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 modelling, 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 (10⁸ to 10⁹ m³). Deposits in non-ponded, base-of-slope environments have intermediate values (10⁷ to 10⁸ m³). Sediment bypass in intraslope settings and flow trapping in ponded basins likely account 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 presented here are also applied to reconstruct the time of deposition of ancient submarine-fan deposits of the Tanqua Karoo basin, South Africa. The volume and recurrence of submarine-fan-building turbidity currents form intermediate values between values measured in submarine canyons and channels (<10⁵ m³ and <10¹ years) and on abyssal plains (>10⁸ m³ and >10³ years), 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.

Keywords
abyssal plain, flow recurrence, sediment gravity flow, submarine canyon, submarine landslide
1 | 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 (Bernhardt et al., 2017; Gulick et al., 2015), sea-level fluctuations (Castelltort et al., 2017), rates of continental erosion (Clift, 2006), land-to-sea delivery of organic carbon (Burdigue, 2005), and continental-margin seismicity (Goldfinger, 2011). 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 and lobe deposits (Bouma et al., 1985; Dill et al., 1954; Heezen et al., 1959; Menard, 1955; Shepard & Emery, 1941). 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 (Adeogba et al., 2005; Fernandez et al., 2014; Jobe et al., 2017b; Mutti & Normark, 1987; Picot et al., 2016; Spinewine et al., 2009). The focus of this paper is on the stratigraphic record of submarine fans, as their deposits 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 geo-hazards, 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 (Bolla Pittaluga & Imran, 2014; Petit et al., 2015; 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 (Cartigny et al., 2013; Hodgson et al., 2006; Hubbard et al., 2014; de Leeuw et al., 2016; Normark, 1970; Pirmez et al., 1997; Sequeiros et al., 2010). Direct monitoring in modern systems provides insight into the short-term morphodynamic and sediment-transport mechanisms (Clare et al., 2016; Cooper et al., 2013; Hughes-Clarke, 2016; Paull et al., 2010). However, understanding the longer term (>10^2 years) 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 eight orders of magnitude, from 10^{-5} to 10^3 km^3 (Clare et al., 2016; Gonzalez-Yajimovich et al., 2007; Piper & Aksu, 1987). Event recurrence is better constrained, with Quaternary core-based studies providing recurrence interval data from multiple basins (Clare et al., 2014; Clare et al., 2016; Paull et al., 2014). 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 (Allin et al., 2017; Allin et al., 2016; Clare et al., 2015).

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 (Figure 1), and is focused on the following fans (Figure 2): (1) the Golo fan system, Corsica (Calvès et al., 2012; Deptuck et al., 2008; Somme et al., 2011), (2) the “X” intraslope fan, Nigeria (Jobe et al., 2017b; Pirmez et al., 2000; Prather et al., 2012), (3) the Brazos-Trinity intraslope fan system, Texas (Beaubouef & Friedmann, 2000; Mallarino et al., 2006; Pirmez et al., 2012; Prather et al., 2012), 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, this work also estimates the time of deposition in ancient submarine-fan successions, which commonly have poor age-constraints. Finally, possible linkages are discussed between event volume and recurrence with (1) source-area characteristics and (2) basin confinement and slope position.

2 | 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 (Talling et al., 2015; Xu et al., 2014). The approach utilized here relies on three basic measurements of submarine-fan deposits from seismic-reflection and core data (Figure 1): (1) total sediment volume $V$ (m$^3$), (2) total duration of deposition $T$ (year), 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
The total duration of deposition $T$ was calculated using chronological 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 (Figure 1). The event count is simply the number of sand beds present in a core (Figure 1). 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., 2007), and so it is assumed that the cores are composed entirely of turbidites and do not include appreciable hemipelagic sediment. It is also assumed that there has been no post-depositional erosion, reworking or mass wasting, though these processes do occur even in distal parts of submarine fans (Croguennec et al., 2017; Dennielou et al., 2017). While some data indicate that event-bed geometries in submarine-fan deposits can be more complex (Deptuck et al., 2008; Jobe et al., 2017b), it is also assumed 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 (Figure 3), but this study conservatively includes 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 $r$ (year) is defined as the total time $T$ divided by the event count $n$ (Equation 1a). Turbidity-current frequency $f$ (year$^{-1}$) has the inverse relationship (Equation 1b):

