Hybrid turbidite-drift channel complexes: An integrated multiscale model

A. Fuhrmann¹, I.A. Kane¹, M.A. Clare², R.A. Ferguson¹, E. Schomacker³, E. Bonamini⁴ and F.A. Contreras⁵
¹Department of Earth and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL, UK
²National Oceanography Centre, European Way, Southampton SO14 3HZ, UK
³Equinor, Martin Linges vei 33, 1364 Fornebu, Norway
⁴Eni Upstream and Technical Services, Via Emilia 1, 20097 San Donato Milanese, Milan, Italy
⁵Eni Rovuma Basin, no. 918, Rua dos Desportistas, Maputo, Mozambique

ABSTRACT

The interaction of deep-marine bottom currents with episodic, unsteady sediment gravity flows affects global sediment transport, forms climate archives, and controls the evolution of continental slopes. Despite their importance, contradictory hypotheses for reconstructing past flow regimes have arisen from a paucity of studies and the lack of direct monitoring of such hybrid systems. Here, we address this controversy by analyzing deposits, high-resolution seafloor data, and near-bed current measurements from two sites where eastward-flowing gravity flows interacted with northward-flowing bottom currents. Extensive seismic and core data from offshore Tanzania reveal a 1650-m-thick asymmetric hybrid channel levee-drift system, deposited over a period of ∼20 m.y. (Upper Cretaceous to Paleocene). High-resolution modern seafloor data from offshore Mozambique reveal similar asymmetric channel geometries, which are related to northward-flowing near-bed currents with measured velocities of up to 1.4 m/s. Higher sediment accumulation occurs on the downstream flank of channel margins (with respect to bottom currents), with inhibited deposition or scouring on the upstream flank (where velocities are highest). Toes of the drift deposits, consisting of thick laminated muddy siltstone, which progressively step back into the channel axis over time, result in an interfering relationship with the sandstone-dominated channel fill. Bottom-current flow directions contrast with those of previous models, which lacked direct current measurements or paleoflow indicators. We finally show how large-scale depositional architecture is built through the temporally variable coupling of these two globally important sediment transport processes. Our findings enable more-robust reconstructions of past oceanic circulation and diagnosis of ancient hybrid turbidite-drift systems.

INTRODUCTION

As the terminal part of sedimentary source-to-sink systems, deep-sea deposits have been used to reconstruct past climates, sediment and carbon budgets, and the distribution of anthropogenic pollution (Sømme et al., 2009; Masson et al., 2010; Rebesco et al., 2014; Drinkorn et al., 2019; Kane and Clare, 2019). Bottom currents, i.e., density-driven circulation in the deep ocean, and sediment gravity flows are the main processes that form and modify these deposits (e.g., Talling et al., 2012; Rebesco et al., 2014). While the influence of bottom currents on submarine channel architecture has been recognized, interpretation has been hampered by a lack of direct monitoring data (Shanmugam et al., 1993; Gong et al., 2018; Sansom, 2018; Fomnes et al., 2020). Modern, integrated data sets, including direct measurements and monitoring of bottom currents, are of great importance in understanding the complexity of oceanographic processes (Fierens et al., 2019; Miramontes et al., 2019; Thieblemont et al., 2019), sediment gravity flows (Clare et al., 2016; Azpiroz-Zabala et al., 2017; Symons et al., 2017), and the preservation of strata within submarine channel complexes (Gamberi et al., 2013; Vendettuoli et al., 2019). This study combines an integrated subsurface study (three-dimensional [3-D] seismic, core, and well-log data) with modern seafloor geomorphology and near-bed current measurements to develop a process-product–based sedimentological model for bottom current–influenced submarine channel complexes.

