Marine and Petroleum Geology 41 (2013) 186–205

Contents lists available at SciVerse ScienceDirect

Marine and Petroleum Geology

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

The flows that left no trace: Very large-volume turbidity currents that bypassed sediment through submarine channels without eroding the sea floor

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ARTICLE INFO

Article history:
Received 13 October 2011
Received in revised form
30 January 2012
Accepted 1 February 2012
Available online 13 February 2012

Keywords:
Turbidity currents
Submarine channels
Bypass
Agadir basin
Moroccan Turbidite system
Turbidites
Sea-floor gradient
Madeira Channels
Sediment cores

ABSTRACT

Turbidity currents are an important process for transporting sediment from the continental shelf to the deep ocean. Submarine channels are often conduits for these flows, exerting a first order control on turbidity current flow processes and resulting deposit geometries. Here we present a detailed examination of the Madeira Channel System, offshore northwest Africa, using shallow seismic profiles, swath bathymetric data and a suite of sediment cores. This shallow (<20 m deep) channel system is unusual because it was fed infrequently, on average once every 10, 000 years, by very large volume (>100 km^3) turbidity currents. It therefore differs markedly from most submarine channels which have well developed levees, formed by much more frequent flows. A northern and a southern channel comprise the Madeira Channel System, and channel initiation is associated with subtle but distinct increases in sea-floor gradient from 0.02° to 0.06°. Most of the turbidity currents passing through the northern channel deposited laterally extensive (>5 km), thin (5–10 cm) ripple cross-laminated sands along the channel margins, but deposited no sand or mud in the channel axis. Moreover, these flows failed to erode sediment in the channel axis, despite being powerful enough to efficiently bypass sediment in very large volumes. The flows were able to reach an equilibrium state (autosuspension) whereby they efficiently bypassed their sediment loads down slope, leaving no trace of their passing.

1. Introduction

Turbidity currents are one of the most important flow processes for moving sediment across the surface of the Earth. Individual events, such as those described in this study, can be extremely large volume, transporting over ten times the annual sediment flux for all the world's rivers (Mulder and Syvitski, 1995). Submarine channels are often conduits for these flows, exerting a first order control on turbidity current flow processes and resulting deposit geometries. Much of our understanding of submarine channel morphology comes from a number of intensely studied modern deep-water fans (Wynn et al., 2007). The channels found across these fans are generally sinuous (>1.2) and are connected to larger feeder canyons, which cut back into the continental shelf. Within the upper parts of the fans the channels are relatively deep (100s m) and narrow (2–20 km), becoming progressively shallower (tens of metres) and broader (tens of km) as they progress distally down the fan (Wynn et al., 2007). In terms of depositional architecture, submarine channels and their flanking levees are commonly referred to as channel-levee systems. Such systems broadly comprises a coarse-grained channel fill, such as massive sands and gravels (Babonneau et al., 2010; Bernhardt et al., 2011; Wynn et al., 2007), and fine-grained levee deposits that thin and fine away from the axis of the channel (Kane et al., 2007). Channel depth may be maintained via a combination of erosion along the channel floor and/or from construction of levees along the channel margins. However, many channels are also net aggradational both in the channel axis and across the levees (Janocko et al., 2013; dalla Valle et al., 2013; Wynn et al., 2007). Channel-levee architecture is pervasive across most modern fan systems and has been interpreted in numerous ancient channel systems (Babonneau et al., 2010; Bernhardt et al., 2011; McHargue et al., 2011; Normark, 1978; Normark et al., 1979; Wynn et al., 2007).

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doi:10.1016/j.marpetgeo.2012.02.008

However, not all channel systems fit the deep-water fan model. For example, the Northwest Atlantic Mid-Ocean Channel (NAMOC) consists of a major "basin draining" trunk channel supplied by numerous tributary and satellite channels that are linked up with the continental slope (Hesse and Rakofsky, 1992; Hesse, 1989; Hesse et al., 2001; Klaucke et al., 1998). Proximally the system is dominated by sandy braid-plains with relatively shallow relief channels (10s m). Little variation in grain size occurs between braided channel and levee elements, with channel axes and levees being sand-rich. As the NAMOC progresses distally (extending over 4000 km) it develops into a deep single channel with a coarse-grained channel fill and thinner, fine-grained channel levees (Hesse et al., 1987; Klaucke et al., 1997, 1998).

Flow processes operating within submarine channels are complex, involving erosive, bypassing and depositional phases (Macauley and Hubbard, 2013; Peakall et al., 2000). These processes are governed by sea-floor/channel morphology and the properties of the flows passing through the channels (e.g. flow thickness, grain size, density and velocity). Specifically, gradient has been shown to be a fundamental control on the ability of turbidity currents to erode, transport and deposit sediment (Mulder and Alexander, 2001; Wynn et al., in press). Therefore, changes in sea-floor gradient down flow can exert a strong control on channel architecture, particularly in complex slope settings (Adeogba et al., 2003; Ferry et al., 2005). However, there have been very few direct measurements of active flows passing through submarine channels (Kripounoff et al., 2003; Vangriesheim et al., 2009; Xu et al., 2004), and sediment concentrations have never been measured in any channel in the deep ocean. This ensures that major questions remain concerning submarine flow dynamics. Thus our understanding rests on analysis of flow deposits in submarine channels. However, the highly complex, often discontinuous nature of deposition within channels (Di Celma et al., 2011) means our understanding of how individual flows actually behave is limited. A novel aspect of this study is that the deposits of individual flows can be correlated between basins that lie up slope and down slope of the channel system. This correlation enables the number, grain size and volume of flows that passed through the intervening channels to be well constrained. Hence, the depositional architectures of individual turbidites within the channels themselves can be placed in context and the flow processes can be better understood. This study aims to:

(1) Document a poorly studied modern channel system and show how it differs from previously described channel-levee models
(2) Document in detail the deposits of individual flows across the channels
(3) Discuss how differences in flow properties can affect depositional architecture across the channels
(4) Discuss the effects of sea-floor gradient on individual flow behaviour (e.g. erosion, bypass and deposition) and the resulting channel architecture

2. The Moroccan Turbidite System

Over the past 200 ka the Moroccan Turbidite System, situated offshore northwest Africa, has been host to some of the largest turbidity currents ever recorded on Earth with volumes exceeding 150 km^3 (Frenz et al., 2008; Talling et al., 2007; Wynn et al., 2010, 2002b). The system spans ~2000 km comprising three interconnected sub-basins (Fig. 1A): the Seine Abyssal Plain to the northeast, the Agadir Basin situated centrally and the Madeira Abyssal Plain forming the western most extent of the system. Entering the system from three sources are: (1) organic-rich siliciclastic flows, sourced from the Moroccan Margin; (2) volcanoclastic flows, sourced from either the Canary Islands or Madeira and; (3) carbonate-rich flows, sourced from local seamount collapses (de Lange et al., 1987; Pearce and Jarvis, 1992; Weaver et al., 1992; Wynn et al., 2002b). Excellent core recovery throughout the system, coupled with a robust geochemical and chronostratigraphic framework, has enabled individual turbidite beds to be correlated between all three sub-basins (Wynn et al., 2002b). A complex series of channels cross the lower continental rise, connecting the Agadir Basin with the Madeira Abyssal Plain. These channels, originally mapped by Masson (1994), are ~700 km long and comprise separate northern and southern channel systems. For clarity this study refers to the southern channel system and northern channel system, of Masson (1994), as the Canary Island Channel System and the Madeira Channel System respectively (Fig. 1B). The Madeira Channel System itself comprises a northern channel and a southern channel that are initially separated by local seamounts before converging ~200 km down slope (Fig. 1B). This study focuses on the proximal parts of the Madeira Channel System. Herein, the term Madeira Rise will be used to describe the immediate area surrounding the Madeira Channels themselves and is restricted to the area of study as shown in Fig. 1B, unless otherwise stated.

The Madeira Channel System is unusual in that it initiates far from the continental shelf, located at the distal end of the relatively flat Agadir Basin (Fig. 1A). Turbidity currents entered the channels obliquely from the northeast, via the Agadir Basin, or perpendicular to the channels, from the Canary Islands to the south (Frenz et al., 2008; Wynn et al., 2002b). Turbidity currents passing into the Madeira Channels from the Agadir Basin were largely unconfined and able to spread across the width of the basin (Frenz et al., 2008). Turbidity currents from the Canary Islands were also unconfined and able to spread across the entire Madeira Rise (Hunt et al., 2011). This makes the Madeira Channels significantly different from most submarine fan channel systems that are directly fed by flows that are confined within large canyons that cut back into the shelf (Wynn et al., 2007).

3. Methods

The geophysical data used in this study were collected during *'RRS Charles Darwin cruise CD166'*. A dense network of 3.5 kHz profiles and continuous EM12 multibeam bathymetry (Figs. 2 and 3) covers the eastern part of the Madeira Channel System. Shallow sediment cores collected from a number of cruises over the past 30 years, situated in three transects across the Madeira Channel System, are used to 'ground truth' the geophysical data (Fig. 1B). Cores were analyzed using a number of methods. First, cores were subject to detailed visual logging. Deposits from turbidity currents were described and categorized into planar laminated sand, ripple cross-laminated sand and mud. Detailed grain size analysis was carried out on turbidite beds using a Malvern Matersizer. Samples (1 cm^3) were taken from turbidites and disaggregated with 1% Calgon solution then shaken continuously for ~10 h. This ensured that individual sediment grains, particularly clay particles, were not clumped together into larger flocs. Samples were then analyzed three times and the average grain size distribution calculated. Geochemical analysis was carried out on cores CD166/17 and 19 using an ITRAX XRF core scanner (Croudace et al., 2006; Rothwell et al., 2006). Elemental abundance was measured down core every 0.5 mm. Cores CD166/15, 16, 17, 18, 19, 23 and 90PCM36, 37 and 39 were subject to high-resolution coccolith biostratigraphic dating, following the method of Weaver and Kuijpers (1983). Smear slides were taken down core every 5–10 cm, although intervals that were considered likely to be eroded were subject to sampling every 1 cm. Approximately 300 coccoliths were counted per smear slide.