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A 1000-yr-old tsunami in the Indian Ocean points to greater risk for East Africa

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ABSTRACT

The December 2004 Sumatra-Andaman tsunami prompted an unprecedented research effort to find ancient precursors and quantify the recurrence time of such a deadly natural disaster. This effort, however, has focused primarily along the northern and eastern Indian Ocean coastlines, in proximal areas hardest hit by the tsunami. No studies have been made to quantify the recurrence of tsunamis along the coastlines of the western Indian Ocean, leading to an underestimation of the tsunami risk in East Africa. Here, we document a 1000-yr-old sand layer hosting archaeological remains of an ancient coastal Swahili settlement in Tanzania. The sedimentary facies, grain-size distribution, and faunal assemblages indicate a tsunami wave as the most likely cause for the deposition of this sand layer. The tsunami in Tanzania is coeval with analogous deposits discovered at eastern Indian Ocean coastal sites. Numerical simulations of tsunami wave propagation indicate a megathrust earthquake generated by a large rupture of the Sumatra-Andaman subduction zone as the likely tsunami source. Our findings provide evidence that teletsunamis represent a serious threat to coastal societies along the western Indian Ocean, with implications for future tsunami hazard and risk assessments in East Africa.

INTRODUCTION

The December 2004 Sumatra-Andaman tsunami is the deadliest teletsunami (a tsunami that travels more than 1000 km from its origin) experienced in modern times. The tsunami struck far-field locations in East Africa, with significant energy on the Horn of Africa, where hundreds of fatalities were reported (Fritz and Borrero, 2006; Okal et al., 2009). The tsunami arrival along the coasts of Somalia, Kenya, and Tanzania was recorded during a low tide of a spring tidal cycle (Obura, 2006). Rapid-response field surveys allowed the quantification of the maximum runup height and flow depth at different coastal sites, and the characterization of the tsunami deposit (Bahlburg and Weiss, 2006; Fritz and Borrero, 2006; Okal et al., 2009). Numerical simulations indicate that the coastline of East Africa is in the path of teletsunamis generated by megathrust earthquakes originating from the Makran and Sumatra-Andaman subduction zones (Okal and Synolakis, 2008), but it can also be affected by locally sourced tsunamis caused by submarine landslides. Here, we describe the first Holocene tsunami deposit identified along the coastlines of East Africa, and one of the few records that includes human remains. We evaluated maximum tsunami wave heights at major East African coastal cities, from Somalia to Mozambique, by simulating different ruptures along the Makran and Sumatra-Andaman subduction zones, while accounting for differences in tidal stage to estimate the inundation range of the events.

RESULTS

Study Area

The study area is located on the southern bank of Pangani Bay, Tanzania (Fig. 1), where Mjema (2018) discovered an ancient Swahili maritime community and described its archaeological significance. The bay is a funnel-shaped estuary (maximum water depth up to 8 m and spring tidal amplitude up to 4.5 m) where the Pangani River enters the Indian Ocean (Fig. 1). The field site is a 400-m-wide strip of estuarine and mangrove-swamp deposits at the toe of the Bweni Escarpment, a carbonate structural high (Figs. 1C and 1D). In 2016–2017, as part of a separate project by the Institute of Marine Science of the University of Dar es Salaam, seven ponds were excavated to host marine fishes for aquaculture research (see Section S1 in the Supplemental Material[1]),

[1]Supplemental Material. Additional information on the study area (Section S1), radiocarbon dating of the samples (Section S2), grain size analysis (Section S3), paleoenvironmental reconstructions (Section S4), tsunami modeling (Section S5), and eyewitnesses of the 2004 tsunami in Pangani (Section S6), and the Ethics statement (Section S7). Please visit https://doi.org/10.1130/GEOL.S.12253040 to access the supplemental material, and contact editing@geosociety.org with any questions.

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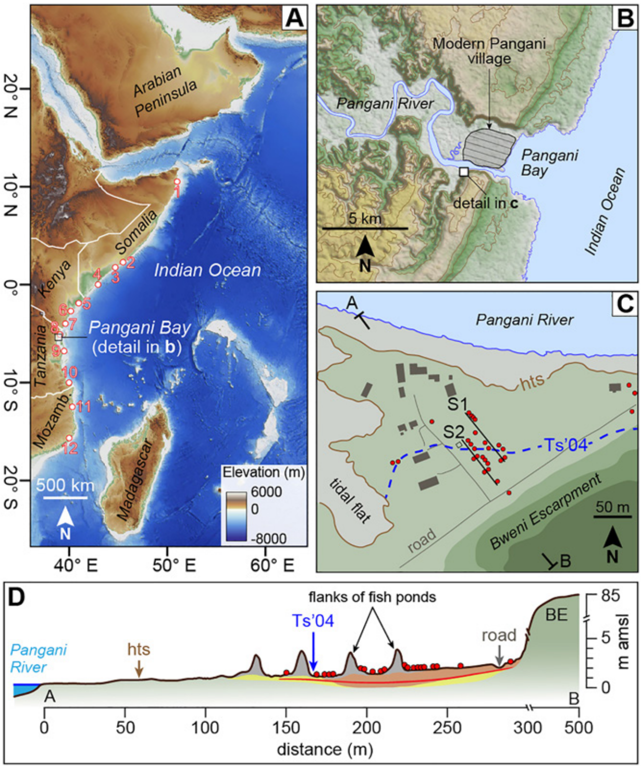

