Foundation through the Monterey Bay Aquarium Research Institute (MBARI). We thank Charles Paull, David Caress, and Stephan Graham for helpful discussions concerning the Lucia Chica dataset. K.L. Maier's work on the Lucia Chica has been supported by the affiliates of the Stanford Project on Deep-water Depositional Systems (SPODDS). Constructive and thoughtful reviews from Tim McHargue, Ian Kane, David Hodgson, and Joris Eggenhuisen largely improved the manuscript. We thank Chevron Energy Technology Company for permission to publish this work.

A.F. would like to dedicate this manuscript to his daughter Livia, whose arrival joyfully delayed this publication.

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