# SUBMARINE CANYONS IN THE BATHTUB

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ABSTRACT: **Submarine megafans and their associated canyons have long attracted the attention of a large community in the earth sciences because they record the history of past erosional processes. As such, their morphology and sedimentary infill may be of use to unravel past climatic and tectonic evolution. Yet despite an important corpus of research on their structural characteristics we lack a well accepted quantitative description for the dynamics of the formation and growth of these sedimentary systems. One of the main reasons for this lies in our inability to successfully understand, reproduce, and predict the dynamics of the channel systems, tens to hundreds of meters deep, several kilometers in width, and hundreds of kilometers in length, that build submarine fans. Here we report on a series of small-scale laboratory experiments on the formation of subaqueous channels and lobes. Our experiments show that steady flow of a dense current on a bed of light particles can induce both spontaneous formation of channels longer than a few channel widths and spontaneous meandering.**

## INTRODUCTION

The life of the largest rivers on earth may not necessarily end once they reach the ocean. Hidden to our sight, they may survive in the abyss in an even larger form. The main submarine canyon of the Zaire fan on the West African coast can be up to 15 km wide and 1300 m deep (Babonneau et al. 2002) whereas its subaerial counter part, the second largest river on earth in terms of discharge, achieves its maximum depth of 30 m in a channel less than 2 km wide. Submarine channels systems are the veins that allow turbidity currents to transport and deposit material eroded from the continents in the deep sea. They are thus responsible for the formation of submarine megafans where millions of cubic kilometers can accumulate for millions of years (Métivier et al. 1999). The sedimentary record buried in these fans constitutes an invaluable archive of the climatic and tectonic processes that shaped the surface of the continents (Mutti et al. 1999; Zhang et al. 2001). Unraveling the dynamics of such channel systems in the deep sea is essential in order to understand both the sedimentary processes responsible for the formation of the largest sedimentary accumulations on earth and the meaning of the sedimentary record (Klaucke et al. 1996; Hagen et al. 1996; Lewis et al. 1999; Mutti et al. 1999; Peakall et al. 2000; Kottke et al. 2003; Khripounoff et al. 2003). This decoding also has enormous consequences for petroleum and gas research conducted in deep-sea fans.

Yet the existence of submarine canyons and meandering channels in the deep sea remains essentially beyond our understanding. Are these channels produced by huge catastrophic turbidity currents, or perhaps by hyperpycnal flows or by steady-state currents formed at the mouths of large rivers? Were they initiated as rivers during past glaciations when sea level was lower? Can present-day currents recorded in some deep-sea channels, like the one in the Zaire fan (Khripounoff et al. 2003), account for such structures? The debate is not closed, mainly for two reasons: the difficulty in making measurements and observations on active or abandoned channels, and the probably long time scale, on the order of thousands of years, needed to develop these structures, that forbids the observation of processes on a human time scale.

Because of these drawbacks, researchers have focused on experimental studies of gravity and turbidity currents and numerical simulations of fan growth (Middleton 1966a, 1966b, 1967; Bonnecaze and Lister 1999; Pantin 1979; Parker 1982; Imran et al. 1998; Imran et al. 1999; Kneller and Buckee 2000; Peakall et al. 2000; Alexander and Mulder 2002; Kubo and Nakajima 2002; Parsons et al. 2002; Kostic and Parker 2003a, 2003b). Experimental models driven by stratigraphic studies have long concentrated on turbidity currents and the deposits they form (Mulder and Alexander 2001; Parsons et al 2002). Experimental knowledge on the dynamics of turbidity surges and currents was then used by modelers to propose mechanisms of channel incision and meandering in the submarine environment (Pantin 1979; Parker 1982; Imran et al. 1998; Imran et al. 1999; Peakall et al. 2000). Because of the lack of knowledge on submarine erosion most of the experiments and models have been aimed at the reproduction of one-dimensional profiles, whether topographic or stratigraphic (Kostic and Parker 2003a, 2003b). But a physical basis for channel incision and evolution in submarine environments still remains to be tackled because of the apparent difficulty in reproducing subaqueous analogues of submarine channels.