Figure 1. (A) Western Indian Ocean and surrounding lands. Red circles are locations reported in Figure 4. (B) Close-up view of Pangani Bay, Tanzania; study area is marked by the white square. (C) Study area, where red dots represent sampling locations. Dashed blue line (Ts'04) marks the landward inundation limit of the 2004 Sumatra-Andaman tsunami, as described by eyewitnesses. Brown line is the limit of high-tide shoreline (hts). A-B is the stratigraphic section presented in D. S1 and S2 are stratigraphic sections in Figure 2. (D) A-B stratigraphic section (see color code in Fig. 2). Topography is derived from a high-resolution (10 cm) digital elevation model generated with unmanned aerial vehicle (UAV) photogrammetry; m asl—meters above sea level; BE—Bweni Escarpment.

and the sediment extracted (facies 4, Anthrosol; Fig. 2) was accumulated next to the ponds to form the ridges that are visible in Figure 1D. During the field work campaign of this study (June and July 2017), we dug 29 pits and two trenches along the flanks of the ponds, up to a depth of ~1 m (Figs. 1D and 2).

Sedimentology and Paleoenvironments

By integrating field observations, grain-size analysis, radiocarbon dates, and paleontological evidence, we recognized three sedimentary facies (Fig. 2; Sections S2–S4 in the Supplemental Material).

Facies 1 was observed in the lower part of the stratigraphic logs. The contact with the underlying sediments was not sampled, while the top of the facies lies at progressively shallower depths landward (Fig. 2). Facies 1 consists of massive fine sands with rare coarser-grained beds of a few centimeters thickness, containing plant debris. Facies 1 is generally barren, with rare small molluscs of continental origin, such as subulinids (Fig. 2). Facies 1 can be best interpreted as an alluvial deposit, likely a fluvial terrace above tidal influence, as indicated by the lack of estuarine fauna.

Facies 2 was encountered in most of the study area, accumulating above the alluvial deposit. It consists of muddy sands, rich in continental and estuarine faunas, and mangrove debris (Fig. 2). Facies 2 contains archaeological remains, including potsherds and beads. Facies 2 represents a swamp-mangrove plain that hosted the settlement of a Swahili maritime community, as also described in Mjema (2018).

Facies 3 is a continuous sand sheet that rests upon an erosional surface. The sand sheet is found throughout the study area, accumulating mainly within the mangrove deposit, with the exception of the northwest portion of stratigraphic section 1, where it is found within alluvial deposits (Fig. 2). Facies 3 consists of poorly to well-sorted, fine to coarse sands often containing carbonate pebbles similar to those visible along the modern shoreline, which originate from the Bweni Escarpment (Fig. 2). Facies 3 lacks sedimentary structures, and the sand is typically massive, although fining-upward trends can be detected at places. Plant debris is observed landward, mostly near the top of the deposit and toward the Bweni Escarpment. The total thickness varies laterally between 30 cm and <5 cm. The deposit thins landward in section 1, while it is more variable in section 2, the transect furthest from the Pangani River (Fig. 2). Facies 3 is characterized by a mixed fossil assemblage sourced from continental, estuarine, and marine habitats including various invertebrates (dominantly molluscs and foraminifera) and vertebrate bones (fishes, rodents, birds, amphibians; Section S4). Facies 3 corresponds to stratum 5 of Mjema (2018), and it contains archaeological remains belonging to an early Swahili maritime community, as confirmed by the decorations identified on pottery fragments recovered from the sediment (Fig. 2). Part of the marine fauna includes large molluscs, which were likely harvested as food (*Saccostrea*, *Isognomon*) or for ornamental purposes (*Monetaria*, *Polinices*) by the early Swahili inhabitants. On the contrary, smaller molluscs and microfossils are interpreted as genuine fingerprints for landward sediment transport processes from marine and transitional sources. The presence of near-complete human skeletons was first described by Mjema (2018). New skeletons, isolated bones, and bone fragments were found during this study to be ubiquitous in the sand sheet throughout the site, and their abundance increases near the Bweni Escarpment. The newly discovered human remains belong to male and female adults as well as children, as determined following Mays (2010) from the degree of epiphyseal closure, tooth formation and eruption, and skull and pelvic bone morphology. The skeletons were discovered in random locations and often presented broken bones, which could have resulted from transport by strong currents. The random placement and the absence of traditional funerary burial indicate an unexpected demise (Mjema, 2018). No weapons were discovered at the site, and the bones lack any indications of pathology or blunt force trauma, thus excluding death caused by epidemic or battle.

