THE GEOLOGICAL SOCIETY OF AMERICA®

Eustatic sea-level controls on the flushing of a shelf-incising submarine canyon

Joshua R. Allin[1,2,†], James E. Hunt[1], Michael A. Clare[1], and Peter J. Talling[3]
[1]*National Oceanography Centre, University of Southampton Waterfront Campus, European Way, Southampton, SO14 3ZH, UK*
[2]*School of Ocean and Earth Sciences, University of Southampton Waterfront Campus, European Way, Southampton, SO14 3ZH, UK*
[3]*Departments of Earth Sciences and Geography, University of Durham, Durham DH1 3LE, UK*

ABSTRACT

Turbidity currents are the principal processes responsible for carving submarine canyons and maintaining them over geological time scales. The turbidity currents that maintain or "flush" submarine canyons are some of the most voluminous sediment transport events on Earth. Long-term controls on the frequency and triggers of canyon-flushing events are poorly understood in most canyon systems due to a paucity of long sedimentary records. Here, we analyzed a 160-m-long Ocean Drilling Program (ODP) core to determine the recurrence intervals of canyon-flushing events in the Nazaré Canyon over the last 1.8 m.y. We then investigated the role of global eustatic sea level in controlling the frequency and magnitude of these canyon-flushing events. Canyon-flushing turbidity currents that reach the Iberian Abyssal Plain had an average recurrence interval of 2770 yr over the last 1.8 m.y. Previous research has documented no effect of global eustatic sea level on the recurrence rate of canyon flushing. However, we find that sharp changes in global eustatic sea level during the mid-Pleistocene transition (1.2–0.9 Ma) were associated with more frequent canyon-flushing events. The change into high-amplitude, long-periodicity sea-level variability during the mid-Pleistocene transition may have remobilized large volumes of shelf sediment via subaerial weathering, and temporarily increased the frequency and magnitude of canyon-flushing turbidity currents. Turbidite recurrence intervals in the Iberian Abyssal Plain have a lognormal distribution, which is fundamentally different from the exponential distribution of recurrence intervals observed in other basin turbidite records. The lognormal distribution of turbidite recurrence intervals seen in the Iberian Abyssal Plain is demonstrated to result from the variable runout distance of turbidity currents, such that distal records are less complete, with possible influence from diverse sources or triggering mechanisms. The changing form of turbidite recurrence intervals at different locations down the depositional system is important because it ultimately determines the probability of turbidity current–related geohazards.

†Present address: School of Geography and Environment, Oxford University Centre for the Environment (OUCE), University of Oxford, South Parks Road, Oxford OX1 3QY, UK; joshua.allin@ouce.ox.ac.uk.

INTRODUCTION

Turbidity currents are among the most volumetrically important sediment transport mechanisms operating on Earth's surface. An individual turbidity current can be capable of transporting as much sediment as all the world's rivers in one year combined (Talling et al., 2007; Korup, 2012). The most voluminous turbidity currents are triggered by large (>1 km^3) submarine landslides originating from continental slopes and volcanic islands. These large landslides, and their often associated turbidity currents, pose considerable geohazard risk and have the potential to generate tsunamis that can damage coastal settlements and cause considerable loss of life (Bondevik et al., 1997; Tappin et al., 2008; Harbitz et al., 2006). Landslides and turbidity currents may also damage expensive submarine infrastructure, such as pipelines and telecommunication cables (Bruschi et al., 2006; Carter et al., 2012, 2014; Pope et al., 2016). For these reasons, understanding the triggering mechanisms and long-term frequencies of volumetrically large submarine landslides and turbidity currents is important for geohazard assessment.

Nonrandom processes like climate-driven sea-level change are proposed to be an important control on the recurrence rates of large-volume landslides and turbidity currents (Maslin et al., 2004; Owen et al., 2007; Brothers et al., 2013; Smith et al., 2013). Similarly, eustatic sea-level change is regarded as a dominant control on submarine fan and canyon development by altering the location of sediment deposition relative to the shelf edge, thereby limiting its delivery to the deep ocean by mass transport processes ("lowstand model"; Vail et al., 1977; Shanmugam and Moiola, 1982; Posamentier and Vail, 1988; Piper and Savoye, 1993; Ducassou et al., 2009; Lebreiro et al., 2009; Covault and Graham, 2010). However, whether or not factors like eustatic sea-level change are a control on the recurrence rates of large-volume landslides and turbidity currents worldwide has little empirical support, based upon few well-dated examples that do not provide the required statistical power for testing (Urlaub et al., 2013; Pope et al., 2015). Furthermore, it is also unclear whether or not signals of environmental change that propagate into deep water (>4000 m) are recorded and preserved in distal marine sedimentary archives (Covault and Graham, 2010; Romans and Graham, 2013; Allin et al., 2016; Romans et al., 2016).

FLUSHING OF SUBMARINE CANYONS

Turbidity currents in submarine canyons are proposed to be one of two broad end-member types: those that are restricted to, and fill or recharge the canyon with sediment, and those that flush sediment from the canyon and continue into deeper water (Parker, 1982; Piper and Savoye, 1993; Canals et al., 2006; Piper and Normark, 2009; Talling et al., 2012; Allin et al., 2016). "Filling" turbidity currents triggered by localized failures, hyperpycnal river discharge, or storms accumulate sediment within canyons over hundreds or even thousands of years (Paull et al., 2005; Canals et al., 2006; Arzola et al., 2008; Khripounoff et al., 2009; Masson et al., 2011; Talling et al., 2012; Talling, 2014). "Flushing" turbidity currents can be defined as the infrequent (>100 yr to >1000 yr) and large-scale (partial) erosion of unconsolidated sediments within a submarine channel by turbulent or cohesive sediment gravity flows, which then

GSA Bulletin; January/February 2018; v. 130; no. 1/2; p. 222–237; https://doi.org/10.1130/B31658.1; 13 figures; 1 table; published online 29 August 2017.

deposit the sediment on slope fan lobes and distal basin plains (Piper and Normark, 2009). Criteria for identifying canyon-flushing events in the depositional record include volumes of >0.2 km^3, the presence of erosional hiatuses within canyons and channels, and lateral continuity of turbidites within a canyon-fed basin (Paull et al., 2005; Talling et al., 2007; Piper and Normark, 2009; Masson et al., 2011; Talling, 2014).

Turbidity currents that fill, or recharge, Nazaré Canyon have previously been analyzed using sediment cores obtained from the canyon levees. These filling turbidity currents are predominantly active during sea-level lowstand, and their recurrences conform to a normal distribution (Allin et al., 2016). Larger turbidity currents that flush Nazaré Canyon periodically have been inferred from thick (>20 cm) turbidites in the central Iberian Abyssal Plain, 140 km from the mouth of the canyon. In the last 80,000 yr, these large-volume canyon-flushing turbidity currents have a recurrence that exhibits an exponential distribution form (i.e., indiscernible from a temporally random signal) and do not correlate with sea-level changes that otherwise control canyon-filling turbidity currents (Allin et al., 2016). However, this 80,000 yr record of canyon flushing in the Iberian Abyssal Plain is limited, with only 28 turbidites identified within a single sediment core. Therefore, it is unclear whether the lack of correlation between sea level and canyon flushing is real or the result of the limited record length. It is also unclear how the exponential distribution of turbidite recurrences in the Iberian Abyssal Plain arose, given the normal distribution of recurrences within Nazaré Canyon.

WHY IS A QUANTITATIVE STATISTICAL APPROACH NEEDED?

While humans possess an innate ability to see patterns and trends, such qualitative assessments of ordering and relationships in empirical data can be guided by prevailing models and intrinsic biases in judgement (Tversky and Kahneman, 1973; Burgess, 2016). Robust and impartial statistical methods are important additions to assessments of stratal organization in deep-marine sedimentary sequences because they avoid any a priori assumptions of order. The lowstand model of submarine fan development has prevailed for several decades as an important concept in continental margin and deep-marine sequence stratigraphy (Vail et al., 1977; Shanmugam and Moiola, 1982; Posamentier and Vail, 1988; Lebreiro et al., 2009). However, since the development of the model, several sediment-routing systems that have been dominant during transgressions and highstands have been documented (Piper and Savoye, 1993; Covault and Graham, 2010; Covault and Fildani, 2014). In addition, several authors have noted that many deep-marine successions display little or no statistically detectable order, and they have argued for more rigorous statistical approaches to complement qualitative assessments of stratal organization (Wilkinson et al., 2003; Sylvester, 2007; Chen and Hiscott, 1999). Furthermore, uncertainties in stratigraphic age control can make distinguishing order from randomness in event recurrence particularly challenging (Urlaub et al., 2013; Pope et al., 2016). The paucity of robust statistical analyses of stratal patterns and turbidite recurrence limits our understanding of eustatic control over sedimentation in deep water and highlights the need to more rigorously test the applicability of sequence stratigraphic models to individual depositional systems (Shanmugam, 2016). In particular, longer abyssal turbidite records are needed to more thoroughly evaluate eustatic control in deep water over multiple sea-level cycles, as well as signal preservation over geological time and the long-term geohazard posed by damaging turbidity currents.

Here, we analyzed a long (1.8 m.y.) record of turbidites originating from Nazaré Canyon using long and complete (average 100% recovery) Ocean Drilling Program (ODP) borehole samples in the Iberian Abyssal Plain. This represents one of the longest ever complete records of turbidity currents, with over 600 individual turbidites. Our work differs from that of previous papers due to the 1.8 m.y. record of canyon flushing that spans multiple sea-level cycles and is perhaps one of the longest spanning turbidite recurrence data sets from any deep-water setting. Additionally, the work is novel because it allows for a more detailed and robust analysis of the recurrence rates of canyon flushing than was previously possible.

We had three main objectives:

(1) use sedimentary core descriptions and biostratigraphic age datums to build an age model and constrain the frequency of canyon-flushing events in Nazaré Canyon over the last 1.8 m.y.

(2) test whether global eustatic sea-level change during the Pleistocene affected the frequency of large-volume canyon-flushing events using regression-based statistical methods. Establishing whether or not eustatic sea-level change affects the recurrence rates of large-volume canyon flushing is important for geohazard assessment in light of future sea-level change projections (Church et al., 2013). It will also help us to understand whether or not signals of environmental change such as sea level can be recorded in deep-water turbidite sequences.

(3) identify the distribution form, or shape, of turbidite recurrence interval data. The distribution form of turbidite recurrence data may yield information about possible triggering mechanisms of canyon-flushing events in Nazaré Canyon, as well as the ways in which different distribution forms arise in depositional systems.

GEOLOGICAL SETTING

The Iberian Abyssal Plain is located 200 km off the western coast of Portugal between 40°N and 43°N. It extends ~700 km to the northwest at an average water depth of 5300 m (Fig. 1). The basin is bounded by the Galicia Bank to the northeast, the Estremadura Spur to the south, and by a series of seamounts along its western margin. The total area of the basin covers ~107,000 km^2 (Weaver et al., 1987). ODP Leg 149 initial reports have detailed the long-term basin infill record extending back to the Early Cretaceous (140 Ma), with the aim of understanding margin rifting (Milkert et al., 1996a, 1996b). This work demonstrated an onset of terrestrial-derived turbidite deposition in the Iberian Abyssal Plain between 2.6 and 2.2 Ma, which continued into the late Pleistocene.

The Iberian Abyssal Plain is fed by the Nazaré Canyon, which begins 500 m from the Portuguese coastline and extends for 200 km down to a water depth of 5200 m (Vanney and Mougenot, 1990; Lastras et al., 2009). Sedimentation in the upper reaches of the canyon originates from both littoral drift off the Iberian Shelf and nepheloid fallout (Oliveira et al., 2007). Nazaré Canyon does not transition into a well-developed, lobate submarine fan at the base of the continental slope (Fig. 1). Instead, the canyon evolves into a base-of-slope channel that is bounded by the Estremadura Spur to the south and a prominent 150-m-high external levee to the north (Fig. 1). The presence of this large levee suggests that the canyon mouth has not shifted position over geological time (Lastras et al., 2009). The Oporto and Aveiro Canyons are two smaller canyon systems that enter the Iberian Abyssal Plain north of Nazaré Canyon (Guerreiro et al., 2007). These canyons are not considered to be active in the present day, but they could have acted as sources of turbidity currents reaching the Iberian Abyssal Plain during times of past sea-level lowstand (Posamentier and Vail, 1988; Guerreiro et al., 2007, 2009). The ODP Site 898A is located in the Iberian Abyssal Plain, north of the Nazaré Canyon mouth at a water depth of 5280 m, and oblique to the canyon axis and main direction of sediment transport (Fig. 1). As only large-volume canyon-flushing turbidity currents are likely to runout to this distance from source, ODP 898A is an ideal site to study their recurrence over time.