Here we show that this problem can be solved in a simple and affordable manner. An experimental procedure is outlined by which microscale analogues of incisional submarine channels can be reproduced in the laboratory. Dimensional considerations are discussed to explain this setup and a phase diagram is presented showing, for a given density contrast, the influence of the density-current mass flux and the bed slope on incisional channelization. Eventually the research possibilities offered by such an experiment are briefly outlined.

## EXPERIMENTAL SETUP

The experimental setup is designed in order to model sustained gravity flows occurring in the sedimentary system connecting a delta and its deep sea fan. It consists of a 100 cm × 50 cm incline immersed in a 200 cm × 50 cm × 50 cm plastic tank filled with fresh water (Fig. 1) The slope ($\theta$) of the incline is adjusted by means of a screw device and measured with a digital inclinometer achieving an accuracy of 0.5°.

The tank is first filled with plastic powder and fresh water. The particles are then dynamically put into suspension, mixed with the water in the tank, and allowed to settle randomly. This leads to the formation of an erodible bed of initial thickness on the order of a few centimeters. The particles composing the plastic powder are made of a mixture of plastic polymer and titanium oxide. Depending on the grade and oxide content, the density of the particles can vary from sample to sample. The sample used in this study has a density $\rho_s = 1080$ kg/m$^3$. The granulometry of the particles has a lognormal distribution with mean D at 27 microns. Once the plastic powder has completely settled, a brine of adjustable density $\rho_f$ is injected at a constant flow rate $Q_f$ through a small 2.5 cm × 2.5 cm tube located at the top of the incline. The injection tube is fixed along the incline so that the density current is injected in the direction parallel to the bed (Fig. 1). Continuous measurement of the mass of the tank holding the brine permits a precise knowledge of the rate of the brine injection mass flow. The flow rate remains constant within less then a percent. In its present state, the setup allows us to adjust the slope of the incline $\tan\theta$, the brine injection flow rate $Q_f$ and the brine density $\rho_f$. Pictures of the experimental area of interest were taken at regular time intervals by mean of a 768 × 576 pixel CCD camera positioned at the vertical of the experimental plane. In some experimental runs, the full 3D topography of the channel incised

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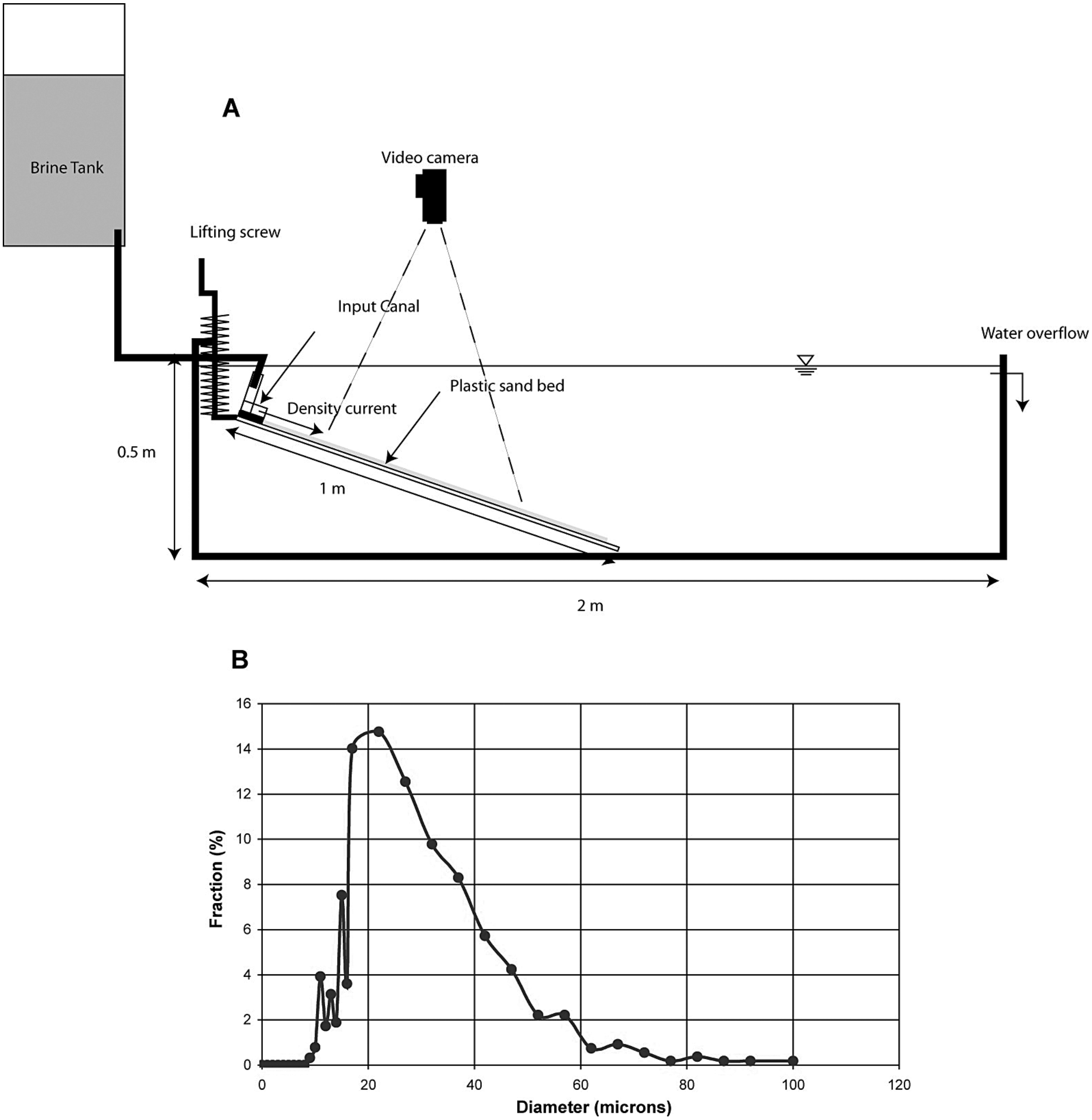

