VOLUME AND RECURRENCE OF SUBMARINE-FAN-BUILDING TURBIDITY CURRENTS

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ABSTRACT

Submarine fans are archives of Earth-surface processes and change, recording information about the turbidity currents that construct and sculpt them. The volume and recurrence of turbidity currents are of great interest for geohazard assessment, source-to-sink modeling, and hydrocarbon reservoir characterization. Yet, such dynamics are poorly constrained. This study integrates data from four Quaternary submarine fans to reconstruct the volume and recurrence of the formative turbidity currents. Calculated event volumes vary over four orders of magnitude (10⁵ to 10⁹ m³), whereas recurrence intervals vary less, from 50 to 650 years.

The calculated turbidity-current-event volume magnitudes appear to be related to slope position and basin confinement. Intraslope-fan deposits have small event volumes (~ 10⁶ m³)
while ponded-fan deposits have very large event volumes ($10^8$ to $10^9$ m$^3$). Deposits in non-ponded, base-of-slope environments have intermediate values ($10^7$ to $10^8$ m$^3$). Sediment bypass in intraslope settings and flow trapping in ponded basins likely accounts for these differences. There seems to be no clear relationship between event recurrence and basin confinement. Weak scaling exists between event volume and source-area characteristics, but sediment storage in fluvial and/or intraslope transfer zones likely complicates these relationships. The methodology and results are also applied to reconstruct the time of deposition of ancient submarine-fan deposits.

The volume and recurrence of submarine-fan-building turbidity currents form intermediate values between values measured in submarine canyons and channels ($<10^5$ m$^3$ and $<10^1$ yr) and on abyssal plains ($>10^8$ m$^3$ and $>10^3$ yr), indicating that small, frequent flows originating in submarine canyons often die out prior to reaching the fan, while rare and very large flows mostly bypass the fan and deposit sediment on the abyssal plain. This partitioning of flow volume and recurrence along the submarine sediment-routing system provides valuable insights for better constraining geohazards, hydrocarbon resources, and the completeness of the stratigraphic record.

**INTRODUCTION**

Turbidity currents carry sand and mud into the deep sea and create submarine fans, the largest sediment accumulations on Earth (Talling *et al.*, 2015). Submarine fans are important depositional archives of climate change (Gulick *et al.*, 2015; Bernhardt *et al.*, 2017), sea-level fluctuations (Castelltort *et al.*, 2017), rates of continental erosion (Clift, 2006), land-to-sea delivery of organic carbon (Burdige, 2005), and continental-margin seismicity (Goldfinger,
They also host significant hydrocarbon resources (Pettingill & Weimer, 2002). Submarine fans exhibit radial or cone-like morphologies in plan view and are composite features, consisting of channel (with or without external levees) and lobe deposits (Shepard & Emery, 1941; Dill et al., 1954; Menard, 1955; Heezen et al., 1959; Bouma et al., 1985). Submarine fans form in net-depositional environments of continental-margin sediment-routing systems, commonly associated with slope breaks that promote sudden deceleration of turbidity currents and localized deposition of sand beyond the slope break (Mutti & Normark, 1987; Adeogba et al., 2005; Spinewine et al., 2009; Fernandez et al., 2014; Jobe et al., 2016; Picot et al., 2016). The focus of this paper is on the stratigraphic record of submarine fans, as their deposits likely contain a more complete record of turbidity-current volume and recurrence (Piper & Normark, 1983) as compared to channelized elements that are primarily conduits for turbidity-current bypass (Hubbard et al., 2014; Stevenson et al., 2015).

The volume and recurrence of submarine-fan-building turbidity currents are of interest for the assessment of geohazards, including tsunami hazards (Bondevik et al., 1997; Goldfinger, 2011) and damage to submarine infrastructure (Carter et al., 2012; Cooper et al., 2013), inputs for numerical models of sediment-routing systems (Petit et al., 2015; Bolla Pittaluga & Imran, 2014; Sylvester et al., 2015), and characterization of subsurface hydrocarbon resources (Saller et al., 2008). Studies utilizing outcrops, modern systems, and physical experiments provide insight into the stratigraphic architecture and morphodynamics of submarine channel-fan depositional systems (Normark, 1970; Pirmez et al., 1997; Hodgson et al., 2006; Sequeiros et al., 2010; Hubbard et al., 2014; Cartigny et al., 2013; de Leeuw et al., 2016). Direct monitoring in modern systems provides insight into the short-term morphodynamic and sediment-transport mechanisms (Paull et al., 2010; Cooper et al., 2013; Hughes-Clarke, 2016; Clare et al., 2016). However,
understanding the longer-term (>10^2 yr) recurrence of turbidity currents and the stratigraphic evolution of submarine fans remains elusive (Talling et al., 2015). In particular, few estimates of sediment volume and recurrence of Holocene fan-building flows have been attempted, and the few calculated volumes to date range seven orders of magnitude, from 10^-5 to 10^2 km^3 (Piper & Aksu, 1987; Gonzalez-Yajimovich et al., 2007; Clare et al., 2016). Event recurrence is better constrained, with Quaternary core-based studies providing recurrence interval data from multiple basins (Clare et al., 2014, 2016). Studies have also focused on the distribution of event recurrence and how allogenic forcing and position along the sediment-routing system can affect the recurrence distribution (Clare et al., 2015; Allin et al., 2016, 2017).

This study integrates seismic-reflection and core datasets from Quaternary submarine fans to reconstruct the volume and recurrence of turbidity currents using simple parameters from their deposits. This study focus on the following fans: 1) the Golo fan system, Corsica (Deptuck et al., 2008; Sømme et al., 2011; Calvès et al., 2012), 2) the ‘X’ intraslope fan, Nigeria (Pirmez et al., 2000; Prather et al., 2012a; Jobe et al., 2016), 3) the Brazos-Trinity intraslope fan system, Texas (Beaubouef & Friedmann, 2000; Mallarino et al., 2006; Pirmez et al., 2012; Prather et al., 2012b), and 4) the Hueneme fan, California (Gorsline, 1996; Normark et al., 1998; Romans et al., 2009). Using the calculated ranges of event volume and recurrence, we estimate the time of fan deposition in ancient submarine-fan successions, which commonly have poor age-constraints. Finally, we discuss possible linkages between event volume and recurrence with 1) source-area characteristics and 2) basin confinement and slope position.

