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CONSERVATION LIMNOGEOLOGY AND BENTHIC HABITAT MAPPING IN CENTRAL LAKE TANGANYIKA (TANZANIA)

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CONSERVATION LIMNOGEOLOGY AND BENTHIC HABITAT MAPPING IN CENTRAL LAKE TANGANYIKA (TANZANIA)

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Arts and Sciences
at the University of Kentucky

By

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Lexington, Kentucky

Director: Dr. Michael McGlue, Professor of Earth and Environmental Sciences

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2018

ABSTRACT OF THESIS

CONSERVATION LIMNOGEOLOGY AND BENTHIC HABITAT MAPPING IN CENTRAL LAKE TANGANYIKA (TANZANIA)

Small scale protected zones are valuable for helping the health and productivity of fisheries at Lake Tanganyika (East Africa). Spatial placement of protected areas relies on accurate maps of benthic habitats, consisting of detailed bathymetry data and information on lake-floor substrates. This information is unknown for most of Lake Tanganyika. Fish diversity is known to correlate with rocky substrates in ≤30 m water depth, which provide spawning grounds for littoral and pelagic species. These benthic habitats form important targets for protected areas, if they can be precisely located.

At the NMVA, echosounding defined the position of the 30-m isobath and side-scan sonar successfully discriminated among crystalline basement, $CaCO_3$-cemented sandstones, mixed sediment, and shell bed substrates. Total area encompassed from the shoreline to 30 m water depth is ~21 km^2 and the distance to the 30-m isobath varies with proximity to deltas and rift-related faults. Total benthic area defined by crystalline basement is ~1.6 km^2, whereas the total area of $CaCO_3$-cemented sandstone is 0.2 km^2. Crystalline basement was present in all water depths (0-30 m), whereas $CaCO_3$-cemented sandstones were usually encountered in water ≤5 m deep. Spatial organization of rocky substrates is chiefly controlled by basin structure and lake level history.

KEYWORDS: Bathymetry, benthic habitats, fisheries, Lake Tanganyika, protected areas, side scan sonar

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09/29/2018

Date

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INTRODUCTION

Lake Tanganyika is the oldest and deepest of the East African rift valley lakes (McGlue et al., 2008). Estimated to be ~9 - 12 Ma, the lake extends from 3° to 9° S and sits at an elevation of ~774 meters above sea level (Figure 1) (Cohen, Bill, Cocquyt, & Caljon, 1993). Owing to its origins as a continental rift, Lake Tanganyika fills a series of opposing half graben structural basins, and in several areas, shorelines are adjacent to high angle border faults that form steep mountain ranges > 2000 m above sea level (Figure 1) (Versfelt & Rosendahl, 1989). Located along the borders of the Democratic Republic of the Congo, Tanzania, Burundi, and Zambia, the Lake Tanganyika watershed is home to a rapidly growing population that exceeds ten million people (The Nature Conservancy, 2018. https://www.africangreatlakesinform.org/article/lake-tanganyika). Lakeshore villagers are challenged by poverty, disease, and the effects of environmental degradation associated with unregulated development (Hess & Leisher, 2011). Poorly-organized local governance and inadequate social services makes the people of Lake Tanganyika reliant on locally acquired natural resources to meet many of their basic needs. Fish are an environmentally-sensitive and non-renewable resource in this context (Kimirei & Mgaya, 2007).

The fish of Lake Tanganyika have been studied for many years, in part due to the spectacular diversity of the lake's endemic cichlids (Day, Cotton, & Barraclough, 2008). Though considerably less diverse, Lake Tanganyika's pelagic zone hosts six endemic fish species, four types of *Lates* (*L. angustifrons, L. mariae, L. microlepis, L. stappersi*), and two sardine-like clupeid species (*Limnothrissa miodon, Strolothrissa tanganicea*) (Coulter, 1991). The littoral zone contains in excess of 200 unique species of cichlid fish and numerous endemic invertebrates, including species flocks of snails, crabs, and ostracodes (Salzburger, Van Bocxlaer, & Cohen, 2014). All of the Lates species, with the possible exception of *L. stappersii,* utilize the shallow littoral zone extensively early in their life cycles (Coulter, 1991; Coulter & Mubamba, 1993). With respect to the commercially valuable fish stocks, the most exploited species are *S. tanganicae* and *L. stappersi* (Mannini, Katonda, Kissaka, & Verburg 1999; Plisnier et al., 2009).

Although Lake Tanganyika is not recognized as highly productive, its pelagic food web has yielded up to 200,000T of fish per year, most of which is exploited locally (Edmond et al., 1993; Mölsä et al., 2002). The clupeids, locally known as *dagaa*, are especially valuable because they can be dried or smoked, which preserves these fish for several weeks and allows them to be shipped and sold as a food commodity regionally (Coulter, 1991). Thus, in addition to their importance as a protein source, fish represent one of the few sources of cash income for lakeshore villagers. In addition to the *dagga*, a market exists for many cichlids, which are valued as aquarium pets in Europe and North America (Hecky, Spiegel, & Coulter 1991; Alin et al., 1999). However, both the nearshore and offshore fisheries at Lake Tanganyika are under pressure from climatic warming (Cohen et al., 2016). Warming of the lake surface appears to induce a strengthening of water column stratification, which alters nutrient cycling, damages primary productivity, reduces benthic oxygen, and has a cascade effect on virtually the entire food web (O'Reilly et al., 2003; Kimirei, Mgaya, & Chande 2008; Plisnier et al., 2009). Notably, each of Lake Tanganyika's four riparian nations have population growth rates >2.4%, which is more than double the world mean (www.cia.gov). Thus, as the threats from climate change materialize at Lake Tanganyika, the regional demand for fish is rising, and factors such as geographic isolation, political volatility, refugee fluxes, and limited infrastructure renders fisheries security an issue of mounting importance (Brown, Hammill, & McLeman, 2007; Kimirei et al., 2008; McIntyre et al., 2016). Furthermore, collapse of Lake Tanganyika's fishery would irreversibly damage one of the most spectacularly diverse freshwater ecosystems in the world (Snoeks, 2000; Yuma et al., 2006).

The human responses to the deleterious impacts of climate change on Lake Tanganyika's fisheries may have, in certain instances, amplified the damage, particularly through overfishing and use of illegal fishing gear (Van der Knaap, 2018). The number of fishers on Lake Tanganyika increased substantially from 2006-2011, most likely due to faltering catch numbers and high demand (Hess & Leisher, 2011). More fishers has led to modifications of artisanal fishing practices, to include the heavy use of fine-mesh beach seines, monofilament gill nets, mosquito nets, and bag nets (Coulter, 1991; van der Knaap, 2018). These techniques place stress on the littoral ecosystem, because they trap juvenile fish before they reach maturity. Another threat to the integrity of the littoral ecosystem is sediment pollution associated with agriculture (Cohen et al., 1993; Alin et al., 1999). Rapid and haphazard clearing of trees from steep hills adjacent to the lake appears to have increased soil erosion, with corresponding increases in downslope and deltaic sediment flux that transforms littoral habitats and spawning grounds (Eggermont & Verschuren, 2003; McIntyre et al., 2005; Soreghan, 2016; Britton et al., 2017). For example, Vadeboncoeur et al. (2013) reported that littoral areas impacted by soil erosion, marked by abnormally-thick silt and sand "blankets" on rocky substrates, hosted significantly lower biodiversity, as well as smaller fish and snail body sizes, than comparable substrates in pristine areas. This is most likely due to the harmful effect of sedimentation on algal growth, which is a critical food source for species at higher trophic levels. Turbidity limits light penetration and algal productivity, which weakens the foundation of the food web and can alter the community structure of fish (Donohue, Verheyen, & Irvine 2003).

Conservation strategies that aim to protect Lake Tanganyika's fish, informed by limnological and ecological sampling, have been discussed for decades (e.g., Ribbink, 1987; Bootsma & Hecky, 1993; Cohen, Kaufman, & Ogutu-Ohwayo, 1996; Van der Knaap, 2018). At present, two large protected areas, Mahale National Park and Gombe Stream National Park, have been relatively successful at protecting swaths of the littoral zone that cichlids and pelagic fish use as breeding and brooding habitat on the Tanzanian side of the lake (Coulter & Mubamba, 1993). Vadeboncoeur et al. (2013) and Sweke et al. (2013) have documented higher species richness and population densities of fish and snails within the littoral waters of Mahale National Park, compared to areas outside of the park boundaries. Undoubtedly, enforcement of fishing policies by Mahale National Park rangers contributes to the stark contrast between the littoral communities within park boundaries versus those in inhabiting impacted areas adjacent to villages where native vegetation has been removed and fishing practices are largely unregulated. However, of the ~630 km of Lake Tanganyika shoreline in Tanzania, only ~65 km falls within a large protected area. Therefore, conservation strategies focusing on small-scale protected areas administered by local stakeholders (e.g., beach management units; Cowx, van der Knapp, Muhoozi, & Othina, 2003) are required in order to improve the health and productivity of littoral fisheries. However, community-based fisheries management requires detailed knowledge of benthic habitats, in order to strategically focus conservation efforts around areas vital to fish breeding and rearing. This information is unavailable for much of Lake Tanganyika. A number of researchers have attempted to map nearshore substrates at Lake Tanganyika by direct sampling with SCUBA (Cohen & Thouin, 1987; Cohen, 1990; McGlue et al., 2010), lake floor dredging or coring (Degens, Von Herzen, & Wong, 1971; Tiercelin et al., 1992; Soreghan & Cohen, 1996), or a combination of these methods, but these studies are usually aerially restricted and focused on understanding processes of modern sedimentation.

The overarching goal of this project was to produce the first benthic habitat maps for Kungwe Bay, a Nature Conservancy (TNC) priority conservation area located north of the Mahale National Park in western Tanzania (Figure 1). Co-management of this area began in 2012, with the launch of the Tuungane Project, a simultaneous population, health, and environmental issues initiative (Vadeboncoeur et al., 2013; Hess, Leisher, Limbu, Magige, & Kahwa, 2017). Although benthic habitat mapping using a combined geophysical-geological approach is relatively well-known in marine ecosystems (Kostylev et al., 2001; Diaz, Solan, & Valente, 2004; Freitas et al., 2011; Brown, Smith, Lawton, & Anderson, 2011), this project was the first of its kind on Lake Tanganyika. Bathymetry for most of the lake is only coarsely resolved, usually derived from widely spaced seismic reflection lines that do not extend completely to the shoreline (Scholz & Rosendahl, 1988; McGlue et al., 2008). Similarly, side scan sonar data are very scarce for Lake Tanganyika, and where surveys have occurred the focus has been on tectonic controls on sedimentation (Burgess et al., 1988). Here, the specific focus was to identify rocky nearshore benthic habitats, which are known hotspots for fish spawning and rearing (Hori, Gashagaza, Nshombo, & Kawanabe, 1993; Rossiter, 1995). In addition to locating candidate sites for small scale protected zones, the study tests the hypothesis that the structural geology of the northern Mahale and Kungwe Bay region controls the occurrence of nearshore rocky benthic habitat. The results show that the hypothesis is largely supported in the cases of sub-lacustrine crystalline basement (Precambrian-aged metamorphic rocks), but that lithified paleo-shoreline deposits (sedimentary rocks) produce a second class of rocky benthic habitat that are mostly unrelated to structural geology and have their origins in lake level change and recent carbonate cementation.

