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Workshop Reports

ICDP workshop on the Lake Tanganyika Scientific Drilling Project: a late Miocene–present record of climate, rifting, and ecosystem evolution from the world's oldest tropical lake

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Abstract. The Neogene and Quaternary are characterized by enormous changes in global climate and environments, including global cooling and the establishment of northern high-latitude glaciers. These changes reshaped global ecosystems, including the emergence of tropical dry forests and savannahs that are found in Africa today, which in turn may have influenced the evolution of humans and their ancestors. However, despite decades of research we lack long, continuous, well-resolved records of tropical climate, ecosystem changes, and surface processes necessary to understand their interactions and influences on evolutionary processes. Lake Tanganyika, Africa, contains the most continuous, long continental climate record from the mid-Miocene ($\sim$ 10 Ma) to the present anywhere in the tropics and has long been recognized as a top-priority site for scientific drilling. The lake is surrounded by the Miombo woodlands, part of the largest dry tropical biome on Earth. Lake Tanganyika also harbors incredibly diverse endemic biota and an entirely unexplored deep microbial biosphere, and it provides textbook examples of rift segmentation, fault behavior, and associated surface processes. To evaluate the interdisciplinary scientific opportunities that an ICDP drilling program at Lake Tanganyika could offer, more than 70 scientists representing 12 countries and a variety of scientific disciplines met in Dar es Salaam, Tanzania, in June 2019. The team developed key research objectives in basin evolution, source-to-sink sedimentology, organismal evolution, geomicrobiology, paleoclimatology, paleolimnology, terrestrial paleoecology, paleoanthropology, and geochronology to be addressed through scientific drilling on Lake Tanganyika. They also identified drilling targets and strategies, logistical challenges, and education and capacity building programs to be carried out through the project. Participants concluded that a drilling program at Lake Tanganyika would produce the first continuous Miocene–present record from the tropics, transforming our understanding of global environmental change, the environmental context of human origins in Africa, and providing a detailed window into the dynamics, tempo and mode of biological diversification and adaptive radiations.

1 Introduction

The Earth has experienced enormous environmental changes during the last 10 million years, including global cooling that culminated in permanent ice in the northern high latitudes, the expansion of C_4 grasslands and other dry tropical biomes, and the development of globally synchronized glacial–interglacial cycles (Cerling et al., 1993; Zachos et al., 2001). Our knowledge of these transitions and their global impacts is primarily based on deep-sea drill cores, yet many of these transitions unfolded on land, where they reshaped the continents and influenced organismal evolution and dispersal, including that of our own species. Scientific drilling under the auspices of the International Continental Drilling Program (ICDP) has begun to elucidate the terrestrial environmental changes that accompanied these events (Soreghan and Cohen, 2013), yet we still lack long, continuous, independently dated sedimentary records to document the rates, amplitudes, and dynamics of continental environmental change from the Miocene to the present. This is particularly the case in the tropics, despite their critical role in maintaining Earth's climate and biodiversity.

Lake Tanganyika (LT), East Africa (Fig. 1) is one of the oldest, largest, and deepest lakes on Earth and is a truly unrivaled site for scientific drilling. Its stratigraphy, which spans the Miocene–present, is the most continuous continental record for this time interval known in the tropics (Colman, 1996). Scientific drilling in LT could thus provide a unique, high-resolution record of tropical continental climate in the late Cenozoic. LT is also one of the most biodiverse lakes on Earth (Salzburger et al., 2014, and fills one of the most deeply subsided parts of the East African rift (Ebinger, 1989). Drilling LT offers outstanding opportunities to investigate evolutionary transitions in aquatic and terrestrial organisms and ecosystems, and the geological evolution of a large continental rift system. In the last 6 years we have convened a series of disciplinary workshops that developed a strong consensus that drilling LT will transform our understanding of climatic, evolutionary, and rift processes (Cohen and Salzburger, 2017; McGlue and Scholz, 2016; Russell et al., 2012). To expand on these objectives, and to develop a fully integrated, interdisciplinary scientific drilling program on Lake Tanganyika, we held an ICDP workshop in Dar es Salaam, Tanzania, from 17 to 20 June 2019, attended by more than 70 scientists. Workshop attendees defined the scientific rationale, drilling targets and logistics, and other plans for the Lake Tanganyika Scientific Drilling Project (TSDP).