ESTIMATION OF TURBIDITY CURRENT VOLUME AND RECURRENCE
This study presents a simple formulation that can be used to estimate sediment supply to submarine fans in areas where data are sparse. While more sophisticated sediment mass balance formulations exist (Paola & Voller, 2005 for short-term (sec) bed evolution), such calculations require measurement of sediment concentration and flow velocity, which are very difficult to obtain (Xu et al., 2014; Talling et al., 2015). The approach utilized here relies on three basic measurements of submarine-fan deposits from seismic-reflection and core data (Fig. 1): 1) total sediment volume $V$ (m$^3$), (2) total duration of deposition $T$ (yr), and (3) event count $n$. The sediment volume $V$ of a deposit was determined from seismic-reflection data using thickness of mapped seismic-reflection horizons. When not provided by the original study, the bulk volume was converted to sediment volume using reported porosity values using the equation bulk volume*(1-porosity) = sediment volume. The total duration of deposition $T$ was calculated using chronologic information correlated between core data along seismic-reflection horizons that bound submarine-fan deposits. Finally, the event count $n$ is the number of turbidity-current deposits in the volume $V$, and was determined from core data (Fig. 1). The event count is simply the number of sand beds present in a core (Fig. 3). Where possible, amalgamated beds are identified (core ‘fan 14 3 inch’ in Figure 3), but it is possible that some amalgamated beds are unaccounted in the event count $n$. There is no interpreted hemipelagic sediment in the cores (cf. Talling et al., 2007a), and so we assume that the cores are composed entirely of turbidites and do not include appreciable hemipelagic sediment. We also assume that there has been no post-depositional erosion, reworking, or mass wasting. However, we recognize that these processes occur, even in distal parts of submarine fans (Dennielou et al., 2017; Croguennec et al., 2017). While we appreciate that event-bed geometries in submarine-fan deposits can be more complex (Deptuck et al., 2008; Jobe et al., 2016), we also assume that core data accurately record the
event count $n$ and that all events spread evenly across the fan/lobe. Where possible, an attempt is made to define ranges of $V$, $T$, and $n$ from multiple datasets to better encapsulate measurement uncertainty and possible sampling bias from non-uniform deposition and the aforementioned assumptions. Reasoning may suggest to only include the highest value of $n$ as it samples the true event count (Fig. 3), but we conservatively include the range derived from multiple cores where possible because basin setting or other local factors may affect the spatial distribution of events.

The recurrence interval $r$ (yr) is defined as the total time $T$ divided by the event count $n$ (Eq. 1a). Turbidity-current frequency $f$ (yr$^{-1}$) has the inverse relationship (Eq. 1b):

$$r = \frac{T}{n} \text{ (Eq. 1a)}; \quad f = \frac{1}{r} \text{ (Eq. 1b)}$$

The average sediment volume deposited during a turbidity-current event ($v_e$) is related to the total volume of a sediment package $V$ (m$^3$) and the number of events ($n$):

$$v_e = \frac{V}{n} \text{ (Eq. 2)}$$

These relationships can be combined into an equation that equates the long-term deposition rate and the average event volume and event recurrence (Eq. 3).

$$\frac{V}{T} = \frac{v_e}{r} = v_ef \quad \text{ (Eq. 3)}$$

It is important to note that $v_e$ is an average event volume, and does not take into account the distribution of flow volumes shown in natural systems (Talling et al., 2007a; Cooper et al., 2013; Clare et al., 2014; Allin et al., 2017) and the spatial distribution of beds on a submarine fan (Deptuck et al., 2008; Jobe et al., 2016). However, not enough detail about these distributions are available to model them properly. Other assumptions about $v_e$ include: 1) all sediment in an individual turbidity current is deposited on the fan (Lamb et al., 2004; Sylvester et al., 2015) and no deposition occurs in the canyon-channel system; 2) there is zero bypass to down-system sites; 3) there is no erosional bulking of the flows during transport; 4) there is no temporal change in $v_e$
during fan/lobe/feeder channel evolution (cf. Deptuck et al., 2008; Clare et al., 2016). While these assumptions sometimes oversimplify the complexity of submarine-fan depositional systems, they provide a general framework for estimating event volume ($v_e$) and recurrence ($r$) for systems with limited data.

**STUDY LOCATIONS**

This study focuses on late Quaternary (< 130 ka) submarine-fan deposits, which are suitable for determining $V$, $T$, and $n$ due to high-quality seismic-reflection data and age-constrained core data. The locales in this study occupy intraslope and base-of-slope settings (Fig. 2, Table 1).

**Niger X fan system, Nigeria**

Mobile shale deformation of the Niger continental slope (Pirmez et al., 2000) created intraslope accommodation where the Niger X submarine fan system was deposited. Jobe et al. (2016) described late Quaternary deposits on the X fan and constrained $V$, $T$, and $n$ of the youngest sediment package (Fig. 2; Fig. 3; Table 2). The range of $V$ is derived from the deposit area and thickness measurements from cores (Table 2). The range of $n$ is obtained by counting event beds from two core descriptions (Fig. 3). The range of $T$ is provided by adding/subtracting the analytical error from radiocarbon ages to the value provided by Jobe et al. (2016). Prather et al. (2012a) also measured values of $V$ for longer term (> 100 kyr), thicker (>100 m) deposits on the X fan, but these deposits are not included in our calculations because core data are lacking to constrain $T$ and $n$.