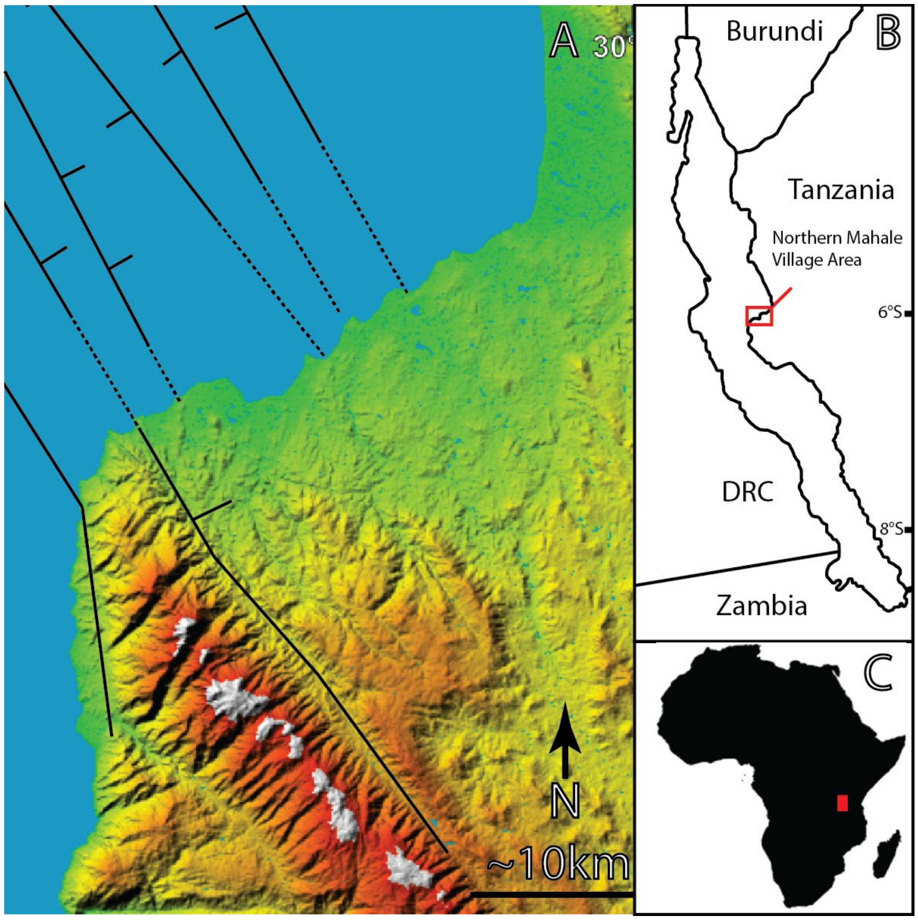

Figure 1: Location Map. (A) SRTM-derived digital elevation map of the northern Mahale Mountains and Kungwe Bay in central Tanzania. Solid lines represent normal faults mapped by Versfelt & Rosendahl (1989) using seismic reflection data. Dashed lines are inferred fault traces that extend along strike through the shallow water area in the bay. (B) Map of Lake Tanganyika, with the location of the northern Mahale Village area boxed in red. (C) Geographic position of the study site within Africa.

METHODS

The study site, Kungwe Bay, has a northeast-southwest oriented shoreline comprised of several small bays separated by high relief headlands or low relief deltas. From northeast to southwest, the micro-bays are named Igalula, Mgambo, Buhingu, Nkonkwa, Katumbi, Stolo, and Kalilani; villages and beach management units receiving assistance from the Tuungane Project are mostly separated along these geomorphic boundaries (Figure 1). Data acquisition efforts focused on the littoral and sub-littoral areas of these bays and their transitional environments.

Single beam echo-sounding was used to map the bathymetry of the Kungwe Bay site (Figure 2A). Soundings were collected in July-August 2015 and 2016 using a Garmin GPSMap 547 echosounder with a transom-mounted transducer deployed from an inflatable Zodiac boat. The echosounder's transducer utilizes a CHIRP-style swept frequency pulse of 50-260 kHz; soundings were recorded every 2 m long survey transects. A total of ~1190 line km of bathymetric data were collected in shoreline perpendicular transects spaced ~150 m apart. Shoreline parallel echo-sounder lines were also collected to improve spatial coverage; the spacing of these lines was more irregular. Line spacing was dictated by the extensive rift-related deformation present at Lake Tanganyika, which occurs on a scale of 100s of meters (e.g., Morley, 1988; Versfelt & Rosendahl, 1989), and because baseline biological surveys associated with the Tuungane Project had encountered variability in benthos at a similar scale (Vadeboncoeur et al., 2013). Bathymetric measurements were recorded in the field and compiled at the University of Kentucky using Surfer®, which enabled contouring via triangulation with linear interpolation. This spatial statistic provided more geologically realistic contour maps than other methods, due to the relatively even spacing of the data grid. Prior to contouring, the data were processed to remove artifacts associated with signal loss and propeller cavitation. The omitted points all fell within very shallow water (<0.8 m). A shoreline zero contour was mapped in the field via hand-held GPS surveying in 2015, at the same time shoreline and shallow water substrates were photographed and documented.

Approximately 108 km of side scan sonar data were collected within the study area using an Edgetech 4125 CHIRP side scan sonar deployed from a vessel of opportunity, *Doria II* (Figure 2A). The side scan sonar technique provides images of acoustic targets by recording sound backscattered from features on the lake floor (Johnson & Helferty, 1990). Backscatter is effectively the amount of energy reflected from the lake floor, and its intensity depends on variability in microrelief and material roughness (i.e., rougher textures reflect more energy back to the sonar system). The Edgetech 4125 topside unit has integrated GPS navigation that tracks the position of survey lines, and internal telemetry aboard the signal-generating towfish that detects altitude in the water column. The Edgetech 4125 employs dual frequency transducers (400 and 900kHz) simultaneously and has the advantage of collecting images that are corrected for slant range, vessel speed, and signal amplitude. Survey lines covered the study area from 2-30m water depth, the effective working limits of a unit equipped with a 50 m long tow cable. The towfish was maintained at an altitude of 10 m above the lake floor when the water depth was ≥10 m, and the position was manually modified as water depths changed. A range of 100 m was used to maximize the side-looking swath coverage and produce acoustic images of benthic substrates and other lake floor features. The nominal spacing between individual side-scan tracklines was ~75 m, in order to achieve enough overlap to cover the Nadir gap associated with each line. The 400 kHz dataset formed the focus of the habitat mapping, since the primary objective was imaging relatively large targets like the rocky benthic substrates that form fish spawning and nursery grounds. The 400 kHz transducer generates sonar images on each side of the towfish out to ~100 m, with a maximum along track resolution of ~80 cm and an across track resolution of ~2.3 cm. Challenges encountered during acquisition included waves (which can generate noise from pitch and heave of the towfish, especially in shallow water) and dense schools of fish, which interfered with bottom tracking. Following acquisition, side scan sonar data were processed using Xylem Hypack 2016 software at the University of Kentucky. Bottom tracking and time-variable gains were applied to individual tracks in order to improve the signal to noise ratio. Hypack 2016 was also used to mosaic the data tracks into seamless images of the lake floor. These images were imported into the ESRI ArcMap geographic information system (GIS) platform for interpretation and map building.

Ground truth for sonar images was acquired through shallow dredging of the lake floor. Lake floor sediments were collected by hand using a Petite Ponar in 2015 and 2016. A total of 110 samples were retrieved (Figure 2A). Additional insights on lake floor substrate were obtained from the work of Busch et al. (2018), who retrieved samples and collected underwater photographs from elsewhere in Kungwe Bay using SCUBA. Upon return to the lab, bulk sediment samples were homogenized, freeze dried, weighed, and sieved to remove the >2000 µm fraction; this coarse fraction was retained and used in final calculations of total particle size distribution. The <2000 µm fraction was suspended in a solution of 15% sodium hexametaphosphate to prevent the flocculation of clay minerals and analyzed using a Malvern Mastersizer 2000 with a Hydro 2000 sample dispersion bench at the University of Kentucky. The grain size percentages were classified using a simplified version of the Wentworth classification system (Wentworth, 1922) into three categories: sand (>63µm), silt (>4µm to <63µm) and clay (<4µm). Lake floor sample locations were integrated into the GIS to provide a spatial perspective on substrate texture.

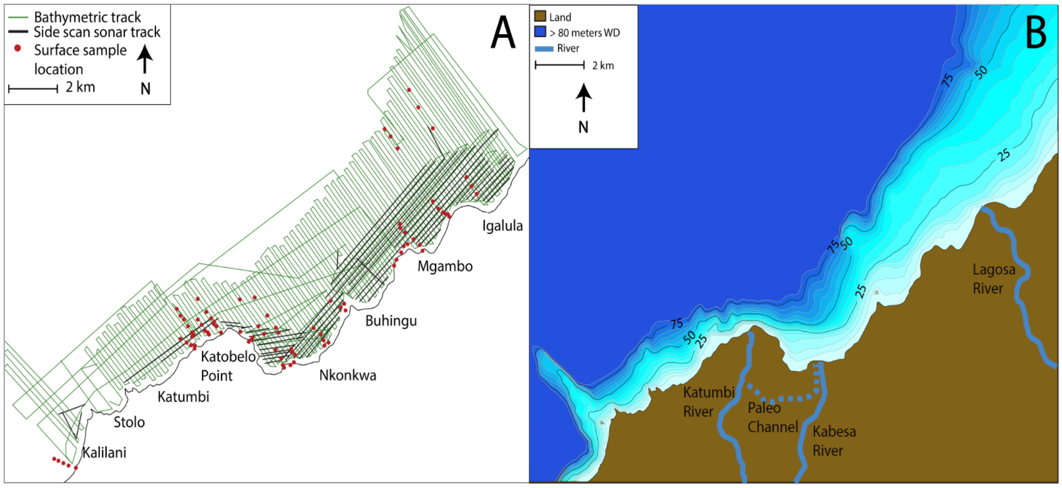

Figure 2: Bathymetry Map. (A) Geophysical survey trackline maps for the study site. ~1190-line km of echosounder data (green) and ~108-line km of side scan sonar data (black) were collected in 2015-2016. Echosounder transects were collected from 1-80 m deep, in order to capture the full range of bathymetric variability in the study area. Side scan sonar coverage extended to the 30 m isobath. Lake floor sediment samples collected by Ponar are marked by red dots; sediment texture and composition were evaluated for geological ground truth of geophysical data. (B) Bathymetric map for the study area. Contour interval = 5 m.