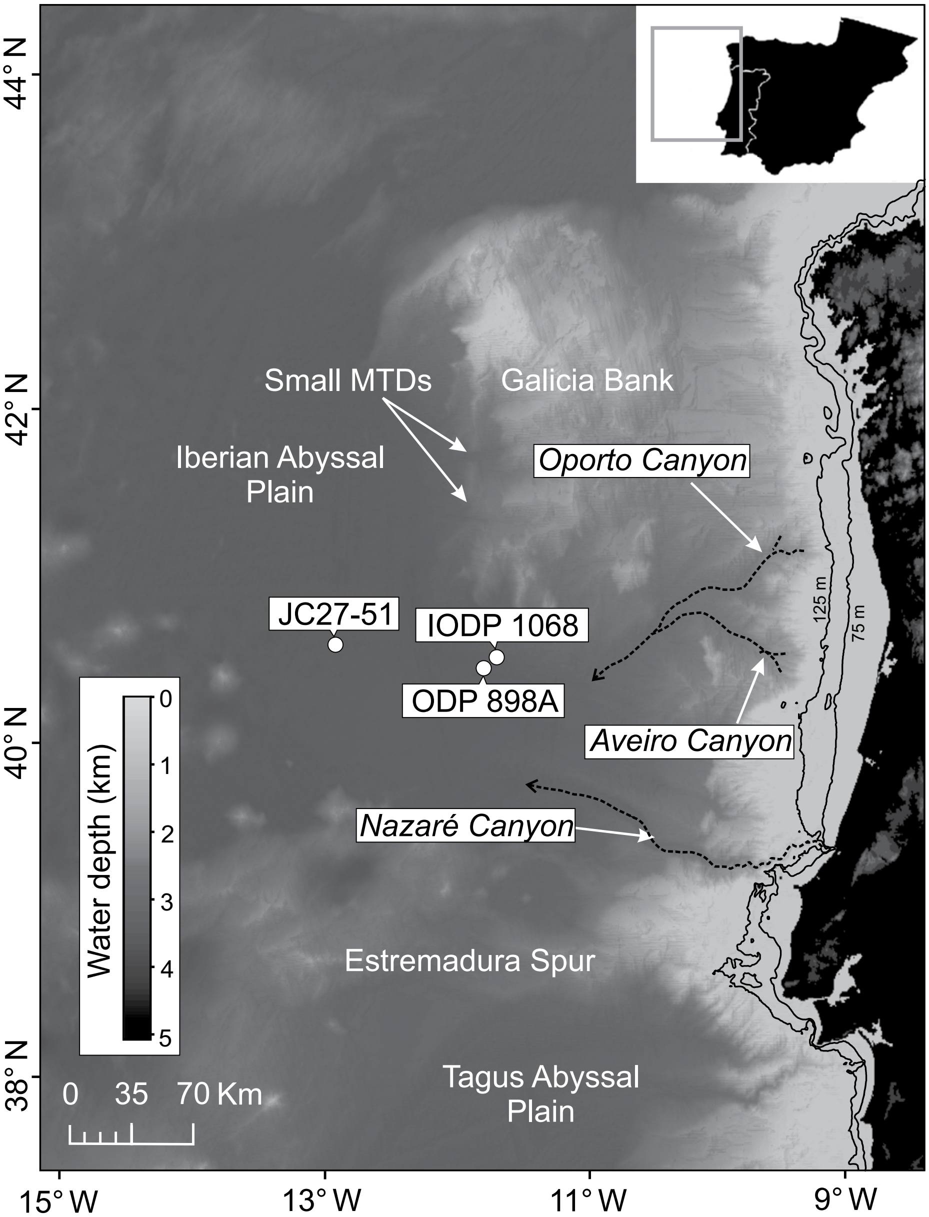

Figure 1. Bathymetry map of the Iberian Abyssal Plain showing the locations of core site Ocean Drilling Program (ODP) Hole 898A. Also shown is the location of small mass transport deposits (MTDs) originating from the Galicia Bank, and the three canyons that feed into the Iberian Abyssal Plain, the Nazaré, Aveiro, and Oporto Canyons. Sites Integrated Ocean Drilling Program (IODP) 1068 and JC27-51 are shown and are discussed later. Bathymetry data are from the GEBCO database (IOC, IHO, BODC, 2003).

METHODS

Identification of Hemipelagic Sediments

Age models are used to determine the recurrence intervals for the deposits of turbidity currents, known as turbidites. These turbidites must be differentiated from "background" hemipelagic sediment that is continuously deposited out of the water column. Turbidites are often well sorted, have normal grading, and have observable internal structure (sometimes representing bed forms) developed from traction beneath the flow. The fine-grained mud cap of turbidites is commonly homogeneous and often devoid of foraminiferal material, while the basal contact of the turbidite is often sharp and erosional (Bouma, 1962; Stow and Piper, 1984). In contrast, hemipelagic sediments typically consist of bioturbated detrital clay that contains dispersed foraminifera and lacks sedimentary structures (Stow and Tabrez, 1998; Hoogakker et al., 2004).

Age Model Development and Recurrence Estimation

Age control for core in ODP Hole 898A was provided by coccolith biostratigraphy. The 13 biostratigraphic datum horizons for Pleistocene deposits were identified using coccolith assemblages and standard acme zonal boundaries (Fig. 2; Liu et al., 1996; Milkert et al., 1996a). Using these datums, and the thicknesses of hemipelagic sediment between them, sedimentation rates were calculated. The thicknesses of hemipelagic sediment were then divided by the sedimentation rates to convert them into time intervals (Thomson and Weaver, 1994; Wynn et al., 2002; Gràcia et al., 2010; Clare et al., 2014). From these time intervals, the ages of individual turbidites were estimated. Using the age model to estimate the emplacement age of each turbidite allowed the calculation of individual recurrence intervals. Here, we define the recurrence interval of a turbidite as the length of time since the turbidite that preceded it (Clare et al., 2014, 2015; Pope et al., 2015). The use of hemipelagic age models in determining the age of turbidites relies on two assumptions: (1) There is minimal fluctuation in the rate of hemipelagic sediment accumulation through time (Milkert et al., 1996a; Lebreiro et al., 2009; Allin et al., 2016; Clare et al., 2015), and (2) there is minimal erosion of the seafloor by turbidity currents (Weaver and Thomson, 1993; Thomson and Weaver, 1994; Wynn et al., 2002; Gutiérrez-Pastor et al., 2009; Gràcia et al., 2010).

Statistical Analysis of Turbidite Recurrence

Testing the Statistical Distribution Form of Recurrence Intervals in Core from ODP Hole 898A

The shapes of recurrence interval distribution forms, which represent the likelihood of recurrence intervals of different durations, can yield information about the dynamics governing the system that gave rise to them (van Rooij et al., 2013). It has been demonstrated that certain statistical distributions of recurrence intervals indicate time-dependent behavior. These statistical distributions may indicate that additive process (e.g., for a normal distribution) or a multiplicative interaction of processes (e.g., for a lognormal distribution) are exerting control on a system (van Rooij et al., 2013; Clare et al., 2016). Equally, distributions may indicate (pseudo)randomness or a lack of memory between successive events (e.g., for an exponential distribution).

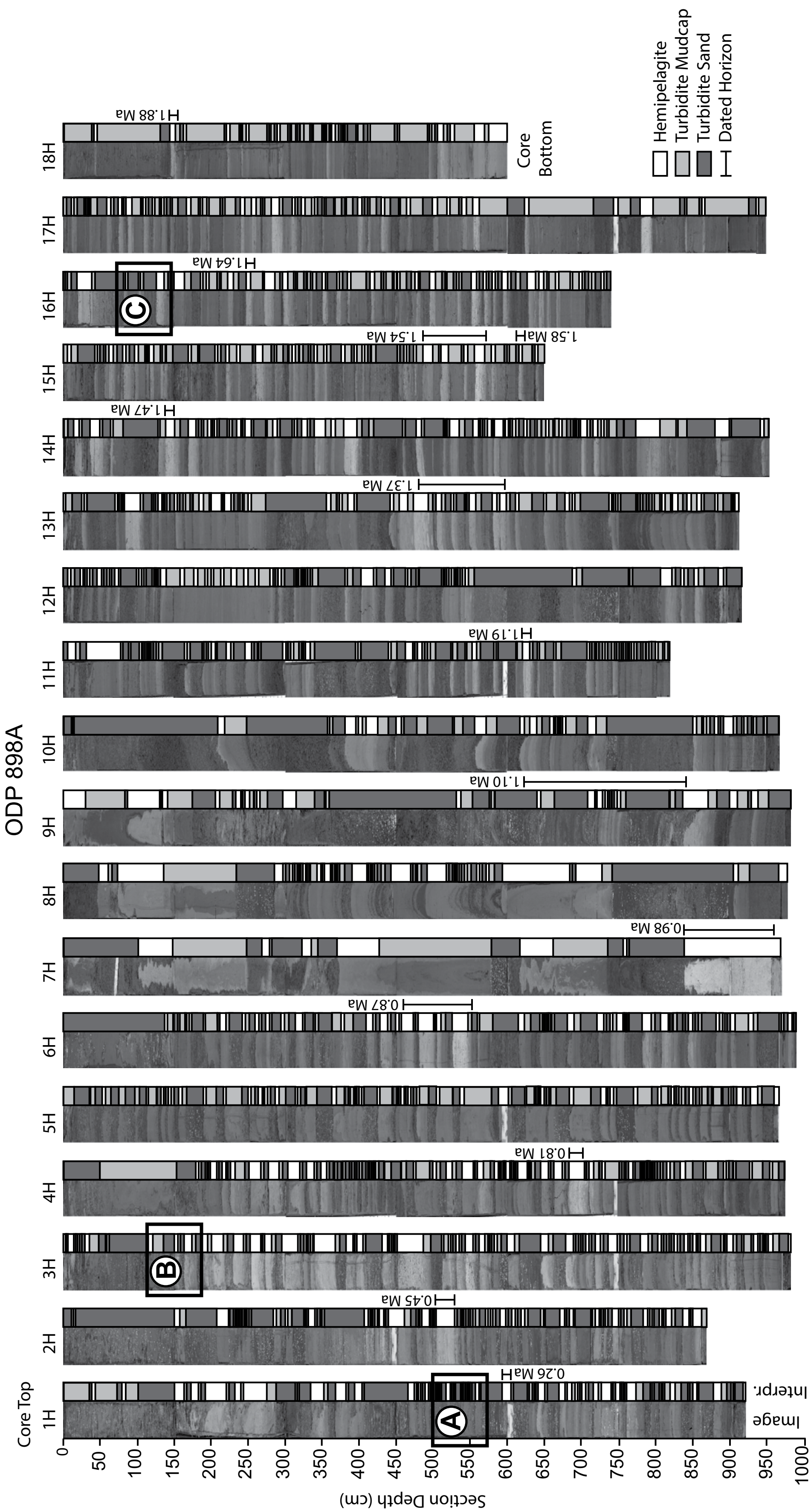

Figure 2. Photographs of cores recovered from Ocean Drilling Program (ODP) Hole 898A and the biostratigraphic datums (yellow) used in the age model. The thickness of the biostratigraphic datums shows their depth uncertainty within the core. Beside the photos are interpretations of the core section. Light and dark gray are turbidite mud cap and sand respectively, and white is hemipelagic sediment. Enlargements of A, B, and C can be seen in Figure 3.

We aimed to determine the frequency distribution form of turbidite recurrence intervals at ODP Hole 898A over the last 1.8 m.y. to understand possible triggers and controls for canyon-flushing turbidity currents. We used exceedance plots to determine the distribution form of turbidite recurrence intervals from the Iberian Abyssal Plain. Exceedance plots have been used as a visual test of data distribution over different scales, and they plot the likelihood that a given recurrence interval will exceed the longest recurrence interval in the data set (Talling, 2001; Sylvester, 2007; Hunt et al., 2013a; Clare et al., 2014, 2016). In addition to exceedance plots, the distribution form of turbidite recurrence in ODP Hole 898A was compared with the lognormally distributed turbidite recurrence data set of Clare et al. (2015). This turbidite recurrence data set originated from Integrated Ocean Drilling Program (IODP) borehole 1068 in the Iberian Abyssal Plain and extends from 48 to 65 Ma (Fig. 1).

Testing for a Persistent Trend over Shorter Time Periods

Given the <1.8 m.y. time span of the ODP Hole 898A core record and the large number of turbidites (N = 665), it is possible that a given distribution does not apply to all of the data. In order to determine whether or not a distribution was persistent over shorter subsets of the data, we divided the data into subgroups (A through K) based on changes in the gradient of the cumulative recurrence curve. The subgroups were plotted on exceedance plots to determine whether they had similar or different distributions. Lack of a common distribution form may indicate that processes governing turbidite recurrence intervals are not consistent through time.

Testing for Sea-Level Control on Turbidite Recurrence at Site ODP Hole 898A

Statistical analyses are widely used to understand geohazard frequency and triggering, and thy are most informative where large (N = >100 events) data sets are available (Green, 1991; Tabachnick and Fidell, 2007; Clare et al., 2016). Previous turbidite records from the Nazaré Canyon and Iberian Abyssal Plain had sufficient numbers of events, but they did not span one full sea-level cycle, meaning its influence over geological time could not be tested (Allin et al., 2016). The use of appropriately long records and suitable statistical analyses has been recognized by multiple authors as essential in identifying patterns or ordering in deep-water sedimentation (Wilkinson et al., 2003; Sylvester, 2007; Burgess, 2016). The large number of turbidites in ODP Hole 898A and the 1.8 m.y. span of the record make it an ideal location at which to test for the influence of eustatic variability on the recurrence rate of canyon-flushing events. While caution should be exercised when making inferences from a single core location within a large depositional system, the size (N = 665) and the length of the record are sufficient for robust statistical analyses. This analysis, combined with existing turbidite records (Allin et al., 2016), will provide a much more comprehensive overview of the Nazaré depositional system.

The first statistical analysis we used was a linear model, which tests for the significance of sea level as an explanatory variable on the recurrence of turbidites (McCullagh and Nelder, 1989; Allin et al., 2016; Clare et al., 2016). Linear models produce a regression coefficient, which is a measure of the change in a response variable (recurrence interval) with a 1 unit (meter) change in the explanatory variable (sea level). They also produce a correlation coefficient (R^2), which is a measure of the variability in the data that is accounted for by the explanatory variable (Schemper and Stare, 1996). General rules of thumb exist for determining the minimum sample size for regression analysis. Prior statistical studies have indicated that testing for statistical power and effect size will require at least between $N = 23$ and $N = 106$ events to detect a large effect of an explanatory variable.

To further test the effect of eustatic sea-level change on turbidite recurrence, we applied a nonparametric Cox proportional hazards (PH) model (Cox, 1972). The Cox PH model requires no a priori specification of frequency distribution form and is independent of time. The Cox PH model is typically used to determine a hazard rate (regression coefficient) in medical studies (e.g., rate of patient fatality), but it has also been applied to turbidite frequency analysis (Hunt et al., 2014; Allin et al., 2016; Clare et al., 2016). The hazard coefficient is analogous to a regression coefficient; it is the ratio between the change in the explanatory variable (e.g., sea level) and the change in the response variable (in this case, turbidite recurrence). Previous work has shown that the Cox PH model requires at least a minimum sample size of N = 20 (Vittinghoff and McCulloch, 2007). In addition to a hazard coefficient, the Cox PH model performs survival analysis using three separate tests (likelihood, Wald, and log-rank), for which p values are derived. For both the linear and Cox PH models, where the resultant p value is small ($p < 0.05$), sea level is shown to significantly explain variations in turbidite recurrence. Where the p value is large ($p > 0.05$), sea level is not found to be a statistically significant control on turbidite recurrence.

