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KEY FUTURE DIRECTIONS FOR RESEARCH ON TURBIDITY CURRENTS AND THEIR DEPOSITS

PETER J. TALLING,[1] JOSHUA ALLIN,[1] DOMINIC A. ARMITAGE,[2] ROBERT W.C. ARNOTT,[3] MATTHIEU J.B. CARTIGNY,[1]
MICHAEL A. CLARE,[1] FABRIZIO FELLETTI,[4] JACOB A. COVAULT,[5] STEPHANIE GIRARDCLOS,[6] ERNST HANSEN,[7]
PHILIP R. HILL,[8] RICHARD N. HISCOTT,[9] ANDREW J. HOGG,[10] JOHN HUGHES CLARKE,[11] ZANE R. JOBE,[12]
GIUSEPPE MALGESINI,[1] ALESSANDRO MOZZATO,[1] HAJIME NARUSE,[13] SAM PARKINSON,[14] FRANK J. PEEL,[1]
DAVID J.W. PIPER,[15] ED POPE,[1] GEORGE POSTMA,[16] PETE ROWLEY,[17] ANDREA SGUAZZINI,[4] CHRISTOPHER J. STEVENSON,[18]
ESTHER J. SUMNER,[19,20] ZOLTAN SYLVESTER,[12] CAMILLA WATTS,[1] AND JINGPING XU[21]

[1] National Oceanography Centre, University of Southampton, Waterfront Campus, European Way, Southampton, Hampshire, SO14 3ZH, U.K.
[2] ConocoPhillips, 600 North Dairy Ashford, Houston, Texas 77079, U.S.A.
[3] University of Ottawa, Department of Earth Science, Ottawa Carleton Geoscience Centre, Ottawa, Ontario K1N 6N5, Canada
[4] Università degli Studi di Milano, Dipartimento di Scienze della Terra, Via Mangiagalli 34, 20133-Milano, Italy
[5] Chevron Energy Technology Company, Houston, Texas, U.S.A.
[6] Section of Earth and Environmental Sciences and Institute for Environmental Sciences, University of Geneva, Rue des Maraîchers 13, 1205 Geneva, Switzerland
[7] Complex Flow Design, Pirsenteret II, NO-7462, Trondheim, Norway
[8] Natural Resources Canada, Geological Survey of Canada, P.O. Box 6000, Sidney, British Columbia V8L 4B2, Canada
[9] Memorial University of Newfoundland, Department of Earth Sciences, St John's, Newfoundland A1B 3X5, Canada
[10] School of Mathematics, University of Bristol, University Walk, Bristol BS8 1TW, U.K.
[11] Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada
[12] Shell Projects and Technology, Houston, Texas 77082, U.S.A.
[13] Chiba University, Faculty of Science, Department of Earth Science, Inage Ku, Chiba 2638522, Japan
[14] Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, U.K.
[15] Natural Resources Canada, Geological Survey of Canada (Atlantic), Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2, Canada
[16] University of Utrecht, Faculty of Geoscience, P.O. Box 80021, NL-3508 TA, Utrecht, The Netherlands
[17] Royal Holloway, University of London, Egham Hill, Egham, TW20 0EX, U.K.
[18] University of Leeds, School of Earth and Environment, Leeds LS2 9JT, West Yorkshire, U.K.
[19] Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Southampton, SO14 3ZH, U.K.
[20] Monterey Bay Aquarium Research Institute, 7700 Sandholt Road, Moss Landing, California 95039, U.S.A.
[21] U.S. Geological Survey, 400 Natural Bridges Drive, Santa Cruz, California 95060, U.S.A.

ABSTRACT: **Turbidity currents, and other types of submarine sediment density flow, redistribute more sediment across the surface of the Earth than any other sediment flow process, yet their sediment concentration has never been measured directly in the deep ocean. The deposits of these flows are of societal importance as imperfect records of past earthquakes and tsunamogenic landslides and as the reservoir rocks for many deep-water petroleum accumulations. Key future research directions on these flows and their deposits were identified at an informal workshop in September 2013. This contribution summarizes conclusions from that workshop, and engages the wider community in this debate. International efforts are needed for an initiative to monitor and understand a series of test sites where flows occur frequently, which needs coordination to optimize sharing of equipment and interpretation of data. Direct monitoring observations should be combined with cores and seismic data to link flow and deposit character, whilst experimental and numerical models play a key role in understanding field observations. Such an initiative may be timely and feasible, due to recent technological advances in monitoring sensors, moorings, and autonomous data recovery. This is illustrated here by recently collected data from the Squamish River delta, Monterey Canyon, Congo Canyon, and offshore SE Taiwan. A series of other key topics are then highlighted. Theoretical considerations suggest that supercritical flows may often occur on gradients of greater than ~ 0.6°. Trains of up-slope-migrating bedforms have recently been mapped in a wide range of marine and freshwater settings. They may result from repeated hydraulic jumps in supercritical flows, and dense (greater than approximately 10% volume) near-bed layers may need to be invoked to explain transport of heavy (25 to 1,000 kg) blocks. Future work needs to understand how sediment is transported in these bedforms, the internal structure and preservation potential of their deposits, and their use in facies prediction. Turbulence damping may be widespread and commonplace in submarine sediment density flows, particularly as flows decelerate, because it can occur at low (< 0.1%) volume concentrations. This could have important implications for flow evolution and deposit geometries. Better quantitative constraints are needed on what controls flow capacity and competence, together with improved constraints on bed erosion and sediment resuspension. Recent advances in understanding dilute or mainly saline flows in submarine channels should be extended to explore how flow behavior changes as sediment concentrations increase. The petroleum industry requires predictive models of longer-term channel system behavior and resulting deposit architecture, and for these purposes it is important to distinguish between geomorphic and stratigraphic surfaces**

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in seismic datasets. Validation of models, including against full-scale field data, requires clever experimental design of physical models and targeted field programs.

INTRODUCTION

Turbidity currents, and other types of submarine sediment density flow[1] (Lowe 1982; Talling et al. 2012), are the volumetrically most important sediment transport process on our planet, and they form the largest sediment accumulations on Earth (submarine fans). A single turbidity current can transport over ten times the annual sediment flux from all of the world's rivers (Talling et al. 2007), and can be more than 200 km wide (see Table 1 of Talling 2014). They can reach speeds of ~ 20 m/s (~ 70 km/h) on seafloor gradients of just 0.3° (Piper et al. 1999). Other types of particle-laden flow (such as pyroclastic flows and snow avalanches) can reach such speeds, but do so on much steeper gradients. Turbidity currents break important networks of seafloor cables that now carry > 95% of trans-oceanic data traffic (Carter et al. 2009), including the internet and financial markets that underpin daily lives. Ancient submarine flows have formed major subsurface oil and gas reservoirs in locations worldwide with considerable economic and strategic importance.

It is over 60 years since the seminal publication of Kuenen and Migliorini (1950) in which they made the link between sequences of graded bedding and turbidity currents. The deposits of turbidity currents have now been described in numerous locations worldwide, and this might lead to the view that these flows are well understood. However, it is sobering to note how few direct measurements we have from these submarine flows in action. Sediment concentration is the critical parameter controlling such flows, yet it has never been measured directly for flows that reach and build submarine fans. Indeed, studies in only six locations (Xu et al. 2010, 2013, 2014; Xu 2011; Hughes Clarke et al. 2012, 2014; Cooper et al. 2012; Khripounoff et al. 2003, 2012; Vangriesheim et al. 2009; Ayranci et al. 2012; Lintern and Hill, personal communication; see Talling et al. 2013) have estimated sediment concentrations for turbidity currents in shallow water, typically using backscatter values from acoustic Doppler current profilers (ADCPs). This indirect technique for measuring sediment concentration (backscatter is also affected strongly by additional parameters including grain size) has large uncertainties and cannot penetrate into high sediment concentrations at the base of the flow. How then do we know what type of flow to model in flume tanks, or which assumptions to use to formulate numerical simulations or analytical models?

An informal workshop was held from 9–13 September at Santa Sofia in the Italian Apennines that combined field examination of classic turbidites and talks from 32 delegates. An overall aim of the workshop was to identify key future research directions for work on turbidity currents and their deposits. How do we make major step changes in understanding in the future? The workshop also highlighted important recent advances in understanding and promoted comparisons between field datasets and numerical or physical modeling. This article tries to engage the wider audience in this debate on what are key future directions for research on these fascinating (and on occasions frustrating) flows.

SUGGESTIONS FOR KEY FUTURE RESEARCH DIRECTIONS

The following suggestions from the workshop are not an exhaustive list. Indeed, such suggestions are inevitably contentious and subjective. In many cases, these future research directions lead on from recent advances in understanding or technology, which are also outlined briefly.

(A) Coordinated Community Efforts for Source-To-Sink Data for Submarine Systems at Key "Test Sites"

Recent Advances.—There have been major recent advances in direct monitoring of flows in shallow-water (< 50–250 m) locations worldwide. For instance, a remarkable data set is now available from direct monitoring of flows on the Squamish River delta in Howe Sound, British Columbia (Fig. 1; Hughes Clarke et al. 2012, 2014). This work used more than 90 repeat multibeam bathymetric surveys (Fig. 1C, D) to understand flow timing, triggers, and character, combined with water-column measurements from acoustic sensors mounted on bottom tripods (Fig. 1B, E), and most recently with innovative moorings that suspend instruments above active channels. Time-lapse animations are available of daily changes in seafloor morphology through the river flood season (Fig. 1D; Hughes Clarke et al. 2012), together with hourly changes during a single low tide (Hughes Clarke et al. 2014). These flows were capable of moving 25–45 kg blocks for tens to hundreds of meters (Hughes Clarke et al. 2014). Core and shallow seismic data is available to better constrain deposits (Fig. 1A). Complementary work on the nearby Fraser River delta (Hill 2012) includes the VENUS cabled observatory on the delta slope (Ayranci et al. 2012). Long-term monitoring of flows in Monterey

TABLE 1.—*Key components that constitute an ideal test site.*

Date Type	Additional Comments
Monitoring of active flow events	Can be split into (i) flow timing and triggers, and (ii) internal character and composition of flows, with the latter often being most challenging to measure. Flows evolve, so data is needed along full flow path.
(A) Timing of potential triggers (e.g. floods, earthquakes, large waves, low tides, etc.)	Needed to establish triggers for monitored flows.
(B) Repeat time-lapse bathymetric surveys	Constrain event timing, and show how events sculpt sea floor or lake floor. Also provide quantitative data on gradient change along flow path.
(C) Sediment cores	Including deposits of monitored flows, to understand links between flow and deposit character. May be only information for infrequent flow types.
(D) Detailed 2-d or 3-d seismic surveys	Needed to understand the larger-scale and longer-term evolution and geometry of the system.
(E) Numerical and laboratory (flume tank) modeling of flows	Needed to understand significance of individual field observations, and key controls on how flows behave and systems evolve in general.

