Marine and Petroleum Geology 27 (2010) 1366–1378

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Effects of topography on lofting gravity flows: Implications for the deposition of deep-water massive sands

Christopher J. Stevenson [a,*], Jeff Peakall [b]

[a] National Oceanography Centre, Southampton, European Way SO14 3ZH, UK
[b] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

ARTICLE INFO

Article history:
Received 3 December 2009
Received in revised form
10 March 2010
Accepted 18 March 2010
Available online 25 March 2010

Keywords:
Hyperpycnal
Lofting
Deep-water massive sands
Experiment
Topography
Scale model
Turbidite

ABSTRACT

Hyperpycnal flows are generated in the marine environment by sediment-laden fresh water discharge into the ocean. They frequently form at river mouths and are also generated in proximal ice-melting settings and are thought to be responsible for transporting a large proportion of suspended river sediment onto and off the continental shelf. Hyperpycnal flows are an example of gravity currents that display reversing buoyancy. This phenomenon is generated by the fresh water interstitial fluid being less dense than that of the ambient seawater. Thus after sufficient particles are sedimented the flow can become positively buoyant and loft, forming a rising plume. Here we present results from physical scale-modelling experiments of lofting gravity currents upon interaction with topography. Topography, in the form of a vertical obstacle, triggered a localised lofting zone on its upstream side. This lofting zone was maintained in a fixed position until the bulk density of the flow had reduced enough to allow lofting along its entire length. The obstructed lofting zone is associated with a sharp increase in deposit thickness. By inference these experimentally established lofting dynamics are applied to improve understanding of the potential for hyperpycnal flows to deposit deep-water massive sands. This study provides a depositional mechanism by which large volumes of sand can be deposited in the absence of traction and the fines removed, leaving thick deposits of structureless sand with a low percentage of mud. This conceptual model for the first time provides a framework by which the geometries of certain deep-water massive sands may be predicted within specific depositional and basinal settings. This is crucial to our understanding of massive sand deposits in modern and ancient turbiditic systems and in the commercial evaluation of hydrocarbon potential of such sedimentary successions.

1. Introduction

Turbidites are ubiquitous in nature and are the primary mechanism by which clastic sediments are deposited within deep-water environments. They are of major importance to the hydrocarbon industry as commercially viable plays with an estimated 1200–1300 discovered and producing oil and gas fields hosted in turbidite reservoirs (Stow and Mayall, 2000). As hydrocarbon exploration has moved to progressively deeper waters it has become necessary to further our understanding as to the origins and depositional processes that govern these systems. The conventional turbidite paradigm, now over 50 years old has come under scrutiny as the understanding of turbidite deposit architecture and processes has improved. Two phenomena form the focus for this study; the origins and depositional processes surrounding deep-water massive sands (DWMS) and the deposits/facies associated with hyperpycnal gravity currents.

1.1. Hyperpycnal flows

Hyperpycnal flows are density currents composed of particles suspended in fresh water such that the bulk density of the flow is greater than the seawater into which it is flowing. This composition generates bottom flowing gravity currents that display reversing buoyancy. They were initially identified over 100 years ago (Gilbert, 1890) but it is only recently that these flows have been considered a significant depositional mechanism in marine basins (Mulder and Syvitski, 1995; Syvitski and Schafer, 1996; Lonne, 1997; Zuffa et al., 2000; Lonne et al., 2001; Mulder et al., 2003; Mutti et al., 2003; Hesse et al., 2004; Plink-Björklund and Steel, 2004; Felix et al., 2006; Piper and Normark, 2009; Pritchard and Gladstone, 2009; Gladstone and Pritchard, 2010). The unique dynamics of flows with reversing buoyancy arises from a positively buoyant fluid, laden with sediment, giving it excess density, flowing into a less dense ambient

---

[*] Corresponding author. Tel.: +44 (0) 23 8059 6563.
E-mail address: chris.stevenson@noc.soton.ac.uk (C.J. Stevenson).

0264-8172/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpetgeo.2010.03.010

fluid. The higher density sediment-laden flow initially plunges downward then flows along the bottom substrate of the ambient fluid body. As sediment is rained out from the flow its bulk density reduces, until neutral buoyancy is reached. This is marked by a sharp cessation of horizontal movement and the generation of a rising plume, the lofting point (Huppert et al., 1986; Carey et al., 1988; Sparks et al., 1993; Hurzeler et al., 1996; Rimoldi et al., 1996; Gladstone and Pritchard, 2010). The lofting point is associated with rapid sediment fallout and the removal of fine material in the rising plume (Klaucke et al., 2000; Gladstone and Pritchard, 2010). In natural submarine systems lofting gravity flows are predominantly hyperpycnal flows, generated from rivers discharging sediment-laden fresh water into the oceans (Mulder et al., 2003; Piper and Normark, 2009) or occasional catastrophic glacial outbursts of fresh water into the ocean (Russell and Knudsen, 1999; Hesse and Khodabakhsh, 2006). Such flows have been measured or estimated to be sustained from between several days to 3–4 weeks (Wheatcroft and Borgeld, 2000; Khan et al., 2005; Hesse and Khodabakhsh, 2006; Nakajima, 2006). The level of suspended sediment is a major control on the frequency of hyperpycnal flow generation through time. Initially modelled on an excess suspended sediment load of 28 kg/m^3, in order to overcome seawater density of less than 1028 kg/m^3 (Mulder and Syvitski, 1995; Hicks et al., 2004; Milliman and Kao, 2005), hyperpycnal flows were thought to be restricted to small-medium sized rivers on steep gradients, prone to flash flooding. However, more recent research shows that estuarine mixing, stratification of the flow and shear induced mixing between the underflow and the ambient fluid can reduce the required sediment load, potentially by several orders of magnitude (Felix et al., 2006). Although these processes would result in much thinner bottom hugging parts of the flow compared with flows with higher sediment load.

