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Notes

Paleo-megalake and paleo-megafan in southern Africa

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ABSTRACT

The near juxtaposition of the Makgadikgadi Basin (Botswana), the world's largest saltpan complex, with the Okavango Delta, one of the planet's largest inland deltas (technically an alluvial megafan), has intrigued explorers and scientists since the middle of the 19th century. It was clear from early observations that the Makgadikgadi Basin once contained a huge lake, paleo-Lake Makgadikgadi. Several authors have since speculated that this lake also covered wide regions to the north and west of the Makgadikgadi Basin. Our interpretation of unusually high-quality helicopter time-domain electromagnetic (HTEM) data indicates that paleo-Lake Makgadikgadi extended northwestward at least into the region presently occupied by the Okavango Delta. The total area of paleo-Lake Makgadikgadi exceeded 90,000 km², larger than Earth's most extensive freshwater body today, Lake Superior (North America). Our HTEM data, constrained by ground-based geophysical and borehole information, also provide evidence for a paleo-megafan underlying paleo-Lake Makgadikgadi sediments.

INTRODUCTION

The sometimes-hostile Makgadikgadi Basin (Botswana), with its seasonal changes from vast barren wasteland to a complex of shallow ephemeral lakes, and the remarkable Okavango Delta, with its rich fauna and flora (Figs. 1 and 2A), both lie within the Kalahari Basin (Thomas and Shaw, 1991). For most of the year, the Makgadikgadi Basin is desiccated, with sand and large salt pans dominating the 37,000 km² landscape. In contrast, the Okavango Delta comprises a vast network of river channels, permanent and seasonal wetlands, and islands (McCarthy, 2006) within an asymmetric graben (bounded by the Gumare, Kunyere, and Thamalakane faults in Fig. 1) that has widely been interpreted to be a southwestward extension of the East African Rift System (Modisi et al., 2000). Offsets of relatively young geological features, the abrupt nature of the faults, and active seismicity testify to recent and ongoing tectonism; a M6.7 earthquake in A.D. 1952 resulted in sufficient landform deformation to redirect water flow in the southwestern Okavango Delta (Hutchison and Midgley, 1973). The Okavango River, which enters the Okavango Delta through a narrow graben bounded by the Panhandle faults, supplies >60% of the delta's water, with direct rainfall making up the remainder (McCarthy, 2006).

Crustal flexuring involving continental-scale subsidence in the center and uplift along surrounding swells created the Kalahari Basin (Moore and Larkin, 2001; Burke and Gunnell, 2008; Moore et al., 2012). Changes in erosion and sedimentation rates in major rivers and offshore sedimentary basins and deltas, together with fission-track cooling ages of basement rocks, suggest that crustal flexuring occurred

in the middle Tertiary. Uplift along the swells blocked the southeasterly flow of the Okavango, Cuando, Upper Zambezi, and Kafue Rivers to the Indian Ocean, creating an internal drainage system that fed large volumes of water to paleo-Lake Makgadikgadi (PLM). Numerous fossil shorelines and offshore bars, the most conspicuous of which is the 250-km-long Gidikwe Ridge (Fig. 1), are the primary evidence for the paleolake (Thomas and Shaw, 1991).

It has been suggested that the water volume entering PLM gradually reduced as the easterly flowing Lower Zambezi River progressively captured the Cuando, Upper Zambezi, and Kafue Rivers (Thomas and Shaw, 1992; Moore and Larkin, 2001; Burrough et al., 2009; Moore et al., 2012). There is also evidence that the rivers occasionally or frequently reverted to their former southeasterly courses. It has been widely accepted that these drainage-pattern changes were significantly influenced by faulting (McCarthy, 2006; Burrough et al., 2009; Moore et al., 2012).

