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ScienceDirect

Marine and Petroleum Geology 24 (2007) 470–486

Marine and Petroleum Geology

www.elsevier.com/locate/marpetgeo

Flow processes and sedimentation in submarine channel bends

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Received 9 March 2006; received in revised form 8 December 2006; accepted 8 January 2007

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.

Keywords: Gravity current; Point bar; Submarine channel

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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0264-8172/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.marpetgeo.2007.01.008

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 superelevation 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