Submarine Fans and Their Channels, Levees, and Lobes

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Abstract Submarine fans are complex morphological features that develop on the continental slope, rise and abyssal plain, normally at the mouths of submarine canyons. They are constructed principally from the deposits of sediment gravity flows (mainly turbidity currents and debris flows) as terrigenous and shallow marine sediment is redistributed into deeper water. In this chapter we focus on the most important building blocks of submarine fans: leveed submarine channels and the submarine lobes they feed. Mass transport deposits are also important components of many submarine fans; they are described in the chapter on “Submarine landslides”. Submarine channels are the most noticeable geomorphic features on submarine fans, linking net erosional elements like canyons and gullies to net depositional elements like submarine lobes. They develop through both erosional and depositional processes, and have straight to highly sinuous planform geometries. Where they are flanked by aggradational levees or are entrenched into the seabed, they provide stable pathways through which sediment is transported and partitioned into different fan settings. Coarse-grained sediment commonly accumulates on the floors or at the mouths of submarine channels; finer-grained sediment preferentially accumulates on channel banks and on adjacent aggradational levees. In this chapter we describe the wide range of morphological features recognized on the surfaces of submarine fans, and the physical processes that shape the seabed in areas where submarine channels, levees, and lobes develop.

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1 Introduction

Submarine fans form the largest sediment accumulations on Earth: they can be hundreds of kilometers long and several kilometers thick, especially where an ample supply of terrigenous material is available. Although the surface of these submarine fans may appear relatively smooth and featureless when compared to erosional landscapes, higher-resolution-bathymetry- and three-dimensional reflection seismic datasets increasingly reveal a complex array of erosional and depositional features, the most notable of which are submarine channels that have variably sinuous planform geometries and commonly resemble rivers on land (e.g. Damuth et al. 1983; Kenyon et al. 1995) (Fig. 1).

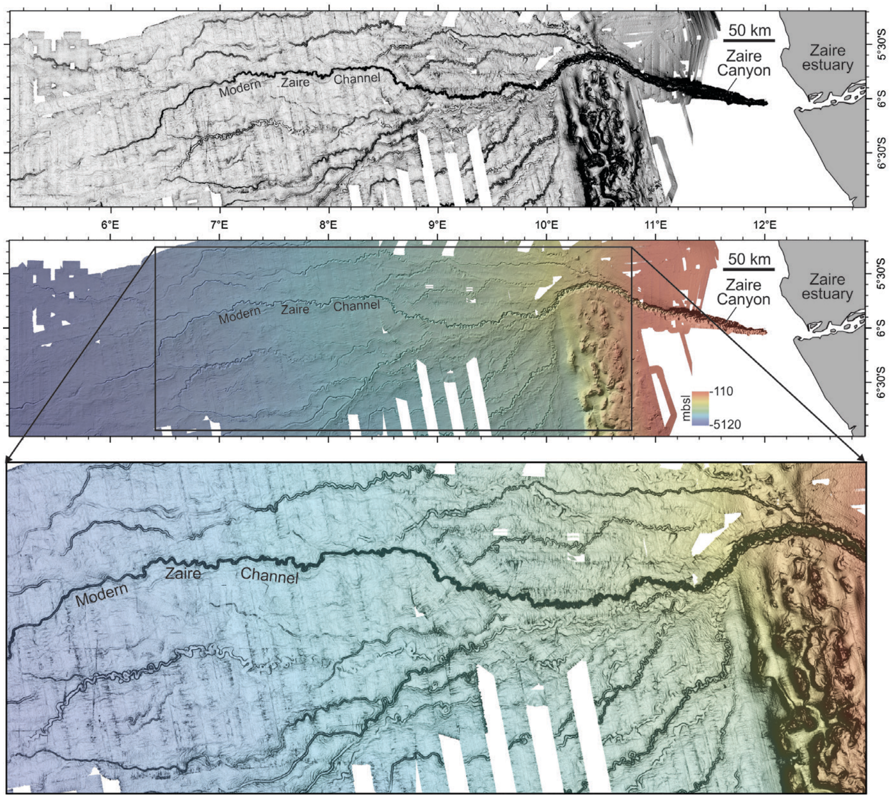

Fig. 1 Dip map (top), shaded relief bathymetry (middle) and close-up of dip map draped by bathymetry (lower) from multibeam echo sounder surveys seaward of the Zaire River, showing the complex pattern of sinuous submarine channels that bifurcate from the Zaire Canyon and ancestral Zaire Channel (images provided by Marie Picot and Nathalie Babonneau). For more details on the evolution of channel-levee systems and lobes in this well-studied system see Picot et al. (2016) and references therein

Although the best known and largest submarine fans like Amazon, Indus, Bengal, Mississippi, and Zaire develop seaward of Earth's largest rivers or their deltas (Wetzel 1993), submarine channels and fans also develop seaward of much smaller deltas supplied both by high-gradient bed-load dominated rivers that cross narrow continental shelves (like the Golo fans off eastern Corsica; Gervais et al. 2006; and the Hueneme Fan off southern California, Piper et al., 1999), and low-gradient suspension-load dominated rivers that cross wide continental shelves (like the Fuji-Einstein system offshore Alabama, eastern Gulf of Mexico; Sylvester et al. 2012; Fig. 2). Submarine fans may also develop in areas remote from direct fluvial-deltaic input, for example at the mouths of shelf-indenting canyons that intercept littoral drift cells (e.g. Covault et al. 2007, Boyd et al. 2008) or along glaciated margins where the advance and retreat of shelf-crossing glaciers, and associated meltwater events, transport large quantities of poorly sorted and unstable glacial material onto the outer continental shelf and slope (Piper et al. 1985, 2012; Klaucke et al. 1998). Submarine fans form on both active and passive margins, in relatively shallow (< 500 m) to very deep water (> 4000 m), at both high and low latitudes, in oceans and in lakes.

The diverse range of submarine fan settings is matched by their architectural variability and wide range of dimensions. For example, the Crati Fan in the tectonically active Ionian Sea is a small system supplied by a coarse-grained, high gradient river with a small catchment area. It is less than 20 km long and covers just 7.0 x 10^1 km^2 (Ricci Lucchi et al. 1985). At the other end of the spectrum, the Bengal

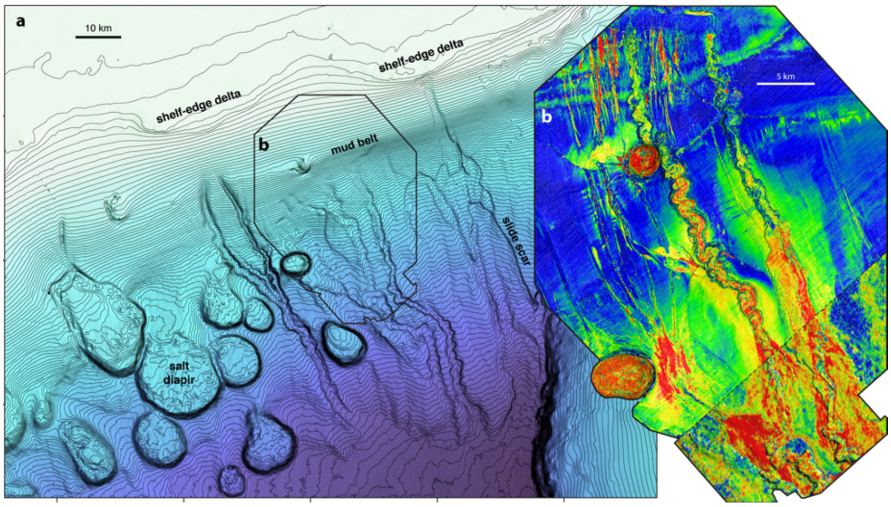

Fig. 2 Seafloor bathymetry in the eastern Gulf of Mexico, showing salt diapirs and largely inactive submarine channels affected by slide scars (contour interval is 20 m; bathymetry data from NOAA). Inset on the right shows the basal seismic surface of the Fuji-Einstein system, colored by seismic amplitude (blue = low amplitude, red = high amplitude; see Sylvester et al. 2012). The two main channels start at the shelf edge and are directly linked to two delta lobes. Changes in slope gradient, salt diapirs, and faults affect these channels

Fan is a giant, long-lived system supplied by the Ganges-Brahmaputra rivers whose catchment areas encompass the southern Himalayas. It is more than 2900 km long and covers an astounding 2.8 x 10^6 km^2 (Emmel and Curray 1985). Fan lengths in these end-member examples vary across three orders of magnitude; the area they cover varies across five orders of magnitude.