$$r = \frac{T}{n};\tag{1a}$$

$$f = \frac{1}{r}.\tag{1b}$$

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 ($n$):

$$v_e = \frac{V}{n}\tag{2}$$

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

$$\frac{V}{T} = \frac{v_e}{r} = \frac{v_e f}{r}\tag{3}$$

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 (Allin et al., 2017; Clare et al., 2014; Cooper et al., 2013; Talling et al., 2007) and the spatial distribution of beds on a submarine fan.

**FIGURE 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., (2017b)
(Deptuck et al., 2008; Jobe et al., 2017b). 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. Clare et al., 2016; Deptuck et al., 2008). 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.

3 | 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 intra-slope and base-of-slope settings (Figure 2, Table 1).

3.1 | Niger X fan system, Nigeria

Mobile shale deformation of the Niger continental slope (Pirimz et al., 2000) created intraslope accommodation where the Niger X submarine fan system was deposited. Jobe et al., (2017b) described late Quaternary deposits on the X fan and constrained $V$, $T$ and $n$ of the youngest sediment package (Figures 2 and 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 (Figure 3). The range of $T$ is provided by adding/subtracting the analytical error from radiocarbon ages to the value provided by Jobe et al., (2017b). Prather et al. (2012) also measured values of $V$ for longer term (>100 kyr), thicker (>100 m) deposits on the X fan, but these deposits are not included because core data are lacking to constrain $T$ and $n$.

3.2 | Hueneme Fan system, California

The Hueneme submarine fan developed in the Santa Monica Basin, offshore California Continental Borderland (Figure 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 (Normark et al., 2006; Piper & Normark, 2001). 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 $r$.

**FIGURE 2** Map showing locations of late Quaternary submarine fan deposits analysed in this study.
TABLE 1 Characteristics of the locales utilized in this study

| Study area(refs.)                  | Tectonic regime                                                                 | Slope/Basin Position       | Water depth (m) | Distance from shelf edge (km) | Age range (ka) |
|-----------------------------------|--------------------------------------------------------------------------------|----------------------------|-----------------|------------------------------|---------------|
| Niger X system, Nigeria(1),(2),(3) | Passive margin with shale tectonics                                            | Intraslope, not ponded     | 1,200           | 61                           | 25-15         |
| Hueneme system, California(4),(5)  | Active; Flexural transpressional basin with fault-controlled basin margins     | Basin floor and ponded     | 850             | 30                           | 7-0           |
| Golo system, Corsica(6),(7),(8)    | Active margin with fault-controlled basin topography                           | Basin floor, not ponded    | 800             | 20                           | 57-15 (5); 130-0 (6) |
|                                   |                                                                                | Intraslope, not ponded     | 800             | 20                           | 25-18 (6)     |
| Brazos-Trinity system, Gulf of Mexico(9),(10) | Passive margin with salt tectonics and ponded mini-basin formation  | Intraslope, ponded         | 900 (Basin II); 1,500 (Basin IV) | 40 (Basin II); 75 (Basin IV) | 23-15 (all basins) |

References cited include: (1)Jobe et al., (2017b); (2)Milliman and Farnsworth (2011); (3)Allen (1965); (4)Romans et al. (2009); (5)Gorsline (1996); (6)Gervais et al. (2006); (7)Somme et al. (2011); (8)Calvès et al. (2012); (9)Pirmez et al. (2012); (10)Prather et al. (2012).

3.3 | 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 (Badalini et al., 2000; Beaubouef & Friedmann, 2000; Mallarino et al., 2006; Winker, 1996). Prather et al. (2012) 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 and provide minimum-maximum ranges of V and T. 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).

