

Flow processes and sedimentation in submarine channel bends

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Abstract

Turbidity currents in sinuous submarine channels are an important mechanism for transporting terrestrial sediments to deep water, and their deposits are of increasing importance as hydrocarbon exploration targets. Despite this, the architecture and dynamics of submarine channel systems are not well understood. Analogies are often drawn with fluvial systems due to similarities between their planform shapes even though differences in channel evolution and hydrodynamics have been noted. A key question is the nature of deposition within submarine channel bends; in particular at inner bends where point bars form in alluvial meandering rivers. Recent experimental and numerical work has demonstrated that the fluid dynamics of submarine channel bend flow are markedly different from rivers. Notably, a reversal in the orientation of secondary (helical) flow at bend apices occurs in submarine channels. The potential influence of these differences in fluid dynamics on deposition within submarine channel bends is investigated herein. We report the results of a series of physical experiments in which solute-driven gravity currents were run through pre-formed sinuous channels containing mobile beds. These experiments reveal sedimentation patterns characterised by accumulation zones downstream of bend apices and erosion zones at outer bends. These patterns are broadly analogous to the point bars and outer-bank pools observed in meandering rivers, demonstrating that the longitudinal flow component dominates over the cross-stream component, as also occurs in rivers. However, the data suggest that the reversal in direction of the cross-stream flow component compared with subaerial flows is important in determining the position and morphology of ‘point bars’ relative to bend apices. From analogy with fluvial compound channels, and fluvial theory, this reversal in secondary flow cell orientation is also expected to influence the spatial variations of grain size in submarine channel ‘point-bar’ deposits.

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1. Introduction

The development of submarine channel systems is a primary control on the geomorphic evolution of continental margins and on the transport of sediments into the oceans. Sandbodies within these deep-sea channel systems can form important hydrocarbon reservoirs (e.g., [Wonham et al., 2000](#); [Abreu et al., 2003](#)), and are of significant interest to the hydrocarbon industry. Understanding

heterogeneity of these reservoir systems is thus important. Despite this, little is known about the deposit-forming sedimentary processes and internal architectures of sinuous turbidite channel systems. This poor understanding is because: (1) modern deep-water channel processes are difficult to study, and high-resolution three-dimensional geophysical datasets are required to study intra-channel architecture; (2) outcrop analogues of passive margin sinuous turbidite channels are rare and lack fully three-dimensional representation; (3) there are limited observations of channelised submarine flow processes in actual channels and laboratory experiments; and (4) many internal architectural elements are typically below the level of seismic resolution. As a consequence, there are only a limited number of (often conflicting) models of

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intra-channel architectural elements (e.g., nested mounds; Timbrell, 1993; Clark and Pickering, 1996; Peakall et al., 2000a,b). For these reasons, it is difficult to predict reservoir distribution in submarine channel deposits.

As a result of this lack of understanding of submarine channel dynamics, analogies are often drawn with fluvial systems due to similarities between their planform shapes (e.g., Pirmez and Imran, 2003), and on qualitative comparisons in which many features of fluvial channels have been observed within submarine channel systems. These include bend cut-offs, high channel sinuosity, crevasse splays, point bars, scroll bars, meander belts and chute channels and pools (see Peakall et al., 2000a for further detail). However, there are differences in channel morphology and flow processes between fluvial and submarine channel systems (Peakall et al., 2000a; Kolla et al., 2001, 2007), such as substantially reduced downstream migration of bends in submarine channels (Peakall et al., 2000a). Processes such as flow stripping and features like nested mounds on the outer-bank side of channel bends have been considered to be unique to submarine channels (Normark and Piper, 1984; Clark and Pickering, 1996). These differences in channel evolution and hydrodynamic processes will result in different channel architectures, and pose the question of how applicable models of fluvial systems are to submarine channels.

Physical experiments have recently demonstrated that gravity current flow dynamics are significantly different in sinuous submarine channels compared with open-channel flows, with a reversed helical flow circulation to that observed in subaerial flows (Corney et al., 2006; Keevil et al., 2006a, 2007). Analytical solutions to the governing equations (Navier–Stokes in cylindrical coordinates) demonstrate that this reversal of helical flow rotation is a function of the downstream velocity profile (Corney et al., 2006). Helical flow with basal flow towards the outer bank and an upper return flow towards the inner bank, occurs when the downstream velocity profile is at a maximum near the channel bed (Corney et al., 2006). This is further reinforced by computational fluid dynamic (CFD) simulations which demonstrate that the bodies of gravity currents exhibit reversed circulation with basal flow towards the outer bank (Corney, 2005). Collectively, these results are in sharp contrast to the work of Kassem and Imran (2004) who suggested, on the basis of CFD simulations, that helical flow rotation in submarine channels is orientated in the same direction as that observed in rivers. The reasons for this discrepancy are unclear. However, the simulations of Kassem and Imran (2004) showed an absence of super-elevation at bends as observed in the physical experiments (Corney et al., 2006; Keevil et al., 2006a) and in natural channels, possibly as a result of a return flow moving upstream above the main flow. Furthermore, they were not tested for grid sensitivity (e.g., Roache, 1998; Hardy et al., 2003), and were not validated against experimental data.

Secondary (helical) flows produced in meandering river bends are important for (1) mixing of fluid (Guymer,

1998), (2) cross-stream transfer of momentum (Smith and McLean, 1984; Odgaard and Bergs, 1988; Johannesson and Parker, 1989) and (3) erosion, lateral transport and deposition of sediments (Engelund, 1974; Hey, 1976; Bridge, 1992; Edwards and Smith, 2002). The combination of secondary and longitudinal flow produces a net convergence of fluid and sediment towards the inner bend, and this convergence of sediment primarily produces the growth of point bars on initially flat beds (Nelson and Smith, 1989). The important role of secondary flows in river bend dynamics and point-bar growth, coupled with the observation that the orientation of these secondary flow cells are reversed in submarine channels, suggests that there may be differences in bend deposition and morphology in submarine channels.

Detailed observations on the deposits of submarine channel bends are still relatively rare. Inner-bend accumulations are widely interpreted from outcrop studies, being recognised from packages of low-angle dipping reflectors, termed lateral accretion packages (e.g., Cook et al., 1994; Elliott, 2000; Haughton, 2000; Abreu et al., 2003; Kneller, 2003). However, the planform sinuosity of channels and the position of the outcrop compared to the bend planform are not unambiguously known in most cases. In contrast, seismic studies do enable the position and sinuosity to be independently determined. However, there are remarkably few observations of inner-bend accumulations in seismic data; those reported from ancient systems show packages of low-angle reflectors dipping towards the channel (Mayall and Stewart, 2000; Kolla et al., 2001; Abreu et al., 2003). ‘Point-bar’ deposits have also been interpreted in a number of modern channels, from a mixture of planform data (e.g., Klaucke and Hesse, 1996; Schwenk et al., 2003) and seismic cross-sections, once again showing beds dipping towards the channel (Hesse and Rakofsky, 1992; Antobreh and Krastel, 2006). A second bend feature has also been observed. Nested mounds are coarse-grained deposits that form preferentially towards the outer bank of channel bends (Phillips, 1987; Timbrell, 1993; Clark and Pickering, 1996).

These limited number of studies, the lack of resolution in many cases, the difficulties in recreating three-dimensional depositional topography from preserved segments and the question of how representative the published examples are, highlight the requirement for detailed modelling of submarine channels where both flow and deposition can be observed. Experimental work to date has reproduced subaqueous channels on the order of a couple of centimetres wide; however, they were not able to reproduce intra-channel architectural elements such as bars (Métivier et al., 2005). Our study addresses these existing limitations and has three primary objectives: (i) to reproduce submarine channel intra-channel architecture in small-scale physical experiments; (ii) to examine the interactions between the three-dimensional fluid dynamics of channelised flows and bed morphology; and (iii) to construct for the first time a process-based

model of intra-channel sedimentation in submarine channels.

