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Large-scale submarine landslide drives long-lasting regime shift in slope sediment deposition

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ABSTRACT

Submarine landslides and associated mass-transport deposits (MTDs) modify the physiography of continental margins and influence the evolution of submarine sediment routing systems. Previous studies highlighted the control of landslides and MTDs on subsequent sedimentary processes and deposits at spatial scales ranging from tens of centimeters to few kilometers, leaving a knowledge gap on how and for how long large-scale submarine landslides (i.e., headscarps wider than 50–100 km) may affect the stratigraphic evolution of continental margins. To fill this gap, we used three-dimensional seismic reflection data tied to an exploration well to investigate the impact of one of the largest submarine landslides discovered on Earth, the Mafia mega-slide (Mms) offshore Tanzania, on slope sediment deposition. Seismic data interpretation indicates that turbidite lobes/lobe complexes and coalescent mixed turbidite-contourite systems formed the pre-Mms stratigraphy between 38 and ca. 21 Ma (age of the Mms), whereas coarser-grained sheet turbidites and debrites accumulated after the Mms for ~15 m.y., primarily on the topographic lows generated by the emplacement of the landslide. We interpret this drastic and long-lasting regime shift in sediment deposition to be driven by the increase in seafloor gradient and the capture and focus of feeding systems within the broad failed area. We propose that the extensive evacuation zones associated with such giant landslides can generate major "conveyor belts", trapping land-derived material or sediments transported by along-slope processes such as bottom currents. During the progressive healing of the landslide escarpments, which may last for several million years, sand-prone facies are deposited primarily in the upper slope, filling up the accommodation space generated by the landslide, while deeper-water environments likely remain sediment starved or experience accumulation of finer-grained deposits. Our study provides new insights into the long-term response of slope depositional systems to large-scale submarine landslides, with implications for the transfer of coarse-grained sediments that can be applied to continental margins worldwide.

INTRODUCTION

Submarine landslides, Earth's largest mass movements, occur when the pulling force exerted by gravity exceeds the resisting strength of seabed material, causing their downslope movement along one or multiple shear surfaces (Hampton et al., 1996). Submarine landslides and related mass-transport deposits (MTDs; *sensu* Weimer, 1990) modify the physiography of continental margins and impact subsequent sediment transport and deposition. Slope failures may capture turbidite channels (Kneller et al., 2016; Qin et al., 2017) and promote the formation of new submarine canyons through retrogressive erosion or by focusing gravity flows (Martínez-Doñate et al., 2021; Wu et al., 2022). The rugose topography of MTDs, generated either by landslide blocks or due to differential compaction (Alves and Cartwright, 2010; Ward et al., 2018), influences the path of subsequent turbidite channels (Bull et al., 2020) and may control the location of channel avulsion (Ortiz-Karpf et al., 2015). Turbidity currents interacting with the complex seafloor above MTDs may also promote the accumulation of ponded sand-rich deposits (Kneller et al., 2016), which have been characterized using outcrop and well data due to their potential as hydrocarbon reservoirs (Armitage et al., 2009; Kremer et al., 2018). To date, there has been a paucity of research conducted on large-scale submarine landslides where headscarps are wider than 50–100 km (hence several times larger than canyons associated with large rivers), surface areas are >10,000 km^2, and the volume of sediments involved are >1000 km^3 (Haflidason et al., 2004; Calvès et al., 2015; Soutter et al., 2018; Bull et al., 2020). Consequently, there are still unanswered questions about the response of slope depositional systems to such large events and the time scales over which it may occur.

With a surface area of at least 11,600 km^2 and a volume >2500 km^3, the Mafia mega-slide (Mms) offshore Tanzania (western Indian Ocean; Fig. 1) is one of the biggest landslides discovered on Earth (Maselli et al., 2020) and is comparable in size with the Storegga Slide along the Norwegian slope (maximum volume of 3200 km^3; Haflidason et al., 2004). The Mms has been interpreted as a major submarine failure event that occurred at ca. 21 Ma in response to the tectonic activity of the East African Rift System (EARS; Maselli et al., 2020). We used high-quality three-dimensional (3-D) seismic reflection data tied to one exploration well to investigate the stratigraphic impact of the Mms on the East African margin in order to understand the effects of such giant submarine landslides on slope depositional systems, and to draw conclusions that can be applied to other continental margins worldwide.