Radiocarbon dating of charcoal, bones, and shells (both continental and marine) sampled in facies 1, 2, and 3 constrained the age of the sand sheet to between 1008 and 802 cal (calendar) yr B.P. (2σ error). See Section S2 and Table S1 for the full description of radiocarbon dates.

TSUNAMI DEPOSIT INTERPRETATION

Coastal sand sheets may be deposited by river floods or extreme waves, such as those generated by hurricanes or tsunamis (Clague and Bobrowski, 1994). Mjema (2018) suggested a flash flood as the potential cause of the widespread destruction found at the site within stratum 5. The presence of marine fauna and the lack of sedimentary structures and mud drapes, however, make it unlikely that the sand sheet represents a river flood (Nishimura and Miyaji, 1995). The integration of physical criteria with the context in which the deposit occurs is the most reliable mean of differentiating tsunami and storm events (Morton et al., 2007). The deposit in Pangani shows massive or slightly fining-upward sands, lack of sedimentary structures due to bed-load transport, mixed fauna rich in marine species, and plant debris at the top—all features that have been associated with tsunami deposition (Morton et al., 2007). Furthermore, the field site is far from the path of tropical cyclones (see Supplemental Material Section S1), and seasonal storms normally have insufficient energy to generate waves or storm surges strong enough to account for the deposit, which is located ~5 km inland from the Indian Ocean, in a sheltered position on the landward side of the Bweni Escarpment (Fig. 1B). While a storm origin cannot be completely ruled out, as demonstrated in other settings where both storm surge and tsunami inundation may occur (Gouramanis et al., 2017), the sand sheet can be