2. Experimental methodology

An analogue modelling approach is adopted herein with the aim of recreating ‘similarity of process’ with natural channels (Hooke, 1968). Analogue models are not scaled from either a specific prototype or generic data, but they aim to reproduce the general processes and features of a natural system (Chorley, 1967; Peakall et al., 1996). Fluvial modelling has made extensive use of analogue physical modelling revealing many process relationships (e.g., Leopold and Wolman, 1957; Schumm and Khan, 1972; Schumm et al., 1987; van Heijst et al., 2001; Sheets et al., 2002). Similarly, analogue models have been utilised to study the initiation and development of submarine channels (Métivier et al., 2005; Keevil et al., 2006a; Yu et al., 2006). In the case of submarine channel flows, scale modelling approaches such as those adopted in some fluvial studies (e.g., Ashmore, 1982; Moreton et al., 2002;

Peakall et al., 2007) are not possible, since there are insufficient measurements from natural systems to provide the prototype or generic data required.

A series of experiments were conducted within a square flume tank ($1.8\text{ m} \times 1.8\text{ m} \times 1.7\text{ m}$ depth) with a 2 m long input channel centred on one face (Fig. 1). In each experiment, saline gravity currents with a density excess of 2.5% were run through a sinuous channel model made of glass reinforced plastic. The channel has a simple planform geometry consisting of a series of arcs of constant radius separated by straight sections, giving a sinuosity of 1.36 (Fig. 1B). This simple planform geometry is appropriate to a wide range of channel types, enabling it to be used to simulate both subaerial and submarine flows. Furthermore, the chosen planform geometry is based on the UK Flood Channel Facility fluvial series B experiments (e.g., Sellin et al., 1993; Willetts and Rameshwaran, 1996; Fig. 1B), enabling comparison with fluvial compound channels that exhibit analogous flow structures to submarine channels (Corney et al., 2006). The cross-section is constant at all points in the downstream (levee-to-levee

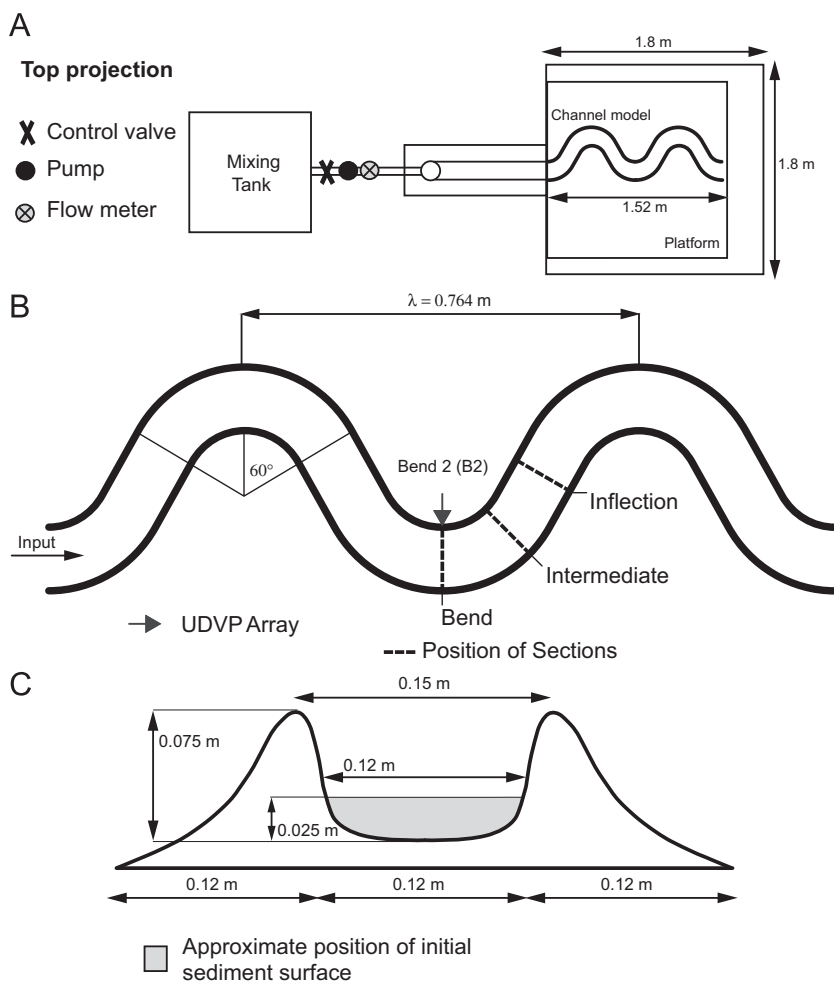


Fig. 1. Schematic illustration of the laboratory flume facility, and detailed planform and cross-sectional geometries of the channel model. (A) Schematic planform view of flume facility illustrating the mixing tank and the position of the channel model. (B) Planform channel model geometry showing position of UDVP array, and bed topography profiles (presented in Fig. 11). (C) Cross-sectional geometry of the channel model and associated initial sediment fill. Adapted from Keevil et al. (2006a).

width = 150 mm and levee height = 75 mm; Fig. 1C) and has curved corners in order to minimise corner-induced circulation (Naot and Rodi, 1982; Nezu and Nakagawa, 1993). The same channel model was used in a series of sediment-free experiments that form a baseline for the interpretation of the present experiments with mobile sediment beds (Keevil, 2005; Corney et al., 2006; Keevil et al., 2006a, 2007). The sinuous channels were placed within the flume on a raised platform (0.4 m above base of tank) and the tank set to a slope of 3° . Saline fluid was mixed in a separate tank and pumped into the flume tank at a constant discharge rate of 1.25 l s^{-1} ($\pm 0.05 \text{ l s}^{-1}$), for periods of up to 9 min. Such constant discharges have been shown to adequately replicate fluvial channel processes and deposits (Schumm et al., 1987; Peakall et al., 2007).

The saline fluid entered the tank through an expansion pipe to reduce the inlet turbulence, and then flowed into a straight channel (0.16 m wide, 1.0 m long) that was mounted flush with the sinuous channel model (Fig. 1A). The influence of gravity current reflections was minimised by the incorporation of a sump (beneath the platform), and by balancing input and output rates using variable speed pumps and electromagnetic flow meters. The sinuous channel was filled to a depth of 25–35 mm with low-density sediment (Poly V[®], $1.1\text{--}1.2 \text{ g cm}^{-3}$). This sediment is subangular, polydisperse and has a median grain size (D_{50}) of $175 \mu\text{m}$. The grain-size distribution is shown in Fig. 2. In order to maintain an initial bed of uniform thickness along the channel length, a low weir was required at the downstream end of the channel, equal in height to that of the initial sediment bed. The sediment bed extended upstream of the pre-formed sinuous channel into the straight section within the inlet channel. After each run, an ultrasonic bed profiler (Best and Ashworth, 1994) mounted to a computer-controlled two-dimensional traverse was

Table 1

Summary of experimental parameters

Initial flow density	2.5%
Flow Reynolds number ^a	7831
Densiometric Froude number ^a	0.63
Slope of the false floor (valley slope)	3°
Discharge	$1.25 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$
Particle specific gravity	1.2
Grain size (D_{50})	$175 \mu\text{m}$

^aBased on baseline experiments of Keevil et al. (2006a).

used to measure the topography of the sediment bed at a 10 mm grid spacing.

Flow velocities were recorded using Ultrasonic Doppler Velocity Profiling (UDVP). The UDVP works by emitting bursts of ultrasound, and then recording any Doppler shift in the signal reflected from particles suspended in the flow, enabling the velocity of those particles to be determined (Takeda, 1991, 1995; Best et al., 2001). The UDVP records velocities from each transducer in sequence; at 128 points along a profile from each transducer. Measurement time per profile was 11 ms, with a 15 ms delay between the recording of each profile, thus generating near-instantaneous two-dimensional flow fields at a frequency of $\sim 4 \text{ Hz}$. In these experiments, a series of ten 4 MHz UDVP transducers were mounted at the apex of the central bend (Bend 2) into and above the channel. At each measurement location cross-stream velocities were recorded at heights of 6, 17, 28, 39, 49, 59, 70, 80, 90 and 101 mm above the base of the channel. The probe array was positioned at the inner bend in order to minimise disturbance of the flow field. All flows were subcritical and turbulent, ensuring similarity of mixing characteristics and comparability with previous experimental research on density currents (Altinaker et al., 1996; Buckee et al., 2001; Table 1).

Two series of experiments were run. The first series investigated cross-stream velocity flow fields and changes in deposit morphology following three separate flows of 60 s duration over the same bed. The second series investigated deposits from an initial flow of 6 min duration and a subsequent flow of 3 min duration.