**Hueneme Fan system, California**
The Hueneme submarine fan developed in the Santa Monica Basin, offshore California Continental Borderland (Fig. 2). The Quaternary fill of the Hueneme fan is ponded due to faults and folds associated with transpressional deformation related to the San Andreas Fault system (Piper & Normark, 2001; Normark et al., 2006). Romans et al. (2009) measured $V$ for five intervals defined from seismic-reflection profiles that covered the entire Hueneme fan system, and calculated $T$ using radiocarbon ages from a core collected by Ocean Drilling Program (Site 1015; Table 2). The five intervals are grouped into three packages (Hueneme 1, 2, and 3-4-5, following nomenclature of Romans et al., 2009) that have values of $n > 2$ (for statistical purposes) and approximately equal volume and time duration (Table 2). Ranges of $n$ are dependent on including or not including thin silt intervals and debris flow deposits, and minimum and maximum values are presented based on this criterion (Table 2). The youngest package (Hueneme 3-4-5) includes $T$ and $n$ values estimated by Gorsline (1996) from box cores taken in a more proximal position. While some of the small, frequent flows discussed by Gorsline (1996) may die out prior to reaching the Hueneme fan, these data are included as a conservative approach to defining the parameter space of $v_e$ and $r$.

**Brazos-Trinity system, Gulf of Mexico**

There are four linked intraslope salt-withdrawal basins in the Brazos-Trinity system that contain Quaternary submarine-fan deposits (Winker, 1996; Badalini et al., 2000; Beaubouef & Friedmann, 2000; Mallarino et al., 2006). Prather et al. (2012b) used 3D seismic-reflection data to map the basin stratigraphy and demonstrate coeval deposition of three packages of sediment in basins II and IV (40 series, 50/60 series, and 70 series in Table 2). Pirmez et al. (2012) used borehole and core chronostratigraphy to calculate a sediment budget for the system, estimating $V$ and $T$ for the three packages. Ranges of $T$ were derived from minimum and maximum estimates.
(Pirmez et al., 2012). Ranges of \( n \) (Table 2) were derived for each package from the International Ocean Discovery Program Site U1320 core description (fig. 4 of Pirmez et al., 2012) in a similar manner to that described for the Hueneme fan (above).

**Golo fan system, Corsica**

The comparatively small (cf. Sømme et al., 2009) Golo submarine-fan deposits can be entirely mapped on seismic-reflection profiles and exhibit base-of-slope fan architecture (Deptuck et al., 2008). Values of \( V \) and \( T \) were derived from Sømme et al. (2011) for Holocene deposits (horizon K to seafloor) and from Calvès et al. (2012) for late Quaternary units S1, S2, and S3 and also a Holocene fan package that occupies an intraslope position (the 'Pineto lobe' of Deptuck et al., 2008). Values of \( n \) were derived from two cores in Golo submarine-fan deposits (Gervais, 2002; Gervais et al., 2006). The cores used (kco62, kco58 upper section, and kco58 lower section) yield \( n \) values of 12, 6, and 8, respectively (figs 10 and 14 of Gervais et al., 2006). These cores are shallow piston cores and do not penetrate the entire intervals of interest; thus, \( n \) values for each interval were extrapolated from these core data assuming no temporal change in event recurrence. These extrapolated values of \( n \) (Table 2) are most appropriate for the youngest deposits, but are also used for the older deposits, acknowledging that there may be temporal changes in event recurrence that are not sampled by existing core data.

**DATA ANALYSIS**

Using measured values of \( V \), \( T \), and \( n \) from each locale, the methodology described above can be used to estimate ranges of event volume and recurrence. Table 2 presents the values of \( V \), \( T \), and \( n \) measured from each studied locale. In all four study locales, ranges are often reported for \( V \), \( T \), and \( n \) due to measurement uncertainty (e.g., measurement error in ages of Fig. 1) or
multiple possible values (Table 2). The Niger X fan is used as an example to explain the measurements and uncertainties of \( V, T, \) and \( n \). The sediment volume \( V \) was calculated using the area of the youngest sediment package and the minimum and maximum thickness measurements of 1 and 3 m based on core penetrations (Fig. 3; Jobe et al., 2016). No areal changes in thickness were assumed, rather a simple area*thickness was used to calculate minimum \( (1.2 \times 10^7 \text{ m}^3) \) and maximum \( (3.6 \times 10^7 \text{ m}^3) \) values of \( V \). The total duration of deposition \( T \) was determined from core-derived radiocarbon ages (fig. 9 of Jobe et al., 2016) and is estimated to be \( 4,000 \pm 200 \text{ yr} \) (Fig. 3). The event count \( n \) was obtained by counting the sand beds in two core descriptions \( ((n=20, n=48; \text{ Fig. } 3; \text{ Table } 2) \).

In order to fully explore the parameter space for \( v_e \) and \( r \), the ranges of the input values \( V, T, \) and \( n \) are determined by using a uniform distribution (Table 2). To create a uniform distribution of each variable \( (V, T, n) \), the range between the minimum and maximum values is divided into 10,000 values. Using random sampling with replacement, \( r \) and \( v_e \) are calculated 10,000 times using Equations 1a and 2, respectively. The 10,000 iterations of \( v_e \) and \( r \) for the Niger X fan can be plotted as a ‘size-recurrence’ plot (Fig. 4A).

A triangular distribution is employed which approximates a normal distribution in cases of limited data. For each variable \( (V, T, n) \), the minimum value, maximum value, and the mean of those two values are used to define the lower limit, upper limit, and peak location of the triangular distribution. Using random sampling with replacement, \( v_e \) and \( r \) are again calculated 10,000 times, with the results displayed in an event volume-recurrence plot (Fig. 4B). A 2D kernel density emphasizes the resulting distribution of \( v_e \) and \( r \), with the kernel shown as a contour map containing 90% of the data (Fig. 4B). Calculating \( v_e \) and \( r \) from uniform distributions of \( V, T \) and \( n \) results in the largest, most conservative parameter space (Fig. 4A).
Using a triangular distribution slightly shrinks the overall distribution of the parameter space but does not significantly alter the results obtained with a uniform distribution (Fig. 4B).