Despite the diversity of submarine fan settings and overall size, studies of individual turbidite systems show that most submarine fans are made up of a combination of submarine channels that progressively build up levees, and submarine lobe-like deposits that accumulate where sediment-gravity flows loose channel confinement. Submarine fans may contain one main channel-levee system (CLS) or a series of CLSs that develop in succession through avulsions. The main channel may be relatively straight and wide, flanked by highly asymmetric levees as is the case for the Laurentian, Var, and Kramis fans along relatively steep margins (e.g., Piper et al. 1985; Savoye et al. 1993; Babonneau et al. 2012), or it may be highly sinuous and narrow, flanked by relatively symmetric levees, as is the case for the Mississippi, Amazon, and Zaire fans (e.g., Damuth et al. 1983; Bouma et al. 1985a; Picot et al. 2016). These basic building blocks of submarine fans are commonly interlayered with deposits from large submarine landslides (slumps, slides, and debris flows – collectively referred to as mass transport deposits) and pelagic or hemipelagic drape, all of which can be variously modified by other marine processes like ocean currents.

While the overall size and bulk composition of submarine fans reflects the volume and composition of terrestrial material delivered to the canyon over longer time frames (Wetzel 1993; Reading and Richards 1994) and overall margin physiography (e.g. slope length and gradient; Sømme et al. 2009), submarine fan architecture and geomorphology also reflect the frequency and nature of triggering mechanisms for sediment gravity flows (Piper and Normark 2001), and processes active on the fan itself or within the substrate above which the fan sits. Seabed deformation associated with basement or thin-skinned tectonics for example (like the development of normal faults and salt diapirs in Fig. 2), may produce a wide variety of structures that impact fan or channel development (see Steffens et al. 2003; Covault and Romans 2009; Clark and Cartwright 2009; Mayall et al. 2010). Indeed, the dynamically evolving surfaces of submarine fans produce some of the most fascinating and beautiful submarine landscapes on Earth.

2 Five Decades of Submarine Fan Research - Challenges and Progress

Over the past five decades, the most profound challenge faced by those who study submarine fans is the dearth of direct observations and measurements from sediment gravity flows in nature and hence limited direct constraints on the physical processes that shape (via erosion and deposition) the surfaces of submarine fans

(Talling et al. 2015). With rare exceptions like the timing of submarine cable breaks (Heezen and Ewing 1952), instrumentation placed in the path of sediment gravity flows (e.g. Normark and Dickson 1976), or sonar images of a turbidity current as it passes through a channel (Hay, 1987), early fan depositional models were largely based on the seafloor morphology of a limited number of fans (mostly off California), coupled with sparse shallow coring (e.g. Normark 1970; 1978) and early observations from outcrops (e.g. Mutti and Ricci Lucchi, 1972; Walker, 1978). Generic representative fan models produced in the 1970s distinguished three reaches: an ***upper fan*** consisting of a leveed ‘fan-valley’ that passes into a channeled convex-upward bulge located on the ***middle fan*** where turbidity currents dissipated after leaving fan-valley confinement, and terminating in a ***lower fan*** consisting of flat-lying, unchannelized, unconfined sediment that grade into basin plain deposits (e.g. Normark 1978). The coarsest material in these models was linked to the floors of submarine channels and near their mouths and finer-grained material was mainly found on levees adjacent to upper fan channels (interpreted as deposits from overbanked turbidity currents) and in distal lower fan settings.

Recognizing that a single general fan model could not capture the increasingly wide array of observations from ancient and modern fans, a number of fan classification schemes emerged in the 20 years that followed, using criteria like the efficiency of sand transport to distal fan reaches (Mutti 1985), tectonic setting (Shanmugam and Moiola 1988), sea level position (Posamentier et al. 1991), or sediment calibre coupled with the number of feeder canyons (Reading and Richards 1994). Concerted efforts were also made to compile results from numerous modern and ancient fan systems through the 1980s (COMFAN I and COMFAN II meetings), resulting in the publication of two seminal volumes (Bouma et al. 1985b; Weimer and Link 1991) that summarized the state-of-the-art and highlighted the wide variability in turbidite systems that exist in nature. These compilations provided a clearer picture of the basic building blocks of submarine fans, with Mutti and Normark (1991) describing a common suite of architectural elements in both modern and ancient turbidite systems that are still used today. Key elements included channel and closely associated overbank deposits (levees), a number of smaller scale features like scours and bedforms near the mouths of submarine channels (referred to as the channel-lobe transition), lobes, and mass transport deposits.

Coring in the 1980s and 1990s, in particular long cores collected during DSDP Leg 96 and ODP Leg 155, provided hundreds of meters of direct calibration through different parts of the Mississippi and Amazon fans, respectively. These cores confirmed the finer-grained composition and sedimentology of thick levees (e.g. Hiscott et al. 1997; Piper and Deptuck 1997), the coarser-grained composition (up to gravel size) of submarine channel deposits (Bouma et al. 1985a; Manley et al. 1997) and high amplitude reflection packages or ‘HARPs’ found at the base of many CLSs (interpreted to form in response to levee avulsions and the temporary loss of flow confinement; e.g., Pirmez et al. 1997; Piper and Normark 2001), as well as the generally muddy composition of large mass transport deposits (Piper et al. 1997).

The proliferation and improved imaging of 3D seismic data, particularly since the early 2000s, heralded a new era in submarine fan research. The concept of *seismic geomorphology* evolved from such data-sets (e.g., Cartwright and Huuse 2005; Davies et al. 2007; Prather et al. 2012). Not only did 3D seismic data provide stunning images of the modern seabed, but it also enabled interpreters to map buried surfaces, providing insight into how the geomorphology of submarine fans or their components evolved through time. Large 3D seismic volumes have also been used to demonstrate the importance of the shape and evolution of the receiving basin (e.g. Prather et al. 1998; Pirmez et al. 2000; Steffens et al. 2003; Adeogba et al. 2005; Ferry et al. 2005; Gee and Gawthorpe 2006), demonstrating that local variations in gradient trigger changes in the erosional or depositional behaviour of sediment-gravity flows (e.g. Mulder and Alexander 2001), and hence geomorphology.

In parallel with the widespread acquisition of 3D seismic data-sets, modern deep-towed sidescan sonar (e.g., Babonneau et al. 2002), multibeam data from autonomous underwater vehicles (AUVs) (e.g., Normark et al. 2009; Maier et al. 2013), and ultra-high resolution subbottom imaging tools capable of resolving m-scale beds (e.g. Piper et al. 1999; Deptuck et al. 2008; Maier et al. 2013), have provided some of the clearest images to date of modern fan systems (e.g. Figs. 1 and 3). These data-sets have enabled a new generation of targeted coring programs (e.g., Babonneau et al. 2004; Gervais et al. 2006; Pirmez et al. 2012; Jobe et al. 2015; 2016) and together should continue to narrow the resolution gap between modern turbidite systems and a new generation of detailed outcrop studies (e.g., Nilsen et al. 2007; Schwarz and Arnott 2007; Prélat et al. 2009; Hubbard et al., 2008) and flume tank experiments (e.g., Straub et al., 2008; Parsons et al. 2010; Fernandez et al, 2014).

