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Distal turbidites reveal a common distribution for large (>0.1 km^3) submarine landslide recurrence

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ABSTRACT

Submarine landslides can be far larger than those on land, and are one of the most important processes for moving sediment across our planet. Landslides that are fast enough to disintegrate can generate potentially very hazardous tsunamis, and produce long run-out turbidity currents that break strategically important cable networks. It is important to understand their frequency and triggers. We document the distribution of recurrence intervals for large landslide-triggered turbidity currents (>0.1 km^3) in three basin-plains. A common distribution of recurrence intervals is observed, despite variable ages and disparate locations, suggesting similar underlying controls on slide triggers and frequency. This common distribution closely approximates a temporally-random Poisson distribution, such that the probability of a large disintegrating slide occurring along the basin margin is independent of the time since the last slide. This distribution suggests that non-random processes such as sea level are not a dominant control on frequency of these slides. Recurrence intervals of major (>M 7.3) earthquakes have an approximately

Poissonian distribution, suggesting they could be implicated as triggers. However, not all major earthquakes appear to generate widespread turbidites, and other as yet unknown triggers or sequential combinations of processes could produce the same distribution. This is the first study to show that large slide-triggered turbidites have a common frequency distribution in distal basin plains, and that this distribution is temporally random. This result has important implications for assessing hazards from landslide-tsunamis and seafloor cable breaks, and the long-term tempo of global sediment fluxes.

INTRODUCTION

Submarine landslides (hereafter “slides”) on continental margins include the largest mass flows on Earth. They can involve hundreds to several thousand cubic kilometers of material (Hühnerbach and Masson, 2004), and be far larger than those on land. Many large slides initiate on sea floor gradients of <2° that would almost always be stable on land (Urlaub et al., 2013). Motion of the slide can potentially generate damaging tsunamis that travel across the ocean for long distances. Mixing of the slide mass with the surrounding seawater can form longer run-out sediment flows called turbidity currents, which can travel for hundreds of kilometers, sometimes with speeds of up to 19 m/s (Piper et al., 1999). Cables that carry over 95% of transoceanic global data (Carter et al., 2009), and expensive oil and gas infrastructure may be damaged by slides and turbidity currents. The most hazardous events are large volume and fast moving slides that disintegrate to produce turbidity currents. They are also the most important events for transporting sediment over long distances. We consider deposit volumes >0.1 km^3 as representing large slides—although some slides can be up to three orders of magnitude larger (Urlaub et al., 2013). Determining whether large-volume slides have a common frequency distribution, and what that distribution may be, has importance for understanding global sediment fluxes and regional hazards associated with tsunamis and damage to seafloor structures. The frequency distribution can also provide insights into triggers and preconditioning factors.

Numerous hypotheses have been proposed for how large submarine slides are triggered and slopes are preconditioned to fail. However, we are yet to monitor a large slide in action, and these hypotheses remain poorly tested. Rapid accumulation of impermeable sediment is often invoked as a preconditioning factor for failure, which may then be triggered by an earthquake (Stigall and Dugan, 2010). However, very large slides also occur in areas of slow sedimentation (Urlaub et al., 2013), failure may occur thousands of years after rapid sedimentation ceases (Leynaud et al., 2009), and some recent large earthquakes did not produce widespread slope failure (Sumner et al., 2013; Völker et al., 2011). The headwalls of most large slides are too deep (> 200 m water depth) for triggering by cyclic wave loading, and some headwalls are too deep (>2000 m) for triggering by gas hydrate dissociation (Hühnerbach and Masson, 2004). It has been suggested that sea-level changes play a key role in preconditioning or triggering slope failure (Lee, 2009). However, a recent analysis of large slide frequency concluded that there was no significant association with sea level (Urlaub et al., 2013).

Aims

We aim to determine the frequency distribution of recurrence intervals for turbidites triggered by large (>0.1 km^3) submarine slides in three deep-sea basins. As a similar frequency distribution of recurrence intervals is observed, we explore the significance of this distribution for understanding how large slides are triggered. This analysis includes potential triggering of slides by sea level changes and large magnitude earthquakes.

