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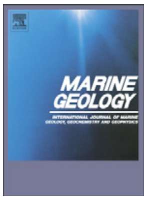

Flow dynamics and mixing processes in hydraulic jump arrays: Implications for channel-lobe transition zones

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ABSTRACT

A detailed field investigation of a saline gravity current in the southwest Black Sea has enabled the first complete analysis of three-dimensional flow structure and dynamics of a series of linked hydraulic jumps in stratified, density-driven, flows. These field observations were collected using an acoustic Doppler current profiler mounted on an autonomous underwater vehicle, and reveal that internal mixing processes in hydraulic jumps, including flow expansion and recirculation, provide a previously unrecognised mechanism for grain-size sorting and segregation in stratified density-driven flows. Field observations suggest a newly identified type of hydraulic jump, that is a stratified low Froude number (<1.5–2) subaqueous hydraulic jump, with an enhanced ability to transport sediment downstream of the jump, in comparison to hydraulic jumps in other subaerial and submarine flows. These novel field data underpin a new process-based conceptual model of channel lobe transition zones (CLTZs) that explains the scattered offset nature of scours within such settings, the temporal variations in infill and erosion between adjacent scours, how bed shear stresses are maintained across the CLTZ, and why the locus of deposition is so far downstream of the scour zone.

1. Introduction

Hydraulic jumps are characterised by a sudden decrease in velocity and an increase in thickness of a flow. In the oceans, hydraulic jumps are thought to occur within gravity-driven flows located on the continental slope (Fildani et al., 2006; Fildani et al., 2013; Kostic et al., 2010; Maier et al., 2011), within submarine canyons and channels (Sumner et al., 2013; Covault et al., 2014; Symons et al., 2016), and in channel-lobe transition zones (Wynn et al., 2002; Kostic and Parker, 2006; Macdonald et al., 2011; Shaw et al., 2013; Hofstra et al., 2015). Hydraulic jumps in these contexts have been linked to a range of processes including: erosion and scour generation, bedform formation, flow mixing, and changes in sediment distribution and stratification (Wynn et al., 2002; Cartigny et al., 2011, 2014; Sumner et al., 2013; Hofstra et al., 2015). The distribution of individual scours in linear trains on the continental slope and within canyons and channels, and in broader zones of erosion at the base-of-slope, has been linked in turn to the presence of multiple hydraulic jumps (Kostic et al., 2010; Macdonald et al., 2011).

Field measurements of hydraulic jumps in natural gravity currents are rare (Sumner et al., 2013). Given the paucity of field measurements, knowledge of subaqueous hydraulic jumps has been dominated by physical and numerical modelling (e.g., Komar, 1971; García and Parker, 1989; García, 1993). Research that follows these modelling approaches has focused on two distinct types of hydraulic jump: those formed by unsteady flows that occur in net depositional settings with chutes-and-pools and cyclic steps, and those that are formed by quasi-steady flows (e.g., Waltham, 2004; Kostic and Parker, 2006; Spinewine et al., 2009; Kostic et al., 2010; Cartigny et al., 2011; Kostic, 2011, 2014; Sumner et al., 2013). Chutes-and-pools and cyclic steps are quasi-permanent features bounded by hydraulic jumps, with chutes-and-pools differentiated by their mild slopes upstream of each hydraulic jump (e.g., Taki and Parker, 2005; Spinewine et al., 2009; Cartigny et al., 2014). Unsteady flows forming cyclic steps and chutes-and-pools are associated with Froude numbers >1.5–2 characterised by breaking waves that form periodic surges, whilst quasi-steady flows have lower

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Froude numbers, typically <1.5–2 (Spinewine et al., 2009; Cartigny et al., 2011, 2014). Cyclic steps and chutes-and-pools have been linked to linear scour trains that are prominent on many continental slopes (e.g., Fildani et al., 2006; Kostic et al., 2010), however the formative processes of distributed scour fields in channel-lobe transition zones remain enigmatic (Macdonald et al., 2011).

To address this knowledge gap we: (i) present the first field measurements of an array of subaqueous hydraulic jumps; (ii) demonstrate that these hydraulic jumps are formed by interaction of a low Froude number, $\lesssim 1$, flow with seafloor topography; and (iii) assess the flow processes within the hydraulic jumps in terms of mixing, fluid entrainment and their spatial influence downstream. We synthesize these observations to propose a novel conceptual model for low Froude number subaqueous hydraulic jumps over scours, and finally to propose a process-based model of channel-lobe transition zones (CLTZ) that addresses the nature of hydraulic jumps across these scour fields. These novel field data, and the new model of a stratified hydraulic jump derived from it, will inform geohazard risk assessment and hydrocarbon extraction in these complex environments.

2. Geological setting

The Mediterranean Sea and Marmara Sea are more saline (~35 ppt) than the adjacent Black Sea (~18 ppt) (Latif et al., 1991; Parsons et al., 2010), creating a sub-aqueous saline exchange flow (gravity current) through the Bosphorus Strait into the southwest Black Sea, Fig. 1 (Latif et al., 1991; Özsoy et al., 2001; Oğuz, 2005; Flood et al., 2009; Parsons et al., 2010; Sözer, 2013; Sumner et al., 2013, 2014). The Mediterranean Sea has a density of ~1026 kg m^{-3} whereas the Black Sea has a density of ~1014 kg m^{-3} (Hiscott et al., 2013; Sumner et al., 2014), forming a relative density difference of 1.3%. This density difference is similar to the density difference between low concentration turbidity currents and ambient seawater (Pirmez and Imran, 2003; Konsoer et al., 2013; Peakall and Sumner, 2015).