3 Processes

Sediment that is ultimately delivered to a submarine fan via sediment-gravity flows may be stored temporarily near the shelf edge or along canyon margins, awaiting an array of potential triggering mechanisms. The triggering mechanism is important because it influences the volume, composition, and duration of individual flows, and may be modulated by sea level variations (Piper and Normark 2001). Once initiated, flow behaviour ultimately controls how coarse- and fine-grained material is partitioned into different fan settings, and is strongly influenced by the overall gradient (Normark and Piper 1991) and seabed morphology (Mulder and Alexander 2001), including the degree of channel-confinement. Sediment-gravity flows may be triggered by earthquakes, large storms or rip currents, or simply by sedimentation once a threshold in slope stability is exceeded (Normark and Piper 1991). Alternatively, rivers in flood may deliver sediment directly into canyon heads via hyperpycnal flows (Mulder and Syvitski 1995), a mechanism that may be most important during periods of low sea level or in systems with canyons that extend

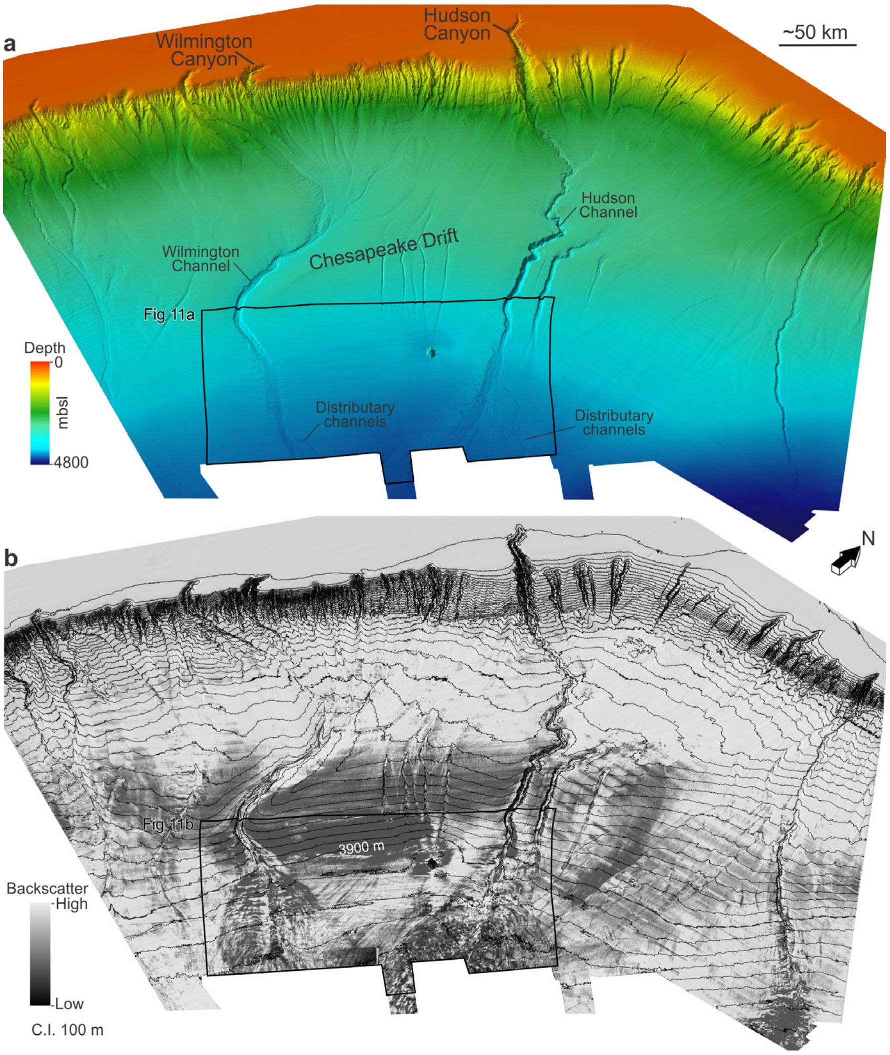

Fig. 3 Perspective view from the southeast showing **a** shaded-relief bathymetry and **b** backscatter (draped above bathymetry) from the continental shelf, slope, and rise off the northeastern United States (offshore Deleware, New Jersey, and New York). Heavily canyoned slope passes seaward into the Wilmington and Hudson submarine fans. Variations in the continental rise morphology, associated with a contourite drift, produced variations in the degree of channel entrenchment or diversion. An abrupt loss of channel-confinement near the 3900 m isobath coincides with a 0.5° decrease in gradient and a change to low-relief ephemeral submarine channels and scoured lobe deposits. Multibeam bathymetry data extracted from the National Geophysical Data Center (www.ngdc.noaa.gov/mgg/bathymetry). Data from the continental rise also available from the University of New Hampshire, Joint Hydrographic Center - Center for Coastal and Ocean Mapping (Gardner, 2004). Data gridded at 100 m and illuminated from the southwest. See also Sweeney et al. (2012) and Brothers et al. (2013)

across the shelf, providing a longer-term connection between the canyon head and river mouth. However, the large fluvial suspended sediment concentrations necessary for hyperpycnal flows to exceed the density of the saline seawater may make these events uncommon in larger low-gradient rivers (Mulder and Syvitski 1995).

The idea that sand-size or coarser sediment can be transported in the deep sea over longer distances by turbidity currents is only a few decades old (Kuenen and Migliorini 1950), but it is widely accepted today that submarine channels are carved, built, and maintained by these underwater density flows. The driving force that keeps turbidity currents in motion over large distances is the density difference between the sediment-water mixture and the surrounding seawater. Sediment in the current is kept in suspension mostly through turbulence, although it is likely that other processes play a role as well in their lowermost, high-concentration layer (e.g., Talling et al. 2015). Turbidity currents are highly stratified, with sediment concentration rapidly decreasing from a maximum value close to the bottom; the grain size of suspended sediment also decreases upward, so that sand or coarser sediment is commonly restricted to the lowermost part of the submarine channel. This produces predominantly fine-grained (mud- and silt-rich) levee deposits with coarser sediment restricted to the lower few tens of metres of the channel (Hiscott et al. 1997).

Another characteristic feature of turbidity currents is their velocity profile: in contrast with rivers, where the velocity maximum is very close to the water surface, the largest velocity in turbidity currents is somewhere between the upper and lower boundaries of the flow, often closer to the bottom (e.g., Peakall and Sumner 2015). The nature of the velocity profile has implications for the structure of secondary flow and resulting development of sinuosity in submarine channels. Some experimental and modeling work suggests that the direction of secondary flow is river-like (e.g., Imran et al. 2007; Abad et al. 2011). However, other experiments and field data indicate that the flow pattern in the lower part of the flow is reversed relative to that in rivers (e.g., Corney et al. 2008; Parsons et al. 2010). Regardless of the exact nature of the secondary flow and the role it plays in sediment distribution within channels, both geomorphologic and seismic stratigraphic observations suggest that the majority of submarine channels develop higher sinuosities through preferential preservation of deposits on the inner bank and long-term erosion on the outer bank (e.g., Deptuck et al. 2003; Sylvester et al. 2011; Maier et al. 2012; Kolla et al. 2012), much like in rivers.

In addition to turbidity currents, sediment gravity flows with higher sediment concentrations, such as slides, slumps, and debris flows, also play a role in the evolution of submarine channels. Large-scale sliding and slumping can cover or remobilize significant portions of a submarine fan (Piper et al. 1997). Smaller-scale slides are often present along channel margins and likely contribute to meander-bend erosion. In addition, larger-scale and more mobile debris flows can travel tens of kilometers downslope along the channel axis and can partially or entirely fill the channel with mass wasted material, in some cases with large blocks that were eroded upstream.

4 Morphology of Submarine Channels and Their Levees

Submarine channels may be stable and long-lived where they are entrenched into the seabed or flanked by aggradational wedge-shaped levees, or ephemeral where both levee heights and entrenchment depths are low. Their dimensions and architecture vary widely; in general, small fans are composed of smaller CLSs than larger fans (see also Skene 1998; Deptuck et al. 2003). The dimensions of CLSs probably scale with some combination of its lifespan and the volume, composition, and recurrence intervals of sediment gravity flows. In general, levees decrease in size and relief further away from their source as does the amount of erosion, if any, along its base (e.g., Fig. 4). However, enhanced erosion or sedimentation (particularly at the base of CLSs) may take place locally anywhere along the path of a CLS in response to changes in seabed morphology produced by underlying tectonic structures or preexisting sedimentary bodies like levees, lobes, or contourite drifts.

