First direct measurements of hydraulic jumps in an active submarine density current

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[1] For almost half a century, it has been suspected that hydraulic jumps, which consist of a sudden decrease in downstream velocity and increase in flow thickness, are an important feature of submarine density currents such as turbidity currents and debris flows. Hydraulic jumps are implicated in major seafloor processes, including changes from channel erosion to fan deposition, flow transformations from debris flow to turbidity current, and large-scale seafloor scouring. We provide the first direct evidence of hydraulic jumps in a submarine density current and show that the observed hydraulic jumps are in phase with seafloor scours. Our measurements reveal strong vertical velocities across the jumps and smaller than predicted decreases in downstream velocity. Thus, we demonstrate that hydraulic jumps need not cause instantaneous and catastrophic deposition from the flow as previously suspected. Furthermore, our unique data set highlights problems in using depth-averaged velocities to calculate densimetric Froude numbers for gravity currents.
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1. Introduction

[2] Submarine sediment density flows transfer terrestrially derived sediment from the continental shelf into the deep ocean [*Talling et al*., 2007]. Such flows are pulled downslope by gravity acting on their excess density relative to ambient seawater. Abrupt changes in flow velocity and density are commonly invoked to occur at hydraulic jumps [*Menard*, 1964; *Komar*, 1971; *Garcia*, 1993] where flow velocity rapidly decreases and flow thickness abruptly increases (Figure 1). Such phenomena are thought to be a key control governing sediment distribution in the deep sea, influencing the loci of seafloor sedimentation, and ultimately controlling the character and distribution of modern and ancient sedimentary sequences. For example, hydraulic jumps are used to explain a change from dominantly erosive, or bypassing, behavior on the continental slope to deposition of submarine fans on the flatter slopes of basin plains [e.g., *Menard*, 1964; *Komar*, 1971; *Kostic and Parker*, 2006]. Recent advances in seafloor imaging have demonstrated that the “transition zone” from channelized flow on the slope to unchannelized flow on the basin floor is often characterized by scattered scours and sediment waves, sometimes extending tens of kilometers from the channel mouth [*Wynn et al*., 2002; *Duarte et al*., 2010; *Macdonald et al*., 2011a]. The exact origin of these transition zones remains unclear, although scours in these zones have been linked with hydraulic jumps [*Macdonald et al*., 2011a]. Hydraulic jumps may also play a role in the transformation of higher-concentration debris flow into lower-concentration turbidity current [*Weirich*, 1988; *Piper et al*., 1999]. Thus, hydraulic jumps are implicated in a range of major seafloor processes; however, they have never been previously observed in a field-scale submarine density current. Therefore, most of our understanding of these flows has been derived from studies that have inferred processes from deposits and by exploring behavior using small-scale experimental flows. A gulf in scale and understanding thus exists between the process dynamics of these flows and their sedimentary deposits.

2. Densimetric Froude Numbers

[3] Hydraulic jumps occur at transitions from supercritical to subcritical flow. In a supercritical flow regime, inertial forces dominate gravitational forces; the flow travels faster than a surface wave propagates along its surface, resulting in a flow that is relatively thin and fast. In a subcritical flow regime, gravitational forces exceed inertial forces; the flow travels more slowly than a surface wave would propagate along its surface, resulting in a flow that is relatively thick and slow. At the point in a flow where flow velocity and wave velocity are equal, a hydraulic jump occurs because surface waves can no longer propagate upstream, resulting in an abrupt increase in flow thickness and decrease in downstream velocity (Figure 1).

[4] The Froude number ($Fr = \frac{U}{\sqrt{gh}}$) is a dimensionless number that compares the velocity of a flow (U, where U is depth-averaged velocity) to the speed that a surface wave would propagate along its surface ($\sqrt{gh}$, where g is acceleration due to gravity, and h is the thickness of the flow). $Fr > 1$ describes a supercritical flow, $Fr < 1$ describes a subcritical flow, and $Fr = 1$ describes the critical point at which a hydraulic jump occurs. In the case of density currents, a

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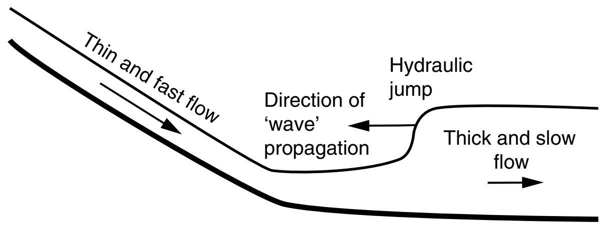

Figure 1. Schematic diagram showing the key features of a hydraulic jump.

densimetric Froude number (Fr_d) is used that modifies the above equation to account for reduced gravity ($Fr_d = \frac{U}{g\rho' h}$, where ρ' is the excess density of the flow).