For both the linear model and Cox PH model, we tested the turbidite recurrence data against the global eustatic sea-level curve of Miller et al. (2005). This sea-level curve was constructed from borehole $\delta^{18}O$ measurements and has a 5 k.y. resolution. Although this resolution is much lower than sea-level curves used in some other statistical analyses of turbidite recurrence (Urlaub et al., 2013; Allin et al., 2016), major sea-level transitions associated with Pleistocene glacial cycles are well recorded. This suggests that the Miller et al. (2005) sea-level curve is appropriate for the analysis of turbidite records through the Pleistocene to test for the response of turbidite recurrence in relation to major eustatic fluctuations.

RESULTS

Core Sedimentology

ODP Hole 898A contains multiple dark, normally graded sequences with silty/sandy bases interspersed with pale microfossil-rich clays (Fig. 2). The normally graded sands capped with muds are interpreted to be turbidites in the sense of Stow and Piper (1984), which vary from 0.5 to 200 cm thick, with an average thickness of 18.5 cm (Fig. 2). The turbidites typically exhibit coarse sandy bases and fine upward into clay mud caps. Some of the turbidites consist primarily of sand and contain very little fine-grained material (Fig. 3A). Certain sandy turbidites have multiple fining-upward sequences that may be subunits representing multistage failures (Fig. 3A; Hunt et al., 2013b). Other turbidites have thin, >2-cm-thick sandy bases and consist primarily of fine-grained mud cap (Fig. 3B), while others have no coarse basal sand/silt units (Fig. 3C). The pale, nanofossil-rich clay is interpreted to be hemipelagite after Stow and Tabrez (1998). The boundaries between turbidite units and overlying hemipelagic clays are sometimes obscured by sediment mixing due to bioturbation (Fig. 3B). In these cases, we delineate the boundary between the two facies to be where they exist in equal proportions.

Age Model and Sedimentation Rate

The biostratigraphic datum horizons for ODP Hole 898A are shown in Figure 2 (Milkert et al., 1996a). Uncertainties associated with these datums are difficult to constrain, because they are rarely reported. Conservative estimates of uncertainty surrounding the use of coccolith biostratigraphy are ±10 k.y. (Hunt et al., 2013b). The age model shows a relatively linear hemipelagic sedimentation rate since 1.8 Ma (R^2 = 0.97; Fig. 4). The average sedimentation rate for the entire record is 2.01 cm/k.y. The sedimentation rate between each datum was used for calculating individual turbidite recurrences. The

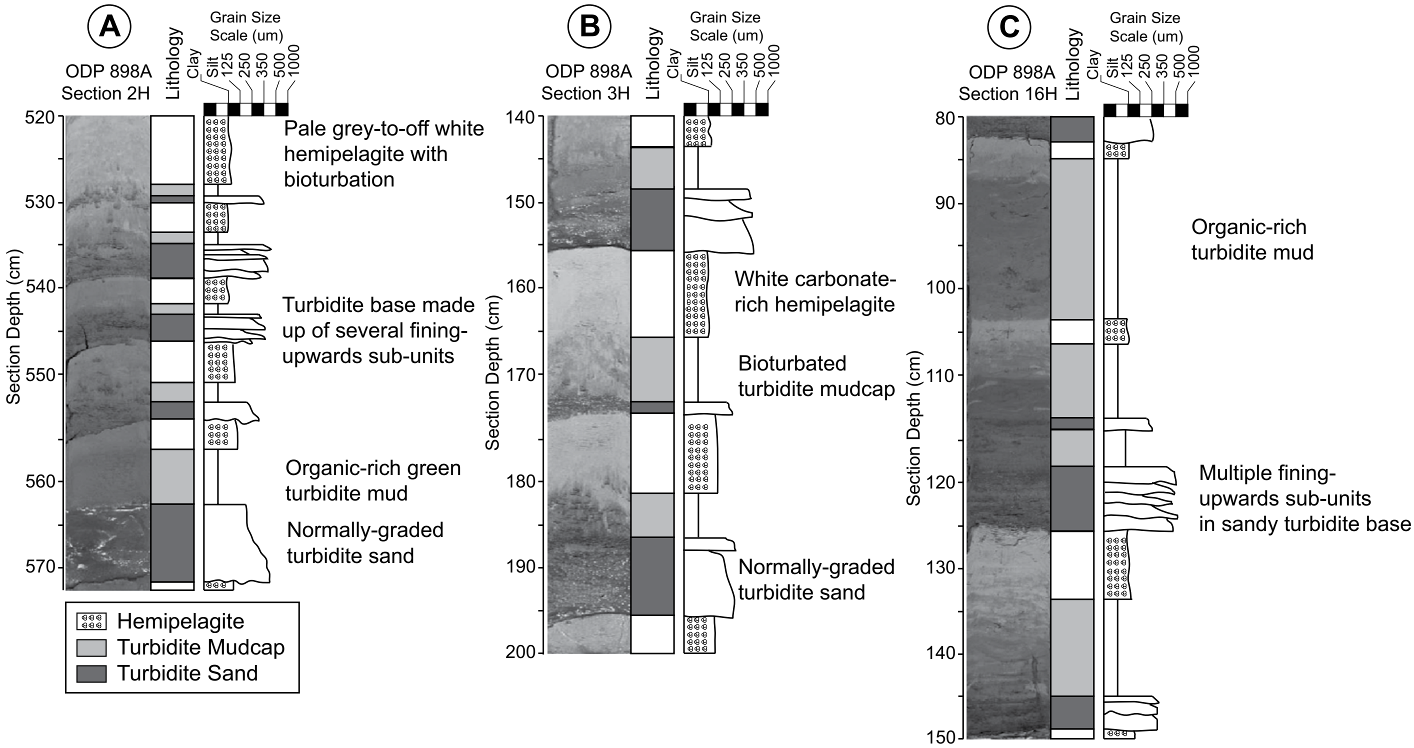

Figure 3. Photographs and lithological logs of deposits within core Ocean Drilling Program (ODP) 898A. (A) Section in the upper core showing several thin and sand-rich turbidites, along with a thicker turbidite toward the base of the section. Several of the thin turbidites have multiple upward-fining sequences within their sandy bases. (B) Section in the upper core showing two thick sandy turbidites, along with one that is largely mud-dominated. (C) Section in the lower core showing a mud-rich turbidite with no coarse base, along with two other thick turbidites with multiple fining-upward sequences.

minimum accurately resolvable hemipelagic interval within core ODP Hole 898A is 0.5 cm thick, due to bioturbation mixing.

Distribution Form of Turbidite Recurrence Intervals at ODP Hole 898A

The ODP Hole 898A turbidite recurrence data plot as a straight line on a log-probability plot, indicating that their distribution form is lognormal (Fig. 5A; Clare et al., 2016). Exceedance plots also show a strong similarity between the lognormally distributed IODP 1068 recurrence data of Clare et al. (2015) spanning 68–48 Ma and the recurrence data from ODP Hole 898A (Fig. 5A). When analyzed using a Mann-Whitney *U*-test, the ODP Hole 898A turbidite recurrence data are not significantly different from a synthetic recurrence data set with a lognormal distribution ($P > 0.05$). When the ODP Hole 898A data set is subdivided based on changes in the slope of cumulative recurrence (Fig. 5B), a largely persistent lognormal trend through time can be seen on exceedance plots (Fig. 5C). All but subgroups A and G exhibit this trend, indicating the bulk of the data conform to a lognormal distribution.

Influence of Sea Level on Turbidite Recurrence and Thickness at ODP Hole 898A

Due to the low temporal resolution (5 k.y.) of the sea-level curve, it is difficult to visually identify any correlation between the individual cycles of sea-level change and turbidite recurrence. Plotting the curves of cumulative turbidite age and cumulative turbidite thickness against a global eustatic sea-level curve shows a change in both trends between 1.1 and 0.9 Ma (Fig. 6). This change coincides with the mid-Pleistocene transition between 1.2 and 0.9 Ma, when long-periodicity (>0.1 m.y.), high-amplitude glacial variability began to persist (Mudelsee and Schultz, 1997; Clark et al., 2006). Prior to the mid-Pleistocene transition, the average

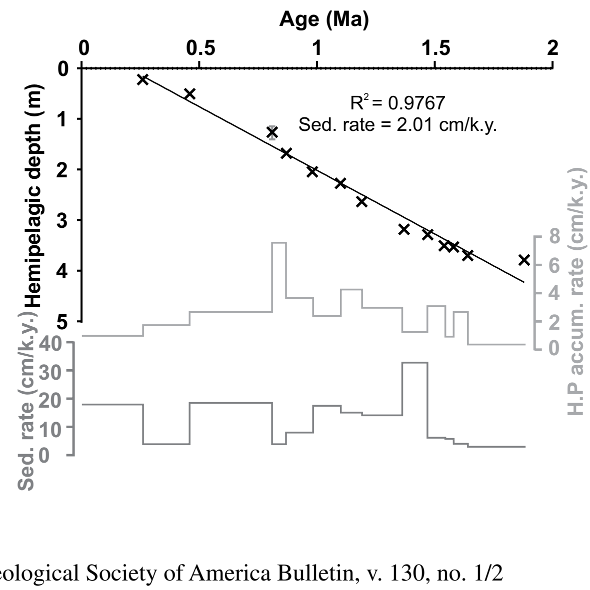

Figure 4. Age model for core from Ocean Drilling Program (ODP) Hole 898A from biostratigraphic datums outlined in Milkert et al. (1996b; Fig. 2). Gray bars on age tie points show depth uncertainty. The R^2 correlation coefficient indicates a relatively constant sedimentation rate through time. The graph in light gray shows the hemipelagic (H.P.) accumulation rate, while the graph in dark gray shows the total sedimentation rate.

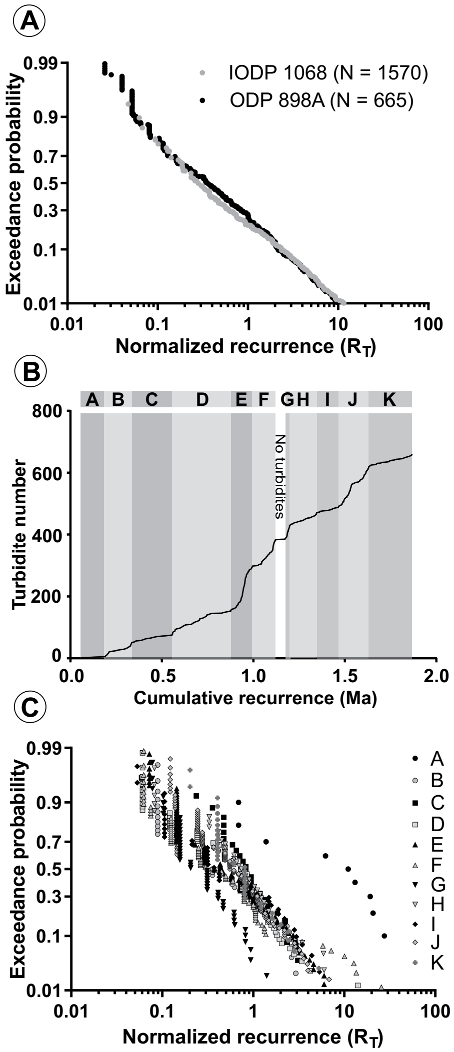

Figure 5. (A) Exceedance plots of the Ocean Drilling Program (ODP) Hole 898A data set compared with the lognormally distributed recurrence data set from Integrated Ocean Drilling Program (IODP)1068 (Clare et al., 2015). Normalized recurrence data are plotted on a log-probability plot. (B) Subdivisions of the ODP Hole 898A data based on changes in the slope of cumulative recurrence. (C) Log-probability plot of normalized recurrence data for all data subdivisions based on changes in the slope of cumulative recurrence.

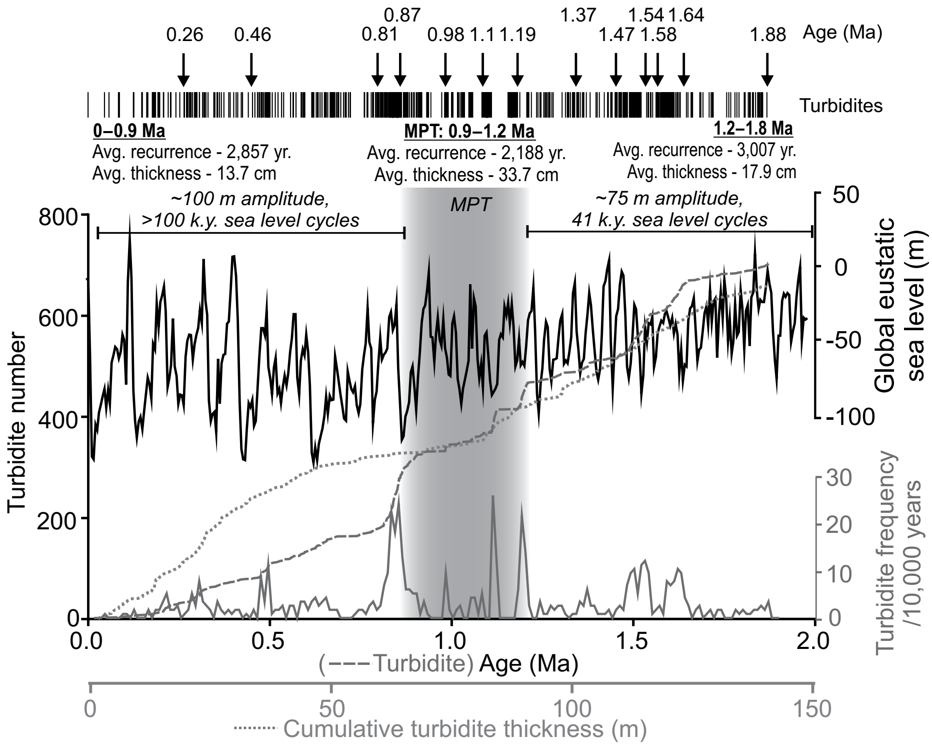

Figure 6. Turbidite ages and thicknesses from Ocean Drilling Program (ODP) Hole 898A (N = 665) plotted against the sea-level curve (black) of Miller et al. (2005). The dashed gray line is the cumulative age of turbidites, the dotted gray line is the cumulative turbidite thickness, and the solid gray line is the frequency of turbidites in 10,000 yr intervals. There is a significant decrease in the average turbidite recurrence, an increase in the frequency, and an increase in the average thickness during the mid-Pleistocene transition (MPT). Following the onset of >0.1 m.y. glacial cycles at ca. 0.9 Ma, the average turbidite recurrence increased, and the average thickness decreased relative to the pretransition values.

recurrence of canyon-flushing was 3000 yr, and the average turbidite thickness was 17.9 cm (Fig. 6). The coefficients of variability for turbidite recurrence and thickness before the mid-Pleistocene transition are 149 and 92, respectively (Fig. 7). The coefficient of variation is a dimensionless ratio of the standard deviation to the mean, with higher values indicating higher variability in turbidite recurrences.