GEOLOGICAL SETTING

The Jurassic to Paleogene basins offshore of East Africa formed during the breakup of Gondwana (Salman and Abdula, 1995). Following Pliensbachian to Aalenian northwest-southeast rifting, ~2000 km of continental drift took place along north-south–striking lineaments, such as the Davie Ridge fracture zone (DFZ) and the Sea Gap fault (SGF) (Fig. 1A), between the Kimmeridgian and Barremian (Reeves et al., 2018) (Fig. 1B). Cessation of rifting was marked by active seafloor spreading between Madagascar and India, leading to the development of the present-day East African passive continental margin (Reeves et al., 2016). Albian transgression resulted in the development of the extensive deep-marine deposits that are the focus of this study. Major river systems drained the African continent and supplied fine-grained sediment, while additional sediment was shed from uplifted rift shoulders along the paleocoastline (Smelror et al., 2008; Fossum et al., 2019).

DATA AND METHODS

This study used high-resolution 3-D seismic reflection data (covering 4885 km²) and 14 exploration wells provided by Equinor ASA (Norway) and ExxonMobil (USA). Seismic data were tied to the biostratigraphically calibrated wells (and core data of Well A; Figs. 1C and 1D) to map seismic and stratigraphic geometries offshore Tanzania (Fig. 1). The average vertical resolution in the Upper Cretaceous of our study area is ~20–30 m (average velocities of ~2.9–3.3 km/s, and average frequency of 35 Hz). The data have a bin spacing of 12.5 x 12.5 m and a
Figure 1. (A) Location of the subsurface data (red outline I) and modern analogue (red outline II), the Sea Gap Fault (SGF) and the Davie Ridge Fracture Zone (DFZ) along the East African Margin. Dotted lines refer to regional oil/gas license boundaries. Wells were used for biostratigraphic correlation; Well A is marked by red dot. (B) Lithology and tectonic history of the deep-water basins offshore of Tanzania. Colors of seismic horizons correlate to the interpreted seismic cross sections in panels E–I. Quat—Quaternary; EARS—East African Rift System. (C,D) Contour map of mid–Campanian (C) seismic horizon and root mean square (RMS) amplitude extraction of the base Turonian to mid-Campanian (D). Coarse-grained sediment (high amplitudes) is influenced by drift-related topography (low amplitudes); white arrows mark direction of sediment gravity flows. TWT—two-way traveltime. (E) Seismic cross section showing Well A (blue line; well tie is shown in Fig. 3C) and lateral seismic facies.
4 ms sampling rate, and are processed in the Society of Exploration Geophysicists (SEG) normal polarity to zero phase, where a peak variation (yellow in Figs. 1E–1I) represents a downward increase in acoustic impedance. High-resolution modern seafloor data covering the modern analog, offshore northern Mozambique, comprises extensive (65 × 50 km) multibeam bathymetric data acquired by our study using an autonomous underwater vehicle (5 m bin size), and a focused (190-m-wide) bathymetric survey using a remotely operated vehicle (0.6 m bin size; Fig. 2).

**SEISMIC EVIDENCE FOR DOWN-AND ALONG-SLOPE SEDIMENT TRANSPORT**

The deep-marine sedimentary systems of the Upper Cretaceous offshore Tanzania were strongly influenced by topographic relief associated with the Sea Gap fault and large drift moorings (moorings B, C, and D in Fig. 2A) measured near-bed (5.5 m above bed) current direction and velocity every 10 min from March 2013 to September 2014 (Figs. 2D and 2E).
New Drifts from the North: Insights from Modern-Day Seafloor Observations and Current Measurements