GEOLOGICAL SETTING

The study area is part of the western Somali Basin offshore Tanzania, the formation of which can be traced back to the Middle Jurassic, when the breakup between East Africa and Madagascar began (Coffin and Rabinowitz, 1992; Klimke and Franke, 2016). Continental rifting continued until the Early Cretaceous (Coffin and Rabinowitz, 1992) and was followed by a quiescent tectonic phase until the

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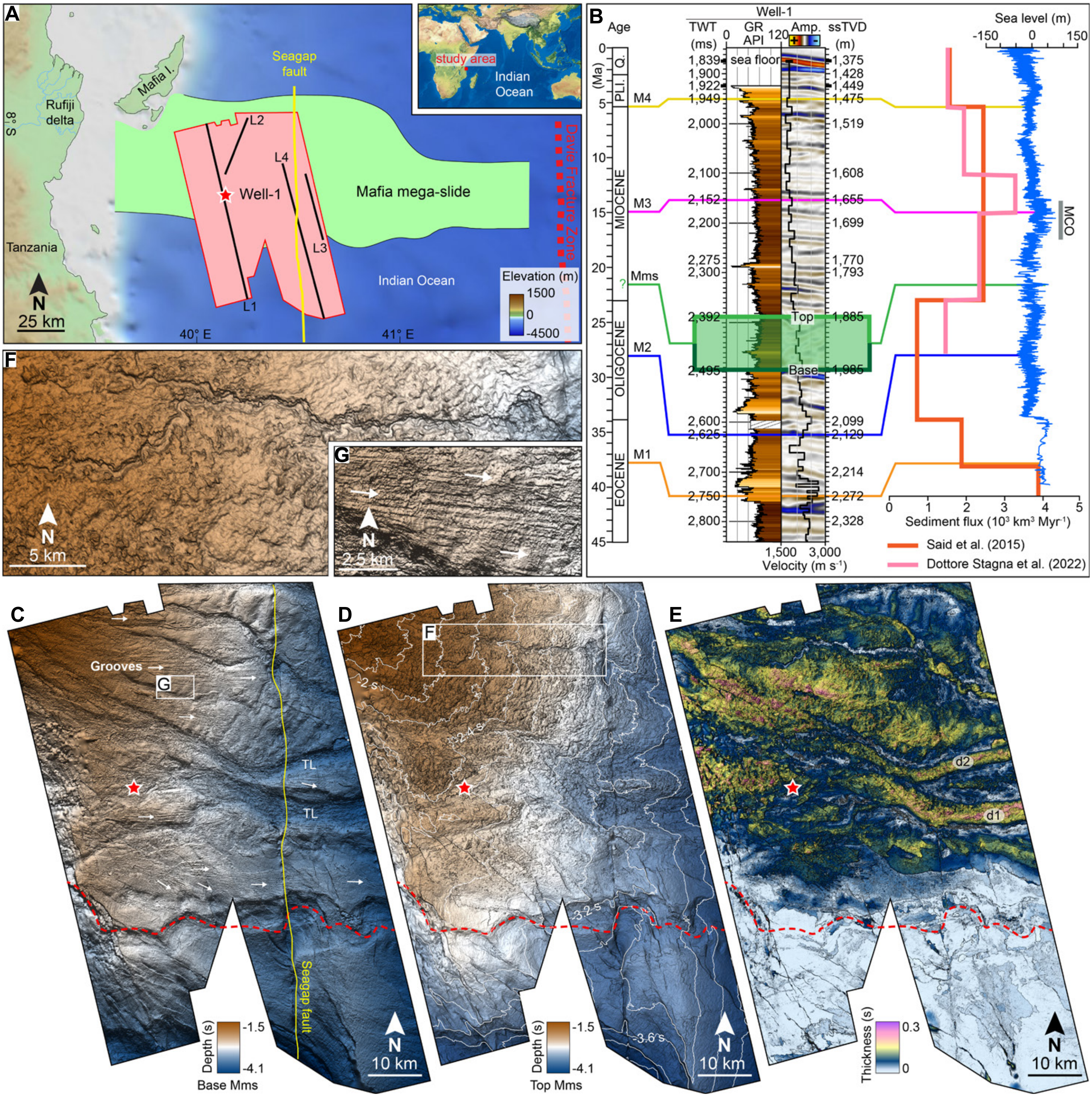