During the mid-Pleistocene transition between 1.2 and 0.9 Ma, the average turbidite recurrence decreased to 2200 yr, while the thickness increased to 33.7 cm. There was a considerable fall in sea level to –110 m at the end of the mid-Pleistocene transition that is associated with the lowest turbidite recurrence intervals contained within the ODP Hole 898A record (Fig. 6). The coefficients of variation for turbidite recurrence and thickness during the mid-Pleistocene transition are 322 and 155, respectively, indicating higher variability in turbidite recurrence values than the period before the onset of the transition.

After the mid-Pleistocene transition, between 0.9 Ma and present, turbidite recurrence restabilized at an average duration of 2850 yr, i.e., slightly shorter than before the mid-Pleistocene transition. The average turbidite thickness for this period is 13.7 cm, although turbidite thickness remained consistently higher than before the mid-Pleistocene transition until ca. 0.5 Ma (Fig. 6). Box and whisker plots of turbidite recurrence and thickness illustrate increased variability in both parameters relative to the pretransition values (Fig. 7). The coefficients of variation for turbidite recurrence and thickness during the mid-Pleistocene transition are 191 and 106, respectively, which are closer to the values observed before the transition (Fig. 7). Kolmogorov-Smirnov and Mann-Whitney tests indicate the populations of both turbidite recurrence and thicknesses are significantly different before and after the mid-Pleistocene transition ($p \leq 0.05$).

The p value (<0.05) and the low correlation coefficient (R^2 = 1.9%) produced by the log-linear model reveal that the majority of the variance in recurrence intervals cannot be statistically explained by eustatic sea level (Fig. 8). However, the low p values from the Cox proportional hazards model indicate that we cannot reject the null hypothesis that turbidite recurrence does not correlate with sea level (Table 1). The hazard coefficient indicates only a small (<1%) change in the recurrence of turbidity currents in response to a 1 m change in sea level (Table 1), and so sea level is a credible control. Both the

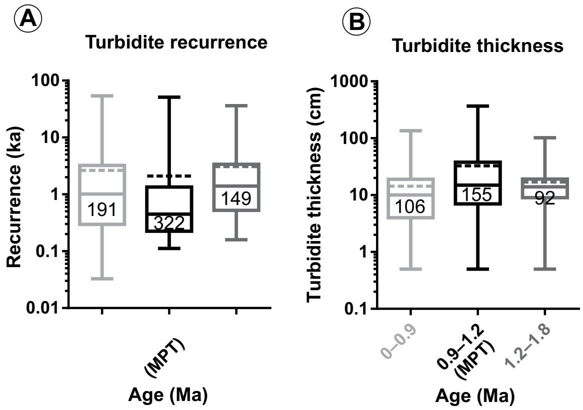

Figure 7. Box and whisker plot illustrating the differences in (A) turbidite recurrence and (B) turbidite thickness before (dark gray) and after (light gray) the onset of 100 k.y. sea-level cycles following the mid-Pleistocene transition (MPT). Boxes show the upper and lower quartiles, whiskers show maximum and minimum values, the solid line in the box shows the median value, and the dashed line shows the average recurrence. Recurrence decreases following the mid-Pleistocene transition, with the median, mean, and upper/lower quartile values lower than values observed before the mid-Pleistocene transition. The same decreases in the median, mean, and upper/lower quartile values are observed in the turbidite thickness data following the mid-Pleistocene transition. Values inset in quartile boxes are coefficients of variation.

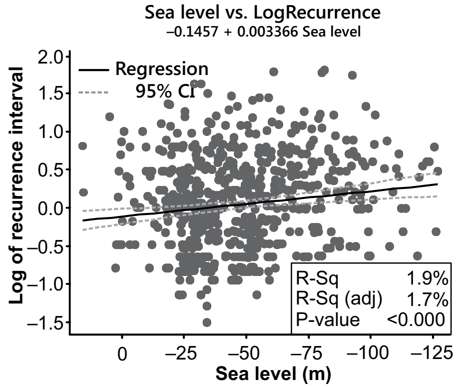

Figure 8. Results of the log-linear regression model of turbidite recurrence with sea level as the explanatory variable. The fitted line plot shows a large amount of variance within the data, indicating sea level is a poor explanatory variable and cannot be implicated as a significant control on turbidite recurrence. CI—confidence interval.

rate of sea-level change (first derivative) and sea-level combined with its first derivative are not significant in either the linear or the Cox proportional hazards models (Table 1).

DISCUSSION

This section will discuss the influence of climatically driven sea-level changes on canyon flushing within Nazaré Canyon. We will also discuss the significance of a lognormal distribution of turbidite recurrence, as well as how it may arise in turbidite records.

Are All Turbidites the Result of Canyon Flushing?

Our use of only a single core (ODP Hole 898A) in the Iberian Abyssal Plain makes it impossible to use turbidite volume or lateral extent to infer that turbidites are the result of canyon flushing. Canyon-flushing events may occur within a wide range of volumes, based on the availability of unconsolidated sediment within the canyon. The ODP Hole 898A site and the JC27-51 site have similar water depths and distances from the Nazaré Canyon mouth (Fig. 1; Allin et al., 2016). Additionally, the recurrence intervals and thicknesses of turbidites in ODP Hole 898A are similar to those reported in distal Iberian Abyssal Plain core JC27-51, interpreted to be canyon-flushing events (Allin et al., 2016). If lateral continuity of turbidites is assumed over the proximal 25% of the Iberian Abyssal Plain, then thicknesses of greater than 0.5 cm equate to >0.1 km³ and are likely the result of considerable sediment erosion (Paull et al., 2005). Furthermore, the location of ODP 898A on the periphery of the basin suggests that turbidites in this core represent the more distal edge of deposits that are likely thicker in the central Iberian Abyssal Plain (Fig. 1; Hunt et al., 2013a). Therefore, we infer that the majority of turbidites in the ODP Hole 898A record are the result of canyon-flushing turbidity currents.

Does Eustatic Sea Level Affect Canyon Flushing?

The role of sea level as an important control on the development of deep-sea sedimentary systems is well established (Vail et al., 1977; Shanmugam and Moiola, 1982; Posamentier and Vail, 1988; Ducassou et al., 2009). This includes turbidity currents that fill submarine canyons (Lebreiro et al., 2009; Covault and Graham, 2010). However, the role of eustatic sea level changes in controlling canyon-flushing events in the Nazaré Canyon is less clear (Allin et al., 2016). Here, as with previous research, the statistical analyses reveal minimal correlation between short-term (120 k.y.) fluctuations in sea level and the recurrence of turbidites in the Iberian Abyssal Plain (Fig. 8; Table 1; Allin et al., 2016). The majority of individual sea-level highstands and lowstands cannot be reliably correlated with clusters of turbidites in Hole ODP 898A, highlighting the need for impartial statistical analyses (Fig. 6). However, the onset of the mid-Pleistocene transition at ca. 1.2 Ma is associated with a marked change in average recurrence rate and thickness of turbidites.

The mid-Pleistocene transition is a recognized global climatic shift from short-periodicity, low-amplitude sea-level cycles into long-

TABLE 1. SUMMARY TABLE OF THE RESULTS OF THE LINEAR MODEL AND COX PROPORTIONAL HAZARDS (PH) MODELS

	Log-linear model			Cox proportional hazards model			
Explanatory variable	p value	Regression coefficient	Correlation coefficient (R^2)	Likelihood (p)	Wald (p)	Log rank (p)	Hazard coefficient
Sea level	<0.005	0.003	1.9	0.0085	0.0088	0.0087	1.004
First derivative of sea level	0.42	0.0002	*	0.1472	0.1453	0.1453	1
Sea level + first derivative	0.939	-3.518×10^{-7}	*		0.3645		1

Note: Sea level appears to be significant in the loglinear model ($p \leq 0.005$), but the regression and correlation (R^2) coefficient is low (1.9%). Similarly, with the Cox proportional hazards model, the p value is significant (<0.05), but the hazard coefficient only indicates a 0.4% change in the hazard with a 1 m change in sea level (1.004). Neither the change in sea level (first derivative) nor the combination of sea level and its derivative (rate) is significant in either linear or proportional hazards models ($p > 0.05$).

*Testing the rate (first derivative) of sea level against turbidite recurrence was done using a generalized linear model. This method is similar to the log-linear model, except no correlation coefficients are generated.

periodicity, high-amplitude sea-level cycles that occurred between 1.2 and 0.9 Ma (Mudelsee and Schultz, 1997; Clark et al., 2006). Sea level before the mid-Pleistocene transition fluctuated with a 41 k.y. periodicity, had ~75 m amplitude, and had lowstands that persisted for only 5000–15,000 yr. Following the mid-Pleistocene transition, the periodicity of sea-level cycles increased to >100,000 yr, while the amplitude increased to >100 m, and lowstands persisted for over 20,000 yr (Fig. 6; Shackleton et al., 1990; Mudelsee and Schultz, 1997; Paillard, 1998; Miller et al., 2005; Clark et al., 2006). Sequence stratigraphic models predict that sea-level lowstands shift sediment deposition toward the shelf edge and promote increased deep-sea fan development (Posamentier and Vail, 1988). The mid-Pleistocene shift from <75 to >100 m sea-level amplitudes is recognized in seismic surveys on the Iberian, Mediterranean, and Moroccan margins, where it corresponds to the onset of thick, notably cyclic packages of sediment (Ercilla et al., 1994; Llave et al., 2001; Hernández-Molina et al., 2002; Le Roy et al., 2014). It is also associated with the appearance of fully shelf-incising canyons on the Ebro margin of the Mediterranean (Mauffrey et al., 2017). The initial increase in the amplitude of sea-level variability associated with the mid-Pleistocene transition would have exposed a greater volume of sediment on the continental shelf to subaerial weathering processes (Fig. 9). Therefore, it might be expected that large-scale canyon-flushing events in Nazaré Canyon would increase after the mid-Pleistocene transition.

Here, we propose a new model for canyon flushing over the last 1.8 m.y. Between 1.8 and 1.2 Ma, canyon flushing occurred largely independent of sea level (Fig. 9A). During this time, large amounts of unconsolidated sediment accumulated on the shelf, below the 75 m amplitude of eustatic sea level. The initial increase in turbidite frequency at the end of the mid-Pleistocene transition is coincident with the lowest sea level in the last 10 m.y., beginning at 0.9 Ma (Fig. 6; Miller et al., 2005). This drop in sea level would have exposed a large portion of the Iberian continental shelf not previously subjected to subaerial weathering, likely resulting in a considerable basinward flux of sediment (Fig. 9B). Despite the increased periodicity and amplitude of sea-level variability after the mid-Pleistocene transition (0.9–0 Ma), the 2850 yr average recurrence interval of turbidites is similar to the pretransition average of 3000 yr (Fig. 6), albeit with more variability in recurrence values (Fig. 7A). Furthermore, turbidites in the Iberian Abyssal Plain are on average thinner after the mid-Pleistocene transition, in spite of the predicted increase in sediment delivery due to longer and more pronounced sea-level lowstands (Fig. 7B). This suggests that the recurrence rates and sediment volumes of canyon-flushing events are associated with changes in the amplitude and periodicity of sea-level change, but they are relatively stable during times of regular sea-level amplitude and periodicity (Figs. 9A and 9C). Therefore, sharp and irregular drops in sea level can lead to an increase in canyon flushing, although at other times, the process appears to be independent of sea level, contrary to the prevailing lowstand model.

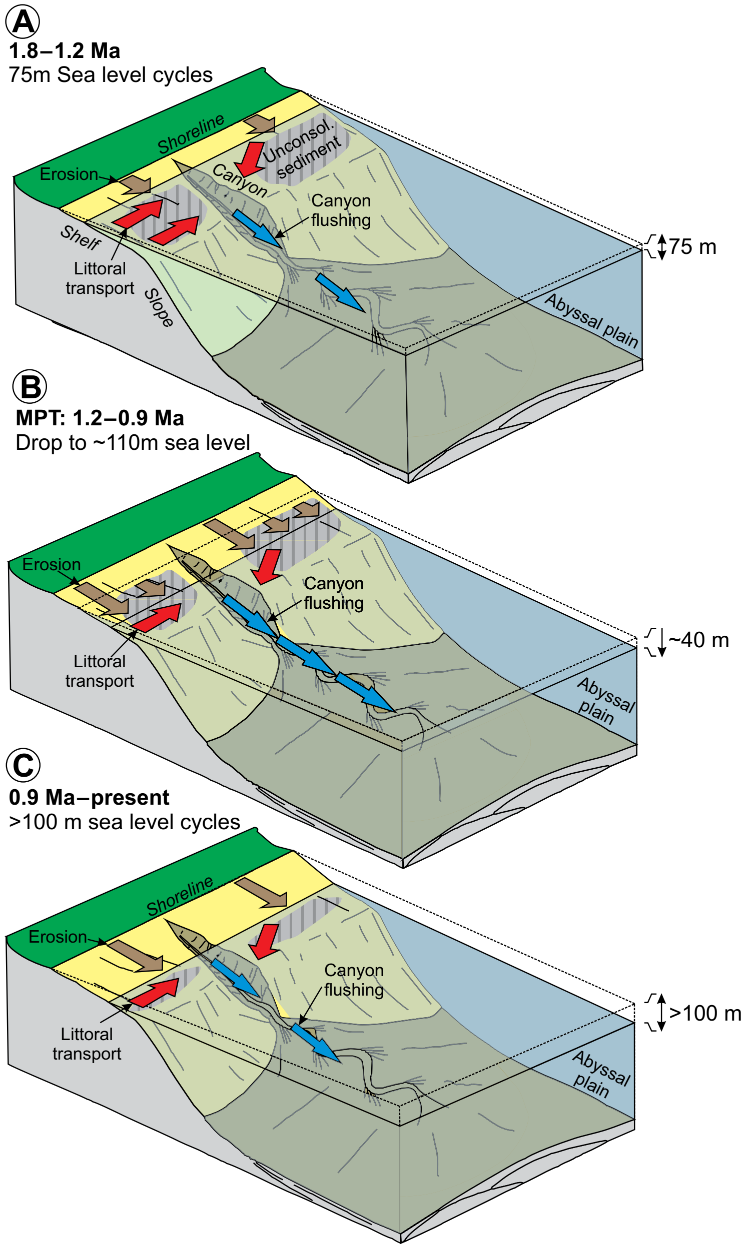

Figure 9. Schematic model of the Iberian continental shelf and Nazaré Canyon. (A) Before the mid-Pleistocene transition, large volumes of sediment accumulated on the shelf owing to the low, 75 m amplitude of sea-level cycles. (B) During the mid-Pleistocene transition (MPT), when sea level dropped to ~110 m below present day, a large amount of this sediment became exposed to subaerial weathering. This temporarily increased the frequency of flushing turbidity currents in Nazaré Canyon. (C) Following the mid-Pleistocene transition, the mean recurrence of canyon flushing returned to near its pretransition value.