FIG. 1.—**A)** Experimental setup, not to scale. **B)** Granulometry of sand used in experiment.

by the brine flow was also measured. This was achieved using an optical Moiré type method (Sansoni et al. 1999; Pouliquen and Forterre 2002)

## RESULTS AND DISCUSSION

### *Observations on the Morphology of Experimental Subaqueous Channels*

During each experiment a bottom density current first develops along the incline. Depending on the experimental conditions, erosion and deposition of the bed particles can occur. Such erosion and deposition induces the formation of an incisional channel and the progradation of a lobe in front of it (Fig. 2). Channel meandering can also occur; if so, it develops through lateral migration and bank erosion. Formation of terraces on the inside loops of meanders is also observed (Fig. 3).

After injection the density current either spreads over the bed and generates some sheet-like erosion or incises the bed a few centimeters downstream of the flow entrance. In the latter case the current confines itself in the newly formed channel segment. This in turn strongly strengthens the

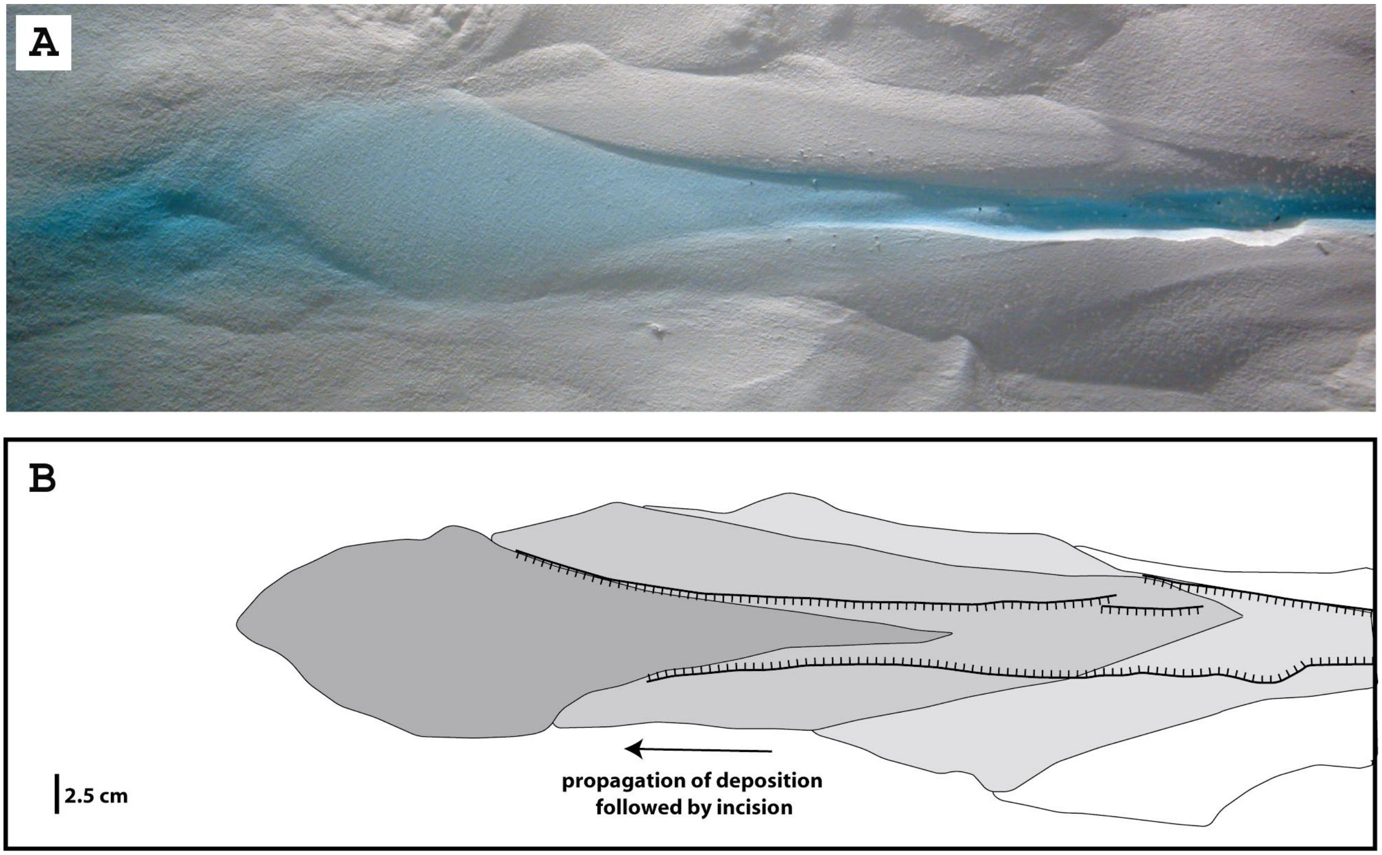

FIG. 2.—Run no. 4. Straight channel and sedimentation lobe. **A)** Photograph of the experiment. Blue dye shows the density current. **B)** Interpretation. Successive prograding lobes are later incised by propagating channel incision.

velocity and facilitates further erosion and incision downstream. Channel inception and development therefore appear to function in a positive feedback mechanism

