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DEEP-SEA FANS: TAPPING INTO EARTH'S CHANGING LANDSCAPES

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ABSTRACT: **Deep-sea fan sediments carry physical and chemical signatures that reflect the conditions under which their native landscapes evolved. Fans are long-lived, strongly net-depositional heaps of terrigenous debris, in some cases directly connected to a major river catchment. Here we use recent findings from deep-sea fans around the world to reason that modern fans might be our most continuous record of Cenozoic landscape change over large geographic scales. We opt for the use of multiple signatures that indicate major shifts in composition, because this approach avoids the problems inherent to measuring sediment flux alone. We emphasize the importance of looking across grain size, in particular at the clay fraction, the fastest carrier of sedimentary signals. Highlighted cases show the range of environmental signals preserved in deep-sea fans, observed over millennial and longer time scales, and how these signals help us understand the climate–surface interactions important to the carbon cycle. Revisiting legacy core with new techniques, in addition to future drilling campaigns, can provide the observational constraints needed to fill recognized gaps in climate models and landscape–erosion projections.**

INTRODUCTION

Our interest in the dynamic landscape has rightly accelerated in recent decades, as we work to understand the feedbacks between climate, uplift, weathering, and erosion and their impact on life. However, the very erosional processes we seek to understand are not only elusive but inherently destructive, making the continental sedimentary record essentially incomplete. Long-lived subaerial deposition over broad geography is relatively rare, and substantial hiatuses are common. In contrast, marine environments tend to be net-depositional over longer time frames and large physical scales and contain what we think is a more complete sedimentary record for use in the reconstruction of climate and other environmental fluctuations, as well as tectonic perturbations.

Deep-sea fans—the giant accumulations of sediment that display a characteristic fan shape at the termini of land-to-sea sediment-routing systems—are a natural receptor for environmental signals carried as part of the sediment load. This is because the growth of a large deep-sea fan more often than not depends on sediment flux from the continent through an associated fluvial system (Wetzel 1993; Sømme et al. 2009). Since their discovery and early study in the mid-twentieth century (Menard 1955; Heezen 1959; Shephard et al. 1969; Normark 1970; Nelson et al. 1970), however, fans have mostly garnered attention for their potential as petroleum systems, and the focus has been on their architecture and the distribution of sandy reservoirs for hydrocarbon accumulation (Bouma et al. 1985; Weimer and Link 1991; Piper and Normark 2001). Furthermore, there has been propagation of the idea that environmental signals are buffered across large drainages (e.g., Allen 2008), giving a sense that the distal settings of sedimentary systems may not preserve meaningful information about continental processes.

In this *Perspective* we propose that deep-sea fans are reliable sources of information on climate and landscapes over a variety of temporal and geographic scales. We now know that fans can accumulate sediment during a variety of climate scenarios, not just at glacial maxima and/or sea-level lowstands, and therefore contain a comprehensive stratigraphic record. Compared with the more transient fluvial, deltaic, and shelfal environments, deep-sea fans are truly terminal sites of deposition with high preservation potential. To unlock this largely unexplored record, we emphasize the use of multiple sedimentary signals, rather than a single focus on sediment supply or bulk sedimentation. We also counter the idea that continental signals are impossibly mixed across large drainages and along continental margins. We do so with the confidence of recent observations in several modern, coupled river-to-fan systems, described below. In short, due to their location at the termini of large source-to-sink systems and their fundamental net-depositional nature over long time frames, deep-sea fan deposits contain a wealth of proxy information about continental and atmospheric processes, including how tectonics, climate periodicity, and ice sheets have modulated the landscape.

A PRIMER ON DEEP-SEA FANS

Deep-sea fans are accumulations of clastic debris onto the lower continental slope and abyssal plain as a result of sediment gravity flows and other submarine mass movements. The terms "deep-sea fan" and "submarine fan" tend to be used interchangeably, because the fundamental processes that build them are basically the same. However, in this *Perspective* we discuss deep-sea fans as a subset, accumulating onto poorly confined seafloor below $\sim$ 1000 m water depth. This designation generally excludes fans that develop in other submarine settings like slope basins or fjords, because our interest here is in larger-scale terminal accumulations that capture sedimentary signals across broad geography.