3.4 | Golo fan system, Corsica

The comparatively small (cf. Somme 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 Somme et al. (2011) for Holocene deposits (horizon K to sea floor) 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...
| Locale      | Bulk volume (m³) | Porosity | Sediment volume V (m³) | Total time, T (years) | n (event bed count) | Catchment area (km²) | Sediment yield (tons/km²/year) | Sediment load (Megatons/year) |
|------------|-----------------|----------|------------------------|-----------------------|---------------------|----------------------|-------------------------------|-------------------------------|
| Niger X    | Data (min; max) |          |                        |                       |                     |                      |                               |                               |
| notes      | 1.72 × 10⁹; 5.16 × 10⁷ | 0.4      | 1.20 × 10⁹; 3.61 × 10⁹ | 3,800; 4,400          | 48; 20              | 5.50 × 10⁴           | 4.55                          | 2.5                           |
| notes      | using area and 1-3 m thickness from (1) |          | Calculated: bulk volume * 1-porosity | Fig. 9 of (1) | Bend 5; fan 14 cores of (1) |                      |                               |                               |
| Hueneme Interval 1 Data (min; max) | 4.58 × 10⁹ | 0.38 | 2.84 × 10⁹ | 2,700; 2,800 | 7; 9 | 5,420 | 2712 | 14.7 |
| notes      | Table 3 of (4) |          | Page 1399 of (4) | Table 3 of (4) | Table 3 of (4) | Table 2, Fig 3 of (4) | Summed values of Santa Clara River, Ventura River, and Calleguas Creek from (2) |
| Hueneme Interval 2 Data (min; max) | 3.57 × 10⁹ | 0.38 | 2.21 × 10⁹ | 2,340; 2,440 | 6; 8 |                      |                               |                               |
| notes      | Table 3 of (4) |          | Page 1399 of (4) | Table 3 of (4) | Table 3 of (4) | Table 2, Fig 3 of (4) |                               |                               |
| Hueneme Intervals 3,4,5 Data (min; max) | 6.12 × 10⁹ | 0.38 | 3.80 × 10⁹ | 500; 1760 | 4; 7 |                      |                               |                               |
| notes      | Table 3 of (4) |          | Page 1399 of (4) | Table 3 of (4) | Value from (5); Fig. 3 of (4) | Value from (5); Fig. 3 of (4) |                               |                               |
| Golo Sømme Data (min; max) | Bulk volume to sediment volume performed by (7) | 4.04 × 10⁹ | 14,000; 16,000 | 68; 136 | 1,214 from (8) | 2.2 from (2) | 0.002 from (2) |
| notes      | Table 4 (seaflor to K) of (7) |          | Fig 7 of (7) |                      | Extrapolated from core data of (6) |                               |                               |
| Golo Pineto Data (min; max) | Bulk volume to sediment volume performed by (8) | 3.12 × 10⁹; 3.55 × 10¹ | 2,444.5; 6,222 | 12; 53 |                      |                  |                               |
| notes      | Supp. Table 3 of (8) |          |                      |                      | Extrapolated from core data of (6) |                               |                               |
| Golo S1 Data (min; max) | 8.06 × 10⁹; 1.33 × 10¹ |          | 68,150; 90,700 | 332; 772 |                      |                  |                               |
| notes      | Supp. Table 3 of (8) |          |                      |                      | Extrapolated from core data of (6) |                               |                               |
| Golo S2 Data (min; max) | 5.89 × 10⁹; 9.66 × 10⁹ |          | 22,000; 29,900 | 107; 248 |                      |                  |                               |
| notes      | Supp. Table 3 of (8) |          |                      |                      | Extrapolated from core data of (6) |                               |                               |
| Golo S3 Data (min; max) | 1.06 × 10⁹; 1.91 × 10⁹ |          | 15,860; 17,100 | 77; 146 |                      |                  |                               |
| notes      | Supp. Table 3 of (8) |          |                      |                      | Extrapolated from core data of (6) |                               |                               |

(Continues)
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.

4 | 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 Figure 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 (Figure 3; Jobe et al., 2017b). No areal changes in thickness were assumed, rather a simple area \( \times \) 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., 2017b) and is estimated to be 4,000 \( \pm \) 200 years (Figure 3). The event count \( n \) was obtained by counting the sand beds in two core descriptions \((n = 20, n = 48; \text{Figure 3; Table 2})\).

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, \( v_e \) and \( r \) 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 (Figure 4A).