[5] Recent studies have suggested that if the densimetric Froude number is applied to density currents in its above form, then the critical Froude number at which a hydraulic jump occurs need not be unity [*Waltham*, 2004; *Huang et al.*, 2009]. This is because density currents can have highly nonuniform vertical velocity and stratification profiles [*Waltham*, 2004] and discharge may not be constant due to entrainment of ambient fluid and erosion and deposition of sediment [*Huang et al.*, 2009]. *Waltham* [2004] suggested that in order for the critical Froude number to be unity for density currents, it might be appropriate to use some other characteristic flow velocity.

3. Study Area and Methods

[6] The Black Sea density current results from an inflow of saline Mediterranean water via the Bosphorus Strait. This flow has carved a sinuous channel system in water depths of 70–120 m (Figure 2) [*Flood et al.*, 2009]. Despite being driven by the salinity contrast, the flow is sufficiently energetic to transport and rework coarse sand within the channel network [*Özsoy et al.*, 2001]. The relatively shallow depths of the channel and the quasi-continuous nature of the associated density current provide a unique opportunity to study three-dimensional flow dynamics and the interaction of the flow with a seafloor channel network. The three-dimensional flow velocity was measured along the channel axis using a 1200 kHz acoustic Doppler current profiler (ADCP) deployed from *Autosub3*, an autonomous underwater vehicle. Additionally, conductivity-temperature-depth (CTD) profiles were also acquired from R/V *Koca Piri Reis* during the 48 h of ADCP measurements. Further details of how the data were analyzed and how errors were calculated can be found online in Text S1 in the supporting information.

4. Results

[7] An ADCP transect taken along the longitudinal axis of the proximal channel (Figures 2 and 3), together with CTD information, reveals that the density current is up to 25 m thick, attains a maximum velocity of 1.5 m/s, and has a depth-averaged density of 1024 kg/m^3, which changes negligibly along the 2.2 km long transect (Figure 3a). The measured flow field exhibits two prominent hydraulic jumps (Figure 3a: jumps I and II) identified from abrupt increases in flow thickness and decreases in downstream velocity. The edges of two further off-axis hydraulic jumps lateral to the measured downstream section also occur (Figure 3a: labels III and IV); these are inferred from abrupt and angular changes in the thickness of denser portions of the flow. The more distal of the two axial hydraulic jumps (jump II) is in phase with a ~100 m long and ~12 m deep scour in the seafloor. This scour forms part of a field of scours within the channel that is ~2 km long and ~0.7 km wide (Figure 2b shows the distal 1.5 km of the scour field). Analysis of the bathymetry (Figure 2) reveals that hydraulic jumps I, III, and IV are also likely associated with seafloor scours. Each hydraulic jump is characterized by locally high vertical velocities: up to 20 cm/s and 30 cm/s for jumps I and II, respectively (Figure 3b). A vertical velocity of 20 cm/s can support a 1.9 mm quartz grain [*Gibbs et al.*, 1971]; thus, flow velocities