Figure 1. (A) Study area location offshore Tanzania. Red area is three-dimensional seismic data; green area is the Mafia mega-slide (Mms). Black lines (L1–L4) are seismic profiles shown in Figures 2 and 3. (B) From left to right: dated stratigraphic horizons (M1–M4) and Mms (Maselli et al., 2020); Well-1 with gamma-ray log (GR), check-shots velocity model (black line), seismic reflection amplitude (Amp.), and depth in two-way traveltime (ms TWT) and true vertical depth (m ssTVD); sediment fluxes (Said et al., 2015; Dottore Stagna et al., 2022); and sea-level curve and gray vertical bar for the Miocene Climatic Optimum (MCO; Miller et al., 2020). Pli.—Pliocene; Q.—Quaternary. (C) Surface map of the Base Mms. Red dashed line is the Mms southern flank. TL—topographic low. White arrows show basal groove marks. (D) Surface map of the Top Mms with contour lines every 0.2 s. (E) Mms isochore map with depocenters (d1–d2). (F,G) Close-up views of the meandering channel at the Top Mms surface and groove marks at the Base Mms surface, respectively.

middle Oligocene (Kent et al., 1971). A new tectonic regime started with the establishment of the EARS during the late Paleogene (Ebinger and Sleep, 1998). The EARS reorganized catchment basins, rerouted fluvial systems toward the Indian Ocean (Roberts et al., 2012; Fossum et al., 2019), and altered the distribution of submarine canyons (Maselli et al., 2019; Dottore Stagna et al., 2022). The interval investigated in this study encompasses the post-Eocene stratigraphy of the area until 5.3 Ma.

DATA AND METHODS

We interpreted a 3-D post-stack, Kirchhoff time-migrated seismic reflection volume covering 6092 km² (Fig. 1A) using Petrel software and applying conventional methods of seismic geomorphology (e.g., Posamentier and