Submarine and, specifically, deep-sea fans were defined for the first time more than half a century ago (Menard 1955). Their growth patterns were first comprehensively described by Normark (1970) as fan-shaped deposits of linked canyon–channel systems and lobes, with lobes being the

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FIG. 1.—Stylized map of the deep-sea fans (in yellow) mentioned in the text. A, Amazon; AT, Astoria–Tufts fans; B, Bengal; BT, Bounty; C, Congo; CB, California borderland fans; I, Indus; M, Monterey; MS, Mississippi; S, Surveyor; V, Var; VC, Veracruz. Select river drainages in green are associated with deep-sea fans: Mississippi, Amazon, Congo, Indus, and Ganges–Brahmaputra (Bengal fan). Major plate boundaries are marked by triangles (convergent) and dotted lines (divergent and transform). Mountain and water motifs are inspired by the maps of the world drawn by Al-Sharif al-Idrisi in the 12th century. The god Neptune rising from the South Pacific is a nod to Jacopo de'Barbari and his beautiful 16th century map of Venice. The modern-day scientific drilling ship *Joides Resolution* (not to scale) is used here for scale.

accumulations at system termini. As put by Mutti and Normark (1987), modeling the stratigraphic growth of fans can be like comparing the "wide variety of wines in the world by a single set of criteria." However, just as wines may be broadly sorted based on (1) grape color and (2) residual sugar, the gross characteristics of deep-sea fans are largely controlled by (1) basin configuration and (2) sediment supply (Mutti and Normark 1987), both factors dependent on the interplay between tectonics, climate, and sea level (Nelson et al. 2009). For example, the largest modern fan systems (e.g., Bengal, Indus, Amazon, and Mississippi) all sit mid-plate on stable oceanic crust and are extensions of major river systems (Fig. 1). At the other end of the spectrum are the relatively small and short-lived (10^4–10^5 years) fans that develop on continental crust along active margins with an intermittent sediment supply, like the modern Navy, La Jolla, and Redondo fans along the transform margin of the California Borderland (Haner 1971; Normark et al. 1979; Graham and Bachman 1983). Hybrid types include fans on oceanic crust that receive sediment from tectonically active catchments (e.g., Monterey and Astoria fans; Nelson 1976; Normark et al. 1983; Fildani and Normark 2004) and those on structurally controlled continental crust near a stable supply of sediment (e.g., exhumed Tertiary examples in northern Apennines and southern Pyrenees; Mutti 1985; Mutti et al. 1985; Ricci Lucchi and Ori 1985).

Within this larger context of basins and morphology, our focus in this paper is on the terrigenous provenance of fan debris, and the connection to continental processes (Fig. 2). We know that the bulk of sediment in deep-sea fans is delivered via sediment gravity flows or mass wasting. Conditions around the initiation and lifespan of these events vary widely (Piper and Normark 2009) but have been monitored in submarine canyons over human timescales (Gennesseaux et al. 1971; Paull et al. 2003; Xu 2011; Symons et al. 2017). Flows can be triggered by catastrophic failures due to seismicity (e.g., Heezen and Ewing 1952; Goldfinger et al. 2003) and storms (e.g., Inman et al. 1976; Mosher et al. 2004), or by more prolonged instabilities related to freshwater discharge (e.g., Wright et al. 1986; Mulder and Syvitski 1995; Normark and Reid 2003) and slope breaching (e.g., van den Berg et al. 2002; Eke et al. 2011). Sediments making up the largest fans on Earth may be dominated by fluvial input (Normark and Piper 1991; Curray et al. 2003; Bourget et al. 2013; Blum et al. 2018), while littoral circulation and/or canyon processes are more important along active margins (Paull et al. 2005; Covault et al. 2007; Romans et al. 2009; Covault and Fildani 2014).

Active growth of a deep-sea fan is localized at any given moment (Normark 1970). Each flow event can deposit sediment in its submarine channel(s) and as part of the levee–overbank and lobe connected to channels, with overall sedimentation rates and run-out length determined by flow volume and frequency and basin geometry. Because the termini of fans are largely unconfined, deposition will migrate laterally as sediment gravity flows seek, fill, and re-seek accommodation space. Inactive sectors of a deep-sea fan will be covered by a continuous hemipelagic and/or pelagic drape but otherwise have high preservation potential due to their terminal position well below erosive storm or sea-level processes, especially in areas without robust contour currents; exceptions could be fans deposited in areas of active contour currents such as offshore Brazil and New Zealand (Gomes and Viana 2002; Marsaglia et al. 2011) or the distal part of large fans like the Mississippi (Kenyon et al. 2002).