There are considerable uncertainties regarding the timing of events in this region. Miocene-age pollen in fluvio-lacustrine deposits overlying basement (Moore et al., 2012) provide incomplete information on the onset of Makgadikgadi Basin sedimentation. Numerous optically stimulated luminescence ages of PLM shoreline sediments have been explained in terms of a repeatedly or continuously filled lake with water levels up to 945 m a.s.l. (above sea level) from at least the middle Pleistocene until the early Holocene (Burrough et al., 2009), whereas interpreted early Stone Age tools on the floor of the Makgadikgadi Basin are taken as evidence for gradual and episodic desiccation

of the lake floor during this same period (Moore et al., 2012). When tectonism began to affect this region is not established; some tectonic-related drainage-pattern changes are estimated to have occurred in the early to middle Pleistocene based on the dispersion patterns and genetic evolution of certain fishes and crocodiles (Moore et al., 2012).

To improve our understanding of the hydrogeology of the Okavango Delta and to determine if PLM once included the region now occupied by the delta (Thomas and Shaw, 1991, and references therein), we have taken advantage of an extraordinarily high-quality helicopter time-domain electromagnetic (HTEM) data set. We corrected, calibrated, processed, and inverted the data using new procedures that allow commercial data designed for mineral exploration to be used for hydrogeological investigations (Viezzoli et al., 2008; Podgorski et al., 2013). To highlight the most important features, the resultant three-dimensional (3-D) resistivity model has been spatially smoothed and displayed using a simplified three-color scheme in Figures 2 and 3. Our interpretation of the model has been constrained by information supplied by newly acquired ground-based electromagnetic, electrical resistivity, and seismic data and recently available information from boreholes at diverse locations (Fig. 1).

ELECTRICAL RESISTIVITY MODELS

Electrical resistivities in and underlying the Okavango Delta are controlled by the total dissolved solids in the water and sediments and by the basement lithologies; freshwater-saturated sand and basement rocks have high resistivities, whereas silt and/or clay and saline-water-saturated sand have low resistivities. The near surface is dominated by high resistivities (>15 Ωm; yellow and red in Figs. 2B, 2C, and 3) of the fresh water in the channels and swamps and shallow freshwater aquifers, together with the low resistivities (<15 Ωm; blue in Figs. 2B, 2C, and 3) of clay- and salt-covered parts of the islands and shallow saline-water aquifers. We interpret the extensive low-resistivity layer (blue in Figs. 2D–2F and 3) underlying the heterogeneous near-surface formations as a combination of lacustrine clay units and saline-water aquifers. Our interpretation of this layer, the thickness of which increases from ~50 m near the panhandle in the northwest to ~200 m in