3. Results

3.1. Flow dynamics

Immediately as the gravity current entered the sinuous channel, dense fluid over-spilled the levees as flow thickness was greater than levee height. Continual overspill of dense fluid from the entire length of the channel model was observed during all of the experiments. Overspill was most prominent on outer channel bends just downstream of bend apices. Continual overspill of fluid is thought to be typical of channel-forming flows in natural channels (Peakall et al., 2000a).

Secondary flow was examined using 30 second mean cross-sectional velocity flow fields at the central bend

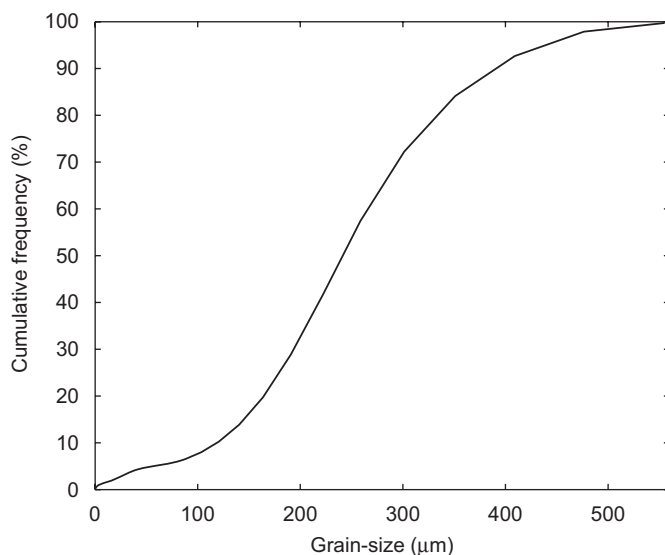


Fig. 2. Cumulative grain-size distribution of the low-density Poly V[®] sediment used in the experiments.

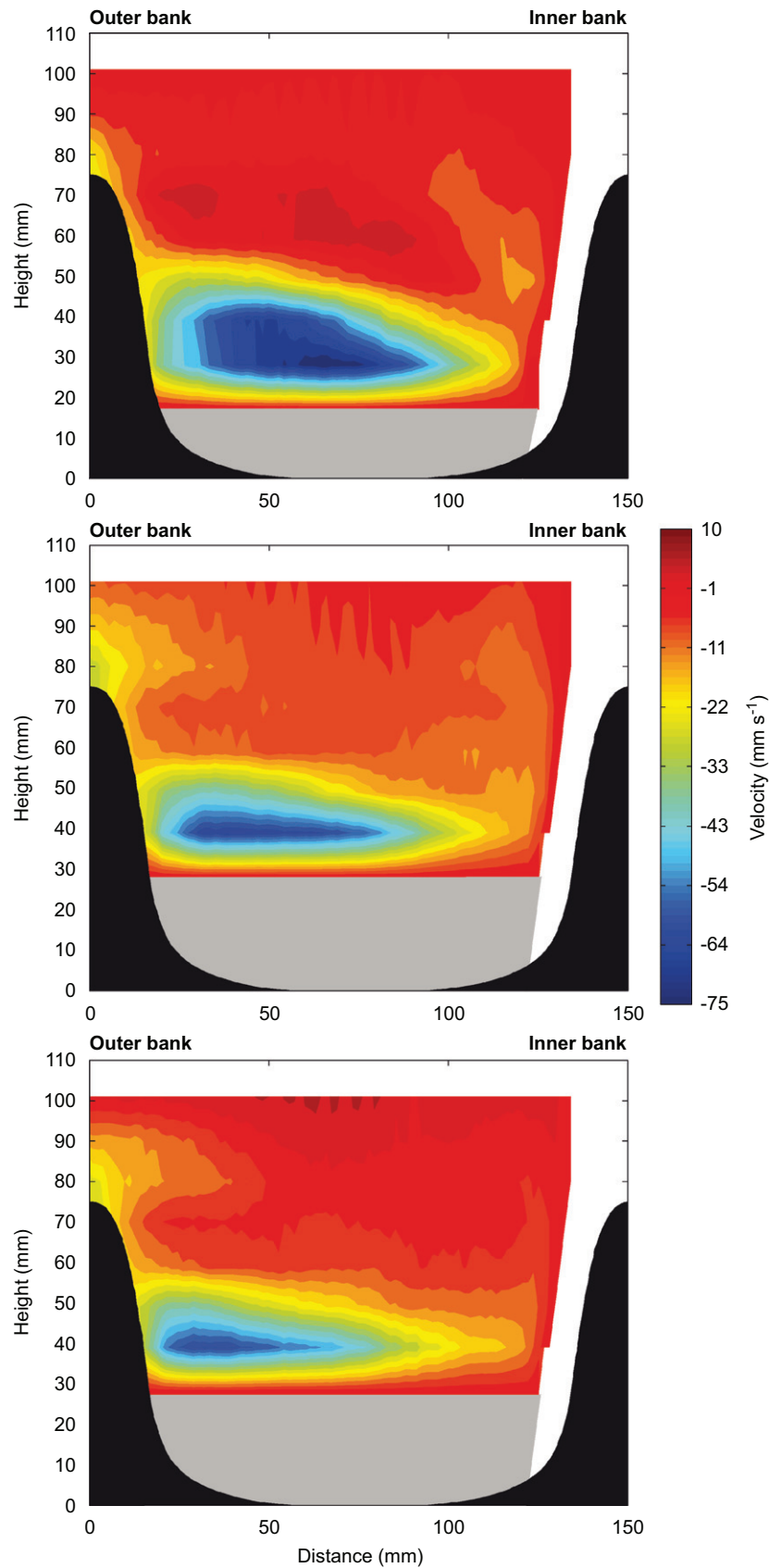


Fig. 3. Cross-sectional velocity flow fields at the apex of Bend 2. All plots are averaged over 30 s. Positive and negative velocities represent flow towards the inner and outer banks, respectively. The grey shaded area in the lowermost part of the channel is the area where velocity measurements were not recorded, and represents the position of the highest part of the sediment surface. Note that the initial sediment thickness within the channel was set to 25 mm: (A) after 1 min of flow, (B) after a cumulative flow of 2 min and (C) after a cumulative flow of 3 min.

(Bend 2; Fig. 1), starting at 1, 2 and 3 min after the head of the flow exited the channel model. These velocity fields exhibit a consistent flow pattern, with a strong basal flow cell moving fluid towards the outer bank (Fig. 3). A weaker return cell is also seen in the upper part of the channel moving fluid back towards the inner bend (Fig. 3). The inclined boundary between the upper and lower flow cells demonstrates the super-elevation of the flow at the bend apex (Fig. 3). This super-elevation of flow causes strong overspill of fluid over the levee crest at the outer bank. Flow velocities towards the outer bank of the channel, below the maximum thickness of the inner-bend sediment accumulation, could not be recorded. This data gap is a result of positioning the probes at the inner bend in order to minimise the effects of the probe array on the flow. A number of temporal variations are observed in the mean cross-stream velocity data. The height of the velocity core above the bed increases with time. This is because sediment transport and deposition results in inner-bank topography that grows in height with time (see Section 3.2). The

changes in bed morphology at the bend apex also led to progressively enhanced overspill at the outer bend.