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[1] See Talling et al. 2012 for a detailed discussion of terminology. In this contribution, "turbidity current" is used to denote any type of subaqueous sediment density flow.

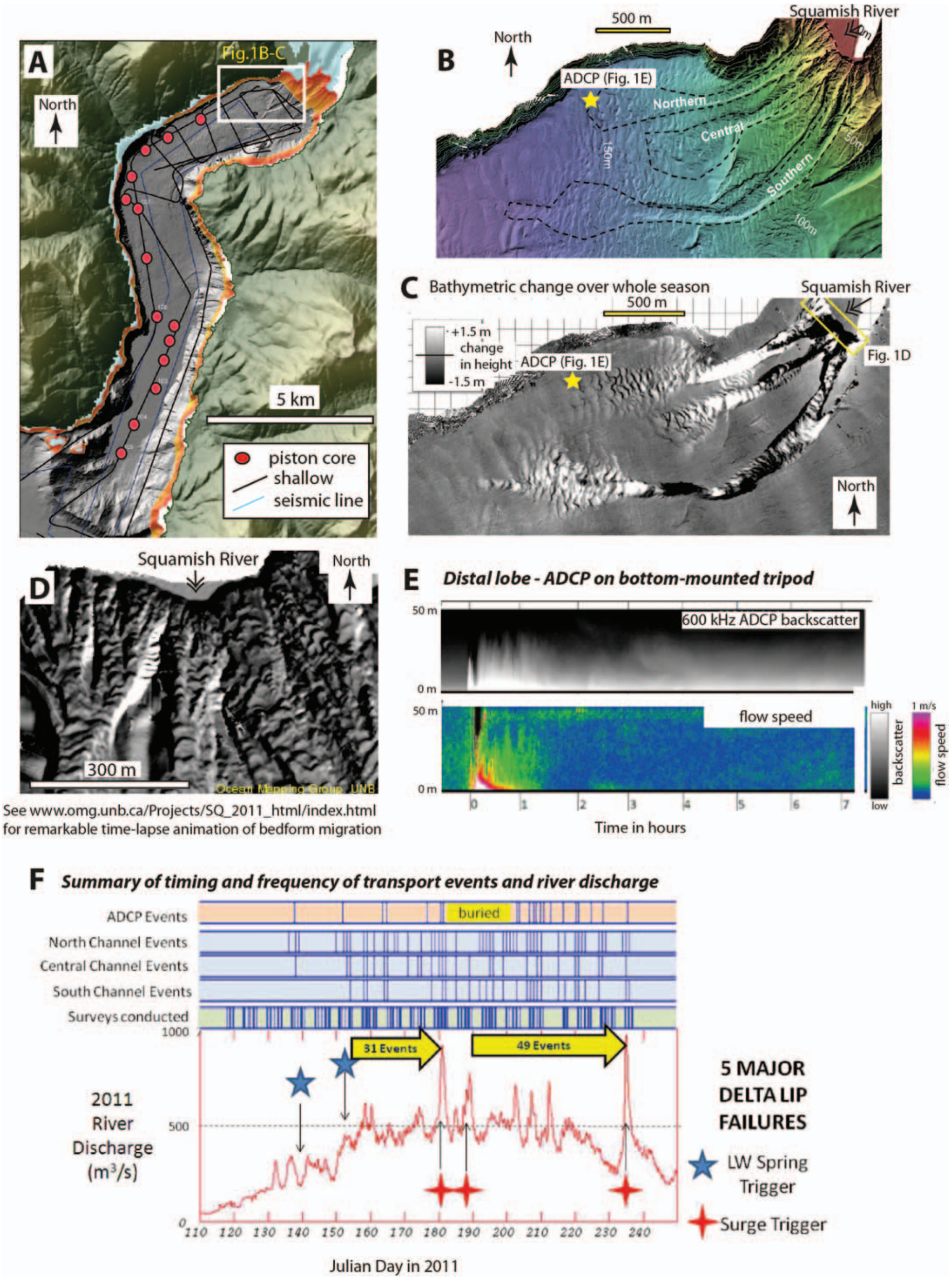


FIG. 1.—Field observations from Squamish River delta in Howe Sound, British Columbia, Canada, that illustrate the concept of a test site for understanding flow triggers and dynamics (also see Table 1). Observations include repeat mapping, direct flow monitoring, and cores, and shallow seismic data to constrain deposit geometries. The system is river fed, but the Squamish River does not reach the elevated sediment concentrations needed for generating plunging (hyperpycnal) flows. **A)** Map of Howe Sound showing existing core and shallow seismic data. The Squamish River delta feeds an enclosed "natural laboratory" dammed by a glacial moraine. **B)** Swath bathymetric map of the delta front that comprises three active channels with lobes at their end. The yellow star indicates the position of the bottom tripod-mounted ADCP. **C)** Map showing change in bed elevation along the three channel-lobe systems during a four-month period. **D)** Upslope-migrating crescentic bedforms in channels on the upper delta front. An animation of daily changes in position of these bedforms can be viewed at www.omg.unb.ca/Projects/SQ_2011_html/index.html. **E)** Time series of flow velocity and backscatter from an ADCP on the distal lobe (yellow star in Part B). **F)** Timing of flow events constrained by 93 bathymetric surveys repeated every weekday in each of the three channels, and by the ADCP on the distal lobe, compared to river discharge (red line). Five major failures of the delta lip occurred that coincide with unusually low spring tides or surges in river discharge. Figures are from Hughes Clarke et al. (2012, 2014).

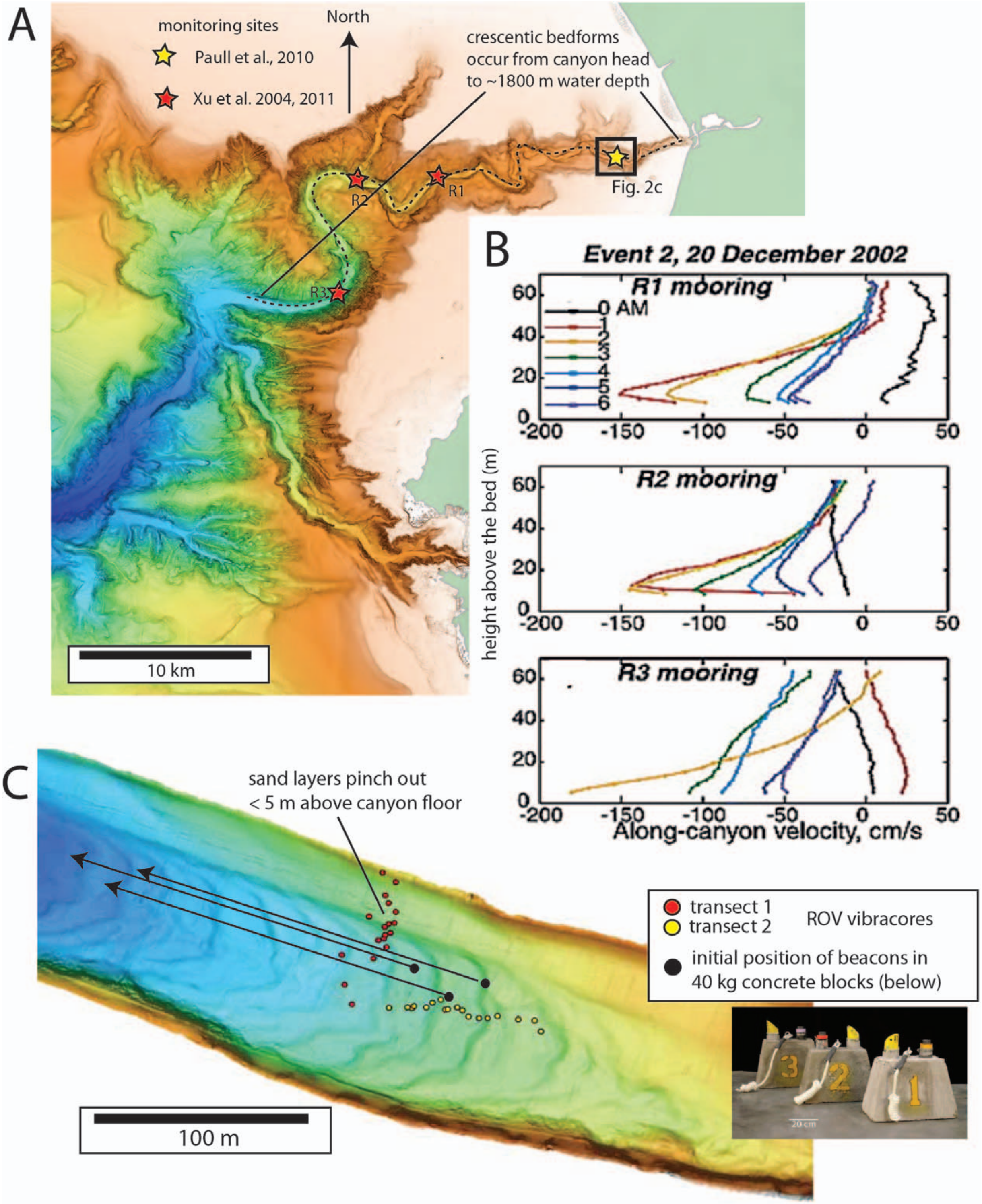


FIG. 2.—**A)** Field observations from Monterey Canyon offshore California, which is an example of a canyon system fed mainly by oceanographic processes (e.g., waves). The location of monitoring sites and extent of crescentic bedforms are indicated. **B)** Velocity profiles through turbidity currents from ADCPs at sites shown in Part A, from Xu et al. (2004). Consecutive profiles are shown for one-hour intervals in the morning (AM), denoted by different colored lines. **C)** Detailed map showing crescentic bedforms that have been tracked from the movement of 40 kg blocks, and existing sediment cores; modified from Paull et al. (2010a). The arrows indicate movement of blocks away from where they were initially deployed. Inset shows the concrete blocks with beacons that allow them to be relocated.

