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Key Points:
- Reduced scale sandbox experiments combine unconfined sediment gravity flows with a falling base level to produce evolving submarine canyons
- Analysis of quantitative topographic imagery shows that the canyons grow in a self-similar form
- Experimental canyon-intercanyon long profiles and planform drainage networks resemble those observed on continental slopes

Supporting Information:
- Supporting Information S1
- Table S1
- Movie S1
- Figure S1

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An experimental approach to submarine canyon evolution

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Abstract We present results from a sandbox experiment designed to investigate how sediment gravity flows form and shape submarine canyons. In the experiment, unconfined saline gravity flows were released onto an inclined sand bed bounded on the downstream end by a movable floor that was used to increase relief during the experiment. In areas unaffected by the flows, we observed featureless, angle-of-repose submarine slopes formed by retrogressive breaching processes. In contrast, areas influenced by gravity flows cascading across the shelf break were deeply incised by submarine canyons with well-developed channel networks. Normalized canyon long profiles extracted from successive high-resolution digital elevation models collapse to a single profile when referenced to the migrating shelf-slope break, indicating self-similar growth in the relief defined by the canyon and intercanyon profiles. Although our experimental approach is simple, the resulting canyon morphology and behavior appear similar in several important respects to that observed in the field.

1. Introduction

Submarine canyons are diagnostic features of most of the world's continental slopes [*Harris and Whiteway*, 2011]. They appear on both active and passive margins and provide a critical pathway for terrestrial sediment delivery to the deep ocean [*Pratson et al.*, 2007, and references therein]. The existence and scale of submarine canyons have long been recognized [*Shepard*, 1934], but only in recent years—due largely to improvements in bathymetric imaging—has their resemblance to terrestrial river valleys and drainage systems been fully appreciated [e.g., *Mitchell*, 2004; *Amblas et al.*, 2012; *Brothers et al.*, 2013]. This observation suggests that the physical processes shaping submarine canyons have some basic similarities to those shaping subaerial landscapes, especially in their upper reaches where local slopes and heights above the basin floor are greatest.

The origin of submarine canyons is not fully understood [*Pratson et al.*, 2007, and references therein]. Nevertheless, the view that sediment gravity flows are the dominant canyon-sculpting process is supported by numerous observations [e.g., *Kuenen*, 1938; *Parker*, 1982; *Shepard*, 1981; *Piper and Aksu*, 1987; *Baztan et al.*, 2005; *Mitchell*, 2005; *Gerber et al.*, 2009]. Such flows may originate within a canyon from local slope failures [*Pratson and Coakley*, 1996; *Mitchell*, 2005; *Sultan et al.*, 2007], but a number of other processes have been documented that can generate near-bottom flows landward of canyon heads, including (a) hyperpycnal plunging [*Mulder and Syvitski*, 1995; *Liu et al.*, 2012], (b) wave resuspension and shelf erosion associated with coastal storms [*Parsons et al.*, 2007; *Sanchez-Vidal et al.*, 2012], (c) delta-front failure [*Piper and Normark*, 2009] and breaching [*Talling et al.*, 2015], and (d) dense shelf water cascading [*Canals et al.*, 2006]. Yet a general understanding for how gravity flows that initiate on the continental shelf are routed through and shape canyons on the continental slope is lacking.

Numerous experimental studies have examined the interaction of sediment gravity flows with mobile substrates [*Paola et al.*, 2009, and references therein]. Far fewer of these have generated fully self-formed channels and those that have were conducted on uniform slopes that in some cases transitioned downstream to a flat floor [*Métivier et al.*, 2005; *Yu et al.*, 2006; *Cantelli et al.*, 2011; *Weill et al.*, 2014]. This setup is appropriate for investigating channel inception on basin floor fans, but it cannot capture the dynamics of flows crossing a shelf-slope break where gradients can increase abruptly ($>5°$) over short distances. Although these experiments addressed the transition of gravity flows from confined to unconfined settings, no experiments have reproduced unconfined, near-bottom, sheet-like flows fully captured by the head of a self-formed canyon downstream.