METHODS

It can be difficult to document slide ages precisely by dating sediment immediately above and below the slide deposit, even when samples are recent enough to be radiocarbon dated (Urlaub et al., 2013). Dated samples are also needed from different lobes of a slide deposit to check whether they were emplaced by a single slide, or multiple slides with variable ages. We therefore use an alternative method for documenting time periods between large slides around a basin margin, using turbidity current deposits ('turbidites') generated by the slides. The recurrence time of slides is inferred from intervals of hemipelagic mud that settles out between turbidity currents, and average accumulation rate of the hemipelagic mud. This provides information on timing of many (>100) slides, which aids robust statistical analysis. It avoids the need to date prohibitively large numbers of slides, each in a different location on the margin.

Study Areas

Turbidite sequences in three deep-water basin plains are considered (Fig. 1; see the GSA Data Repository[1]), including the Madeira Abyssal Plain (offshore northwest Africa), the Balearic Abyssal Plain (western Mediterranean Sea), and the Marnoso-arenacea Formation (Italian Apennines). The Madeira Abyssal Plain record comes from Ocean Drilling Program (ODP) cores and spans the past ~7 m.y., while piston coring of the Balearic Abyssal Plain provides a sequence for the past ~150 k.y. Outcrops of the Marnoso-arenacea Formation provide a record of events between 13.5 and 14.1 Ma. There are few (if any) other locations worldwide that fulfill the following key criteria needed for this approach; that there are a sufficient number (> ~100) of turbidites for robust statistical analyses, hemipelagic mud can be easily distinguished from turbidite mud in the field, and there is evidence that erosion was limited below turbidites.

Age Control

It was not feasible to date every hemipelagic mud interval. The time period between turbidites was derived by dividing the thickness of hemipelagic mud between turbidites by the average hemipelagic mud accumulation rate. This accumulation rate was calculated between adjacent dated horizons by dividing their difference in age by cumulative hemipelagic mud thickness. Detail on the dating methods for each data set is provided in the Data Repository, together with analysis of effects of short-term variations in hemipelagic accumulation rate.

Distinguishing Hemipelagic Mud and Turbidite Mud

It is essential to be able to distinguish between mud deposited by hemipelagic fallout and turbidity currents, in order to measure the thickness of hemipelagic mud between each turbidite and hence calculate recurrence times. The three data sets were chosen because the two types of mud have distinctive features and colors (Fig. DR1 in the Data Repository). It is often very difficult to identify the two types of mud (Talling et al., 2012). Visually diagnostic features of hemipelagic mud in our sequences are common dispersed foraminifera, reduced organic carbon content, higher calcium carbonate content, lighter color and bioturbation (Table DR1). This visual differentiation is consistent with detailed geochemical (Rothwell et al., 2004), and microscopic analyses (Talling et al., 2007).

Erosion by Turbidity Currents

Our method requires that significant thicknesses of hemipelagic mud were not eroded beneath turbidity currents, and we show how erosion would affect recurrence time estimates in the Data Repository. This view is supported by mapping of hemipelagic mud thickness beneath individual beds in the Marnoso-arenacea Formation, showing that this thickness varies by <5–10 cm over ~120 km (Fig. DR1). A lack of spatial variation in coccolith assemblages and thickness of turbidite mud caps in the Madeira Abyssal Plain indicate minimal erosion—interpreted to be less than a few centimeters (Weaver and Thomson, 1993). The turbidite beds in the Madeira and Balearic Abyssal Plain cores lack irregular bases indicative of erosion, although the narrow core width (<10 cm) precludes observation of larger-scale erosional features.

Short-term Fluctuations in Hemipelagic Mud Accumulation Rates

Our method for calculating recurrence intervals assumes that no significant fluctuation in hemipelagic mud accumulation rates occurred between dated horizons. Such horizons occur every 0.4 k.y. to 18.5 k.y. in the Balearic Abyssal Plain, and every 5 k.y. to 1 m.y. in the Madeira Abyssal Plain. This issue is most important for the Marnoso-arenacea Formation, where a constant hemipelagic accumulation rate is assumed over the entire interval. This assumption may not be unreasonable, as hemipelagic accumulation rates in the Balearic Plain only vary by ~30% over an interval of 150 k.y.