3.2. Deposits

The deposits resulting from cumulative flow periods of 1, 2 and 3 min over an initial bed 25 mm thick are presented in Fig. 4. Areas of high elevation are observed at or just downstream of the apex of each bend adjacent to the inner bank after the first minute of flow. These highs increase in elevation with time. After the second and third minutes of flow, these regions of high topography have an elevation which varies longitudinally, such that there is an upstream peak in elevation, and decrease in height with distance downstream. Regions of lowest in-channel topography are observed towards the outer bank at the apices of all bends, although these low areas do not fully develop at Bend 3 until after 2 min of flow. Close to the fluid input there is a region of low elevation after the first minute. This becomes more pronounced with time such that after the third

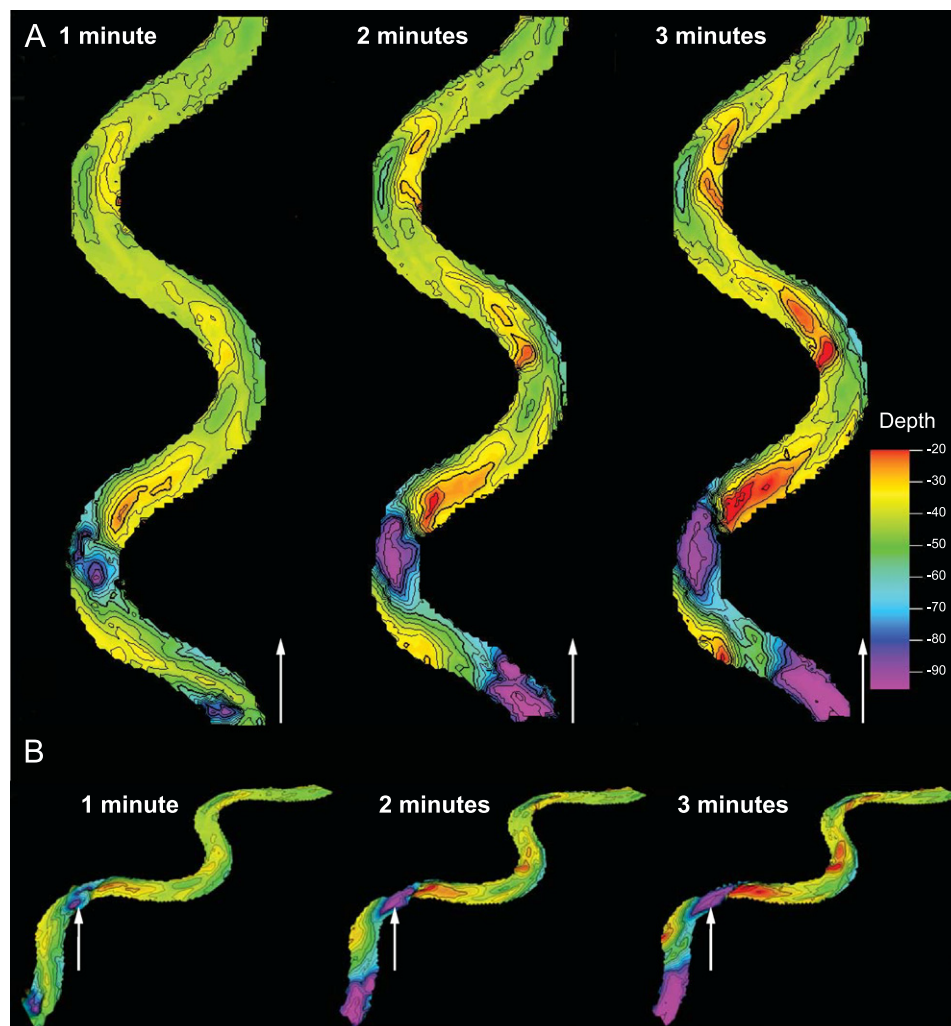


Fig. 4. Contour images of in-channel depositional topography after 1, 2 and 3 min of cumulative flow, visualised in (A) plan view and (B) perspective view. Flow directions are indicated by arrows. The depth scale is from an arbitrary datum and is measured in millimetres. Initial bed sediment thickness was 25 mm.

minute of flow, the bed in the first quarter wavelength of channel has been scoured down to the fixed floor of the channel model.

The inner-bend accumulations exhibit very steep upstream faces and shallow downstream slopes. Transverse slopes are also steep in the upstream parts, generally decreasing downstream. The topographically lower parts of the inner-bend accumulations exhibit transverse slopes that remain quite steep until past the mid-point of the accumulation (see Fig. 4). The widths of the inner-bend accumulations increase downstream, whilst the elevation

and cross-channel topographic variation gradually reduces. On the inside of the inner-bend accumulations a topographic low develops which gradually broadens and shallows downstream. The position of the upstream end of the accumulation remains fixed with time, and growth proceeds through a progressive increase in topographic elevation coupled to downstream elongation (Fig. 4). The widths of the initial upstream parts of the accumulations remain largely constant with time and as a consequence there is a growth in the magnitude of the transverse slopes as the morphology develops.

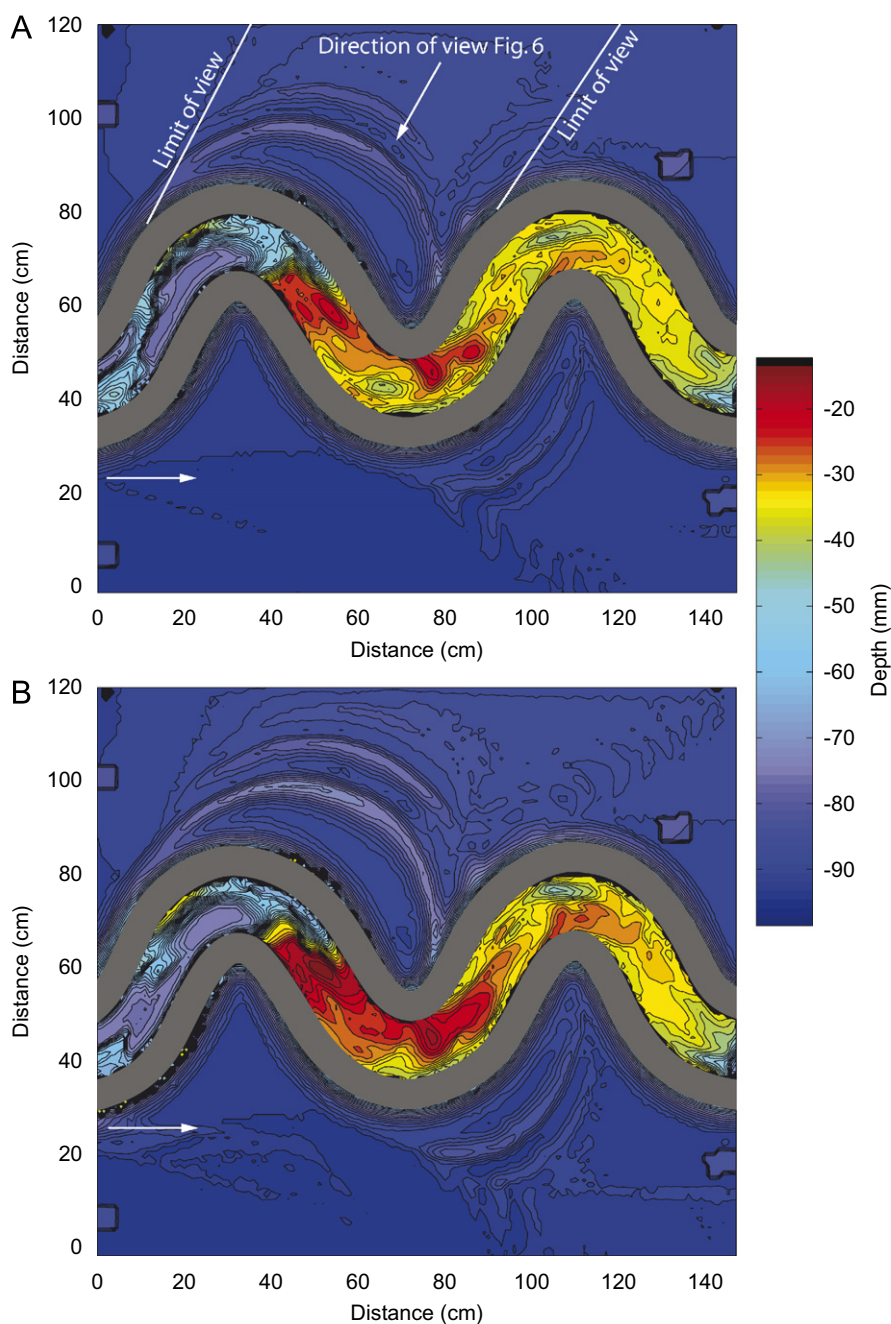


Fig. 5. Contour plots of depositional topography after (A) 6 and (B) 9 min of cumulative flow. The depth scale is from an arbitrary datum and is measured in millimetres. Grey shading represents high gradient channel levees. Flow direction, marked by an arrow, was from left to right, and initial bed sediment thickness was 35 mm.

