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Quantifying the influence of channel sinuosity on the depositional mechanics of channelized turbidity currents: A laboratory study

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ABSTRACT

Here we present results from a suite of laboratory experiments that highlight the influence of channel sinuosity on the depositional mechanics of channelized turbidity currents. We released turbidity currents into three channels in an experimental basin filled with water and monitored current properties and the evolution of topography via sedimentation. The three channels were similar in cross-sectional geometry but varied in sinuosity. Results from these experiments are used to constrain the run-up of channelized turbidity currents on the outer banks of moderate to high curvature channel bends. We find that a current is unlikely to remain contained within a channel when the kinetic energy of a flow exceeds the potential energy associated with an elevation gain equal to the channel relief; setting an effective upper limit for current velocity. Next we show that flow through bends induces a vertical mixing that redistributes suspended sediment back into the interiors of depositional turbidity currents. This mixing counteracts the natural tendency for suspended sediment concentration and grain size to stratify vertically, thereby reducing the rate at which sediment is lost from a current via deposition. Finally, the laboratory experiments suggest that turbidity currents might commonly separate from channel sidewalls along the inner banks of bends. In some cases, sedimentation rates and patterns within the resulting separation zones are sufficient to construct bar forms that are attached to the channel sidewalls and represent an important mechanism of submarine channel filling. These bar forms have inclined strata that might be mistaken for the deposits of point bars and internal levees, even though the formation mechanism and its implications to channel history are different.

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1. Introduction

High resolution mapping of continental slopes has revealed ubiquitous channels (Clark et al., 1992; Demyttenaere et al., 2000; Droz et al., 1996; Flood and Damuth, 1987; Kenyon et al., 1995; Pirmez et al., 2000; Pratson et al., 1994; Schwenk et al., 2003), some extending in excess of 3000 km and into water depths exceeding 4000 m (Schwenk et al., 2003). These channels are primarily constructed by turbidity currents, mixtures of water and suspended sediment that move down continental margins as underflows. Turbidity currents dominate the transport of terrigenous sediment to deep-marine locations (Kneller and Buckee, 2000) and have built some of the largest sediment accumulations found on Earth (Bouma et al., 1985). These deposits host many of the largest producing petroleum reservoirs in the world today (Weimer and Link, 1991). In spite of this, our knowledge of the system properties allowing for sediment in turbidity currents to be transported for great distances is incomplete. This limits our ability to both model the evolution of deep-marine stratigraphy and invert stratigraphic architecture observed in outcrop (Fildani et al., 2009; Romans et al., in this issue; Flint et al., 2011; Kane and Hodgson, 2011; Pyles, 2008) or seismic data (Abreu et al., 2003; Nakajima et al., 2009) for formative flow conditions. This deficiency is largely a consequence of difficulty in instrumenting natural flows due to the great water depth, infrequent occurrence, and high velocities associated with many turbidity currents. We argue here that furthering our understanding of the evolution of seascapes requires not only a refinement of internal turbidity current dynamics, but also a refinement in our knowledge of how interactions with seafloor topographies mediate the transport properties of turbidity currents. In particular we focus on the influence that channel sinuosity has on the depositional mechanics of turbidity currents.

Comparison of channelized terrains in terrestrial and submarine environments provides scientists with an opportunity to explore

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the generality of landscape evolution models in settings with substantially different environmental conditions. To date most theory describing channel initiation and evolution has been tested for terrestrial conditions where the density (ρ_c) of the transporting flow is substantially greater than the ambient fluid density (ρ_a). For rivers and air on the Earth's surface, ρ_c/ρ_a is ~830. However, for turbidity currents this ratio is typically only 1.01–1.1 (Simpson, 1987). Expanding terrestrial theories that describe the interactions between fluid flow and channel development to environments with different ratios of ρ_c/ρ_a will help us interpret environmental settings on other planets and moons where channels have recently been discovered. For example, on Venus and Titan the ratio for channel-forming flows is thought to fall somewhere in between the terrestrial and submarine environments. Channels on Venus are hypothesized to be the result of either lava flows or sediment gravity flows (Bray et al., 2007; Williams-Jones et al., 1998). Given the high surface density of the Venus atmosphere, lava flows would have a ρ_c/ρ_a of ~32 and sediment gravity flows would have a ρ_c/ρ_a of 1.01–1.1. On Titan, ρ_c/ρ_a is expected to be ~75, an order of magnitude less than the value for terrestrial rivers as a result of the low density of liquid methane (Perron et al., 2006; Tomasko et al., 2005).

Published data on submarine channels reveals that many are moderately to highly sinuous (sinuosity > 1.2); including three of the four longest, the Bengal (Schwenk et al., 2003), Indus (Kenyon et al., 1995), and Amazon (Flood and Damuth, 1987) channels. These sinuous submarine channels share many planform characteristics with rivers, including comparable scaling relationships between channel widths and meander-bend wavelengths and amplitudes (Pirmez and Imran, 2003). In addition, the properties of long profiles for channels in both environments adjust in response to changes in sediment fluxes, liquid fluxes, and tectonic activity (Kneller, 2003; Pirmez et al., 2000). The similarities have been used to justify the adoption of models for subaerial channelized flow as semi-quantitative guides for interpreting flow through sinuous submarine channels even though significant differences exists between the two environments (Imran et al., 1999; Komar, 1969).