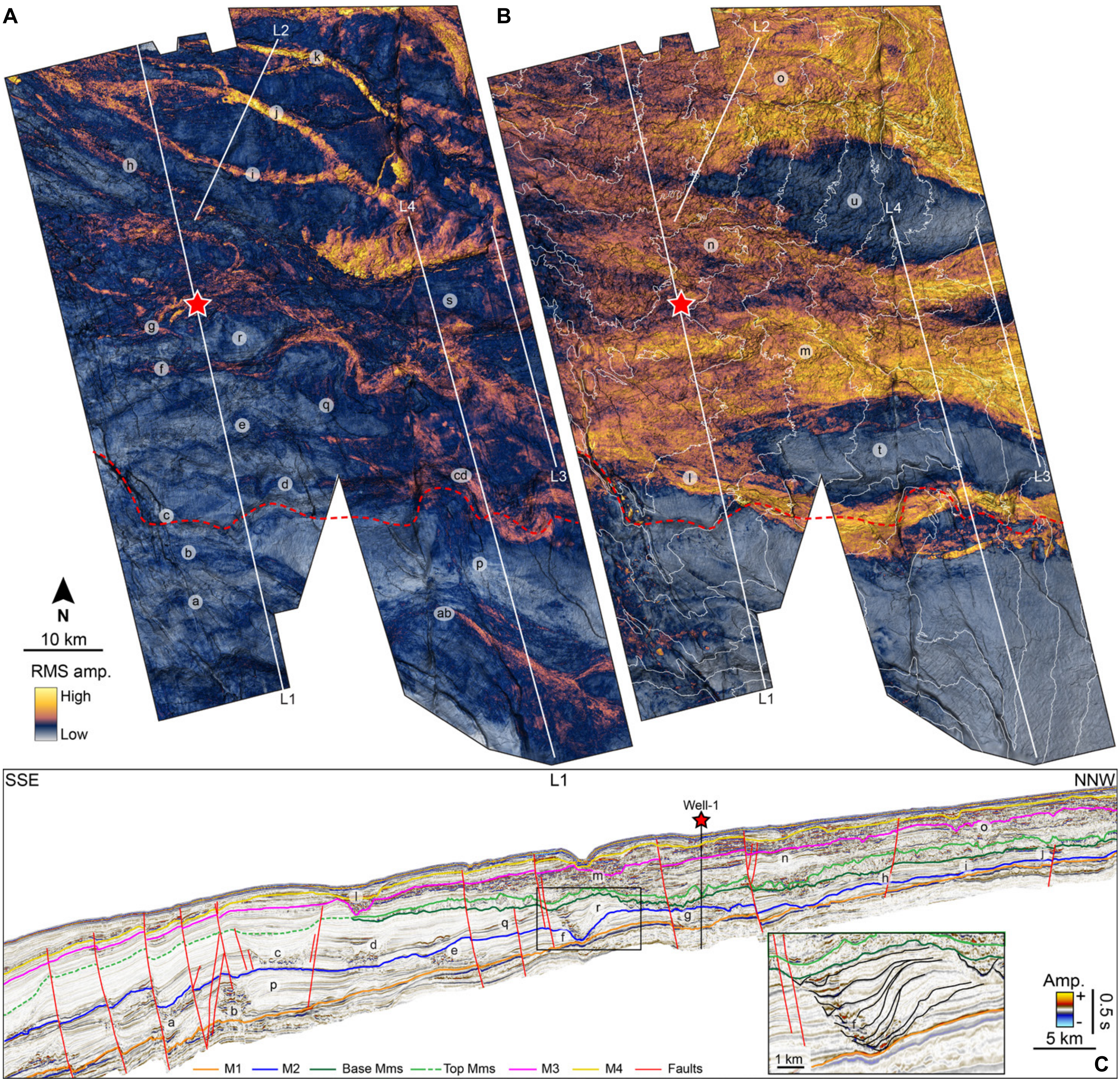

Figure 2. Root-mean-square (RMS) amplitude extraction between M1 and Base Mms (Mafia mega-slide; Offshore Tanzania) horizons (A) and between the Top Mms and M4 horizons (B). White lines (L1–L4) are locations of seismic profiles; letters indicate channel systems (a–l, ab, cd), sheet-like turbidites/debrites (m–o), and levee/drift deposits (p–u). (C) Seismic line L1 with main seismic horizons presented with seismic reflection amplitude. Black rectangle is the position of the close-up view of channel f; black vertical line is location of Well-1, the position of which is indicated in A and B by the red star.

Kolla, 2003; for seismic facies, see Fig. S1 in the Supplemental Material[1]). The line spacing is 12.5 m in both in-line and cross-line directions, and the data are zero phase and displayed with SEG normal polarity (depth values are in seconds [s] two-way traveltime [TWT]). The dominant frequency in the interval of interest, seafloor to a depth of ~3 s at Well-1 (Fig. 1B), is ~70 Hz. Well-1 (original name changed for confidentiality) was drilled in a water depth of 1375 m offshore Mafia Island (Fig. 1). Four seismic horizons, M1 (38 Ma), M2 (28 Ma), M3 (15 Ma), and M4 (5.3 Ma), named and dated by Maselli et al. (2020) using biostratigraphic data from Well-1 (Fig. 1B), were mapped in the 3-D seismic dataset, together with the base and top of the Mms, named Base Mms and Top Mms horizons, respectively (Figs. 1C and 1D). Root-mean-square (RMS) amplitude maps, extracted between M1 and Base Mms (Fig. 2A) and between Top Mms and M4 (Fig. 2B), were used to image coarse-grained bodies (Chen and Sidney, 1997) such as turbidite channels, lobes, and sediment waves.

[1]Supplemental Material. Supplemental Figures S1–S6. Please visit https://doi.org/10.1130/GEOL.S.21606072 to access the supplemental material, and contact editing@geosociety.org with any questions.