Once incision is initiated the sediments eroded are transported down the slope and deposited to form a small prograding lobe at the tip of the forming channel. A dynamic system therefore develops where an aggradational wave propagates downslope directly followed by an incisional wave (Fig. 4A, B). The channel so formed reexcavates older deposits as sketched in Figure 2 and 3. This coupled aggradation–degradation wave may be responsible for features such as fluvial-like terrace systems, which may form even though the input flux of the dense current remains constant (Fig. 3). A very important consequence of this mechanism is that levee-like systems may form by the superposition of aggradation of a lobe followed by incision of a canyon. The resulting morphology (Fig. 4A, C) closely resembles deep-sea morphologies as seen in, for example, the Orinoco submarine channel system (Deville et al. 2003)

TABLE 1.—*Experimental conditions for the 17 runs reported in Figure 4.*

| Run Number | Density Contrast | Discharge (g/s) | Incline Slope (°) | Incisional Channel | Meander |
|---|---|---|---|---|---|
| 1 | 36 | 0.2 | 13.8 | No | Yes |
| 2 | 36 | 0.2 | 18 | No | Yes |
| 3 | 36 | 0.6 | 20.5 | Yes | No |
| 4 | 36 | 0.7 | 14 | Yes | No |
| 5 | 36 | 0.8 | 9.5 | Yes | No |
| 6 | 36 | 1.2 | 20.5 | No | Yes |
| 7 | 36 | 1.4 | 9 | No | No |
| 8 | 36 | 1.7 | 12 | Yes | No |
| 9 | 36 | 2.1 | 17.4 | Yes | No |
| 10 | 36 | 3.4 | 15 | Yes | No |
| 11 | 36 | 3.7 | 17 | Yes | No |
| 12 | 36 | 4.2 | 20.5 | No | Yes |
| 13 | 36 | 5.7 | 12 | No | No |
| 14 | 36 | 5.9 | 9.5 | No | No |
| 15 | 36 | 6.8 | 13.8 | No | No |
| 16 | 36 | 9.6 | 9.4 | No | No |
| 17 | 36 | 11.1 | 18 | Yes | No |