The Black Sea shelf gravity current is confined within a sinuous channel (Fig. 1), achieves velocities of up to 1.5 m/s, is up to 30 m thick, and is sufficiently energetic to transport and rework coarse sand (Özsoy et al., 2001; Sumner et al., 2013). There has been extensive debate on the history of the Holocene reconnection of the Mediterranean and Black Seas, in particular on whether this was associated with a catastrophic flood into the Black Sea (e.g., Ryan et al., 1997, 2003; Thom, 2010), or gradual overtopping of the Black Sea into the Mediterranean via the Marmara Sea (e.g., Hiscott et al., 2002, 2007; Aksu et al., 2016). The most recent connection has been estimated at >8 ka to ~11 ka BP (e.g. Ryan et al., 2003; Hiscott et al., 2007; Thom, 2010; Mertens et al., 2012; Aksu et al., 2016), and activation of the channel on the Black Sea Shelf (Fig. 1), constrained through levee development, has been dated to ~7.5 ka BP suggesting that the channel formed subaqueously rather than via a subaerial catastrophic flood (Flood et al., 2009). The inflow to the Black Sea channel has a quasi-steady discharge, except when very strong onshore winds strengthen the Black Sea outflow, blocking the saline-driven inflow (Latif et al., 1991; Özsoy et al., 2001).

From the Strait of the Bosphorus, the main channel curves northwest following the seafloor slope. Upstream of the curved section, the flow passes over a series of steps and scours on the seafloor (Fig. 2). These seafloor features, and the varying width of the channel, force complex adjustment of the flow resulting in flow acceleration, deceleration and development of hydraulic jumps, as discussed in Sections 4 and 5. After this initial bend, the local channel relief decreases and the flow

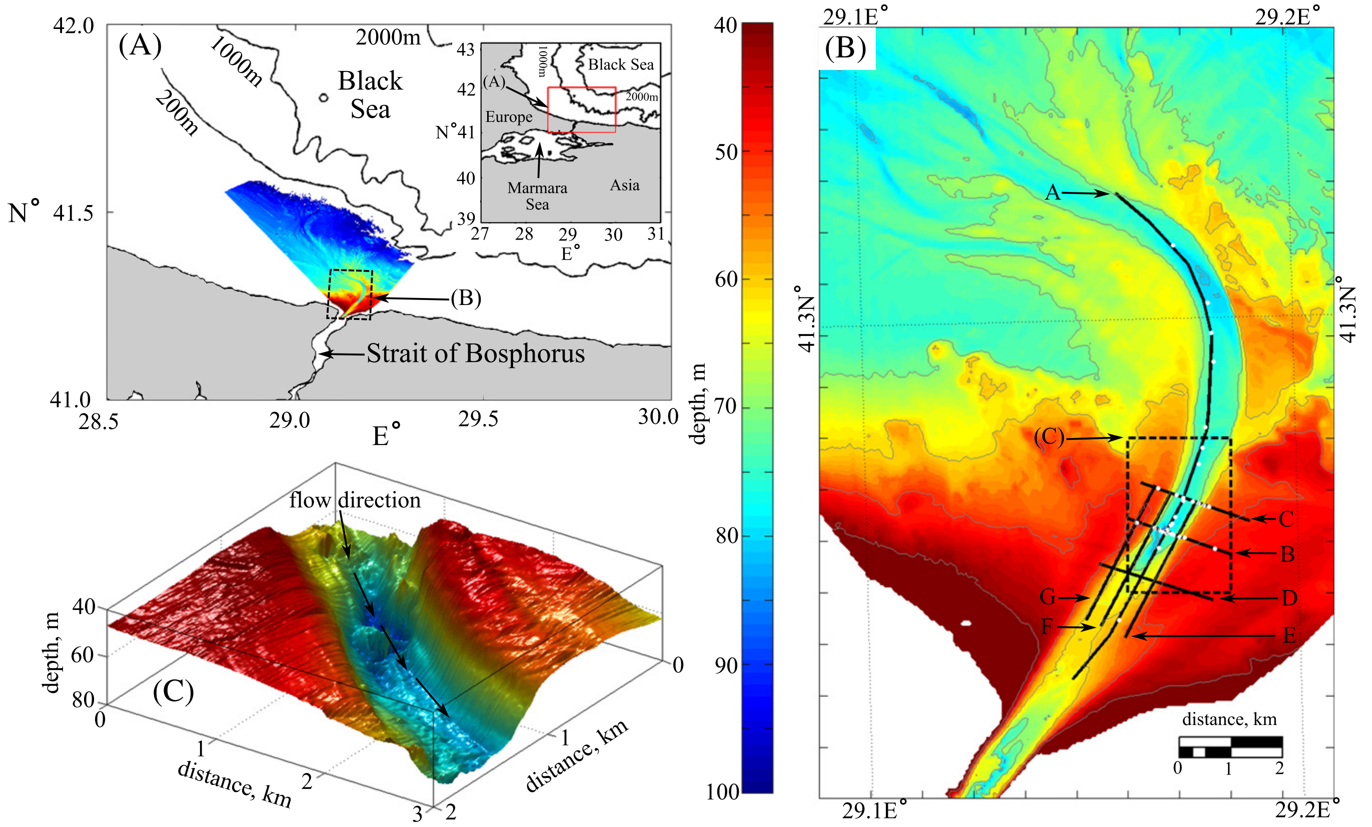

Fig. 1. (a) The location of the field site, in the southwest Black Sea (bathymetry data from GEBCO, 2014). (b) A bathymetric map of the channel system showing depth below sea-level, ADCP Transects A–G, denoted by solid black lines, and locations of CTD profiles, denoted by white circles. (c) Three-dimensional visualization of the channel system, at the location of the largest hydraulic jump located at the intersection of Transects A and B.