Were These Extensive Basin Plain Turbidity Currents Triggered by Large Landslides?

It is known that slope failures can generate turbidity currents that reach distal basin plains, from often very large slides on the open continental slope (Piper et al., 1999) or smaller failures that lead to canyon flushing flows (Piper and Savoye, 1993; Talling et al., 2012). However, it is possible that flows reaching basin plains can be triggered in other ways. Turbidite volume provides the best evidence of triggering by slope failure, as other triggers most likely produce small (<0.1 km^3) sediment volume flows. Even the largest flood discharges into the ocean tend to involve <0.1 km^3 of sediment (Dadson et al., 2005), although such flood-triggered submarine flows could pick up sediment en-route to basin plains. The data sets considered here were chosen because each turbidite contains large (>0.1 km^3 to 500 km^3) volumes of sediment (Tables DR3–DR5). Volume estimates are based on unusually detailed long distance (>100 km) mapping of individual beds in the Marnoso-arenacea Formation, the Madeira Abyssal Plain and the Balearic Abyssal Plain (Table DR1). However, even if these turbidity currents were generated by floods and eroded very large sediment volumes during canyon flushing, understanding their recurrence times is still important for geohazards to seafloor infrastructure.

Not all slides trigger long run-out turbidity currents, as some slides may be too slow moving to disintegrate. This study only considers faster-moving and larger slides that disintegrate to produce voluminous turbidites. It is these events that pose the greatest regional threat to seafloor infrastructure, may produce hazardous tsunamis, and are most important for continental margin evolution and global sediment transport.

RESULTS

Common Frequency Distribution of Landslide-Turbidite Recurrence Intervals

The recurrence interval distributions form a nearly straight line on a log-linear exceedence plot for all three data sets (Fig. 1). This linear trend indicates an exponential relationship, characteristic of a Poisson distribution, although there is a slight deviation for the longest recurrence intervals. A Poisson distribution implies a lack of memory, such that the probability of a new event occurring is independent of the time since the last. It is characterized by only one parameter (λ)—the mean recurrence interval or rate parameter. Equation 1 defines the Probability Function (P) that a discrete random recurrence interval (X) is less than a specific value for the data series (x). The solution is related to an exponential function (e^x) and the rate parameter (λ). Values of X, x, and λ are integers defined in thousands of years.

$$P(X < x) = 1 - e^{\frac{-x}{\lambda}}. \quad (1)$$

A common distribution in data sets from multiple disparate settings may indicate a common underlying control, and this has not been shown previously for large slide-triggered turbidites preserved in distal basin plains.

Is This Distribution Temporally Random (Poissonian)?

To test that the data are truly exponential and they share a common distribution, they are normalized by sub-dividing each recurrence interval, T, by mean recurrence interval (λ) for each of the data sets to plot a dimensionless variable, R_T. The data sets show close agreement when plotted in this way, despite disparity in their age, location and setting. R_T values closely approximate an exponential distribution; however, some slight overpopulation is observed at the tail for $R_T > 3$, suggesting a small deviation from a strictly Poisson distribution.

To test whether this is a Poisson distribution, a Generalized Linear Model is applied to the data using a Gamma distribution (of which the exponential is a special function). This defines a dispersion parameter, α, for the curve fitted to each of the data sets. A true exponential distribution is represented by α = 1; however, values between 1 and 2 can be treated as Poissonian. The values derived for the data sets in this study are between 1.03 and 1.21. This indicates that they are near-exponentially distributed, albeit with some overpopulation in the tail of the data.