### *Influence of Bed Slope and Mass Flux on Subaqueous Morphologies*

Figure 5 shows the resulting morphology obtained for different values of both the input mass flux and the slope. The density contrast between the current and fresh water $\Delta\rho_{cw}$ is 36 g/l while the density contrast between the particles and fresh water $\Delta\rho_{bw}$ is 80 g/l. Two different states of the system can be evidenced: a first one in which the density current does not incise channels and a second one in which channels (straight or mildly meandering) develop. For a given slope, channel incision takes place for values of the mass flux lower than some critical value. For a given mass flux, incision takes place for values of the slope above some critical value. One interesting feature observed is that, before channel inception, the current initially spreads on the incline both in the direction of the slope and perpendicular to it because of the density contrast between the current and the surrounding fluid. Although no definitive conclusion can be drawn at that point, the angle of spreading is an increasing function of the input flow rate as predicted by the theoretical description of a dense current by Bonnecaze and Lister (1999). In their theoretical analysis the width of a spreading current is both an increasing nonlinear function of the flux and a decreasing nonlinear function of the slope. For a given slope there might then be a critical value of the angle of spreading under which the current

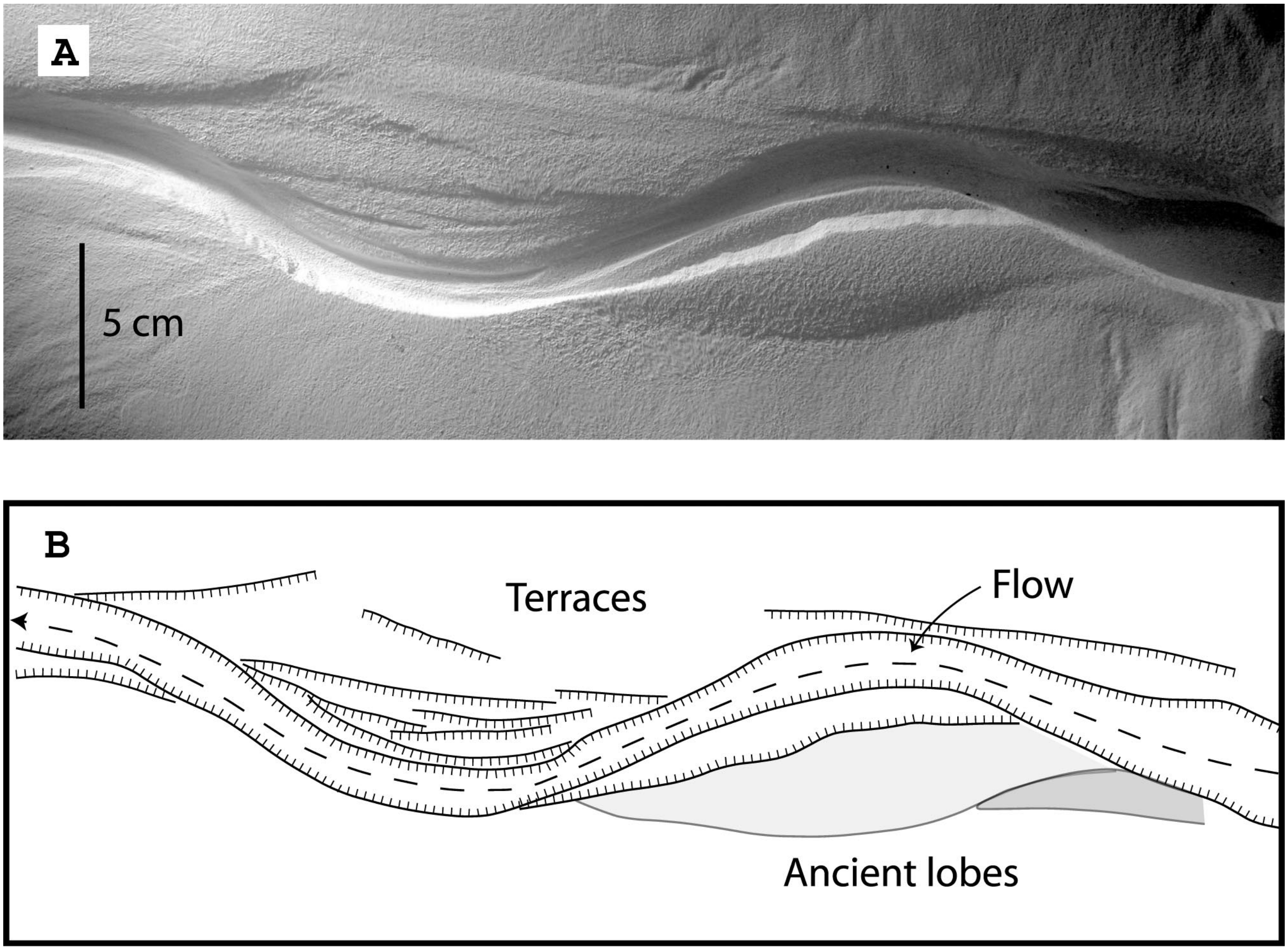

FIG. 3.—Run no. 12. **A)** Meandering channel and associated morphology. Cut terraces can be seen in second meander. **B)** Interpretation showing ancient progradational lobes and terrace risers.

remains strong enough in the slope direction to induce the formation of a small channel. Lateral spreading stops once the channel depth is equal to the height of the current (on the order of 1 cm). This would then be in agreement with the results shown on Figure 4 because both low values of the input mass flux and high values of the slope tend to focus the flow. On the other hand, both high values of the flux and low slopes encourage dispersion and current spreading. Our experiments therefore clearly suggest that if channel inception takes place at a distance from a river mouth then the plunging point may be of crucial importance. This point corresponds to the location where sediments and salt water form a denser fluid that sinks and generates a turbidity current that spreads on the seafloor.