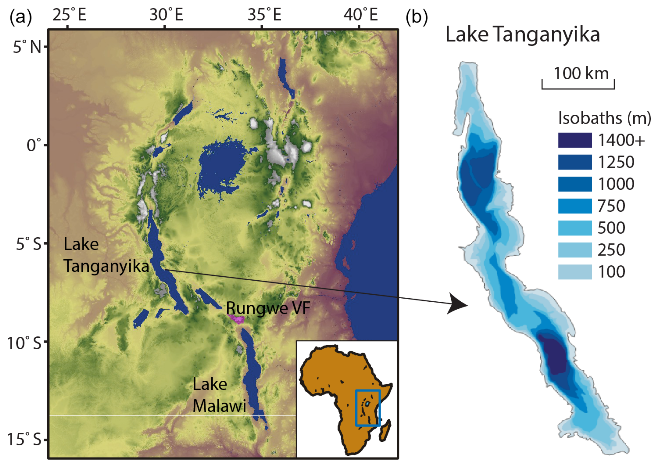

Figure 1. Topographic map of East Africa from SRTM data showing the location of Lake Tanganyika; figure modified from Russell et al. (2012). The lower left inset shows the location of the region within Africa. In panel **(b)**, a bathymetric map of Tanganyika illustrates the major depositional sub-basins within the lake.

2 Lake Tanganyika: a world-class site for scientific drilling

Lake Tanganyika (32 600 km^2, 1470 m deep, 4–9° S, 29–31° E) is near the center of the western branch of the East African Rift on the border between Tanzania, the Democratic Republic of Congo (DRC), Burundi, and Zambia (Fig. 1). Precipitation is strongly seasonal, with a pronounced dry season from June to August when the tropical rain belt shifts northward. During this season, strong southerly winds associated with the East African and Indian monsoons flow over the basin and cause lake upwelling that drives primary production by algae, especially diatoms, forming the basis for a fishery that has yielded up to ∼ 200 000 t of fish annually (Descy et al., 2005), one of the largest inland fisheries in the world. All of these components of LT vary in response to climate, as documented in intricate detail by geochemical and fossil records in shallow sediment cores (Cohen and Salzburger, 2017; Tierney and Russell, 2007).

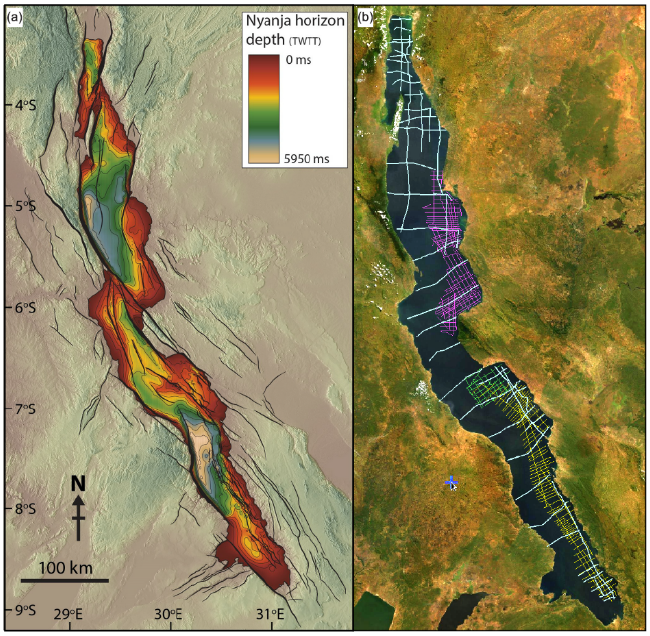

Figure 2. In panel **(a)**, a contour map shows the two-way travel time from lake surface to acoustic basement (i.e., the Nyanja Event) deduced from seismic reflection data shown within a regional digital elevation model based on 90 m Surface Radar Topography Mission data. Major interpreted faults are shown. In panel **(b)**, a map of seismic lines collected from Lake Tanganyika overlain on a satellite image (© Esri imagery – source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS). Light blue lines are 24-fold multichannel seismic lines collected by Project PROBE 1993–1984. Green lines are single-channel sparker profiles collected during the Nyanza Project (McGlue et al., 2008). Yellow profiles are 60-fold data acquired in 2012 as part of a commercial exploration program. Magenta lines are single-channel high-resolution air-gun profiles collected in 1997.

