Turbidity Current Flow out of Channels and its Contribution to Constructing the Continental Slope

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Summary

We combine analysis of shallow seismic data from industry grade 3D volumes with results from physical models that resolve channel-to-overbank sedimentation by turbidity currents to explore how regional surfaces are constructed by unconfined flows. Depositional patterns measured from seismic and laboratory data are used to define properties of proximal versus distal overbank sedimentation. Both data sets reveal a significant drop in variability of depositional thickness associated with the transition to distal sedimentation. This drop in standard deviation is a useful metric for defining the transition from levee to distal overbank deposits.

Data from three laboratory channels with sinuosities of 1.00, 1.03 and 1.28 are used to define relevant details of how currents move out of channels. Overbank sedimentation is roughly axi-symmetric for the straight channel, but significantly asymmetric for the low channel sinuosity of 1.03. For this sinuous channel the levee deposits on the outer banks of bends were about 1.8 times thicker than inner bank deposits. For the channel with a sinuosity of 1.28 the outer bank deposits were about 3.4 times thicker than the levee deposits on the inner banks of bends. These differences are related to bend-induced cross-channel flow. The style of this cross-channel flow and the resulting distribution of particle sizes that move out of the channel will be discussed. Importance of the channel sidewall slope is highlighted. Accurate modeling of currents moving out of channels at bends requires the use of realistic cross-sectional geometries. The ties between overbank sedimentation and channel sinuosity measured in the laboratory will be compared to natural systems that are seismically resolved.

Introduction

Mapping of continental margins has revealed surfaces covered by numerous submarine channel systems [*Damuth et al.*, 1983; *Pirmez and Flood*, 1995; *Posamentier and Kolla*, 2003]. These channels are the dominant conduits for transport of terrigenous sediment into the deep sea and impart a first-order control on continental-slope topography [*Kostic et al.*, 2002; *Pirmez et al.*, 2000]. Submarine channels are bounded over much of their length by prominent natural levees. These levees are built from the overspill and deposition of sediment contained in turbidity currents [*Dennielou et al.*, 2006; *Hay*, 1987; *Pirmez et al.*, 1997; *Skene et al.*, 2002; *Straub et al.*, in press]. In net aggradational settings, levees are the primary elements of self-formed channels and their deposits provide a cumulative record of channel history compared to deposits located in channel thalwegs where frequent episodes of local erosion can produce complicated stratigraphic histories. For self-formed channels the temporal and spatial growth of levees sets channel relief or depth. This relief in turn influences the degree to which turbidity currents are able to spill out of the confining channels and construct the regional overbank surface. Unfortunately, the wealth of geometric data defining the levees of submarine channels is not matched by an equivalent set of data defining the levee-building processes. Measurements of out-of-channel flow are less common than the small set of direct observations from turbidity currents confined to submarine channels themselves [*Hay*, 1987; *Khripounoff et al.*, 2003; *Xu et al.*, 2004].

This paper links measurements of submarine levees and stratigraphy from a continental slope setting with data from laboratory experiments. We begin by analyzing the depositional patterns associated with a tributary system of submarine channels with low sinuosity on the continental margin offshore Borneo. Using an industry-grade 3D seismic volume we quantify how levee thickness decays with distance from channels. Observations from offshore Borneo motivate laboratory studies where we document the influence of sinuosity on the depositional pattern, both deposit thickness and particle size, of overbank deposits.

Observations from offshore Borneo

Our study of leveed submarine channels takes advantage of a 4000 km^2 industry-grade 3-D seismic volume covering the continental slope offshore Brunei Darussalam. The specific area is a tributary network of channels that covers 555 km^2 of this larger survey. We focused on the shallow sedimentary section positioned between the seafloor and a subsurface depth defined acoustically by an additional 0.3 seconds of two-way travel-time. The frequency roll-off for this portion of the seismic volume is near 80 Hz, providing a vertical resolution for buried deposits of $\leq$ 3 m. The entire survey was collected on a horizontal grid with 25 x 25 m^2 spacing.

Turbidity Current Flow out of Channels

In the study area the continental shelf-slope break occurs at a water-depth of ~200 m. The seabed then descends for the next roughly 60 km until reaching the floor of the Borneo Trough at a water depth of 2800. The upper slope is characterized by a relatively steep average gradient of 3.2^{o}. Superimposed on this regional dipping surface are several tributary networks of submarine channels and a series of strike-parallel ridges. These ridges are the product of diaperism by mobile overpressured shale [*Demyttenaere et al.*, 2000; *Ingram et al.*, 2004; *van Rensbergen et al.*, 1999]. The combination of the high surface gradient and shale diapirism has lead to multiple mass-failure events on the upper slope.