### *Discussion on Plausible Conditions for Channel Inception*

From our observations two conditions are found to be necessary for channel incision to occur. The current must be long lived and the shear stress at the base must be compatible with erosion of the bed. Long-range entrainment of the current depends upon sedimentation of the particles that make up the flow. This can be characterized by the settling length $X$

$$X = uh/v_s \cos \theta \tag{1}$$

where $u$ and $h$ are the velocity and height of the current, $v_s$ is the settling velocity of particles, and $\theta$ is the slope of the bed (Bonnecaze and Lister 1999).

For a long-lived current this ratio must be large. In the natural environment fine particles are the essential component of the density contrast between a turbid current and surrounding oceanic waters. For example, in the case of the turbidity current recorded in the Zaire fan channel by Khripounoff et al. (2003), measurements of both velocity and depth of the current suggest values of $X$ on the order of $10^5$ m or more for 10 micron clay particles. Given the depth of the flow (on the order of 1 cm) the plastic particles used in our experiment correspond to sands in the natural environment. If we were using a turbid current the length scale would then be on the order of 0.2 m, so that the particles would settle rapidly. In order to permit the formation of a long-lived current the density contrast must therefore be modeled through the use of a brine. In this case the length scale $X$ is infinite. The use of a dense current therefore solves the difficult experimental problem of the long-range entrainment of a microscale current. It also solves the problem of sedimentation of the particles composing the current, an initial problem always encountered in experiments performed with turbidity currents. As a direct consequence, however, the use of a density current forbids the study of the sedimentation of fine particles suspended within the system. This problem can partly be solved in the future by addition of small quantities of solid particles to the brine. Nev-