Lake Tanganyika is part of East Africa's western rift (Rosendahl, 1987; Ebinger, 1989). Extension is accommodated by steeply dipping border faults that commonly form the coastlines of the lake (Fig. 2). Nine border faults link together to form the Lake Tanganyika rift, producing several sub-basins with water depths of 1000 m or more separated by deep-water horsts (Scholz and Rosendahl, 1988). The Rungwe Volcanic Province (RVP) lies ~ 250 km south of LT. RVP volcanism has been ongoing since at least 9 Ma and is dominated by effusive and explosive eruptions, with the oldest pyroclastic units dated to ~ 8.6 Ma (Fontijn et al., 2012). Several volcanic ash beds derived from the RVP have been found in shallow cores from southern LT (e.g., Livingstone, 1965), suggesting great potential for tephra-based age control in our project.

Several thousand kilometers of reflection seismic data have been acquired on Lake Tanganyika (McGlue et al., 2008; Muirhead et al., 2019; Rosendahl, 1988; Scholz et al., 2003), including a commercial survey of the southeastern part of the Tanzanian side of the lake completed in 2012 (Fig. 2). LT's seismic stratigraphic section is comprised of a set of four major depositional sequences (Fig. 3) that overlie a set of reflections referred to as the "Nyanja Event", which is interpreted to mark the onset of the current phase of rifting and the initiation of the present-day LT (Rosendahl, 1988). Its Cenozoic sedimentary succession has been divided into six sequences (Muirhead et al., 2019) that vary widely in thickness across the basin. These sequences include the following:

- *Sequence S1, characterized by low-amplitude, discontinuous reflections.* The relatively uniform thickness and character of this sequence implies low-relief, shallow lacustrine and fluvial environments formed during the earliest phase of the formation of LT.

- *Sequence S2, which consists of high-frequency reflectors and thickens westward, indicating subsidence of the western border fault.* Zones of high continuity extend over tens of kilometers, implying that a deep rift lake was in place by this time.

- *Sequences S3–S5 are characterized by alternating high- and low-amplitude reflectors, often with incised channels and paleodeltaic deposits.* This suggests varying lake levels, probably caused by Plio-Pleistocene climatic changes, with water-level changes of up to 600 m.

- *Sequence S6, characterized by low-amplitude but high-frequency, high-continuity sediments.* The character, lateral extent, and external draping form are all similar to fine-grained hemipelagic muds drilled in nearby Lake Malawi (Scholz et al., 2011).

Most core-based research at LT has focused on the last glacial cycle to the present, as only short piston cores (~ 10 m or less from within S6) are available. Sedimentological data documented a lake lowstand of ~ 200 m during the Last Glacial Maximum (McGlue et al., 2008), when temperatures ~ 3 °C cooler than present allowed Afromontane forests to expand around the lake (Ivory and Russell, 2016). Following these cold, dry conditions, climate rebounded during the Pleistocene–Holocene transition, marked by a very warm, wet early-Holocene interval known as the "African Humid Period" (Tierney et al., 2008). These events occurred throughout much of equatorial and northern Africa (Otto-Bliesner et al., 2014), highlighting LT's potential as a "master record" of African environmental history. Organic geochemical analyses of short cores have shown that the lake has warmed by 1–2 °C in the last century in response to anthropogenic greenhouse gas forcing, resulting in significant reductions in nutrient upwelling, primary productivity, mollusks, and fish (Cohen et al., 2016). These results highlight the potential of an LT drill core to provide quantitative estimates of tropical climate, to record climate variations, and to