We produced a map of sediment deposition associated with the leveed channels utilizing regional maps of two surfaces, the seafloor and a prominent horizon in the shallow subsurface (Yellow Horizon in Figure 1). Using the 3D seismic volume we have mapped the shallow (<0.25 sec TWT below seafloor) regional surface beneath the network of interest. The subsurface horizon mapped was chosen because it possesses consistently strong reflection amplitude that allowed us to track the horizon beneath the majority of the network area. Inspection of a map of this surface reveals a dearth of local topography associated with paleo-channels, as well as a laterally persistent detachment scarp and slide plane associated with a regionally extensive, mass-failure event. Development of the leveed channels on top of the regional extensive and relatively smooth slide plane provides us with the simplest possible initial condition for studying the evolution of aggradational submarine channels.

A map of sediment deposition associated with the channel network was created by differencing the seafloor and subsurface horizons. Thick levee deposits define the margins of every channel and indicate that this tributary network grew under net depositional conditions.

To characterize the overbank depositional pattern we have performed the following analysis. First, we identified the location of every grid node on the thickness map that corresponds to a channel thalweg. With this network in place we calculated the path length to the nearest channel thalweg for every grid node on the map. This allowed us to examine every local measure of thickness as a function of distance from the closest channel thalweg. We then sorted and assembled all of the data points using this distance. The binning width was 25 m. Collapsing the data onto a single trendline allows us to capture both the mean depositional signal as well as the magnitude of variability about this trend associated with local topographic effects. Mean thickness and coefficient of variation, *CV*, defining both levee and background overbank deposition are presented in Figure 2.

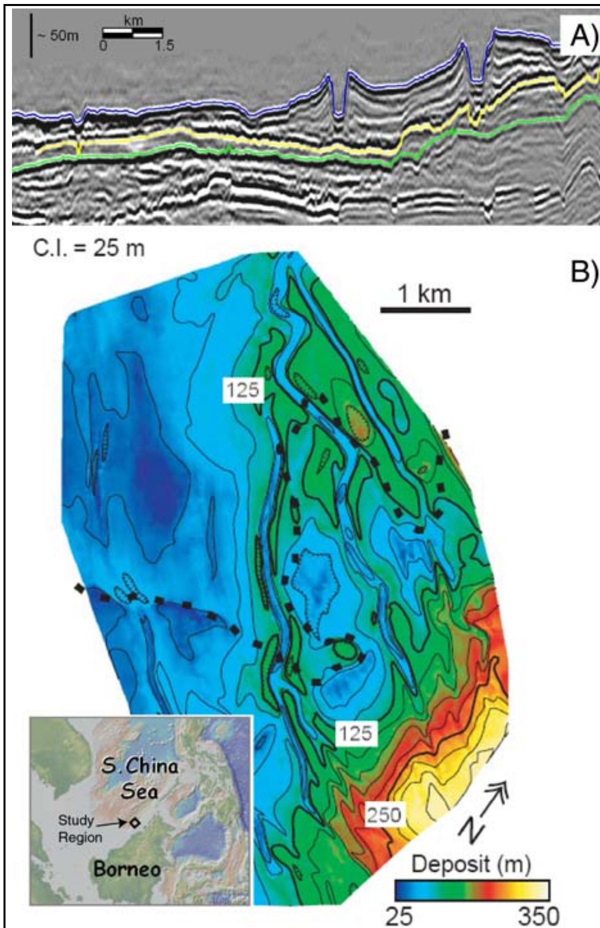

Figure 1: A) Characteristic stike-oriented seismic line for study region showing portion of the regional stratigraphy from the seafloor (blue line) to regional (Yellow) horizon. B) Deposit thickness measured between seafloor and regionally (Yellow) mapped subsurface horizon. Contour interval is 25 m. Dashed lines mark location of failure scarp. Insert delineates location of study region.