Thiéblemont et al., 2019). Bathymetric observations of north- to north-northeast–oriented current systems would be variable due to, for example, seasonal eddies and benthic storms (Thran et al., 2018; Miramontes, et al., 2019). During this time, the channel and levee deposits are reworked and redistributed, forming one-sided, hybrid levee-drift deposits to the north (sensu Shanmugam et al., 1993; Palermo et al., 2014; Sansom, 2018; Fonnesu et al., 2020). Deceleration and partial deflection of bottom currents interacting with the topography of the channel cause high accretion rates on the upstream-facing channel flank (relative to the bottom current) under lee-wave conditions (Flood, 1988). Thick homogeneous muddy siltstones (facies F6d) deposited by bottom currents step into the channel and ultimately interact with the channel margin (facies F1 and F2; Fig. 3A) and reworked overbank and/or levee facies (facies F6a; Fig. 3). For this reason, there is minimal levee development on the bottom current–upstream side of the channel (cf. Gong et al., 2018). Sedimentary facies and architecture of the hybrid turbidite-drift channel systems are therefore controlled by the frequency of sediment gravity flow activity and the relative persistence and strength of bottom currents. Deposit modification would mostly occur during periods when bottom currents dominate; during this time, the strength and character or direction of the bottom current system would be variable due to, for example, seasonal eddies and benthic storms (Thran et al., 2018; Miramontes, et al., 2019). However, changes in sediment flux (i.e., frequency of sediment gravity flows) and fluctuation of bottom currents over geological time scales (10^6 m.y.) govern
Figure 3. (A) Sedimentological log of Well A, offshore Tanzania (see Fig. 1A). Vfs—very fine sand; Fs—fine sand; Ms—medium sand; Cs—coarse sand. (B) Well A core photographs: i—drift deposits interbedded with turbidites; ii—reworked turbidites interbedded with toes of drift; iii—drift facies transitioning into muddy turbidites. Zoom on individual facies associations (Fa): Fa6—drift deposit with parallel, cross-cutting lamination.
the large-scale architecture and stacking pattern of hybrid turbidity-drift channel complexes along the East African margin (Fig. 4B).

CONCLUSIONS

Modern and ancient submarine slope channels offshore of Tanzania and Mozambique are, and were, formed by episodic, unsteady, high-energy but short-duration, east-flowing turbidity current events superimposed on long-lived, quasi-steady, northward-flowing bottom currents. The channels are bordered by hybrid levee-drift deposits on their bottom current–downstream (northern) sides, which step progressively southward. Channels have steep eroded margins on their bottom current–upstream (southern) side, and gently dipping downstream flanks where the drift-levees step into the channel. We relate the upstream-migrating levee-drifts to lee-wave conditions as bottom currents traverse the channel. The continued development of the drift-levee pins the channels to the slope for protracted time periods. Well core data indicate that the “toes” of the drift stepping into the channel are dominantly finely laminated siltstones, and that the internal channel architecture and facies distributions are strongly controlled by turbidity- and bottom-current interaction. Our integrated study is likely applicable to many other drift systems globally, and provides new quantitative data to

Figure 4. (A) Sedimentological model of hybrid levee-drift systems: i— with concurrent gravity-driven turbidity currents; ii— during dominance of bottom currents. Red arrow represents turbidity current; blue arrows represent bottom current. (B) Laterally offset channel complexes after repeated intervals of bottom current– dominated and turbidity current–dominated deposition. (C) Graphic visualization of the spatial variation of turbidity currents and bottom-current flows over time. Velocity (U) values are taken from published work (Tables DR2 and DR3 [see footnote 1]) and bottom-current measurements offshore of Mozambique (Fig. 2; see footnote 1).
enable the inference of bottom-current direction from ancient sedimentary sequences, which can be applied to existing and future studies.

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REFERENCES CITED

Azpiroz-Zabala, M., Cartigny, M.J.B., Talling, P.J., Parsons, D.R., Summer, E.J., Clare, M.A., Simmons, S.M., Cooper, C., and Pope, E.L., 2017, Newly recognized turbidity current structure can explain prolonged flushing of submarine canyons: Science Advances, v. 3, e1700200, https://doi.org/10.1126/sciadv.1700200.