Effects of Variable Erosion Beneath Beds

We now explore how erosion of hemipelagic mud to variable depths by turbidity currents could potentially influence our results. Random amounts of erosion to depths of 0–10 cm are simulated for the original hemipelagic mud thickness data (Fig. DR1). This depth range was chosen as it is the maximum difference in hemipelagic mud thickness beneath Marnoso-arenacea turbidites mapped over 120 km (Talling et al., 2007). Additional erosion was only simulated below turbidites that are equal or thicker than the mean turbidite thickness, rather than beneath every turbidite. Erosion is likely to be greater beneath thicker beds, which represent larger and more powerful turbidity currents. Accounting for differential erosion also provides a near-exponential distribution. This supports the view that erosion of up to 10 cm between beds would not modify our main conclusion that recurrence times approximate a Poisson distribution.

Effects of Short-Term Changes in Hemipelagic Accumulation Rates

Random variations between ± 50% of the mean recurrence interval between turbidites were applied to the data from the Madeira Abyssal Plain (Fig. DR1). This simulates short-term temporal variations in hemipelagic accumulation rates. A near-exponential distribution of inter-event times is still observed.

DISCUSSION

We first discuss the implications of the observed Poisson distribution for understanding triggers and preconditioning factors for large disintegrative slides.

Geological Significance of Poisson Distribution

A Poisson distribution results from a process that is random and lacks memory, in the sense that the probability of an event occurring is independent of the time since the last. A Poisson distribution of landslide-turbidite frequency could form in three ways. First, the distribution could result from a single basin-wide triggering process that is randomly distributed in time. Second, it could result from numerous different basin-wide triggers, or from many different triggering processes that each affects a localized area along the basin margin. Third, it could result from a sequential chain of multiple processes, each occurring one after the other. The Poisson distribution suggests that triggering of landslide-turbidites is not due to a single process, or a small number of processes, whose distribution is non-random through time.

Landslide-Turbidite Frequency and Sea Level

It has been proposed that glacial-eustatic sea-level fluctuations are a major control on the frequency of large slides (Lee, 2009). However, all three data sets show no evidence for a strong eustatic sea level control that is not temporally random. This suggests that sea level is not a major triggering or preconditioning factors for large disintegrative slides. Such a view is consistent with a recent global analysis of large slide ages during the past 30 k.y. (Urlaub et al., 2013), but is contrary to that of previous workers (e.g., Lee, 2009). Processes that fluctuate in conjunction with eustatic sea level and climate cycles are also unlikely to be temporally random, and this study suggests that they too are not dominant single controls on slide timing. Such process may include dissociation of gas hydrates due to ocean warming, or increased sedimentation rates on continental slopes during sea-level lowstands.

Comparison to the Frequency Distribution of Large Magnitude Earthquakes

It has been proposed that recurrence intervals of large magnitude (M > 7.3) earthquakes in global databases, documented by seismometers since ca. A.D. 1900, are temporally random and follow a Poisson distribution (Corral, 2006). These analyses exclude aftershocks. Other workers have argued that this instrumental record contains too few events to be sure that the distribution is Poissonian (e.g., Daub et al., 2012). This result is only found for measurements made over large areas, as individual fault segments can have characteristic earthquake recurrence periods.

It might therefore be suggested that large slides are triggered by major earthquakes, based on the similarity between the shape of the frequency distribution of recurrence intervals of slide-turbidites and large magnitude earthquakes (Fig. DR2). In contrast, the frequency distribution of river floods is far from an exponential Poisson distribution (Bobée et al., 1993). Although some large slides are known to have been triggered by earthquakes (Piper et al., 1999), some large (M 8.4 and 9.1) earthquakes do not always cause widespread seafloor failure (Sumner et al., 2013; Völker et al., 2011). This suggests that only a subset of major earthquakes trigger large slides, such that there is not a one-to-one correlation between major earthquakes and large slides. This view is consistent with the average recurrence intervals recorded here (1.4–36.5 k.y.), which tend to be significantly longer than average historical recurrence intervals of major (>M 7.3) earthquakes of tens to several hundred years (e.g., Meghraoui et al., 1988). It could then be argued that only very large magnitude (M 8 or 9) earthquakes trigger slides, but field observations suggest that sometimes even these do not produce extensive slides (Sumner et al., 2013; Völker et al., 2011).