Towards the outside of the channel bends are areas of low-deposit elevation that start just upstream of the bend apex and extend around the bend to approximately the mid-point of the inner-bend accumulations. These topographic lows are deepest in their central area, adjacent to the areas of steepest transverse slopes of the inner-bend accumulations. The depth and spatial extent of these features are also observed to grow with time (Fig. 4). The region of erosion at the apex of the first bend is much greater than that at Bends 2 and 3 and is associated with large-scale erosion throughout the first quarter wavelength of the channel. This upstream zone of erosion represents a region of flow adjustment from the initial straight fully confined flow, to a curved partially unconfined flow. Helical flow takes time to develop and is not as fully developed at the first bend as it is in subsequent bends, with a much smaller upper return flow cell and a corresponding increase in overbank flow (Keevil et al., 2006a, their Fig. 4). This flow adjustment leads to enhanced erosion at the input. A proportion of this material is lost overbank at the first bend apex due to the stronger outward-directed flow on the outside of the bend.

As morphology in the first experiment was observed to evolve through time and had not reached an equilibrium state, a second experiment was run to investigate bed morphology over longer time periods (after 6 and 9 min of flow). To account for the scour of material at the bend apices the initial bed thickness was increased to 35 mm. In general, the same pattern of inner-bend accumulations and low in-channel topography at the outer banks was observed in these longer runs, but the scour at the first bend was exacerbated even with the initially greater bed

thickness (Fig. 5). The inner-bend accumulations grew through time in the same manner as the previous shorter duration experiment, increasing in both length and topographic relief, whilst the positions of the upstream ends remained fixed at or just downstream of the bend apices. External to the channel, prominent arcuate deposits formed in the lee of the channel outer-bank levees, most notably at the first bend and to a lesser extent at the second bend (Figs. 5 and 6). These arcuate deposits formed on the flat overbank surface, grew in height and width with time, and increased in number. Analysis of their development and flow dynamics indicate that they are sediment waves formed by deposition of intra-channel derived sediment from channel overspill (Keevil, 2005; Keevil et al., 2006b).

4. Discussion

Fluid flow and sedimentation in channel bends are strongly coupled and feedback on one another. The nature of this coupling and the feedback mechanisms have become increasingly well understood and modelled for the case of river channels (e.g., Johannesson and Parker, 1989; Bridge, 1992; Darby and Delbono, 2002; Darby et al., 2002). For submarine channels, both the nature of the fluid flow and the intra-channel sedimentation are poorly understood, as are the coupling and feedback processes between them. Consequently, in this discussion we first consider the three-dimensional fluid dynamics of the submarine flows and compare these against fluvial processes. Then we examine the bed morphology and how this morphology is controlled at the large scale by the three-dimensional fluid dynamics. Finally, the implications of the findings are explored.

4.1. Velocity distribution

The velocity data from the bend apex demonstrates that submarine channel flow, above the level of the upper surface of the inner-bend accumulation, was reversed in orientation relative to that in river channels. The flow pattern showed basal flow towards the outer bank and a weaker upper return flow towards the inner bank. These cross-stream velocity data can be compared against the baseline studies undertaken in the same channel model but in sediment-free conditions (Corney et al., 2006; Keevil et al., 2006a; Fig. 7A). The baseline studies demonstrated that the secondary flow cell was reversed in submarine channels relative to the orientation observed in river channels (Keevil et al., 2006a, 2007), and that this reversal in helical flow rotation was controlled by the nature of the downstream velocity profile (Corney et al., 2006). These previous sediment-free experimental studies also confirmed that subaerial flows, passing through exactly the same channel model, exhibit the classical fluvial secondary flow cell response with basal flow towards the inner bank (Corney et al., 2006; Fig. 7B). Experimental data from rotating annular flumes further demonstrates that the

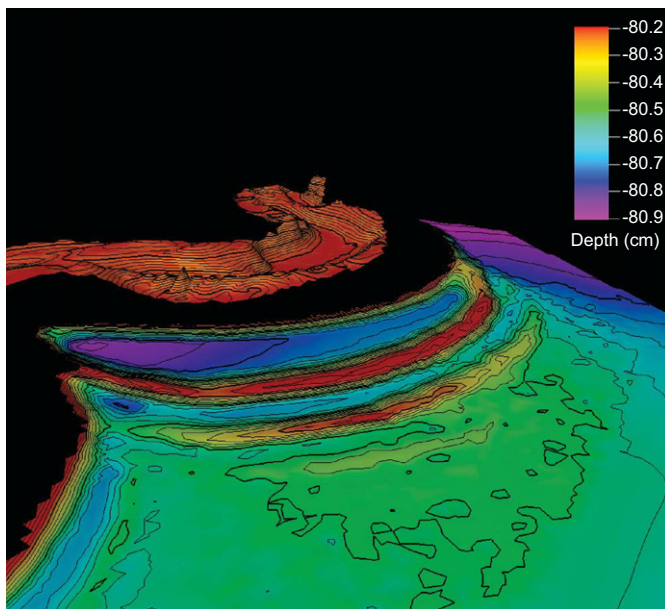


Fig. 6. Sediment thickness map of arcuate sediment waves beyond the outer-bank levee. View looking obliquely upstream at first bend, with channel inlet in background. The scale bar shows the depth from an arbitrary datum to the upper surface of the sedimentary deposits in centimetres. The position and orientation of Fig. 6 is shown in Fig. 5.

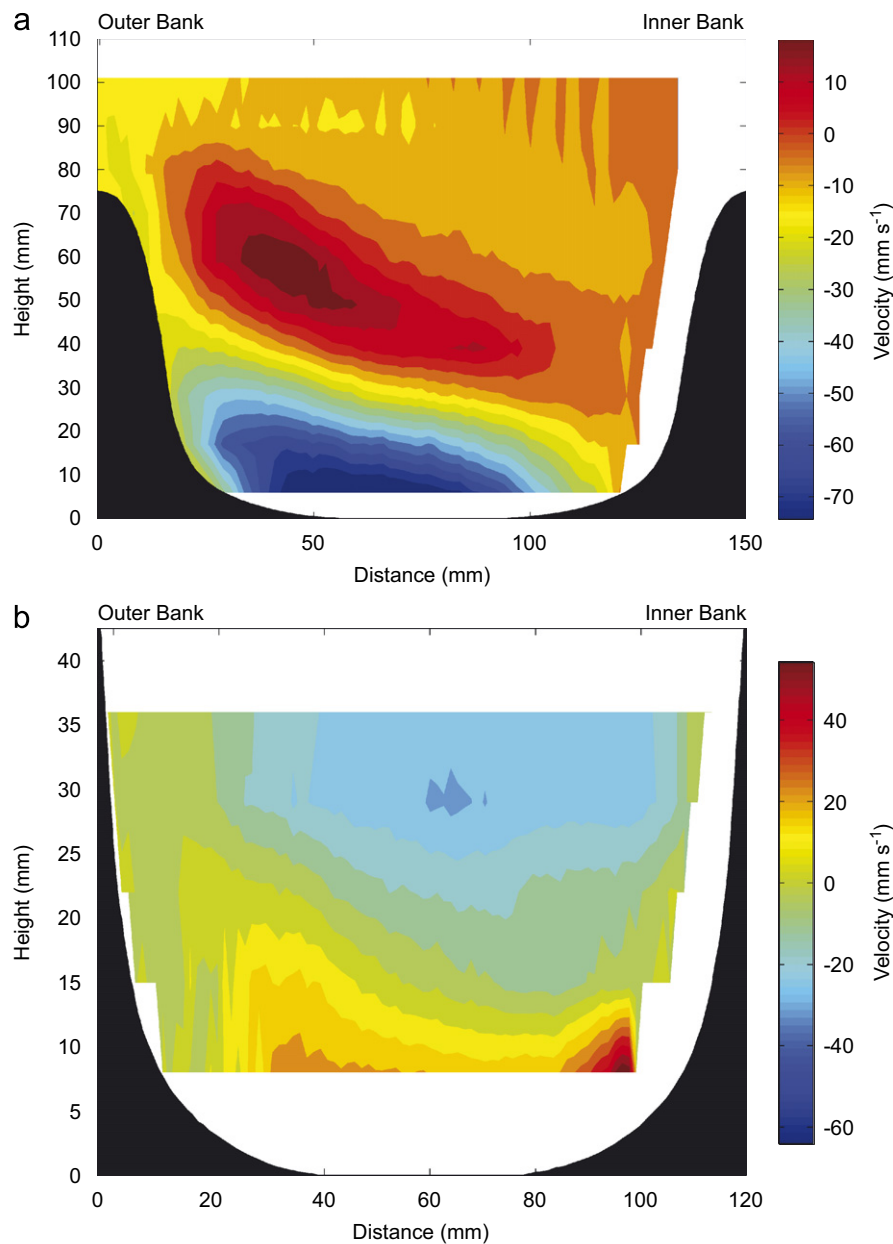


Fig. 7. Cross-sectional velocity distributions at bend apices for sediment-free runs in the same channel model used herein: (A) gravity-current flow and (B) open-channel flow. The saline gravity current had an excess density of 2.5%. Both panels were taken at the apex at Bend 2 and show a view looking upstream. Positive and negative velocities represent flow towards the inner and outer banks, respectively. In the subaerial experiment (B), slope was 0.5° , and discharge was 0.51 s^{-1} ; the flow depth was necessarily lower as the flow velocities are higher than for the gravity current case (see Corney et al. (2006) and Keevil et al. (2006a) for further details).