Most large, long-lived river-fed submarine fans (e.g., Amazon, Indus, Bengal, Zaire, and Mississippi) develop down-slope from a well-established canyon and are composed of a number of stacked submarine channels flanked by wedge-shape levees (Fig. 4). Successive CLSs originate through large-scale avulsions, as illustrated in Fig. 5. The location and frequency of avulsions varies within and between different fan systems (Kolla 2007); the surface expression of the Zaire Fan in Fig. 1 records fifty-two channel-levee-lobe systems, each developing in response to an avulsion that took place anywhere between the canyon mouth and the distal reaches of the fan (Picot et al. 2016). On the Indus Fan, some of the largest CLSs on Earth experience major avulsions near the canyon mouth, with successive CLSs heavily cannibalizing previous ones near the avulsion node. Preservation increases down system where individual CLSs are offset from each other by their thick wedge-shaped levees (Fig. 5). A closer view of the morphology of an upper fan avulsion on Amazon Fan is shown in Fig. 6a. The abandoned segments of CLSs down-slope from avulsion nodes remain largely inactive as sediment delivery is re-routed to other parts of the fan. As such, proximal avulsions have a greater impact on overall sediment routing than distal ones. Abandoned CLSs, however, may be resuscitated if they are intercepted and re-occupied by younger submarine channels, complicating fan geomorphology (e.g. Jégou et al. 2008; Jobe et al. 2015).

One of the most striking characteristics of many submarine channels is their pronounced sinuosity (Wynn et al. 2007). Braiding in submarine channels in contrast appears to be rare (Foreman et al. 2015). The discovery of highly sinuous channels on the surface of the Amazon Fan (Damuth et al. 1983) was a surprise and an important moment in the history of submarine geomorphology. Later bathymetric surveys and more recent three-dimensional seismic datasets across many submarine fans have shown that sinuous submarine channels are the norm, not the exception. While the sinuous planform patterns are quite similar to fluvial systems, aggradation rates in submarine CLSs can be more than an order of magnitude larger than those observed in rivers (Peakall et al. 2000; Jobe et al. 2016).

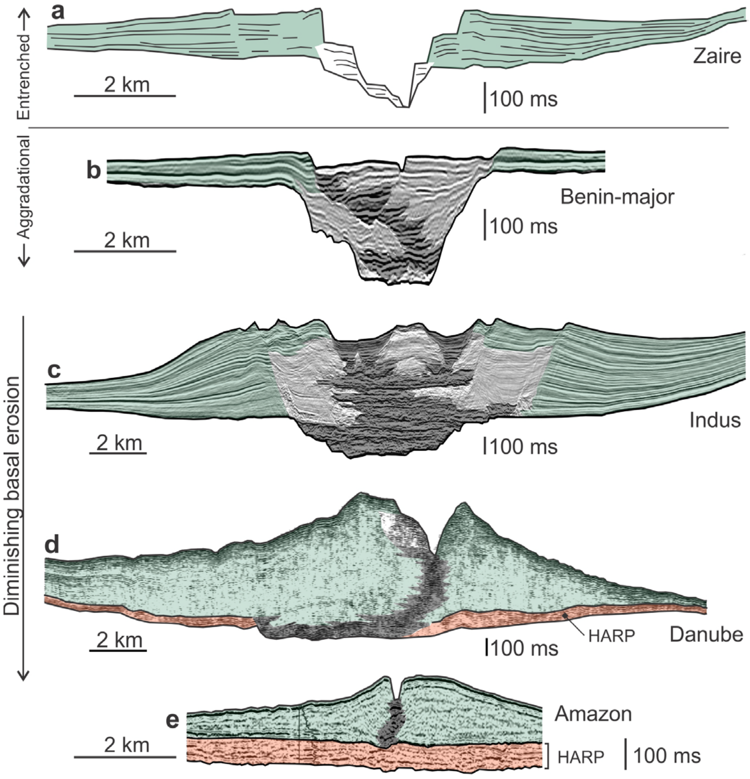

Fig. 4 Architectural variations in long-lived channel-levee systems (CLS). **a** Zaire Channel (redrawn from Babonneau et al. 2002); **b** Benin-major CLS, western Niger Delta slope (see Deptuck et al. 2012); **c** Indus Fan CLS C (modified from Deptuck 2003); **d** Danube CLS, Black Sea (Reprinted from Marine Geology, 179, Popescu et al., Late Quaternary channel avulsions on the Danube deep-sea fan, Black Sea, 2001, with permission from Elsevier); **e** Amazon Channel (Amazon Fan; Reprinted from Pirmez et al. 2000, with permission from GCSSEPM Foundation). In **a** to **c**, inner levees (*light grey*) are well-developed and are at least in part contemporaneous with outer levee deposits (*green*). Channel deposits shown in *dark grey*, and avulsion-related lobe deposits (HARPs - 'high amplitude reflection packages') are shown in *orange*. Diminished erosion near the base of the highly aggradational CLSs in **b** to **e** strongly influence their overall architecture

Individual submarine channels may be perched above the surrounding seafloor, flanked directly by the crests of relatively simple wedge-shaped levees (e.g. Figs. 4d, e and 6) or they may be flanked by much more complex deposits that form multi-tiered bench-like terraces adjacent to the active channel floor (e.g. Figs. 4a-c and 7). Measuring the width and depth of submarine channels is not as straightforward as in rivers, especially if multiple terraces are present. In general, however, submarine channels are wider, deeper, and steeper than their subaerial counterparts – their widths range from ~100 m to more than 10 km, their depths from a few metres to ~200 m, and their slopes cover the range from 0.0001 to 0.01 (Konsoer et al. 2013). Gradients along submarine channels can be up to two orders of

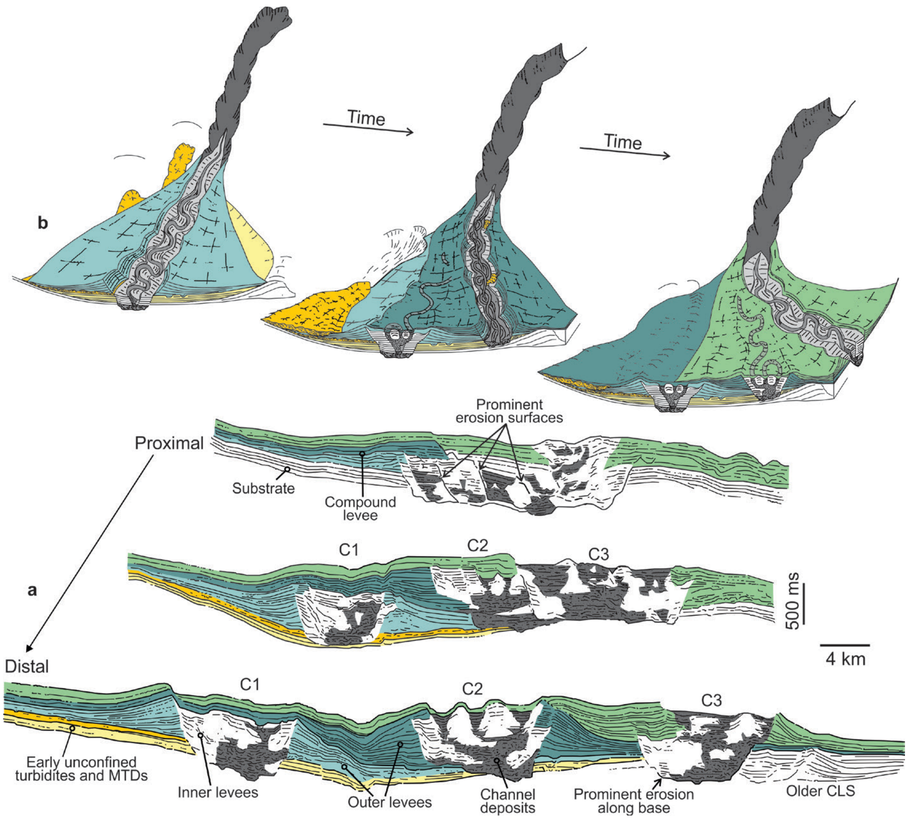

Fig. 5 **a** Three transects across part of the Indus fan – one of the largest submarine fans in the world – showing changes in fan architecture with increasing distance from the canyon-mouth. Highly self-cannibalized channel-levee systems (CLSs) with prominent erosive surfaces near the canyon-mouth pass down-system into well-preserved compensationally stacked CLSs, each bordered by prominent wedge-shaped outer levees with erosion limited to the base of each system. **b** Schematic illustrations showing a succession of upper fan avulsions on the Indus fan and resulting fan architecture. From Deptuck (2003).

magnitude steeper than rivers of similar size. The size of the channel bends scales with the overall channel size, according to a scaling relationship that is close to the one observed in the case of rivers (Clark et al. 1992). However, for the same meander wavelength, submarine channels seem to be wider than rivers (Pirmez and Imran 2003).