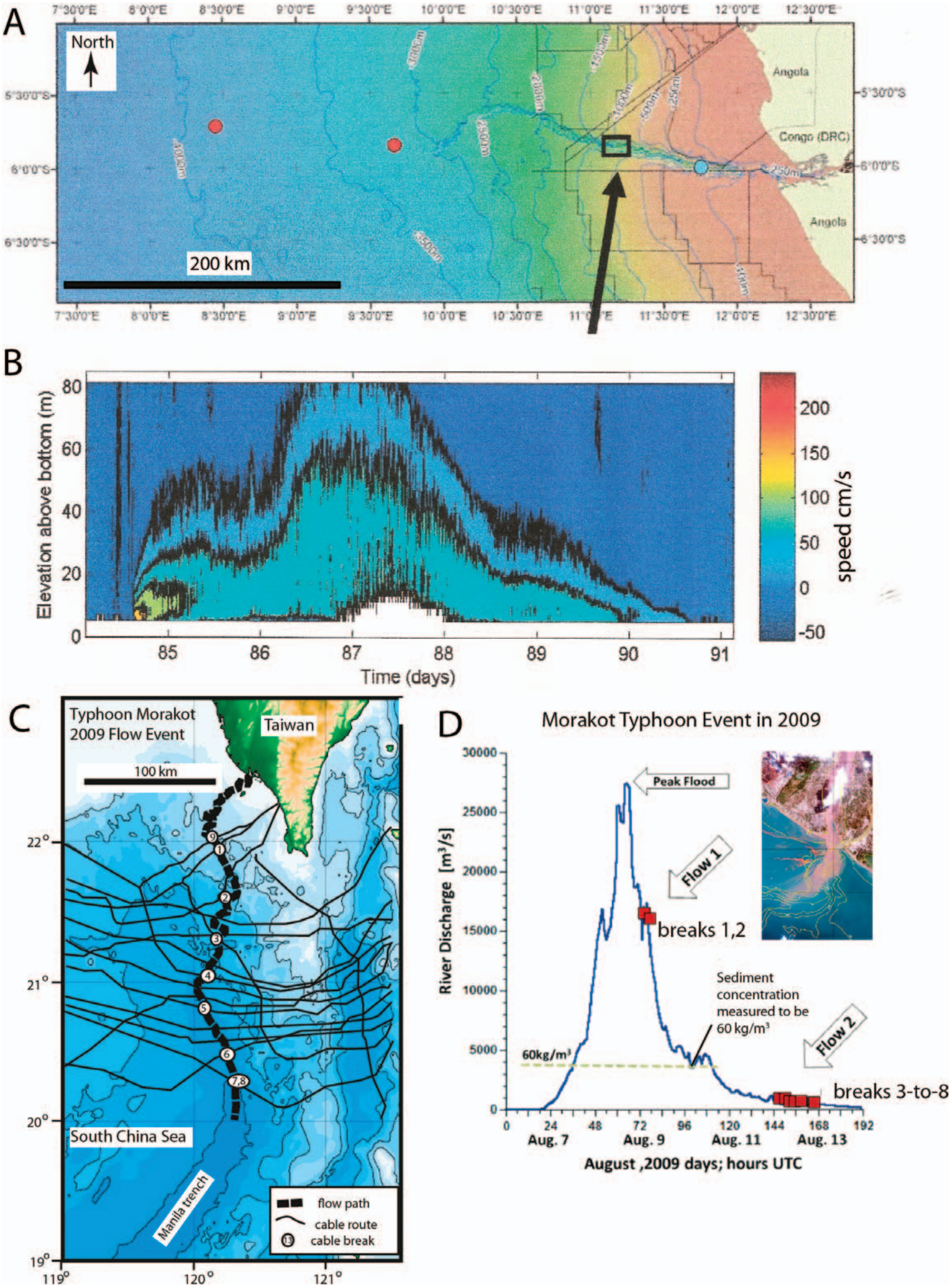


FIG. 3.—Field measurements from powerful flows in river-fed canyons that ran out into the deep ocean. **A, B)** Remarkably prolonged flow documented by ADCP measurements in the Congo Canyon, modified from Cooper et al. (2012). Black box shows the location of monitoring data shown below. Red and blue dots indicate sites of previous monitoring studies (Khripounoff et al. 2003; Vangresheim et al. 2009; and unpublished data). **C)** Cable breaks along the Gaoping Canyon offshore SE Taiwan in 2009, due to a turbidity current following extreme river-flood discharge. **D)** Timing of cable breaks compared to river-flood discharge. Red squares indicate the time of individual cable breaks. Flow 1 may have been produced by plunging river flood water. However, the more powerful Flow 2 occurred several days after the flood finished and was most likely triggered by failure of recently and rapidly deposited sediment. Inset is an aerial photograph of the Gaoping River mouth during the flood, showing the resulting plume of sediment. Parts C and D are modified from Carter et al. (2012).

Canyon, offshore California, provided the first detailed profiles of flow velocity and sediment concentration (Fig. 2; Xu et al. 2004, 2013, 2014; Xu 2010, 2011). This is part of collaborative work by Paull and others at the Monterey Bay Aquarium Research Institute (MBARI), who are developing new sensors embedded in moving near-bed layers that record their acceleration and sense of rotation, and techniques for recovering data from such sensors through gliders. New insights have also been gained from studies of saline density flows in the Black Sea (Flood et al. 2009; Parsons et al. 2011; Hiscott et al. 2013; Sumner et al. 2013a, 2014). Together with work in other locations (e.g., Paull et al. 2010a, 2013; Maier et al. 2013), this highlights the potential of autonomous underwater vehicles (AUVs) for flow monitoring and mapping. Cumulatively, these recent and ongoing studies are showing how innovative techniques and technology can be used successfully for the next generation of flow monitoring.

Future Coordinated Studies at Test Sites.—There is a compelling need to monitor flows directly if we are to make step changes in understanding. The challenges of selecting locations where turbidity currents are frequent and designing instruments that can make the necessary measurements are well known (Inman et al. 1976; Talling et al. 2013). The flows evolve significantly, such that source-to-sink data are needed. We need to monitor flows in different settings with variable triggering factors and flow-path morphologies because their character can vary significantly (Piper and Normark 2009; Talling 2014). It was suggested that coordinated international efforts should be made to monitor active sediment-laden flows at a set of key "test sites" (Table 1), such that the sum of these efforts is greater than the parts. Such work needs to integrate numerical and physical modeling with the collection of field observations, in order to understand the significance of field observations. As stressed at the workshop, such an international initiative also needs to include coring of deposits to link flow processes to deposit character (Table 1), because in most global locations flow behavior must be inferred from deposits alone. Collection of seismic reflection datasets is also crucial for understanding the larger-scale evolution and resulting stratigraphic architecture of these systems (Table 1), and to link with studies of subsurface reservoirs. Major recent advances have been made in understanding sediment dispersal on the shelf and dense water cascading, through large-scale initiatives such as STRATAFORM, EU-STRATAFORM, and MARGINS.

The following test sites were proposed as examples of the main types of turbidity-current systems. They include systems fed by rivers or by waves, tides, or geostrophic currents, marine and freshwater systems, where plunging hyperpycnal river-floods are common or absent, and systems that produce powerful flows that reach the deep ocean. Test sites are chosen where flows are known to be active, occurring on annual or shorter time scales, where previous work provides a basis for future projects, and there is access to suitable vessels and other infrastructure. A few additional test sites could be added to this list, carefully chosen to capture other types of flow triggering and dynamics.

(1) *Squamish River, Fraser River, Kitimat, Bute, and Knight Inlets.* These locations along the Pacific coast of Canada represent river-fed submarine systems (Fig. 1) that normally lack hyperpycnal river discharge (Prior et al. 1987; Hill 2012; Hughes Clarke et al. 2012, 2014). Comparison between these systems suggests a continuum of progressively better developed submarine channels (Conway et al. 2012), so that work at these locations can address questions about flow dynamics in sinuous channels (research direction D below), as well as work on societal risk due to tsunami hazards from delta-front collapse.

(2) *Lake Geneva in Switzerland and France* was where turbidity currents were first noted by Forel (1885) and have cut well developed channel systems (Hsü and Kelts 1985; Lambert and Giovanoli 1988; Girardclos et al. 2012). The Rhône delta represents a river-fed system where hyperpycnal river outflows often plunge and allows comparisons to be made between marine and freshwater systems.

(3) *Monterey Canyon–Fan offshore California* provides an example of a canyon in which present-day flows are driven mainly by wave action rather than by river outflow (Fig. 2). It is already the location of detailed and technologically sophisticated monitoring efforts (Paull et al. 2010a), including the first velocity and density profiles through active flows (Fig. 2; Xu et al. 2004, 2010, 2013, 2014; Xu 2010). A major Monterey Bay Aquarium Research Institute (MBARI), US Geological Survey, and UK Natural Environment Research Council monitoring experiment is already funded from 2014–2017, which includes deployment of a seafloor observatory, event detectors along the flow path of the sandy floor of the canyon, and four sets of ADCP moorings at water depths of 300 m to 1850 m. An extensive set of cores (including vibracores taken with a remotely operated vehicle (ROV); Fig. 2C) have been described (Paull et al. 2005, 2010a). MBARI is also currently field testing innovative sensors embedded within flowing sediment, and wave-powered gliders as mobile communications hubs for data recovery.