A triangular distribution is also 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 (Figure 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 (Figure 4B). Calculating \( v_e \) and \( r \) from uniform distributions of \( V \), \( T \) and \( n \) results in the largest, most conservative parameter space (Figure 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 (Figure 4B).
5 | RESULTS

For the four studied locales, values of $v_e$ vary over four orders of magnitude ($10^5$ to $10^9$ m$^3$), while values of $r$ vary by one order of magnitude (50 to 650 years, Figure 5). The intraslope deposits of the Niger X and Golo Pineto locales show the smallest values of $v_e$, ca. $10^6$ m$^3$ (Figure 5). The base-of-slope Golo deposits have intermediate $v_e$ values ($\sim 10^7$ m$^3$, Figure 5). The ponded Brazos-Trinity and Hueneme deposits have the largest values of $v_e$ ($>10^8$ m$^3$) and the most variability in $r$ (Figure 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).

5.1 | 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., 2017b) 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 to 57 cm) for cores from the X fan (Jobe et al., 2017b) as well as other reported event-bed thickness ranges (3 to 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; Prélat et al., 2009; Sylvester, 2007; Talling, 2001).

6 | DISCUSSION

6.1 | Estimating the total time of deposition ($T$) in ancient submarine fan deposits

Ancient submarine-fan deposits are well-described from subsurface data (Kane & Ponten, 2012; Normark, 1970; Saller et al., 2008) and outcrop exposures (Auchter et al., 2016; Hodgson et al., 2006; Prélat et al., 2009; Pyles, 2008; Walker, 1978). 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 ancient 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 (Figure 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 Prélat et al. (2009). These six packages were classified hierarchically as “lobes” by Prélat et al. (2009) and the encompassing unit a “lobe complex”; however, they will be generically referred to 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 (Prélat 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 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 \( \approx 10^8 \) 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 (Figure 5). The range of \( r \) is conservatively chosen as 50 to 650 years, 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 (Figure 6). The \( P_{50} \) prediction of \( T \) for each package is on the order of 10\(^3\) years (Figure 6). Specifically, “lobe” 2 has \( T_{P50} = 1.5 \) kyr, “lobe” 5 has \( T_{P50} = 2.5 \) kyr, and “lobe” 6 has \( T_{P50} = 0.9 \) kyr (Figure 6). These lobe duration estimates compare reasonably to the Holocene Amazon (15 to 20 lobes in 10 kyr, Jegou et al., 2008) and Zaire (38 to 52 lobes in 210 kyr, Picot et al., 2016) submarine fan deposits (vertical gray bars in Figure 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 to 68 kyr, with median values ranging from 5 to 15 kyr. This analysis provides a simple methodology for estimating the total time of deposition (\( T \)) for ancient submarine-fan successions where no other data are available. This analysis and its associated uncertainties also highlights the need for more volumetric and geochronological characterization of ancient submarine-fan deposits.

### 6.2 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 (Figure 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\(^2\)/year), and sediment load (tons/year). 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

![FIGURE 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 (see Figure 4). 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 Section 6 in text)](image-url)
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 (Figure 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 (Figure 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 suggests poor connectivity between source and sink. When comparing source parameters and event volume, researchers often assume complete transfer of sediment from the source to the sink, but many modern systems have significant sediment storage in the fluvial transfer zone (Romans et al., 2016; Wilson & Goodbred, 2015) 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 Figure 7.

6.3 | 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 (Figure 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 (Figure 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 (Pirmez et al., 2012; Prather et al., 2012), and the Hueneme fan is