RESULTS

For the four studied locales, values of $v_e$ vary over four orders of magnitude ($10^5$-$10^9$ m$^3$), while values of $r$ vary by one order of magnitude (50-650 yr, Fig. 5). The intraslope deposits of the Niger X and Golo Pineto locales show the smallest values of $v_e$, approximately $10^6$ m$^3$ (Fig. 5). The base-of-slope Golo deposits have intermediate $v_e$ values ($10^7$ m$^3$, Fig. 5). The ponded Brazos-Trinity and Hueneme deposits have the largest values of $v_e$ ($>10^8$ m$^3$) and the most variability in $r$ (Fig. 5). Interestingly, the three time intervals in the Brazos-Trinity system have quite different values of $r$ but very consistent values of $v_e$. The Golo Pineto locale has the largest variability in $v_e$ and $r$ of any deposit, likely due to the wide ranges of input values of $T$ and $n$ (Table 2).

Validation of the calculated values of $v_e$ and $r$

In order to ensure that the calculated values of $v_e$ are reasonable, the distribution of event-bed thickness in a submarine fan deposit can be estimated and compared to well-constrained examples from outcrops and modern systems. For the Niger X fan, values of $n$ (Table 2) and a package thickness of 2 m (the average thickness estimate of Jobe et al., 2016) are used to estimate average event-bed thickness of 4.2 cm and 10 cm (for $n = 48$ and 20, respectively).

These thickness values are well within the observed range of event-bed thickness (1-57 cm, average of 10 cm) for cores from the X fan (Jobe et al., 2016) as well as other reported event-bed thickness ranges (3-110 cm from Prélat & Hodgson, 2013). These ranges of event-bed thickness
are also comparable to other well-characterized submarine-fan deposits (Murray et al., 1996; Talling, 2001; Sylvester, 2007; Prélél et al., 2009).

255 DISCUSSION

256 Estimating the total time of deposition \(T\) in ancient submarine fan deposits

Ancient submarine-fan deposits are well described from subsurface data (Normark, 1970; Saller et al., 2008; Kane & Ponten, 2012) and outcrop exposures (Walker, 1978; Hodgson et al., 2006; Pyles, 2008; Prélél et al., 2009; Auchter et al., 2016). Facies relationships and stratigraphic architecture are mappable in outcrops and, with areally extensive exposures, volumes can be estimated. However, the total time of deposition \(T\) and the event recurrence interval \(r\) are difficult to determine accurately due to large uncertainties of chronostratigraphic methods for sedimentary rocks. However, we can use estimated volumes \(V\) for outcropping submarine-fan deposits and calculated ranges of \(r\) and \(v_e\) from Quaternary systems (Fig. 5) to estimate the total time of deposition \(T\) for the ancient, outcropping deposits. These estimates of \(T\) can aid in the interpretation of the incomplete and low-resolution geochronology typical of ancient submarine-fan deposits.

Submarine-fan deposits containing six discrete sediment packages were mapped in the Permian Skoorsteenberg Formation in the Tanqua Karoo sub-basin, South Africa by Prélél et al. (2009). These six packages were classified hierarchically as ‘lobes’ by Prélél et al. (2009) and the encompassing unit a ‘lobe complex’; however, we will refer to them generically as sediment packages to avoid terminology confusion. These submarine-fan deposits are interpreted to have formed in a base-of-slope position in an unconfined (i.e., non-ponded) basin (Prélél et al., 2009),
most similar to the Golo locale (Table 1). The U-Pb ages from ashes interbedded with the
sediment packages of the Skoorsteenberg Formation are all within error of each other (Fildani et
al., 2009) and may include erroneous ages due to magmatic crustal recycling during volcanic
eruptions (McKay et al., 2015). Hence, it is not possible to accurately calculate $T$ values from
these U-Pb ages; it is, however, possible to estimate ranges of $T$ using the approach described
above. Prélat et al. (2009) calculated $V$ for three of the mapped packages (‘lobes’ 2, 5, and 6),
with values of $1.3 \text{ to } 3.5 \times 10^9$ m$^3$ (Table 3), similar to calculated sediment volumes from this
study (Table 2) and other Quaternary submarine-fan deposits (Prélat et al., 2010). Using lobe
volume and event count data (Table 2), Equation 2 is used to define potential values of $v_e$ for
lobes 2, 5 and 6, which are $~ 10^8$ m$^3$ (Table 2). To be conservative, values of $v_e$ that bracket these
estimates are chosen ($10^7$ to $10^9$ m$^3$), which are also most similar to other base-of-slope systems
(Fig. 5). The range of $r$ is conservatively chosen as 50-650 yr, encompassing all of the data in
Figure 5. Uniform distributions of each variable are created as inputs into Equation 3 (using the
same methods as described above) to calculate a range of $T$ for the three packages (Fig. 6). The
$P_{50}$ prediction of $T$ for each package is on the order of $10^4$ yr (Fig. 6). Specifically, ‘lobe’ 2 has
$T_{P_{50}=1.5}$ kyr, ‘lobe’ 5 has $T_{P_{50}=2.5}$ kyr, and ‘lobe’ 6 has $T_{P_{50}=0.9}$ kyr (Fig. 6). These lobe
duration estimates compare reasonably to the Holocene Amazon (15-20 lobes in 10 kyr, Jegou et
al., 2008) and Zaire (38-52 lobes in 210 kyr, Picot et al., 2016) submarine fan deposits (Fig. 6).
The hierarchically larger package (‘lobe complex’ of Prélat et al., 2009 often informally referred
to as ‘Fan 3’) consists of six ‘lobes’; if minimum and maximum values from Figure 6 are used to
estimate $T$ for the lobe complex, the range of $T$ for ‘Fan 3’ is 1.6-68 kyr, with median values
ranging from 5-15 kyr. This analysis provides a methodology for estimating the total time of
deposition ($T$) for ancient submarine-fan successions where no other data are available. This
analysis also highlights the need for more volumetric and geochronologic characterization of ancient submarine-fan deposits.