Sources of Uncertainty in Age-Depth Modeling and Statistical Analyses

The age model used to estimate the recurrence interval of turbidites is based on two main assumptions: (1) continuous hemipelagic accumulation between age datums and (2) largely noneroding turbidity currents at their point of emplacement. While there is evidence that hemipelagic sedimentation in the Iberian Abyssal Plain is relatively consistent over glacial-interglacial time scales, there is likely to be some variability in hemipelagic sedimentation rate that is not captured due to the limited number of age datums (Lebreiro et al., 2009; Gràcia et al., 2010; Clare et al., 2015; Allin et al., 2016). The age datums that underpin the model are subject to depth uncertainty in the ODP Hole 898A core, with some having hemipelagic depth uncertainty of up to ±50 cm (Fig. 2). This is due to uncertainty in the precise position of first and last occurrences of key coccolith species. The age uncertainties of the datums are much more variable (Milkert et al., 1996a). Error on biostratigraphic datums within the late Quaternary are conservatively taken to be ±10,000 yr (Hunt et al., 2013a), although this error is most likely greater beyond 100 ka.

Turbidity currents within abyssal basins can be nonerosional, but some may contain higher concentrations of sediment and subsequently erode the seafloor (Weaver and Thomson, 1993; Thomson and Weaver, 1994; Wynn et al., 2002; Gutiérrez-Pastor et al., 2009; Gràcia et al., 2010; Allin et al., 2016). Basal erosion has the potential to bias the age model by removing hemipelagic sediment as well as older turbidites, although Clare et al. (2015) demonstrated that error due to minor systemic erosion may not significantly affect the distribution form of recurrence intervals. In addition to uncertainties in the hemipelagic accumulation rate, the exact position of the boundaries between turbidites and hemipelagic sediment can also be unclear. The hemipelagic age model relies on accurately identifying the boundary between the two sediment types in order to estimate the amount of hemipelagic accumulation between age datums, as well as the age of turbidites through interpolation. Bioturbation by infaunal organisms can mix sediment types and make defining this boundary difficult. In order to account for this, any bioturbated boundaries between turbidites and hemipelagite are taken to be where both types of sediment occur in equal proportions. Bioturbation can therefore result in additional uncertainty in the age of turbidites and in the statistical analyses.

The results of the log-linear model and Cox proportional hazards model indicate that neither sea level nor the rate of sea-level change is a dominant control on the recurrence intervals of canyon-flushing turbidity currents (Table 1). However, the sea-level curve of Miller et al. (2005) has a 5000 yr resolution, which is sufficient to capture broad glacial-interglacial variability, but it may be too coarse to capture any statistical correlation with recurrence intervals (Fig. 6). Furthermore, the Miller et al. (2005) sea-level curve is a global eustatic sea-level curve and may not capture local variability associated with isostatic and tectonic influences (Shanmugam and Moiola, 1982; Stow and Piper, 1984; Covault and Graham, 2010). Other sea-level curves covering the Pleistocene exist, but they are either too short to cover the full length of the ODP 898A record (Rohling et al., 2009), or they are too coarse to provide any meaningful comparison (Haq and Schutter, 2008). The uncertainties associated with age datums have potentially imparted error onto the recurrence intervals of turbidites, masking the influence of sea-level change. However, positions of the age datums within the core do not seem to affect the clustering of turbidites, implying the clusters are real rather than an artifact of the age modeling (Fig. 6). Therefore, the effect of the mid-Pleistocene transition on turbidite recurrence can also be considered to be real.

Were Earthquakes Responsible for Increased Canyon Flushing during the Mid-Pleistocene Transition?

The southwestern Iberian margin is tectonically active as a result of the compressional rotation associated with the Azores-Gibraltar fracture zone (Buforn et al., 1988; Borges et al., 2001; Zitellini et al., 2004; Custódio et al., 2015). Several turbidites observed in the Tagus and Horseshoe Basins to the south of the Iberian Abyssal Plain are proposed to have been caused by regional earthquakes (Gràcia et al., 2010; Masson et al., 2011). However, it is not clear whether earthquakes trigger canyon-flushing events in Nazaré Canyon (Allin et al., 2016). It has been proposed that eustatic sea-level cycles affect the flexural stress of faults proximal to the coastline and thus can increase earthquake generation (Brothers et al., 2013). It is therefore implied that the sudden drop in sea level at the end of the mid-Pleistocene transition could be responsible for the increased frequency of earthquakes, and thus increased the frequency of canyon flushing during this period.

Flexural stress modeling has suggested that offshore fault activity is inhibited during times of sea-level lowstand, while onshore fault activity is promoted (Luttrell and Sandwell, 2010). Offshore fault activity that triggers large canyon-flushing turbidity currents reaching the Tagus and Horseshoe Basins is unlikely to trigger flushing in Nazaré Canyon (Allin et al., 2016). Earthquakes originating from onshore faults near the head of Nazaré Canyon are proposed to be more likely triggers of canyon flushing. However, these onshore faults have a low likelihood of reactivation as a result of sea-level change (Neves et al., 2015). Therefore, it is difficult to implicate seismicity as a cause of increased canyon flushing during the mid-Pleistocene transition.

Significance of a Lognormal Distribution

Lognormal distributions are typically observed where the mean value is low and where large variance is observed in the data (Limpert et al., 2001). A lognormal distribution of data can result from a lognormally distributed random variable, but it more likely results from multiplication of the probabilities of two or more independent random variables (Limpert et al., 2001; Grönholm and Annila, 2007; van Rooij et al., 2013). A theoretical example of lognormal multiplicative interactions between independent probabilities after Clare et al. (2015) can be seen in Equation 1:

$$P_{(\text{TC at ODP Hole 898A site})} = P_{(\text{trigger generates LS})} \times P_{(\text{LS disintegrates to TC})} \times P_{(\text{TC reaches ODP Hole 898A})}, \quad (1)$$

where P is recurrence probability, LS represents landslide, and TC represent turbidity current. Previous work on the distribution form of basin turbidite recurrence intervals has revealed exponential distributions in basin records in five locations (Clare et al., 2014; Allin et al., 2016). This exponential distribution is indicative of temporally random behavior resulting from an exponential trigger, multiple input sources, or multiplicative processes.

The lognormal distribution of turbidite recurrence intervals observed in ODP Hole 898A is fundamentally different from the exponential distribution observed in these basins, including more distally in the Iberian Abyssal Plain (Fig. 10). The lognormal distribution of turbidite recurrence intervals observed in core IODP 1068 between 65 and 48 Ma suggests that the distribution form of turbidite recurrence has remained consistent in this part of the Iberian Abyssal Plain through geological time (Fig. 4; Clare et al., 2015). A lognormal distribution of turbidite recurrence likely results from at least one temporally ordered process, although time dependence is not a fundamental characteristic of a lognormal distribution. However, the ODP Hole 898A turbidite recurrence data during the last 1.8 m.y. cannot be correlated confidently with sea level using linear or Cox regression

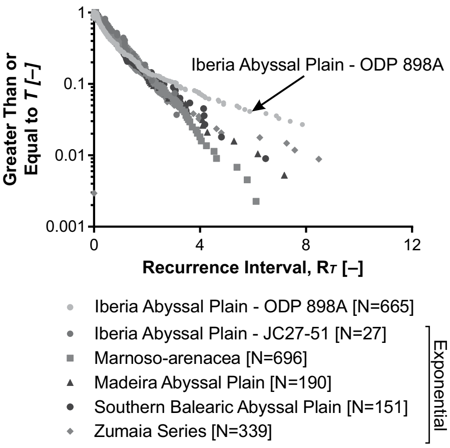

Figure 10. Comparison of exceedance plots showing recurrence data from several basin turbidite records worldwide. The lognormal distribution of recurrence data from Ocean Drilling Program (ODP) Hole 898A (light gray) is fundamentally different from the exponential form observed in five other distal basin records. Recurrence data are from Clare et al. (2014) and Allin et al. (2016).

methods. Rescaled range analysis also shows no temporal ordering within the data. The absence of any statistically significant sea-level effect on turbidite recurrence implies that a lognormal distribution is not a direct result of sea-level influence and may not be indicative of temporal ordering.

Origin of a Lognormal Distribution

We propose two hypotheses to explain the lognormal distribution of turbidite recurrences at ODP Hole 898A: (1) The variable turbidity current runout distance is biasing the depositional record. This variable runout distance may have resulted in a different recurrence distribution at ODP Hole 898A than the exponential form observed at the more distal JC27-51 site. (2) The distribution may have resulted from a combination of turbidity currents with different triggering mechanisms or sources on the continental margin. Next, we will discuss the two hypotheses.

Variable Turbidity Current Runout Distance Is Truncating the Depositional Record

Long-term sedimentary archives, like those found in abyssal plain settings, can store records (signals) of climatic or environmental variability through time. One of the ways in which the signal of sea-level variability is recorded in the deep-sea stratigraphic record is through the deposition of sediment via mass transport processes (Romans and Graham, 2013; Romans et al., 2016). This is because sea-level change can limit, or otherwise increase, sediment supply to the shelf edge, where mass transport processes dominate (Stow and Piper, 1984; Posamentier and Vail, 1988; Covault and Graham, 2010; Covault et al., 2010). However, the fidelity of such a record is dependent on the ability of sediment transport processes to reach and deposit sediment at core sampling locations.

Turbidite recurrence intervals within the lower Nazaré Canyon have been documented as conforming to a normal distribution resulting from the dominant control of eustatic sea level (Allin et al., 2016). However, turbidite recurrence intervals in the distal Iberian Abyssal Plain site JC27-51 conform to an exponential or time-independent distribution (Fig. 1; Allin et al., 2016). This fundamental difference in the distribution form of recurrence intervals could be due to more distal locations in the Iberian Abyssal Plain receiving fewer turbidity currents. Additionally, debris-flow deposits in core JC27-51 (Allin et al., 2016) suggest that the transformation and collapse of erosive flows due to choking by sediment entrainment may also act to limit the runout distance of canyon-flushing events (Amy et al., 2006; Talling et al., 2007, 2012). Core site ODP Hole 898A, with a lognormal distribution, is more proximal to the mouth of Nazaré Canyon than the more distal JC27-51 site, which displays an exponential distribution of turbidite recurrences (Fig. 1). It is possible that the lognormal distribution in ODP Hole 898A results from more turbidity currents reaching this site than the more distal JC27-51 site.

To test the hypothesis that the distance from source truncates the turbidity current record, creating lognormal and exponential distributions of recurrences further downslope, we generated a synthetic turbidite recurrence data set ($N = 500$; mean of 1500 yr; standard deviation of 500) with a normal distribution. To simulate a slope-to-deep-water system, we progressively stripped an increasing percentage (from 10% to 75%) of the smallest turbidite recurrence intervals from the data set, to account for the inefficiency of some flows to reach distal localities (Fig. 11). A lognormal form initially arises when the lowest 20% of the recurrences are removed. Further removal of the smallest recurrence intervals ultimately yields an exponential distribution, thus shredding any evidence of the original normal distribution (Figs. 12A and 12B). Probability density function plots show how the incremental removal of the lowest recurrence intervals effectively truncates the lower end of the distribution, and also adds a heavier tail (Fig. 12C).

This model illustrates that progressive truncation of initially normally ordered turbidite recurrence records can produce both lognormal and exponential distributions of turbidite recurrence in increasingly distal settings. This downslope truncation of the record is likely due to the availability of readily erodible sediment within the canyon, which can limit the capacity of flows to travel long distances. This truncation process likely explains why the influence of sea level on turbidite recurrence is more difficult to detect (i.e., shredded; Romans et al., 2016) in deep water.

Combination of Turbidity Currents with Different Triggers or Sources

While the truncation of turbidite records with increasing distance from source can account for the lognormal distribution of recurrence, the Iberian margin is prone to large-magnitude (Mw >7) earthquakes (Custódio et al., 2015). These large-magnitude earthquakes (~2000 yr average recurrence) have been invoked as the trigger of canyon-flushing turbidity currents that deposit large-volume turbidites in the Tagus and Horseshoe Basins, south of the Iberian Abyssal Plain (Fig. 1; Gràcia et al., 2010, Masson et al., 2011). The role of earthquakes in triggering large canyon-flushing turbidity currents in the Nazaré Canyon is less clear. Only three out of the six turbidites in the distal Iberian Abyssal Plain during the last 20,000 yr were deposited coeval with interpreted seismoturbidites in the Tagus and Horseshoe Basins to the south (Gràcia et al., 2010; Masson et al., 2011; Allin et al., 2016). This makes it difficult to infer an effective seismic trigger for turbidites that traveled to the Iberian Abyssal Plain. The combined effect of turbidites associated with sea-level changes and earthquakes could result in a distinct, possibly lognormal distribution form (Fig. 13A). However, this assertion is difficult to test because it is impossible to discriminate between seismically and nonseismically triggered turbidites in core ODP Hole 898A (e.g., Sumner et al., 2013).