Rising sea level and climate change during the Holocene has reduced the fluvial supply to certain canyon–fan systems (e.g., Mississippi and Amazon). However, a number of fans have remained at least partly

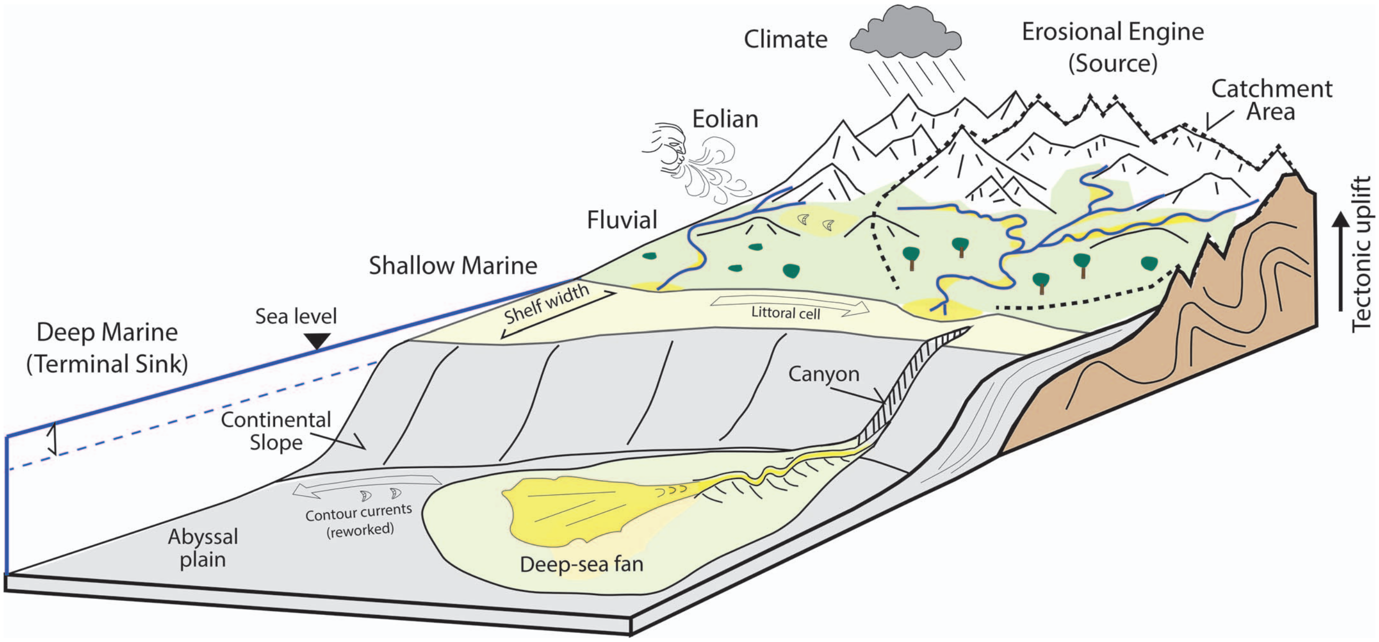

FIG. 2.—Key components of a sediment-routing system. Modified from Clark et al. (2017). A deep-sea fan may receive a significant part of its sediment from a linked catchment area, particularly where uplift and climate work together to enhance erosion. Ideally, this integrated pathway from source to terminal sink is defined as a sediment routing system. However, sediment can also be delivered to a deep-sea fan from outside the nearest catchment, via near-shore and shelfal (i.e., littoral cells) and/or eolian transport. These external processes can be extracted by detailed provenance work and show the limitation of defining older sediment routing systems using modern morphologies.

connected to a sediment routing system despite sea-level changes, including some active-margin fans in the California Borderland (Covault et al. 2007) and offshore southern Alaska (Reece et al. 2011) and New Zealand (Marsaglia et al. 2011), as well as stable-basin fans like the Congo (Picot et al. 2019), Bengal (Blum et al. 2018), and Indus (Clift et al. 2002). There are several possible scenarios for the delivery of sediment to the deep sea during sea-level high stands. For one, coarse fluvial sediment can be sequestered on a wide shelf (Fig. 2) while hemipelagic sediment continues to be delivered to the deep sea via muddy turbidity currents or suspension fallout of clays and/or eolian dust. Also, littoral transport along a narrow shelf can intercept drowned canyon heads (Fig. 2), thereby supplying longshore sediment to deep-sea fans. Whether sea level is high or low, growth of deep-sea fans does not require a large fluvial catchment as long as other conditions like uplift, volcanism, shelf width, and/or climate favor sediment production and delivery (Milliman and Syvitski 1992; Wetzel 1993; Covault et al. 2007; Hessler et al. 2018).

