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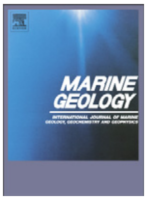

On the triggers, resulting flow types and frequencies of subaqueous sediment density flows in different settings

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ABSTRACT

Turbidity currents, and other types of underwater sediment density flow, are arguably the most important flow process for moving sediment across our planet. Direct monitoring provides the most reliable information on the varied ways in which these flows are triggered, and thus forms the basis for this contribution. Recent advances in flow monitoring make this contribution timely, although monitoring is biased towards more frequent flow types. *Submarine deltas fed by bedload dominated rivers* can be very active with tens of events each year. Larger events are generated by delta-lip failures, whilst smaller events can be associated with motion of up-slope migrating bedforms. *River-fed submarine canyons* are flushed every few years by powerful long run-out flows. Flows in river-fed delta and canyon systems tend to occur during months of elevated river discharge. However, many flows do not coincide with flood peaks, or occur where rivers do not reach hyperpycnal concentrations, and are most likely triggered by failure of rapidly deposited sediment. Plunging of hyperpycnal river floodwater commonly triggers dilute and slow moving flows in lakes and reservoirs, and has been shown to produce mm-thick fine-grained deposits. It is proposed here that such thin and fine deposits are typical of flows triggered by hyperpycnal river floods, rather than thicker sand layers with traction structure or displaying inverse-to-normal grading. *Oceanographic canyons* are detached from river mouths and fed by oceanographic processes (wave and tide resuspension, longshore drift, etc.). Most events in these canyons are associated with large wave heights. Up-slope migrating crescentic bedforms are seen, similar to those observed in river-fed deltas. Oceanographic processes tend to infill canyons, which are flushed episodically by much more powerful flows, inferred to result from slope failure. This filling and flushing model is less applicable to river-fed canyons in which flushing events are much more frequent. Oceanographic canyons may result from rapid sea level rise that detaches river mouths from canyon heads, and they can remain active during sea level highstands. Deep-water basin plains are often dominated by infrequent but very large flows triggered by failure of the continental slope. Recurrence intervals of these flows appear almost random, and only weakly (if at all) correlated with sea level change. Turbidites can potentially provide a valuable long-term record of major earthquakes, but widespread slope failure is the only reliable criteria for inferring seismic triggering. However, not all major earthquakes trigger widespread slope failure, so that the record is incomplete in some locations.

1. Introduction

Turbidity currents, and other types of submarine sediment density flow (Talling et al., 2012a), are arguably the volumetrically most important process for transporting sediment across our planet (Table 1). They dominate sediment transport into many parts of the deep ocean, and form the most extensive sediment accumulations on Earth (submarine fans). Subsurface deposits from ancient flows contain major oil and gas reserves. Individual turbidity currents can on occasions contain more than ten times the annual sediment flux for all of the world's rivers (Table 1), and be more than 200 km wide (Talling et al., 2007a). Some flows can travel at speeds of 3 to 19 m/s for hundreds of kilometres, and break networks of sea floor cables (Piper at al., 1999; Hsu et al., 2008; Carter et al., 2012; Cattaneo et al., 2012). These cables now carry 95% of transoceanic data traffic, including the internet and financial markets (Carter et al., 2009). Seafloor infrastructure for recovering oil and gas, in some cases worth tens of millions of pounds, can also be damaged by fast moving flows (Barley, 1999). Flow deposits (turbidites) potentially provide a record of even larger (up to >3000 km^3) submarine landslides, which can produce damaging tsunamis (Masson et al., 2006). Some slope failures are triggered by earthquakes, and turbidites may provide a valuable long-term record of major earthquakes (Goldfinger, 2011), although this record may sometimes be incomplete (Völker et al., 2011; Atwater and Griggs, 2012; Sumner et al., 2013). Turbidity currents play an important role in the burial of organic material and thus in the global carbon cycle (Galy et al., 2007). Understanding the frequency of these flows,

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Table 1
Volumes and frequencies of different types of event.