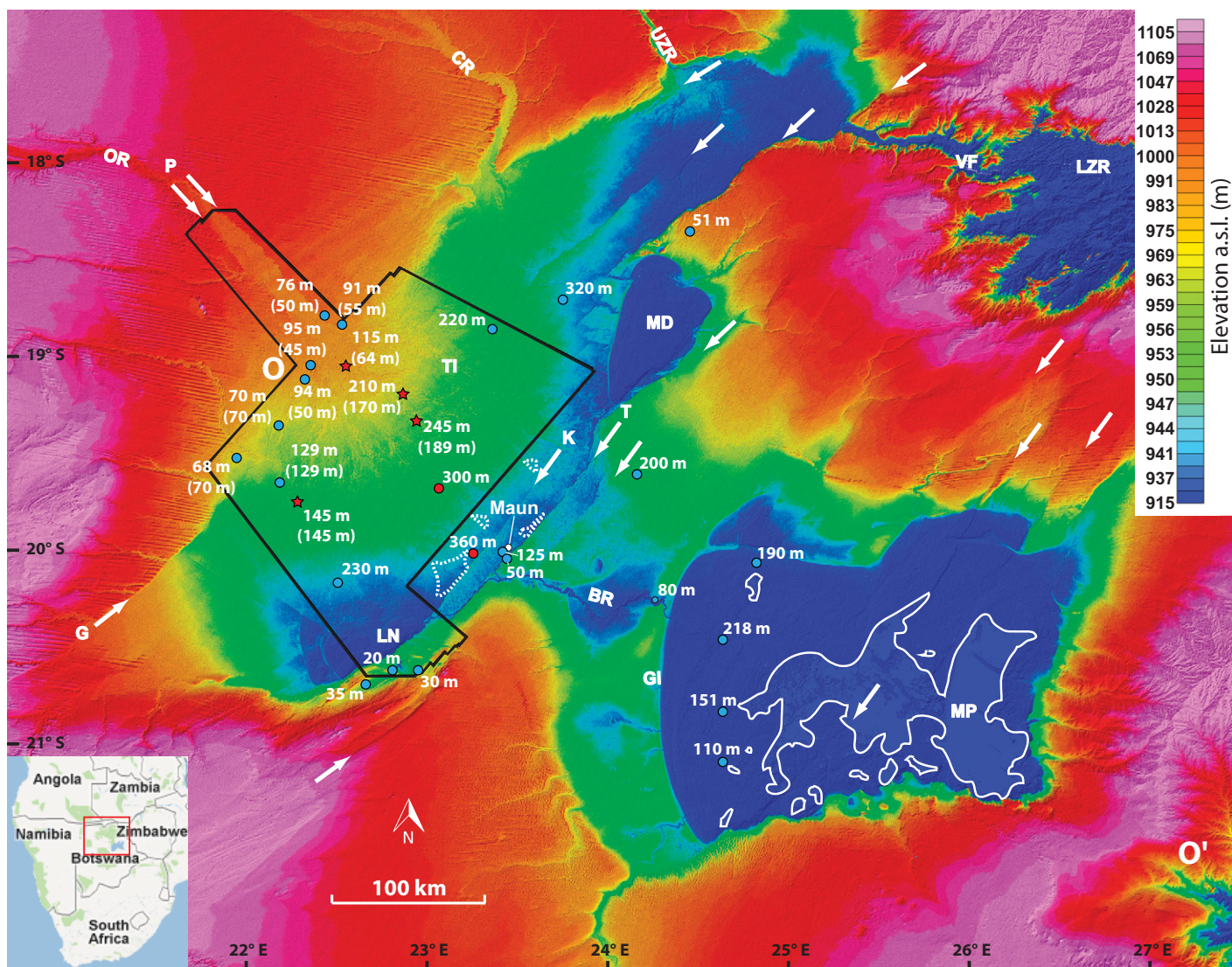


Figure 1. Topographic map (SRTM-3 [Shuttle Radar Topography Mission] data) of northern Botswana (a.s.l.—above sea level). O-O' is approximate location of cross section in Figure 5D. White arrows show faults: G—Gumare; K—Kunyere; P—Panhandle; T—Thamalakane. White solid lines indicate pans. Black polygon is Okavango Delta helicopter time-domain electromagnetic survey area. Blue dots indicate basement depths defined by boreholes; red dots and stars indicate basement depths defined by seismic surveys. White numbers in parentheses are depths to base of electrically conductive layer. White dashed lines indicate clusters of boreholes that do not reach basement. Rivers: BR—Boteti; CR—Cuando; LZR—Lower Zambezi; OR—Okavango; UZR—Upper Zambezi. Gi—Gidikwe Ridge; LN—Lake Nagami; MD—Mababe Depression; MP—Makgadikgadi Pans; TI—Thata Island; VF—Victoria Falls. Kafue River is north of the map. Makgadikgadi Basin encompasses the Makgadikgadi Pans and surrounding low-elevation regions. Except for a borehole on Thata Island, sediment lithologies beneath survey area are unknown.

the southeast (Fig. 3), is based on a thick clay unit observed in the lower 35 m of a 96-m-deep borehole on Thata Island (Fig. 1) and thick intercalated units of clay and saline-water-saturated sand in the lower parts of numerous boreholes drilled immediately southeast of the HTEM survey area (MMEWR, 2004); individual clay units are >40 m thick in some boreholes.

Thick layers of intercalated clay, sand, limestone, and chert encountered in mineral-exploration boreholes in the Makgadikgadi Basin (Fig. 1) have recently been interpreted as lacustrine deposits (Moore et al., 2012). We cannot correlate one-to-one the lacustrine sediments underlying the Okavango Delta with those

within the Makgadikgadi Basin, but considering the proximity of the two features and their connection via the Boteti River and low-lying regions on either side (Fig. 1), it is highly probable that the same lake occupied both regions. Like the lacustrine sediments within the Makgadikgadi Basin, practically all lacustrine sediments beneath the Okavango Delta (as delineated by the low-resistivity layer) lie below the highest water level (945 m a.s.l.) of PLM.