Deep-sea fans are constructed over a range of time scales. The world's largest fans—Bengal, Indus, and Amazon—have a total sedimentary record reaching back 15–30 million years (Clift et al. 2001; Curray et al. 2003; Figueiredo et al. 2009). Smaller, active-margin fans, like those along the western North American margin, are mostly Quaternary in age and hold records of Holocene climate events as recent as $\sim$ 3 ka (Romans et al. 2009). One large and ignitive density flow can deliver some volume of sediment through a submarine canyon and onto a deep-sea fan within hours to weeks (Hughes Clarke et al. 1990; Mulder et al. 1998; Piper and Normark 2009). However, estimates for recurrence intervals of high-magnitude Quaternary flows— those with the capacity to exit a submarine canyon and traverse an associated fan—range from $\sim$ 50 to $\sim$ 700 years (Savoye et al. 1990; Mulder et al. 1998; Fildani et al. 2006; Jobe et al. 2018). These observations suggest the potential to resolve, from well preserved fan turbidites, the changes occurring within centennial–millennial time frames, where intervening hemipelagic and pelagic intervals may provide additional information at even higher temporal resolution. All in all, deep-sea fans are strongly net-depositional over millennial to longer (10^7 years) time scales, with discrete but interfingering channel–lobe complexes that preserve, in aggregate, nearly continuous stratigraphy.

ENVIRONMENTAL SIGNALS

Here, an environmental signal is a function in sediment or sedimentary rocks that conveys information about a process that altered Earth's surface. Such signals encompass changes in sediment and solute production, erosion, transport, and/or deposition that were forced by near-surface factors like precipitation, uplift, subsidence, sea level, and biology. Propagation of an environmental signal through its medium, or sediment routing system (*sensu* Allen 2008), may be hampered in transit by storage opportunities (e.g., floodplains), but also could be amplified as like signals converge down-system. In the end, signals are nothing if not detected. Their preservation in a sedimentary system—as measurable quantities such as volume and composition—depends on finding a final resting spot (e.g., delta, deep-sea fan) before these quantities decay.

Beyond Sediment Supply

Nearly all discussion around signal propagation focuses on sediment supply (Q_s) (see Romans et al. 2016). In terms of landscape evolution, this is the total volume of sediment liberated by erosion and discharged through a transfer zone (i.e., fluvial system) into a depositional sink. In a perfect world (numerical or experimental set-up), we want to see that a certain volume of sediment eroded from a landscape during a system-wide event has been transferred downstream and deposited into a basin within a predictable response time. Perfection is the enemy of good, however, and nature uses many strategies to render Q_s a cryptic measure. Long-term storage in a floodplain or sluggish bedload will damp Q_s and increase response time to an external trigger (Allen 2008). Furthermore, sediment flux for a particular catchment can be distorted by along-strike atmospheric (i.e., eolian) input–output (Fig. 2). Bed thickness, a one-dimensional proxy for Q_s, often says more about spontaneous avulsions than systemic events, as observed in both outcrop (Hajek et al. 2012; Prelat and Hodgson 2013) and models (Trampush and Hajek 2017; Burgess et al. 2019). There is also the self-limiting relationship between sediment yield and transport capacity, where high yield inhibits capacity and does not necessitate high discharge (see Congo fan example; Picot et al. 2019).

Looking at signals other than Q_s opens up all kinds of opportunities. More than volume alone, sediment composition gives detailed information about a variety of environmental conditions, such as weathering, the exposure of certain rock types, and river routes. This kind of information in most cases transcends Q_s and the problem of shredded signals (Jerolmack and Paola 2010), because most compositional shifts are attributed not to autogenic processes but to large systemic changes. Finally, with composition signals we are not tethered to the downstream arrival of a certain volume of sediment. We can assess the character of what sediment does arrive—the imperfect beauty of natural systems is that at any given moment, there is always some sediment passing through.

Across Grain Size

The sand and mud in a deep-sea fan tell unique, only partly overlapping stories about the upstream environment. Most attention has been given to the sand fraction, specifically its zircon population, in order to understand the geography of the sediment source area. Detrital-zircon datasets have supplied critical insights into hinterland tectonics, drainages, and climate, and the number of zircon analyses has continually increased (Vermeesch 2004; Anderson 2005; Pullen et al. 2014; Saylor and Sundell 2016) to achieve higher and higher confidence that the resulting age distribution accurately describes a sample's provenance. In reality what is being very accurately described is some fraction of provenance, because the single focus on zircons has inherent bias toward zircon-rich terranes (i.e., zircon fertility; Moecher and Samson 2006; Malusà et al. 2016) and those with certain-size crystals (Heitpas et al. 2011; Ibañez-Mehia et al. 2018). As it should, sandstone petrography has been long used in provenance analysis (Dickinson 1970 and countless others). Still, an emphasis on sand does filter one's view to the most resistant minerals and lithic fragments coming off a source.