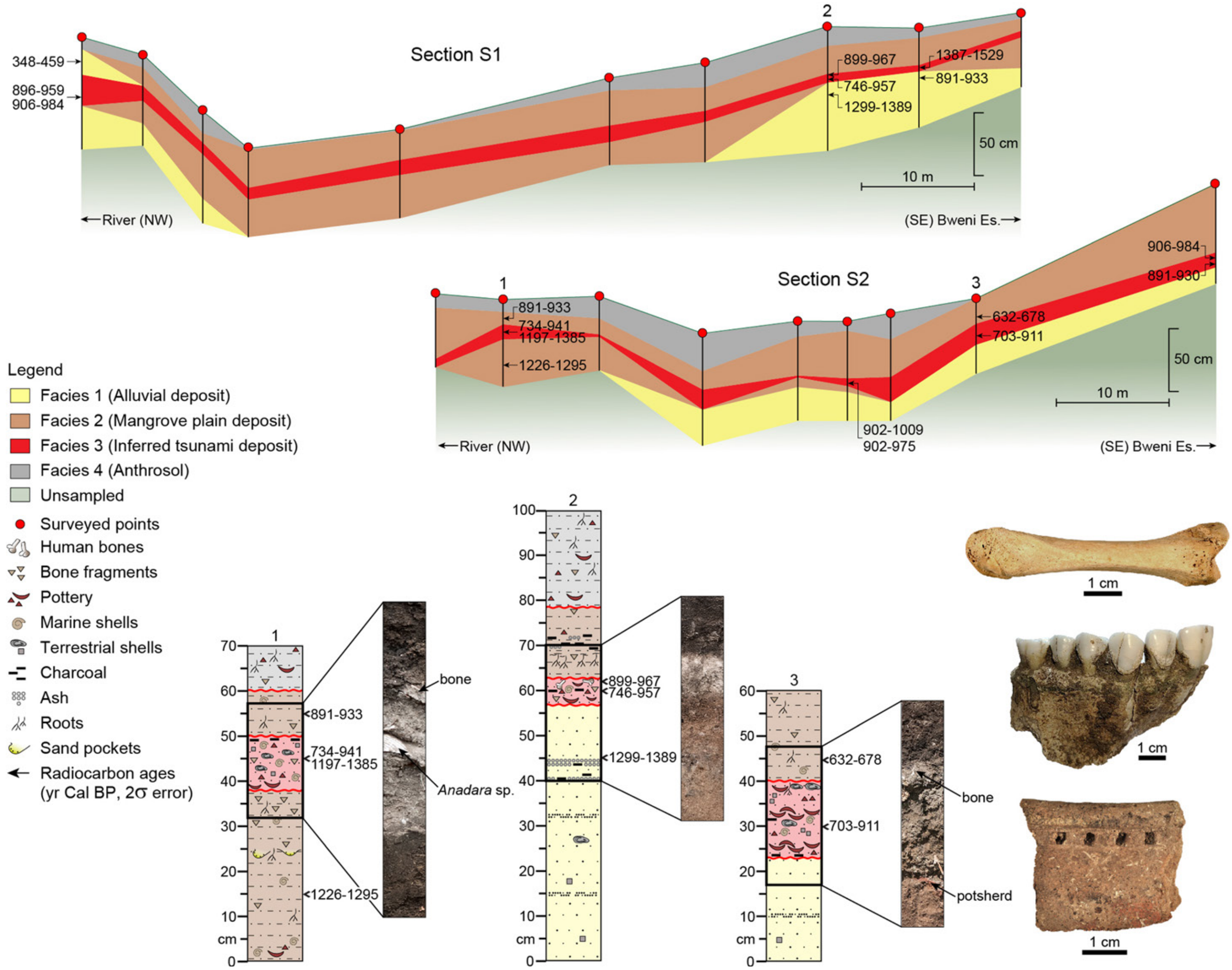

Figure 2. Top: Stratigraphic sections S1 and S2 (at Pangani Bay, Tanzania; location shown in Fig. 1) with reported radiocarbon ages (calendar yr B.P., 2σ error). Numbers 1–3 are stratigraphic logs presented below. Bottom: Stratigraphic logs of selected pits with pictures of inferred tsunami deposit (facies 3) and bounding sediment (facies 1 and 2). Bottom right: Examples of human remains used to date the event and characterize gender and age. Pottery fragment of plain-ware ceramic highlights typical decoration used by early Swahili coastal communities.

best explained as the deposit of a tsunami that inundated the Pangani Bay floodplain at ~1000 cal yr B.P., destroying a Swahili settlement. A tsunami event is inferred not only by the sedimentology of the deposit and its geographic context, but also by the widespread, random presence of human skeletons lacking traditional funerary burial (Mjema, 2018). This evidence is taken as an indication that the instantaneous deposition of the sand layer would have buried the bodies, possibly preventing recovery of the remains, or that the tsunami destroyed the entire village, leaving no survivors. We draw these conclusions based on the scenarios observed in the aftermath of recent large tsunamis, such as the Sumatra-Andaman, Tōhoku (Japan), and Palu (Indonesia) tsunamis.

Sedimentary evidence of a paleotsunami event impacting the coastlines of the northern and eastern Indian Ocean at ~1000 cal yr B.P. has been reported from Thailand, India, Indonesia, southern Sri Lanka, and the Maldives (Fig. 3, and associated references). These records support our interpretation that a tsunami was responsible for the destruction of the Swahili settlement, but they also indicate that the Sumatra-Andaman subduction zone was the potential source for the earthquake that generated the teletsunami deposit preserved at Pangani Bay.

TSUNAMI MODELING

To test this hypothesis, we compared numerical simulations of tsunami wave propagation

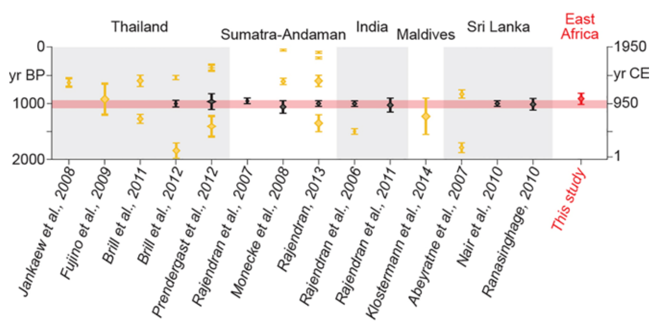

Figure 3. Tsunami deposits found in Indian Ocean coastal sites (ages are plotted as the median value, and uncertainties as the standard errors). Horizontal red line, calculated as the propagated standard error for deposits with age uncertainties <200 yr (in black), highlights the timing of the inferred Tanzania teletsunami.