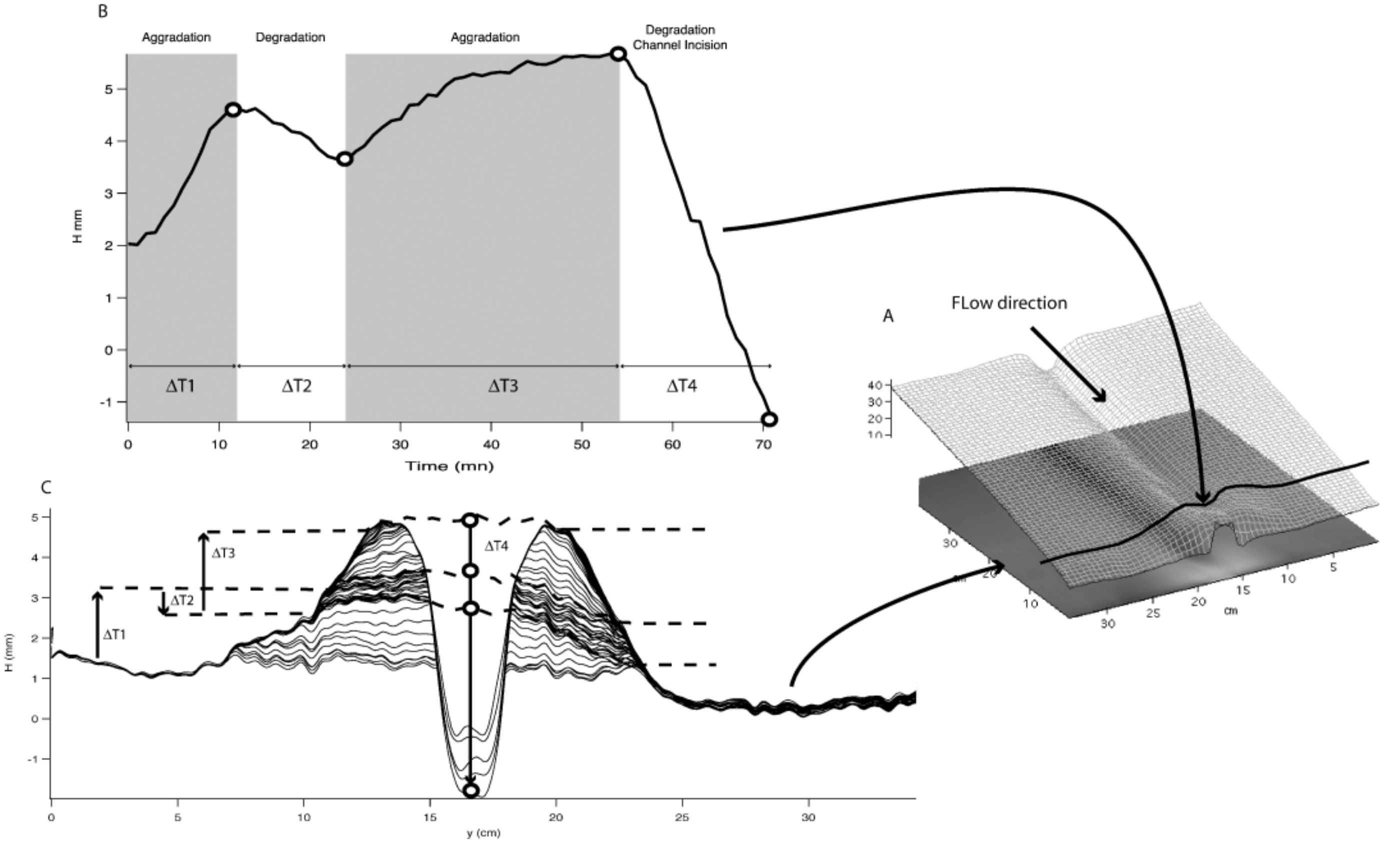

FIG. 4.—Run no. 11. **A)** Topography both in 3D and gray-shade image of the final stage. **B)** Time evolution of elevation of the final channel centerpoint. Distance from origin of the current is 36 cm. Two successive aggradation–degradation waves occur at this point. Definitive channel incision occurs during second degradation phase. Recall that the density current mass flux remains constant throughout the experiment. **C)** Stacked timelines of the topography along a section located at 36 cm from the origin of the density current. Time interval between two topographic profiles is 60 s. Correspondence between parts B and C given by circles and dotted lines.

ertheless our experiments clearly show that, apart from this density contrast, fine clays and mud are needed neither for the formation of a channel nor for the formation of aggradational levee-like topographies (Figure 4C).