It is a missed opportunity to ignore the finer fractions. First, most stratigraphy is fine-grained, in the deep sea and elsewhere. Second, a number of common rock types (i.e., basalt, shale, phyllite) weather entirely to clay and solutes under most conditions. Third, the downstream partitioning of grain sizes is a normal consequence of fluid dynamics (Seal et al. 1997; Strong et al. 2005; Allen et al. 2016), with mud more likely to survive transport across large drainages and into deep-sea fans. And finally, clays and organics move relatively quickly through fluvial systems, and as much as 25% of a tropical river's suspended-sediment load will ultimately be transferred to its associated deep-sea fan (Wetzel 1993). Clays therefore tend to be the first signal-carrying particles to reach a basin following an environmental shift. For instance, along the northernmost fringe of the now-buried Veracruz fan in the western Gulf of Mexico (Fig. 1), the first appearance of sediment coming from glaciated North America was observed as an inorganic geochemical shift within a 200-meter-thick section of early Pleistocene mud, roughly 50 meters below the first appearance of sand (Hessler et al. 2018). For the Holocene or older interglacial periods, the clay fraction may often be the only option for measuring high-resolution climate or paleogeographic signals. In both the Bengal and the Indus fans, for example, coarse terrigenous material is sequestered on the shelf during sea-level high stands while hemipelagic particles continue to reach the fan through muddy turbidity currents, and suspension or eolian fallout (Milliman et al. 1975; Prins and Postma 2000; Maslin et al. 2006; Blum et al. 2013).

Terrestrial organic carbon, whose burial in deep-sea fans impacts the global carbon cycle (Leithold et al. 2016), is another fine-grained environmental marker that can be rapidly transferred to the deep sea with almost no degradation or dilution by marine organic carbon, as in the case of the Bengal (Galy et al. 2007, 2013) and many other fans (e.g., Nelson 1976). We can also make use of the non-terrigenous sediment deposited on a wholly or partly inactive fan, as a link between the stratigraphic records from distal or pelagic environments and the continental margins. In one of the first studies to make this connection in a tectonically active setting, Castelltort et al. (2017) looked at stable carbon isotopes in hemipelagic marls intercalated with sandstone turbidites to track the importance of eustasy and climate versus uplift on sediment supply to the Eocene Ainsa basin in the Spanish Pyrenees.

CONNECTION TO THE LANDSCAPE

Many deep-sea fans receive much of their sediment via a connection to a major drainage system, and therefore can record landscape changes occurring over large geographic scales. The sediment in a fan represents a composite view of the many local events happening across a catchment (and margin) within a given timeframe, including uplift, weathering, erosion, and transport (Fig. 2). Below we touch on how signals from these types of events are detected in deep-sea fans around the world.

Sediment Origins: Terranes and Terrain

Most simply, a deep-sea fan is the terminus of a sediment routing system (Fig. 2). A fan contains the end products of erosion of the terrane(s) underlying its correlative catchment, some of which may be buried or missing from the terrestrial rock record. Lower-frequency ($\sim 10^6$ yr) provenance signals, especially in ancient fan deposits (i.e., turbidites), have long helped reconstruct now-obscured tectonic and volcanic events (e.g., Dickinson and Rich 1972; Fildani and Hessler 2005; Hessler and Fildani 2015). The stratigraphic record of the largest modern fan on Earth—the Bengal—reaches back to the late Oligocene and the middle phase of India–Asia collision and Himalayan growth (Curray et al. 2003; Clift et al. 2008; Krishna et al. 2016). Recent IODP coring in the Bay of Bengal penetrated > 1000 meters below the seafloor (mbsf) into early Miocene turbidite deposits (France-Lanord et al. 2016), providing a potentially highly resolved record over ~ 18 million years. New detrital-zircon ages from 25 sands and silts shows geologically rapid signal transfer from exhumed Himalayan sources across > 4000 kilometers to the deep-sea fan, as well as discrete events related to Plio-Pleistocene exhumation of the eastern Himalayan syntaxis and the integration of the Brahmaputra drainage with Asia during the Miocene (Blum et al. 2018).

