Marine Geology 369 (2015) 19–33

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Are large submarine landslides temporally random or do uncertainties in available age constraints make it impossible to tell?

E.L. Pope [a,*], P.J. Talling [a], M. Urlaub [b], J.E. Hunt [a], M.A. Clare [a], P. Challenor [c]

[a] National Oceanography Centre, Southampton, European Way, Southampton SO14 3ZH, UK
[b] GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstr. 1–3, 24148 Kiel, Germany
[c] College of Engineering, Mathematics and Physical Sciences, Harrison Building, North Park Road, EX4 4QF, UK

ARTICLE INFO

Article history:
Received 15 April 2015
Received in revised form 18 July 2015
Accepted 24 July 2015
Available online 29 July 2015

Keywords:
Submarine landslides
Sea level
Timing
Tsunami

ABSTRACT

Large (>~1 km^3) submarine landslides can potentially generate very destructive tsunamis and damage expensive sea floor infrastructure. It is therefore important to understand their frequency and triggers, and whether their frequency is likely to change significantly due to future climatic and sea level change. It is expensive to both collect seafloor samples and to date landslides accurately; therefore we need to know how many landslides we need to date, and with what precision, to answer whether sea level is a statistically significant control. Previous non-statistical analyses have proposed that there is strong correlation between climate driven changes and landslide frequency. In contrast, a recent statistical analysis by Urlaub et al. (2013) of a global compilation of 41 large (>1 km^3) submarine landslide ages in the last 30 ka concluded that these ages have a temporally random distribution. This would suggest that landslide frequency is not strongly controlled by a single non-random global factor, such as eustatic sea level. However, there are considerable uncertainties surrounding the age of almost all large landslides, as noted by Urlaub et al. (2013). This contribution answers a key question that Urlaub et al. (2013) posed, but could not address — are large submarine landslides in this global record indeed temporally random, or are the uncertainties in landslide ages simply too great to tell? We use simulated age distributions in order to determine the significance of available age constraints from real submarine landslides. First, it is shown that realistic average uncertainties in landslide ages of ±3 kyr may indeed result in a near-random distribution of ages, even where there are non-random triggers such as sea level. Second, we show how combination of non-random landslide ages from just 3 different settings, can easily produce an apparently random distribution if the landslides from different settings are out of phase. Third, if landslide frequency was directly proportional to sea level, we show that at least 10 to 53 landslides would need to be dated perfectly globally — to show this correlation. We conclude that it is prudent to focus on well-dated landslides from one setting with similar triggers, rather than having a poorly calibrated understanding of ages in multiple settings.

1. Introduction

Submarine landslides are one of the volumetrically most important mechanisms through which sediment is transported from the continental slope to the deep ocean (Hühnerbach and Masson, 2004; Masson et al., 2006; Korup, 2012; Talling et al., 2012; Urlaub et al., 2013, 2014). Landslide deposits have been mapped on many continental slopes as disparate as southeast Australia (Clarke et al., 2012) and the Grand Banks, Newfoundland (Piper et al., 1999). Submarine landslides can be far larger than any terrestrial landslide, and can involve the movement of hundreds or even several thousands of cubic kilometres of material (Hampton et al., 1996; Hühnerbach and Masson, 2004; Talling et al., 2007). Perhaps the most remarkable aspect of large submarine landslides is that they typically can occur on very low gradients of just 1–2° (Hühnerbach and Masson, 2004; Talling et al., 2007; Urlaub et al., 2012, 2014). Such low gradients are almost always stable on land. Once in motion, the submarine slide mass can entrain ambient seawater and disaggregate to form longer runout sediment flows, known as turbidity currents. These turbidity currents can themselves travel many hundreds of kilometres (Weaver and Kuijpers, 1983), and reach speeds of up to ~20 m/s (Piper et al., 1999; Hsu et al., 2008).