While many similarities in the morphodynamics of rivers and submarine channels exist, differences in the physics of the two systems also impart significant differences in their spatial and temporal evolution. In rivers, gravity acts on water which in turn drags sediment down slope. In submarine channels, gravity acts on the excess density associated with sediment suspended within the turbidity current which in turn drives the down slope flow. This difference in driving force substantially changes the down slope evolution of turbidity currents relative to rivers. For example, some river systems evolve to a state where their slope, channel depth, width, planform and roughness are mutually adjusted in response to changes in flow discharge and sediment discharge to transport all sediment load through a system without aggradation or degradation of the channel (Mackin, 1948). This situation leads to an equilibrium profile for rivers in which the channel-forming flow in the alluvial section of the profile is at capacity with the local sediment transport limit (Howard, 1980). This situation does not occur in the medial and distal segments of most submarine channel systems where the topography and the currents constructing it are clearly net depositional (Babonneau et al., 2002; Pirmez et al., 2000; Pirmez and Imran, 2003). The work presented in this study is most applicable to the mid to distal ends of submarine channel systems that are net depositional.

During the past decade multiple studies have compared the interactions of river flows and turbidity currents with channel bends (Abreu et al., 2003; Corney et al., 2006; Das et al., 2004; Imran et al., 2007, 1999; Islam et al., 2008; Kane et al., 2008; Kassem and Imran, 2005; Peakall et al., 2007, 2000; Pirmez and Imran, 2003; Straub et al., 2008). These studies have utilized 3-D seismic data, laboratory experiments, and numerical models to highlight both similarities and differences in fluid dynamics and sediment transport in the two environments. While much work on this subject has been performed, several fundamental questions still exist, some of which we hope to address in this manuscript. For example, how does the interaction of turbidity currents with channel bends affect their sediment transport capacity and what constraints can we place on the velocity of turbidity currents in sinuous channels. Here we address these and other issues related to turbidity current-channel bend interactions using reduced scale laboratory experiments. Due to a lack of direct measurements of the interactions of currents with submarine channels in the field, physical experiments have played a critical role in testing the intuition we have regarding these processes derived from fluvial systems (Metivier et al., 2005; Mohrig and Buttles, 2007; Straub et al., 2008). In addition, they provide the community with dynamic measurements to test numerical models against (Kassem and Imran, 2005; Sylvester et al., 2011; McHargue et al., in this issue). We released sequences of depositional turbidity currents into three channels. These channels shared a similar cross-sectional geometry but varied in sinuosity. Where possible, we examine how our observations might also inform studies of current-channel interactions in extraterrestrial environments.

2. Experimetal setup

We released density currents into a basin 5 m long, 5 m wide, and 1.2 m deep, that remained filled with water throughout each experiment (Fig. 1). Five experiments were performed in the basin. For experiments 1, 2, and 3, sequences of sediment laden turbidity currents were released into channels with sinuosities of 1.00 (straight), 1.04 (low sinuosity), and 1.32 (high sinuosity). In these three experiments the initial conditions were held constant for each turbidity current in order to isolate the effect of sinuosity on deposition in submarine channels (Table 1). Before filling the basin with water at the start of each experiment, a channel was built on the basin floor. The planform geometry for the three channels was designed using a sine-generated curve which has been shown to reproduce the shapes of many subaerial and subaqueous channels (Langbein and Leopold, 1966; Pirmez, 1994). This curve describes the local direction of the channel centerline, φ, as a function of streamwise distance, x:

$$\varphi = \omega \sin \frac{x}{X_t 2\pi} \quad (1)$$

Where ω is the maximum angle at which the centerline deviates from the mean downstream direction and X_t is the centerline distance associated with one channel wavelength. Parameters used to design the planform shape of the three channel types are listed in Table 2 and their initial morphologies are displayed in Figs. 2, 3 and 4. Channel sidewalls and banks were constructed from a 15:1 mixture of sand and cement mortar. The initial cross-sections for the three channels were trapezoidal in shape. The straight and high sinuosity channels had initial depths of 0.11 m and basal and top widths of 0.20 m and 0.40 m, while the low sinuosity channel had an initial depth of 0.08 m and basal and top widths of 0.10 m and 0.515 m. The three channels were built with no initial downstream bed slope. After traversing the channels each current spread out onto a short unconfined surface before plunging into a moat where it was removed from the basin via perforated pipes, thereby preventing current reflections off of tank sidewalls.

The turbidity currents released in experiments 1–3 were composed of the same mixture of clear water, dissolved $CaCl_2$ and suspended sediment. This mixture produced currents that entered