Along seismically prone margins, but particularly those with high sedimentation rates (Piper and Normark 2009; Atwater et al. 2014), deep-sea canyon–fan deposits can help constrain earthquake recurrence intervals based on seismo-turbidite frequency, as along the Cascadia and Ionian margins (Goldfinger et al. 2003; Nelson et al. 2012; Polonia et al. 2017). Regional volcanic activity can readily be signaled in deep-sea deposits by the presence of syndepositional zircon grains or other volcanic material, like the occurrence of Holocene Mazama ashes in the Astoria fan (Nelson et al. 1968) and Miocene zircons from southern Mexico > 600 kilometers offshore in the Veracruz fan (Hessler et al. 2018).

We can also get information about terrain—the breadth and geomorphology of an existing catchment and any major changes due to erosion and/or glaciation. Recent observations from the Amazon (Mason et al. 2019), Mississippi (Fildani et al. 2016; 2018), and Bengal (Blum et al. 2018) deep-sea fans all make the same point: these fans capture sediment from the whole of their associated catchment (Fig. 1), thereby faithfully recording changes to the whole or any subset of that catchment. For instance, over millennial to longer (10^3–10^4 yr) time frames, glacially driven changes across the enormous Mississippi catchment have been observed in detrital-zircon patterns for latest Pleistocene turbidites of the Mississippi fan (Fildani et al. 2016; Mason et al. 2017), where U-Pb crystallization ages and U-Th/He uplift ages point to geologically rapid influxes of sediment eroded from the Superior terrane along the retreating Laurentide ice front. Likewise, zircons in Pleistocene sands of the Amazon fan reveal differential incision and flux across the Amazon basin while sea level and onshore hydroclimates changed at glacial–interglacial transitions (Mason et al. 2019). As we discuss here, the aptness of a modern deep-sea fan—as the end product of turbidity currents—to integrate sediment eroded from large drainages validates the many decades of work on the provenance and regional significance of turbidites.

Sediment Production: Weathering and Climate

As mentioned earlier, sediment supply (Q_s) has been the favored signal for landscape changes related to climate and/or hydrologic discharge. There is significant debate around Q_s as appropriately sensitive to external forcing, or at times obscured by background variation or spontaneous intrabasinal events (i.e., autogenic noise; see summary in Romans et al. 2016). However, some deep-sea fans show sedimentation patterns that are clearly linked to upstream sediment supply rather than spontaneous lobe switching or progradation. The Holocene Hueneme fan offshore California, U.S.A., demonstrates a particularly rapid ($\sim$ 2000 kyr) Q_s response to increasing sediment discharge related to intensifying El Nino–Southern Oscillation events (Romans et al. 2009). Channel avulsions on the Congo fan over the last 210 ka have been linked to 1–5 kyr humid–arid cycles controlled by the West African monsoon (Picot et al. 2019). The high-latitude Surveyor Fan in the Gulf of Alaska (Fig. 1) preserves a dramatic increase in sedimentation rate across the Mid-Pleistocene Transition ($\sim$ 1200 to 600 ka), a direct consequence of accelerated glacial erosion of nearby mountains with lengthening ($\sim$ 100 ky) and intensifying glacial cycles (Gulick et al. 2015).

Composition signals can transcend Q_s where autogenic process dominate sediment supply. Various geochemical and mineralogical markers extracted from clastic sediment will reflect chemical processes in the source region (Fig. 2). This is because sediment is produced as bedrock minerals decompose into resistate grains and secondary clays. The degree to which the sediment diverges from the original bedrock composition depends on the degree of chemical weathering, related positively to precipitation and temperature at higher erosion rates (Nesbitt and Young 1989; Riebe et al. 2004; West et al. 2005; Hessler and Lowe 2017). The bulk of the chemical and mineralogical changes occur in a soil profile (Johnsson and Meade 1990; Le Pera et al. 2001; Scarciglia et al. 2007; Hessler and Lowe 2017) rather than during transport, except in cases of rapid mechanical erosion (Lupker et al. 2012). Therefore, we can look at the mineralogy and geochemistry of transported sands and clays in terms of their maturity (i.e., abundance of mobile versus immobile elements) to say something about climate and chemical weathering in the source region.