In addition sediment trapping and convection cell development at river mouths generates hyperconcentrated layers, enabling hyperpycnal flows to form from rivers carrying as little as 1–5 kg/m^3 (Parsons et al., 2001; Geyer et al., 2004). Indeed case studies have shown hyperpycnal flows being generated frequently with as little as 0.1–1 kg/m^3 of suspended sediment (Ruch et al., 1993; Johnson et al., 2001). Hyperpycnal flows are therefore likely to be more widespread than previously thought, occurring as a component in many river fed turbidite systems around the world.

1.2. Deep-water massive sands

Deep-water massive sands (DWMS) are a well established classification of deposit that has been identified in many turbidite systems around the world (Johansson et al., 1998; Stow et al., 1999; Hickson and Lowe, 2002; Grecula et al., 2003; Duranti and Hurst, 2004; Wynn et al., 2005). Truly massive deep-water sands are defined as very thick (>1 m) sand beds that are devoid of primary sedimentary structures, which occur in association with deep-water turbidite systems (Stow and Johansson, 2000). However, these sands can exhibit a range of grading patterns from normally graded, weakly graded to ungraded and include single and amalgamated beds. These essentially structureless sand bodies have been found to be important reservoirs in many hydrocarbon plays throughout the world, examples include; Cretaceous, Palaeogene North Sea fields (Argent et al., 2000), offshore Cretaceous fields in northern Norway, and numerous plays associated with the east South-American and West African continental margins (Stow and Mayall, 2000). Despite their importance these deposits are still largely enigmatic and poorly understood in terms of their origins and the depositional processes surrounding their emplacement.

A number of potential transport processes and associated depositional mechanisms have been proposed for DWMS formation over the last two decades including: sustained high density turbidites with very high aggradation rates (Johansson et al., 1998; Stow and Johansson, 2000); en masse freezing of large sandy debris flows (Shanmugam, 2000); retrogressive slumping of fine unconsolidated sands causing sustained, high aggradation rates (Van de Berg et al., 2002; Masterbergen and Van den Berg, 2003); lack of a sharp rheological boundary at the basal zone of the flow acting to suppress traction bedform development (Kneller and Branney, 1995); deposition in two-layer hydraulic jumps (Postma et al., 2009); and bedform structures preserved in the top section of the deposit that are subsequently eroded off by successive flows. The massive base that is left is amalgamated by subsequent flows leaving a thick bedded, structureless deposit (Baas, 2004). Secondary processes such as liquefaction and fluidisation have also been acknowledged as a potential cause (Duranti and Hurst, 2004). However, the idea that DWMS's form due to high bed aggradation rates is questionable as more recent experiments have shown planar laminae to form rapidly, even under high rates of deposition (Leclair and Arnott, 2005). This conflicting experimental evidence undermines the validity of depositional mechanisms that rest on high aggradation rates (e.g. Johansson et al., 1998; Van de Berg et al., 2002; Baas, 2004). In contrast, en masse freezing of sandy debris flows can explain ungraded, structureless deposits but does not explain the range of normally and inversely graded DWMS facies. In addition it has yet to be established how sandy debris flows could travel far from source on low angle slopes without freezing. Development of DWMS during hydraulic jump formation (Postma et al., 2009) appears more plausible for those deposits in proximal areas or near sharp breaks in slope, but seems less likely for deposits further out on basin floors where sub-critical turbidity currents would be expected. Given that many of these mechanistic arguments are unresolved the depositional processes and origins of DWMS remain elusive.

1.3. Lofting as a potential mechanism for DWMS formation

Based on the understanding that at the point of lofting the flow ceases lateral movement and forms a rising plume with an associated rapid fallout of sediment from the flow (Sparks et al., 1993), it is possible to postulate a scenario whereby tractional bedform development is suppressed. If the lofting point is stationary or largely stationary then material settling from the rising plume will settle in the absence of traction structures. Furthermore, if the rising plume carries with it the fines from the flow and disperses them over a wide area (Hesse and Khodabakhsh, 2006) or ocean currents transport the fines away from the area (Klaucke et al., 2000), then local accumulations of clean massive sands might be expected to form. Numerical modelling of sedimentation during lofting flows suggests that these lofting processes can indeed form massive beds, dependent on flow character and the behaviour of the rising plume (Gladstone and Pritchard, 2010). The simulations of Gladstone and Pritchard (2010) modelled surge-type turbidity currents over smooth horizontal surfaces and produced thin DWMS deposits. Accumulations of larger thicknesses of DWMS from this mechanism, as commonly observed in deposits, would be dependent on either i) longer lived flows remaining fixed at a single-point, or ii) flows repeatedly lofting at exactly the same point. However, given that the lofting current will alter the local density field, more continuous quasi-steady flows will likely exhibit a migration of the lofting point with time with a resulting change from massive to structured beds. Furthermore, variations between flows in terms of volume, concentration, grain-size distribution and the relative buoyancy of the fluid phases, will almost certainly lead to variation in the lofting points of successive flows. Consequently, it remains unclear how thick accumulations of DWMS can form from the lofting mechanism.