The plot of average sediment thickness versus distance from a channel center allows us to define and characterize three depositional zones. The first zone makes up the channels themselves. Average channel half-width is 125 m and over this distance deposit thickness increases from 65 m at the thalweg to 122 m at the levee crest**.** The second zone defines the average levee form and runs between 125 m to 2200 m from a channel centerline. Over this distance, sediment thickness drops from 122 m at the levee crest to 55 m its distal termination. It is not obvious where to place the distal end of the levee based only on mean thickness. We have refined the location by taking advantage of the spatial structure in the coefficient of variation for deposit thickness. Coefficient of variation maintains an approximately constant value for a distance up to 2200 m from a channel center. After this point values for *CV* decrease with increasing separation from a channel. We take the transition from a roughly constant *CV* to a continuously decreasing one as defining the boundary between the levee and background overbank surface. We expect a greater variation in depositional thickness to be associated with focused levee deposition versus the background sedimentation building the regional overbank surface. Sedimentation on the distal overbank has produced a deposit with a nearly constant thickness of 55 m.

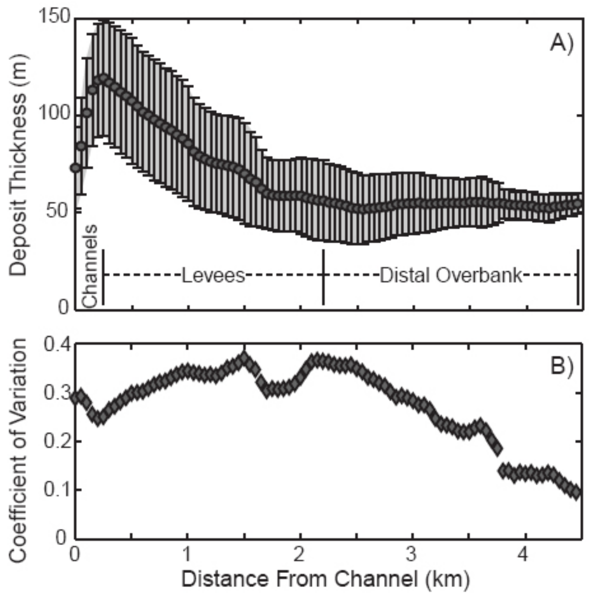

Figure 2: Change in deposit thickness as a function of shortest distance to a channel thalweg. A) Mean thickness of deposit measured in bins spaced every 25 m from closest channel thalwed. Error bars represent +/- one standard deviation of data in each bin. B) Coefficient of variation for deposit thickness sample bins.

Analysis of the three depositional zones reveals two system properties that are particularly relevant to inferring behavior of the evolving network. First, sedimentation in channel thalwegs is 1.3 times greater than the background deposition associated with the far-field overbank surface. This difference results in progressive elevation of channels above their overbank surface with overall slope deposition. The observed ratio of in-channel deposition rate to far-field deposition rate is similar to the Amazon system [*Pirmez et al., 2000*] and based off results from reduced-scale experiments [*Mohrig and Buttles, 2007*] points to currents that are at least 5 times thicker than the local channel depth. Second, 89% of the total deposit volume contained within the mapped region is found within overbank deposits (levees and regional overbank). This observation points to the relative importance of levee deposits in evolution of continental margins relative to channel bottom deposits (Table 1).

The submarine channels offshore Brunei are relatively low sinuosity. To quantify the influence of sinuosity on overbank deposition and quantify the dynamics of levee building we performed several reduced scale laboratory experiments.

17 km³ of slope deposit (area: 192 km²)	% of total area	% of total deposit volume
Channel bottom	11	11
Levee	81	85
Regional Overbank	8	4

Table 1: Percent of total area and deposit volume for three depositional enivronments in study region between the seafloor and (Yellow) regional subsurface horizon.

Observations from laboratory experiments

The influence of channel bends on turbidity current flow out of channels was studied in the laboratory at reduced scale. We monitored the evolution of channel and overbank topography resulting from deposition of turbidity currents interacting with three laboratory channels. The three channels had sinuosities of 1.00, 1.03, and 1.28.

The aim of our experimental study was to quantify the relative importance of two commonly sited processes by which sediment is transferred from channelized turbidity currents to overbank flow: flow splitting and flow spilling. Flow splitting describes a process where the upper fraction of the flow traveling above the channel detaches from the body of the current as it moves through a channel bend. This detachment takes place along the outer bank of a bend [*Piper and Normark, 1983*]. Flow spilling, however, is not a site-specific mechanism. Flow spilling describes a process in which a suprachannel fraction of a current spreads laterally as a result of the gravitational collapse of the supra-channel flow [*Clark and Pickering, 1996*].