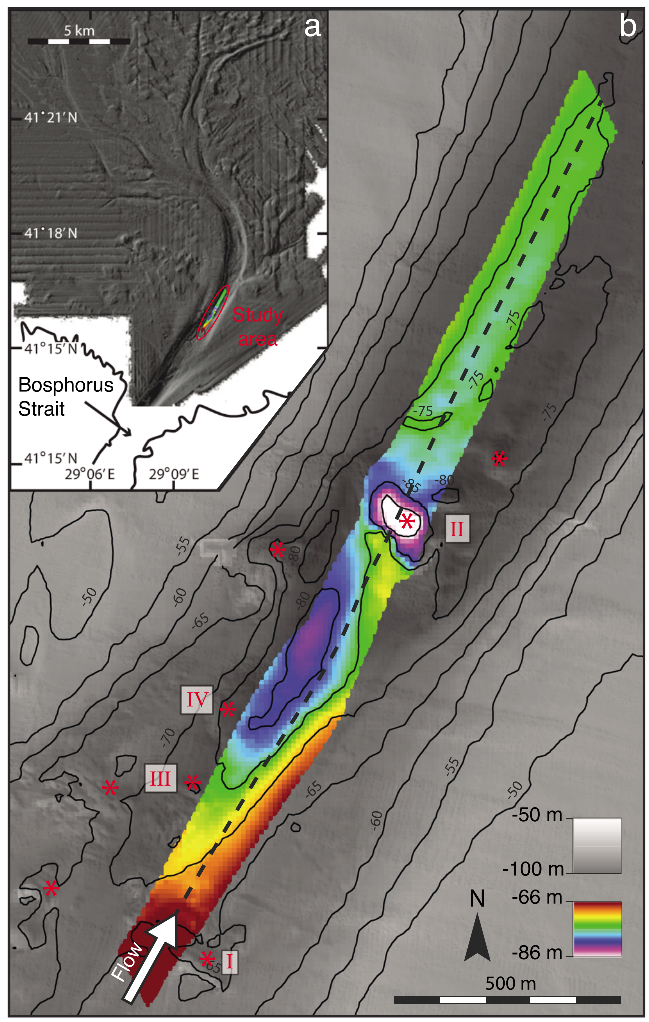

Figure 2. (a) The location of the study area in the proximal part of a submarine channel system on the southwest Black Sea shelf (bathymetry reproduced from *Flood et al.* [2009]). (b) Colored bathymetry shows high-resolution bathymetry data along the *Autosub3* path presented in this study (background gray scale bathymetry derived from R/V *Alliance* multibeam data courtesy of NATO Undersea Research Centre). Dashed black line shows the position of the ADCP transect presented in Figure 3, large white arrow shows the dominant flow direction from SW to NE, and red asterisks highlight the positions of scours in the seafloor. Roman numerals I–IV associate individual scours with the hydraulic jumps similarly numbered in Figure 3.

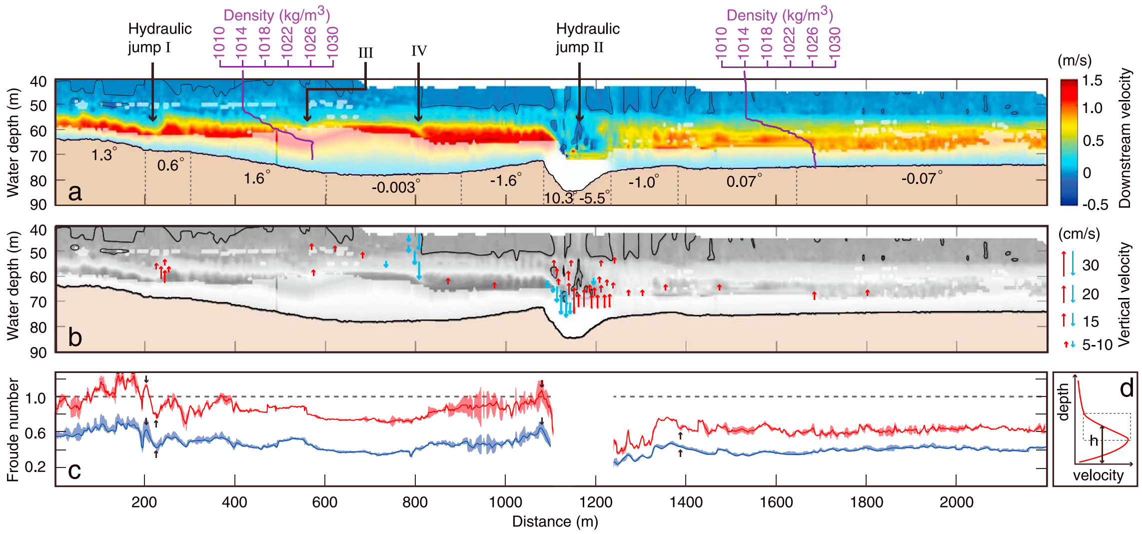

Figure 3. (a) Downstream velocity along the 2.2 km long straight channel section indicated by the dashed line in Figure 2b. ADCP data suffer a blank zone adjacent to the seafloor; in this region, velocities have been linearly interpolated to zero velocity at the seafloor, with interpolated data indicated by lighter shading. The black line in the water column indicates downstream velocities of zero. The downstream profile exhibits two hydraulic jumps (I and II) and, potentially, the edges of two further hydraulic jumps (III and IV) that occur lateral to the measured downstream section. The image is vertically exaggerated, and seafloor gradients are provided in Figure 3a. Two vertical density profiles are superimposed on the primary velocity field. (b) Gray scale image of the velocity field in Figure 3a, with colored arrows superimposed showing the magnitude of vertical velocities within the flow. Only the vertical velocities with magnitude greater than 5 cm/s are shown. (c) Densimetric Froude numbers along the velocity transect. Blue line is calculated using depth-averaged velocity, and red line is calculated using the maximum flow velocity (see text); shaded red and blue areas represent the maximum and minimum values of Froude number calculated using the standard deviation in the error measurements (see Text S1); black arrows indicate the values used in Figure 4. (d) Cartoon illustrating the depth over which flow velocities (and densities) were depth averaged.

across the hydraulic jumps are capable of transporting sediment up to very coarse sand.