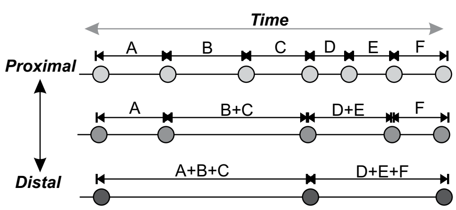

Figure 11. Method for modeling the effect of down-system truncation of turbidite records on the distribution form of recurrence. To simulate a slope-to-deep-water system, increasing percentages of turbidites with the lowest recurrences were stripped from the data set, thereby combining time intervals before and after each removed turbidite.

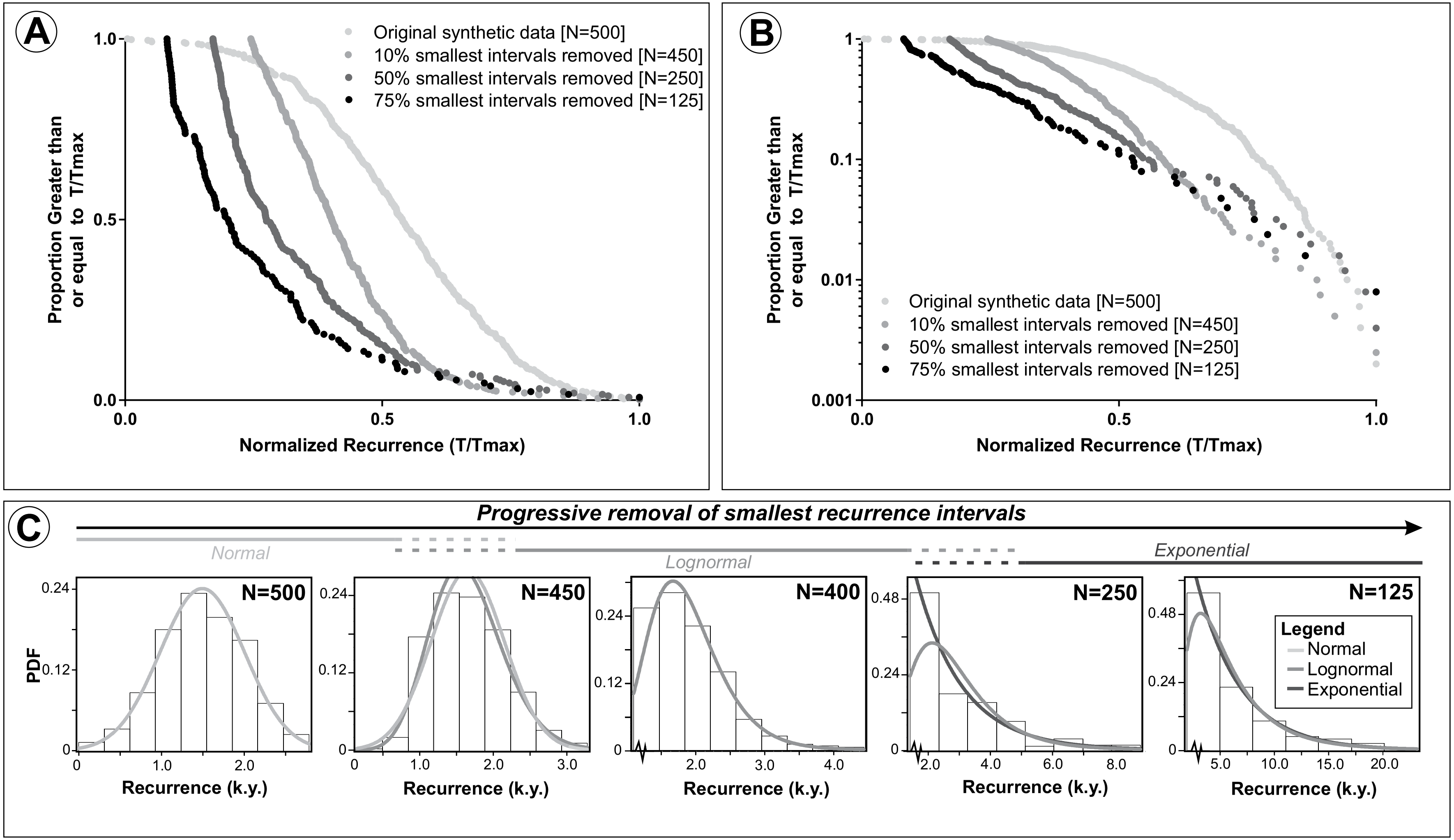

Figure 12. Model illustrating how the distribution form of turbidite recurrence may change with increasing distance from sediment source in the Iberian Abyssal Plain. (A–B) Exceedance plots showing the change in distribution form as increasing percentages of recurrence intervals are stripped from the synthetic, normally distributed recurrence data set, on normal (A) and log (B) axes. (C) Probability density functions (PDFs) of recurrence data with increasing percentages of the lowest recurrences removed, showing a change from normal through to lognormal and exponential.

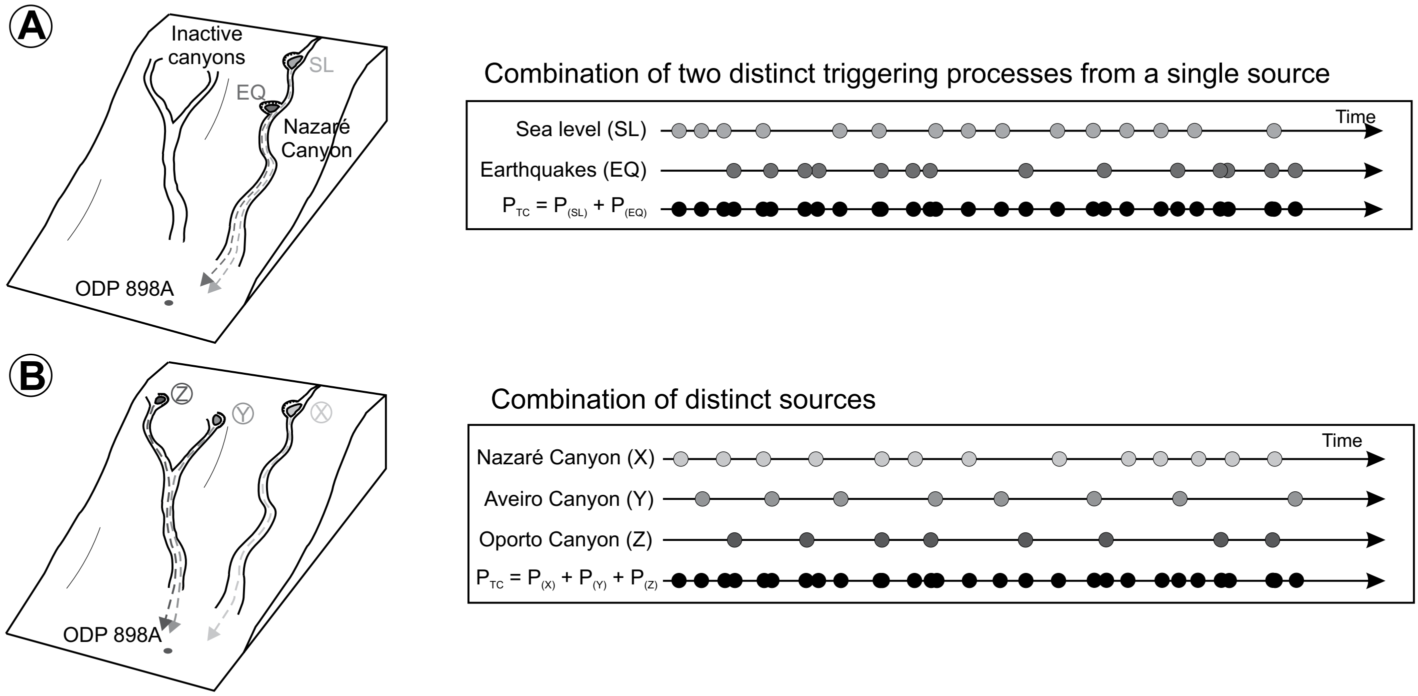

Figure 13. Schematic cartoons and abacus plots illustrating two of the different scenarios that might result in a lognormal distribution of turbidite recurrence. (A) Different triggering mechanisms operating within the Nazaré Canyon. (B) A combination of different sources of turbidites along the Portuguese margin. P—probability, TC—turbidity current, ODP—Ocean Drilling Program.

The western slopes of Galicia Bank feature mass transport deposits (Fig. 1), indicating that some turbidites in ODP Hole 898A may not have originated from the Portuguese margin (Hernández-Molina et al., 2008). However, sediment supply to the western Galicia Bank area is largely pelagic, and turbidites derived from this biogenic sediment are calcareous-rich units and are readily distinguishable from those of terrigenous origin (Milkert et al., 1996b; Alonso et al., 2008). In ODP Hole 898A core, less than 5% of turbidites are calcareous, and the Galicia Bank can be ruled out as a significant source of turbidites (Milkert et al., 1996b). Furthermore, no known landslide scars exist on the margins of the Iberian Abyssal Plain, suggesting that the Portuguese margin, and its submarine canyons, has been the dominant source of large turbidity currents reaching deep water.

There are two smaller canyons on the Portuguese margin that feed into the Iberian Abyssal Plain, the Oporto and Aveiro Canyons. Core site ODP Hole 898A is located 70 km away from where these canyons reach the Iberian Abyssal Plain (Fig. 1). These canyons do not incise the shelf, and they are considered to be largely inactive in the present day (Guerreiro et al., 2007, 2009). However, littoral transport may have fed the heads of these canyons during lowstand conditions, similar to the Nazaré Canyon today. This littoral sediment supply may have resulted in increased instability and turbidity current generation, similar to other such stranded canyons (Stow and Piper, 1984; Posamentier and Vail, 1988; Covault and Graham, 2010; Paull et al., 2014). Therefore, it is possible that the lognormal distribution at ODP Hole 898A represents a mixing of turbidites with more than one source area (Fig. 13B). However, multiple sources of turbidity currents that feed into basin plains are proposed to generate exponential distributions of turbidite recurrence, making this scenario unlikely (Clare et al., 2014).

Climate Change and Geohazard Implications

Previous statistical work has suggested that global eustatic sea-level change cannot be determined to be a significant control on the recurrence rates of large landslide-triggered turbidity currents (Urlaub et al., 2013; Clare et al., 2014), although some of the largest events occur at or after sea-level transitions (Hunt et al., 2013a). We have demonstrated that only large, infrequent shifts in sea-level amplitude and periodicity appear to have significantly altered the recurrence of canyon flushing in Nazaré Canyon. While canyon-flushing events are relatively rare, and do not pose the same tsunami risk as open slope failures, they can still break submarine telecommunication and damage hydrocarbon infrastructure (Carter et al., 2012, 2014; Pope et al., 2016). Canyon flushing should therefore be incorporated into risk models for infrastructure design. The lognormal distribution provides a probability density function from which hazard models can be derived. However, given the lack of any apparent eustatic sea-level control on these canyon-flushing events in the present day, their recurrence rate may not change significantly with projected sea-level rise.

CONCLUSIONS

In this study, we have demonstrated that the recurrences and volumes of canyon-flushing events in shelf-incising canyons are associated with changes in the periodicity and amplitude of eustatic sea-level variation, such as during the mid-Pleistocene transition. The increases in frequency and thickness of turbidites during the mid-Pleistocene transition were likely the result of increased subaerial exposure of the continental shelf and increased basinward sediment transport; however, tectonic factors associated with sea level cannot be ruled out. Additionally, during periods of minimal change in sea-level amplitude, canyon flushing remains temporally (pseudo)random in time. This is somewhat in contrast to previous research, which has suggested that canyon flushing is entirely unaffected by changes in sea level. This work further demonstrates the importance of robust and impartial statistical analyses in testing for controls on deep-water sedimentation, and it highlights the need for suitably long and complete turbidite records.

Large-volume turbidites in core ODP 898A conform to a lognormal distribution of recurrence over the last 1.8 m.y., which is fundamentally different to the exponential form observed in other basins worldwide. A persistent lognormal trend in turbidite recurrence through time appears to arise from progressive truncation of the turbidite record due to distance from source; however, multiple sources of turbidites or distinct triggering mechanisms may have contributed to this trend. The truncation model indicates that turbidite recurrence records become increasingly disordered with distance from source, thereby progressively shredding any environmental signals that might be preserved. Statistical distributions of geohazard recurrence and their probability density functions are important for designing predictive hazard models. This work indicates that the distribution form of turbidite recurrence intervals can vary significantly with sampling location along a sediment-routing system. While this presents some uncertainty when attempting to predict turbidity current geohazards, it highlights the usefulness of statistical distributions in understanding environmental signal propagation and preservation in deep water.

ACKNOWLEDGMENTS

We wish to thank Bradley Singer, Ganqing Jiang, Zoltan Sylvester, Steve Hubbard, and Andrea Fildani. Their comments and suggestions have greatly improved this manuscript. Financial support for this work was provided by the Marine Geoscience group at the National Oceanography Centre, Southampton, and by the Natural Environment Research Council (NE/K00008X/1). This research was completed as part of the European Union (EU) FP7–funded ASTARTE (Assessment, Strategy and Risk Reduction for Tsunamis in Europe) Project (603839). The research materials from this work, including data sets and statistical models, can be freely requested from the corresponding author.

REFERENCES CITED

Allin, J.R., Hunt, J.E., Talling, P.J., Clare, M.E., Pope, E., and Masson, D.G., 2016, Different frequencies and triggers of canyon filling and flushing events in Nazaré Canyon, offshore Portugal: Marine Geology, v. 371, p. 89–105, doi:10.1016/j.margeo.2015.11.005.