RESULTS

Figure 2B shows the bathymetric map for Kungwe Bay, which was compiled from 2015 data only, due to dynamic changes in water depth around Katobelo Point in 2016. The data range extends from the shoreline (0 m) to ~80 m deep, the approximate position of the platform slope break in many areas. This region covers a total area of ~72 km^2, with a total shoreline length of ~26 km. The area from the shoreline to the 30-m isobath is ~ 21 km^2; defining this region is important because equipment andresource limitations make it a focal point for community-led fisheries management. The location of nearshore isobaths varies, and a greater than 3° increase in lake floor gradient is apparent from northeast to southwest in Kungwe Bay. In general, the coastline morphology is highly cuspate for Igalula, Mgambo, Buhingu, Nkonkwa bays, whereas Kalilani and Katumbi bays have more linear shoreline segments. A small cuspate bay known as Stolo sits to the northeast of Kalilani Bay.

Mapping of Igalula and Mgambo bays reveals a gentle lake floor gradient ($slope_{avg} = 1.2°$) and the 30-m isobath in a position ~2 km from the shoreline (Figure 2B). Igalula Bay has a prominent and wide shallow platform, with water depths shallower than 50 m extending more than 4 km offshore. The location of the 30-m isobath reaches a maximum of ~2.5 km directly offshore of the Lagosa River delta (Figure 2B). The nearshore slope is gentle ($slope_{avg} = 1.4°$) in Buhingu Bay and the 30-m isobath is positioned ~2 km offshore. Buhingu Bay is notable in that the shape of its isobaths mimic that of its cuspate shoreline, and a narrow bathymetric shoal extends offshore from the headland on its western side (Figure 2B). The largest micro-bay in greater Kungwe Bay is the asymmetrically shaped Nkonkwa Bay ($slope_{avg} = 1.7°$), which has a steep western margin locally known as Katobelo Point, where the distance to the 30-m isobath is <0.5 km from the shoreline. The transition to water greater than 50 m deep is less than 2 km in central and eastern Nkonkwa Bay, indicating a relatively narrow platform in comparison to Buhingu, Mgambo, and Igalula bays. The Kabesi River formerly emptied into central Nkonkwa Bay and produced a prominent delta (McKee et al., 2005; Cohen, 2018), but today the flow of this river is much reduced due to diversions for agriculture and other uses in Nkonkwa village. The Nkonkwa Bay shoreline retains evidence of that riverine inflow in the form of a slight deltaic bulge near it geographic center (Figure 2B).

Along the western side of Nkonkwa Bay, the shoreline curves sharply at nearly a 90° angle to form Katobelo Point, which is influenced by the construction of the narrow, wave-dominated Katumbi delta (Busch et al., 2018). This shoreline deflection results in the protrusion of the Katumbi and Kalilani bay shorelines more than 2 km into the lake, in comparison to the micro-bays situated to the northeast (Figure 2B). The 30-m isobath sits between 0.15-1.0 km from the shoreline of Katobelo Point and Katumbi Bay. Offshore from Katobelo Point, the lake floor is very steep (~4.4°) and in some areas is marked by channel-like furrows (Figure 2B). The channels were most likely produced by the Katumbi River (Busch et al., 2018), a human-modified river course that has been straightened for irrigation of agricultural fields. Katumbi Bay is particularly narrow (<250 m wide) and shallow, but the lake floor gradient steepens rapidly offshore, achieving a slope of ~4.5°. West of Katumbi is Stolo Bay, which is very narrow (~1.2 km wide) and enclosed by headlands. Within Stolo Bay the 30-m isobath sits ~0.75 km offshore. The western margin of Stolo is Bulu Point, a headland that juts ~1 km farther offshore than the surrounding bays (Figure 2B). Offshore of Bulu Point, a prominent bathymetric shoal was encountered, with a relatively broad and flat top and steeply sloping flanks that projects offshore with a NW-SE trend. This feature extends for ~4 km (Figure 2B). The southwestern margin of the study site is Kalilani Bay, which is a narrow (~1.4 km in width) littoral platform. Part of Kalilani Bay is occupied by the entrance to the Mahale National Park, a large protected area that lacks major recent human modifications or deforestation. Mapping of isobaths shows that the lake floor within Kalilani Bay is the steepest in the study area, with a gradient that exceeds ~6.0°.

Shoreline substrates vary in the study area (Figure 3). Large villages are usually found on broad sandy beaches, such as those in Igalula, Buhingu, and portions of Katumbi, Stolo, and Kalilani bays. Undeveloped shorelines are defined by narrow sandy beaches, river deltas with riparian vegetation, headlands or cliffs consisting of crystalline bedrock (dominantly Paleoproterozoic high grade metamorphic rocks such as gneiss and amphibolite; Lenoir, Liegeois, Theunissen, & Klerkx, 1994), pocket beaches comprised of bedrock cobbles and sand, or interdeltaic reed and sedge banks. Bulu Point is the most prominent headland; smaller headlands form the western horns of Buhingu and Mgambo bays. Small, mixed bedrock cobble-sandy pocket beaches occur in western Buhingu, Stolo, and Kalilani bays. Mgambo Bay's shoreline consists of tall reeds and other dense vegetation, which surround a small channel mouth that enters the bay on its western side, as well as the Lagosa River delta on its eastern flank. Nkonkwa Bay's shoreline substrates are particularly diverse and include a sandy beach with emergent vegetation on its western side, deltaic vegetation in the center, and a mixed reed-rich sandy beach on its eastern flank. Around Katobello Point, tilled fields associated with a palm oil plantation nearly extend to the shoreline and surround much of the delta plain. The delta mouth of the Katumbi River is marked by native riparian vegetation and narrow sandy beach. Several prominent nearshore rocky islands form transition points in the study area, such as the boundaries between Kalilani Bay and Bulu Point, as well as Nkonkwa and Buhingu bays (Figure 3).

Four lake bottom sonar facies (SF) were encountered and mapped in the study area (Table 1 and Figure 4). Two types of rocky substrate exist in Kungwe Bay: crystalline basement bedrock (SF-1) and $CaCO_3$-cemented sandstone (SF-2). Acoustic characteristics common to both rocky substrates include moderate-high backscatter, high relief bottom features that cast shadows (Figure 4A, B) (e.g., Manley & Singer, 2008). The acoustic response of SF-2 suggests flat and relatively smooth positive relief lake floor features with well-defined and often linear edges, whereas SF-1 is characterized by high surface roughness, more irregular or blocky boundaries on large positive relief features and scattered high-relief shadow-casting features up to several meters or more in breadth (Figure 4). Acoustic features associated with SF-2 are almost always oriented parallel or sub-parallel to the shoreline, whereas the orientation of bottom features in SF-1 could be at high angles to the lakeshore. In some instances, dredge sampling was able to recover cobbles of crystalline basement, and direct observations in shallow water from boats or via SCUBA confirmed the compositional differences between SF-1 and SF-2

(Figure 5A, B). Both rocky substrates are aerially restricted in Kungwe Bay. The total lake floor covered by crystalline basement (SF-1) was ~1.6 km^2, or ~7.5% of the study area (Figure 6). Crystalline basement substrate occurs in all sonar-accessible water depths (0-30 m), and the largest concentrations exist between Buhingu and Mgambo bays, and in areas on the western side of Bulu Point. Lake floor samples adjacent to crystalline bedrock consistently exhibited a unimodal grain size distribution around ~75µm (very fine sand), whereas unlithified sediments elsewhere in the study site exhibit a much broader distribution of sizes. The $CaCO_3$-cemented sandstone covered ~0.2 km^2, or ~1.1% of the study area (Figure 6). $CaCO_3$-cemented sandstone is limited to water depths $\leq$5 m deep, with large broken sheets encountered in eastern Nkonkwa Bay and Katumbi Bay, west of the Katumbi River delta on Katobelo point.

Two types of unlithified "soft" sonar facies also occur within Kungwe Bay: mixed sediment (SF-3) and shell beds (SF-4). The most common acoustic facies, SF-3, was a uniform, low to high intensity backscatter response that lacked shadows or linear patterns, but in some locales contained circular depressions marked by reflectivity contrasts between the margins and centers of those features (Figure 4C, D). Dredge sampling in SF-3 areas recovered unlithified siliciclastic sediments that varied in texture from clay to coarse sand, though sand and silt were usually the most common particle sizes (Figure 5C). Recently dead mollusks, especially the large endemic gastropod *Neothauma tanganyicense,* were also recovered from many SF-3 samples, particularly between ~15-30 m water depth (Figure 5D). Clay was the least abundant grain size encountered; the highest nearshore concentrations of very fine-grained sediment was found associated with the Lagosa River delta (Figure 6). In water deeper than 40 m, lake floor sediments were increasingly silt-rich (~40-80% in the 4–62.9 µm range). Thus, SF-3 was interpreted as mixed siliciclastic sediment dominated substrate with variable calcareous bioclast content. The presence of circular depressions indicated fish nesting activity, which was confirmed by diver observations in select locales (Busch et al., 2018). The SF-4 substrate class is more spatially restricted than SF-3. This sonar facies lacks the homogeneity of SF-3 and was defined by irregularly shaped patches of high backscatter bottom return amid a low reflectivity background signal (Figure 4D). Sizeable swaths of SF-4 occur offshore from the Lagosa River delta, and in Mgambo and Buhingu bays, whereas smaller areas of lake floor with this acoustic response were found in Nkonkwa and Katumbi bays (Figure 6). Sediment samples collected from this substrate contain abundant large (>2000µm) whole and fragmented bioclasts, with subordinate amounts of pebble-sized and sand-sized detritus. These data suggest that SF-4 is best interpreted as a shell-bed substrate.

A number of features were observed on side scan sonar tracks that provide clues on lake floor substrate, environmental energy, and depositional processes (Figure 7). For example, littoral areas with mixtures of coarse silt, sand and gravel can generate differences in backscatter energy recorded by the sonar. In Figure 7A, a sandy benthic habitat is interpreted, but sediment textures is varied; fish depression nests and scattered cobbles are clear on this example. Lake floor with uniformly low-moderate backscatter with individual, groups of individuals, or continuous patches of high-reflectivity that cast shadows away from the sonar track are interpreted as aquatic vegetation. Fully submerged aquatic vegetation, such as *Chara* meadows, were encountered in water 2-5 m deep in central Nkonkwa Bay; sonar shadows from these patchy, high reflectivity features were short (Figure 7B). By contrast, emergent vegetation, such as reeds and lake margin sedges, cast shadows that extended to the edge of individual tracks (Figure 7C). Emergent vegetation was commonly only found in water ≤3 m deep; it was mapped by sonar near the shoreline in Igalula Bay, the Lagosa River delta, Mgambo Bay, and on the western side of Nkonkwa Bay (Figure 6). It was not unusual to find sonar evidence of emergent vegetation in areas with SF-2 and SF-3 benthic substrate types. Fish nests form prominent lake floor features, most typically within sand-rich SF-3 substrates (Figure 7B). Depressions that exceed 1 m deep were routinely imaged with the sonar. The depression nests were encountered in isolation on sand-rich SF-3 or adjacent to bedrock masses (SF-1) (Figure 4A, C) or occur in densely clustered groups on mixed substrate (SF-3), in several instances with an apparent preference for coarser sediment (Figure 7D).