**Linking catchment parameters to event volume**

Source (e.g., catchment dimensions) and sink (e.g., submarine-fan length) parameters have been shown to generally scale to one another (Sømme et al., 2009). The event volume measured in the sink (Fig. 5) should scale to a sediment supply parameter (e.g., sediment load) in the source area, given minimal storage in the transfer zone (Romans et al., 2016). In order to investigate these relationships, source parameters (Table 2) were compiled for the four systems from Milliman and Farnsworth (2011), including catchment area (km$^2$), sediment yield (tons/km$^2$/yr), and sediment load (tons/yr). For the Golo, Hueneme, and Brazos-Trinity systems a weighted average was calculated for catchments that feed these systems (see Table 2), and for the Niger system, one-quarter of the Niger river parameters were used, as Allen (1965) estimates that the study area of the western Niger Delta receives approximately one-quarter of the water and sediment discharge. Figure 7 plots catchment area, sediment yield, and sediment load against the median value of event volume ($v_e$) calculated for each system, which show positive, but weak, correlations between catchment parameters and event volume. The Niger forms a consistent outlier to this dataset (Fig. 7), suggesting that sediment partitioning in the Niger Delta may not be accurately estimated by Allen (1965); unfortunately, more detailed data are not available. While these scaling relationships (Fig. 7) seem reasonable and corroborate other source-to-sink scaling relationships (Sømme et al., 2009), more systems are needed to further test this hypothesis and derive any statistical significance.

The weak scaling shown in Figure 7 indicates poor connectivity between source and sink. When comparing source parameters and event volume, we assume complete transfer of sediment
from the source to the sink, but many modern systems have significant sediment storage in the
fluvial transfer zone (Wilson & Goodbred, 2015; Romans et al., 2016) that could complicate
scaling between catchment parameters and $v_e$. For example, the Niger X system may have
significant transfer-zone storage not accounted for by Allen (1965), and thus would plot far
below its current position in Fig. 7.

**Linking event volume to the basin setting of submarine fans**

While the values of $r$ remain relatively consistent across all basin settings, the values of
$v_e$ vary by orders of magnitude (Fig. 5). The studied submarine sediment-routing systems occupy
different tectonic and topographic basin settings (Table 1) that may control the values of $v_e$. (e.g.,
basin ponding, intraslope basin development). These different basin settings can lead to the
sequestration of sediment and thus a further decoupling of the source-to-sink scaling
relationships described above. For example, the calculated values of $v_e$ for ponded basin floor
settings (the Brazos-Trinity and Hueneme systems) are much larger than for base-of-slope and
intraslope fans (Fig. 5). There is no sediment bypass in the Brazos Trinity and Hueneme systems
as compared to the intraslope X fan and Golo Pineto locales. The Brazos-Trinity system is fully
ponded by a large salt diapir at the distal edge of Basin IV (Prather et al., 2012b; Pirmez et al.,
2012), and the Hueneme fan is ponded by various fault-related ridges and knolls (Normark et al.,
1998). On the intraslope Niger X fan, on the other hand, there is direct seafloor and core
evidence for sediment bypass in the form of an exit channel at the distal edge of the fan (Fig. 3;
Jobe et al., 2016) and thus small values of $v_e$ may be expected. The Golo Pineto deposit also
occupies an intraslope position (Deptuck et al., 2008) and likely experienced sediment bypass
and thus smaller values of $v_e$. The larger Golo submarine fan deposits (Fig. 5) occupy a non-
ponded base-of-slope position, and thus show intermediate ranges of $v_e$. 
Comparison to other turbidity-current volumes and frequencies: from proximal submarine canyons to abyssal plains

This study focuses on event volumes and frequencies of turbidity currents that build submarine fans. However, there is a full spectrum of event-based measurements from upslope submarine canyons to downslope abyssal plains, measured using direct monitoring data as well as core and outcrop data. These emerging datasets enable a comparison of event volumes and recurrence intervals across the entire submarine sediment-routing system. It is important to note that these trends are only valid for abyssal plains that are fed by the same feeder system as the canyon/channel and fan (cf. Talling et al., 2007b).

Abyssal plains

Abyssal plains have been recognized as a source for palaeoclimate (Clare et al., 2015) and palaeoearthquake (Goldfinger, 2011) records because they preserve a relatively complete depositional record due to little or no erosion and/or post-depositional modification (Weaver et al., 1992). A large compilation by Clare et al. (2014) of turbidite volumes ($V_e$) and recurrence intervals ($r$) for three abyssal plains allows us to assess the magnitude differences between turbidity currents that build submarine fans and those that deposit sand in the most distal locations on Earth. The data (Clare et al., 2014) are derived from well-studied and dated cores from the modern Madeira Abyssal Plain (offshore northwest Africa) and the modern Balearic Abyssal Plain (western Mediterranean Sea), and also from outcrops of the Miocene Marnoso-Arenacea Formation, Italy (Amy & Talling, 2006). Generally, values of $V_e$ and $r$ for turbidity currents building submarine fans are 10-1,000 times smaller and 10-100 times more frequent than turbidity currents depositing sand onto the abyssal plain (Fig. 8). This is an intuitive relationship that was also recognized by Piper and Normark (1983). Large-volume turbidites on
abyssal plains can have many triggers, including large-magnitude earthquakes (Normark and Piper, 1991; Piper and Normark, 2011), glacial advances (Haflidason et al., 2004), sea-level regressions (Kolla & Perlmutter, 1993), and sea-level transgressions (Hunt et al., 2013). However, Clare et al. (2014) find that some abyssal plain turbidites are temporally random and not linked to sea level at all. Regardless of the mechanism, abyssal plain turbidites have 10-1,000 times larger event volumes than turbidity currents building submarine fans, but occur 10-100 times less frequently (Fig. 8). However, there is some overlap between the abyssal plain values and large volume flows that characterize the ponded locales of the Hueneme and Brazos-Trinity systems. The ponding in both these systems may result in larger calculated $v_e$ values, as ponding is an effective sediment-trapping mechanism.