The experiments were performed in a tank 5 m long, 5 m wide and 1.2 m deep. Within this basin we constructed the three experimental channels, each had the same mean width and depth. The planform shape of the channels was designed using sine-generated curves. The 1.03 and 1.28 sinuosity channels had 3 channel bends. 10-32 turbidity currents were released into each experimental channel. Current thickness at the channel entrance was held constant at 0.1 m; the initial depth of the channels. Current Froude numbers varied between 0.5 – 0.7. All turbidity currents were composed of the same mixture of clear water, dissolved $CaCl_2$, and suspended sediment. This mixture produced currents that entered the channel with an absolute density of 1021 kg/m^3. D10, D50, and D90 of the sediment were 12.9 μm, 31.0 μm, and 52.1 μm respectively.

Maps of the channel form following each experimental current were produced using either a 1-MHz ultrasonic transducer connected to a pulse-receiver box or a submerged 1KHz long range displacement laser connected to a datalogger. The precision at each location for the two data collection systems is better than 0.2 mm. This resolution makes it possible to successfully determine the patterns of sediment deposition associated with individual currents by differencing successive maps of channel topography.

Following the last current in each experiment, the water level in the basin was lowered, and the deposit was allowed to dry. After drying, the deposit was sampled for particle-size characterization. The sediment samples were then analyzed with a Horiba LA-300 laser-particle size analyzer (LPSA). The LPSA uses a diode laser to accurately measure a distribution of sizes from 0.001 to 0.3 mm in nominal diameter.

Cross-channel asymmetry of overbank deposits resulting from flow splitting was characterized by comparing the levee crest deposit thickness of the inner and outer bank levees at bend apexes. For the straight channel experiment overbank sedimentation was roughly axi-symetric. For the low sinuosity channel, outer bend levee deposits were 1.8 times thicker than inner bend levee deposits. This ratio increased for the high sinuosity channel where outer bend levee deposits were 3.4 times thicker than inner bend levee deposits.

Next we compared the total amount of sediment deposited in the overbank environment for the three channel configurations. For this calculation we utilized the first 10 deposits in each experiment, measured over the first 1.5 m of channel length from the channel entrance. The total amount of overbank sedimentation in the 1.03 sinuosity channel was 1.12 times greater than the straight channel. This ratio was slightly higher for the 1.28 sinuosity channel where the overbank sedimentation was 1.31 times greater than the straight channel. The combination of these observations with the measurements of deposit asymmetry at channel bend apexes illustrate that planform irregularity imparts significant spatial variability in thickness of proximal overbank deposits but has a minimal affect on the total volume of overbank sedimentation.

Finally, we observed a strong asymmetry in the cross-channel deposit grain size pattern at bend apexes (Figure 3). This asymmetry was so great that outer bank levee crest deposits were as course as deposits in the adjacent channel thalweg. This depositional pattern suggests cross-channel flow in bends is strongly influenced by runup of currents onto outer channel bend banks. Past studies have demonstrated that the magnitude of runup is strongly influenced by the surface slopes [*Hungr et al., 1984*]. This observation illustrates that accurate modeling of currents moving out of channels at bends will require the use of realistic cross-sectional geometries.

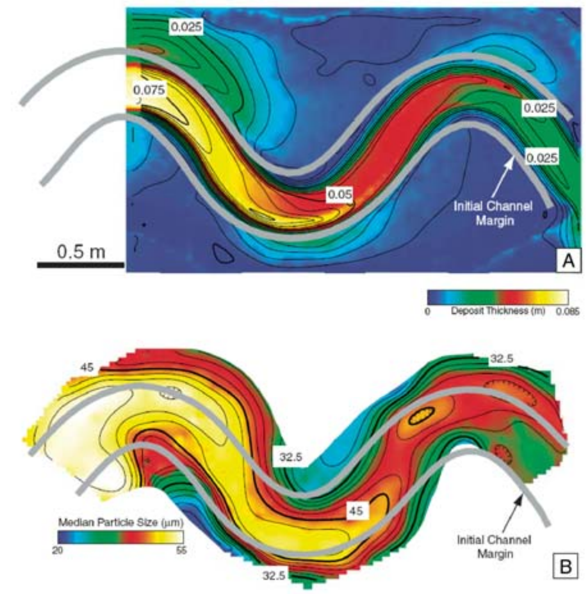

Figure 3: Maps from the 1.28 sinuosity channel. Channel flow was from left to right. A) Map of deposit thickness resulting from sedimentation by 24 turbidty currents. Contour interval is 5 mm. Gray bold lines represent location of channel margin prior to deposition of turbidity currents. B) Map of median (D50) particle size for the deposit of 24 turbidiity currents.