cross-stream component has a reversed direction when the radial vertical velocity profile has a basal maximum (Booij, 2003). Lastly, detailed measurements of bedform orientations around bar forms in outcrop studies also suggest a reversed circulation relative to river channels (Pyles et al., 2006). These results again emphasise how different the three-dimensional flow within submarine and alluvial channels is, and suggests that the CFD simulations of Kassem and Imran (2004) are anomalous.

Despite not recording velocities towards the outer bank, below the maximum level of the inner-bank deposit, it can be anticipated that the growth of inner-bend deposition

with time will add a spatial (convective) acceleration. This spatial acceleration will further enhance the outward movement of fluid at the upstream end of the deposit, relative to that in the channel model in the absence of sediment. The three-dimensional flow pattern within the sediment-free channel experiments can therefore be used for the purposes of comparison, with the additional convective accelerations considered. Fig. 8 shows flow vectors from the lowermost UDVP probes (7 and 17 mm above the channel base) for a range of positions within the central bend (Bend 2). In addition, Fig. 8 shows basal flow directions obtained from time-series visualisation of pieces

of thread attached to the channel base (see Keevil et al., 2006a for details). The basal component of the helical flow is observed to be outwardly directed, up to and beyond the bend apex, at which point the flow begins to strongly converge towards the inner bank (Fig. 8). In our mobile-bed experiments, the convective accelerations around the upstream and downstream ends of the point bar will further reinforce the outward and inward basal flows, respectively. This spatial variation in the helical flow is in contrast to river channels, where the flow, particularly at the inner bend, is inwardly directed earlier, in the upstream limb of each meander bend (e.g., Dietrich et al., 1979). This

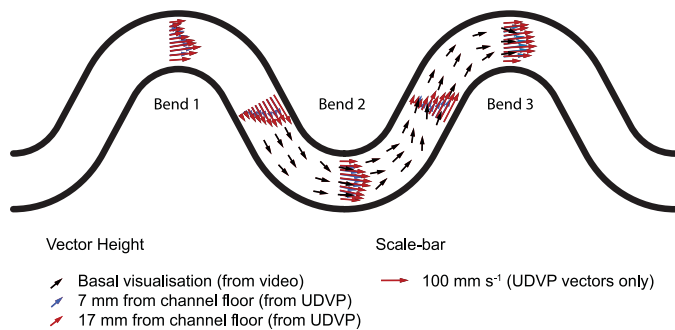


Fig. 8. Spatial distribution of velocity within the submarine channel model for the case of sediment-free runs. The red and blue vectors show both current orientation and magnitude and are derived from three-dimensional UDVP arrays. The black vectors show basal flow orientation derived from flow visualisation (adapted from Keevil et al., 2006a).

point is well illustrated by fluvial experiments within the UK Flood Channel Facility (Wormleaton et al., 2005), and by planforms close to those used here (Shiono and Muto, 1998).

4.2. Bed morphology

4.2.1. Comparison of experimental deposits to meandering river deposits

The experimental submarine channel deposits reveal a relatively simple pattern with two primary geomorphological units: inner-bend accumulations that initiate at or downstream of bend apices, and outer-bank erosion zones, which are separated at or beyond bend inflections by areas of reduced topographic variation. These geomorphological units broadly correspond to their fluvial counterparts in terms of point bars, outer-bank pools and riffles (e.g., Dietrich, 1987; Fig. 9). Similarly, the topographic lows at the inner bank on the downstream limb of the meander bend form in the same approximate position in which chute channels or sloughs form in river channels (e.g., Leopold et al., 1964, p. 317); however, the topographic lows are more prominent in the experiments herein. The key differences between our experimental subaqueous deposits and fluvial morphologies are (1) the position of the inner-bend accumulations, which are further downstream in the case of the subaqueous experiments than in fluvial experiments and river channels (e.g., Hooke, 1975; Dietrich,

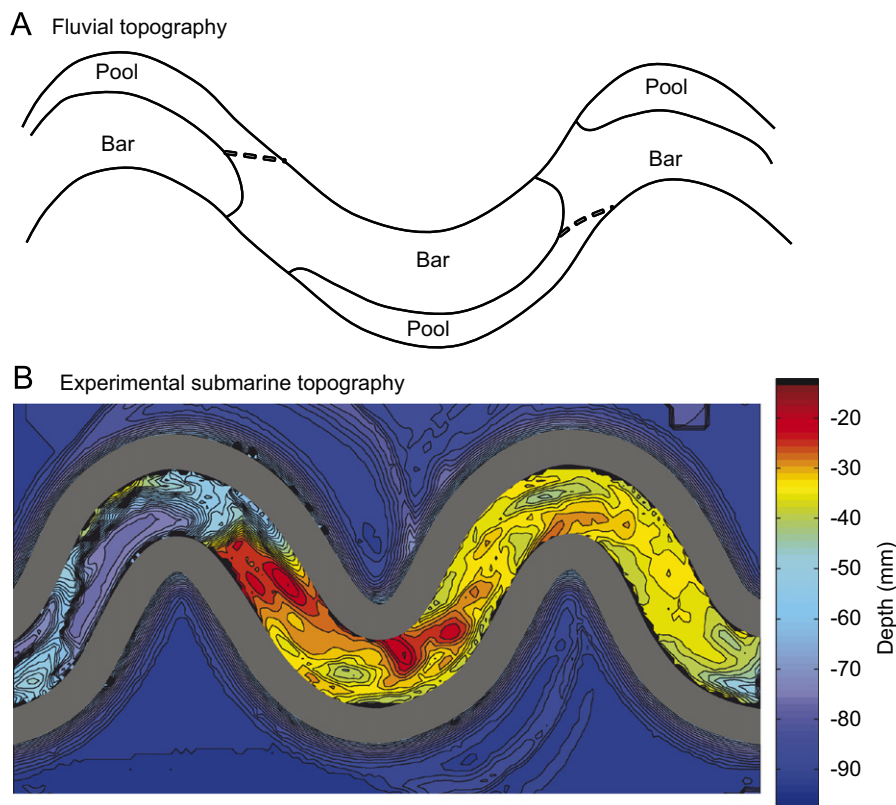


Fig. 9. Comparison between fluvial bed morphology and deposit topographies from the submarine channel experiments. (A) Schematic diagram of topography within a river (after Dietrich, 1987). (B) Plot of experimental deposit topography (Fig. 5B).

1987; Wormleaton et al., 2004, 2005) and (2) the partially related changes in the widths and transverse slopes of the inner bank accumulation as a function of bend position.

4.2.2. Inner-bend sedimentation

Two types of bar are commonly observed in river channels and fluvial experiments, alternate (free bars), and point bars (forced bars) following the terminology of Kinoshita and Miwa (1974). Alternate bars migrate along the channel and were not observed in these experiments. This is in keeping with observations from physical modelling of rivers, where width:depth ratios >10 , and curvatures <10 degrees are required for alternate bar formation and migration (Whiting and Dietrich, 1993). Forced bars form as a direct result of channel curvature and remain relatively stable; bars formed in these experiments are of this type. In these experiments a forced bar formed at the apex of each bend and grew with time. The presence of these bars at the inner bends of submarine channels, and the similarity with river channels, is in large part a reflection of the dominance of the longitudinal flow component over the cross-stream component in the formation of these features (e.g., Nelson and Smith, 1989). Secondary flows are, however, known to be important in fluvial systems for the initiation of point bars (Nelson and Smith, 1989) and for influencing the width and transverse slopes of these bars (e.g., Hooke, 1975; Bridge, 1992; Darby et al., 2002).