Proximal submarine canyons

The heads of submarine canyons, at the other extremity of the submarine sediment routing system, have been instrumented for decades (Prior et al., 1987; Paull et al., 2010), and have served as natural laboratories that enable a better understanding of turbidity current morphodynamics (Cooper et al., 2013; Hughes-Clarke, 2016; Jobe et al., 2017; Symons et al., 2017). While event volumes have thus far eluded the flow monitoring datasets, recurrence intervals spanning from hours (Hughes-Clarke, 2016) to years (Paull et al., 2014) have been documented. However, many of these flows, while very frequent, dissipate prior to reaching the submarine fan (Paull et al., 2005; Talling et al., 2015) and thus must have relatively small event volumes ($v_e < 10^5$ m$^3$). Further evidence of frequent and small-volume flows not reaching submarine fans comes from the Iberian abyssal plain (not discussed here, see Allin et al., 2017) and the Hueneme submarine fan. Romans et al. (2009) suggest that frequent, thin-bedded
turbidites with short recurrence intervals (Table 2) recovered in cores from the proximal Hueneme canyon by Gorsline (1996) are not represented in the Hueneme submarine fan deposits, indicating that these frequent, small magnitude flows dissipated prior to reaching the fan.

**Event volumes and frequencies across the submarine sediment-routing system**

The observations above are summarized in a generalized parameter space for event volume and recurrence (Fig. 8) that is inspired by pioneering work on the size spectrum of turbidity currents (Piper & Normark, 1983). The ranges of event volume and recurrence can be classified into three overlapping categories: submarine canyon, submarine fan, and abyssal plain (Fig. 8). This continuum of flow processes is reflected in the often-smooth geomorphic transition from canyon to fan to basin plain (Piper & Normark, 2001). Small flows are generated in submarine canyons very frequently, but few of those flows reach the submarine fan (Stevens et al., 2013; Clare et al., 2016). Very large and infrequent flows deposit sediment onto the abyssal plain, and likely partially bypass the submarine fan (Fig. 8). It seems that flows that build submarine fans occupy an intermediate position in terms of event volume ($10^5$ - $10^9$ m$^3$) and recurrence ($10^1$ - $10^3$ yr), where flow filtering through submarine canyons and channels (McHargue et al., 2011) and distance from source (Stevens et al., 2013; Allin et al., 2017) probably play significant roles in modulating flow volume and recurrence to submarine fans. Thus, fans are constructed by flows large enough to bypass and sculpt canyons, but small enough to die out before reaching the abyssal plain. It is important to note that event volume and recurrence are not single values, but rather distributions, and it is likely that these distributions are truncated as flows move from canyon to basin plain (Allin et al., 2017). As more data are collected and analyzed, event volume and recurrence will become better understood and better able to provide sediment flux estimates and assessments of submarine geohazards.
CONCLUSIONS

This study applies a simple mass-balance approach to four well-characterized Quaternary submarine-fan deposits in order to calculate the volumes of sediment deposited by turbidity currents and the recurrence of those events. The ranges of event volume vary over four orders of magnitude, from $10^5$ to $10^9$ m$^3$, while recurrence intervals vary by one order of magnitude, from 50 to 650 yr. These flow parameters seem to typify turbidity currents that build submarine fans, and form intermediate values between events measured in submarine canyons and on abyssal plains. Measured turbidity currents in submarine canyons have small volumes (less than $10^5$ m$^3$) and short recurrence intervals (hours to years), while turbidites deposited on abyssal plains have very large event volumes (greater than $10^8$ m$^3$) and long recurrence intervals ($10^2$ to $10^6$ yr). The segmentation of flow volume and recurrence along the submarine sediment-routing system provides valuable insights for better constraining models for geohazard assessment and resource characterization. Calculations of event volume and recurrence can also be used to estimate the time of deposition in ancient submarine-fan successions where high-resolution chronologic data are not available. Applying this methodology, to the well-known ‘Fan 3’ of the Tanqua Karoo fan system (South Africa), we estimate the time of deposition of Fan 3 to be 5-15 kyr.

The volumes of submarine-fan-building turbidity currents calculated by this study show correlations to slope position and topographic complexity, with ponded submarine fans having larger event volumes than base-of-slope and intraslope fans. Non-ponded intraslope submarine fans have smaller event volumes than ponded or base-of-slope submarine fans, likely because of flow bypass (as opposed to flow trapping in ponded basins) and because only the largest flows reach the basin floor/abyssal plain. There is weak positive scaling of event volume to source area
characteristics (e.g., catchment area, sediment yield), but submarine topographic complexity (e.g., ponding, bypass) and sediment storage in the fluvial transfer zone potentially complicate these scaling relationships. Further work should focus on improved volumetric and geochronologic characterization of modern and ancient submarine fan deposits from a range of sediment supply characteristics, source-to-sink configurations, tectonic settings, and geographic locations to enable investigation of trends in event volume and recurrence and how various system characteristics may influence deviations from norms.

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Dallmeier-Tiessen, S., Benetti, S., Weaver, P.P.E., Georgiopoulou, A., Zühlsdorff, C. and Amy, L.A.,


<table>
<thead>
<tr>
<th>Study area (refs.)</th>
<th>Tectonic regime</th>
<th>Slope/Basin Position</th>
<th>Water depth (m)</th>
<th>Distance from shelf edge (km)</th>
<th>Age range (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niger X system, Nigeria (1), (2), (3)</td>
<td>Passive margin with shale tectonics</td>
<td>Intraslope, not ponded</td>
<td>1200</td>
<td>61</td>
<td>25-15</td>
</tr>
<tr>
<td>Hueneme system, California (4), (5)</td>
<td>Active; Flexural transpressional basin with fault-controlled basin margins</td>
<td>Basin floor and ponded</td>
<td>850</td>
<td>30</td>
<td>7-0</td>
</tr>
<tr>
<td>Golo system, Corsica (6), (7), (8)</td>
<td>Active margin with fault-controlled basin topography</td>
<td>Basin floor, not ponded</td>
<td>800</td>
<td>20</td>
<td>57-15 (5); 130-0 (6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intraslope, not ponded</td>
<td>800</td>
<td>20</td>
<td>25-18 (6)</td>
</tr>
<tr>
<td>Brazos-Trinity system, Gulf of Mexico (9), (10)</td>
<td>Passive margin with salt tectonics and ponded mini-basin formation</td>
<td>Intraslope, ponded</td>
<td>900 (Basin II); 1500 (Basin IV)</td>
<td>40 (Basin II); 75 (Basin IV)</td>
<td>23-15 (all basins)</td>
</tr>
</tbody>
</table>