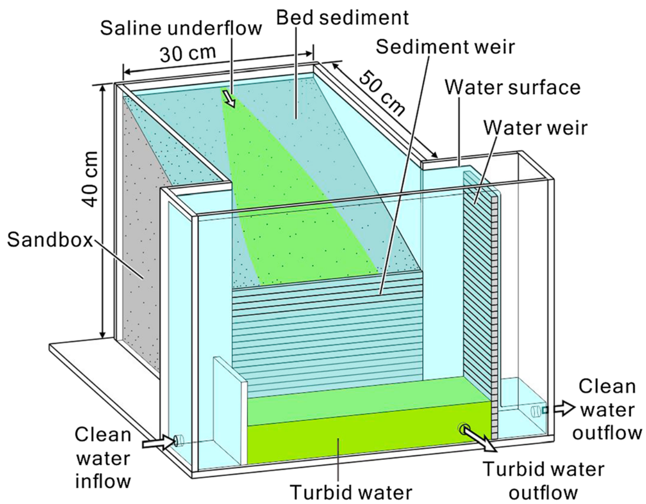

Figure 1. Oblique view of the experimental setup.

Here we present the design and results of a physical experiment on submarine canyon inception and evolution under the influence of increasing relief and unconfined downslope gravity currents. The relief across the continental slope is generated by sedimentation (i.e., the topset-to-bottomset relief of continental margin clinoforms) and, on active margins, through tectonic shortening. Since we are unable to generate relief in a way that mimics these processes at laboratory scale, we instead created a simplified escarpment configuration that allowed for controlled increases in relief during the course of an experiment. And as is commonly done in reduced-scale experimental studies on sustained sediment gravity flows, we used saline currents as a proxy for mud-rich turbidity currents [*Métivier et al.*, 2005; *Lai and Capart*, 2007, 2009; *Weill et al.*, 2014]. By isolating two controls on slope morphology at reduced scale, we were able to explore their interaction in detail using high-resolution topography and overhead photographic imagery. We want to make clear that our aim was not to replicate all processes that give rise to and shape continental slopes and submarine canyons but rather to test a minimal physical representation of slope development that would allow for canyon development at reduced scale.

2. Experimental Setup

Our experimental setup consisted of a sandbox submerged within a water tank (see Figure 1). Inside the sandbox we prepared an erodible substrate made of very fine silica sand ($d_{50} = 0.1$ mm), which was well mixed with kaolinite (the proportion of silica sand to kaolinite was 100:1 by weight, as suggested by *Hasbargen and Paola* [2000]). Instead of starting from a horizontal surface, the homogenous water-saturated paste was shaped to produce a planar surface with a downstream slope of 10°. An exaggerated slope increases the shear stresses transmitted by the thin currents and thus facilitates rapid landscape evolution over short time periods.

To simulate an evolving continental slope with increasing relief, we placed a stack of slotted weirs at the downstream end of the sandbox (Figure 1). A weir was removed at fixed intervals during an experiment, causing an effective base-level drop (or equivalently, an increase in slope relief). With this design, we abstracted the progradation of a continental margin into increasing water depths through a series of discrete base-level drops. These drops produced an escarpment delineated by a sharp increase in slope from a relatively flat shelf to a steeper slope. This setup provides a dynamic shelf-slope break, albeit one that retreats as the slope adjusts to base-level drops.

As in previous studies [*Lai and Capart*, 2007, 2009; *Foreman et al.*, 2015], we assume the gravity flows in question are dominated by fine-grained sediment that remains in suspension over the domain of interest. Due to the difficulties in keeping fine-grained sediment suspended at reduced scale, we replaced the fine sediment in suspension with brine (specific gravity = 1.2) that, as a solute, does not settle on the bed. Consequently, the morphodynamics observed in our experiments were predominantly a result of bed load transport beneath dense (saline) currents.