Around Katobelo Point, a number of sonar tracks provided indications of sub-lacustrine channelized flow and mass wasting, most likely due to high sedimentation rates and gravitational instabilities associated with progradation of the Katumbi River delta across the narrow platform. For example, lobate features with concentric, highly reflective rings are interpreted as slumps (Figure 7E). Contrasts in backscatter energy within the lobes are consistent with compressional ridges of sand that form from a slowly moving, down-slope flow; partial analogs for this feature exist offshore from high-relief drainages in Lake Malawi (Johnson, Wells, & Scholz, 1995). Well defined, low backscatter, shoreline-perpendicular features are also present on Katobelo Point, which are interpreted as sub-lacustrine channels emanating from the delta (Figure 7G). Low backscatter, low relief lobate features that cast short acoustic shadows were encountered at the northern terminus of the channel features, which are interpreted as bars that are being reworked by wave energy. Tiercelin et al. (1994) noted that deltas at Lake Tanganyika are strongly influenced by hyperpycnal flow development, because these erosive flows cut channels into littoral platforms and transport sand into deepwater far offshore. Other prominent sedimentary structures observed on sonar profiles included sand ripples, which were encountered in Igalula Bay (Figure 7D). Ripples were oriented oblique and, in some instances, perpendicular to the lakeshore, which is interpreted to reflect the influence of longshore drift. The presence and intensity of bottom currents have not been systematically studied at Lake Tanganyika, but field observations suggest that an east-west current of variable intensity affects Kungwe Bay during the dry season, which may also influence the distribution of nearshore sands. Local villagers refer to the phenomenon as the Lukuga current, because the westerly flow is on strike with the Lukuga River outlet, situated ~70 km west of Buhingu Bay. Wave ripples with similar morphologies were found offshore from major deltas in side scan sonar tracks from Lake Malawi (Johnson & Ng'ang'a, 1990).

Table 1: Sonar Facies. Summary of sonar facies identified in the study.

Name	Sonar Characteristics	Interpretation
Sonar Facies 1	Irregular, high relief, moderate-high backscatter bottom features that cast prominent shadows	Crystalline bedrock sheets, ridges, boulders, cobbles
Sonar Facies 2	Shoreline parallel or oblique linear high backscatter bottom features; cast shadows away from the center track	$CaCO_3$-cemented sandstone ("beach rock") ledges or slabs
Sonar Facies 3	Low-high backscatter, continuous bottom return; may contain depressions or low-relief, shadow-casting bedforms or other constructional depositional features	Mixed siliciclastic sediments (sand and silt dominant) with variable clay and bioclast content; fish nests, sand waves, or mass wasting deposits present in some locales
Sonar Facies 4	Discontinuous low backscatter bottom return with scattered high amplitude patches	Shell beds

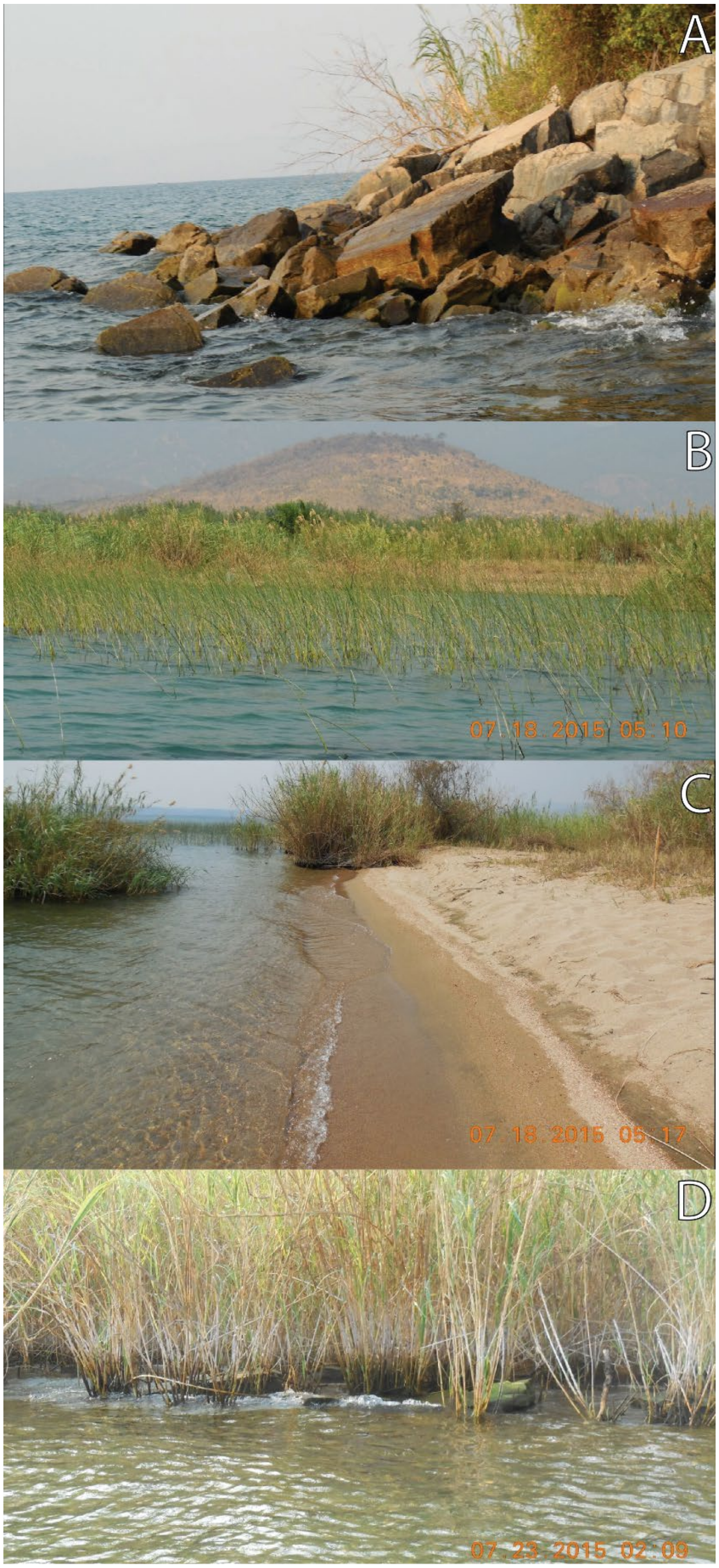

Figure 3: Shoreline Substrates. Examples of shoreline substrate types mapped in the study area. (A) Crystalline bedrock outcrops typically found forming headlands between bays. Bedrock can exist as intact cliffs, colluvium from mass wasting events, or cobbles reworked by wave action. (B) Reedy beaches are shorelines that consist of narrow sandy beaches with intermittent reed clumps. Emergent vegetation is often encountered offshore from these shorelines. (C) Typical sandy beach found in many areas in the study site. Sandy beaches are often inhabited and used for fishing, boat mooring, bathing and washing clothes. (D) Vegetated shoreline. Vegetation consists of tall reeds and bushes that extend to the waterline. Sand is the typical substrate found between the reeds, though in some locales beachrock blocks or sheets have been present.

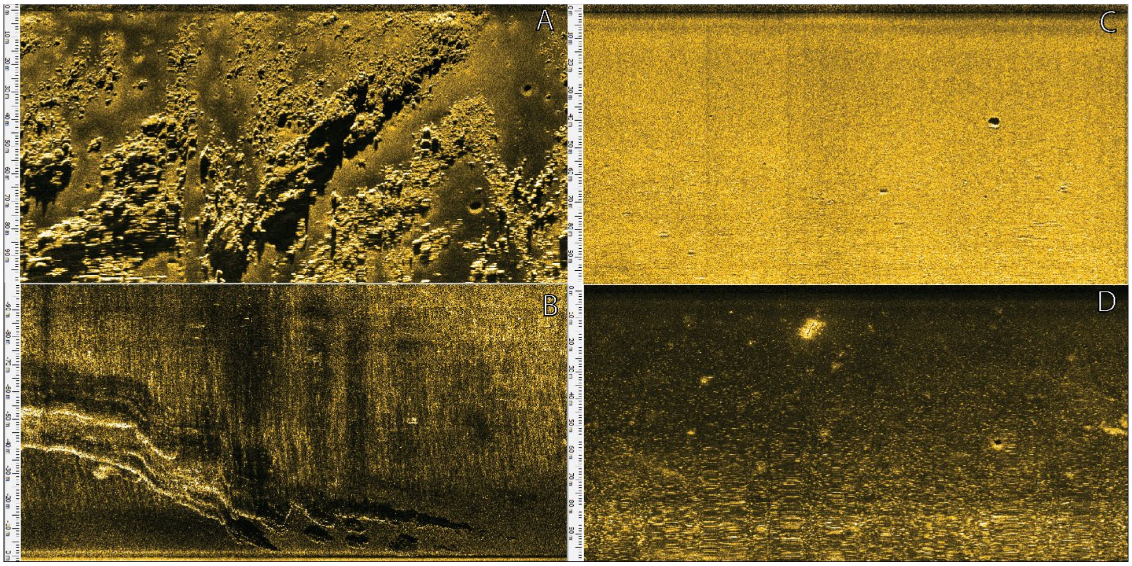

Figure 4: Examples of sonar facies (SF) identified along the northern Mahale Village littoral zone. (A) SF-1, crystalline bedrock (example from Mgambo Bay). Rocky substrates of this kind are critical fish spawning and rearing grounds found in 0-30 m water depth. SF-1 consists of high backscatter, positive relief features that cast shadows away from the centerline (0 m on the scale to the left). (B) SF-2, $CaCO_3$-cemented sandstone (beachrock) (example from Nkonkwa Bay). SF-2 is distinguished by moderate-high backscatter, strongly linear positive relief features that trend parallel the shoreline. Beachrock is exclusively found in water depths of <5 m. (C) SF-3, mixed substrate (example from Mgambo Bay). SF-3 is distinguished by a homogenous, moderate-high backscatter intensity and may contain low reflectivity circular depressions (fish nests). SF-3 comprises the majority of the benthic substrate in the study area and appears to be sand rich in many locales, with variable bioclastic carbonate content. (D) SF-4, shell bed substrate (example from offshore of the Lagosa delta in Mgambo Bay). SF-4 is defined by a variable sonar response with patches of high reflectivity amid a more homogenous background. This material consists of a mixture of broken and intact shells, most prominently the large gastropod *Neothauma tanganyicense*.

Figure 5: Benthic Substrate Types. Benthic substrates in <30 m water depth in Kungwe Bay. (A) Sub-lacustrine crystalline bedrock has been observed as intact masses or large cobbles and boulders in water depths to 30 m. Example here is from an island in the study area; note the presence of multiple large clast sizes. Fish diversity is high on bedrock substrate. (B) $CaCO_3$-cemented sandstone (beachrock). Beachrock typically was found in large tabular sheets in shallow water (< 3 m) with high densities of small fish. (C) Sandy substrate typical of water depths <15 m. Example is from Katumbi Bay. In very shallow water, well sorted sands commonly were organized into waves or were pockmarked from bioturbation (burrows)and escaping gas. (D) Patchy shell bed substrate typically found at 5-30m water depth. These areas consist of both whole and broken shells of bivalves and mollusks, with varying amount of unconsolidated siliciclastic sediment that ranged from silt to gravel. SCUBA observations suggest that the shell bed substrate was varied with respect to lateral continuity and shell density.