Clare, M.A., Harris Clarke, J.E., Talling, P.J., Cartigny, M.J.B., and Pratomo, D.G., 2016, Preconditioning and triggering of offshore slope failures and turbidity currents revealed by most detailed monitoring yet at a fjord-head delta: Earth and Planetary Science Letters, v. 450, p. 208–220, https://doi.org/10.1016/j.epsl.2016.06.021.

de Ruijter, W.P.M., Ridderinkhof, H., Lutjeharms, J.R.E., Schouten, M.W., and Veth, C., 2002, Observations of the flow in the Mozambique Channel: Geophysical Research Letters, v. 29, p. 140–141-143, https://doi.org/10.1029/2001gl013714.

Drinkorn, C., Saynisch-Wagner, J., Uenzelmann-Neben, G., and Thomas, M., 2019, Transport, Removal and Accumulation of Sediments Numerically Simulated for Paleo-Oceans and Reconstructed from cores of the Eirik Drift (TRANSFROG): Abstract presented at International Ocean Discovery Program—International Continental Scientific Drilling Program Kollqium, Cologne, Germany, 18–20 March.

Fauquères, J.-C., Stow, D.A., Imber, P., and Viana, A., 1999, Seismic features diagnostic of contourite drifts: Marine Geology, v. 162, p. 1–18, https://doi.org/10.1016/S0025-3227(99)00006-7.

Fierens, R., Droz, L., Toucanne, S., Raison, F., Jouet, G., Babonneau, N., Miramontes, E., Landurain, S., and Jorry, S.J., 2019, Late Quaternary geomorphology and sedimentary processes in the Zambezi turbidite system (Mozambique Channel): Geomorphology, v. 334, p. 1–28, https://doi.org/10.1016/j.geomorph.2019.02.033.

Flood, R.D., 1988, A lee wave model for deep-sea mudwave activity: Deep-Sea Research: Part A, Oceanographic Research Papers, v. 35, p. 973–983, https://doi.org/10.1016/0012-2787(88)90071-4.

Fonnes, M., Palermo, D., Galbiati, M., Marchesini, M., Bendini, A., and Zaccarelli, G., 2020, A new world-class deep-water play-type, deposited by a sydendepositional interaction of turbidity flows and bottom currents: The giant Eocene Coral Field in northern Mozambique: Marine and Petroleum Geology, v. 111, p. 179–201, https://doi.org/10.1016/j.marpetgeo.2019.07.047.

Fossam, M., Morton, A.C., Dypvik, H., and Hudson, W.E., 2019, Integrated heavy mineral study of Jurassic to Paleogene sandstones in the Mandalawa Basin, Tanzania: Sediment provenance and source-to-sink relations: Journal of African Earth Sciences, v. 150, p. 546–565, https://doi.org/10.1016/j.jafrearsci.2018.09.009.

Gambeti, F., Rovere, M., Dykstra, M., Kane, I.A., and Kneller, B.C., 2013, Integrating modern seafloor and outcrop data in the analysis of slope channel architecture and fill: Marine and Petroleum Geology, v. 41, p. 83–103, doi: https://doi.org/10.1016/j.marpetgeo.2012.04.002.

Gong, C., Wang, Y., Rebesco, M., Salon, S., and Steel, R.J., 2018, How do turbody flow interacts with contour currents in unidirectionally migrating deep-water channels?: Geology, v. 46, p. 551–554, https://doi.org/10.1130/G39024.1.

Habich, J.A., and Keith, A.I., 1988, Geomorphological evolution of the Saldanha Shelf: A case study in the eastern South Atlantic: Geomorphology, v. 12, p. 179–201, https://doi.org/10.1016/0169-555X(88)90071-4.

Kane, I.A., and Clare, M.A., 2019, Dispersion, accumulation, and the ultimate fate of microplastics in deep-marine environments: A review and future directions: Frontiers of Earth Science, v. 7, 80, https://doi.org/10.3389/feart.2019.00080.

Martin-Chivelet, J., Fregenal-Martínez, M.A., and Chacón, B., 2008, Traction structures in contourites, in Rebesco, M., and Camerlenghi, A., eds., Contourites: Amsterdam, Elsevier Science, Developments in Sedimentology, v. 60, p. 159–182, https://doi.org/10.1016/S0070-4571(08)10100-3.