A continuous source of clean water was placed on one side of the tank while a weir on the opposite side of the tank controlled the water level. At the upstream end, a point-sourced brine was continuously released onto the surface and flowed downslope as an unconfined gravity current. The underflow naturally spread but covered only a portion of the surface at any given time. At the downstream end, a deep-water tank received the sediment and water outflow from the sandbox. To keep the entire water basin clean for observation and measurement, a bottom outlet was kept open to drain turbid saline water and minimize water mixing during experiments.

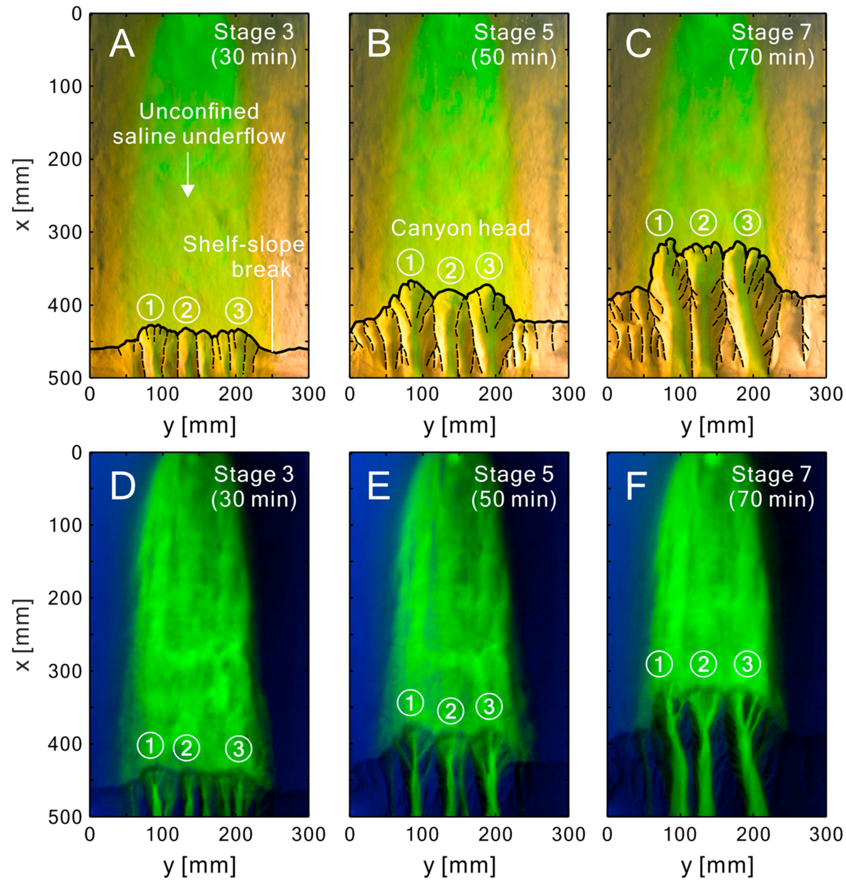

Figure 2. Orthophotography of Stages 3, 5, and 7 (developed time = 30, 50, and 70 min, respectively) displayed (a–c) with and (d–f) without yellow light. Unconfined fluorescent saline underflows (in green) move from the top to the bottom. Submarine canyons are distinguished by numbers (1 to 3). Thick solid lines represent the shelf-slope break, and thin dashed lines are intercanyon ridges (see Movie S1 in the supporting information).

In this paper we present two experimental runs with similar inflow discharge (3.3 mL/s for Run 1 and 3.2 mL/s for Run 2). Each experiment was divided into 10 successive stages (10 min for each experimental stage). The first stage began after removing a weir downstream to provide a 10 mm increase in relief. At the same time the saline inflow upstream was released. The unconfined current (visualized with green fluorescent dye) then flowed downstream across the sand bed and into the deep receiving tank. After 10 min, we turned off the inflow to form a temporarily frozen landscape. Without draining out the ambient water, the newly generated "submarine" landscape was scanned. The same procedure was then repeated in nine additional stages for a total duration of 100 min.