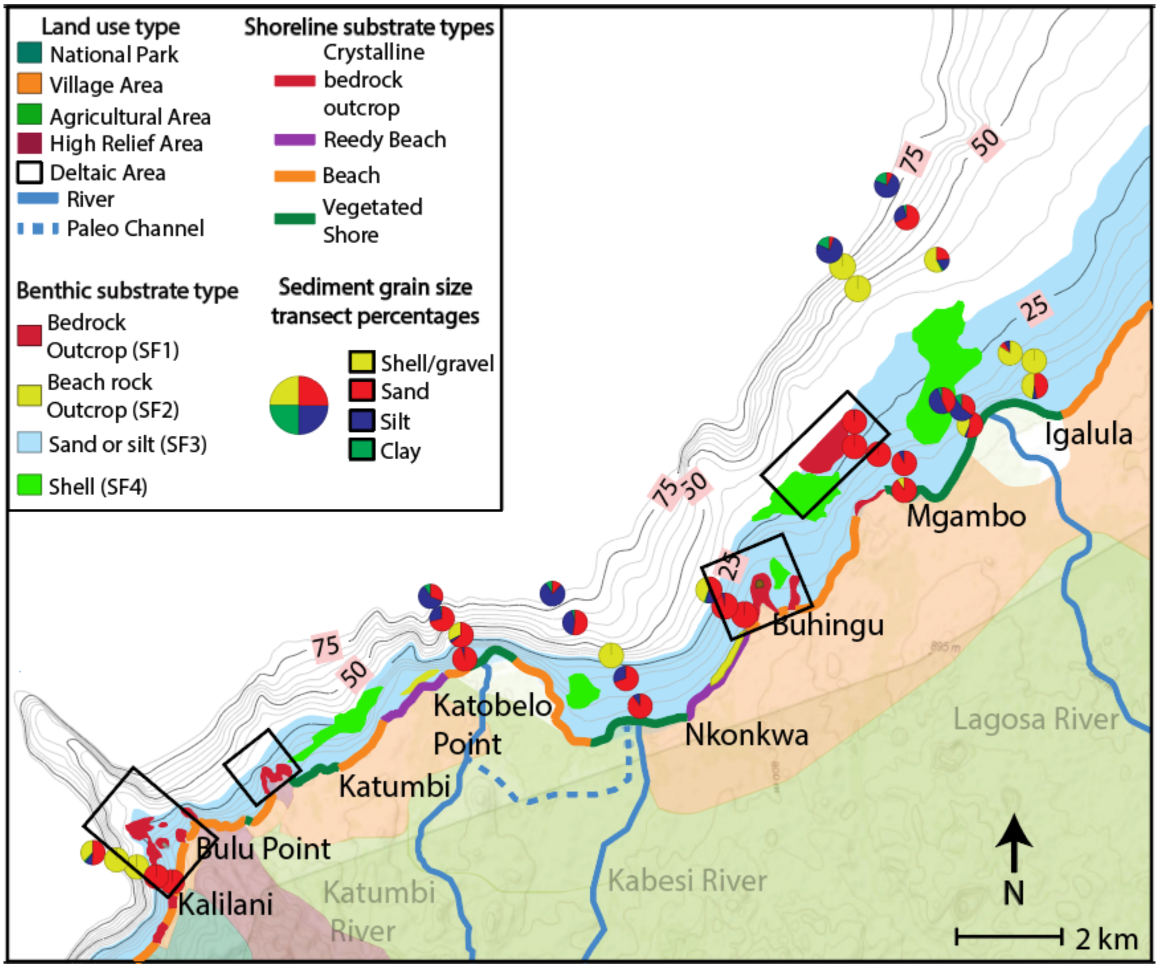

Figure 6: NMVA Habitat Map. Benthic habitat map for the TNC-Tuungane co-management area at Northern Mahale villages including generalized information on land use, sonar-inferred benthic substrate type, shoreline substrate type, and littoral sediment grain size data. Sonar was highly successful in distinguishing between rocky and soft substrates, the major objective for placing small-scale protected zones. Black boxes mark candidate sites for placing small scale protected areas based on the presence of crystalline basement. Two types of rocky substrates have been identified along with acoustic criteria for distinguishing between crystalline basement and beachrock. Data from the 400 kHz transducer was not well suited to distinguishing fine differences in siliciclastic particle size, for instance sand versus silt, especially where the lake floor lacks relief (e.g., Igalula Bay). Additionally, the sonar likely underestimates the extent of shell bed substrate, which may relate to the patchiness of the substrate or conditions during surveying. See text for details.

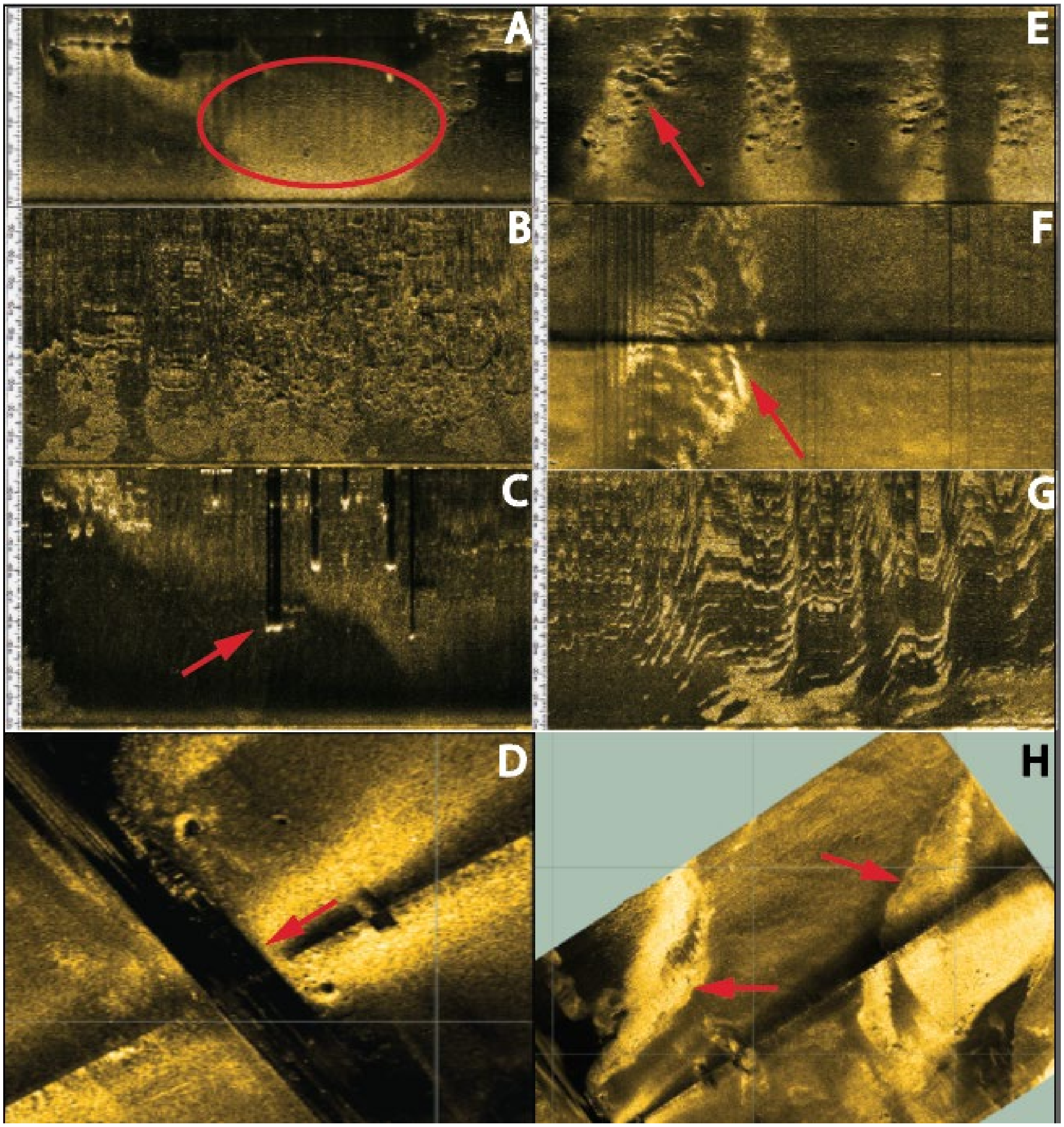

Figure 7: Sonar Features. Sonar features encountered in the field site provide evidence for substrate type and environmental processes. (A) Coarse substrate (>2000 µm) found in shallow waters near shore (red oval). (B) Submerged vegetation (most likely *Chara* meadows) encountered in water deeper than ~5 m. Example is from Nkonkwa Bay. (C) Emergent vegetation, in this example a dense cluster of reeds found in 2-3 m water depth. Long shadows cast to the edge of the track from high reflectivity spots mark the location of rooted plants. (D) Sub-lacustrine channel extending from the Katobelo Point. These features cut perpendicular to the shoreline and range from 6 to 12 m in width and over 150 m in length. (E) Clusters of fish nests in sandy substrate. Fish nests are circular depressions on the lake floor, represented in the sonar response by low reflectivity spots with a bright ring opposite of the center line. (F) Evidence of mass wasting encountered near Katobelo Point, near the Katumbi delta. The highly reflective pattern is interpreted as a slump with compressional ridges that are moving down slope into deeper water. (G)

Nearshore sand ripples in Igalula Bay. Note that contrasts in reflectivity between the crest and trough may reflect minor changes in texture, but fine-grained sediment typically does not persist in this environment. Every observed channel terminated in lobe shaped sub-lacustrine fan in water over 20 m in depth (Figure 7H).