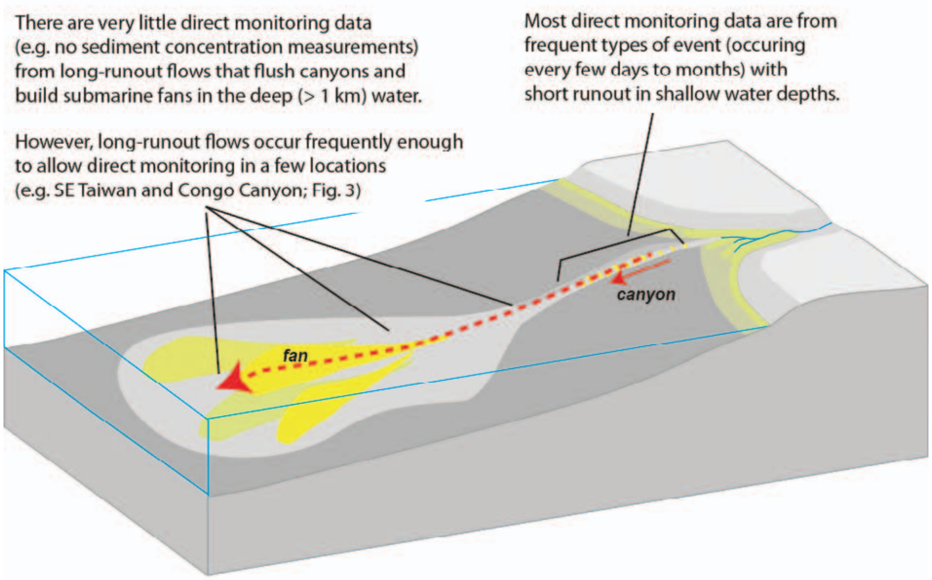
(4) *Gaoping Canyon, Taiwan* represents a river-fed system with hyperpycnal discharge (Liu et al. 2013). It is one of the relatively few locations where the canyon head is adjacent to the river mouth, and where long-runout flows commonly reach the Manila Trench (Fig. 3C, D; Hsu et al. 2008; Carter et al. 2012).

(5) *Congo Canyon, offshore West Africa,* is an example of a large-scale (0.3×10^6 km^2) submarine fan system on a passive margin. The distal parts of such fans can form thick sequences on the modern seafloor and in the ancient rock record. Flows occur frequently in the Congo Canyon, as shown by recent ADCP monitoring (Fig. 3A, B; Cooper et al. 2012) as well as older cable breaks (Heezen et al. 1964).

(6) *Other canyon-fan systems.* The Santa Monica Basin and Southern California Borderland canyon-fan systems also offer excellent opportunities for extending existing relatively detailed field datasets that include IODP cores (Romans et al. 2009; Normark et al. 2009). The Var Canyon-fan system in the Mediterranean may also provide a suitable location to extend previous unusually detailed monitoring work (Khripounoff et al. 2012) and detailed studies of sediment deposits (Mas et al. 2010).

Understanding Infrequent, Long-Runout Flows.—Ongoing monitoring efforts are concentrated in shallow-water settings, and are biased towards frequent (sub-annual) events (Fig. 4; Talling et al. 2013). However, it is the longer-runout flows which reach submarine fans that form much of the rock record, and their character may differ significantly from shorter and more frequent events. Workshop participants emphasized the need to include study of these longer-runout flows at the test sites. Due to their infrequent occurrence in most locations (every few hundred to thousand years) we can only study their deposits in these systems (Fig. 4). However, long-runout flows are more frequent in a few modern systems, typically where canyon heads are still connected to major river mouths (Fig. 3). A view was expressed that we must eventually aim to monitor long runout flows in locations such as the Congo Canyon and offshore Taiwan where they are relatively frequent (Fig. 3). Cable breaks show that four flows in six years have reached the deep ocean through the Gaoping Canyon offshore Taiwan (Hsu et al. 2008; Carter et al. 2012) and 11 events occurred in eight months at a water depth of ~ 1900 m in the Congo Canyon (Cooper et al. 2012). However, the technology and operational insights needed to do this will be best developed initially in shallower-

(A) General biases in direct monitoring data



(B) Flow Frequency along the Monterey Canyon-Fan System

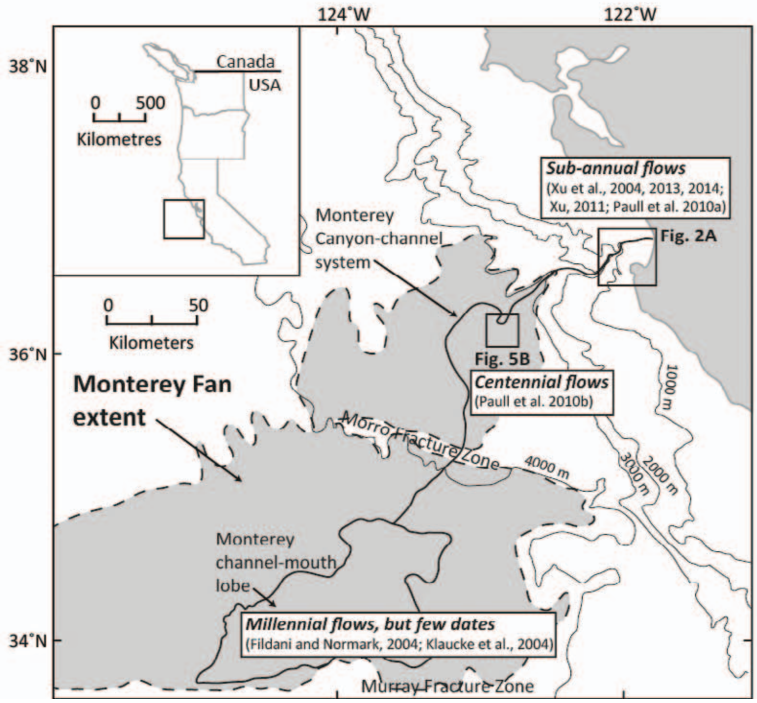


FIG. 4.—**A)** Summary of general biases in direct monitoring data, which documents more frequent flows, typically those that have shorter runout distances and do not reach submarine fans (although see Fig. 3 for exceptions). Types of flow that are infrequent must therefore be reconstructed mainly from deposits. **B)** Changes in flow frequency that span several orders of magnitude along the Monterey Canyon–Fan system, offshore California. Modified from Fildani and Normark (2004), Klaucke et al. (2004), Xu et al. (2004, 2013) and Paull et al. (2005, 2010a, 2010b).

water settings. This may include revisiting deposits of flows and slides that occurred off the Grand Banks event in 1929, and Nice in 1979.

Monitoring Using Existing Seafloor Infrastructure.—The offshore geohazards sector needs to understand the potential impacts on seafloor structures of higher sediment concentration (>~ 10% volume) layers at the bases of flows. Suitable information on such layers is not currently available, potentially leading to over-conservative design criteria and extra costs. Addition of flow monitoring instruments to deep-water oil and gas field developments (such as through sensors attached to manifolds, pipelines, flowlines, or risers) could provide long-term (lifetime of field) monitoring datasets. Such initiatives would involve relatively low cost, and would inform future phases of field development and geohazard assessment. Oceanographic water-column information and measurements of structural pile settlement are already often recorded in such a manner. Future opportunities to add scientific instruments to repeater nodes in submarine telecommunication cable networks should also be explored.

(B) Supercritical-Flow Dynamics and Deposits

Recent Advances.—Supercritical flow occurs when the Froude number is greater than ~ 1, such that the flow is relatively thin and fast. Unlike rivers, turbidity currents are likely to be supercritical on slopes steeper than approximately 0.6° (Komar 1971; Hand 1974; Sequeiros 2012),