We used a topographic imaging system (see *Lai* [2010] for further details) to construct high-resolution digital elevation models (DEMs) of the submarine slope and canyons over successive stages of each experimental

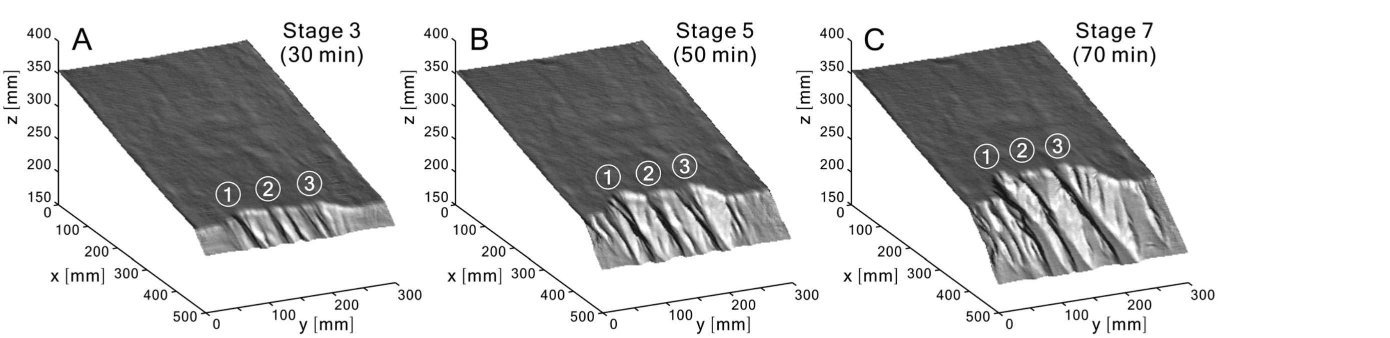

Figure 3. Hillshaded digital elevation model (DEM) for Stages 3, 5, and 7 (Run 1).

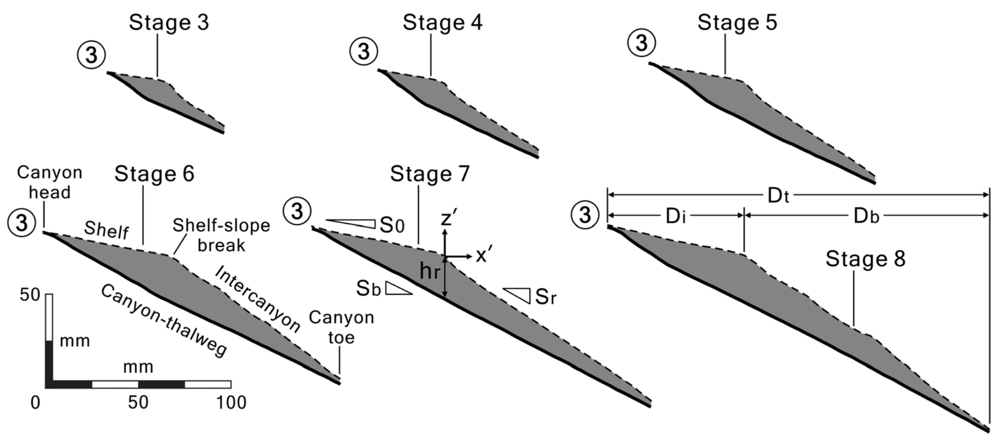

Figure 4. Measured long profiles of Canyon 3 from Stages 3 to 8 (Run 1). The bottom panel includes labels for the main geomorphic features and measurements.

run. This system includes the following: (i) a linear motor-driven laser sheet (100 microwatts, 90° fan angle, produced by the company LASER COMPONENTS) for topographic scanning; (ii) one color video camera (Sony, PJ760V) placed below the water level for capturing the laser stripes on the topography; and (iii) a digital single lens reflex (DSLR, Nikon D800) camera placed in front of the sandbox for the acquisition of high-quality color images every 5 s throughout each experimental stage. Before we started the experiment, all the cameras were calibrated separately with a rigid target that included 98 target points at known positions.