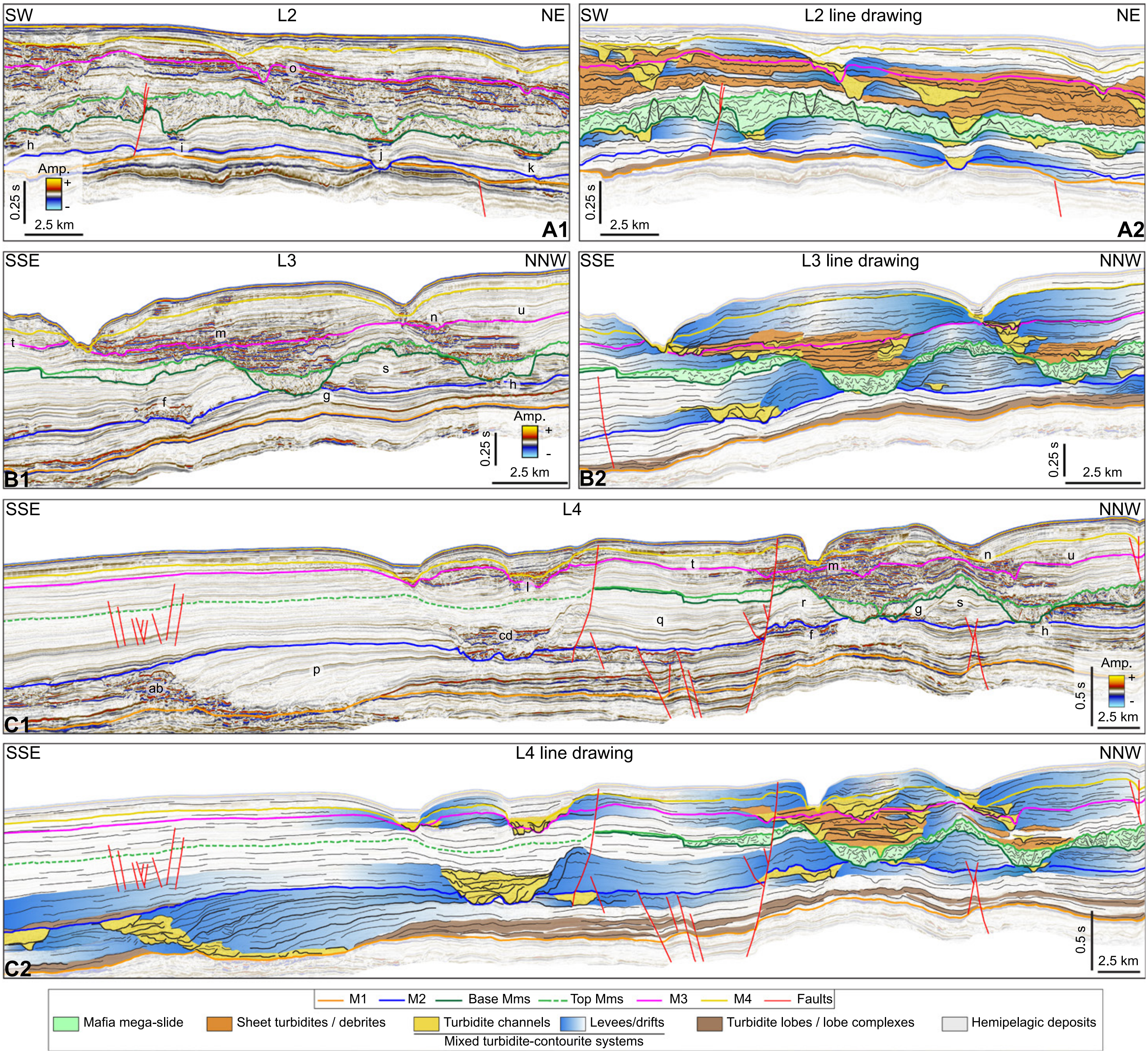

Figure 3. Arbitrary seismic lines extracted from three-dimensional volume and presented with reflection amplitude (A1, B1, and C1) and line drawings (A2, B2, and C2); see Figures 1 and 2 for line locations. Horizons M1 to M4 are also marked. Letters indicate channel systems (ab, cd, f–l), sheet-like turbidites/debrites (m–o), and levee/drift deposits (p–u). Mms—Mafia mega-slide (offshore Tanzania).