| TABLE 3 | Values of parameters used to calculate total time of deposition ($T$) for submarine-fan deposits of the Skoorsteenberg Formation, South Africa |
|------------------------------------------|------------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|
| Skoorsteenberg Formation lobe deposits (Prelat et al., 2009) | Lobe volume $V$ (m$^3$) | Event count $n$ from Prelat | $v_e$ (m$^3$) using Equation 2 | Range of $r$ (yr) from Figure 5 | Range of $v_e$ (m$^3$) from Figure 5 | $T$ ($P_{10}$ estimate, year) | $T$ ($P_{50}$ estimate, year) | $T$ ($P_{90}$ estimate, year) |
|------------------------------------------|------------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|
| Lobe 2 | $2.2 \times 10^9$ | 7 | $3.1 \times 10^8$ | 50; 650 | $1.0 \times 10^7; 1.0 \times 10^9$ | 446 | 1,526 | 7,260 |
| lobe 5 | $3.5 \times 10^9$ | 20 | $1.8 \times 10^8$ | 50; 650 | $1.0 \times 10^7; 1.0 \times 10^9$ | 745 | 2,486 | 11,339 |
| lobe 6 | $1.3 \times 10^9$ | 12 | $1.1 \times 10^8$ | 50; 650 | $1.0 \times 10^7; 1.0 \times 10^9$ | 273 | 900 | 4,332 |
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 sea floor and core evidence for sediment bypass in the form of an exit channel at the distal edge of the fan (Figure 3; Jobe et al., 2017b) and thus show intermediate ranges of \( v_e \). The larger Golo submarine fan deposits (Figure 5) occupy a non-ponded base-of-slope position, and thus show intermediate ranges of \( v_e \).

6.4 | 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., 2007).

6.4.1 | 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, Rothwell, Ebbing, Gunn, & Hunter, 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 to 1,000 times smaller and 10 to 100 times more frequent than turbidity currents depositing sand onto the abyssal plain (Figure 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 & Piper, 1991; Piper & Normark, 2009), 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 to 1,000 times larger event volumes than turbidity currents building submarine fans,
but occur 10 to 100 times less frequently (Figure 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 \( v_c \) values, as ponding is an effective sediment-trapping mechanism.

### 6.4.2 Proximal submarine canyons

The heads of submarine canyons, at the other extremity of the submarine sediment routing system, have been instrumented for decades (Paull et al., 2010; Prior et al., 1987), and have served as natural laboratories that enable a better understanding of turbidity current morphodynamics (Azpiroz-Zabala et al., 2017; Cooper et al., 2013; Hughes-Clarke, 2016; Jobe et al., 2017b; 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 (\( v_c < 10^5 \text{ m}^3 \)). 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.

### 6.4.3 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 (Figure 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/channel, submarine fan, and abyssal plain (Figure 8). This continuum of flow processes is reflected in the often-smooth geomorphic transition from canyon/channel 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 (Clare et al., 2016; Stevens et al., 2013). Very large and infrequent flows deposit sediment onto the abyssal plain, and likely partially bypass the submarine fan (Figure 8). It seems that flows that build submarine fans occupy an intermediate position in terms of event volume (\( 10^5 \) to \( 10^9 \text{ m}^3 \)) and recurrence (\( 10^1 \) to \( 10^3 \) years), where flow filtering through submarine canyons and channels (McHargue et al., 2011) and distance from source (Allin et al., 2017; Stevens et al., 2013) 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 analysed, event volume and recurrence will become better understood and better able to provide sediment flux estimates and assessments of submarine geohazards.

7 | 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 individual 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 years. 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 $10^6$ years). 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 chronological 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 to 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 geochronological 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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REFERENCES

Adeogba, A. A., McHargue, T. R., & Graham, S. A. (2005). Transient fan architecture and depositional controls from near-surface 3-D seismic data, Niger Delta continental slope. AAPG Bulletin, 89, 627–643. https://doi.org/10.1306/11200404025

Allen, J. R. L. (1965). Late Quaternary Niger delta, and adjacent areas: Sedimentary environments and lithofacies. AAPG Bulletin, 49, 547–600.