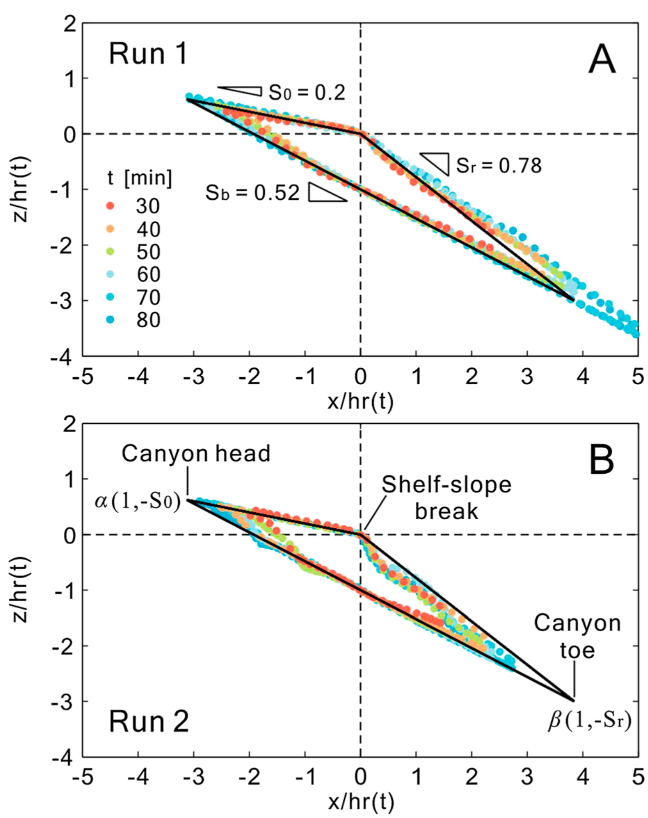

Figure 5. Comparison between normalized long profiles of experimental (a) Run 1 and (b) Run 2. Long profiles extracted from the DEM of Stages 3 to 8 are colored in red to blue. Thick solid lines are predicted long profiles according to the geometric relationships described in the main text. The origin is referenced to the shelf-slope break of each experimental stage (highlighted with dashed lines). See Table S1 in the supporting information for the main morphometric parameters derived from the data set.

3. Results

The surface evolution observed in Experiment 1 is summarized in Figure 2. Submarine breaching (a thin, slow-moving bed load layer) together with flowsliding (defined as a large amount of sediment sliding downslope similar to submarine landslides) initiated after the removal of the first sediment weir, forming a landward retreating front that rested at the angle of repose for the substrate (38°). Upon release, the saline underflow evolved into an unconfined, bottom-hugging gravity current that was less than 3 mm thick and entrained negligible amounts of ambient water (see Figure 2 and Movie S1 in the supporting information). The absence of significant mixing preserved water clarity and thus facilitated continuous observation and measurement.

The thin, unconfined gravity current was effectively steered by small topographic variations and converged quickly into evolving topographic lows. Where the flow encountered the downstream breaching front it generated canyon incisions just beyond the shelf-slope break (Figures 2a to 2c). We dimmed the yellow lights to provide a clear view of the transition from an unconfined, laterally spreading density current to locally confined, convergent flow in canyon tributaries (Figures 2d to 2f). By Stage 3, a series of adjacent, equally spaced small canyons had developed on the slope. By Stage 5 three deeply incised shelf-indenting canyons (Canyons 1–3) had grown from the smaller canyons of Stage 3 and together captured all of the flow crossing the shelf. The size, amount of shelf indentation, and extent of their tributary networks had all increased by Stage 7.