DISCUSSION

Clear evidence exists that the fisheries at Lake Tanganyika are under heavy pressure from complex environmental and anthropogenic threats, which jeopardize the health and well-being of a rapidly growing population (Ogutu-Ohwayo et al., 2016). The IPCC AR5 reports that in the tropics, reductions in fish productivity and yields are dramatic consequences of climate change that must be mitigated through adaptation and build-up of social resilience (Field et al., 2014). One opportunity for building resilience and mitigating the threats to Lake Tanganyika's fisheries is to establish protected areas that are co-managed (e.g., Saunders, Meeuwig, & Vincent, 2002). Until recently, fisheries conservation strategies pursued at Lake Tanganyika have focused on large freshwater reserves, which have been successful at protecting broad swaths of the littoral zone (e.g., Coulter & Mubamba, 1993). Large freshwater reserves, such as the Mahale National Park, regulate human activity by strictly enforcing a "no take" policy and thus safeguarding fish diversity over relatively large areas. Other measures, such as initiatives to curb illegal fishing, have proven difficult to enforce (Van der Knaap, 2018). Small scale protected zones modeled after larger protected underwater parks may be valuable for helping the health and productivity of the littoral fishery to recover at Lake Tanganyika (Alin et al., 1999, Sweke et al., 2012). Yet lake managers charged with fisheries conservation require detailed knowledge of the nearshore area <30 m deep, which in Lake Tanganyika is strongly shaped by geological and limnological processes that vary spatially as well as temporally. Thus, spatial placement of protected areas relies on accurate maps of benthic habitats, which consist of detailed bathymetry data and information on lake-floor substrate. Importantly, considerable fish diversity is known to correlate with rocky lake floor substrates in <30 m water depth, because this bottom type provides refuge and nursery space for both littoral and pelagic species (Coulter, 1991; Coulter & Mubamba, 1993; Alin et al., 1999, Mannini et al., 1999). The bathymetric mapping and side-scan sonar surveying completed in this study has produced one of the most detailed acoustic surveys of the nearshore area of Lake Tanganyika available. The resultant benthic habitat map compiled from these datasets is shown in Figure 6. The analysis pinpointed the location of rocky benthic habitat in greater Kungwe Bay, including sub-lacustrine areas with crystalline bedrock (SF-1) and $CaCO_3$-cemented sandstones (SF-2). In areas <30 m deep, the new map provides well-constrained targets for placing small protected areas, which include sites between the Buhingu and Mgambo bays at $\geq$25 m deep, between Buhingu and Nkonkwa Bays at <10 m water depth, around the western horn of Katumbi Bay to ~20 m depth, and from the Bulu Point southwest into the Kalilani Bay extending into water >30 m deep. These areas all had sonar characteristics consistent with high relief crystalline bedrock features surrounded by scattered boulder and cobble-sized bedrock clasts. It must be emphasized that where crystalline bedrock was encountered in water deeper than 25 m, benthic substrate area calculations should be considered minimum estimates, due to survey equipment limitations.

Lake Tanganyika's shoreline, shape, and bathymetry are controlled by high-angle, basin-bounding boarder faults and pre-existing deformation patterns of the East African Rift Valley (Versfelt & Rosendahl, 1989). Normal faults with Lake Tanganyika can exhibit up to several km of displacement and therefore can create bathymetric shoals adjacent to deeply subsided depocenters (Rosendahl et al., 1986). Within Kungwe Bay, a large basin-bounding normal fault system is located on its western side, forming the Kavala Island Ridge offshore and the Mahale Mountains onshore (Ebinger, 1989; Burnett, Soreghan, Scholz, & Brown, 2011). Notably, the rivers entering Kungwe Bay from the south have their headwaters in the Mahale Mountains or the adjacent foothills. Within the study area, offshore faults mapped from early seismic studies increase in frequency and displacement with proximity to the Mahale Mountains (Figure 1) (Versfelt & Rosendahl, 1989; Versfelt et al., 1986; Morley et al., 1990). Therefore, Kalilani, Stolo, and Katumbi bays, as well as the Bulu Point headland, are strong candidates to have tectonic influences on their geomorphology (Figure 1). Notably, large areas of SF-1 were encountered in the littoral zone in these areas, particularly from Bulu Point west (Figure 6). Here, sub-lacustrine crystalline bedrock outcrops were mapped along the shoreline and offshore in waters up to 30 m and possibly further; limitations of the sonar tow cable prevented deeper surveying. This area has several normal faults that strike perpendicular to the shoreline and correspond with mapped lineaments and faults in the Mahale Mountains (Figures 1, 6) (Versfelt & Rosendahl, 1989). Bathymetry data in Figure 2 clearly show that the relief associated with Bulu Point extends offshore as a prominent shoal. This feature, and its associated rocky islands, are interpreted to have resulted from the presence of the Kalemie boundary fault system discussed in Versfelt & Rosendahl (1989). Winnowing, made possible by lateral sub-lacustrine currents, is likely to prevent sediment from accumulating on these shoals in the nearshore environment, though deeper expressions of these types of features found offshore can accumulate a thick drape of mud (e.g., Felton et al., 2007). West of Bulu Point, onshore topography is rugged, steep and comprised dominantly of crystalline basement. Mass wasting (i.e., landslides, rock falls) of rocky nearshore outcrops, coupled with wave erosion, are interpreted to maintain the SF-1 mapped within Kalilani Bay. Thus, nearshore fault-related topography, especially margin-coincident faults exposed to wave action, may form areas of interest for small scale protected zones lake-wide, due to the likelihood of crystalline bedrock substrates in the adjacent littoral zone.

East of Katobelo Point, bedrock outcrops along the shoreline and lake margin topography are less common and more subdued, respectively (Figure 6). Shorelines comprised of crystalline basement are only present on headlands, such as those between Nkonkwa, Buhingu, and Mgambo bays (Figures 3, 6). The presence of crystalline bedrock in these locales is also interpreted to relate to the basin's structural configuration. Small normal faults antithetic to the Kalemie fault presented in Versfelt & Rosendahl (1989), if projected to the shoreline, are on strike with these headlands (Figure 1). An important discovery in this study is the presence of extensive offshore SF-1 between Buhingu and Mgambo bays. This large area of crystalline bedrock outcrop is present at 25-30 m, but its complete spatial footprint in water deeper than 30 m is still not well known. Given its large spatial footprint, this area could represent an important fish habitat that warrants consideration as a protected area (Figure 6). Exceptions to the correlation between known fault traces and the presence of crystalline bedrock benthic substrate occur in the areas around the Lagosa River delta and Katobelo Point. These areas are on strike with mapped faults, yet mixed sediment or shell bed substrates appear to dominate the littoral zone in these locales (Figure 6). Both sites are strongly influenced by deltaic sedimentation, however, and thus it is plausible that sediments delivered to the lake by rivers has buried or obscured bedrock. Busch et al. (2018) observed considerable mud admixed with shell beds in the shallow water areas of the Lagosa River delta. Those authors attributed a higher mud flux to Igalula bay from the Lagosa River to land use changes in that watershed, because removal of native vegetation and tilling promotes weathering and erosion of hillslope soils (Soreghan, 2016).

In addition to crystalline bedrock, $CaCO_3$-cemented sandstone beachrock is another potential rocky substrate that is utilized as fish habitat, though it is likely that fish diversity associated with this substrate is considerably lower than that of the crystalline basement. In general, beachrock is an arkosic sandstone with $CaCO_3$-cement found along the shorelines of different types of water bodies (Binkley, Wilkinson & Owen, 1980). In Lake Tanganyika, shoreline beachrock deposits have been described as long, tabular, lakeward-dipping beds of carbonate cemented sandstones in Burundi and Tanzanian (Cohen & Thouin, 1987). Examples encountered in this study at Nkonkwa Bay were tabular and often fractured beds up to 1 m thick in 0-2 m water depth; close to the shoreline, broken sections were marked by an ingression of reeds. West of Katobelo Point, beach rock is totally submerged and disconnected from the shoreline. Beachrock composition at Lake Tanganyika is consistent with the local sand supply, typically feldspar-rich sands (Cohen & Thouin, 1987). Cohen & Thouin (1987) indicated that carbonate cemented beachrock in nearshore areas most likely formed by an aeration-precipitation mechanism (Binkley, Wilkinson & Owen, 1980). Shoreline beachrock is believed to have formed less than 100 years before present, due to the presence of machine woven fabric embedded within the rock in some locales, as well as fossil content that matches modern species distributions (Cohen & Thouin, 1987); this is probably the situation for beachrock in Nkonkwa Bay. At Katobelo, the more deeply submerged beachrock slabs trends similarly to the modern-day shore and isobaths, suggesting that it was lithified when lake level was lower, at those specific points. The submersed beachrock could have been lithified at lake level lowstands, which have occurred periodically throughout the past 2000 years (Alin & Cohen, 2003). Lake Tanganyika's water level has been below 2018 averages due to both global and regional changes in climate and precipitation (Cohen, Talbot, Awramik, Dettman, & Abell, 1997). One recent prominent regression took place during the Little Ice Age (late 16th to early 19th centuries), when water levels fell at least 15 m (Cohen, Talbot, Awramik, Dettman, & Abell, 1997). During the Little Ice Age, lake level decline was caused by a decrease in tropical precipitation in response to northern hemisphere cooling (Russel & Johnson 2007). Another regression occurred in the late 18th to early 19th century, due to lower regional precipitation causing an negative shift in the water balance (Cohen, Talbot, Awramik, Dettman, & Abell, 1997). Due to the intact nature and shallow depth of the submersed beachrock west of the Katobelo Point, we interpret that it was most likely formed during the most recent regression.

Land-use changes continue to modify the bathymetry in the study region. The area near Katobelo Point and the Katumbi River provide a striking example, as the position of isobaths varied between the 2015 and 2016 surveys. Here, the lake floor has a steep average slope (~4.5˚) and the substrate consists of coarse sand (mean size = ~273 μm); distinct acoustic features consistent with delta progradation and slope failure mark this region (Figure 7). Similar deltaic mass wasting features were identified in Lake Malawi on the basis of their morphology and contrasts in reflectivity (Johnson, Wells & Scholz, 1995). The shoreline morphology and shallow littoral platform in Nkonkwa Bay attest to the former importance of the Kabesi River. Today, the Kabesi River discharge to Nkonkwa Bay is much reduced, as villagers have diverted much of the river's flow for irrigation. The Kabesi River watershed was described as partially deforested in the study of McKee et al. (1998), who discovered elevated offshore sedimentation rates in Nkonkwa Bay compared to more pristine deltaic systems in national parks, which were attributed to erosion associated with the change in land cover. Enhanced erosion and littoral sedimentation has the potential to transform lithified rocky substrates through burial. Onshore protected areas may help to slow down or prevent the fouling of rocky benthic substrate, the negative effects of which on habitat heterogeneity, reproductive success, and foraging strategies are well documented (Donohue, Verheyen, & Irvine, 2003; Britton et al., 2017). As recommended by Cohen (2018), additional study of offshore sedimentation patterns and rates is warranted and will help elucidate the spatial footprint of sediment pollution and its impact on substrate type.