A prominent southeast-dipping, high-resistivity feature characterizes the deeper parts of the HTEM resistivity model (red in Figures 2D–2F and 3). Models derived from single and joint inversions of ground-based time-domain

electromagnetic, natural and controlled-source audiomagnetotelluric, and electrical resistivity tomographic data that we acquired at four Okavango Delta investigation sites (red stars in Fig. 1) confirm its depth distribution and high resistivity. Based on its resistivity alone, this approximately fan-shaped feature could represent a prominent basement dome, a freshwater-saturated sand and/or gravel unit, or a combination of both.

Basement depths within the Okavango Delta are available from a limited number of boreholes, simple dipping layered models derived from 1970s vintage seismic refraction data recorded at several locations (Greenwood and

Carruthers, 1973), and high-resolution seismic reflection images and refraction tomograms derived from data collected at our four Okavango Delta investigation sites. The unconsolidated sediment-basement boundary is well delineated in the modern seismic images and tomograms by an abrupt transition from material characterized by horizontally layered reflectors and 1750–1850 m/s P-wave velocities above, to material that is largely reflector-free and has 4600–5500 m/s P-wave velocities below. In one region, where our investigation site is close to that of a 1970s survey, the old and new basement depth estimates are essentially the same, giving us confidence in the quality of the older data and derived models.

In the western part of the Okavango Delta, the borehole- and seismic-determined basement depths practically coincide with the depths to the top of the lowermost resistive layer (Fig. 1). In other parts, the borehole- and seismic-determined basement depths are deeper than the top of the resistive layer by 20–55 m (see example in Fig. 3B). Based on these comparisons, the upper part of the deep resistive layer in the western part of the Okavango Delta is unequivocally the basement and in other parts it is interpreted to comprise a freshwater-saturated sand and/or gravel unit overlying basement.

The fan shape of the postulated freshwater-saturated sand and/or gravel unit (Figs. 2E and 2F), which has low seismic velocities and is highlighted by its concentric curvilinear depth contours in Figure 4A and the arcuate shape of its characteristic resistivities in Figure 4B, suggests that it encompasses the remnants of a paleo-Okavango megafan (POM). If our interpretation is correct, laterally continuous silt and/or clay units within the overlying low-resistivity layer must act as effective barriers to the mixing of saline water above with the freshwater aquifer below.

PALEO-LAKE MAKGADIKGADI AND PALEO-OKAVANGO MEGAFAN

One of a number of evolutionary models for PLM and the POM is sketched in Figure 5. Although the Makgadikgadi Basin probably subsided during the period represented by the sketches, for simplicity we maintain the basement at constant depth. Our model includes the original creation of the Makgadikgadi Basin as a consequence of crustal flexuring and subsidence, termination of major southeasterly flowing rivers in the Makgadikgadi Basin to form PLM, and formation of the POM (Fig. 5A). Tectonism subsequently causes major faulting throughout the region (Figs. 1, 5B, and 5C); displacements predominantly along the Kunyere and Thamalakane faults generate an asymmetric graben that contains an expanded part of the evolving PLM. Subsidence and sedimentation lead to burial of the POM. Major reductions in water flowing into the region result in the