Table 1. Characteristics of the locales utilized in this study. References cited include: (1) Jobe et al. (2016); (2) Milliman and Farnsworth (2011); (3) Allen (1965); (4) Romans et al. (2009); (5) Gorsline (1996); (6) Gervais et al. (2006); (7) Sømme et al. (2011); (8) Calves et al. (2012); (9) Pirmez et al. (2012); (10) Prather et al. (2012b).
### Table 2. Values of $V$, $T$, $n$, and other pertinent data for the four studied locales.

See list of citations in Table 1 for data sources.

<table>
<thead>
<tr>
<th>Locale</th>
<th>Bulk volume (m$^3$)</th>
<th>Permeability</th>
<th>Sediment volume $V$ (m$^3$)</th>
<th>total time $T$ (years)</th>
<th>$n$ (event load count)</th>
<th>Catchment Area (km$^2$)</th>
<th>Sediment Yield (ton/km$^2$/yr)</th>
<th>Sediment Load (Mg/m$^2$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niger X</td>
<td>1.72 x 10$^7$</td>
<td>0.4</td>
<td>1.20 x 10$^7$; 5.61 x 10$^7$</td>
<td>3800; 4400</td>
<td>48; 20</td>
<td>5.50 x 10$^7$</td>
<td>4.55</td>
<td>2.5</td>
</tr>
</tbody>
</table>

These values represent one-fourth of the Niger River values from (2), as one-fourth of sediment discharge is distributed to the S.Senegal (2).

<table>
<thead>
<tr>
<th>Hurricane Interval</th>
<th>Bulk volume (m$^3$)</th>
<th>Permeability</th>
<th>Sediment volume $V$ (m$^3$)</th>
<th>total time $T$ (years)</th>
<th>$n$ (event load count)</th>
<th>Catchment Area (km$^2$)</th>
<th>Sediment Yield (ton/km$^2$/yr)</th>
<th>Sediment Load (Mg/m$^2$/yr)</th>
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<td>Hurricane Interval 1</td>
<td>4.58 x 10$^7$</td>
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<td>2.84 x 10$^7$</td>
<td>3790; 2800</td>
<td>3; 9</td>
<td>5420</td>
<td>2712</td>
<td>14.7</td>
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<tr>
<td>Hurricane Interval 2</td>
<td>3.67 x 10$^7$</td>
<td>0.22</td>
<td>2.51 x 10$^7$</td>
<td>2340; 2440</td>
<td>6; 8</td>
<td>3140</td>
<td>1562</td>
<td>16.7</td>
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<tr>
<td>Hurricane Interval 3, 4, 5</td>
<td>6.12 x 10$^7$</td>
<td>0.38</td>
<td>3.96 x 10$^7$</td>
<td>500; 1750</td>
<td>4; 7</td>
<td>1244</td>
<td>622</td>
<td>4.7</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Gulf Stream</th>
<th>Bulk volume (m$^3$)</th>
<th>Permeability</th>
<th>Sediment volume $V$ (m$^3$)</th>
<th>total time $T$ (years)</th>
<th>$n$ (event load count)</th>
<th>Catchment Area (km$^2$)</th>
<th>Sediment Yield (ton/km$^2$/yr)</th>
<th>Sediment Load (Mg/m$^2$/yr)</th>
</tr>
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<tbody>
<tr>
<td>Gulf Stream</td>
<td>4.06 x 10$^7$</td>
<td>0.28</td>
<td>4.06 x 10$^7$</td>
<td>14000; 10500</td>
<td>58; 154</td>
<td>1240</td>
<td>622</td>
<td>4.7</td>
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<tr>
<td>Gulf Stream</td>
<td>8.06 x 10$^7$</td>
<td>0.33</td>
<td>8.06 x 10$^7$</td>
<td>2445; 622</td>
<td>12; 53</td>
<td>3520</td>
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<tr>
<td>Gulf Stream</td>
<td>1.05 x 10$^7$</td>
<td>0.39</td>
<td>1.05 x 10$^7$</td>
<td>15800; 17100</td>
<td>57; 166</td>
<td>1630</td>
<td>862</td>
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<table>
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<tr>
<th>Brasen Trinity 30 series</th>
<th>Bulk volume (m$^3$)</th>
<th>Permeability</th>
<th>Sediment volume $V$ (m$^3$)</th>
<th>total time $T$ (years)</th>
<th>$n$ (event load count)</th>
<th>Catchment Area (km$^2$)</th>
<th>Sediment Yield (ton/km$^2$/yr)</th>
<th>Sediment Load (Mg/m$^2$/yr)</th>
</tr>
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<tbody>
<tr>
<td>Brasen Trinity 30 series</td>
<td>2.72 x 10$^7$</td>
<td>0.28</td>
<td>2.72 x 10$^7$</td>
<td>2000; 3000</td>
<td>10</td>
<td>1.960 x 10$^7$</td>
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<td>Brasen Trinity 50/40 series</td>
<td>3.5 x 10$^7$</td>
<td>0.33</td>
<td>3.5 x 10$^7$</td>
<td>1000; 1500</td>
<td>12</td>
<td>3.0 x 10$^7$</td>
<td>100</td>
<td>10.0</td>
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<tr>
<td>Brasen Trinity 40 series</td>
<td>1.3 x 10$^7$</td>
<td>0.39</td>
<td>1.3 x 10$^7$</td>
<td>2000; 3000</td>
<td>6</td>
<td>1.3 x 10$^7$</td>
<td>64</td>
<td>10.0</td>
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<table>
<thead>
<tr>
<th>Skoorsteenberg Formation lobe deposits (Prelat et al., 2009)</th>
<th>Lobe volume $V$ (m$^3$)</th>
<th>event count $n$ from Fig. 8 of Prelat</th>
<th>$v_a$ (m$^3$) using Eqn. 2</th>
<th>Range of $r$ (yr) from Fig. 5</th>
<th>Range of $v_a$ (m$^3$) from Fig. 5</th>
<th>$T$ ($P_{10}$ estimate, yr)</th>
<th>$T$ ($P_{50}$ estimate, yr)</th>
<th>$T$ ($P_{95}$ estimate, yr)</th>
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<tbody>
<tr>
<td>Lobe 2</td>
<td>2.2 x 10$^8$</td>
<td>7.3 x 10$^8$</td>
<td>50; 650</td>
<td>1.0 x 10$^7$; 1.0 x 10$^8$</td>
<td>446</td>
<td>1.526</td>
<td>7.260</td>
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<tr>
<td>lobe 5</td>
<td>3.5 x 10$^8$</td>
<td>20 x 10$^8$</td>
<td>50; 650</td>
<td>1.0 x 10$^7$; 1.0 x 10$^8$</td>
<td>745</td>
<td>2.486</td>
<td>11.339</td>
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<tr>
<td>lobe 6</td>
<td>1.3 x 10$^8$</td>
<td>12 x 10$^8$</td>
<td>50; 650</td>
<td>1.0 x 10$^7$; 1.0 x 10$^8$</td>
<td>273</td>
<td>900</td>
<td>4.332</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Values of parameters used to calculate total time of deposition ($T$) for submarine-fan deposits of the Skoorsteenberg Formation, South Africa.
Fig. 1. Framework for calculating event volume and recurrence interval of submarine-fan-building turbidity currents, using three variables ($V, T, n$) from deposits. $V =$ total sediment volume, $T =$ total duration of deposition, $n =$ event count, $r =$ recurrence interval, $v_e =$ event volume. Figure modified after Jobe et al. (2016).
\[ v_e = \frac{V}{n} \]