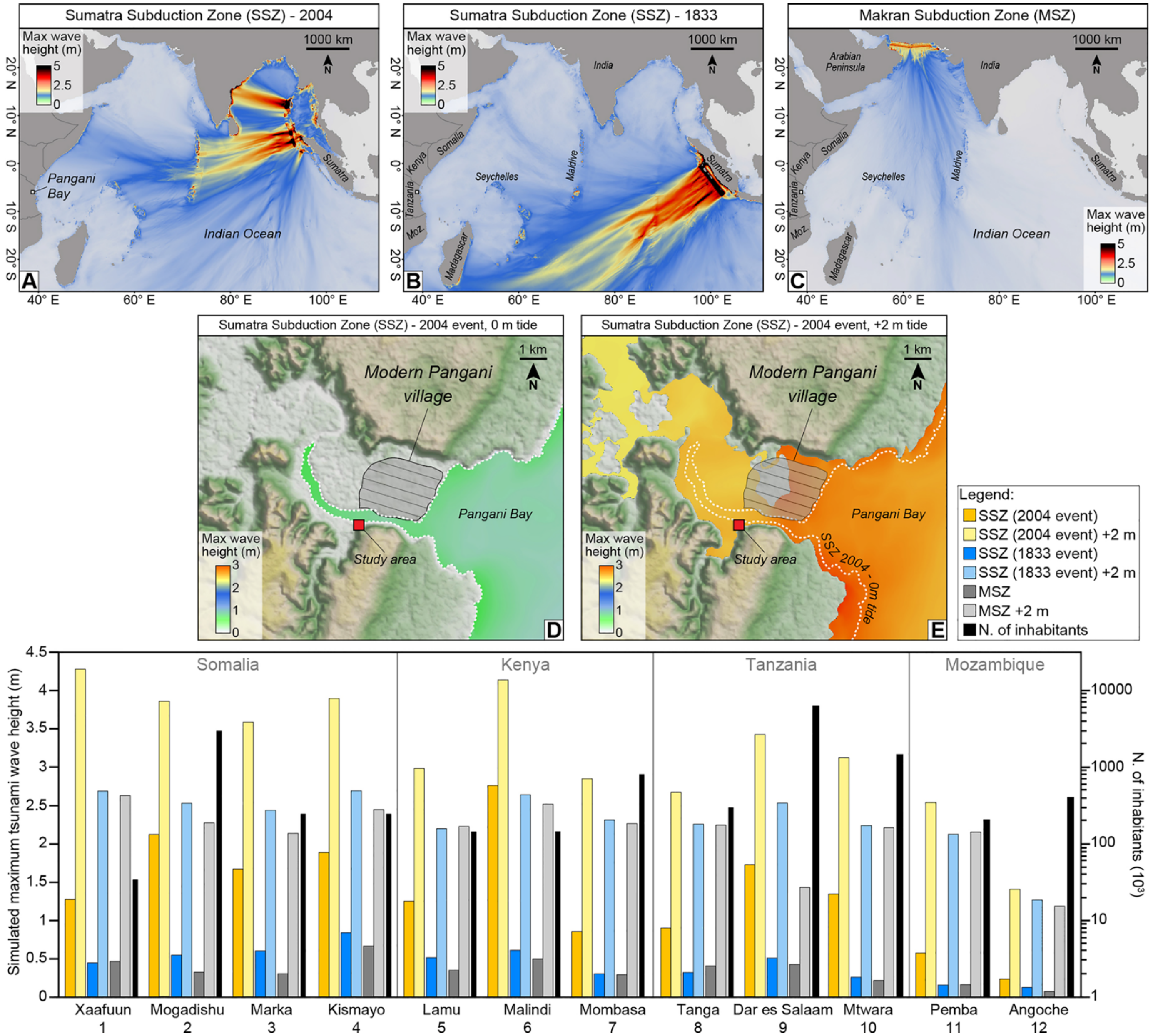

Figure 4. Top: Tsunami maximum wave heights of the 2004 Sumatra-Andaman subduction zone (SSZ) earthquake, the 1833 CE earthquake, and a hypothetical earthquake for the complete rupture of the Makran subduction zone (MSZ). Center: Close-up view in Pangani Bay, Tanzania, of tsunami inundation simulations for the 2004 SSZ earthquake using the Hirata et al. (2006) source model and the same event considering high tide in Pangani Bay (+2 m). Bottom: Tsunami maximum wave heights at 0 m (i.e., mean tide level) and at +2 m (high tide level) for the 2004 SSZ earthquake, the 1833 earthquake, and a hypothetical earthquake for the complete rupture of the Makran subduction zone. Maximum wave heights were evaluated for major coastal cities in East Africa (locations in Fig. 1) with reported number of inhabitants.

generated by three potential earthquakes (Fig. 4; Supplemental Material Section S5): the 2004 Sumatra-Andaman event using the Hirata et al. (2006) source model, the 1833 CE Sumatra earthquake based on Natawidjaja et al. (2006), and an earthquake generated from a complete rupture of the Makran subduction zone (Okal and Synolakis, 2008). Modeling results show that the 2004 Sumatra-Andaman earthquake formed larger tsunami waves in East African countries (i.e., Somalia, Kenya, Tanzania, and Mozambique) in comparison to the other two events (Fig. 4). In addition, high-resolution tsunami inundation simulations for Pangani Bay (Figs. 4D and 4E) indicate that the minimal impact of the 2004 tsunami resulted from the fortuitous, extreme, low spring tide conditions at the time of the first-wave arrival, as confirmed by tide-gauge measurements across the country (Merrifield et al., 2005) and by an eyewitness account (Supplemental Material Section S6).