RESULTS

Pre-Mms Stratigraphy

Above horizon M1, seismic data show thick and high-amplitude tabular to lens-shaped reflection packages (Figs. 2C and 3; Fig. S2) with medium RMS amplitude response (Fig. S3), which we interpret as turbidite lobes/lobe complexes. Sinuous, northwest-southeast–oriented, meandering channels with medium to high RMS amplitude values stand out in the southern and central portions of the study area (a–g in Fig. 2A; Fig. S3), which is mainly characterized by low RMS values. These channels have different stacking patterns, from organized (a, b, and e–g in Figs. 2 and 3) to disorganized (c and d in Figs. 2 and 3; *sensu* McHargue et al., 2011). In cross section, they show discontinuous high-amplitude reflections bounded on the northern side by wedge-shaped, continuous, low-amplitude reflections (p–s in Figs. 2C and 3C). Overall, the channels progressively migrate southward moving up through the sequence (Figs. 2C and 3) and are interpreted as mixed turbidite-contourite systems with highly asymmetric, northward-elongated levees/drifts influenced by margin-parallel northward-flowing bottom currents (see Sansom, 2018; Fuhrmann et al., 2020). While the base of channels b, e, and f can be traced down to horizon M1, the base of channels a, c, d, and g corresponds to M2 (Figs. 2C and 3). Straight, northwest-southeast–oriented turbidite channels with high RMS amplitude values (h–k in Figs. 2A and 3; Fig. S3) are also visible in the northern portion of the study area and are capped by the Mms (Figs. 2C and 3A). The thickness of Pre-Mms deposits reaches as much as 1.1 s southward, outside of the Mms, while it is ~0.15 s beneath the Mms, thus reflecting the erosional nature of the landslide (Fig. 2C; Fig. S4).

Mafia Mega-Slide

The Base Mms horizon is a laterally continuous, medium- to high-amplitude reflection (soft