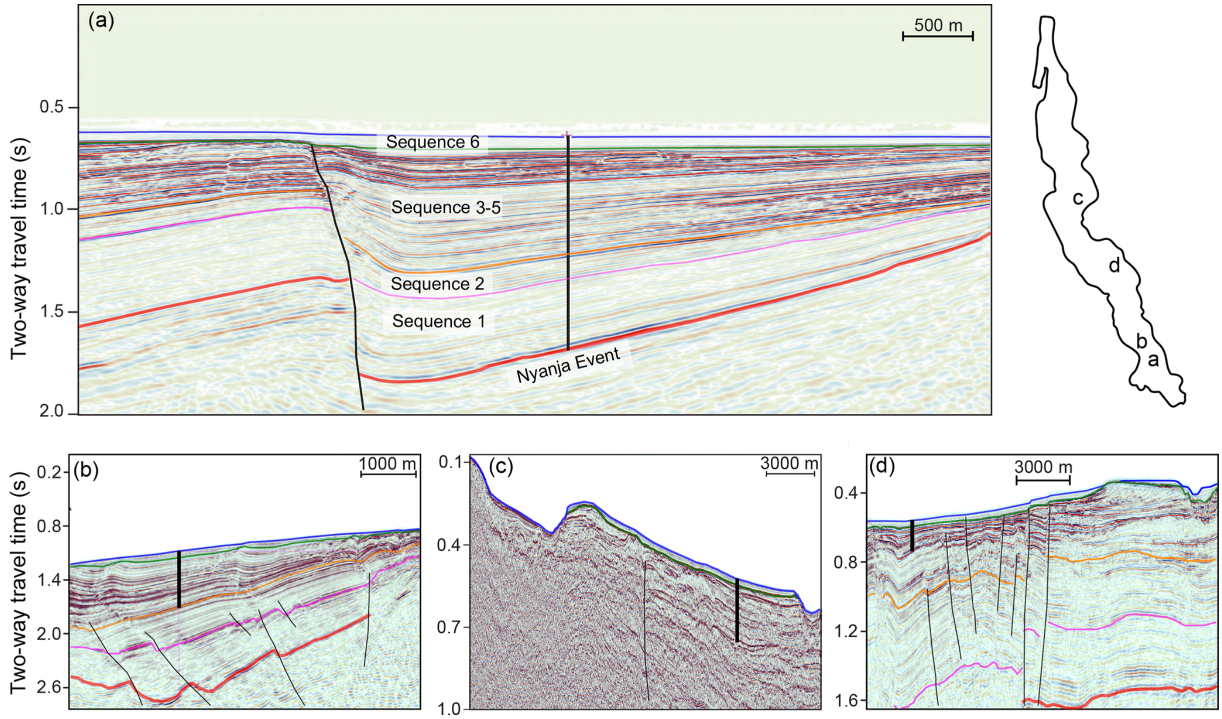

Figure 3. Seismic reflection profiles showing potential drilling sites at Lake Tanganyika. Panel **(a)** illustrates a potential drilling site that captures the major seismic sequences (S1–S6) present in the lake. Sequences S3–S5 are condensed and likely truncated by erosion at this site, but these sequences can be drilled at a nearby site in deeper water **(b)**. Panels **(c)** and **(d)** illustrate sections in shallower water where fossiliferous sediments can be drilled for evolutionary biological studies. In all panels, black lines indicate potential drill holes, blue lines trace the lake floor; red lines indicate the Nyanja event (the interpreted base of the modern rift); and pink, orange, and green lines trace the boundaries between sequences 1 and 2, 2 and 3, and 5 and 6, respectively.

record the response of equatorial climate to global forcings and processes.

3 Workshop structure and findings

We convened a workshop to define scientific priorities and analyses, logistics, drilling targets, and education and outreach plans for a deep scientific drilling project in Lake Tanganyika. Presentations on the first day focused on the limnology of Lake Tanganyika and the evolutionary history of its biota, the structural geology of the East African and Tanganyikan rifts, the sedimentary architecture of LT, and the environmental history of East Africa. Participants then spent the next three days in breakout groups to develop scientific hypotheses and strategies in the broad areas of paleoclimatology, basin evolution, source-to-sink sedimentology, organismal evolution, paleolimnology, terrestrial paleoecology, paleoanthropology, geomicrobiology, and geochronology. These scientific breakout discussions led to prioritized research goals within each group linked to drilling targets, from which we developed a coordinated, parsimonious drilling plan.