Submarine landslides, debris flows and associated turbidity currents may represent significant geohazards. Submarine landslides have the potential to generate damaging tsunamis (Ruffman, 2001; Tappin et al., 2001; Haflidason et al., 2005; Boe et al., 2007; Hornbach et al., 2007); whilst both landslides and turbidity currents can damage expensive sea floor infrastructure, such as that associated with the hydrocarbon industry or seafloor telecommunications (Bruschi et al., 2006; Carter et al., 2009; 2012; Parker et al., 2008, 2009). Some authors have argued that the occurrence of large submarine landslides can have significant climatic impacts through the release of large amounts of

* Corresponding author.
E-mail address: Ed.Pope@noc.soton.ac.uk (E.L. Pope).

http://dx.doi.org/10.1016/j.margeo.2015.07.002
0025-3227/

methane into the water column and the atmosphere (Kennett et al., 2000; Maslin et al., 2004; Pecher et al., 2005; Vanneste et al., 2006; Beget and Addison, 2007; Paull et al., 2007). Understanding the frequency and triggers of large submarine landslides is therefore important.

1.1. Triggering and preconditioning of submarine landslides

A large number of triggers and preconditioning factors have been hypothesised as possible causes for large submarine landslides. Potential preconditioning factors and triggers include earthquakes, rapid sedimentation that leads to high excess pore pressure and conditions close to failure, and gas hydrate dissociation that reduces sediment strength (Hampton et al., 1996; Maslin et al., 1998; Stigall and Dugan, 2010; Goldfinger, 2011; Masson et al., 2011; Talling et al., 2014). However, not all large (>7 M_w) earthquakes appear to generate major slides (Völker et al., 2011; Sumner et al., 2013), large submarine landslides occur in locations with slow sediment accumulation (Urlaub et al., 2012), and some landslide headwalls occur in water depths that are too deep for gas hydrate dissociation (Hühnerbach and Masson, 2004). In general, many of these hypotheses for landslide preconditioning and triggering are weakly tested, in part because we are yet to directly monitor large slides in action in sufficient detail (Talling et al., 2014).

1.2. Submarine landslide frequency and sea level — previous work

A series of previous studies explored the potential relationship between landslide frequency and sea level. The first set of studies used compilations of landslide ages, typically from widespread locations.

1.2.1. Global databases of landslide ages

The initial analyses did not include full uncertainties in landslide ages, or test the certainty of their conclusions through quantitative statistical methods. These studies suggest that increased landslide frequency occurred during specific periods in glacial cycles, corresponding to sea level low-stands, high-stands, or rapid rates of sea level change. Brothers et al. (2013) identify a causal relationship between sea level rise and landslide triggering. Paull et al. (1996) identify increased numbers of landslides during low-stands related to reduced overburden pressure of the water column on gas hydrate bearing sediments. Leynaud et al. (2009), Maslin et al. (1998, 2004), Lee (2009) and Lebreiro et al. (2009) recognised that different margins responded differently to sea level. For example, low latitude margins experienced more large submarine landslides during low-stands while high latitudes were more likely to see slope failures during rising sea levels or high-stands.

Subsequent analysis has sought to evaluate these qualitative conclusions using statistical approaches. Urlaub et al. (2013) considered a collection of 68 large (>~1 km^3) submarine landslide ages from locations worldwide, which includes the last 120 ka (Fig. 1). This is the largest number of landslide ages yet compiled. It included dates from landslide deposits themselves from open slope failures (but not volcanic island failures) where ages were obtained by radiocarbon AMS measurements or by applying a combination of several methods (e.g. biostratigraphy and oxygen isotopes). It also included large (>~1 km^3) turbidites inferred to be landslide-triggered. Such large volume turbidites are unlikely to be triggered by processes other than slope failure, as their volume far exceeds even the largest historical river flood (Talling et al., 2014). In general, such turbidites will tend to record faster moving landslides that disintegrate to produce turbidity currents. See Urlaub et al. (2013) for a fuller discussion on the consistent selection criteria.

