Earth and Planetary Science Letters 450 (2016) 208–220

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Preconditioning and triggering of offshore slope failures and turbidity currents revealed by most detailed monitoring yet at a fjord-head delta

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ARTICLE INFO

Article history:
Received 25 February 2016
Received in revised form 13 June 2016
Accepted 15 June 2016
Available online 5 July 2016
Editor: M. Frank

Keywords:
river delta
submarine landslides
turbidity current
geohazard
mass failure
sediment flow

ABSTRACT

Rivers and turbidity currents are the two most important sediment transport processes by volume on Earth. Various hypotheses have been proposed for triggering of turbidity currents offshore from river mouths, including direct plunging of river discharge, delta mouth bar flushing or slope failure caused by low tides and gas expansion, earthquakes and rapid sedimentation. During 2011, 106 turbidity currents were monitored at Squamish Delta, British Columbia. This enables statistical analysis of timing, frequency and triggers. The largest peaks in river discharge did not create hyperpycnal flows. Instead, delayed delta-lip failures occurred 8–11 h after flood peaks, due to cumulative delta top sedimentation and tidally-induced pore pressure changes. Elevated river discharge is thus a significant control on the timing and rate of turbidity currents but not directly due to plunging river water. Elevated river discharge and focusing of river discharge at low tides cause increased sediment transport across the delta-lip, which is the most significant of all controls on flow timing in this setting.

1. Introduction

Rivers and offshore turbidity currents are the two most volumetrically important sediment transport processes on Earth, and form its most extensive sedimentary deposits (Ingersoll et al., 2003). It is important to understand how these two types of sediment-and-water flows are linked. For instance, how do changes in discharge from a river affect the frequency and character of turbidity currents, and how exactly are turbidity currents triggered immediately offshore from river mouths? Understanding controls on turbidity current frequency is also societally important as turbidity currents damage important seafloor infrastructure including telecommunications cables or pipelines (Carter et al., 2014), whilst submarine slope failures can trigger tsunamis (e.g. Prior et al., 1982).

River deltas can be sub-divided according factors that include the degree of wave or tidal action (Bhattacharya and Giosan, 2003), magnitude and type of river (e.g. bedload or suspended load-dominated; sand or gravel), offshore gradient, development of mouth bars and inertial or frictional mouth jets, and whether the river enters seawater or freshwater (Wright, 1977; Orton and Reading, 1993). Here we study offshore slope failure and turbidity currents generated at a marine fjord-head delta, which is one of the most common type of delta system globally. Fjord-head deltas are often characterised by limited fetch and hence wave heights, relatively steep offshore gradients, and coarse grained (sand or gravel) rivers with significant bedload transport from surrounding mountainous catchments. As with many other fjord head systems (e.g. Syvitski and Shaw, 1995), the delta that we study here is also affected by significant tides.

Multiple triggers are proposed for turbidity currents and landslides offshore from river mouths, including fjord-head systems (Fig. 1; Forel, 1888; Mulder et al., 2003; Piper and Normark, 2009). Debate surrounds the relative importance of these different triggers in river-fed systems, and there is a compelling need to test these alternative hypotheses (Fig. 1; Table 2). These preconditioning and triggering factors can be grouped into those due to plunging (hyperpycnal) river discharges that continue along the seafloor as turbidity currents, settling of sediment from a lower concentration surface (homopycnal) plume that generated underflows along the bed, or submerged slope failures that disintegrate to form turbidity currents. If sediment-laden river-water is dense enough to plunge, it continues to form a hyperpycnal turbidity current (Forel, 1888; Mulder and Syvitski, 1995; Parsons et al., 2001;

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http://dx.doi.org/10.1016/j.epsl.2016.06.021