These differences in size and slope are due to the fact that the driving force per unit volume is smaller in the case of turbidity currents than in rivers, a consequence of the much smaller density difference between the low-concentration sediment suspension and ambient seawater. In addition, the majority of submarine channels, certainly the ones on large submarine fans, are fundamentally different from rivers in two aspects: (1) they commonly do not have tributaries and instead originate

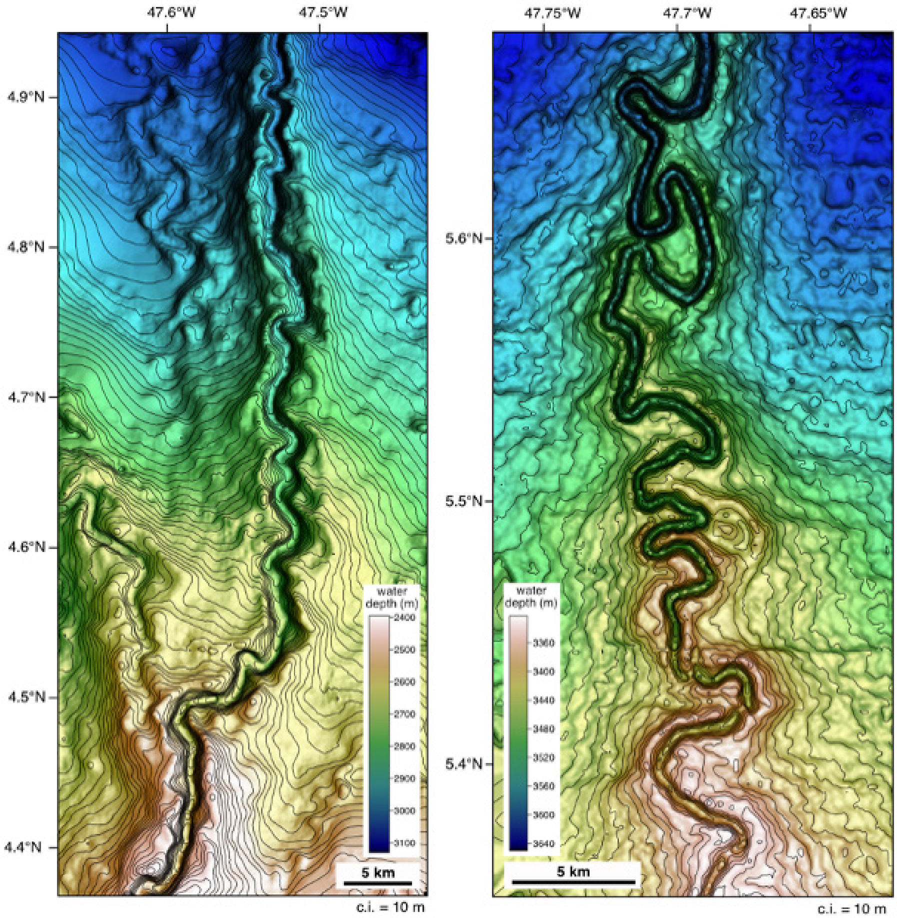

Fig. 6 Sinuous submarine channels on the Amazon Fan. **a** Avulsion on the upper fan (left), **b** Higher sinuosity and recent and incipient cutoffs on the middle fan. Bathymetry data from NOAA

from a single source, usually a canyon; and (2) their size systematically decreases downstream. There are notable exceptions: some of the largest submarine channels like the North Atlantic Mid-Ocean Channel (NAMOC; Klaucke et al. 1998) are fed by a number of tributaries, and some canyons (or channels extending from them) may intersect and re-occupy pre-existing channels, producing tributary-like channel patterns (e.g. landward parts of the Wilmington fan in Fig. 3a).

The decrease in width, depth, and channel cross-sectional area is the result of decreasing discharge towards the distal parts of fan systems as some of the sediment in the flow is deposited on the channel floor and levees (Pirmez and Imran 2003; Spinewine et al. 2011). The width and height of levees also decline in a downdip direction (Skene et al. 2002), allowing increasingly deeper parts of the turbidity current to spill and deposit sediment over the levees. This produces generally coarser-grained levees in the distal parts of CLSs (Hiscott et al. 1997).

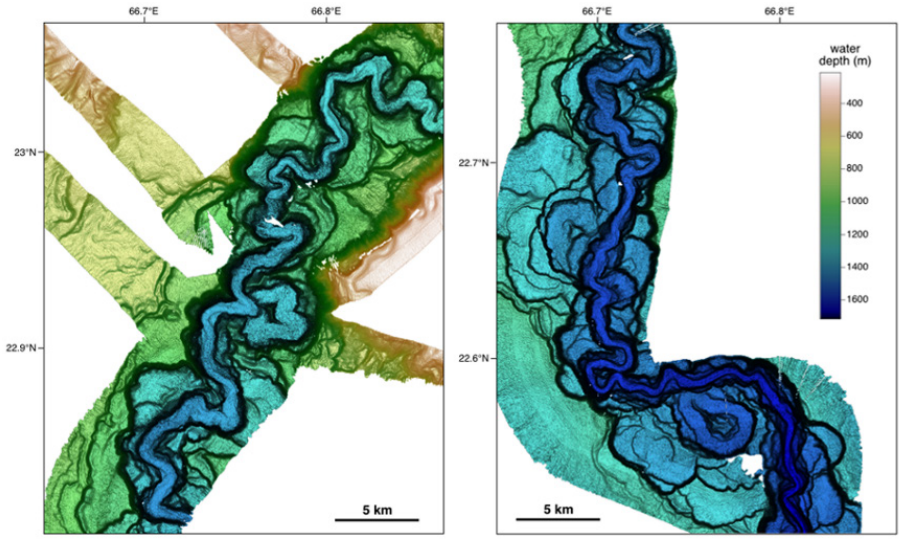

Fig. 7 Morphology of large channel-levee systems: the canyon-channel transition zone on the upper part of the Indus Fan, with terraces and cutoffs. Data from Clift and Henstock (2015).

Finer-Scale Geomorphic Features In addition to avulsions and their common sinuous planform geometries, the improved quality of seabed and shallow subsurface imaging tools reveals a number of other geomorphic features in leveed submarine channels like sediment waves (e.g. Normark et al. 2002), thalweg deposits like plugs (Deptuck et al. 2007), bars (Nakajima et al. 2009), and coarse- grained bedforms (Wynn et al. 2002b), and erosional features like scours, knickpoints and erosional terraces (Clark and Pickering 1996; Heiniö and Davies 2007; Micallef et al. 2014; Sylvester and Covault 2016), as well as a range of near-channel or channel-margin features including lateral accretion packages and inner levees (e.g., Abreu et al. 2003; Deptuck et al. 2003; Babonneau et al. 2004). These features provide clues about the finer-scale controls on channel-levee geomorphology.

Although the aggradation rates in CLSs are generally higher than in rivers, in some cases aggradation is preceded by a period of vertical incision that exerts a long-lasting influence on younger aggrading channels (e.g. Figs. 4b, c, 7, 8). Overbank deposits adjacent to these early aggradational channels are commonly confined within the initial incision and have been referred to as ‘inner levees’ to distinguish them from ‘outer levees’ that form outside of the erosional surface (Deptuck et al. 2003). Long-lived sinuous channel systems that aggrade within the initial incision commonly have complex morphologies and stratigraphic architectures, characterized by scalloped valley margins, draped terraces, and a complicated network of time-transgressive erosional surfaces (Sylvester et al. 2011). Fine-grained overbank deposits are commonly unable to erase earlier erosional products like cut-off loops, scalloped canyon margins, or different generations of inner levees, and as a result some aspects of the seabed geomorphology in channel systems reflect the draped expression of older submarine landforms that are no longer active (e.g. Figs. 7, 8). As such, it is important to consider *geomorphic inheritance* when deducing modern processes from seabed images.