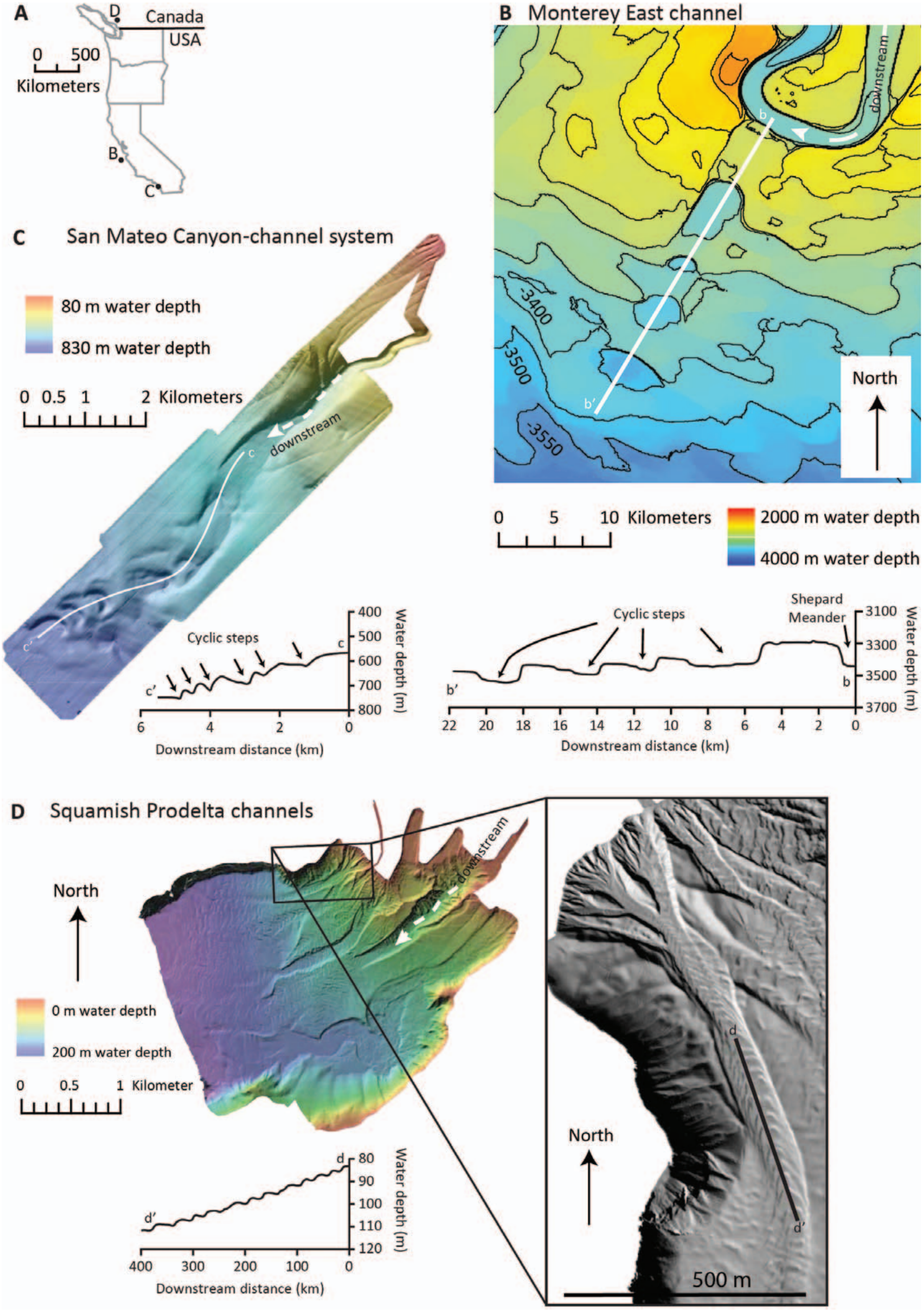


FIG. 5.—Bathymetric features on the seafloor that have been interpreted, numerically modeled (B and C), and directly observed (D) to result from repeated hydraulic jumps in supercritical flows (cyclic steps). Note the variable length scale and morphology of these bathymetric features. **A)** Map showing the locations of these features. **B)** Train of depressions interpreted and numerically modeled as cyclic steps on the outer bend of the Shepherd Meander of the Monterey East channel (Fildani et al. 2006). **C)** Cyclic steps of the San Mateo Canyon–channel system (Covault et al. 2014). **D)** Upstream-migrating cyclic steps of the Squamish prodelta (Hughes Clark et al. 2012, 2013; also see Fig. 1C, D).

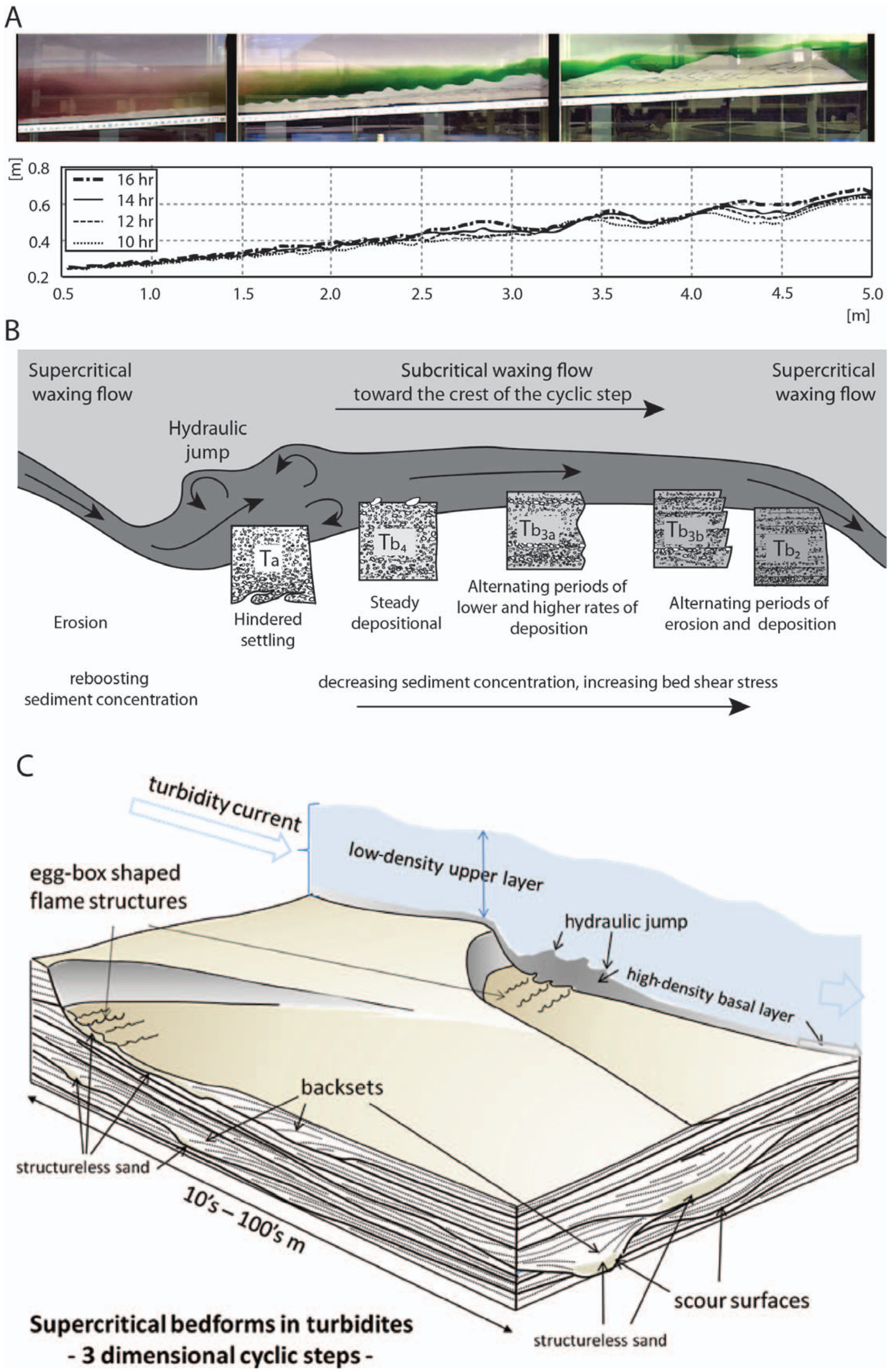


FIG. 6.—**A)** Antidunes and cyclic steps formed by experimental density currents (Modified from Spinewine et al. 2009). **B)** Idealized sedimentary facies on the stoss side of a cyclic step (modified from Postma and Cartigny 2014). **C)** Block diagram of cyclic step deposits in in three-dimensions (modified from Postma et al. 2014).

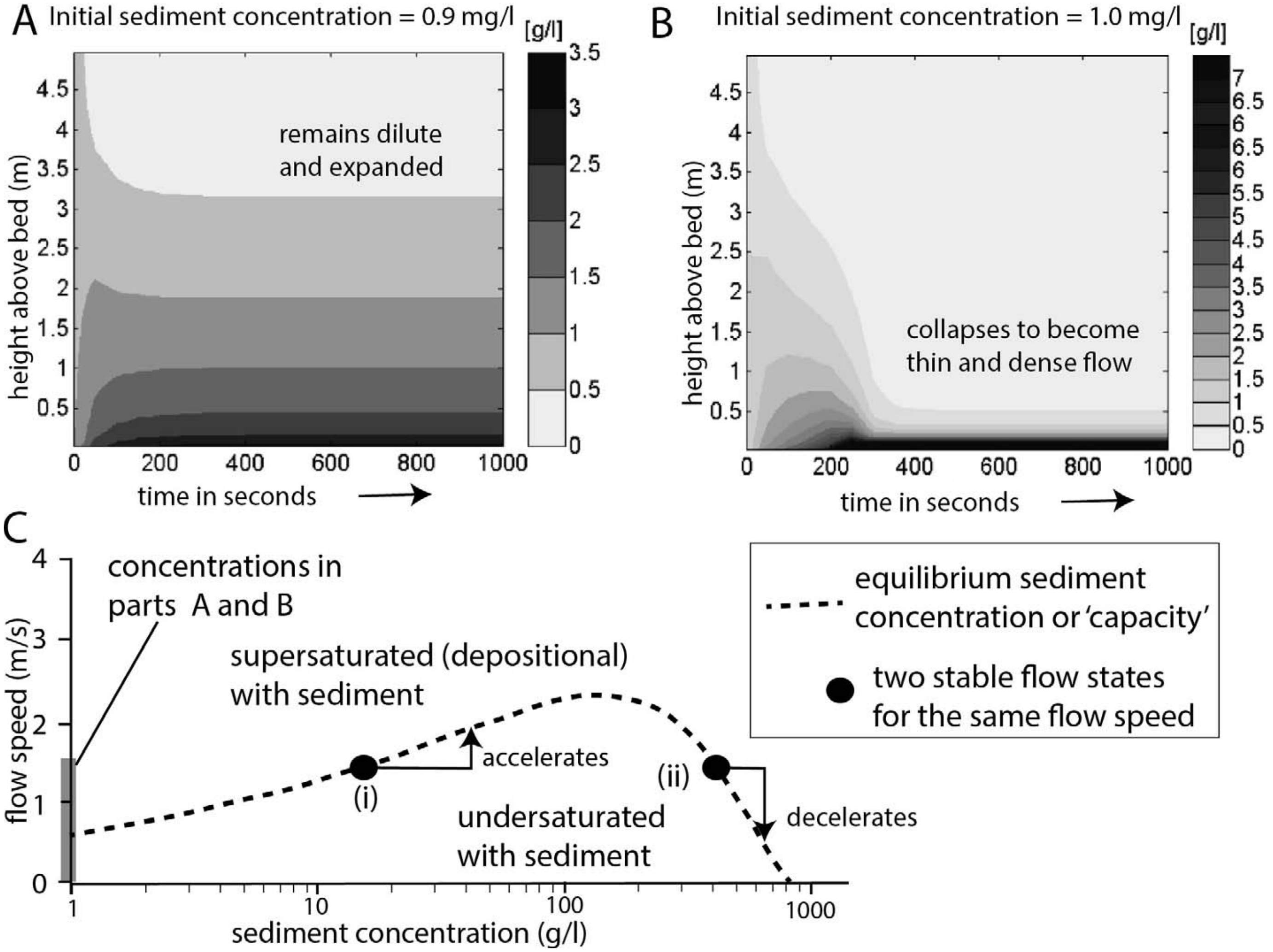


FIG. 7.—**A**, **B)** Modeling results of Winterwerp (2006) that suggest that flows may evolve into two distinctly different stable states, depending on a small initial difference in sediment concentration. The figure illustrates how the sediment concentration profile at a single location evolves over time, from different initial conditions. The model includes feedbacks between density stratification and vertical turbulent mixing, and hindered settling of sediment at higher sediment concentrations (see Winterwerp 2001, 2006). **C)** Plot of flow speed against the sediment carrying capacity of a flow (i.e., equilibrium sediment concentration) based on theory and field data from the Yellow River (from Van Maren et al. 2009; after Winterwerp 2001). It shows that there are two stable states for a flow with the same speed. The first stable state is dilute, whilst the second state is dense. Arrows denote how increases in flow concentration, such as those due to bed erosion, may affect the flow speed.