Among other measures, the Chemical Index of Alteration (CIA; Nesbitt and Young 1982) for clay and the Mineral Index of Alteration (MIA; Johnsson 1993) for sand are used to quantify the loss of mobile elements and minerals relative to immobile elements and resistant minerals, respectively, during the *in situ* chemical weathering of bedrock. These and similar metrics have been successfully applied in distal, marine deposits in recent years (e.g., Hessler et al. 2017; Zhao et al. 2018), including deep-sea fans (Fildani et al. 2018; Picot et al. 2019). Fildani et al. (2018) identified CIA/MIA patterns in the Mississippi fan that followed climate trends across Marine Isotope Stages (MIS) 2–5. In the case of the Congo fan (Fig. 1), pollen and kaolinite/smectite ratios suggest that fluvial discharge and down-fan progradation increased during higher-intensity West African monsoons over the last $\sim$ 40 kyr (Picot et al. 2019).

Sediment Transport: Ice, Rivers, Longshore, and Wind

Deep-sea fans also preserve information about the overland routes taken by their sediment load, which in turn can say a lot about the geomorphology and climate of their associated drainage basin (Fig. 2). The Tufts deep-sea fan off the Cascadia margin (Fig. 1) contains enormous volumes of sediment linked to glacial-lake outbursts during North America's latest deglaciation, the same events that eroded the northwest U.S. scablands (Brunner et al. 1999; Zuffa et al. 2000; Normark and Reid 2003). Similarly, the composition of the latest Pleistocene Mississippi fan sediment (Fildani et al. 2018) suggests that the Missouri River was mostly absent from the drainage from ca. 70,000 to 20,000 years ago, either diverted or dammed by the Laurentide ice front. The active-margin Bounty fan offshore New Zealand (Fig. 1) received no sediment for $\sim$ 8 million years across the Miocene–Pliocene transition due to the tectonic routing of rivers into transpressional lakes; geochemical weathering patterns and mineralogical provenance indicators in fan sediments reflect the post-hiatus flushing of lacustrine deposits through re-established river systems (Marsaglia et al. 2011). From zircons in Plio-Pleistocene sands of the Bengal fan, Blum et al. (2018) discerned that the Ganges and Brahmaputra sediment loads were mostly merged downstream via high-frequency delta-plain avulsions, thereby delivering a composite provenance signal offshore. Transform-boundary fans of southern California (Fig. 1) demonstrate how the delivery of sediment to canyon heads can occur through direct fluvial connections or littoral transport (Fig. 2), depending on shelf width, sea level, and fault movements (Covault et al. 2007; Romans et al. 2009; Covault et al. 2011). Complex continental shelf dynamics (i.e., longshore drift) could favor sediment transport and/or storage on the shelf, and its eventual disposal into canyons and on to deeper waters (Fig. 2). Robust shelf circulation has been documented along the California Borderland (Covault et al. 2007) and Australia (Boyd et al. 2008). Although canyons intercepting these littoral cells appear to play an important role, canyon sediment storage and flushing (Paull et al. 2005; Covault and Fildani 2014) ultimately controls sediment transfer into the deep.

Sediment input to the deep-sea can at times be dominated by processes related to wind and ice. Hemipelagic clays in the Indus fan show that eolian dust from the Arabian Peninsula came to dominate over turbidite deposition during Holocene warming and sea-level rise (Prins and Postma 2000). And Pleistocene sediment in the Surveyor Fan was derived directly from glaciers that flowed off the St. Elias Mountains and carved troughs and sea valleys across the Alaskan shelf (Reece et al. 2011).

ANTHROPOGENIC IMPACTS

Humans have clearly modified the landscape, as farming over the last millennium may have made us Earth's "premier geomorphic agent" (Hooke 2000). The effects include a several-fold increase in cropland erosion over pre-settlement rates, and a shift from erosion at mostly high elevations to low elevations (Wilkinson and McElroy 2007). On the flip side, dam construction across the upper reaches of large drainages like that of the Mississippi (Meade and Moody 2010; Heimann et al. 2011) has had a negative effect on sediment supply to some continental margins over the last century (Palanques et al. 1990; Blum and Roberts 2009; Bentley et al. 2016). No one can know to what degree the geologic record will preserve our influence. But whether or not we earn "Anthropocene" status, there are early signs that our impact is being felt in the sediment flux to deep-sea fans. Detrital-zircon patterns in late Holocene sands of the Mississippi fan suggest a higher pre-dam influx of Missouri River sediment compared to what reaches the lower Mississippi River and delta today (Mason et al. 2017). A $<$ 1-meter-thick turbidite across the Var canyon–fan system (Piper and Savoye 1993) is the sandiest Holocene deposit and was the result of a submarine landslide induced by construction activities at the

Nice airport in 1979, which also caused a tsunami and the deaths of 11 people (Mulder et al. 1998).