Similar to many meandering rivers, the banks immediately adjacent to submarine channels are commonly asymmetric (e.g. Babonneau et al. 2002; Reimchen et al., 2016), with the steepest and highest bank coinciding with the cut-bank where erosion is focused (see Fig. 8c). The asymmetry in levee height also reflects increased overspill due to the inertia of flows as they adjust to sharp changes in channel orientation (Piper and Normark 1983). Asymmetry in some large CLSs has also been linked to the Coriolis effect where thick muddy flows are diverted to the right

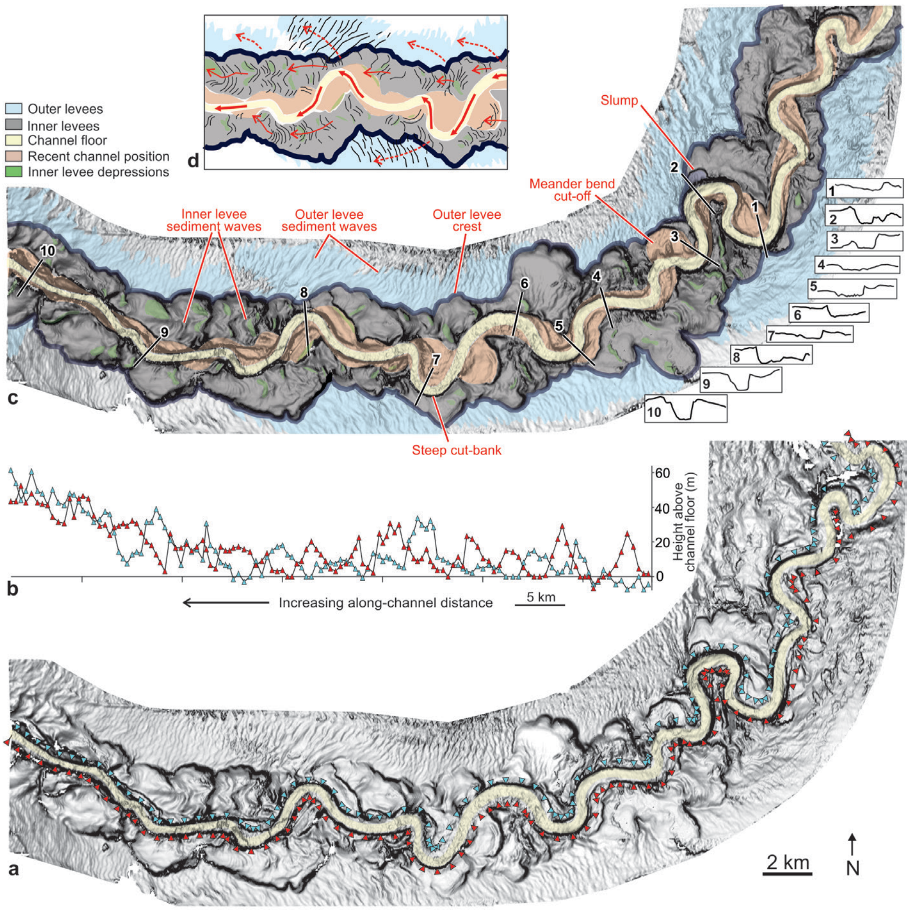

Fig. 8 a Dip map of the Benin Channel, western Niger Delta slope. Flow direction is to the left. **b** the left- and right-hand channel banks are highly asymmetric, showing the greatest elevation adjacent to cut-banks (see also Deptuck et al. 2007). **c** Dip map colour coded according to different submarine channel-levee settings, with representative channel cross sections. **d** Flow vectors inferred from the thalweg and the crests of both inner and outer levee sediment waves (facing down the channel) in the northern hemisphere (Klaucke et al. 1998; Popescu et al., 2001). Overbank deposits in some systems form distinct up-flow migrating sediment waves (Normark et al. 2002). These are most commonly reported in outer levee settings, particularly outboard sharp meander bends, but have also been recognized in inner levee settings (e.g. Deptuck et al. 2012). In some cases, rather that forming net depositional features, flows that overspill levee crests at sharp meander bends can be erosive, producing regularly spaced scours called cyclic steps that may be precursors to new submarine channels (Fildani et al. 2006).

The crests of sediment waves in Fig. 8 provide insight into variations in flow trajectory at different elevations above the channel thalweg (Fig. 8d) (see also Kane and Hodgson 2011). The deepest and coarsest material follows the most sinuous path along the channel floor. Finer-grained material carried higher up in the flow has contributed to inner levee sediment waves with crests generally normal to the overall channel-belt trend, but only loosely tied to the more sinuous channel thalweg. The more elevated parts of flows were guided by the confining crests of outer levees, but the relatively uniform, normal to oblique orientation of sediment wave crests on outer levees suggests that sediment carried at the highest elevation above the channel floor escaped confinement and travel obliquely away from the overall trend of the CLS.

Channel Initiation, Migration and Planform Adjustments In existing submarine channels, stratified sediment-gravity flows will contribute finer-grained material to the levees if the through-put flow is thicker than the channel banks, sustaining or increasing flow confinement unless the channel floor aggrades correspondingly. But how are submarine channels initiated in the first place? A number of studies have documented trains of up-stream migrating scours or bedforms, referred to as cyclic steps, that appear to be pre-cursors to at least some submarine channels (Fildani et al. 2006, 2013; Heiniö and Davies 2009; Kostic, 2011). Cyclic steps range from net-erosional to net-depositional features and also appear to be common on floors of established canyons and channels, particularly those with steep gradients (Covault et al. 2014; Hughes-Clarke 2016). Turbidity currents that shape these bedforms are relatively shallow and supercritical over the steep sides of the cyclic steps and undergo a hydraulic jump at the upslope end of lower-gradient sections (Kostic 2011; Hughes-Clarke 2016). Fildani et al. (2013) interpreted early linear channels to evolve through erosion and linkage of net-erosional cyclic steps (trains of scours).

The Lucia Chica channels in Fig. 9 provide several clues about the inception and subsequent development of submarine channels. The system consists of a single deeper, longer-lived and more sinuous feeder channel (inset B) that is replaced downslope by at least four separate lower-relief, ephemeral and less sinuous channels (near a subtle reduction in slope angle) that, in turn, rejoin a single deep channel 12 km further down the slope (inset A - where the gradient abruptly increases and a number of prominent knickpoints are evident; Maier et al. 2013). In settings where channels are preserved in early stages of their evolution, as in Fig. 9, there are indications that sinuosity develops gradually from straight channels or gullies (Gee and Gawthorpe 2007; Sylvester et al. 2012; Maier et al. 2013).

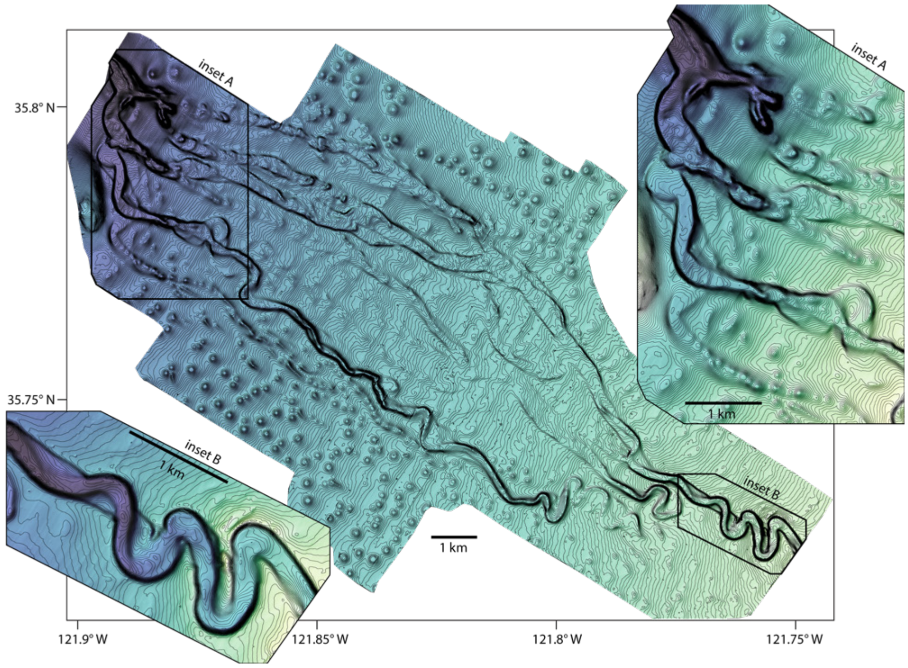

Fig. 9 Lucia Chica channel system, located off the central California coast, showing the diversity of low relief channel systems that developed above a lower-gradient step of the slope. There are multiple channel avulsions and channels with diverse morphologies that reflect, at least in part, the maturity of the channel. Flow from *lower right* to *upper left*. For more details see Maier et al. (2013)