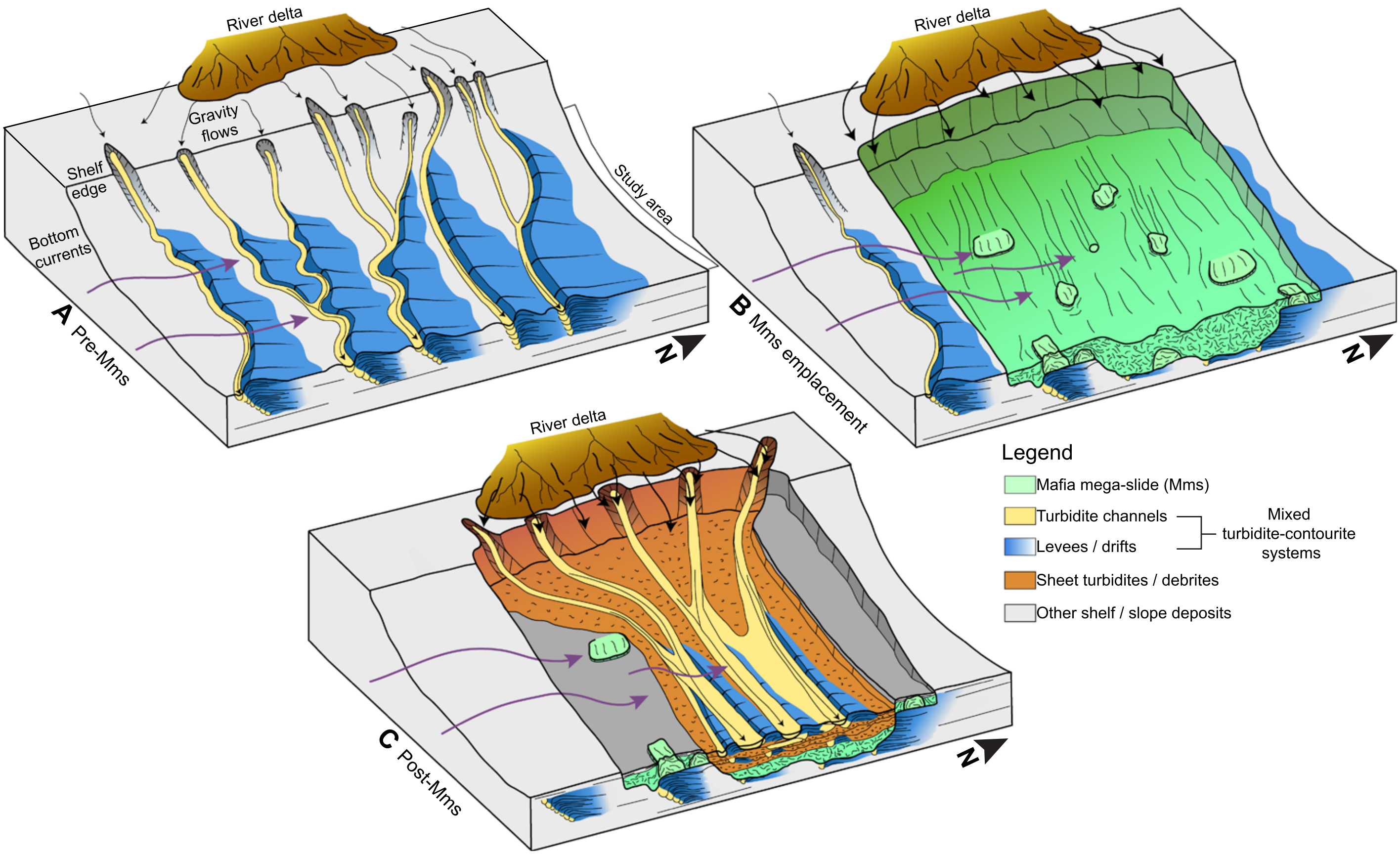

Figure 4. Conceptual model for evolution of continental margin slope sediment deposition Pre–Mms (Mafia mega-slide; offshore Tanzania) (A), during Mms (B), and Post-Mms (C) emplacement. Purple and black arrows indicate bottom currents and turbidity currents, respectively, and inferred changes in flow strength.

kick) characterized by an irregular morphology, mostly discordant with, and strongly affected by, the deposits underneath (Figs. 1C, 2C, and 3; Fig. S2). The strong erosional nature of this surface is evidenced by the presence of downslope-oriented linear features as much as 20 km in length, ~50–150 m wide, ~0.01 s deep, and V-shaped in cross section (Figs. 1C and 1G; Fig. S5), which are interpreted as groove marks. To the east, the Base Mms shows two U-shaped and west-east–oriented topographic lows (Figs. 1C and 2C), which correspond to the depocenters d1 and d2 visible on the isochore map (Fig. 1E) where the Mms reaches a thickness of 0.3 s. These lows are probably associated with pre-existing slope channels, as indicated by the presence of high-amplitude reflections, either vertically stacked or shingled, immediately below the landslide (Figs. 2A, 2C, and 3). The Mms deposit is characterized primarily by transparent to chaotic seismic facies, but coherent, semi-continuous, and parallel to deformed reflections are also visible and interpreted as translated and/or rotated or remnant blocks (Figs. 2C and 3; Fig. S1). The Top Mms horizon is marked by a low-to-high amplitude, laterally discontinuous reflection (hard kick). The roughness of the Top Mms surface is highly variable due to the presence of landslide blocks, which may create local elevation changes of as much as 0.1 s (Figs. 1D, 1E, and 2C), as well as Post-Mms erosional processes (Fig. 1D). A notable example is a west-east–oriented sinuous channel (Fig. 1F) that almost entirely eroded the Mms, as visible in the thickness map (Fig. 1E).