Erosion of a noncohesive bed made of fine particles can be to the first order quantified by the Shields' stress $\tau$, which is the dimensionless ratio between the net shear stress exerted on the bed by the flow and the buoyancy of the particles (Yalin and Ferreira 2001) In a quasi-equilibrium subaqueous density flow this can be expressed as

$$\tau_* = \frac{(\rho_f - \rho_w)h \tan \theta}{(\rho_s - \rho_w)D} \quad (2)$$

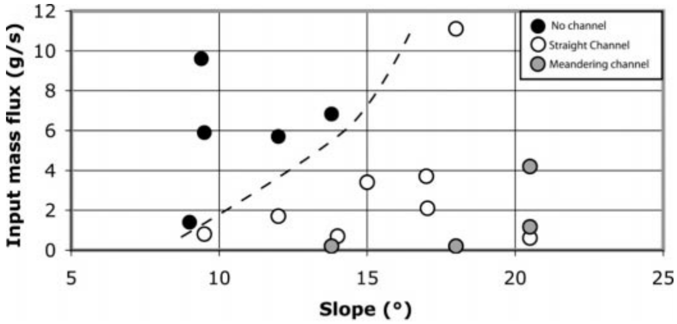

FIG. 5.—Submarine morphology obtained depending on input flow and slope conditions for a dense current $\Delta\rho_{cw}$ on a bed composed of $\Delta\rho_{bw}$ particles.

In the case of the current recorded in the Zaire fan, for example (Khripounoff 2003), with an height of about 150 m a velocity of 1.2 m/s, a slope of 0.2 to 0.4%, transporting clays to fine sands up to 150 microns one can roughly estimate the Shields' stress. It is found to be on the order of 2 for sand and 30 for a 10 micron clay particle. These values should be considered as minimum values of $\tau_*$ because the total height and the average velocity of this huge current were most probably higher (Khripounoff et al. 2003). Our experimental currents have $\tau_*$ on the order of 30 to 40. Both experimental and natural values are comparable. If we assume as a surrogate for our ignorance (Parker 1982) that entrainment of bed particles in the submarine environment to the first order is similar to its fluvial counterpart, use of the Shields' diagram (Yalin and Ferreira 2001) confirms that these Shields' stresses are well above the necessary limits to produce erosion of the particles composing the bed. Because the primary goal of the experiments reported in this article was to explore the experimentally controlled parameter space in order to delineate conditions for channel inception, the Shields' stress was not estimated during all the runs. Smaller or larger values of the Shields' stress will be achieved in the future by adjusting both the brine density and the slope in order to confirm this hypothesis.

If, as one would await and as we suspect, the Shields' stress is a relevant quantity in the problem of channel inception and sediment transfer, then, because of the very large current height reduction (on order of $10^4$ when compared to the current described by Khripounoff et al. in 2003), both the density contrast and the slope have to be greatly enlarged in order to raise the Shields' stress by the same amount. This strategy is conventional in fluvial hydraulics, but in that latter case the density which is tuned is that of the sediment rather than of the fluid. At that point we of course acknowledge that the ideas developed above need to be confirmed by further experiments.

## *Open Problems*

Our experimental investigations demonstrate that, under given conditions of both high shear stress and low angle of spreading, a dense bottom current is able to induce incision of a self-formed channel and that meandering can develop for the smaller values of the current flux. Many questions of course remain. What exactly is the incision mechanism? Under what conditions does a spreading current focus into a narrow channel-like flow? What are the scaling laws that control the dynamics of such systems? Under what conditions and timescales do submarine meanders develop? What are the characteristic length of sediment transport and velocity of channel propagation? We believe that solving these questions is important because although subaqueous channels resemble their subaerial counterparts they exhibit clear differences. For instance for the range of parameters we used we did not observe bedforms like bars even in meanders. This is at first sight surprising because in the fluvial environment one would expect point bars to develop, even if the channel is incising. Here this is not the case. Careful inspection of particle movement shows that it is tractive and sheet-like. Furthermore the transport distance seems to be on the order of the channel length until sedimentation occurs in the prograding lobes. This observation, if confirmed by further experiments and analyses, could have interesting consequences both for our understanding of submarine morphologies and for petroleum exploration in the deep sea.

We therefore believe that the simple experimental setup described above and the first results obtained open a pathway to these many important, yet unsolved, problems of marine geoscience.

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