Allin, J. R., Hunt, J. E., Clare, M. A., & Talling, P. J. (2017). Eustatic sea-level controls on the flushing of a shelf-incising submarine canyon. Geological Society of America Bulletin, 130, 222–237. https://doi.org/10.1130/B31658.1

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

Amy, L. A., & Talling, P. J. (2006). Anatomy of turbidites and linked debrites based on long distance (120 x 30 km) bed correlation, Monsno Arenacea Formation, Northern Apennines, Italy. Sedimentology, 53, 161–212. https://doi.org/10.1111/j.1365-3091.2005.00756.x

Auchter, N. C., Romans, B. W., & Hubbard, S. M. (2016). Influence of deposit architecture on intrastratal deformation, slope deposits of Tres Pasos Formation, Chile. Sedimentary Geology, 341, 13–26. https://doi.org/10.1016/j.sedgeo.2016.05.005

Azpiroz-Zabala, M., Cartigny, M. J. B., Talling, P. J., Parsons, D. R., Summer, E. J., Clare, M. A., . . . Pope, E. L. (2017). Newly recognized turbidity current structure can explain prolonged flushing of submarine canyons. Science Advances, 3, e1700200. https://doi.org/10.1126/sciadv.1700200
Gonzalez-Yajimovich, O. E., Gorsline, D. S., & Douglas, R. G. (2007). Frequency and sources of basin floor turbidites in Alfonso basin, Gulf of California, Mexico: Products of slope failures. *Sedimentary Geology*, 199, 91–105. https://doi.org/10.1016/j.sedgeo.2005.09.025

Gorsline, D. S. (1996). Depositional events in Santa Monica Basin, California Borderland, over the past five centuries. *Sedimentary Geology*, 104, 73–88.

Gulick, S. P., Jaeger, J. M., Mix, A. C., Asahi, H., Bahlburg, H., Belanger, C. L., ... Swartz, J. M. (2015). Mid-Pleistocene climate transition drives net mass loss from rapidly uplifting St. Elias Mountains, Alaska. *Proceedings of the National Academy of Sciences*, 112, 15042–15047. https://doi.org/10.1073/pnas.1512549112

Halfdadsen, H., Sejrup, H. P., Nygård, A., Mienert, J., Bryn, P., Lien, R., ... Masson, D. (2004). The Storegga Slide: Architecture, geometry and slide development. *Marine Geology*, 213, 201–234. https://doi.org/10.1016/j.margeo.2004.10.007

Heezen, B. C., Tharp, M., & Ewing, M. (1959). The Floors of the Oceans I. The North Atlantic. In: The Floors of the Oceans: I. The North Atlantic (Eds B. C. Heezen, M. Tharp & M. Ewing), *Geological Society of America Special Paper*, 65. https://doi.org/10.1130/spe65-p1

Hodgson, D. M., Flint, S. S., Hodgetts, D., Drinkwater, N. J., Johannessen, E. P., & Luthi, S. M. (2006). Stratigraphic Evolution of Fine-Grained Submarine Fan Systems, Tanqua Depocenter, Karoo Basin, South Africa. *Journal of Sedimentary Research*, 76, 20–40. https://doi.org/10.2110/jsr.2006.03

Hubbard, S. M., Covault, J. A., Fildani, A., & Romans, B. W. (2014). Sediment transfer and deposition in slope channels: Deciphering the record of enigmatic deep-sea processes from outcrop. *Geological Society of America Bulletin*, 126, 857–871. https://doi.org/10.1130/B30996.1

Hughes-Clarke, J. E. (2016). First wide-angle view of channelized turbidity currents links migrating cyclical steps to flow characteristics. *Nature Communications*, 7, 1–13. https://doi.org/10.1038/ncomms11896

Hunt, J. E., Wynn, R. B., Talling, P. J., & Masson, D. G. (2013). 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*, 346, 274–291. https://doi.org/10.1016/j.margeo.2013.09.004

Jegou, L., Savoye, B., Pirmez, C., & Droz, L. (2008). Channel-mouth lobe complex of the recent Amazon Fan: The missing piece. *Marine Geology*, 252, 62–77. https://doi.org/10.1016/j.margeo.2008.03.004

Jobe, Z. R., Sylvester, Z., Howes, N., Pirmez, C., Parker, A., Cantelli, A., ... Prather, B. (2017a). High-resolution, millennial-scale patterns of bed compensation on a sand-rich intraslope submarine fan, western Niger Delta slope. *Geological Society of America Bulletin*, 129, 23–37. https://doi.org/10.1130/B31440.1