Post-Mms Stratigraphy

The Post-Mms stratigraphy in the southern part of the study area is characterized by low- to medium-amplitude, parallel, continuous seismic reflections (Figs. 2C and 3; Fig. S2) with low RMS amplitude response (Fig. 2B; Fig. S3), which are interpreted as hemipelagic and overbank deposits. Those deposits are dissected by a turbidite channel (l in Fig. 2B) that cuts down to horizon M3 (Fig. 3C). Above the Mms, a sequence of slope sediments as much as 0.3 s thick accumulated in correspondence of the bathymetric lows of the Top Mms horizon (m–o in Figs. 3A and 3B; Fig. S4), which are highlighted by the landward-convex contour lines in Figure 2B. These deposits are characterized by discontinuous high- to medium-amplitude reflections, locally interrupted by U-shaped incisions with discontinuous high-amplitude infill, interbedded with more continuous and high-amplitude ones that slightly migrate southward moving up through the sequence (Figs. 2C and 3; Figs. S1 and S6). Overall, they are interpreted as coarse-grained sheet-like turbidites interbedded and alternated with debrites and small-scale (maximum ~1 km wide and ~0.08 s deep) turbidite channels (Fig. 3; Fig. S1). The local erosion of the Mms (Figs. 2C and 3A; Figs. S4 and S6) indicates the energetic nature of the gravity flows in the Post-Mms sequence. Conversely, the deposits accumulating above the topographic highs of the Top Mms horizon are characterized by low RMS amplitude values (t–u in Fig. 2B; Fig. S3), with continuous and high-frequency reflections in cross section (t–u in Figs. 3B and 3C), and are interpreted as fine-grained levee/drift deposits. These deposits are still asymmetric, although less elongated and steep, thus testifying to the influence of northward-flowing bottom currents (Figs. 2C and 3C).

DISCUSSION

Seismic data show that the margin collapse associated with the Mms disrupted Miocene sediment routing systems and promoted the instauration of a new depositional regime (Figs. 2B, 2C, and 3). RMS amplitude response and seismic facies indicate that Pre-Mms deposits (between the M1 and Base Mms horizons) consist of turbidite lobes/lobe complexes and mixed turbidite-contourite systems, whereas

Post-Mms deposits (between the Top Mms and M4 horizons) are made of coarse-grained turbidites and debrites (Fig. 2B; Sansom, 2018; Fuhrmann et al., 2020). We interpret this regime shift in sediment deposition toward more energetic and coarse-grained flows to reflect primarily the increase in seafloor gradient and the funneling generated by the Mms headscarp (Martínez-Doñate et al., 2021). The formation of the EARS in Tanzania (Roberts et al., 2012) and the Miocene Climatic Optimum (Miller et al., 2020) also increased sediment fluxes to the western Indian Ocean (Fig. 1B; Said et al., 2015), enhancing the progradation of the Rufiji River delta on a narrow Miocene shelf (Burgess et al., 2022) and favoring the supply of coarse-grained sediments directly into the Mms headscarp. The healing of the Mms occurred over an interval of ~15 m.y. (until horizon M4), during which sand-prone facies accumulated primarily in the topographic lows generated by the emplacement of the landslide.

From the study of the Mms, we propose a conceptual model for the evolution of a continental margin affected by a large-scale landslide (Fig. 4), where the disruption of submarine slope channel systems over a wide area promotes the development of a major conveyor belt through the formation of topographic lows and confluence zones (see also Wu et al., 2022) that focus the transport of land-derived material and trap sediments carried by bottom currents. During the progressive healing of the landslide topography, which we observe can last for several million years, deposition of sand-prone facies may occur primarily on the upper slope, filling up the accommodation space generated by the landslide (Fig. 4C), while deeper-water environments likely remain sediment starved or experience accumulation of finer-grained deposits (Olafiranye et al., 2013). Even though the topography and rheology of MTDs influence sediment deposition and dispersal patterns particularly during the initial healing phases (Armitage et al., 2009, their Tier 2 and 3), as observed in other systems (Moscardelli et al., 2006; Alves and Cartwright, 2010; Ortiz-Karpf et al., 2015; Ward et al., 2018), the impact of giant landslides is most dominant on topographic wavelengths (*sensu* Kneller et al., 2016) > 10 km, as visible offshore Tanzania after the emplacement of the Mms.

CONCLUSION

This study demonstrates that large-scale submarine landslides have a paramount control on the evolution of sediment transfer zones along continental margins. By capturing multiple slope channel systems over wide areas spanning tens of kilometers, they promote the development of major sediment conveyor belts, funneling land-derived material for millions of years. Their topographic surfaces, the impact of which is most dominant on topographic wavelengths of tens of kilometers, hamper or buffer downslope sediment distribution, influencing the loci and timing of accumulation of coarse-grained facies. This dichotomy in the depositional style between upper and lower slope regions and the time scale over which it occurs has important implications for the prediction of reservoir sands in deep-water basins.

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