The sharp contrasts in the geomorphology of immediately adjacent submarine channels in Fig. 9 – ranging from narrow and sinuous to wide and straight – probably reflect variations in channel maturity, with avulsions terminating the development of some channels before they could evolve more sinuous planform geometries (Maier et al. 2013). As such, the Lucia Chica system illustrates the connection between geomorphology and time; all else being equal, it takes more time (and more flows) for sinuous channels to develop than straight channels, and differences in channel lifespan (as measured by the number of transited flows prior to an avulsion) allows channels with very different morphologies to sit adjacent to each other on seemingly similar slope segments, or upslope and downslope from avulsion nodes.

A spectrum of depositional and erosional processes may explain how submarine channels migrate, ranging from the development of barforms on inner channel bends to alternating periods of cut-and-fill. In the latter, a period of vertical fill (e.g. emplacement of a debrite plug along a long channel reach) onlaps channel walls and raises the elevation of the channel floor without a corresponding change in the elevation of the channel banks or levee crests. Such events widen the channel floor and may prompt a stepwise change in channel migration and planform geometry during the passage of subsequent flows, and can lead to the development of chute-like cut-offs (Deptuck et al. 2007; Maier et al. 2012). In extreme cases, thick channel-plugging deposits may block the passage of subsequent turbidity currents (Bouma et al. 1985a), increasing the potential for major avulsions. In a number of fans, systematic patterns of channel migration, with signs of relatively gradual inner bend growth and lateral accretion, are increasingly evident on seismic profiles (e.g., Abreu et al. 2003; Sylvester et al. 2011; Kolla et al. 2012). Well-imaged examples are still rare, but it appears that both types of channel migration can be present at the same time; the longer-term result is deposition on the inner bend and erosion on the outer bend (Conway et al. 2012; Biscara et al. 2013). While meander cutoffs seem to be less common in submarine channels than in rivers (Peakall et al. 2000), their importance in long-lived, high-sinuosity systems is increasingly clear (Babonneau et al. 2004; Sylvester et al. 2011; Kolla et al. 2012; Jobe et al. 2015; Sylvester and Covault, 2016; Hansen et al. 2017).

Although there is a natural tendency for many submarine channels to develop and maintain high sinuosity, their planform geometry and cross-sectional shape can be strongly influenced by local tectonic deformation (Clark and Cartwright 2009; Mayall et al. 2010). For example, the relatively straight channel segment on the left side of Fig. 8 developed in response to amplification of an underlying fold, prompting both vertical incision and a decrease in sinuosity (Deptuck et al. 2007). This was accomplished through knickpoint migration (e.g., Pirmez et al. 2000; Heiniö and Davies 2007) as the channel adjusted to a new gradient profile.

5 Morphology of Submarine Lobes

Submarine lobes are deposited where turbidity currents exit channel confinement and lose competence or capacity to carry some or all of their load. This mostly happens at the channel-mouth where levee relief is low, but may also form in response to a local ‘en-route’ reduction in gradient (e.g. ‘transient fans’ described by Adeogba et al. 2005), or as an initial response to a channel-levee avulsion where the confining levee is eroded (e.g. ‘avulsion lobes’ or ‘HARPs’ described by Pirmez et al. 1997). Lobes are elongate low-relief features with gradients that usually do not exceed 1°. The distribution of lobe deposits at the seaward ends of submarine channels is closely linked to the channel-levee avulsion history in both large (e.g., Jégou et al. 2008; Picot et al. 2016) and small (e.g., Piper and Normark 2001; Deptuck et al. 2008) fan systems. The largest known submarine lobes are on the Amazon and Zaire fans and can reach several tens of km in length (Jégou et al., 2008; Picot et al. 2016), but represent relatively small features compared to the length-scale of the channels that feed them. Submarine lobes in smaller fans are volumetrically more important compared to the overall fan size (e.g. complex stacked lobes at the mouths of the South Golo channel in Fig. 10a).

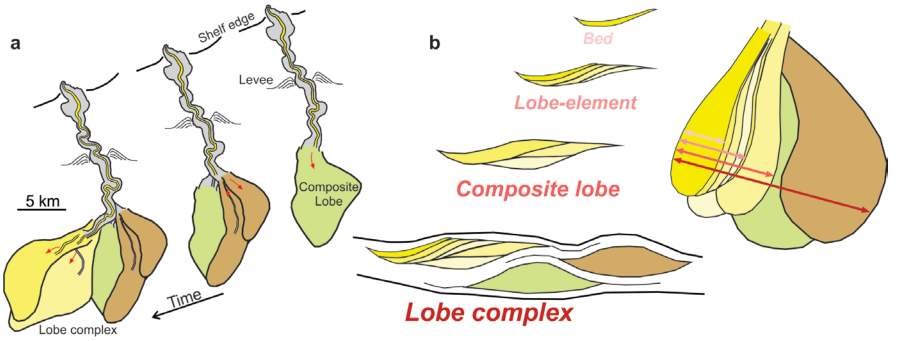

Fig. 10 **a** Development of the lobe complex seaward of the South Golo channel-levee system, offshore eastern Corsica, composed of three main composite lobes, each in turn composed of a number of higher-order lobe elements. **b** Schematic diagram showing the general hierarchy of compensation stacking in submarine lobes (terminology from Deptuck et al. 2008)

Within the same system, planview lobe dimensions correlate well with thickness (Deptuck et al. 2008), but the correlation does not hold well across a variety of systems, potentially due to a difference between entirely unconfined lobes and ones that are affected by the underlying basin topography (Prelat et al. 2010). Still, relatively little is known about the fine-scale internal structure and depositional history of large lobes like those of the Amazon and Zaire Fan. Lobe architecture is ultimately controlled by smaller-scale avulsions near the channel mouth that to varying degrees redirect sediment to different lobe settings. A number of hierarchies in lobe compensation stacking are evident (Fig. 10b). Individual beds or bed-sets stack to form lobe-elements; lobe-elements stack to form composite lobes; and composite lobes stack to form lobe complexes (Deptuck et al. 2008). The dimensions, shape, and architecture of lobe deposits reflect a number of interrelated factors including: flow properties (volume, duration, composition); the number flows and their degree of variation through time; sea floor morphology at the mouth of the leveed channel; and lobe lifespan prior to avulsion or abandonment (Deptuck et al. 2008). As in submarine channels, lobe lifespan is important because even very large fan systems supplied by large-volume turbidity currents like Amazon may not produce correspondingly large lobes if frequent avulsions prematurely terminate sediment delivery to the lobe (Prelat et al. 2010). In general, longer-lived lobes contain a larger volume of sediment, cover larger areas, are longer and have the potential to be architecturally more complex.