Sub-Saharan Africa is highly socioeconomically vulnerable to future climate change. However, considerable uncertainty remains in climate predictions for the continent (Niang et al., 2014), demanding that we test climate model simulations against reconstructions of climate under higher greenhouse gas concentrations than the present. The Miocene–Pliocene presents the best analog for future climate, as continental configurations were similar to the present yet greenhouse gas concentrations were higher than present (Haywood et al., 2016; Zhang et al., 2013). Shallow cores from LT have provided outstanding records of late Quaternary to recent changes in climate (Cohen et al., 2016; Tierney et al., 2008) and benchmark targets for late-Pleistocene paleoclimate modeling (Otto-Bliesner et al., 2014), highlighting the lake's potential to establish a tropical paleoclimate reference section for the late Neogene. Thus, LT offers an unmatched opportunity to evaluate the response of tropical rainfall and temperature to changes in high-latitude glaciation, greenhouse gas concentrations, insolation forcing, and other changes in global climate boundary conditions during the last ~ 10 million years. The occurrence of severe hydroclimate fluctuations and lake level draw-downs over the past 200 kyr in the Malawi Rift are well-documented (Scholz et al., 2011), and other extant lakes in Africa, including LT (Burnett et al., 2011), show evidence of similar variability. Drilling in LT is critical for determining the phasing of this high-amplitude variability across the African tropics. Moreover, TSDP will represent the culmination of several decades of scientific drilling and coring in East African lakes and paleolakes. ICDP records from Lake Malawi, the Hominin Sites and Paleolakes Drilling Project (HSPDP), and Lake Challa have provided considerable insight into East African climate but continuously span only the last ~ 1.2 Myr at Lake Malawi (Ivory et al., 2016), with more discontinuous HSPDP records back to 3.3 Ma (Campisano et al., 2017). A long, continuous record from LT will therefore provide a master stratigraphy from the region to contextualize the Lake Malawi, HSPDP, and Lake Challa records within late Miocene–present environmental change.

The western branch of the East African rift is the global archetype of an active, amagmatic early-stage rift, and its thick sediments preserve a multimillion-year record of extensional tectonics and landscape evolution. The western branch of the rift experiences the largest magnitude earthquakes of the African continent, and presents textbook examples of rift segmentation and fault behavior (Lavayssière et al., 2019). This deep, anoxic, freshwater body is also commonly cited as a classic example of a continental basin accumulating lacustrine petroleum source rocks (Katz, 1996), yet stratigraphic prediction in ancient low-latitude rift basins has been a major challenge. TSDP will provide opportunities to investigate (1) how along-strike basin segmentation and fault growth impact sedimentation and source-to-sink processes; (2) the dynamics of fault slip, propagation and linkage, and whether they conform to rifting models; (3) the history of magmatic activity and geothermal gradients and how they relate to basin evolution in a "cold rift"; and (4) how these processes influence Tanganyika's limnological and biological evolution, stratigraphy, and resources.

Understanding how ecosystems are assembled and altered through time, and how speciation, dispersal, and extinction shape species assemblages and communities has been a fundamental problem in ecology and evolutionary biology ever since Darwin. LT harbors spectacular endemic faunas, with hundreds of unique species of fish, in particular cichlids, as well as mollusks, and crustaceans that have evolved over the lake's long history (Salzburger et al., 2014). These endemic species form unique communities in benthic and pelagic habitats, and many of these organisms have left fossil records in LT's sediments (e.g., Cohen et al., 2016). Together with ancient DNA (aDNA) analyses these fossils will provide records of the evolution, radiation, and extinction of endemic taxa and coevolved ecosystems. The combination of LT's antiquity and size probably accounts for its extraordinary diversity, but the role of limnological, climatic, and tectonic changes in shaping LT's flora and fauna remain largely hypothetical. The availability of a continuous paleolimnological record of the lake together with fossil and, in the younger intervals, aDNA records of the lake's endemic organisms would allow us for the first time to understand the rates, dynamics, and drivers of adaptive radiation – a truly transformative advance for evolutionary biology.

Lake Tanganyika is surrounded by Miombo woodlands, part of the largest dry forest tropical biome on Earth. It is generally assumed that these ecosystems arose at the expense of the Guineo-Congolian rainforests to the west, but there is little evidence to support this hypothesis. Palynological records from LT have highlighted the sensitivity of Miombo and other surrounding ecosystems to climate and environmental changes, including human impacts (Ivory and Russell, 2016). Our understanding of the processes that generated the present-day structure of these ecosystems would be greatly enhanced by records spanning the larger range of climate variations occurring from the Miocene to the present. Moreover, Africa has a long history of hominin–environmental interactions. A Miocene–present record from LT will provide a benchmark record of the environmental context in which our ancestors lived and evolved.