We see already the arrival in the deep ocean of our own synthetics and pollutants. The first documentation of the pesticide DDT in deep-ocean (> 3000 m) sediment was made in the Monterey canyon–fan system and indicates the relatively rapid transfer of fine-grained fluvial sediment to the deep sea after 1944–1972 (Gwiazda et al. 2015). This is not unexpected, as rivers are the ultimate sewage system in every society. More than 90% of plastic waste in the ocean derives from just ten rivers (Schmidt et al. 2017) and at least two of these rivers—the Ganges and Indus—are known to feed material directly to submarine canyons and large deep-sea fans. In fact, of the various ocean environments, submarine canyons trap the most microplastics and other marine litter; also, marine trash is more abundant on the abyssal plain than along the continental shelf (Kane and Clare 2019). It appears that human-generated debris is seeking—and finding—the termini of source-to-sink systems well within human time frames, fueling our inclination that naturally eroded sediment may be capable of the same.

DIRECTIONS

The international efforts in climate assessment and modeling have produced clear insights into global and regional change, and nearly constant reflection on how to improve the models themselves. A recognized gap in climate projections is the limited understanding of the sensitivity of Earth surface processes to global atmosphere and hydrosphere changes (IPCC 2013), partly due to up-scaling problems as well as a long-held assumption that the relevant geologic processes (e.g., weathering, erosion, and sediment burial) are not responsive over human timescales (see perspective by Knight and Harrison 2013). However, we observe short-term natural and anthropogenic forcings in deep-sea fan sediments. We consider these results an indication that (1) the landscape is indeed a sensitive part of the global carbon cycle, and (2) that deep-sea fans may preserve a helpful record of short-term change averaged over potentially large catchment areas. These are the types of geologic constraints needed to better understand climate-landscape feedbacks within a range of conditions, and to begin to make predictions about future erosion and sedimentation patterns across Earth's varied geography.

To gather these observations, a sensible first step is to look back over legacy core, some of it untouched since collected and analyzed decades ago. For instance, some of the first cores drilled by the Deep Sea Drilling Project (DSDP; predecessor to today's International Ocean Discovery Program (IODP)) recovered distal terrigenous Miocene–Pleistocene sand and mud on the Veracruz fan (Fig. 1; Ewing et al. 1969), but these cores were not reopened until nearly 50 years later (Hessler et al. 2018). All in all, the IODP and other scientific cores are an underutilized resource that can be accessed at virtually no further cost, financial or environmental. The original work on these and other cores was groundbreaking and insightful, but it is a missed opportunity to not look at them again through new techniques and theoretical frames.

Moving forward, with advanced drilling we have the opportunity to sample at greater sub-seafloor depths, thus capturing earlier parts of the geologic record (e.g., mid-Pliocene warm period) that are analogs for future change. We should revisit fans like the Mississippi, which was drilled in 1983 and recovered latest Pleistocene turbidites (Bouma et al. 1985), but together with its neighboring Bryant fan (Tripsanas et al. 2007) contains a storehouse of sediment shed off North America during dramatic climate shifts like the Plio-Pleistocene and mid-Pleistocene transitions. And fans like the Nile and Congo have not yet been explored by an international organization like IODP but have strong potential to preserve millennial and longer anthropogenic and African monsoonal change. While deep-sea drilling does not come without risk, the comprehensive information gained from a few holes on a large fan may provide—compared to widespread surface monitoring or sampling—adequate observational constraints at lower environmental and efficiency costs.

SUMMARY

The climate–land relationship is a significant component of Earth's carbon and other cycles. However, direct evidence of surface processes in terrestrial deposits is intermittent due to erosion. More and more, we are looking for evidence of subaerial conditions in distal marine deposits like those of deep-sea fans, often the termini of sub-continental-scale sediment routing systems. Fans across the globe contain physical and chemical signals for various environmental conditions, such as bedrock weathering, drainage patterns, aridity, tectonism, and ice-sheet dynamics. These signatures demonstrate a level of sensitivity and transport efficiency that runs counter to earlier thinking about signal propagation across large systems. We encourage looking beyond sediment flux, particularly at measures related to chemical composition across all grain sizes. All in all, we consider deep-sea fans a comprehensive but underutilized record of Cenozoic environmental change, providing the physical constraints needed to model and predict future scenarios.

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