4.2.3. Inner bar position

The position of the point bar relative to the bend apex for moderately curved river channels is determined by the relative importance of cross-stream divergences to stream-wise divergences of sediment flux (Nelson and Smith, 1989). In their numerical model of flow and deposit characteristics in a curved fluvial channel, Nelson and Smith (1989) found that the growth of a point bar on an initially flat bed is primarily produced by the convergence of sediment towards the inner bank. The convergence is caused by the helical circulation, and specifically by the lowermost part of the flow cell. Nelson and Smith (1989) modelled the case where sediment transport occurred solely as bedload. Similarly, sediment in our experiments was primarily moved as bedload. Our velocity results (see Fig. 3 and Fig. 8) indicate that sediment flux convergence occurs further downstream in these submarine channel experiments relative to river channels. This downstream shift occurs as a result of outwardly directed helical motion up to and just beyond the bend apex, followed by flow convergence towards the inner bank at a point beyond the bend apex (Fig. 8). It is therefore possible that the variation in point-bar position relative to the bend apex, between these submarine channel experiments and fluvial systems (e.g., Hooke, 1975; Dietrich, 1987; Wormleaton et al., 2004, 2005), may be related to this variation in the location of flux convergence. This flux convergence is a product of the reversal in direction of the cross-stream flow component at and just beyond bend apices.

A second mechanism for bar formation downstream of the bend apex may be an area of slow downstream velocity close to the inner bank, related to the curvature of the inner bend at the apex (Fig. 8). Previous work on rivers has suggested that when the ratio r_c/w is $<2-3$ flow separation is likely to occur, where r_c is the radius of curvature of the bend centreline and w is channel width (Bagnold, 1960). The r_c/w ratio in these experiments is 1.5; however, flow visualisation using neutrally buoyant particles demonstrated that there was no permanent zone of recirculation as is observed in natural rivers with sharp bends (e.g., Leopold et al., 1960; Ferguson et al., 2003), although occasional upstream movement of particles at the inner bend was observed. Even in the absence of large-scale flow separation, the presence of a slow velocity zone close to the inner bank downstream of the bend apex will enhance the effects of flux convergence in this area and encourage development of a point bar. These two mechanisms appear to reinforce one another in these experiments, controlling the position of the inner bar.

4.3. Comparison with compound channels

Reversal of helical flow orientation in parts of meander bends during flood events has long been recognised in fluvial compound (or two-stage) channels (Toebe and Sooky, 1967; Kiely, 1990). Compound channels have narrow overbank areas either as a result of artificial berms or naturally constrained floodplains, and these overbank areas become included in the submerged cross-section during flood events (Fig. 10). These systems exhibit prominent shear layers between predominantly parallel downstream overbank flow and sinuous within-channel flow, this shear resulting in secondary flow reversal in parts of channel bends (Knight and Shiono, 1990; Sellin et al., 1993). The position and strength of this secondary flow reversal are controlled by the height of overbank flow and the degree of floodplain roughness (Wormleaton et al., 2004, 2005). This shearing mechanism has also been observed in some submarine channel experiments (Keevil et al., 2007). However, the dominant mechanism for secondary flow reversal in submarine channels is quite different, being a function of the downstream velocity profile (Corney et al., 2006). Although the mechanisms of secondary flow reversal are very different, the influence of secondary flow reversal on bed morphology in submarine and compound channels can be compared. The mobile-bed compound channel experiments of Wormleaton et al. (2004, 2005) are also at a larger scale (planform area was 35 m long by 8 m wide) enabling comparison of these submarine channel experiments with larger-scale experiments of similar planform geometry.

The experimental run of Wormleaton et al. (2004, 2005), with high overbank flow and a rough floodplain surface, is most similar to the experiments described here. Their experiment exhibits dominantly outward-directed flow at the bend apex, which then becomes strongly inwardly



Fig. 10. Example of an experimental compound channel in the Flood Channel Facility (FCF). Roughening elements are shown on the floodplain. The flume tank shown is 60 m long and 10 m wide, of which the experimental channel occupies a length of 35 m. At high flow, overbank fluid flows strongly parallel to the sides of the flume, whilst within-channel flow moves in a sinuous path through the main channel. From Wormleaton et al. (2005). Reproduced with permission from ASCE.

directed past the bend apex (Wormleaton et al., 2005, their Fig. 9), in excellent agreement with the submarine channel flows described here (see Figs. 3 and 8). At the bend apex the cross-section is relatively deep, the floor of the channel is quite flat and there is an absence of any significant point-bar deposit. Downstream of the bend, at an intermediate position between the bend apex and inflection (equivalent to the intermediate position in Figs. 1B and 11), there is a prominent point-bar deposit which has a flat upper point-bar platform extending across ~60% of the channel. The platform exhibits steep transverse slopes leading down into a deep pool (Wormleaton et al., 2005, their Figs. 9 and 13). The bed morphology in the compound channel experiments is very similar to that observed in the submarine channel experiments, with an absence of significant point-bar deposits at the bend apex and muted cross-sectional topography (Fig. 11). There is also very close agreement in terms of the width and morphology of the upper platform in the intermediate position, and in the steepness of the transverse slopes dipping into a deep pool (see Fig. 11). The one exception is the inner slough channel of the submarine channel bars which is considerably larger than in the compound experiments.

A bankfull run was also modelled in the Wormleaton et al. (2004, 2005) study, producing a point bar that starts upstream of the bend apex. Comparison between the

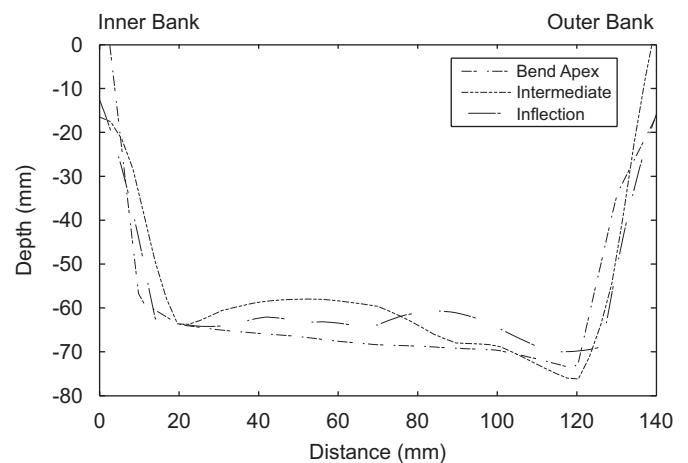


Fig. 11. Development of main channel bed profiles through time at different positions. (A) Bend apex, (B) intermediate position between apex and inflection and (C) inflection. The positions of the different cross-sections are shown in Fig. 1B.

bankfull and overbank compound channel cases demonstrates that the reversal in secondary flow cell orientation is responsible for erosion of the upstream part of the point bar, and also downstream movement of the upstream end to just beyond the bend apex position. The corresponding increase in transverse gradients on the upstream end of the

point bar is a result of the enhanced inner-bank directed flow beyond the bend apex (Wormleaton et al., 2005). In summary, there is a marked similarity between the submarine and high overbank compound channel experiments in terms of planform geometry, helical flow structure and bed morphology. This similarity, and the observed links between bed morphology and flow structure within the compound channels, reinforce the suggestion that the position and morphology of point bars in these experiments are primarily a function of the helical flow structure, rather than the specific bend geometry used in the experiments.