The 1000-yr-old inferred teletsunami deposit discovered in Pangani Bay can therefore best be explained by a teletsunami sourced by a 2004-like earthquake that originated along the Sunda megathrust, which likely struck during local high-tide conditions. Alternatively, the deposit could indicate a tsunami sourced by an earthquake stronger than the 2004 event, such as one generated by a combined rupture of the Sumatra-Andaman and Nias-Simeulue segments. Although our scenario does take into consideration potential amplification of the tsunami wave(s) by the funnel-shaped geometry of Pangani Bay, the lack of high-resolution multibeam bathymetry for the area under spring tidal conditions prevents us from refining the upper limit on the simulated maximum wave heights. A tsunami generated by a submarine landslide is excluded because bathymetric data acquired offshore of Tanzania do not present evidence for large, contemporaneous, submarine landslides at the seabed capable of generating destructive tsunami waves during the Holocene (Dorschel et al., 2018; Maselli et al., 2019).

DISCUSSION AND CONCLUSIONS

The northern and eastern Indian Ocean coastlines have been hit by tsunami waves during the last few millennia with an uneven recurrence time ranging from 300 to 1000 yr (Jackson et al., 2014; Rubin et al., 2017), while so far only a 1000-yr-old tsunami deposit has been found in the western Indian Ocean. If compared with the 2004 December teletsunami, which left little or no evidence of its impact on the Tanzanian coastline (Okal et al., 2009), the tsunami deposit found in Pangani Bay implies a stronger teletsunami wave either generated by a larger earthquake or amplified by local factors, such as the tide or the shape of the coastline with respect to the direction of the waves (see Yeh et al., 1994). Tsunami modeling indicates that a large rupture of the Sumatra-Andaman plate boundary is the most likely source for any large, potentially devastating tsunami in eastern Africa as well as southern Asia.

Tsunami risk is considered to be low in coastal East African countries, mainly because the impact of the 2004 December teletsunami generated limited damage in such regions (Kijko et al., 2018), with Tanzania being the least affected. The 1000-yr-old tsunami deposit and the evident loss of life indicate, instead, that teletsunamis from the Sumatra-Andaman subduction zone may represent a real threat to life and property on the eastern coast of Africa. This appears to be true even in countries where, due to its arrival during low tide, the impact of the 2004 tsunami was limited, such as in Kenya and Tanzania. Further studies are needed to quantify the recurrence time of tsunami impacts in East Africa and to develop proper tsunami hazard and risk assessments, particularly for the megacities facing the western Indian Ocean.

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REFERENCES CITED

Abeyratne, M., Jayasingha, P., Hewamanne, R., Mahawatta, P., and Pushparani, M.D.S., 2007, Thermoluminescence dating of palaeo-tsunamis and/or large storm-laid sand deposits of a small estuary in Kirinda, southern Sri Lanka: A preliminary study, *in* Proceedings of the 23rd Annual Session of the Geological Society of Sri Lanka: Geological Society of Sri Lanka, p. 6.

Bahlburg, H., and Weiss, R., 2006, Sedimentology of the December 26, 2004, Sumatra tsunami deposits in eastern India (Tamil Nadu) and Kenya: International Journal of Earth Sciences, v. 96, p. 1195–1209, https://doi.org/10.1007/s00531-006-0148-9.

Brill, D., Brückner, H., Jankaew, K., Kelletat, D., Scheffers, A., and Scheffers, S., 2011, Potential predecessors of the 2004 Indian Ocean tsunami: Sedimentary evidence of extreme wave events at Ban Bang Sak, SW Thailand: Sedimentary Geology, v. 239, p. 146–161, https://doi.org/10.1016/j.sedgeo.2011.06.008.

Brill, D., Klasen, N., Jankaew, K., Brückner, H., Kelletat, D., Scheffers, A., and Scheffers, S., 2012, Local inundation distances and regional tsunami recurrence in the Indian Ocean inferred from luminescence dating of sandy deposits in Thailand: Natural Hazards and Earth System Sciences, v. 12, p. 2177–2192, https://doi.org/10.5194/nhess-12-2177-2012.