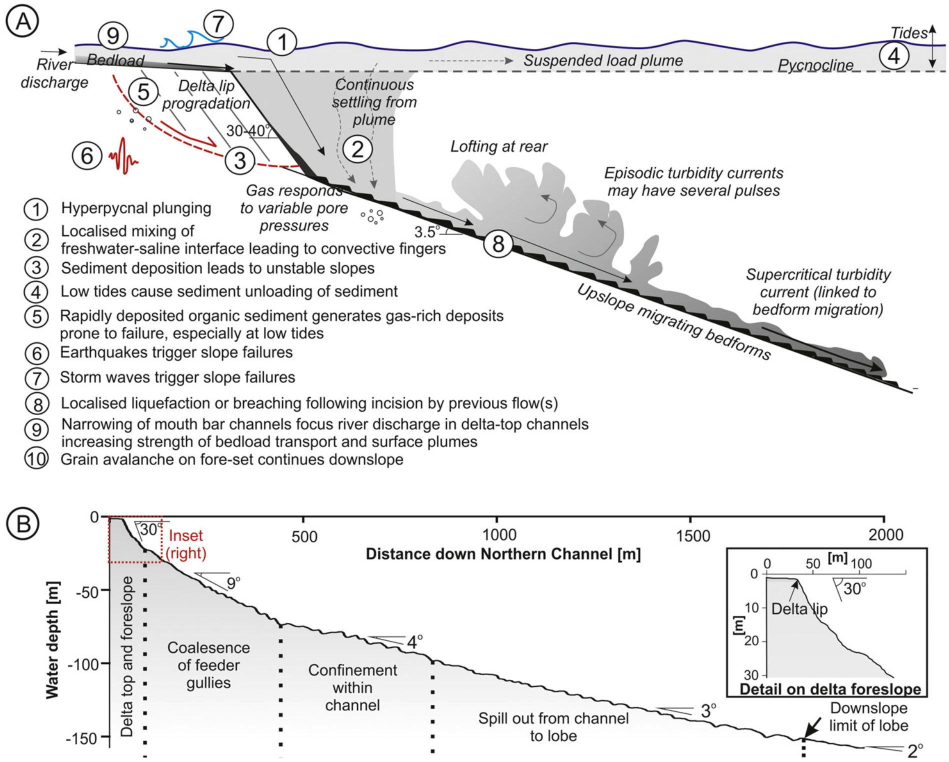

Fig. 1. (A) Previous hypotheses for triggering of slope failures and turbidity currents at fjord-head deltas with bedload-dominated rivers (upper panel; also see Table 2). (B) Water depth and slope angles based on Squamish delta slope (lower panel).

Mulder et al., 2003; label *1* in Fig. 1). Mixing of the freshwater-saline interface can cause enhanced settling of sediment due to convective fingers, at much lower (>1 kg/m^3) sediment concentrations (*2*; Parsons et al., 2001). As river flow expands at the coast, rapid sediment deposition can create unstable slopes prone to failure, resulting in turbidity currents (*3*, Prior et al., 1987; Carter et al., 2014). It has been proposed that slope failures can result from high excess pore pressures due to such rapid sedimentation, tidal unloading of sediments (*4*) and expansion of gas bubbles within organic rich deltaic sediment (*5*; Christian et al., 1997), earthquake shaking (*6*; Carter et al., 2014), or cyclic loading by storm waves (*7*; Prior et al., 1989). An initial turbidity current may cause failure by undercutting slopes, and contraction of sediment may create prolonged failures called breaches (*8*; Van Den Berg et al., 2002; Mastbergen and Van Den Berg, 2003). Low tides may also focus river discharge in delta-top channels thereby increasing significantly the strength of bedload transport and surface plumes (*9*; Prior et al., 1987; Hughes Clarke et al., 2012a; Dietrich et al., 2016). In areas of steep offshore topography, avalanching of sediment across the delta-lip may generate steep (30°) foresets that characterise Gilbert-type deltas (*10*; Gilbert, 1885; Postma et al., 1988).

However, these hypotheses are problematic to test as very few field data sets document the exact timing of turbidity currents and submerged slope failures, as they are difficult to monitor directly (Talling et al., 2015). Such information is key for determining the relative importance of river discharge, tides, or other triggering factors. No previous direct monitoring study has documented more than a few tens of turbidity currents; and in most cases far fewer (e.g. Prior et al., 1987 at Bute Inlet; Lambert and Giovanoli, 1988 in Lake Geneva; Cooper et al., 2013 in Congo Canyon; Carter et al., 2014 in Gaoping Canyon; Xu et al., 2014 in Monterey Canyon). Statistical analysis of event frequency and triggers has therefore been restricted to much less precisely dated ancient turbidity current and landslide events, with comparisons only possible with longer-term processes such as sea level change (e.g. Droxler and Schlager, 1985; Clare et al., 2014).

Here we present the first statistical analysis of >100 precisely-timed individual submarine landslide and turbidity current events from Squamish Delta in British Columbia, Canada (Hughes Clarke et al., 2012a, 2014). Event timing was determined from (i) a seafloor Acoustic Doppler Current Profiler (ADCP), and (ii) 93 approximately-daily repeat multibeam echo-sounder (MBES) surveys that document changes in seafloor morphology. This location represents arguably the most detailed monitoring of a turbidity current system that combines an exceptional number of repeat mapping surveys with direct flow measurements (Hughes Clarke et al., 2012a, 2012b, 2014; Hughes Clarke, 2016).

Three distinct types of event are recorded in this dataset (Hughes Clarke et al., 2012a, 2014). Infrequent, large-scale, deep-seated collapses of the prograding delta-lip are termed “delta-lip failures” More frequent events involve the upstream-migration of bedforms within channels on the submarine prodelta are termed “bedform events”. These bedform events may be further subdivided into those associated with an initial slope failure scar, and those that lack a visible (<0.5–1 m high) failure scar (“events without a headscar”).

2. Aims

Our overall aim is to understand the factors that precondition or trigger slope failure and turbidity currents on this fjord-head delta using an exceptionally detailed field data set. The first specific aim is to understand the factors that cause large-scale (>20,000 m^3) failures of the delta-lip, whilst the second aim is to understand the causes of bedform events. In the case of the second aim this includes statistical analysis of their relationship between the timing of these events and changes in river discharge and tidal elevation. Is river discharge or tidal elevation a stronger control, and do these two factors have independent or combined effects on