The strength of the similarity also enables some inferences to be made about spatial variations in grain size across submarine channel point bars. Grain size was not measured in the present experiments, but grain-size variations were observed in the compound channels. Wormleaton et al. (2005) show that the outwardly directed near-bed helical flow and relatively flat topography at the bend apex is associated with similar sized bed material across the bend, in contrast to the fining-inward sequence observed at the bend apex in bankfull river experiments. The strongly inward-directed basal flows beyond the bend apex at the intermediate section of the overbank experiments resulted in abundant fine-grained material at the inner bank (Wormleaton et al., 2005). These experimental observations support previous studies that have linked the inner-bank directed basal component of helical flow to grain-size sorting on the point bar (e.g., Bridge, 1982, 1992; Parker and Andrews, 1985). The combination of physical experiment and theory suggests that these submarine channel experiments should exhibit little lateral grain-size variation at the bend apex, but should rapidly develop fining-inwards profiles past the bend apex where inward-directed basal flows are strong. These fining-inwards profiles should then persist around the point bar. A rapid longitudinal development of a fining-inward profile, or a fining-upwards profile once progradation of the point bar is accounted for, is in contrast to the pattern of fluvial point bars, where coarsening-upwards sequences are observed in the upstream parts of bends (Jackson, 1976; Willis, 1989). This fluvial distribution is a function of the more gradual longitudinal increase in the strength of the inwardly directed basal helical flow in meander bends.

4.4. Comparison with previous observations of intra-channel submarine bend morphology

Our experiments are dominated by inner-bank bars and therefore replicate the inner-bend accumulations at bend apices previously observed in seismic studies (e.g., Kolla et al., 2001; Abreu et al., 2003) and modern channels (e.g., Klaucke and Hesse, 1996; Schwenk et al., 2003). Furthermore, there are similarities in the position of these bar forms with those published in the literature. The Bengal Fan point bars imaged by Schwenk et al. (2003, their Fig. 2) are strongly asymmetric with respect to bend apices,

initiating just upstream of apices and with deposition dominantly concentrated downstream of apices. The lateral accretion packages preserved in the Green Channel, offshore Angola, also display evidence for asymmetric elongation of some of the lateral accretion packages downstream of bend apices (Abreu et al., 2003, their Fig. 10). This agreement between physical modelling and submarine channels, albeit with the caveat that the number of observations from natural systems is extremely limited, suggests that the position of the inner-bend accumulation relative to bend apices is further downstream for submarine channels relative to meandering river channels.

Whilst the experiments reproduce inner-bend accumulations, they reveal no indication of other features described from seismic and well-log studies such as nested mounds on outer banks (e.g., Phillips, 1987; Timbrell, 1993; Clark and Pickering, 1996). The absence of these features from our experimental deposits suggests that these sedimentary features cannot be explained in terms of broad channel-scale helical flow-dominated fluid dynamics. These same features are also not observed in river channels and therefore cannot be explained in terms of fluvial theory. The present experiments therefore support in part the contention that features such as nested mounds may instead be linked to external processes such as levee or bank collapse, as proposed by Peakall et al. (2000b). Such bank collapse features have been frequently observed in submarine channels (Prior et al., 1986; Ren et al., 1996; Lawver and Davey, 2005).

4.5. Comparison with previous subaqueous physical experiments

A previous experimental modelling study of subaqueous channels was unable to reproduce intra-channel morphological elements such as bars in meanders, and noted that the absence of such bars was surprising (Métivier et al., 2005). Furthermore, Shanmugam (2006, p. 270) has argued that the failure of experimental studies to generate point bars is important. Here we have shown that for a pre-formed sinuous channel, bar features do form and that these features can be understood in terms of the gross-scale fluid dynamics. The question remains, however, as to what range of flow and sediment conditions such bar features form in, and what the nature and variability of the bar forms are for the phase-space in which they do form. The Métivier et al. (2005) experiments consisted of laminar flows on a mobile substrate producing self-forming channels on very steep slopes (9–21°). In contrast, the present study had fully turbulent flow over pre-formed channels with a mobile bed, on lower slopes (3°).

4.6. Modelling of sedimentation in density current experiments

Previous small-scale turbidity current experiments have been limited by the inability of turbulent laboratory-scale

currents to adequately erode, suspend and transport significant quantities of sediment. Most experiments have mechanically mixed the initial sediment prior to release and have used sediment densities on the order of $2.6\text{--}3.0\text{ g cm}^{-3}$, producing currents that deposit rapidly and that exhibit virtually no erosion (e.g., Gladstone et al., 1998; de Rooij and Dalziel, 2001). In the present experiments, a low-density plastic (Poly V[®], 1.2 g cm^{-3}) was used, that has a similar shape and grain-size distribution to natural sediments (i.e., subangular and polydisperse). This material can both be eroded and suspended by gravity currents, and maintains realistic sedimentary slopes (most low-density plastics are perfectly spherical and will not support significant slopes). Such material offers great promise for future work on sedimentation within subaqueous density currents.

4.7. A model of sedimentation in submarine channel bends

Based on the results of these experiments, and comparison against both the existing fluvial and submarine channel literature, a large-scale model of sedimentation in submarine channel bends can be proposed. Sedimentation by traction-dominated processes is dominated by the accumulation of inner-bend deposits and outer-bank scours, here termed point bars and outerbank pools in common with the terms for equivalent features in meandering river bends. The presence of reversed helical flow in the upstream portion of submarine channel bends leads to point bars forming further downstream relative to the bend apex than in river channels. The upstream parts of these submarine point bars may be characterised by steep transverse gradients and a rapid downstream change to fining-upwards successions relative to their fluvial counterparts, as a result of strongly inwardly dominated basal flow downstream of bend apices. This large-scale depositional structure is then complicated by the development of coarse-grained mounds of sediment. Whilst the origin of these features is still poorly understood, and may be polygenetic, previous work has suggested that they may be related to bank/levee collapse (Peakall et al., 2000b). These mounds appear to form at any point within a bend but may preferentially be associated with outer bends (Phillips, 1987; Timbrell, 1993; Clark and Pickering, 1996). The distribution of these deposits will be harder to predict relative to the depositional features formed purely as a result of intra-channel helical flow-dominated fluid dynamics.

This new model of intra-channel sedimentation in submarine channels reveals that both the fluid dynamics and depositional morphology differ from those observed in river channels. Point bars appear to be distinctive in both position, morphology and the spatial distribution of grain size, and are potentially predictable in the same manner that fluvial point bars have been successfully modelled (e.g., Bridge, 1992). On this basis they should vary as a function of key planform variables observable in seismic

data, such as sinuosity, channel curvature and channel width. Other elements, however, such as the distribution of mounds, appear to be independent of primary helical-flow-dominated fluid dynamics. Such independence suggests that the intra-channel facies of submarine systems are less predictable and probably more complex than their fluvial counterparts. Sedimentary architecture is likely to be more heterogeneous on the channel scale, and there is greater potential for barriers and baffles related to nested mounds and deposits surrounding these features. These variations in intra-channel architecture between submarine and fluvial channels have significant implications for reservoir modelling of intra-channel architecture in submarine systems.

5. Conclusions

A series of physical experiments have investigated the patterns of sedimentation within sinuous submarine channels of constant width, and examined how these are controlled by the three-dimensional fluid dynamics of channel flow. The experiments reveal that the previously observed reversal in the orientation of helical flow within submarine channels can significantly modify the distribution and morphology of depositional elements relative to those of meandering rivers. Close agreement is observed between these depositional patterns and those from certain larger-scale fluvial compound channel experiments that also exhibit reversed helical flow orientation. There is also good agreement between the experiments and the observed large-scale patterns of natural submarine channels, albeit that such natural data are scarce. The strength of agreement between the experiments and the available comparative datasets enables a process-based model of intra-channel sedimentation in submarine channels to be proposed, consisting of a number of key elements: (i) point bars form at inner bends but are located further downstream compared with point bars in equivalent fluvial bend geometries; (ii) the upstream parts of point bars may exhibit steep transverse slopes, these decreasing downstream; (iii) fining-upwards sequences may develop rapidly with distance along the point bar; (iv) non-helical flow related processes such as bank/levee collapses may lead to the formation of mounds of coarser-grained sediment at any position around submarine bends; and (v) mounds may preferentially form on the outer banks of channels. This proposed model for submarine channel sedimentation has significant implications for reservoir modelling of these systems.

The experimental techniques developed here represent a powerful methodology for exploring the full range of fluid and sedimentary processes operating within submarine channels. In particular, further work is required to examine the response of parameters such as sinuosity, width:depth ratio, flow duration and along-stream width variations on bed morphology, and the feedback between this morphology and three-dimensional flow dynamics.

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