Clague, J.J., and Bobrowski, P.T., 1994, Tsunami deposits beneath tidal marshes on Vancouver Island, British Columbia: Geological Society of America Bulletin, v. 106, p. 1293–1303, https://doi.org/10.1130/0016-7606(1994)106<1293:TDBTMO>2.3.CO;2.

Dorschel, B., Jensen, L., Arndt, J.E., Brummer, G.-J., de Haas, H., Fielies, A., Franke, D., Jokat, W., Krocker, R., Kroon, D., Pätzold, J., Schneider, R.R., Spieß, V., Stollhofen, H., Uenzelmann-Neben, G., Watkeys, M., and Wiles, E., 2018, The Southwest Indian Ocean Bathymetric Compilation (swIOBC): Geochemistry Geophysics Geosystems, v. 19, p. 968–976, https://doi.org/10.1002/2017GC007274.

Fritz, H.M., and Borrero, J.C., 2006, Somalia field survey after the December 2004 Indian Ocean tsunami: Earthquake Spectra, v. 22, p. S233, https://doi.org/10.1193/1.2201972.

Fujino, S., Naruse, H., Matsumoto, D., Jarupongsakul, T., Sphawajruksakul, A., and Sakakura, N., 2009, Stratigraphic evidence for pre-2004 tsunamis in southwestern Thailand: Marine Geology, v. 262, p. 25–28, https://doi.org/10.1016/j.margeo.2009.02.011.

Gouramanis, C., Switzer, A.D., Jankaew, K., Bristow, C.S., Pham, T.D., and Ildefonso, S., 2017, High-frequency coastal overwash deposits from Phra Thong Island, Thailand: Scientific Reports, v. 7, p. 43742, https://doi.org/10.1038/srep43742.

Hirata, K., Satake, K., Tanioka, Y., Kuragano, T., Hasegawa, Y., Hayashi, Y., and Hamada, N., 2006, The 2004 Indian Ocean tsunami: Tsunami source model from satellite altimetry: Earth, Planets, and Space, v. 58, p. 195–201, https://doi.org/10.1186/BF03353378.

Jackson, K.L., Eberli, G.P., Amelung, F., McFadden, M.A., Moore, A.L., Rankey, E.C., and Jayasena, H.A.H., 2014, Holocene Indian Ocean tsunami history in Sri Lanka: Geology, v. 42, p. 859–862, https://doi.org/10.1130/G35796.1.

Jankaew, K., Atwater, B.F., Sawai, Y., Choowong, M., Charoentitrat, T., Martin, M.E., and Prendergast, A., 2008, Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand: Nature, v. 455, p. 1228–1231, https://doi.org/10.1038/nature07373.

Kijko, A., Smit, A., Papadopoulos, G.A., and Novikova, T., 2018, Tsunami hazard assessment of coastal South Africa based on mega-earthquakes of remote subduction zones: Pure and Applied Geophysics, v. 175, p. 1287–1304, https://doi.org/10.1007/s00024-017-1727-3.

Klostermann, L., Gischler, E., Storz, D., and Hudson, J.H., 2014, Sedimentary record of late Holocene event beds in a mid-ocean atoll lagoon, Maldives, Indian Ocean: Potential for deposition by tsunamis: Marine Geology, v. 348, p. 37–43, https://doi.org/10.1016/j.margeo.2013.11.014.

Maselli, V., Iacopini, D., Ebinger, C., and Kroon, D., 2019, Margin instability at the onset of the EARS in Tanzania and impact on the deep-water depositional systems of the western Somali Basin: Detailed Conference Program of the 34th IAS Meeting of Sedimentology, 10–13 September, Rome, Italy, p. 72.

Mays, S., 2010. The Archaeology of Human Bones (2nd ed.): London, Taylor and Francis Group, 432 p., https://doi.org/10.4324/9780203851777.

Merrifield, M.A., et al., 2005, Tide gauge observations of the Indian Ocean tsunami, December 26, 2004: Geophysical Research Letters, v. 32, L09603, https://doi.org/10.1029/2005GL022610.

Mjema, E., 2018, Catastrophes and deaths along Tanzania's western Indian Ocean coast during the Early Swahili period, AD 900–1100: Azania, v. 53, no. 2, p. 135–155, https://doi.org/10.1080/0067270X.2018.1473208.

Monecke, K., Finger, W., Klarer, D., Kongko, W., McAdoo, B.G., Moore, A.L., and Sudrajat, S.U., 2008, A 1,000-year sediment record of tsunami recurrence in northern Sumatra: Nature, v. 455, p. 1232–1234, https://doi.org/10.1038/nature07374.