Multiple Local or Sequential Controls Along Basin Margin

It is also possible that slides are mainly triggered by one or more currently unknown factors that have a Poisson distribution, or that different factors trigger slides locally along the margin. The latter view implies that there is not a single dominant source location for most turbidites in a basin-floor data set, and slides are triggered in variable ways at different points around the margin. This results in a temporally-random, regionalized sum of slide recurrence times. However, a rigorous test of this model is problematic as the source of each turbidite in our data sets cannot be pinpointed with sufficient precision. It is also possible that a temporally random distribution may result from cumulative triggering by a series of factors that occur one after another, at a single location.

CONCLUSIONS

Analysis of large volume turbidites (>0.1 km^3) in three basin plains indicates that there is a common frequency distribution of inter-event times for larger and faster-moving slides that disintegrate. Such slides tend to form relatively large tsunamis, pose the greatest regional hazard to seafloor infrastructure, and are most important for global sediment fluxes. This novel conclusion may indicate similar controls on slide frequency and triggers occur in disparate areas. The common frequency distribution approximates a Poisson distribution, such that the time to the next slide is independent of the time since the last. This suggests that temporally non-random processes, such as glacio-eustatic sea-level change, are not dominant single controls on slide frequency, contrary to the conclusions of some previous work. It appears that processes that fluctuate in conjunction with eustatic sea-level and climate cycles (e.g., shelf edge sedimentation rates or hydrate dissociation driven by ocean warning) are also not dominant single controls on slide timing. Major earthquakes have an approximately Poisson distribution of recurrence intervals suggesting they may play a role in slide triggering, although not all major earthquakes appear to generate large disintegrating slides. Alternatively, slides may be triggered by processes that are yet unknown which are temporally random, by many disparate processes acting locally along a basin margin, or by a series of processes that occur one after another at a single location. It is feasible that our records may also include large volume canyon flushing events; however, regardless of this, our study has important implications for predicting frequency of landslide-tsunamis, the occurrence of cable breaks, and the global tempo of sediment transport. It suggests that the frequency of large volume flows, such as those triggered by disintegrative landslides is unlikely to change significantly due to rapid eustatic sea-level rise during forthcoming decades.

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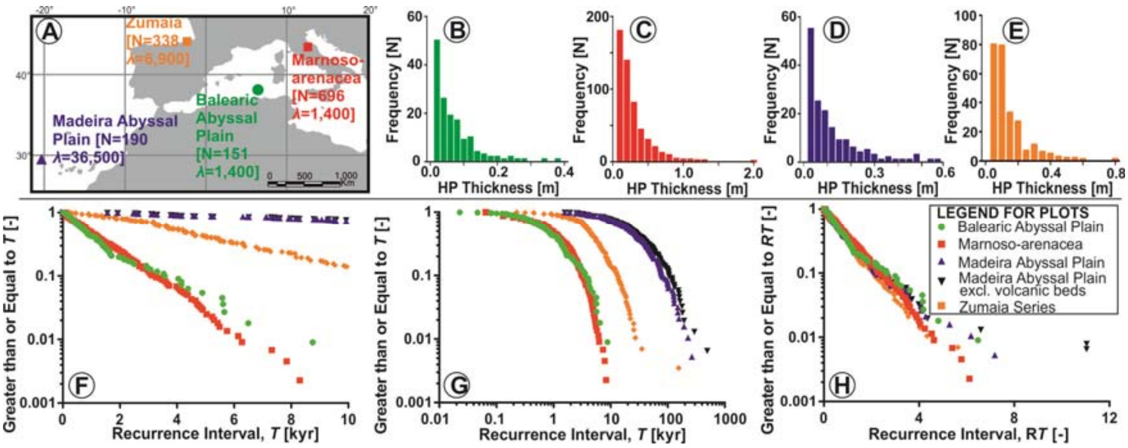
FIGURE CAPTION

Figure 1. A: Location map. B–D: Frequency histograms of hemipelagic mud thickness. E–G: Recurrence intervals plotted on log-linear axes (E), log-log axes (F), and with recurrence intervals normalized by rate parameter (λ) (G).



[1]GSA Data Repository item 2014xxx, available chronostratigraphic control, summary logs, and detail on hemipelagic mud deposits, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.