which is consistent with available field observations (Xu 2011; Talling 2013). The dynamics of supercritical flows is an active field of research, and laboratory experiments reveal that important flow properties are substantially different from subcritical flow, such as the velocity and sediment concentration profiles (Sequeiros 2012; Xu 2011). Recent flume and numerical models indicate that supercritical flows can produce upstream-migrating asymmetric bedforms with a wide range of scales (Figs. 5, 6; Sun and Parker 2005; Kostic and Parker 2006; Fildani et al. 2006; Spinewine et al. 2009; Cartigny et al. 2011; Kostic 2011; Cartigny et al. 2014). They provide a potential explanation for bedforms seen in fjord-head deltas (Figs. 1, 5D; Hughes Clarke et al. 2012, 2014), channels and canyon floors (Figs. 2C, 5C; Paull et al. 2010a; Covault et al. 2014), and on levees of deep-water channel systems (Fig. 5B; Migeon et al. 2001; Normark et al. 2002; Fildani and Normark 2004; Armitage et al. 2012).

Dunes-scale cross bedding is rarely observed in the majority of turbidite sequences (Arnott 2013). However, features including top-cut-out Bouma sequences, backset bedding, facies associated with shallow scours, and rapid pinch-out of beds could be formed by cyclic steps within supercritical flows (Fig. 6; Postma et al. 2009; Cartigny et al. 2011, 2014; Kostic 2011; Postma et al. 2014; Postma and Cartigny 2014). Other bedforms in the supercritical regime include a variety of antidunes (Middleton 1965; Hand 1974; Cartigny et al. 2014). This topic generated significant debate at the workshop, with disparate views on the abundance of supercritical bedforms in turbidites. It is now timely to go back to outcrops to better understand what features are (or are not) formed by supercritical flows (Figs. 5, 6; Postma et al. 2014; Postma and Cartigny 2014), guided by analysis of deposits from directly monitored flows that are known to be supercritical (cf. Hughes Clarke et al. 2012, 2014).

Upslope-migrating crescent-shaped bedforms with wavelengths of tens to hundreds of meters are common in canyon and channel heads in both marine and freshwater locations worldwide (Figs 1, 2, 5; Paull et al. 2010a, 2013; Kostic 2011; Girardclos et al. 2012; Hill 2012; Covault et al. 2014; Hughes Clarke et al. 2012, 2014). Such crescentic bedforms can indeed be associated with supercritical flows, as illustrated by the most recent observations presented at the workshop by Hughes Clarke from the Squamish delta. However, it is not yet clear whether these bedforms are exclusively formed by supercritical flows, or whether other processes,

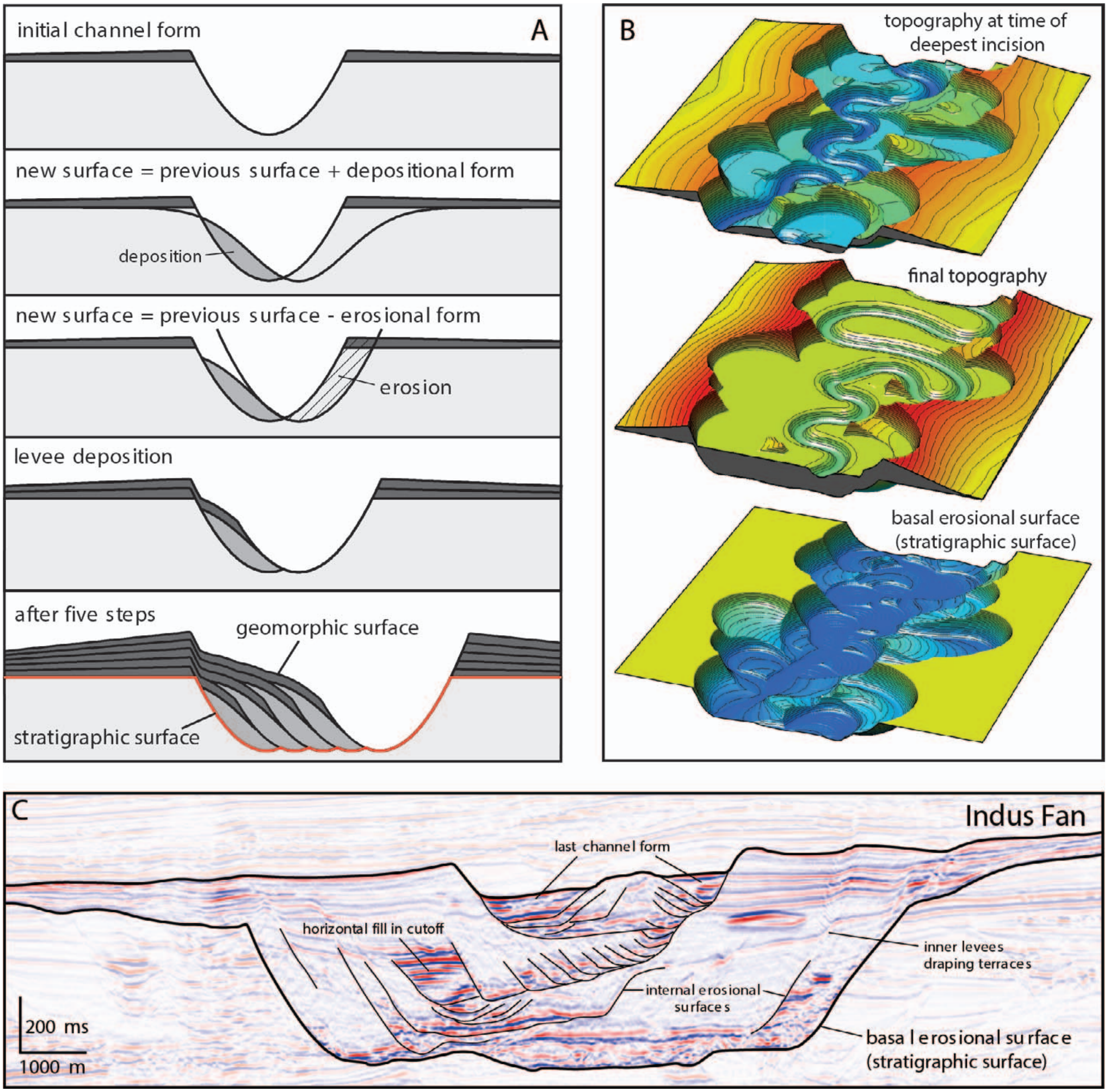


FIG. 8.—**A)** Schematic summary of patterns of erosion and deposition in a vertical section across a submarine channel, from Sylvester et al. (2011). It shows why geomorphic surfaces (i.e., the seafloor at various times) may differ from the stratigraphic surfaces finally preserved in the rock record and subsurface seismic reflectors. **B)** Model simulations showing the geomorphic surface corresponding to deepest erosion, the final geomorphic surface, and the stratigraphic surface (basal erosion surface). **C)** Example of a high-resolution seismic line across a submarine channel from the Indus Fan, which records long-term channel-system evolution (from Sylvester et al. 2011).

such as breaching (Van Den Berg et al. 2002; Mastbergen and Van Den Berg 2003; Cartigny et al. 2014; Talling et al. 2013) or liquefied slumps (Paull et al. 2010a; their fig. 12) may be involved. Such processes are supported by ROV observations of liquefying canyon floors (see video in supplementary material of Paull et al. 2013), master headscarps (large scarps that occur at the up-slope termination of some trains of bedforms; see Paull et al. 2012 their fig. 5A), and movement of very heavy (25–1000 kg) blocks by the flows (Fig. 2C; Paull et al. 2010a, 2013; Hughes Clarke et al. 2014). It is important to determine whether such heavy blocks (Fig. 2C), which are initially buried within the bed, could be transported by dilute flows travelling at speeds of up to 1 to 2.5 m/s thus far observed in these locations (Fig. 2B; Xu et al. 2004; Xu 2011; Hughes Clarke et al. 2012, 2014).

Future research on supercritical flows will need to address at least the following questions. Are crescentic bedforms in the field typically associated with cyclic hydraulic jumps, and if so, which is the cause

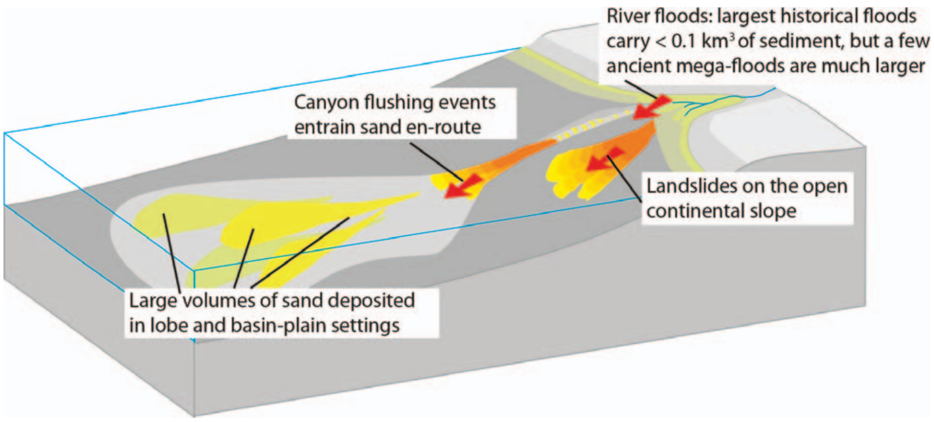


FIG. 9.—Where do the large volumes of sand originate, which are seen in large-volume flow deposits in distal fan-settings? Alternative sources are from (i) open-continental-margin landslides, and (ii) flows that flush sand from canyons. Continental slope landslides have a range of scales. They can contain several hundred to several thousand km^3 of sediment that is mainly mud.

and which is the effect? What is the role of these bedforms in initiating, filling, and maintaining submarine channels and canyons (Fildani et al. 2013; Covault et al. 2014)? The field of morphodynamics is exploring how flow structure and bed morphology may coevolve (Sun and Parker 2005; Kostic 2011; Parker 2013; Cartigny et al. 2014). Are large sandy and gravelly bedforms in deeper-water channels (Wynn et al. 2002) of similar origin? Or do these crescentic bedforms occur only on steep gradients in the proximal parts of systems? Are high-density flows necessary to generate these bedforms, or can low-density flows also generate them? Exactly what types of deposit are formed by supercritical flows (Postma et al. 2014; Postma and Cartigny 2014), and what is their preservation potential in the rock record? Are trains of more widely spaced scours the result of cyclic steps (Fig. 5; Fildani et al. 2006; Armitage et al. 2012; Covault et al. 2014), or are they due to retrogressive head scarps or local erosion (Sumner et al. 2013a, 2014)? This topic of supercritical flow will see important theoretical and experimental progress in the next few years, and links between process and product will require technically difficult field observations to be made.