Process	Volume	Average frequency	Some key references
Slope failures			
Storegga Slide offshore Norway	>3000 km^3	–	Haflidason et al. (2005)
15 non-volcanic slides in last 36 ka >100 km^3; only well dated examples	>100 km^3	Less than 2400 years	Urlaub et al. (2013a) (global database)
1929 Grand Banks landslide-turbidite	~175 km^3	–	Piper et al. (1999)
Turbidites in Madeira, Agadir, Seine, and Balearic abyssal plains	~5–250 km^3	1 per 1,000 to 40,000 years	Clare et al. (2014), Talling et al. (2007a)
Volcanic island flank collapses of the Western Canary Islands	50–500 km^3	1 per 150,000 years	Masson et al. (2006), Hunt et al. (2011)
Canyon head failures (can run out to deep ocean)	~0.01–0.001 km^3	0.1–5 per year	Piper and Savoye (1993), Cooper et al. (2013), Carter et al. (2012), Hsu et al. (2008), Marshall (1978).
Delta-lip failures — Canadian fjords	~0.0001 km^3	1–5 per year	Hughes Clarke et al. (2012), Hill (2012)
Individual river floods			
Largest floods of single rivers Single river in one flood in Taiwan	0.03–0.06 km^3	1–50 years	Liu et al. (2013)
Single flood of Santa Clara River	0.04 km^3	Decadal	Gorsline et al. (2000)
Single large flood of Var River	0.007 km^3	Decadal	Mas et al. (2010)
Jokullhlaup in Iceland, 1996	0.07 km^3	–	Maria et al. (2000)
Average annual river fluxes			
Var River	0.0006 km^3	Annual	Khripounoff et al. (2012)
Rhone River	0.003 km^3	Annual	Lambert and Giovanoli (1988)
Taiwan (total of all rivers on island)	0.1–0.2 km^3	Annual	Liu et al. (2013)
Largest annual flux from a single river (Amazon)	0.4 km^3	Annual	Milliman and Syvitski (1992)
All the rivers in world for a year	~6 km^3	Annual	Milliman and Syvitski (1992)
Oceanographic or anthropogenic events			
Deep water cascading (sediment) in single canyon during a winter event	0.005 km^3	–	Canals et al. (2006, 2009)
Trawling in Fonera Canyon (one year)	0.00024 km^3	Annual	Puig et al. (2012)
Volcanic processes			
Largest caldera forming eruptions, e.g. Toba ~74 ka	2800 km^3	1 per 800,000 years globally	Self (2006)
Super-eruptions (>450 km^3) — e.g. Taupo 26 ka	>450 km^3	1 per 100,000 years globally	Self (2006)
Krakatoa in 1883	~12 km^3	1 per 50 years globally	Self (2006)
Mount St Helens in 1980 (erupted)	~1 km^3	1 per 10 years globally	Self (2006)
Dome collapse and pyroclastic flow on Montserrat in 2003	0.21 km^3	–	Trofimovs et al. (2006)
Other processes			
Snow avalanches	Typically <0.001 km^3	–	McClung and Shaerer (2005)
Lahars at Nevado del Ruiz in 1985 and Mount St Helens in 1980	0.1 km^3		Pierson et al. (1990)
Sediment mobilised on land during a single major earthquake	5–15 km^3		Parker et al. (2011)

and their timing and triggers, is therefore important for understanding how sediment is moved globally, effective recovery of oil and gas reserves, hazards to strategic cable networks, and the recurrence intervals of tsunamis and earthquakes.

This contribution starts (Section 2) by summarising how flows are triggered, and the character of flows triggered in different ways, including flow power and run-out distance. The summary is based mainly on studies that have monitored modern flows in action, as they provide the most unambiguous evidence on flow timing and triggers. This includes some highly informative recent studies (Paull et al., 2010a, 2012; Xu et al., 2010, 2013; Xu, 2011; Carter et al., 2012; Hill, 2012; Hughes Clarke et al., 2012, 2013; Khripounoff et al., 2012; Liu et al., 2012, 2013; Puig et al., 2012, 2014; Cooper et al., 2013). This body of new monitoring work makes this review timely. Hyperypcnal river floods can coincide with large wave heights during storms, or failure of rapidly deposited sediment, making triggers difficult to isolate. General comments are therefore made on the evidence for triggering of submarine flows by hyperpycnal floods. This is timely because previous studies have inferred that such flows are common, and sufficiently powerful to transport sand into the deep ocean (Mulder et al., 2003).

The deposits of flows triggered by different processes are also discussed in Section 2. This is important because in most situations the only information available from a submarine flow is its deposit (Talling et al., 2012a). It is particularly important to determine whether flow deposits can provide a reliable record of major earthquakes that generate tsunamis (Goldfinger, 2011; Atwater and Griggs, 2012),

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