The dynamics of deltaic sedimentation at Kungwe Bay are also discussed in the study of Busch et al., (2018). That study found elevated nearshore silt and clay content near the mouths of the Lagosa and Rukoma Rivers, an apparent effect of heavy watershed deforestation exposing clay and silt-rich soils to erosion. Ponar sediment samples from the Lagosa delta recovered mixed siliciclastic sediments with high silt content, especially transitional areas classified as shell beds based on sonar facies. These fine grain sizes may explain the patchy reflectivity associated with the SF-4 type sonar response. It is notable that although shoreline parallel, wide-swath sonar mapping was effective for discriminating among rocky and soft substrates, the technique was not always effective at discriminating shell beds from sand or sand from mixtures of sand and mud. The texturally diverse shell beds, which provide habitat for an array of specialized benthic organism (including shell dwelling cichlids, bryozoans, and sponges; McGlue et al., 2008) are widespread across Kungwe Bay, yet conclusive interpretations of shell bed substrate only was achievable for ~4.75 km^2. This is considerably lower than the inferred area of shell beds noted by Busch et al. (2018), who inferred broader occurrences of *Neothauma tanganyicense*-rich shelly substrates across Kungwe Bay in water ~10-35 m deep based on SCUBA observations and sampling along shore-perpendicular transects. Between Katobelo Point and Igalula Bay, our ponar samples yielded a median grain size of ~480 μm (coarse sand) from 0 to 25 m water depth; whole mollusk shells and hash (> 2000 μm) were abundant at 20-40 m deep. Thus, we infer that facies boundaries are gradational and irregular, particularly in areas where deltaic sediments are being deposited and reworked by currents, waves, and bioturbating organisms. Variability in currents or onshore landuse can either deposit or erode sediment in the littoral zones, altering grain size distributions and shifting unlithified substrate boundaries in short periods of time. This is in contrast to lithified facies which have sharp, well defined boundaries that are less influenced by lake floor hydrodynamics and benthos.

Ultimately, geophysical surveying of Lake Tanganyika's vast littoral zone is a time and resource consumptive process, requiring vessels, fuel, personnel, and shoreline access that spans four international borders. In addition, high resolution geophysical surveying requires relatively calm environmental conditions (i.e., minimal waves), which on large tropical lakes are subject to seasonal and orographic precipitation, may only be available for 1-2 months per year. These factors make extensive habitat mapping using ship-based geophysical tools a daunting prospect at Lake Tanganyika, even when low cost, commercial off the shelf acoustic bottom mapping tools are employed (Meadows, 2013). However, data produced from this study may hold value for conditioning optical remote sensing analyses of nearshore bathymetry elsewhere in the basin. A number of studies of marine coastal bathymetry and benthic habitats have utilized satellite data conditioned by ground-truth such as underwater photos, sediment sampling, and echo-sounding (e.g., Louchard et al., 2003; Stumpf, Holderied & Sinclair, 2003; Dekker et al., 2011; Schill et al., 2011). Though less common in lakes, recent advances in multi-spectral imaging have made remote classification of water depth and lake-floor substrate more successful, though challenges remain due to the variability of lake optical properties and the high spatial resolution required for small-scale mapping (Palmer, Kutser, & Hunter, 2015; Dörnhöfer & Oppelt, 2016). For example, Giardino et al. (2014) used Rapid Eye and Landsat 8 data to qualitatively assess bathymetry in Lake Garda (Italy) from the shoreline to 7 m deep. Yuzugullu & Aksoy (2014), working on a shallow eutrophic lake in Turkey, were able to quantitatively assess bathymetry to 6 m deep using WorldView-2 images. Limnological conditions at Lake Tanganyika may be amenable to attempt guided classification of bathymetry and some benthic substrates using remote sensing products in certain areas, though additional *in situ* data will likely be required for the broadest possible application. Light penetration, for example, is controlled by a number of factors including latitudinal position, proximity to riverine sediment plumes, and growing season (algal blooms) (Hecky & Kling, 1981). Reported Secchi disk values range up to 20 m deep in highly transparent regions of the lake (Hecky & Fee, 1981; Verburg, Hecky & Kling, 2003). Recent research using DigitalGlobe high resolution imagery have shown promise for mapping deltaic progradation and sediment plumes in Kungwe Bay (Busch et al., 2018). Other efforts to use satellite remote sensing products for habitat on large lakes have had success in correctly identifying zones of submerged aquatic vegetation (Shuchman, Sayers, & Brooks, 2013). Future benthic mapping efforts at Lake Tanganyika should consider onshore topography, geological map, and human population data, in addition to remote sensing products, in order to locate targets for small protected areas.

APPENDIX: RESULTS

Table A1: MNVA Grain Size Results. Result of the grain size analysis conducted in the study area.

Sample Name	Latitude	Longitude	Depth	% >2000µm	<2000µm >64µm	<64µm >4µm
G-LT15-001	-5.99523	29.78527	1.6	0.00	100	0.00
G-LT15-002	-5.99538	29.78513	1.50	34.23	58.90	6.40
G-LT15-003	-5.99575	29.78528	0.00	16.69	81.56	1.76
G-LT15-004	-5.99461	29.78394	3.00	0.00	0.00	0.00
G-LT15-005	-5.99395	29.78235	3.20	0.00	97.66	2.28
G-LT15-006	-5.99295	29.7802	5.30	0.00	96.37	3.52
G-LT15-007	-5.9906	29.79468	0.00	28.54	69.85	1.61
G-LT15-008	-5.99052	29.79463	1.00	0.00	95.45	4.23
G-LT15-009	-5.98888	29.79318	3.40	0.00	94.10	5.29
G-LT15-010	-5.98823	29.79275	5.00	0.00	95.28	4.32
G-LT15-011	-5.98803	29.79265	10.00	0.00	96.19	3.53
G-LT15-012	-5.99027	29.80147	1.80	0.00	100.00	0.00
G-LT15-013	-5.99365	29.80475	0.00	3.13	95.97	0.90
G-LT15-014	-5.99358	29.80485	1.30	0.00	87.10	11.85
G-LT15-015	-5.98333	29.80577	3.40	0.00	53.97	42.57
G-LT15-016	-5.99268	29.806	5.90	0.00	71.76	26.53
G-LT15-017	-5.99245	29.8061	11.00	0.00	62.73	35.49
G-LT15-018	-5.96462	29.85927	0.00	0.00	100.00	0.00

G-LT15-019	-5.9625	29.86053	0.00	0.00	100.00	0.00
G-LT15-020	-5.96197	29.86128	1.60	0.00	100.00	0.00
G-LT15-021	-5.96392	29.86673	0.00	9.57	90.19	0.25
G-LT15-022	-5.96368	29.86665	1.00	48.94	44.24	6.23
G-LT15-023	-5.96182	29.86568	2.90	0.00	92.65	6.23
G-LT15-024	-5.96017	29.8638	5.00	0.00	92.29	6.98
G-LT15-026	-5.95693	29.85893	20.10	0.00	100.00	0.00
G-LT15-027	-5.95562	29.85882	20.30	0.00	100.00	0.00
G-LT15-028	-5.95292	29.87645	0.00	20.93	79.07	0.01
G-LT15-029	-5.95237	29.87615	1.00	0.63	96.64	2.45
G-LT15-030	-5.95192	29.87502	3.20	0.00	33.74	56.77
G-LT15-031	-5.95162	29.87412	5.20	0.00	35.41	54.98
G-LT15-032	-5.95075	29.87298	9.80	0.00	36.16	55.78
G-LT15-033	-5.94805	29.8712	19.80	0.00	43.11	50.51
G-LT15-034	-5.93098	29.85827	40.90	0.00	99.00	1.00
G-LT15-035	-5.92707	29.85528	60.00	0.00	100.00	0.00
G-LT15-036	-5.92503	29.85367	81.00	0.00	4.69	77.06
G-LT15-037	-5.94538	29.88658	4.80	0.00	94.82	4.57
G-LT15-038	-5.94296	29.88456	10.90	0.00	100.00	0.00
G-LT15-039	-5.94018	29.88257	19.80	83.99	14.70	1.21
G-LT15-040	-5.92438	29.87047	40.60	34.05	53.23	11.09
G-LT15-041	-5.91765	29.8653	60.50	0.00	67.86	27.02
G-LT15-042	-5.9123	29.862	78.80	0.00	7.75	72.94

G-LT15-043	-5.98722	29.79195	23.40	0.00	90.60	8.65
G-LT15-044	-5.9863	29.79132	39.00	32.72	62.10	4.68
G-LT15-045	-5.984	29.78955	57.60	0.00	71.38	26.27
G-LT15-046	-5.97997	29.78652	80.80	0.00	31.02	59.39
G-LT15-047	-5.98647	29.78657	57.80	0.00	62.31	35.26
G-LT15-048	-5.9885	29.78783	38.50	0.00	78.32	20.38
G-LT15-049	-5.9898	29.78867	21.20	0.00	62.59	35.31
G-LT15-050	-5.99048	29.7894	9.40	0.00	89.65	9.47
G-LT15-051	-5.99068	29.78957	4.80	0.00	96.51	3.43
G-LT15-052	-5.99082	29.7897	3.00	0.00	98.20	1.80
G-LT15-053	-5.99198	29.78473	2.10	8.78	89.51	1.71
G-LT15-054	-5.99147	29.78493	5.00	0.92	97.06	1.95
G-LT15-055	-5.99133	29.78502	12.50	0.00	96.88	3.06
G-LT15-056	-5.99085	29.78457	21.30	2.23	95.20	2.49
G-LT15-057	-5.98868	29.78295	18.00	0.00	97.37	2.55
G-LT15-058	-5.98671	29.78143	41.70	0.00	100.00	0.00
G-LT15-059	-5.98522	29.78012	63.50	0.00	85.29	13.15
G-LT15-060	-5.98323	29.77885	81.00	0.00	14.30	76.46
G-LT15-061	-6.00113	29.81722	1.50	0.00	45.54	49.16
G-LT15-062	-6.00055	29.8169	3.00	0.00	46.12	47.59
G-LT15-063	-5.99903	29.81622	5.00	0.00	68.80	27.67
G-LT15-064	-5.99636	29.81438	10.50	0.00	100.00	0.00
G-LT15-065	-5.99646	29.81445	10.20	0.00	100.00	0.00

G-LT15-066	-5.99084	29.81013	20.10	0.00	100.00	0.00
G-LT15-067	-5.98835	29.80827	44.00	39.62	53.78	6.31
G-LT15-068	-5.98628	29.8066	61.40	0.00	27.20	67.21
G-LT15-069	-5.97997	29.80171	80.80	0.00	17.93	73.10
G-LT15-070	-5.99833	29.82135	3.10	0.00	89.90	8.50
G-LT15-071	-5.99774	29.82085	5.00	0.00	100.00	0.00
G-LT15-072	-5.9979	29.82102	5.00	0.00	86.48	11.18
G-LT15-073	-5.99608	29.81967	10.00	0.00	69.49	28.89
G-LT15-074	-5.99079	29.8155	22.70	0.00	100.00	0.00
G-LT15-075	-5.98909	29.81436	41.20	0.00	100.00	0.00
G-LT15-076	-5.98518	29.81123	60.70	0.00	52.93	42.58
G-LT15-077	-5.97937	29.80672	80.70	0.00	11.75	78.98
G-LT16-175	-6.15198	29.74705	80.00	0.00	97.65	1.94
G-LT16-176	-6.02516	29.80762	64	0.00	100.00	0.00
G-LT16-177	-6.02516	29.80762	40.5	0.00	97.74	2.16
G-LT16-178	-6.01526	29.76952	20.00	0.00	100.00	0.00
G-LT16-179	-6.01407	29.76952	8.70	0.00	100.00	0.00
G-LT16-180	-6.01407	29.76952	5.00	0.00	100.00	0.00

Table A2: Lubulungu Grain Size Results. Results of grain size data from the Lubulungu River Delta.