Alonso, B., Ercilla, G., Casas, D., Estrada, F., Farrán, M., Garcia, M., Rey, D., and Rubio, B., 2008, Late Pleistocene and Holocene sedimentary facies on the SW Galicia Bank (Atlantic NW Iberian Peninsula): Marine Geology, v. 249, p. 46–63, doi:10.1016/j.margeo.2007.09.012.

Amy, L.A., Talling, P.J., Edmonds, V.O., Sumner, E.J., and Lesueur, A., 2006, An experimental investigation of sand-mud suspension settling behaviour: Implications for bimodal mud contents of submarine flow deposits: Sedimentology, v. 53, no. 6, p. 1411–1434, doi:10.1111/j.1365-3091.2006.00815.x.

Arzola, R.G., Wynn, R.B., Lastras, G., Masson, D.G., and Weaver, P.P.E., 2008, Sedimentary features and processes in the Nazaré and Setúbal submarine canyons, west Iberian margin: Marine Geology, v. 250, p. 64–88, doi:10.1016/j.margeo.2007.12.006.

Bondevik, S., Svendsen, J.I., Johnsen, G., Mangerud, J., and Kaland, P.E., 1997, The Storegga tsunami along the Norwegian coast: Its age and run-up: Boreas, v. 26, p. 29–53, doi:10.1111/j.1502-3885.1997.tb00649.x.

Borges, J., Fitas, A.J.S., Bezzeghoud, M., and Teves-Costa, P., 2001, Seismotectonics of Portugal and its adjacent Atlantic area: Tectonophysics, v. 331, p. 373–387, doi:10.1016/S0040-1951(00)00291-2.

Bouma, A.H., 1962, Sedimentology of Some Flysch Deposits: A Graphic Approach to Facies Interpretation: Amsterdam, Netherlands, Elsevier, 168 p.

Brothers, D.S., Luttrell, K.M., and Chaytor, J.D., 2013, Sea-level–induced seismicity and submarine landslide occurrence: Geology, v. 41, p. 979–982, doi:10.1130/G34410.1.

Bruschi, R., Bughi, S., Spinazzè, M., Torselletti, E., and Vitali, L., 2006, Impact of debris flows and turbidity currents on seafloor structures: Norsk Geologisk Tidsskrift, v. 86, p. 317–337.

Buforn, E., Udías, A., and Colombás, M.A., 1988, Seismicity, source mechanisms and tectonics of the Azores-Gibraltar plate boundary: Tectonophysics, v. 152, p. 89–118, doi:10.1016/0040-1951(88)90031-5.

Burgess, P.M., 2016, Identifying ordered strata: Evidence, methods, and meaning: Journal of Sedimentary Research, v. 86, no. 3, p. 148–167, doi:10.2110/jsr.2016.10.

Canals, M., Puig, P., de Madron, X.D., Heussner, S., Palanques, A., and Fabres, J., 2006, Flushing submarine canyons: Nature, v. 444, p. 354–357, doi:10.1038/nature05271.

Carter, L., Milliman, J.D., Talling, P.J., Gavey, R., and Wynn, R.B., 2012, Near-synchronous and delayed initiation of long run-out submarine sediment flows from a record-breaking river flood, offshore Taiwan: Geophysical Research Letters, v. 39, L12603, doi:10.1029/2012GL051172.

Carter, L., Gavey, R., Talling, P.J., and Liu, J., 2014, Insights into submarine geohazards from breaks in subsea telecommunication cables: Oceanography (Washington, D.C.), v. 27, p. 58–67, doi:10.5670/oceanog.2014.40.

Chen, C., and Hiscott, R.N., 1999, Statistical analysis of facies clustering in submarine-fan turbidite successions: Journal of Sedimentary Research, v. 69, no. 2, p. 505–517, doi:10.2110/jsr.69.505.

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D., and Unnikrishnan, A.S., 2013, Sea level change, *in* Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex V., and Midgley, P.M., eds., Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, UK, Cambridge University Press, p. 1137–1216.

Clare, M.A., Talling, P.J., Challenor, P., Malgesini, G., and Hunt, J.E., 2014, Distal turbidites reveal a common distribution for large (>0.1 km^3) submarine landslide recurrence: Geology, v. 42, p. 263–266, doi:10.1130/G35160.1.

Clare, M.A., Talling, P.J., and Hunt, J.E., 2015, Implications of reduced turbidity current and landslide activity for the initial Eocene thermal maximum—Evidence from two distal, deep-water sites: Earth and Planetary Science Letters, v. 420, p. 102–115, doi:10.1016/j.epsl.2015.03.022.

Clare, M.A., Talling, P.J., Challenor, P.G., and Hunt, J.E., 2016, Tempo and triggering of large submarine landslides: Statistical analysis for hazard assessment, *in* Lamarche, G., et al., eds., Submarine Mass Movements and their Consequences: Cham, Switzerland, Springer International Publishing, Advances in Natural and Technological Hazards Research 41, p. 509–517, doi:10.1007/978-3-319-20979-1_51.

Clark, P.U., Archer, D., Pollard, D., Blum, J.D., Rial, J.A., Brovkin, V., Mix, A.C., Pisias, N.G., and Roy, M., 2006, The middle Pleistocene transition: Characteristics, mechanisms, and implications for long-term changes in atmospheric pCO_2: Quaternary Science Reviews, v. 25, p. 3150–3184, doi:10.1016/j.quascirev.2006.07.008.

Covault, J.A., and Fildani, A., 2014, Continental shelves as sediment capacitors or conveyors: Source-to-sink insights from the tectonically active Oceanside shelf, southern California, USA, *in* Chiocci, F.L., and Chivas, A.R., eds., Continental Shelves of the World: Their Evolution During the Last Glacio-Eustatic Cycle: Geological Society, London, Memoir 41, p. 315–326, doi:10.1144/M41.23.

Covault, J.A., and Graham, S.A., 2010, Submarine fans at all sea-level stands: Tectono-morphologic and climatic controls on terrigenous sediment delivery to the deep sea: Geology, v. 38, p. 939–942, doi:10.1130/G31081.1.

Covault, J.A., Romans, B.W., Fildani, A., McGann, M., and Graham, S.A., 2010, Rapid climatic signal propagation from source to sink in a southern California sediment-routing system: Journal of Geology, v. 118, p. 247–259, doi:10.1086/651539, doi:10.1086/651539.

Cox, D.R., 1972, Regression models and life-tables: Journal of the Royal Statistical Society, ser. B, Methodological, v. 34, p. 187–220.

Custódio, S., Dias, N.A., Carrilho, F., Góngora, E., Rio, I., Marreiros, C., Morais, I., Alves, P., and Matias, L., 2015, Earthquakes in western Iberia: Improving the understanding of lithospheric deformation in a slowly deforming region: Geophysical Journal International, v. 203, p. 127–145, doi:10.1093/gji/ggv285.

Ducassou, E., Migeon, S., Mulder, T., Murat, A., Capotondi, L., Bernasconi, S.M., and Mascle, J., 2009, Evolution of the Nile deep-sea turbidite system during the late Quaternary: Influence of climate change on fan sedimentation: Sedimentology, v. 56, p. 2061–2090, doi:10.1111/j.1365-3091.2009.01070.x.

Ercilla, G., Alonso, B., and Baraza, J., 1994, Post-Calabrian sequence stratigraphy of the northwestern Alboran Sea (southwestern Mediterranean): Marine Geology, v. 120, p. 249–265, doi:10.1016/0025-3227(94)90061-2.

Gràcia, E., Vizciano, A., Escutia, C., Asioli, A., Rodés, Á., Pallàs, R., Garcia-Orellana, J., Lebreiro, S., and Goldfinger, C., 2010, Holocene earthquake record offshore Portugal (SW Iberia): Testing turbidite paleoseismology in a slow-convergence margin: Quaternary Science Reviews, v. 29, p. 1156–1172, doi:10.1016/j.quascirev.2010.01.010.

Green, S.B., 1991, How many subjects does it take to do a regression analysis?: Multivariate Behavioural Analysis, v. 26, p. 499–510, doi:10.1207/s15327906mbr2603_7.

Grönholm, T., and Annila, A., 2007, Natural distribution: Mathematical Biosciences, v. 210, p. 659–667, doi:10.1016/j.mbs.2007.07.004.

Guerreiro, C., Rodrigues, A., Duarte, J., Oliveira, A., and Taborda, R., 2007, Bottom sediment signature associated with the Oporto, Aveiro and Nazaré Submarine Canyons (NW off Portugal): Thalassas, v. 23, p. 9–18.

Guerreiro, C., Oliveira, A., and Rodrigues, A., 2009, Shelf-break canyons versus "Gouf" canyons: A comparative study based on the silt-clay mineralogy of bottom sediments from Oporto, Aveiro and Nazaré Submarine Canyons: Journal of Coastal Research, v. 56, p. 722–726.

Gutiérrez-Pastor, J., Nelson, C.H., Goldfinger, C., Johnson, J.E., Escutia, C., Eriksson, A., and Morey, A.E., and the Shipboard Scientific Party, 2009, Earthquake control of Holocene turbidite frequency confirmed by hemipelagic sedimentation chronology on the Cascadia and Northern California active tectonic continental margins, *in* Kneller, B., McCaffrey, W., and Martinsen, O.J., eds., External Controls on Deepwater Depositional Systems: Society for Sedimentary Geology (SEPM) Special Publication 92, p. 179–197.

Haq, B.U., and Schutter, S.R., 2008, A chronology of Paleozoic sea-level changes: Science, v. 322, p. 64–68, doi:10.1126/science.1161648.

Harbitz, C.B., Løvholt, F., Pedersen, G., and Masson, D.G., 2006, Mechanisms of tsunami generation by submarine landslides: A short review: Norsk Geologisk Tidsskrift, v. 86, p. 249–258.

Hernández-Molina, F.J., Somoza, L., Vázquez, J.T., Lobo, F., Fernández-Puga, M.C., Llave, E., and Díaz del Río, V., 2002, Quaternary stratigraphic stacking patterns on the continental shelves of the southern Iberian Peninsula: Their relationship with global climate and palaeoceanographic changes: Quaternary International, v. 92, p. 5–23, doi:10.1016/S1040-6182(01)00111-2.

Hernández-Molina, F.J., Llave, E., Ercilla, G., Maestro, A., Medialdea, T., Ferrin, A., Somoza, L., Gràcia, E., Masson, D.G., García, M., Vizcaino, A., and León, R., 2008, Recent sedimentary processes in the Prestige site area (Galicia Bank, NW Iberian margin) evidenced by high-resolution marine geophysical methods: Marine Geology, v. 249, p. 21–45, doi:10.1016/j.margeo.2007.09.011.

Hoogakker, B.A.A., Rothwell, R.G., Rohling, E.J., Paterne, M., Stow, D.A.V., Herrle, J.O., and Clayton, J., 2004, Variations in terrigenous dilution in western Mediterranean Sea pelagic sediments in response to climate change during the last glacial cycle: Marine Geology, v. 211, p. 21–43, doi:10.1016/j.margeo.2004.07.005.

Hunt, J.E., Wynn, R.B., Talling, P.J., and Masson, D.G., 2013a, Frequency and timing of landslide triggered turbidity currents within the Agadir Basin, offshore NW Africa: Are there associations with climate change, sea level change and slope sedimentation rates?: Marine Geology, v. 346, p. 274–291, doi:10.1016/j.margeo.2013.09.004.

Hunt, J.E., Wynn, R.B., Talling, P.J., and Masson, D.G., 2013b, Multistage collapse of eight western Canary Island landslides in the last 1.5Ma: Sedimentological and geochemical evidence from subunits in submarine flow deposits: Geochemistry Geophysics Geosystems, v. 14, p. 2159–2181, doi:10.1002/ggge.20138.

Hunt, J.E., Talling, P.J., Clare, M.A., Jarvis, I., and Wynn, R.B., 2014, Long-term (17 Ma) turbidite record of the timing and frequency of large flank collapses of the Canary Islands: Geochemistry Geophysics Geosystems, v. 15, p. 3322–3345, doi:10.1002/2014GC005232.

Intergovernmental Oceanographic Commission, International Hydrographic Organization, British Oceanographic Data Centre, 2003, Centenary Edition of the GEBCO Digital Atlas: Liverpool, UK, British Oceanographic Data Centre, http://www.gebco.net/data_and_products/gebco_digital_atlas/ (last accessed July, 2016).

Khripounoff, A., Vangriesheim, A., Crassous, P., and Etoubleau, J., 2009, High frequency of sediment gravity flow events in the Var submarine canyon (Mediterranean Sea): Marine Geology, v. 263, p. 1–6, doi:10.1016/j.margeo.2009.03.014.

Korup, O., 2012, Earth's portfolio of extreme sediment transport events: Earth-Science Reviews, v. 112, p. 115–125, doi:10.1016/j.earscirev.2012.02.006.

Lastras, G., Arzola, R.G., Masson, D.G., Wynn, R.B., Huvenne, V.A.I., Hühnerbach, V., and Canals, M., 2009, Geomorphology and sedimentary features in the central Portuguese submarine canyons, Western Iberian margin: Geomorphology, v. 103, p. 310–329, doi:10.1016/j.geomorph.2008.06.013.

Lebreiro, S.M., Voelker, A.H.L., Vizcaino, A., Abrantes, F.G., Alt-Epping, U., Jung, S., Thouveny, N., and Grácia, E., 2009, Sediment instability on the Portuguese continental margin under abrupt glacial climate changes (last 60 kyr): Quaternary Science Reviews, v. 28, p. 3211–3223, doi:10.1016/j.quascirev.2009.08.007.

Le Roy, P., Sahabi, M., Maad, N., Rabineau, M., Gutscher, M.-A., Babonneau, N., Van Vliet, Lanoë B., Ait Brahim, L., M'hammdi, N., Trentesaux, A., Dakki, M., and Hssain, M., 2014, 3D architecture of Quaternary sediment along the NW Atlantic Moroccan Rharb continental shelf: A stratal pattern under the dual control of tectonics and climatic variations: Marine and Petroleum Geology, v. 49, p. 129–142.