Finer-Scale Geomorphic Features Although submarine lobes are net depositional features, their finer-scale morphology is shaped both by erosion and sedimentation. Seafloor images (Decker et al., 2004) and extractions from 3D seismic data (e.g., Prelat et al. 2010; Oluboyo et al. 2014) reveal some of the finer-scale geomorphic characteristics of lobes, and suggest that many consist of an intricate network of bifurcating channels of decreasing dimensions. The depth of these ephemeral channels is commonly not more than a few metres and often less than 1 m (Decker et al. 2004). In Fig. 11, the change from confined to relatively unconfined

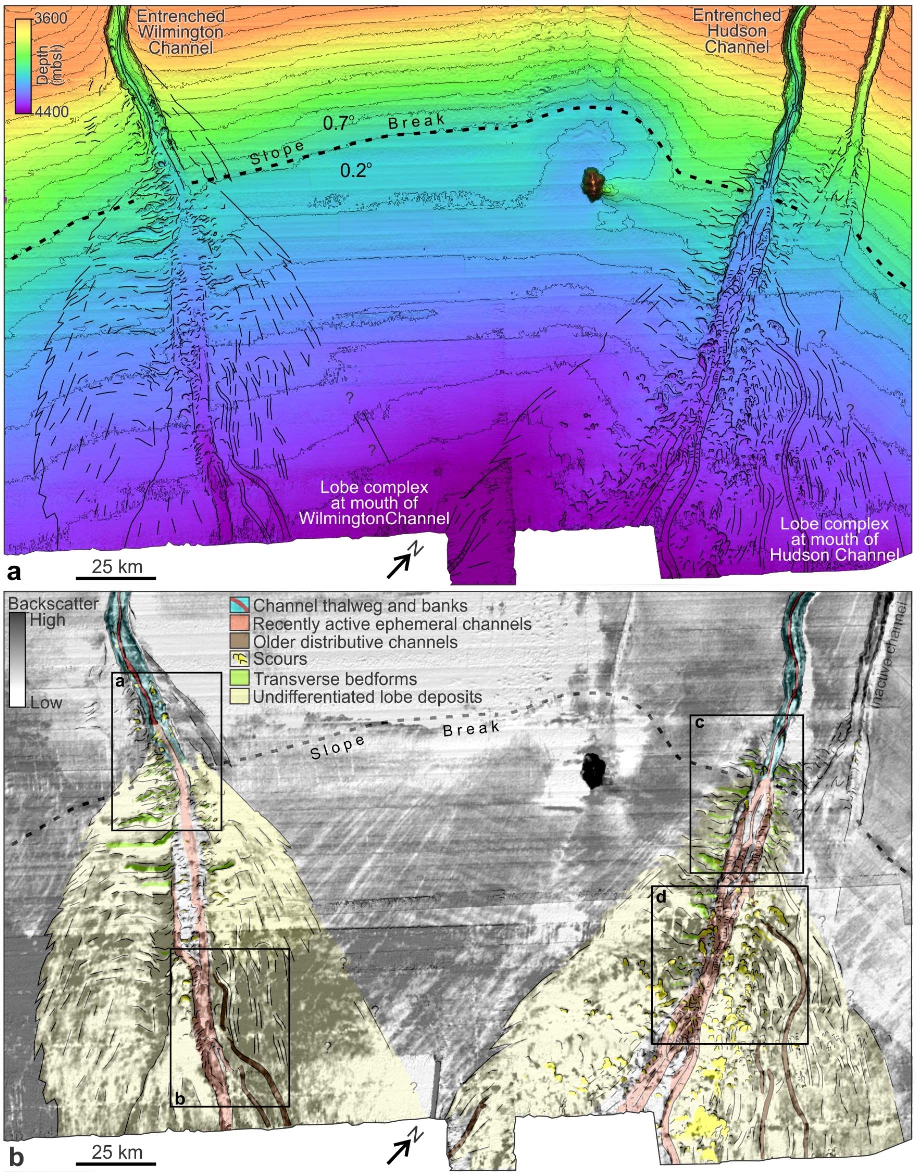

Fig. 11 Interpretation of geomorphic features near the channel-lobe transition seaward of Wilmington and Hudson channels. **a** bathymetry; **b** backscatter. See Fig. 3 for location. Data collected by the University of New Hampshire Joint Hydrographic Center (Center for Coastal and Ocean Mapping) (see Gardner, 2004)

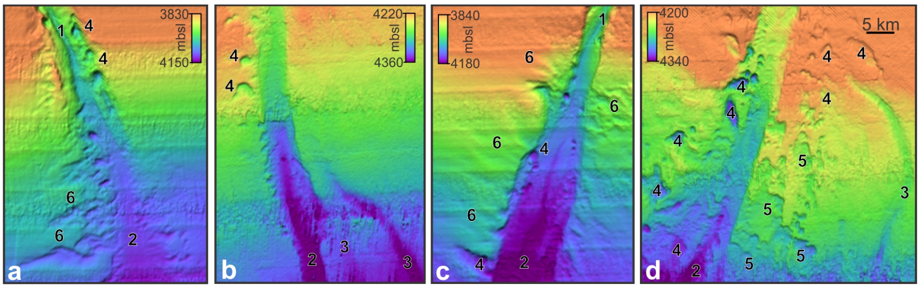

Fig. 12 Close-up multibeam bathymetric images near the channel-lobe transition of the Wilmington (**a**, **b**) and Hudson (**c**, **d**) fans. 1 – channel thalweg; 2 – recent lower-relief erosive channel; 3 – relict distributary channel; 4 – chevron to spoon-shaped scours; 5 – amalgamated scours; 6 – orthogonal bedforms (sediment waves). Location shown in Fig.11b

flows takes place where the gradient abruptly drops by 0.5°. A number of relict and more recently active channels are recognized near the channel-mouth, as are large-scale bedforms (Fig. 12). A number of spoon- to chevron- shaped scours are also present that locally amalgamate into broad erosive surfaces (Fig. 12d). Scours, in some cases exceeding 20 m deep and 2 km wide, are recognized near the channel-lobe transition zone in a number of submarine fans, and reflect the erosive behaviour of flows that undergo hydraulic jumps upon exiting channel-confinement (e.g., Piper and Normark 1983; Mutti and Normark 1991; Wynn et al. 2002a). In some instances, an abnormally large flow may erode and rework older lobe deposits as it continues towards more basinal settings, as may be the case in Fig. 11 where a number of wider, low-relief channels eroded even the distal parts of lobes (Fig. 12b).

6 Key Research Questions and Future Directions

Significant progress has been made over the past five decades in unravelling the geomorphology of submarine fans, particularly following the initial discovery of sinuous submarine channels on the Amazon Fan. However, only a small fraction of present-day submarine fans is covered with high-resolution bathymetric data, and our knowledge is even more limited when it comes to processes that govern the formation of these systems. Measurements of velocities and concentrations of large turbidity currents are difficult to obtain and are exceedingly sparse compared to what is available in the case of rivers (Talling et al. 2015). Recent direct observations of turbidity currents are very promising (Cooper et al. 2013; Hughes-Clarke 2016). The increasing utilization of autonomous underwater vehicles (AUVs) in the collection of multibeam bathymetry data, with repeat surveys, will certainly contribute to a larger and more diverse dataset of morphologies and to a better understanding of the associated processes (e.g., Covault et al. 2014). 3D seismic surveys have been and will be among the most important sources of information, as they also provide insight into how geomorphology translates into stratigraphy; and their resolution and quality will continue to improve, further reducing the scale gap between conventional surveys and fine-scale observations.

Some of the subjects that are still relatively poorly understood and form active areas of research include: (1) the concentration and degree of turbulence in the lowermost parts of turbidity currents; (2) the role of subcritical vs. supercritical flow and the types of bedforms linked to each; (3) relative importance of punctuated versus gradual meander bend growth and mechanisms responsible for the development of cutoffs in submarine environments; (4) mechanisms for sinuosity development and the nature of secondary circulation in submarine channels; (5) controls on the timing and location of channel-levee avulsions; (6) investigations of the full range of submarine channel geometries, including whether braided or multi-thread channels are present in nature; and (7) latitudinal controls and the influence of the Coriolis force on channel-levee morphology.

As these research topics advance, variations in submarine fan geomorphology – both between different modern systems and temporal changes within individual systems – will increasingly be used to constrain the flow processes responsible for building submarine fans (Peakall and Sumner 2015). Improved understanding of the links between process and geomorphology will likely lead to increased usage of geomorphology – and temporal changes in geomorphology – as kinematic indicators for reconstructing the deformation history of passive and active margin slopes. Finally, recent studies examining first-order scaling relationships between different segments of the sediment delivery and repository system (i.e. source-to-sink studies; Sømme et al. 2009) may provide the best approach for classifying the broad-scale morphology of submarine fans.

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