Masson, D.G., Huvenne, V.A.L., de Stigter, H.C., Wolfe, A., and Klaas, R.G., 2010, Blackbird, S., 2010, Efficient burial of carbon in newly recognized turbidity current structure can explain prolonged flushing of submarine canyons: Science Advances, v. 3, e1700200, https://doi.org/10.1126/sciadv.1700200.

Miramontes, E., et al., 2019, The influence of bottom currents on the Zambezi Valley morphology (Mozambique Channel, SW Indian Ocean): In situ current observations and hydrodynamic modeling: Marine Geology, v. 410, p. 42–55, https://doi.org/10.1016/j.margeo.2019.01.002.

Nauw, J.J., van Aken, H.M., Webb, A., Lutjeharms, J.R.E., and de Ruijter, W.P.M., 2008, Observations of the southern East Madagascar Current and undercurrent and countercurrent system: Journal of Marine Systems, v. 71, C08006, https://doi.org/10.1016/j.jmarsys.2007.04.039.

Palermo, D., Galbiati, M., Faggioni, M., Marchesini, M., Mezzapesa, D., and Fonnes, F., 2014, Insights into a new super-giant gas field—Sedimentology and reservoir modeling of the Coral Reservoir Complex, offshore northern Mozambique: The interplay between processes: State-of-the-art and future considera- tions: Marine and Petroleum Geology, v. 41, p. 83–103, doi: https://doi.org/10.1016/j.marpetgeo.2014.03.011.

Rebesco, M., Hernández-Molina, F.J., Llave, E., Sayago-Gil, M., Díaz del Río, V., and Branson, A., 2009, Bedform-velocity matrix: The estimation of bottom current velocity from bedform observations: Geology, v. 37, p. 327–330, https://doi.org/10.1130/G25259A.1.

Symons, W.O., Summer, E.J., Paull, C.K., Cartigny, M.J.B., Xu, J.P., Maer, K.L., Lorenson, T.D., and Talling, P.J., 2017, A new model for turbidity current behavior based on integration of flow monitoring and precipitation core in a submarine canyon: Geology, v. 45, p. 367–370, https://doi.org/10.1130/G38764.1.

Talling, P.J., Masson, D.G., Summer, E.J., and Malgesini, G., 2012, Subaqueous sediment density flow deposition in the passive margin prone Mozambique Channel: Sedimentology, v. 59, p. 1937–2003, https://doi.org/10.1111/j.1365-3091.2012.01353.x.

Thiéblemont, A., Hernández-Molina, F.J., Miramontes, E., Raissone, F., and Penven, P., 2019, Contourite depositional systems along the Mozambique Channel: The interplay between bottom currents and sedimentary processes: Deep-Sea Research: Part I, Oceanographic Research Papers, v. 147, p. 79–99, https://doi.org/10.1016/j.dsr.2019.03.012.

Thran, A.C., Dutkiewicz, A., Spencer, P., and Müller, R.D., 2018, Controls on the global distribution of contourite drifts: Insights from an evolving ocean model: Earth and Planetary Science Letters, v. 489, p. 228–240, https://doi.org/10.1016/j.epsl.2018.02.044.

van Aken, H.M., Ridderinkhof, H., and de Ruijter, W.P.M., 2004, North Atlantic deep water in the south-western Indian Ocean: Deep-Sea Research: Part I, Oceanographic Research Papers, v. 51, p. 755–776, https://doi.org/10.1016/j.dsr.2004.01.008.

Vendettuoli, D., et al., 2019, Daily bathymetric surveys document how stratigraphy is built and its extreme incompleteness in submarine channels: Earth and Planetary Sciences Letters, v. 515, p. 231–247, https://doi.org/10.1016/j.epsl.2019.03.033.

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