We traced the evolution of canyon thalwegs and intercanyon ridges by extracting topographic long profiles from the DEM of Canyon 3 for Stage 3 to Stage 8 (Figures 3 and 4). The progressive growth of canyon-intercanyon relief is easily seen. The slope of the canyon thalweg at each stage is lower than the angle of repose (i.e., the intercanyon slope) but steeper than the initial shelf slope. By referencing each profile to its migrating shelf-slope break, the canyon head and canyon toe can be characterized as two moving boundaries that control the landward and seaward extension of the canyon. Interestingly, when profiles from each stage are scaled by the maximum canyon-intercanyon relief (x/h_r and z/h_r) and are plotted together using coordinates referenced to the shelf-slope break (x', z'), they collapse to a single profile (Figure 5a). In other words, the canyon-intercanyon long profile pairs measured at different times during the experiment are scaled versions of each other. This result held when we repeated the experiment under nearly identical conditions (Experiment 2; Figures 5b and S1 in the supporting information).

The measured initial slope (S_0), intercanyon slope (S_r), and canyon thalweg slope (S_b) are approximately uniform (Figures 4 and 5). These slopes define the dimensionless position of the canyon head and toe, respectively,

$$\alpha(1, -S_0) \tag{1}$$

$$\beta(1, -S_r) \tag{2}$$

where $\alpha = 1/(S_0 - S_b)$ and $\beta = 1/(S_r - S_b)$. Upscaled positions of the canyon head and toe can easily be obtained from the maximum canyon-intercanyon relief (h_r) at each stage. The profiles overlain on the experimental measurements in Figures 5a and 5b were constructed using (1) and (2) and the following average slopes from the experiments: $S_0 = 0.2$, $S_r = 0.78$, and $S_b = 0.52$.

4. Discussion

In this work, we presented a simple experimental method for studying submarine canyon and continental slope morphologies at reduced scale. By imposing incremental relief and introducing unconfined saline gravity flows to a relatively flat "shelf" surface, we are able to generate a progression of erosional slope morphologies from incipient gullies to mature canyons with tributary networks. Though our primary aim in this paper is to point the way toward a new phase of reduced-scale experimentation on slope evolution, some of our initial observations are noteworthy in light of what has been learned from field studies.

The canyon-intercanyon long profiles and planform drainage networks that evolved during each experimental run resemble those observed on the continental slopes of both passive (e.g., *Pratson et al*. [1994] and *Obelcz et al*. [2014] in the U.S. mid-Atlantic Ocean, *Amblas et al*. [2006] in Northwestern Mediterranean Sea, and *Gee et al*. [2007] in Southwestern Indian Ocean) and active (e.g., *Mountjoy et al*. [2009] in New Zealand Pacific Ocean and *Brothers et al*. [2013] in the U.S. Pacific Ocean) continental margins. At the end of the experiment reported here, each of the three active canyons consisted of multiple heads that acted as tributaries to the main downslope thalweg. These tributaries were initially gullies before being captured by adjacent gullies that had lengthened and deepened more rapidly. This sequence of numerous gullies eventually giving way to a few large canyons was observed in each of our experiments. Some authors have proposed a similar process to explain the origin of submarine canyons [e.g., *Farre et al*., 1983; *Pratson and Coakley*, 1996; *Micallef et al*., 2014]. The progression from numerous small canyons to fewer large canyons has been documented in 3-D seismic images of the subsurface [e.g., *Kertznus and Kneller*, 2009; *Amblas et al*., 2012]. As interpreted in these field studies, the evolution in our experiments results from the progressive capture of cross-shelf flows by the surviving canyons, which in turn causes them to deepen and widen as they capture additional tributaries in their upper reaches.

In closing, we again acknowledge that our experimental setup produces only erosional topography. We do not claim to have produced an experimental analogue of any or all continental slopes. Rather, we have argued for the importance of a shelf-slope morphology and growing slope relief as controls on canyon development. Thus, in comparing the long profiles of Figure 5, we highlight the differences in erosional backstepping between canyon thalwegs and the breaching-dominated slope, which defines the relief between the canyon and intercanyon areas. As we show, this relief grows through time even as the long profile slopes (i.e., shelf, intercanyon, and canyon) remain fixed. These profiles are not unlike those measured from present-day bathymetry along shelf-indenting canyons [*Mitchell*, 2004, 2005]. Whether our results would look different in a setup where relief was generated by net sedimentation is an open question that we may be able to address in future work.

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