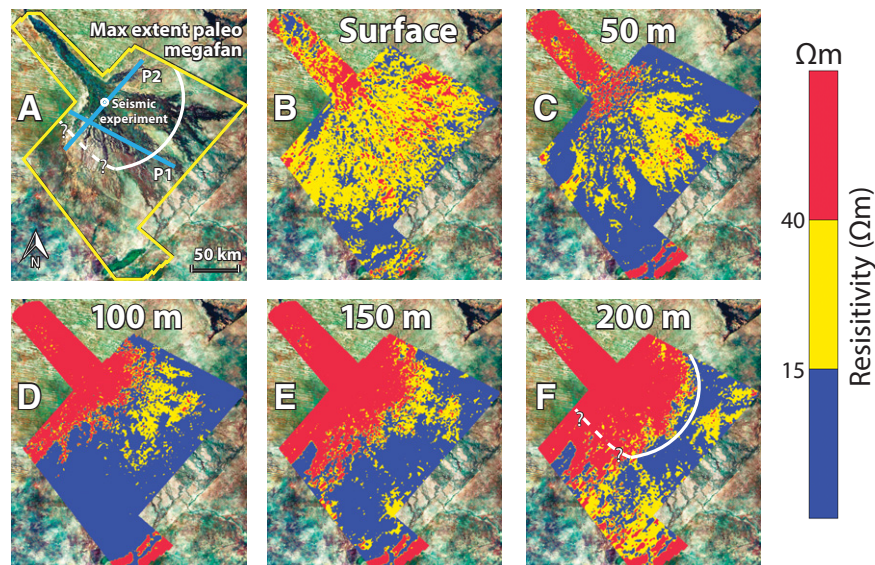


Figure 2. Satellite image and resistivity depth slices. **A:** Satellite image showing Okavango Delta helicopter time-domain electromagnetic (HTEM) survey area and locations of two cross sections (P1 and P2) and seismic experiment in Figure 3. **B–F:** Depth slices at 50 m intervals extracted from three-dimensional (3-D) resistivity model obtained from inverting HTEM data using a quasi-3-D spatially constrained scheme (Viezzoli et al., 2008; Podgorski et al., 2013). The 28,000 km² of data were acquired at an average height of 50 m along northeast-directed profiles separated by 2 km.

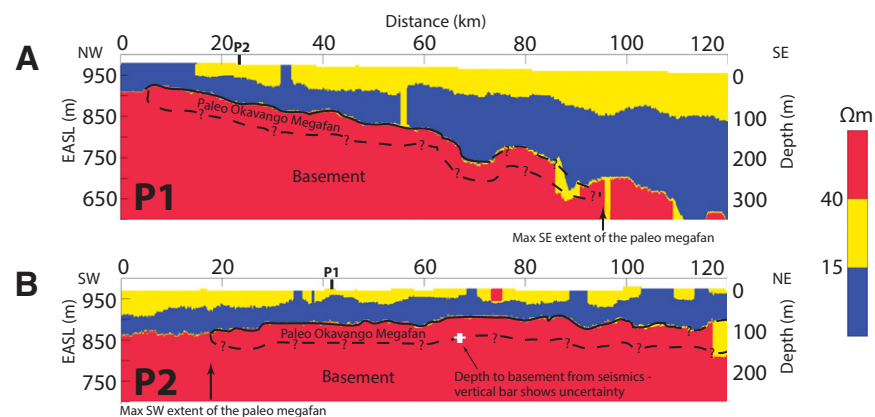


Figure 3. Vertical cross sections extracted from three-dimensional resistivity model obtained from inverting helicopter time-domain electromagnetic data. For locations see Figure 2A. Basement depth indicated by white cross is from combined interpretation of high-resolution seismic reflection images and seismic refraction tomograms. EASL—elevation above sea level. Note large (80:1) vertical exaggeration of these images.

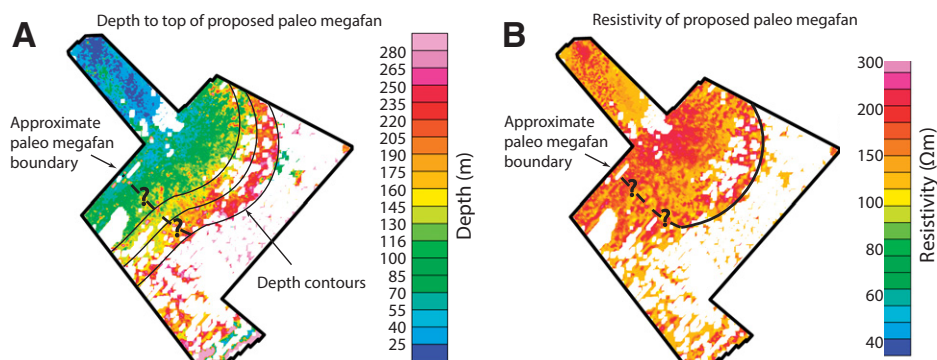


Figure 4. Depth (A) and resistivity (B) of postulated paleo-Okavango megafan as defined by the 40–300 Ωm layer. Southwestern boundary of paleo-megafan is only poorly resolved by resistivity model and borehole-defined basement depths.