While Lake Tanganyika is renowned for its aquatic biodiversity, its microbial diversity in the water column and sediments remain largely unknown. Drill cores will allow us to explore LT's deep biosphere, the role it plays in the lake's carbon, nitrogen, sulfur, and other elemental cycles, and how the water column and sedimentary microbial communities vary in relation to climatic and tectonic changes. Changes in the microbial community, acting in concert with limnological processes and climatically and tectonically driven changes in the lake's physical structure, should govern key aspects of the lake ecosystem, including primary productivity, and ultimately its biodiversity.

Investigations of Lake Tanganyika's depositional history will require a robust geochronology. Participants reviewed state-of-the-art geochronological techniques and their applicability to LT sediments. In addition to the Rungwe Volcanic Province (RVP) in southern Tanzania, significant Neogene–Quaternary volcanic events in the Central Kenyan Rift, northern Tanzania and the Virunga Volcanic Province could have transported ash to the LT basin. RVP-derived tephra are relatively rich in potassium (Fontijn et al., 2012), and several are known to be present in Holocene-age sediments from southern LT (e.g., Livingstone, 1965). Ar–Ar ages from RVP tephra in the lake core, or from coarser correlative proximal outcrops, will provide multiple anchor points for our core chronology, and this opportunity guides us to concentrate our drilling efforts in LT's southern basin. Ar–Ar, together with ^{14}C, luminescence dating, paleomagnetic, and other dating techniques, will provide vital independent age estimates for the LT core chronology, as well as contributing to future regional geochronologic and earth system studies. This effort will provide a new eastern African palaeomagnetic reference curve back to the Miocene and a stratified multi-million-year record of explosive volcanism from the southern East African rift volcanic provinces.

Ultimately our goal is to integrate information from these different fields to understand the coupled climatic, geologic, and biological processes that control the evolution of Africa's largest rift lake. Participants discussed possible drilling targets and strategies to address these issues, and the need for continuity, resolution, and lithologies through the different sedimentary units (sequences S1–S6) to address the goals outlined above. Participants emphasized the importance of determining LT's age and early conditions, and the transformative nature of a Miocene–present paleoclimate record from the tropics. Subsidence and sedimentation rate estimates suggest the Nyanja Event occurred between 9 and 12 Ma (Cohen et al., 1993). Accordingly, sequences S1 and S2 could date to the Miocene and Pliocene, and S3–S6 to the Pleistocene and Holocene. Thus, the team agreed on the importance of obtaining a complete representative section from the lake – i.e., a record extending to the Nyanja Event. Participants also highlighted the importance of obtaining fine-grained, continuous sediments for state-of-the-art paleoenvironmental analyses and for essential geochronologic control. It is prohibitively expensive to drill 2–3 km holes from LT's deep basins, where sedimentation rates are rapid (0.5 m kyr^{-1} or more). However, our team has identified hemipelagic sections that include all of the major sedimentary units in LT, in water depths below the maximum depth of lake lowstands and with combined water and sediment depths of $\sim$ 1500 m (Fig. 3), achievable with intermediate-scale drilling technology.

Based on these needs, we anticipate an offset drilling program at two sites in southern Lake Tanganyika, proximal to the Rungwe volcanoes and where we have excellent seismic stratigraphic constraints. Two offset holes drilled to $\sim$ 1500 m depth (combined water and sediment) will allow recovery of a relatively complete Miocene–present record (Fig. 3a and b). A shallow ($\sim$ 100 m) hole at one of these sites will provide sediment for geomicrobiological investigations across the strong biogeochemical gradients that should exist in the uppermost sediment column. We anticipate also recovering a set of shallow holes in central LT to evaluate evolutionary and paleolimnological gradients during lake level lowstands that might bifurcate LT into multiple basins (Fig. 3c and d). We are now pursuing pre-drilling logistical and scientific activities including the assembly of a Tanganyika database to improve access to information about the lake, drilling platform design, safety evaluations and project permitting, methodological tests using existing sediment cores, and educational and outreach activities within the riparian countries.

Data availability. No data sets were used in this article.

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Competing interests. The authors declare that they have no conflict of interest.

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