- \( V \) = Volume
- \( r \) = Rate
- \( n \) = Number of event beds
- \( T = 4,292 \) years
- \( n = 22 \) event beds

\[ \frac{V}{T} = \frac{v_e}{r} \]

\[ r = \frac{T}{n} \]
Fig. 2. Map showing locations of late Quaternary submarine fan deposits analyzed in this study.
Fig. 3. Niger X fan seafloor depth map (10 m contours) with seismic amplitude (colour) and core locations (white circles). Two cores used in the calculation of turbidity current recurrence are shown at left and right. The black shaded region delineates the youngest sediment package of the Niger X fan. Figure modified after Jobe et al. (2016).
Fig. 4. Size-recurrence plot for formative turbidity currents of the Niger X fan using (A) uniform distributions of input values \(V, T,\) and \(n\) and (B) triangular distributions of input values \(V, T,\) and \(n\). Grey dots are the 10,000 iterations, and the dashed line is the convex hull of the uniformly distributed data shown in part A. In (B), the black contour lines represent a 2D kernel density contour map of 90% of the data, and the cross is the data centroid.
A uniform distribution

B triangular distribution

recurrence interval $r$ (years)

event volume $v_e$ ($10^6$ m$^3$)
Fig. 5. Parameter-space for event volume ($v_e$) and recurrence interval ($r$) of Quaternary submarine fan deposits. The convex hull is shown for each locale as calculated from uniformly distributed variables. Event volume varies over four orders of magnitude while recurrence interval only varies by one. Note that intraslope deposits tend to have lower event volumes than deposits of base-of-slope and ponded systems (see discussion in text).
Fig. 6. Cumulative distribution of the estimated total time of deposition ($T$) for submarine-fan deposits of the Permian Skoorsteenberg Formation, South Africa (nomenclature from Préal et al., 2009). Vertical bars represent ranges of $T$ for Late Quaternary Amazon and Zaire submarine-fan deposits.
The graph shows the cumulative distribution function of total time of deposition $T$ (in years) with different lobes and ranges. Key data points include:

- **$P_{10}$**: 273
- **$P_{50}$**: 900
- **$P_{90}$**: 4,332

The ranges are:
- **lobe 2 (Prelat et al., 2008)**
- **lobe 5 (Prelat et al., 2008)**
- **lobe 6 (Prelat et al., 2008)**
- **Amazon range (Picot et al., 2016)**
- **Zaire range (Jegou et al., 2008)**

The graph indicates that the deposition time varies significantly with the range and lobe, with the Zaire range showing the longest total time of deposition.
Fig. 7. Scaling relationships between median event volume and catchment parameters (A) catchment area, (B) sediment yield, and (C) total sediment load. There is weak positive scaling between median event volume and catchment parameters (dashed arrows), particularly sediment yield. More systems need to be characterized to validate these scaling relationships. The Niger forms a consistent outlier, suggesting that the sediment partitioning (Allen, 1965) is inaccurate.
Fig. 8. Simplified parameter space for event volume and recurrence of turbidity currents across the submarine sediment routing system (inspired by Piper & Normark, 1983). Frequent, small volume flows begin in the canyon, but often do not reach the fan. Larger and less frequent flows build submarine fans, but generally do not reach the abyssal plain. Only very rare, very large flows reach the abyssal plain. The plot is overlain with a simplified submarine sediment routing system for visualization purposes. Note the overlap between the largest scales calculated by this study and that of abyssal plain turbidites, suggesting a continuum of flow properties between submarine fans and abyssal plains.
Recurrence Interval (years)

Turbidity Current Event Volume (m$^3$)

- Flows restricted to canyon/channel
- Flows building submarine fans
- Flows depositing on abyssal plain

Atlantic abyssal plain

- Balearic abyssal plain
- Madeira abyssal plain

Submarine-fan deposits (this study)

Submarine canyons (e.g., Paull et al., 2010; 2014)

Clare et al. (2014)

Flows building submarine fans

Flows depositing on abyssal plain

Flows restricted to canyon/channel