Jobe, Z. R., Sylvester, Z., Bolla Pittaluga, M., Frascati, A., Pirmez, C., Minisini, D., ... Cantelli, A. (2017b). Facies architecture of submarine channel deposits on the western Niger Delta slope: Implications for grain-size and density stratification in turbidity currents. *Journal of Geophysical Research: Earth Surface*, 122, 473–491. https://doi.org/10.1002/2016JF003903

Kane, I. A., & Ponten, A. S. M. (2012). Submarine transitional flow deposits in the Paleogene Gulf of Mexico. *Geology*, 40, 1119–1122. https://doi.org/10.1130/G33410.1

Kolla, V., & Perlmuter, M. A. (1993). Timing of Turbidite Sedimentation on the Mississippi Fan. *AAPG Bulletin*, 77, 1129–1141.

Lamb, M. P., Hickson, T., Marr, J. G., Sheets, B., & Paola, C. (2004). Surging versus continuous turbidity currents: Flow dynamics and deposits in an experimental intraslope minibasin. *Journal of Sedimentary Research*, 74, 148–155.

de Leeuw, J., Eggenshuijsen, J. T., & Cartigny, M. J. B. (2016). Morphodynamics of submarine channel inception revealed by new experimental approach. *Nature Communications*, 7, 1–7. https://doi.org/10.1038/ncomms10886

Mallarino, G., Beaubouef, R. T., Droxler, A. W., Abreu, V., & Labeyrie, L. (2006). Sea level influence on the nature and timing of a minibasin sedimentary fill (northwestern slope of the Gulf of Mexico). *AAPG Bulletin*, 90, 1089–1119. https://doi.org/10.1306/02210605058

McHargue, T., Pyrćz, M. J., Sullivan, M. D., Clark, J. D., Fildani, A., Romans, B. W., ... Drinkwater, N. J. (2011). Architecture of turbidite channel systems on the continental slope: Patterns and predictions. *Marine and Petroleum Geology*, 28, 728–743. https://doi.org/10.1016/j.marpetgeo.2010.07.008

McKay, M. P., Weislogel, A. L., Fildani, A., Brunt, R. L., Hodgson, D. M., & Flint, S. S. (2015). U-Pb zircon tuff geochronology from the Karoo Basin, South Africa: Implications of zircon recycling on stratigraphic age controls. *International Geology Review*, 57, 393–410. https://doi.org/10.1080/00206814.2015.1008592

Menard, H. W. (1955). Matching land and sea floor topography and structures off California. *AAPG Bulletin*, 39, 137.

Milliman, J. D., & Farnsworth, K. L. (2011). River discharge to the coastal ocean: A global synthesis (p. 384). Cambridge: Cambridge University Press.

Murray, C. J., Lowe, D. R., & Graham, S. A. (1996). Statistical analysis of bed-thickness patterns in a turbidite section from the Great Valley Sequence, Cache Creek, Northern California. *Journal of Sedimentary Research*, 66, 900–908.

Muti, E., & Normark, W. R. (1987). Comparing Examples of Modern and Ancient Turbidite Systems: Problems and Concepts, in Marine Clastic Sedimentology, Dordrecht (pp. 1–38). Dordrecht: Springer.

Normark, W. R. (1970). Growth Patterns of Deep-Sea Fans. *AAPG Bulletin*, 54, 2170–2195.

Normark, W. R., & Piper, D. J. W. (1991). Initiation processes and flow evolution of turbidity currents: Implications for the depositional record. *SEPM Special Publication*, 46, 207–230.

Normark, W. R., Piper, D., & Hiscott, R. N. (1998). Sea level controls on the textural characteristics and depositional architecture of the Hueneme and associated submarine fan systems, Santa Monica Basin, California. *Sedimentology*, 45, 53–70.

Normark, W. R., Piper, D. J. W., & Sliter, R. (2006). Sea-level and tectonic control of middle to late Pleistocene turbidite systems in Santa Monica Basin, offshore California. *Sedimentology*, 53, 867–897. https://doi.org/10.1111/j.1365-3091.2006.00797.x

Paola, C., & Voller, V. R. (2003). A generalized Exner equation for sediment mass balance. *Journal of Geophysical Research*, 110, F04014. https://doi.org/10.1029/2004JF000274