Conclusions

1) Irregularity in channel planform affects local variability in thickness of proximal overbank deposits (e.g., inner versus outer banks of bend).
2) Irregularity in channel planform weakly influences the total amount of overbank sedimentation. We found that high sinuosity & straight experimental channels produce the same degree of overbank sedimentation.
3) Overbank sedimentation rates on Quaternary Amazon submarine fan and Brunei continental slope is ~ 80 % of channel-bed sedimentation rates. This condition in experimental channels requires thick turbidity currents, ≥ 5x channel depth.
4) Recent sedimentation on Brunei continental slope is 89 % overbank deposits and 11 % channel-bed deposits.

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2008 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Clark, J., and K. Pickering, Architectural elements and growth patterns of submarine channels: applications to hydrocarbon exploration: Petroleum Geologist Bulletin.

Damuth, J. E., V. E. Koola, R. D. Flood, R. O. Kawsmann, M. C. Monteiro, J. J. C. Palma, and Belderson, 1996, Distributary channel meandering and bifurcation patterns on Amazon Deep-Sea Fan as revealed by long-range side-scan sonar (GLORIA): 80, 194–221.

Demyttenaere, R., J. P. Tromp, A. Ibrahim, P. Allman-Ward, and T. Meckel, 2000, Brunei deep water exploration: From sea floor images and shallow seismic analogues to depositional models in a slope-turbidite setting: Annual Research Conference, Deep-Water Reservoirs of the World.

Dennielou, B., A. Huchon, C. Beaudouin, and S. Berne, 2006, Vertical grain-size variability within a turbidite levee: Autocyclicity or allocyclicity?: A case study from the Rhone neofan, Gulf of Lions: Western Mediterranean, 213.

Hay, A. E., Turbidity currents and submarine channel formation in Rupert Inlet, British Columbia: The role of continuous and surge-type flow.

Hungr, O., G. C. Morgan, and R. Kellerhals, 1984, Quantitative analysis of debris torrent hazards for design of remedial measures: 238.

Ingram, G. M., T. J. Chisholm, C. J. Grant, C. A. Hedlund, P. Stuart-Smith, and J. Teasdale, Deepwater North West Borneo: Hydrocarbon accumulation in an active fold and thrust belt.

Khripounoff, A., A. Vangriesheim, N. Babonneau, P. Crassous, B. Dennielou, and B. Savoye, Direct observations of intense turbidity current activity in the Zaire submarine valley at 4000 m water depth.

Kostic, S., G. Parker, and J. G. Marr, Role of turbidity currents in setting the forset slope of clinoforms prograding into standing fresh water.

Mohrig, D., and J. Buttles, Shallow channels constructed by deep turbidity currents: 11, 94–98.

Piper, D. J. W., and W. R. Normark, 2000, Turbidite depositional patterns and flow characteristics, Navy submarine fan, California Borderland, Pirmez, C., R.T. Beaubouef, S.J. Friedmann, and D. Mohrig, Equilibrium profile and baselevel in submarine channels: examples from Late Pleistocene systems and implications for the architecture of deepwater reservoirs, in 20th Annual Research Conference, Deep-Water Reservoirs of the World 805.

D. J. W. Pipper, A. Klaus, and L.C. Peterson, 1995, Ocean drilling program: 23–45.

Pirmez, C., and R. D. Flood, 2007, Morphology and structure of Amazon channel: 35, 155–158.

Pirmez, C., R. N. Hiscott, and J. D. Kronen, 1997, Sandy turbidite successions at the base of channel-levee systemsof the Amazon fan revealed by FMS logs and cores: Unraveling the facies architecture of large submarine fans, in Ocean Drilling Program, 7–33.

Posamentier, H. W., and V. E. Kolla, Seismic geomorphology and stratigraphy of depositional elements in deep-water settings: Proceedings of the Journal of Sedimentary Research, 73.

Skene, K. I., D. J. W. Piper, and P. S. Hill, 2003, Quantitative analysis of variations in depositional sequence thickness from submarine channel levees: 367–388.

Straub, K. M., and D. Mohrig, Quantifying the morphology and growth of levees in aggrading submarine channels: in press.

van Rensbergen, P., C. K. Morley, D. W. Ang, T. Q. Hoan, and N. T. Lam, Structural evolution of shale diapirs from reactive rise to mud volcanism: 3D seismic data from the Baram delta, offshore Brunei, Darussalam, Society of London.

Xu, J. P., M. A. Noble, and L. K. Rosenfeld, 2002, In-situ measurements of velocity structure within turbidity currents, 1411–1430.