(C) Importance of Turbulence Damping, Grain Size, Competence, and Capacity

Recent Advances.—Recent experimental and numerical modeling has emphasized how surprisingly small (sometimes $< 0.1\%$ volume) concentrations of sediment (particularly cohesive mud) can damp turbulence, especially during the final stages of decelerating flows (Baas et al. 2009, 2011; Sumner et al. 2009; Cantero et al. 2012). These results are consistent with field observations from rivers where damping can modify velocity profiles in very-low-sediment-concentration ($< 0.1\%$) flows (Wright and Parker 2004). Turbulence damping may lead to rapid sediment settling that increases near-bed sediment concentration, resulting in yet stronger damping. This positive feedback may lead to bifurcation in flow behavior (Fig. 7A). Thus two stable states for flow of the same velocity are possible: a dilute state where strong turbulence balances nonhindered sediment settling, and a dense state where weak turbulence balances hindered settling (Fig. 7B; Winterwerp 2006). Turbulence damping and subsequent collapse, and associated sediment settling into denser non-Newtonian near-bed layers within the flow (Fig. 7A), may explain the widespread occurrence of debris flow deposits in the relatively distal parts of hybrid beds (Ito 2008; Haughton et al. 2009; Hodgson 2009; Talling 2013), although these debris flows can themselves sometimes be far travelled on low gradients.

The importance of multiple grain sizes is emphasized (e.g., Harris et al. 2002) in developing realistic flow models, as they occur in most natural flows and strongly influence model results. Felletti proposed that the anisotropy of magnetic susceptibility (AMS) is a valuable tool to estimate paleocurrents in turbidites (Dall'Olio et. al. 2013). More generally, the relationship between flow speed and the mass of sediment suspended (capacity) and grain size suspended (competence) is of fundamental importance for flow behavior, as noted previously (Kuenen and Sengupta 1970; Hiscott 1994). For instance it governs whether incorporation of eroded material into a flow will lead to acceleration or deceleration (Fig. 7C). We are just beginning to develop an appropriate underpinning theoretical framework for systems with multiple grain sizes (see, for example, Dorrell et al. 2011, 2013a).

Future work is needed to assess whether effective and widespread turbulence damping occurs in (especially decelerating) submarine flows and its implications for bed-scale and system-scale deposit architecture. Turbulence damping may need to be addressed more fully in numerical modeling of such flows (Cantero et al. 2012). The relationships between flow power, capacity, and competence needs to be better constrained through experimental observation, and their implications explored by numerical modeling.

(D) Submarine Channels: Flow Dynamics and Deposit Architecture

Recent Advances.—Our understanding of flow dynamics within submarine channels has advanced significantly in recent years, such as the controls on secondary flow around bends. A combination of laboratory experiments and numerical analysis has determined what controls the sense of secondary (across-channel) circulation in dilute flows, and whether it is reversed with respect to subaerial river bends. These controls include the height of the velocity maximum and Froude number (e.g., Corney et al. 2006; Imran et al. 2007; Peakall et al. 2007; Abad et al. 2011; Giorgio Serchi et al. 2011; Abd El-Gawad et al. 2012; Huang et al. 2012; Dorrell et al. 2013b; Sumner et al. 2014). At least in some cases, the sense of secondary circulation is reversed with respect to that seen in river bends, as confirmed by recent ADCP measurements from saline underflows that enter the Black Sea (Parsons et al. 2011; Sumner et al. 2014).

Diagnosis of a surface as either geomorphic or stratigraphic is fundamental to the interpretation of the stratigraphic record (Fig. 8; Sylvester et al. 2011). A geomorphic surface is that of the seafloor at a point in time. If a surface in the rock record or seismic data is inferred to be a geomorphic surface, then it is interpreted to have been locked in place with no subsequent interaction with overriding sediment gravity flows. This is most likely not the case for many large (several kilometers wide and hundreds of meters of relief), erosional surfaces interpreted in the subsurface, such as slope valleys offshore of West Africa (Mayall et al. 2006), which likely reflect a composite stratigraphic evolution, with multicycle phases of erosion and deposition (Fig. 8).

Sylvester presented field observations from channels on the Niger Delta attempting to precisely define strong density stratification in flows, in which sand is carried only a short distance from the bed. Observations from cores in Monterey Canyon (Paull et al. 2010a), the Congo Channel (Babonneau et al. 2010), and Bengal Fan (Kolla et al. 2012) also show sand deposits restricted to near the canyon floor, implying that caution is needed in relating sand transport in flows to observations of deposits. This appears inconsistent with data reported by Xu (2011) and Xu et al. (2013), who found sand in traps suspended 70 m above the floor of Monterey Canyon.

Longer-term deposition and erosion by flows going through sinuous submarine channels and lobes results in a complex three-dimensional stratigraphic architecture and distribution of sand and mud (Fig. 8B; Deptuck et al. 2003, 2008; Gee et al. 2007; Hodgson et al. 2011; McHargue et al. 2011; Sylvester et al. 2011). The coarser-grained parts of these systems often form important hydrocarbon reservoirs. Detailed studies from the Niger Delta show the importance of flow size and type, which can result in highly variable submarine channel sequences.

Ongoing work highlights the rich, composite nature of geomorphic and stratigraphic records of deep-water channel systems. For instance, combined numerical modeling of flows with seafloor and shallow subsurface observations of a channel system of the California Borderland illustrates the morphodynamic evolution of cyclic steps in the channel thalweg (Covault et al. 2014). These cyclic steps, and other channelized deposits imaged in bathymetric datasets (e.g., in the fjords of British Columbia; Conway et al. 2012; Hughes Clark et al. 2012, 2013), demonstrate the composite nature of and downstream heterogeneity within channelized stratigraphy, with implications for characterization of petroleum reservoirs. The Cretaceous Tres Pasos Formation in Patagonia also illustrates composite, multicyclic evolution and downstream heterogeneity within channels (Romans et al. 2011; Hubbard et al. 2014).

Future work should investigate how strong density stratification (and turbulence damping—see research direction C above) may affect secondary flow circulation in submarine channels. There is still much to learn about flow within these channels, as shown by the remarkable monitoring data of Cooper et al. (2012) from the Congo Canyon that recorded powerful flows lasting for over six days (Fig. 3A, B). Future coordinated efforts to monitor sinuous channels, perhaps based around test sites such as the Congo Canyon or Bute Inlet (Conway et al. 2012), can extend ongoing work on channelized saline underflows in the Black Sea (Parsons et al. 2011; Hiscott et al. 2013; Sumner et al. 2013a, 2014). Measurements from overbank areas (Khripounoff et al. 2003) can complement recent advances made by detailed studies of ancient outcrop and subsurface (Hodgson et al. 2011; Kane and Hodgson 2011) and modern (Nakajima and Kneller 2013) levee deposits.

More generally, the petroleum industry requires a predictive understanding of the relationships between flows, deposit type, and deposit architecture, particularly at scales below the resolution of 3-D seismic imaging (Fig. 8B). This requires advances in physical modeling in channels and channel-termination zones, validated by field studies, to be applied to numerical modeling (Fildani et al. 2006; Abd El-Gawad et al. 2012; Covault et al. 2014). It will be important to distinguish between geomorphic and stratigraphic surfaces in seismic datasets (Fig. 8A; Sylvester et al. 2011) to understand the longer-term temporal evolution of channel systems and consequent reservoir heterogeneity. The value of high-resolution seismic data (both 2D and 3D) is emphasized for understanding the large-scale architecture of these systems and bridging the gap between conventional industry seismic data and outcrop-scale studies.

(E) Turbidites as a Record of Societally Important Geohazards

Recent Advances.—In some situations, submarine flow deposits can provide a record of their triggers including major earthquakes, or faster-moving and more tsunamigenic landslides that disintegrate. However, it is often difficult to ascribe a flow deposit to a triggering mechanism with certainty (Piper and Normark 2009; Talling 2014). Slower-moving landslides are less tsunamigenic, and will disintegrate and form flows to a lesser extent. There is currently vigorous debate over the extent to which turbidites can be used as a record of major earthquakes (e.g., Goldfinger 2011; Atwater et al. 2014), and why some major earthquakes fail to produce extensive slope failure and widespread turbidites (Sumner et al. 2013b; Völker et al. 2012). Recent work on volcanic island landslides suggests that they can occur in multiple prolonged stages, as shown by associated turbidites with numerous subunits (Hunt et al. 2011), thereby reducing tsunami magnitude.