[8] Densimetric Froude numbers were calculated along the length of the transect (Figure 3c, blue line); density and velocity were depth averaged from the seafloor to halfway up the mixing zone (Figure 3d). The excess density of the flow was calculated using a depth-averaged density of 1024 kg/m^3 and an ambient density of 1012 kg/m^3. Hydraulic jump I has an incoming densimetric Froude number of 0.65 (range including error: 0.58–0.78) and a postjump densimetric Froude number of 0.42 (0.39–0.50); hydraulic jump II has an incoming densimetric Froude number of 0.65 (0.63–0.72) and a postjump densimetric Froude number of 0.45 (0.44–0.46). Thus, the densimetric Froude number is everywhere less than 0.73, and the critical Froude number is approximately 0.5 based on the Froude number when the flow passes through the two hydraulic jumps.

5. Discussion

5.1. Critical Froude Number for Subaqueous Density Currents

[9] The critical densimetric Froude number of our flow is nonunity when the Froude number is defined using depth-averaged quantities. However, given that the Froude number represents the ratio of flow velocity to wave speed, conceptually, it makes sense for it to be unity when a hydraulic jump occurs. We therefore consider how the densimetric Froude number might be appropriately modified. This approach is constructive because it should enable comparison of our data with previous studies where the critical Froude number has been assumed to be unity. Adjusting our Froude numbers requires either that the velocity used in the calculation is greater than the depth-averaged flow velocity or that the thickness and excess density of the flow are reduced. We experimented with characterizing velocity, density, and flow thickness in different ways, including depth averaging the flow over different flow thicknesses. We found that the critical densimetric Froude number becomes unity for both hydraulic jumps if the maximum flow velocity is used and all other parameters remain unchanged. This results in jump I having an incoming densimetric Froude number of 1.14 (1.13–1.15) and a postjump densimetric Froude number of 0.79 (0.77–0.79) and hydraulic jump II having an incoming densimetric Froude number of 1.06 (0.95–1.17) and a postjump densimetric Froude number of 0.66 (0.63–0.69). Conceptually, this suggests that so long as part of the flow has equal velocity to the surface wave, then the surface wave cannot propagate upstream. We do not suggest that this is an exhaustive consideration of how the Froude number should be modified; further discussion is provided in *Waltham* [2004]. It is likely that the stratification of the flow needs to be more fully considered, which is beyond the scope of this paper. Hopefully, we have provided a starting point for future studies.

5.2. Comparison With Small-Scale Experiments

[10] The Froude number of a flow prior to a hydraulic jump controls the characteristics of the hydraulic jump [e.g., *Bélanger*, 1828; *Garcia*, 1993]. With increasing incoming

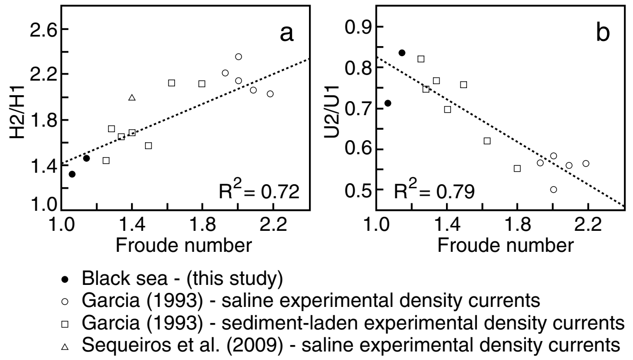

Figure 4. Ratios of (a) outgoing flow depth to incoming flow depth (H2/H1) and (b) outgoing velocity to incoming velocity (U2/U1) plotted against incoming Froude number for experimental hydraulic jumps and data from this study.