Sample Name	Latitude	Longitude	Depth	%>2000μm	<2000μm >63μm	<63μm >4μm	<4μm

G-LT15-078	-6.00177	29.81738	0.00	0.00	100.00	0.00	0.00
G-LT15-079	-6.0009	29.8198	0.00	0.00	100.00	0.00	0.00
G-LT15-080	-6.0003	29.82073	1.30	0.00	92.97	6.48	0.55
G-LT15-081	-5.99402	29.83273	0.80	0.00	99.15	0.85	0.00
G-LT15-082	-5.99429	29.83281	0.00	0.00	0.00	0.00	0.00
G-LT15-083	-5.9938	29.83218	3.00	0.00	97.45	2.50	0.04
G-LT15-084	-5.99305	29.83168	5.00	0.00	98.53	1.47	0.00
G-LT15-085	-5.99144	29.83052	10.40	0.00	100.00	0.00	0.00
G-LT15-086	-5.9895	29.82862	20.20	0.00	93.52	6.23	0.24
G-LT15-087	-5.9834	29.83898	0.00	0.00	100.00	0.00	0.00
G-LT15-088	-5.98192	29.83928	1.10	0.00	90.36	8.42	1.22
G-LT15-089	-5.98193	29.8386	2.90	0.00	90.72	9.06	0.22
G-LT15-090	-5.9822	29.83772	5.50	0.00	96.22	3.55	0.22
G-LT15-091	-5.98018	29.83433	20.60	0.00	87.71	10.66	1.62
G-LT15-092	-5.96688	29.85763	0.00	0.00	100.00	0.00	0.00

G-LT15-093	-5.96683	29.85748	0.00	0.00	100.00	0.00	0.00
G-LT15-094	-5.96912	29.85698	0.00	0.00	99.94	0.06	0.00
G-LT15-095	-6.16032	29.73307	2.00	0.00	99.33	0.67	0.00
G-LT15-096	-6.16107	29.73237	15.00	0.00	95.35	4.65	0.00
G-LT15-097	-6.16258	29.73127	43.00	0.00	92.65	7.35	0.00
G-LT15-098	-6.16473	29.73023	83.00	0.00	84.77	14.59	0.65
G-LT15-099	-6.1583	29.73133	1.00	0.00	99.41	0.59	0.00
G-LT15-100	-6.15965	29.73055	10.00	0.00	99.16	0.84	0.00
G-LT15-101	-6.15967	29.73053	24.50	0.00	88.03	11.28	0.70
G-LT15-102	-6.16063	29.72963	43.50	0.00	84.37	14.82	0.81
G-LT15-103	-6.1618	29.72858	63.50	0.00	70.06	28.53	1.41
G-LT15-104	-6.16312	29.72767	81.50	0.00	54.79	43.30	1.91
G-LT16-105	-6.02513	29.84424	131.40	0.00	88.42	9.24	2.34
G-LT16-106	-6.13611	29.74406	120.00	0.00	82.71	12.67	4.62
G-LT16-107	-6.13611	29.74406	108.00	0.00	65.61	28.42	5.97

G-LT16-108	-6.13611	29.74406	107.00	0.00	76.08	21.02	2.90
G-LT16-109	-6.13611	29.74406	86.00	0.00	92.44	5.13	2.43
G-LT16-110	-6.13611	29.74406	78.00	0.00	96.17	2.72	1.11
G-LT16-111	-6.13611	29.74406	79.00	0.00	100.00	0.00	0.00
G-LT16-112	-6.13611	29.74406	81.00	0.00	100.00	0.00	0.00
G-LT16-113	-6.15357	29.74182	86.00	0.00	100.00	0.00	0.00
G-LT16-114	-6.15357	29.74182	106.00	0.00	86.89	9.80	3.31
G-LT16-115	-6.15357	29.74182	117.00	0.00	92.47	5.31	2.22
G-LT16-116	-6.15357	29.74182	2.60	0.00	100.00	0.00	0.00
G-LT16-117	-6.15357	29.74182	72.00	0.00	98.12	1.43	0.45
G-LT16-118	-6.15357	29.74182	2.10	0.00	100.00	0.00	0.00
G-LT16-119	-6.15357	29.74182	40.00	0.00	99.21	0.58	0.21
G-LT16-120	-6.15357	29.74182	59.00	0.00	98.68	0.91	0.41
G-LT16-121	-6.15357	29.74182	25.00	0.00	100.00	0.00	0.00
G-LT16-122	-6.15357	29.74182	48.00	0.00	100.00	0.00	0.00

G-LT16-123	-6.15357	29.74182	1.00	0.00	100.00	0.00	0.00
G-LT16-124	-6.15357	29.74182	4.00	0.00	100.00	0.00	0.00
G-LT16-125	-6.15357	29.74182	11.00	0.00	100.00	0.00	0.00
G-LT16-126	-6.15103	29.73905	26.00	0.00	100.00	0.00	0.00
G-LT16-127	-6.15103	29.73905	30.00	0.00	100.00	0.00	0.00
G-LT16-128	-6.15103	29.73905	30.50	0.00	100.00	0.00	0.00
G-LT16-129	-6.15103	29.73905	14.30	0.00	100.00	0.00	0.00
G-LT16-130	-6.15103	29.73905	4.30	0.00	100.00	0.00	0.00
G-LT16-131	-6.15103	29.73905	0.80	0.00	100.00	0.00	0.00
G-LT16-132	-6.15103	29.73905	0.70	0.00	100.00	0.00	0.00
G-LT16-133	-6.15103	29.73905	2.10	0.00	100.00	0.00	0.00
G-LT16-134	-6.15103	29.73905	13.00	0.00	100.00	0.00	0.00
G-LT16-135	-6.15103	29.73905	28.00	0.00	100.00	0.00	0.00
G-LT16-136	-6.15103	29.73905	28.60	0.00	100.00	0.00	0.00
G-LT16-137	-6.15103	29.73905	19.30	0.00	100.00	0.00	0.00

G-LT16-138	-6.15103	29.73905	4.60	0.00	100.00	0.00	0.00
G-LT16-139	-6.15103	29.73905	2.60	0.00	100.00	0.00	0.00
G-LT16-140	-6.15103	29.73905	1.90	0.00	100.00	0.00	0.00
G-LT16-141	-6.15103	29.73905	9.20	0.00	100.00	0.00	0.00
G-LT16-142	-6.15103	29.73905	21.00	0.00	100.00	0.00	0.00
G-LT16-143	-6.15103	29.73905	30.50	0.00	100.00	0.00	0.00
G-LT16-144	-6.15103	29.73905	30.20	0.00	100.00	0.00	0.00
G-LT16-145	-6.15103	29.73905	11.00	0.00	100.00	0.00	0.00
G-LT16-146	-6.15103	29.73905	1.40	0.00	100.00	0.00	0.00
G-LT16-147	-6.15388	29.73705	1.70	0.00	100.00	0.00	0.00
G-LT16-148	-6.15388	29.73705	18.80	0.00	100.00	0.00	0.00
G-LT16-149	-6.15388	29.73705	32.60	0.00	99.12	0.72	0.16
G-LT16-150	-6.15388	29.73705	30.00	0.00	100.00	0.00	0.00
G-LT16-151	-6.15388	29.73705	4.40	0.00	100.00	0.00	0.00
G-LT16-152	-6.15388	29.73705	0.50	0.00	100.00	0.00	0.00

G-LT16-153	-6.15388	29.73705	2.20	0.00	100.00	0.00	0.00
G-LT16-154	-6.15388	29.73705	21.80	0.00	100.00	0.00	0.00
G-LT16-155	-6.15388	29.73705	33.00	0.00	98.21	1.30	0.49
G-LT16-156	-6.15388	29.73705	29.50	0.00	99.21	0.72	0.07
G-LT16-157	-6.15388	29.73705	2.20	0.00	100.00	0.00	0.00
G-LT16-158	-6.15388	29.73705	1.40	0.00	100.00	0.00	0.00
G-LT16-159	-6.15388	29.73705	18.80	0.00	100.00	0.00	0.00
G-LT16-160	-6.15388	29.73705	33.00	0.00	92.89	7.04	0.07
G-LT16-161	-6.15388	29.73705	24.00	0.00	100.00	0.00	0.00
G-LT16-162	-6.15388	29.73705	2.80	0.00	100.00	0.00	0.00
G-LT16-163	-6.15388	29.73705	1.80	0.00	100.00	0.00	0.00
G-LT16-164	-6.15388	29.73705	1.80	0.00	100.00	0.00	0.00
G-LT16-165	-6.15388	29.73705	18.80	0.00	100.00	0.00	0.00
G-LT16-166	-6.15388	29.73705	31.20	0.00	97.74	2.12	0.14
G-LT16-167	-6.15198	29.74705	30.40	0.00	100.00	0.00	0.00

G-LT16-168	-6.15198	29.74705	17.50	0.00	100.00	0.00	0.00
G-LT16-169	-6.15198	29.74705	1.40	0.00	100.00	0.00	0.00
G-LT16-170	-6.15198	29.74705	2.40	0.00	100.00	0.00	0.00
G-LT16-171	-6.15198	29.74705	70.00	0.00	92.13	6.91	0.96
G-LT16-172	-6.15198	29.74705	52.30	0.00	97.86	1.87	0.27
G-LT16-173	-6.15198	29.74705	23.80	0.00	100.00	0.00	0.00
G-LT16-174	-6.15198	29.74705	6.20	0.00	100.00	0.00	0.00

Table A3: Radiocarbon Results. Radiocarbon dating results for core T16-TANG16-8A-1G-1.

CENTER FOR ACCELERATOR MASS SPECTROMETRY										
Lawrence Livermore National Laboratory										
^{14}C results										
Submitter:	Lucas/Zimmerman					DATE:	August 7, 2017			
CAMS #	Sample		d^{13}C	fraction	±	D^{14}C	±	^{14}C age	±	
	Name			Modern						
177416	1067-1		-25	1.0284	0.0059	28.4	5.9	>Modern		
177417	1067-2		-25	1.1743	0.0053	174.3	5.3	>Modern		

177418	1067-3		-25	0.9647	0.0062	-35.3	6.2	290	60	
177419	1067-4		-25	0.9520	0.0045	-48.0	4.5	395	40	
177420	1067-5		-25	0.9445	0.0058	-55.5	5.8	460	50	
1) d^{13}C values are the assumed values according to Stuiver and Polach (Radiocarbon, v. 19, p.355, 1977) when given										
without decimal places. Values measured for the material itself are given with a single decimal place.										
Samples with an (*) were large enough, and as requested, to take a sample specific split for IRMS d13C analysis.										
2) The quoted age is in radiocarbon years using the Libby half life of 5568 years and following the conventions of Stuiver and Polach (ibid.).										
3) Radiocarbon concentration is given as fraction Modern, D^{14}C, and conventional radiocarbon age.										
4) Sample preparation backgrounds have been subtracted, based on measurements of samples of ^{14}C-free coal.										
Backgrounds were scaled relative to sample size.										

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