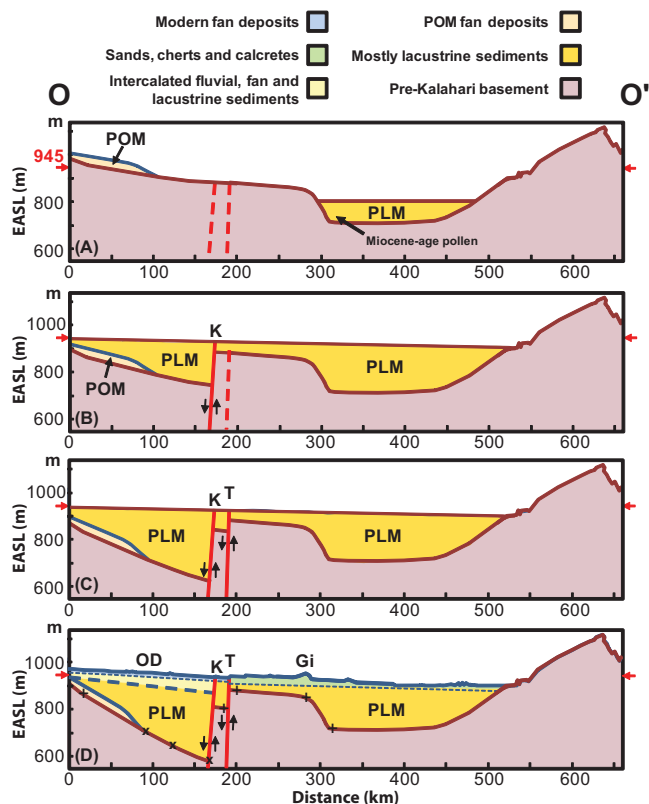


Figure 5. Cartoon showing one evolutionary model for paleo-Lake Makgadikgadi (PLM) and Okavango Delta (OD). For approximate location of simplified cross section see O-O' in Figure 1. Basement depths determined from nearby boreholes, and seismic surveys in D are shown by pluses (+) and x's, respectively. EASL—elevation above sea level; Gi—Gidikwe Ridge; K—Kunyere fault; POM—paleo-Okavango megafan; T—Thamalake fault. Arrows point to highest water level of PLM.

establishment of the gently sloping Okavango Delta megafan and desiccation of the Makgadikgadi Basin (Fig. 5D). Intercalated silt and/or clay and sand layers in boreholes immediately southeast of the HTEM survey area (MMEWR, 2004) suggest that water flow to the region was highly variable over extended periods as a result of fault movements and climate change. The hydrological and depositional environment likely varied from lacustrine to fluvial, megafan, and aeolian. Some lacustrine units were probably deposited in saline lakes.

Our results establish the total area of PLM at >90,000 km² with a high degree of confidence. Recognizing the possibility that low-lying regions to the northeast and southwest of the Okavango Delta (Fig. 1) also overlie lacustrine sediments, PLM may well have covered the ~120,000 km² originally speculated by Thomas and Shaw (1991).

Changes in flow direction of major rivers due to tectonism and substantial climatic variations have both been invoked to explain large PLM water-level fluctuations during the Pleistocene and Holocene (Hutchison and Midgley, 1973; Moore et al., 2012; Burrough et al., 2009). Because the Okavango Delta is highly sensitive to climatic changes, as witnessed by recent flooding generated by relatively minor changes in precipitation patterns, modern geochronological, isotopic, geochemical, biochemical, and biostratigraphic analyses of sediments extracted from Okavango Delta boreholes would likely provide a new understanding of tectonic,

climatic, and biological variability and human development throughout the Quaternary on a regional, continental, and possibly hemispheric scale (Thomas and Burrough, 2012). Of course, boreholes that penetrate the entire sedimentary section would also provide information to test our stratigraphic model of the Okavango Delta.

To our knowledge, this is the first time that HTEM data have been used to determine new hydrological and geological information on such a large scale. Our results suggest that relatively inexpensive HTEM surveying has the potential to provide fundamental new insights into the hydrological and geological evolution of many other relatively hostile and remote locations.

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