Froude number, hydraulic jumps have been shown to exhibit a greater increase in flow depth (Figure 4a) and a larger decrease in flow velocity (Figure 4b) across the transition from supercritical to subcritical states. Our understanding of how hydraulic jumps function in field-scale systems is, at present, necessarily underpinned by small-scale experimental studies [e.g., *Garcia and Parker*, 1989]. To compare our field-scale data with previous experimental data, it is necessary to assume a critical Froude number of 1, and therefore, in what follows, we use the maximum flow velocity to calculate the Froude number. If we do this, field-scale data from the Black Sea and existing experimental data follow similar trends (Figure 4), suggesting that earlier scaled laboratory experiments do capture the essential physics of natural systems. However, it is notable that all previous experiments have been conducted at higher incoming Froude numbers than we have observed in the field-scale data [*Garcia and Parker*, 1989; *Garcia*, 1993]. Importantly, the effect of this is to exaggerate the potential importance of hydraulic jumps in decelerating field-scale density currents.

[11] Experimental and theoretical studies have suggested that on average, hydraulic jumps cause doubling in flow thickness and halving of flow velocity [e.g., *Komar*, 1971; *Garcia and Parker*, 1989; *Garcia*, 1993]. However, this would be only true if the average flow has a Froude number in excess of 2 just prior to the hydraulic jump (Figure 4). This is not the case for the field data herein, where we calculate much lower incoming Froude numbers, even using maximum incoming flow velocity. Interestingly, it also does not appear to be the case for many full-scale density currents based on estimates of unmeasured natural flows, calculated using three methods: (i) slope gradients, (ii) flow superelevation around bends, and (iii) the character of the deposited sediment [e.g., *Bowen et al.*, 1984; *Pirmez and Imran*, 2003]. Using the first method, it is inferred that flows in the Navy Channel, California, probably did not exceed Froude numbers of 1.4 and approached unity around the upper fan [*Bowen et al.*, 1984]. Using all three methods for the Amazon Canyon and Fan, *Pirmez and Imran* [2003] concluded that Froude numbers were probably just greater than 1 in the canyon and less than 1 on the fan. There are a limited number of studies that have estimated the supercriticality of submarine density currents; however, the available data suggest that it is unusual for flows to have sufficiently high incoming Froude numbers to result in halving in downstream velocity and doubling in flow thickness.

5.3. Implications for Sedimentation in the Deep Sea

[12] The hydraulic jumps measured in the Black Sea are each associated with scours in the seafloor. As discussed previously, the decrease in downstream velocity and increase in flow thickness across the jumps is less than expected based on previous (experimental) work. However, each hydraulic jump is associated with a localized region with strong vertical velocities. Given that the Reynolds number does not change across a hydraulic jump, turbulence is not expected to fall [*Waltham*, 2004], so these vertical velocities represent a local repartitioning of turbulence within the flow, rather than additional turbulence. If, as this study suggests, submarine density currents are commonly only weakly supercritical, then contrary to current theory, individual hydraulic jumps may not result in rapid deceleration of the flow and catastrophic deposition of sediment. Instead, the density current may undergo the transition from supercritical to subcritical flow at different points spatially, producing a region of scattered hydraulic jumps and strong vertical uplift, similar to that observed on the Black Sea shelf. This field of hydraulic jumps would help to maintain sediment in suspension, rather than causing instantaneous and catastrophic deposition of sediment from the flow. This provides an explanation for currently enigmatic features on the seafloor such as fields of scattered scours commonly observed in channel-lobe transition zones [e.g., *Wynn et al.*, 2002; *Duarte et al.*, 2010; *Macdonald et al.*, 2011a, 2011b].

6. Conclusions

[13] Hydraulic jumps have been implicated in a wide array of major seafloor processes. Despite their importance, hydraulic jumps have never been previously measured in a field-scale submarine density current, and therefore, their presence has been only postulated, and their impact on the flow has had to be surmised from small-scale experiments, numerical modeling, and analysis of their deposits. We provide the first direct field evidence of hydraulic jumps in a submarine density current. Each hydraulic jump appears to be in phase with a scour in the seafloor and causes a localized region with strong vertical velocities.

[14] Calculation of the densimetric Froude number reveals that either the critical Froude number for this flow is nonunity, or alternatively, it is inappropriate to employ the traditional method that uses depth-averaged flow velocities when calculating Froude numbers for gravity currents. Instead, it may be more appropriate to use the maximum flow velocity in the profile. Comparison of our field data with small-scale experiments suggests that the experiments capture the principal physics of the natural system. However, these previous experiments have likely exaggerated the impact of individual hydraulic jumps in reducing the velocity and increasing the thickness of submarine density currents because the experiments were conducted at high prejump Froude numbers. This, combined with the strong localized vertical velocities across an array of hydraulic jumps, provides an explanation for previously enigmatic seafloor features such as the fields of scours that commonly form within channel-lobe transition zones.

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