A fascinating dataset is now available for flows associated with the 2011 Tohoku-Oki tsunami offshore Japan (Arai et al. 2013). There is also evidence of a common distribution of recurrence times for large-volume (> 0.1 km^3) turbidites in disparate basin-plain sequences (Clare et al. 2014), which is temporally random. If these turbidites are triggered by landslides, this distribution suggests that nonrandom processes such as sea-level change are not a dominant control on the frequency of large landslide. Such a distribution also has implications for assessing future hazards from landslide-tsunamis and seafloor cable breaks. However, it is not clear whether all large volume turbidites are associated with slope failure, either from the open slope or from failure within canyons. This also raises the issue of the source for the very large volumes of sand seen in basin-plain deposits, such as those examined during the workshop in the Marnoso-Arenacea Fm. outcrops, suggesting that this sand may have been flushed from deposits of smaller flows in canyons (Fig. 9).

Future research should concentrate on how submarine flow deposits record the frequency and character of geohazards that have significant societal importance, including whether future sea-level rise or ocean warming will increase the frequency of landslides or hyperpycnal flows that trigger turbidity currents (Brothers et al. 2013; Urlaub et al. 2013, 2014). IODP drill cores may be needed to obtain statistically meaningful datasets for event frequency, such as for turbidites generated by major tsunamigenic slides in the Nordic Seas.

(F) Signal Shredding and the Tempo of Sediment Transport

Recent Advances.—Recent work has shown that the timing of increased submarine flow activity can be highly variable (Covault and Graham 2010). Some systems are active during sea-level highstands Covault et al. 2007; Romans et al. 2009), and maximum activity need not occur during lowstands of sea level (Ducassou et al. 2009), as implied by older sequence stratigraphic models. The timing of large flows that reach basin plains may be temporally random, suggesting limited sea-level control for such events (Clare et al. 2014). The frequency of sediment transport also has important implications for the efficiency of burial of organic carbon in submarine settings, and hence for the global carbon cycle (Galy et al. 2007). It is important to analyze the controls on larger scale system evolution on longer time scales, in order to constrain the influence of climate and tectono-morphologic controls on deep-sea sedimentation.

Future work: A key point is whether changes in external controls such as climate or sea level are recorded in deep water settings, and the extent to which such signals become “shredded” (Allen 2008; Jerolmack and Paola 2010) as they propagate through the depositional system. This question links to allied work on other sediment transport systems in the earth-surface-processes community. Further studies may focus on Quaternary systems or other locations where key external controls are independently well constrained and source-to-sink sediment budgets can be reconstructed (Clift et al. 2001; Covault et al. 2011; Guillocheau et al. 2012; Petter et al. 2013). This topic is important for understanding the climatic record in submarine fan sequences as well as how these systems are perturbed by humans. It has important implications for predicting the frequency, location, and geometry of subsurface oil and gas reservoirs, as well as the efficiency of burial of organic carbon in submarine settings (Galy et al. 2007).

(G) Modeling: How Do You Test Models?

Recent Advances.—A variety of approaches have been used to simulate turbidity currents (e.g., Parker 1982; Parker et al. 1986; and review of Meiburg and Kneller 2010). They include integral ("box") models (e.g., Huppert 1998), and layer-averaged shallow-water models (e.g., Parker et al. 1986) or models that simulate the vertical structure of the flow (e.g., Blanchette et al. 2005). Vertically resolved models may use Reynolds-averaged Navier-Stokes equations to capture vertical turbulent mixing, or possibly some other parameterization of the turbulent motions, such as large eddy simulations (LES), and in recent years there have been direct numerical simulation of the governing equations (DNS; Meiburg and Kneller 2010; Cantero et al. 2012), although such DNS simulations are computationally expensive and are currently only benchmarked against laboratory experiments. Indeed it is not currently possible to compute appropriately resolved DNS schemes over length scales relevant to many field settings. Most previous modeling has assumed that direct particle interactions can be neglected, and hence that the flow is dilute, although there are exceptions (e.g., Tinterri et al. 2003). Key areas of uncertainty are how sediment is transported close to the bed, and how it is eroded and resuspended. It is also unclear how the presence of the sediment feedbacks on the fluid motions, interacting with turbulence, in some cases causing turbulence damping (see research direction C).

The question of how to test numerical models is important. One view is that the fundamental fluid dynamical equations used in such models are already well tested, although another view is that it is unclear how to formulate models for full-scale submarine flows without knowing the concentration of sediment (especially whether they are dilute or dense—and in the latter case, the sedimentary interactions are not well understood at a fundamental level). One view is that it is sufficient for numerical models to be tested only against laboratory-scale experiments, although another view is that the scaling issues associated with some experiments may ensure that full-scale submarine flows are different in key regards. For instance, many but not all laboratory experiments are too weak to fully suspend sediment, and may be unable to carry the sediment load that is initially imposed upon them (see research direction D). Scaling of laboratory experiments needs to go beyond Froude or Reynolds Number similarity, and also consider the ratio of flow power (shear velocity) to sediment settling velocity, such as that needed to suspend sediment or generate bedload. Furthermore, the scale of laboratory experiments may preclude many other processes such as mixing with the surrounding ambient water, which may significantly alter the dynamics (see, for example, Johnson and Hogg 2013). Field data from the Agadir Basin, offshore NW Africa, was presented by Stevenson et al. (2014). They showed that some large-volume (100's km^3) and very long-runout (up to 2000 km) flows only suspended sand a few meters from the bed. This observation is at odds with many numerical models whereby flows are required to be thick (> 100 m) to be able to runout for such distances.

The links between flow conditions and sediment deposition or erosion are still sometimes poorly constrained (Talling et al. 2012), especially for higher-density ($>\sim$ 10% volume sediment) and faster ($>\sim 1$ ms^{-1}) flows (Cartigny et al. 2013). This emphasizes the importance of having direct observations that document near-bed sediment concentrations and how flows interact with and sculpt the bed. For instance, even ADCPs often have a "blanking distance" of up to a few meters above the bed, due to sidelobe interference, where they do not record meaningful data, yet field datasets such as that presented by Stevenson et al. (2014) suggest that this is where much of the sand may be carried.

Possible future approaches are to focus both physical and numerical models on certain smaller-scale processes within the flow, without capturing the overall flow geometry. Examples of this approach are physical modeling of the boundary layer under high shear stress (Sumner et al. 2008), or using high-resolution direct numerical simulations (Cantero et al. 2012). Once detailed processes are understood and experimentally verified at a fundamental level, these processes can be parameterized, scaled up, and included in computationally cheaper models that have the capability of testing real-world-scale scenarios. Such models need to simulate stacking of deposits from multiple consecutive submarine flows above evolving seafloor morphologies to understand larger-scale sandbody geometries, such as those comprising oil and gas reservoirs (Groenenberg et al. 2010). Future research on these smaller-scale processes, involving close cooperation between modelers working at different resolutions, seems vital to establish models that can lead to step changes in our ability to model real-world-scale flows. If full-scale field observations are indeed needed (see research direction A), then a key question is what type of field data is sufficient for model validation. Future modeling research needs to ensure that key physical processes are appropriately captured at a fundamental level. It may need to consider during model formulation how the models can be tested against field data.

SUMMARY

The objective of this contribution is to present a range of ideas originating from a recent workshop on how to make fundamental step changes in understanding of turbidity currents, and to engage the wider community in that debate.

There is a compelling need to make direct measurements from active flows, as their sediment concentration has never been measured directly in the deep ocean. Monitoring work should be coordinated around a series of test sites (Table 1) that capture the main types of turbidite system. Such an initiative is timely and feasible due to major recent advances in sensors, mooring design, and autonomous methods for data recovery, as illustrated by outstanding datasets collected recently at Squamish and Fraser deltas (Fig. 1), Monterey Canyon (Fig. 2), Congo Canyon, and offshore SE Taiwan (Fig. 3). Physical and numerical modeling must also play an important role in understanding the significance of field observations. Test sites should also include analysis of flow deposits using cores and seismic data, which may be the only information available for more infrequent types of flow. Linking flow and deposit character is critical for interpreting ancient turbidite sequences and for developing reservoir models used in petroleum development (Fig. 8; Table 1).

Supercritical flow is most likely predominant in steeper proximal settings. Such flows may generate trains of upslope-migrating bedforms (Fig. 6), which have recently been mapped in many locations worldwide (Figs. 1, 2, 5), although dense liquefied flows or slumps may also be implicated in moving heavy blocks within such bedform fields. Future work should aim to understand the relationship of such bedforms to sand and gravel waves in deeper water, their preservation potential, whether they are the result or cause of cyclic hydraulic jumps, and the role of dense near-bed layers. It is also important to know the extent of turbulence damping within turbidity currents, especially as flows decelerate, and whether it produces late-stage flow transformation (Fig. 7). More precise quantitative constraints on what controls the sediment carrying-capacity and competence of flows is essential. Considerable advances have been made in understanding flow dynamics in dilute experiments or models, and saline density currents in the field. It is now important to understand how higher sediment concentrations change this behavior, perhaps through flow monitoring at suitable channelized test sites such as Congo Canyon or Bute Inlet.

Turbidity currents and their deposits are in some cases an important record of other hazardous events, such as major earthquakes (Goldfinger 2011). However, not every major earthquake appears to produce a widespread sediment flow (Völker et al. 2011; Sumner et al. 2013b), and there is a need for more studies of the seafloor where it is known that a major earthquake occurred. Turbidites can record the emplacement dynamics of submarine landslides, and suggest that some volcanic island collapses occur in multiple stages over a prolonged period (Hunt et al. 2011). There is a need for long-term, well-dated sequences of turbidites to analyze the recurrence times of such hazards. Such studies would contribute to better understanding of the tempo of sediment transport by turbidity currents: whether external controls such as climate or sea level are recorded in their deposit sequences and the extent to which such signals are destroyed. Such work would contribute directly to predictive models of turbidite system architecture used in petroleum exploration.

Finally, there is debate over how numerical models can be tested, for instance given the paucity of direct measurements of sediment concentration from field-scale flows. Existing models mainly simulate dilute flows in which sediment interactions and viscous (e.g., colloidal) forces are neglected. An important objective for future modeling is to place better constraints on near-bed processes, such as erosion or sediment resuspension from the bed, and turbulence damping as sediment concentrations increase (Fig. 7). It is hoped that this synthesis of ideas originating from the workshop will stimulate further research into the volumetrically most important sediment transport process on our planet.

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