Morton, R.A., Gelfenbaum, G., and Jaffe, B.E., 2007, Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples: Sedimentary Geology, v. 200, p. 184–207, https://doi.org/10.1016/j.sedgeo.2007.01.003.

Nair, R.R., Buynevich, I., Goble, R.J., Srinivasan, P., Murthy, S.G.N., Kandpal, S.C., Vijaya Lakshmi, C.S., and Trivedi, D., 2010, Subsurface images shed light on past tsunamis in India: Eos (Washington, D.C.), v. 91, p. 489–490, https://doi.org/10.1029/2010EO500002.

Natawidjaja, D., Sieh, K., Chlieh, M., Galetzka, J., Suwargadi, B., Cheng, H., Edwards, R.L., Avouac, J.P., and Ward, S., 2006, Source parameters of the great Sumatran megathrust earthquakes of 1797 and 1833 inferred from coral microatolls: Journal of Geophysical Research, v. 111, B06403, https://doi.org/10.1029/2005JB004025.

Nishimura, Y., and Miyaji, N., 1995, Tsunami deposits from the 1993 Southwest Hokkaido earthquake and the 1640 Hokkaido Komagatake eruption, northern Japan, *in* Imamura, F., and Satake, K., eds., Tsunamis: 1992–1994: Basel, Switzerland, Birkhäuser, Pageoph Topical Volumes, https://doi.org/10.1007/978-3-0348-7279-9_19.

Obura, D., 2006, Impacts of the 26 December 2004 tsunami in eastern Africa: Ocean and Coastal Management, v. 49, p. 873–888, https://doi.org/10.1016/j.ocecoaman.2006.08.004.

Okal, E.A., and Synolakis, C.E., 2008, Far-field tsunami hazard from mega-thrust earthquakes in the Indian Ocean: Geophysical Journal International, v. 172, p. 995–1015, https://doi.org/10.1111/j.1365-246X.2007.03674.x.

Okal, E.A., Fritz, H.M., and Sladen, A., 2009, 2004 Sumatra-Andaman tsunami surveys in the Comoro islands and Tanzania and regional tsunami hazard from future Sumatra events: South African Journal of Geology, v. 112, p. 343–358, https://doi.org/10.2113/gssajg.112.3-4.343.

Prendergast, A.L., Cupper, M.L., Jankaew, K., and Sawai, Y., 2012, Indian Ocean tsunami recurrence from optical dating of tsunami sand sheets in Thailand: Marine Geology, v. 295–298, p. 20–27, https://doi.org/10.1016/j.margeo.2011.11.012.

Rajendran, C.P., Rajendran, K., Machado, T., Satyamurthy, T., Aravazhi, P., and Jaiswal, M., 2006, Evidence of ancient sea surges at the Mamallapuram coast of India and implications for

previous Indian Ocean tsunami events: Current Science, v. 91, p. 1242–1247.
Rajendran, C.P., Rajendran, K., Anu, R., Earnest, A., Machado, T., Mohan, P.M., and Freymueller, J., 2007, Crustal deformation and seismic history associated with the 2004 Indian Ocean earthquake: A perspective from the Andaman-Nicobar Islands: Bulletin of the Seismological Society of America, v. 97, p. 174–191, https://doi.org/10.1785/0120050630.
Rajendran, C.P., Rajendran, K., Srinivasalu, S., Andrade, V., Aravazhi, P., and Sanwal, J., 2011, Geoarchaeological evidence of a Chola-period tsunami from an ancient port at Kaveripattinam on the southeastern coast of India: Geoarchaeology, v. 26, p. 867–887, https://doi.org/10.1002/gea.20376.
Rajendran, K., 2013, On the recurrence of great subduction zone earthquakes: Current Science, v. 104, p. 880–892.
Ranasinghage, P.N., 2010, Holocene Coastal Development in Southeastern-Eastern Sri Lanka: Paleodepositional Environments and Paleo-Coastal Hazards [Ph.D. thesis]: Kent, Ohio, Kent State University, 437 p.
Rubin, C.M., Horton, B.P., Sieh, K., Pilarczyk, J.E., Daly, P., Ismail, N., and Parnell, A.C., 2017, Highly variable recurrence of tsunamis in the 7,400 years before the 2004 Indian Ocean tsunami: Nature Communications, v. 8, p. 16019, https://doi.org/10.1038/ncomms16019.
Yeh, H., Liu, P., Briggs, M., and Synolakis, C., 1994, Propagation and amplification of tsunamis at coastal boundaries: Nature, v. 372, p. 353–355, https://doi.org/10.1038/372353a0.

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