The Urlaub et al. (2013) study took a subset of 41 events in the last 30 ka to analyse statistically from the compiled global database. This subset was chosen to avoid a strong bias due to undersampling of older events, caused by limits to core penetration below the sea floor; most sediment cores extended back to 30 ka, but few reached 120 ka. The analysis by Urlaub et al. (2013) included the often considerable uncertainties in landslide ages in this analysis (Fig. 1), unlike most previous studies that considered only the calibrated mean ages or most probable ages (Ramsey, 1998). The greatest uncertainties in landslide age typically result from where samples are taken for dating, above and below the landslide or turbidite deposit, rather than the error bars in the (typically AMS radiocarbon) dates themselves. This is discussed more fully in Urlaub et al. (2013), and illustrated by our Fig. 2.

Urlaub et al. (2013) analysed these 41 landslide ages. They first divided their 30 ka study period into a series of equal time intervals, termed bins (e.g. 0–5 kyr, 5–10 kyr, and 10–15 kyr). They then counted the number of landslide ages that fell within each bin. This allowed them to plot the number of bins with a single landslide age, two landslide ages, three landslide ages, and so forth (Urlaub et al., 2013; their Fig. 8a, b). A random number generator was then used to produce a set of synthetic landslide ages, assuming landslide occurrence was temporally random. The same procedure was followed to count the number of synthetic landslide ages in each bin, and the number of bins with one, two or more landslide ages. It was found that there was no statistically significant difference between the frequency of bins with 1, 2, 3 or more landslide ages, both real and synthetic landslide ages using the χ^2 statistic (their Fig. 8c). The duration of bins was varied between 1 kyr and 5 kyr, as this affects the frequency distribution of the landslide ages. Both the 'best guess' landslide ages, and landslide ages acknowledging age uncertainty were tested in this way. In each case, landslide ages were described by the χ^2 statistic as occurring randomly, such that they approximated a Poisson distribution (Urlaub et al., 2013).

1.2.2. Landslide recurrence intervals on the margins of a single basin

A second type of study used different types of data and statistical methods to consider the recurrence intervals of landslides around the margins of a single sedimentary basin (Hunt et al., 2013; Clare et al., 2014), as opposed to a global dataset of landslide ages. These studies used large volume turbidites as a proxy for large landslides that disintegrate, which are presumably faster moving. Clare et al. (2014) considered large (>0.1 km^3 in these cases) landslide turbidite recurrence intervals in three disparate abyssal plain sequences of variable age, whilst Hunt et al. (2013) considered landslide–turbidites in the Agadir Basin offshore NW Africa. They compared the frequency distribution of landslide turbidite recurrence intervals, with a Poisson frequency distribution. It was found that the frequency distribution of the landslide–turbidite recurrence intervals did not differ significantly from the (Poisson) distribution produced by a temporally random process. Both of these studies therefore suggest that large landslides, which disintegrate to form long run-out turbidity currents, are temporally random, or near random (Hunt et al., 2013; Clare et al., 2014).

1.2.3. Discrete vs continuous data

The Urlaub et al. (2013), Hunt et al. (2013) and Clare et al. (2014) studies all concluded that the occurrence of submarine landslides followed a Poisson distribution. A Poisson distribution implies a lack of memory in the system which it is describing, such that the probability of a new event occurring is independent of the time since the last. The methodology used by the different studies is dependent on the type of data. The global nature of the Urlaub et al. (2013) study and the uncertainty regarding the duration of inter-event timing required the study to use 'discrete' (count) data that was binned. The number of landslides within a given time period was compared to the number that would theoretically be produced by a random process. In contrast, the availability of landslide–turbidite recurrence intervals (inter-event time) allowed Hunt et al. (2013) and Clare et al. (2014) to use 'continuous' data. This study follows the approach of Urlaub et al. (2013) and therefore uses discrete data.