Limpert, E., Stahel, W.A., and Abbt, M., 2001, Log-normal distributions across the sciences: Keys and clues: Bioscience, v. 51, p. 341–352, doi:10.1641/0006-3568(2001)051[0341:LNDATS]2.0.CO;2.

Liu, L., Maiorano, P., and Zhao, X., 1996, Pliocene-Pleistocene calcareous nanofossil from the Iberian Abyssal Plain, *in* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G., eds., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 149: College Station, Texas, Ocean Drilling Program, p. 147–164.

Llave, E., Hernández-Molina, F.J., Somoza, L., Díaz del Río, V., Stow, D.A.W., Maestro, A., and Alveirinho Dias, J.M., 2001, Seismic stacking pattern of the Faro Albufeira contourite system (Gulf of Cadiz): A Quaternary record of paleoceanographic and tectonic influences: Marine Geophysical Researches, v. 22, p. 487–508, doi:10.1023/A:1016355801344.

Luttrell, K., and Sandwell, D., 2010, Ocean loading effects on stress at near shore plate boundary fault systems: Journal of Geophysical Research, v. 115, BO8411, doi:10.1029/2009JB006541.

Maslin, M., Owen, M., Day, S., and Long, D., 2004, Linking continental-slope failures and climate change: Testing the clathrate gun hypothesis: Geology, v. 32, no. 1, p. 53–56, doi:10.1130/G20114.1.

Masson, D.G., Arzola, R.G., Wynn, R.B., Hunt, J.E., and Weaver, P.P.E., 2011, Seismic triggering of landslides and turbidity currents offshore Portugal: Geochemistry Geophysics Geosystems, v. 12, Q12011, doi:10.1029/2011GC003839.

Mauffrey, M.A., Urgeles, R., Berné, S., and Canning, J., 2017, Development of submarine canyons after the mid-Pleistocene transition on the Ebro margin, NW Mediterranean: The role of fluvial connections: Quaternary Science Reviews, v. 158, p. 77–93, doi:10.1016/j.quascirev.2017.01.006.

McCullagh, P., and Nelder, J.A., 1989, Generalized Linear Models (2nd ed.): London, Chapman and Hall/CRC, 532 p., doi:10.1007/978-1-4899-3242-6.

Milkert, D., Alonso, B., Liu, L., Zhao, X., Comas, M., and de Kaenel, E., 1996a, Sedimentary facies and depositional history of the Iberia Abyssal Plain, *in* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G., eds., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 149: College Station, Texas, Ocean Drilling Program, p. 685–704.

Milkert, D., Weaver, P.P.E., and Liu, L., 1996b, Pleistocene and Pliocene turbidites from the Iberia Abyssal Plain, *in* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G., eds., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 149: College Station, Texas, Ocean Drilling Program, p. 281–294.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005, The Phanerozoic record of global sea-level change: Science, v. 310, p. 1293–1298, doi:10.1126/science.1116412.

Mudelsee, M., and Schultz, M., 1997, The mid-Pleistocene climate transition: Onset of 100 ka cycle lags ice volume build-up by 280 ka: Earth and Planetary Science Letters, v. 151, p. 117–123, doi:10.1016/S0012-821X(97)00114-3.

Neves, M.C., Cabral, J., Luttrell, K., Figueiredo, P., Rockwell, T., and Sandwell, D., 2015, The effect of sea level changes on fault reactivation potential in Portugal: Tectonophysics, v. 658, p. 206–220, doi:10.1016/j.tecto.2015.07.023.

Oliveira, A., Santos, A.I., Rodrigues, A., and Vitorino, J., 2007, Sedimentary particle distribution and dynamics on the Nazaré Canyon system and adjacent shelf (Portugal): Marine Geology, v. 246, p. 105–122, doi:10.1016/j.margeo.2007.04.017.

Owen, M., Day, S., and Maslin, M., 2007, Late Pleistocene submarine mass movements: Occurrence and causes: Quaternary Science Reviews, v. 26, p. 958–978, doi:10.1016/j.quascirev.2006.12.011.

Paillard, D., 1998, The timing of Pleistocene glaciations from a simple multiple-state climate model: Nature, v. 391, p. 378–381, doi:10.1038/34891.

Parker, G., 1982, Conditions for the ignition of catastrophically erosive turbidity currents: Marine Geology, v. 46, p. 307–327, doi:10.1016/0025-3227(82)90086-X.

Paull, C.K., Mitts, P., Ussler, W., III, Keaton, R., and Greene, H.G., 2005, Trail of sand in upper Monterey Canyon: Offshore California: Geological Society of America Bulletin, v. 117, p. 1134–1145, doi:10.1130/B25390.1.

Paull, C.K., McGann, M., Sumner, E.J., Barnes, P.M., Lundsten, E.M., Anderson, K., Gwiazda, R., Edwards, B., and Caress, D.W., 2014, Sub-decadal turbidite frequency during the early Holocene: Eel Fan, offshore Northern California: Geology, v. 42, p. 855–858, doi:10.1130/G35768.1.

Piper, D.W.J., and Normark, W.R., 2009, Processes that initiate turbidity currents and their influence on turbidites: A marine geology perspective: Journal of Sedimentary Research, v. 79, p. 347–362, doi:10.2110/jsr.2009.046.

Piper, D.J.W., and Savoye, B., 1993, Processes of late Quaternary turbidity current flow and deposition on the Var deep-sea fan, north-west Mediterranean Sea: Sedimentology, v. 40, p. 557–582, doi:10.1111/j.1365-3091.1993.tb01350.x.

Pope, E.L., Talling, P.J., Urlaub, M., Hunt, J.E., Clare, M.A., and Challenor, P., 2015, Are large submarine landslides temporally random or do uncertainties in available age constraints make it impossible to tell?: Marine Geology, v. 369, p. 19–33, doi:10.1016/j.margeo.2015.07.002.

Pope, E.L., Talling, P.J., and Carter, L., 2016, Which earthquakes trigger damaging submarine mass movements: Insights from a global record of submarine cable breaks?: Marine Geology, v. 150, p. 55–66.

Posamentier, H.W., and Vail, P.R., 1988, Eustatic controls on clastic deposition II—Sequence and systems tract models, *in* Wilgus, C.K., et al., eds., Sea-Level Changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publication 42, p. 125–154, doi:10.2110/pec.88.01.0125.

Rohling, E.J., Grant, K., Bolshaw, M., Roberts, A.P., Siddall, M., Hemleben, C., and Kucera, M., 2009, Antarctic temperature and global sea level closely coupled over the past five glacial cycles: Nature Geoscience, v. 2, p. 500–504, doi:10.1038/ngeo557.

Romans, B.W., and Graham, S.A., 2013, A deep-time perspective of land-ocean linkages in the sedimentary record: Annual Review of Marine Science, v. 5, p. 69–94, doi:10.1146/annurev-marine-121211-172426.

Romans, B.W., Castelltort, S., Covault, J.A., Fildani, A., and Walsh, J.P., 2016, Environmental signal propagation in sedimentary systems across timescales: Earth-Science Reviews, v. 153, p. 7–29, doi:10.1016/j.earscirev.2015.07.012.

Schemper, M., and Stare, J., 1996, Explained variation in survival analysis: Statistics in Medicine, v. 15, p. 1999–2012, doi:10.1002/(SICI)1097-0258(19961015)15:19<1999::AID-SIM353>3.0.CO;2-D.

Shackleton, N.J., Berger, A., and Peltier, W.R., 1990, An alternative astronomical calibration on the Lower Pleistocene time scales based on ODP Site 677: Transactions of the Royal Society of Edinburgh–Earth Sciences, v. 81, p. 251–261, doi:10.1017/S0263593300020782.

Shanmugam, G., 2016, Slides, slumps, debris flows, turbidity currents, and bottom currents, *in* Reference Module in Earth Systems and Environmental Sciences: Amsterdam, Netherlands, Elsevier, https://doi.org/10.1016/B978-0-12-409548-9.04380-3 (current as of 7 October 2015).

Shanmugam, G., and Moiola, R.J., 1982, Eustatic control of turbidites and winnowed turbidites: Geology, v. 10, p. 231–235, doi:10.1130/0091-7613(1982)10<231:ECOTAW>2.0.CO;2.

Smith, D.E., Harrison, S., and Jordan, D.T., 2013, Sea level rise and submarine mass failure on open continental slopes: Quaternary Science Reviews, v. 82, p. 93–103, doi:10.1016/j.quascirev.2013.10.012.

Stow, D.A.V., and Piper, D.J.W., 1984, Deep-water fine-grained sediments: Facies models, *in* Stow, D.A.V., and Piper, D.J.W., eds., Fine-Grained Sediments: Deep-Water Processes and Facies: Geological Society, London, Special Publication 14, p. 611–645.

Stow, D.A.V., and Tabrez, A.R., 1998, Hemipelagites: Processes, facies and model, *in* Stoker, M.S., Evans, D., and Cramp, A., eds., Geological Processes on Continental Margins: Sedimentation, Mass Wasting and Stability: Geological Society, London, Special Publication 129, p. 317–337.

Sumner, E.J., Siti, M.I., McNeill, L.C., Talling, P.J., Henstock, T.J., Wynn, R.B., Djajadihardja, Y.S., and Permana, H., 2013, Can turbidites be used to reconstruct a paleoearthquake record for the central Sumatran margin?: Geology, v. 41, no. 7, p. 763–766, doi:10.1130/G34298.1.

Sylvester, Z., 2007, Turbidite bed thickness distributions: Methods and pitfalls of analysis and modelling: Sedimentology, v. 54, p. 847–870, doi:10.1111/j.1365-3091.2007.00863.x.

Tabachnick, B.G., and Fidell, L.S., 2007, Using Multvariate Statistics (5th ed.): Boston, Massachuestts, Pearson Education, Inc., 1008 p.

Talling, P.J., 2001, On the frequency distribution of turbidite thickness: Sedimentology, v. 48, p. 1297–1329, doi:10.1046/j.1365-3091.2001.00423.x.

Talling, P.J., 2014, On the triggers, resulting flow types and frequencies of subaqueous sediment density flows in different settings: Marine Geology, v. 352, p. 155–182, doi:10.1016/j.margeo.2014.02.006.

Talling, P.J., Amy, L.A., and Wynn, R.B., 2007, New insights into the evolution of large volume turbidity currents; comparison of turbidite shape and previous modelling results: Sedimentology, v. 54, p. 737–769, doi:10.1111/j.1365-3091.2007.00858.x.

Talling, P.J., Masson, D.G., Sumner, E.J., and Malgesini, G., 2012, Subaqueous sediment density flows: Depositional processes and deposit types: Sedimentology, v. 59, p. 1937–2003, doi:10.1111/j.1365-3091.2012.01353.x.

Tappin, D.R., Watts, P., and Grilli, S.T., 2008, The Papua New Guinea tsunami of 17 July 1998: Anatomy of a catastrophic event: Natural Hazards and Earth System Sciences, v. 8, p. 243–266, doi:10.5194/nhess-8-243-2008.

Thomson, J., and Weaver, P.P.E., 1994, An AMS radiocarbon method to determine the emplacement time of recent deep-sea turbidites: Sedimentary Geology, v. 89, p. 1–7, doi:10.1016/0037-0738(94)90079-5.

Tversky, A., and Kahneman, D., 1973, Availability: A heuristic for judging frequency and probability: Cognitive Psychology, v. 5, no. 2, p. 207–232, doi:10.1016/0010-0285(73)90033-9.

Urlaub, M., Talling, P.J., and Masson, D.G., 2013, Timing and frequency of large submarine landslides: Implications for understanding triggers and future geohazard: Quaternary Science Reviews, v. 72, p. 63–82, doi:10.1016/j.quascirev.2013.04.020.

Vail, P.R., Mitchum, R.M.J., Todd, R.G., Widmier, J.M., Thompson, S.I., Sangree, J.B., Bubb, J.N., and Hatelid, W.G., 1977, Seismic stratigraphy and global changes of sea level, *in* Payton, C.E., ed., Seismic Stratigraphy—Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoir 26, p. 49–212.

Vanney, J.-R., and Mougenot, D., 1990, Un canyon sous-marin du type 'gouf': Le Canhao da Nazare (Portugal): Oceanologica Acta, v. 13, p. 1–14.

van Rooij, M.M., Nash, B.A., Rajaraman, S., and Holden, J.G., 2013, A fractal approach to dynamic inference and distribution analysis: Frontiers in Physiology, v. 4, p. 1, doi:10.3389/fphys.2013.00001.

Vittinghoff, E., and McCulloch, C.E., 2007, Relaxing the rule of ten events per variable in logistic and Cox regression: American Journal of Epidemiology, v. 165, p. 710–718, doi:10.1093/aje/kwk052.

Weaver, P.P.E., and Thomson, J., 1993, Calculating erosion by deep-sea turbidity currents during initiation and flow: Nature, v. 364, p. 136–138, doi:10.1038/364136a0.

Weaver, P.P.E., Thomson, J., and Hunter, P., 1987, Introduction, *in* Weaver, P.P.E., and Thomson, J., eds., Geology and Geochemistry of Abyssal Plains: Geological Society, London, Special Publication 31, p. vii–xii.

Wilkinson, B.H., Merrill, G.K., and Kivett, S.J., 2003, Stratal order in Pennsylvanian cyclothems: Geological Society of America Bulletin, v. 115, no. 9, p. 1068–1087, doi:10.1130/B21927.1.

Wynn, R.B., Weaver, P.P.E., Stow, D.A.V., and Masson, D.G., 2002, Turbidite depositional architecture across three interconnected deep-water basins on the north-west African margin: Sedimentology, v. 49, p. 669–695, doi:10.1046/j.1365-3091.2002.00471.x.

Zitellini, N., Rovere, M., Terrinha, P., Chierici, F., Matias, L., and Team, B., 2004, Neogene through Quaternary tectonic reactivation of SW Iberian passive margin: Pure and Applied Geophysics, v. 161, p. 565–587, doi:10.1007/s00024-003-2463-4.

Science Editor: Bradley S. Singer
Associate Editor: Ganqing Jiang

Manuscript Received 16 September 2016
Revised Manuscript Received 26 May 2017
Manuscript Accepted 3 July 2017

Printed in the USA