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COMMENT
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Key Points:

- The model proposed by Jolivet et al. cannot describe the geohydrological functioning of the Okavango Delta
- Previous studies of subsurface soils on 18 islands have failed to reveal the presumed deeper clay-rich layer
- We attribute REE fractionation in subsurface soils observed by Jolivet et al. to be caused by the precipitation of calcite from groundwater

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Comment on "Highly Contrasted Geochemical Pattern in Sediments of the Okavango Delta, Botswana Driven by Dust Supply, Hydrological Heritage and Biogeochemical Reactions" by Jolivet et al.

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Abstract The Okavango Delta in southern Africa has been the subject of geomorphological and hydrological investigations since the 1970s. In the early 1990s, McCarthy and co-workers developed a geomorphological and hydrological model which describes the processes that give rise to the gently undulating topography and the lack of saline surface water in this semi-arid environment. This model is based on extensive investigations of soil and water chemistry conducted across the Okavango Delta, and has been subject to rigorous testing by a number of independent researchers. In their recent paper, Jolivet et al. (2023, https://doi.org/10.1029/2023GC010978) proposed an alternative hydrological model based on chemical and mineralogical analyses of samples from six auger holes drilled at a site on the lower fringe of the permanent swamp. We provide a critique of their model and explain how this model cannot describe the geohydrological functioning of the Okavango Delta. Jolivet et al. suggest there are two shallow aquifers, one hosted in sand and the other in clay-rich material. Previous studies of subsurface soils on 18 islands have failed to reveal a deeper clay-rich layer. Rather, the shallow groundwater is laterally fully connected and salinity varies in response to evapotranspiration. We attribute REE fractionation in subsurface soils observed by Jolivet et al. to be caused by the precipitation of calcite from groundwater which strongly accumulates REE. We are of the opinion that Jolivet et al. have insufficient data to suggest revisions to the current understanding of the functioning of the Okavango hydrological and sedimentological system.

1. Introduction

The Okavango Delta (Figure 1a) has been the subject of geomorphological and hydrological investigations since the 1970s, particularly by the Botswana Department of Water Affairs and the United Nations Development Programme, and by university groups since the 1980s. The hydrology is now very well-known and it has been established that only ~2% of the inflowing water leaves the Delta as surface flow, with the bulk of the remainder lost to evapotranspiration. The total amount of particulate sediment entering the Delta each year is estimated to be made up of 170,000 tonnes of fine sand and 39,000 tonnes of silt (McCarthy & Metcalfe, 1990). Approximately 380,000 tonnes of dissolved solutes enter the Delta, of which only 23,000 tonnes leaves as surface outflow (McCarthy, 2006). It is estimated that ~260,000 tonnes of mineral salts precipitate in the Delta each year, primarily in the form of calcium and magnesium carbonate, and amorphous silica. The most soluble solute accumulates as sodium bicarbonate brine in the groundwater beneath islands. Notwithstanding the high water loss, surface water in the Delta remains fresh. Researchers have developed a geomorphological and hydrological model (Figure 1b) which describes the processes that give rise to the gently undulating topography and the lack of saline surface water in this semi-arid environment (McCarthy & Ellery, 1994; McCarthy et al., 1991, 1993). Establishing the model involved investigations of ground and surface water and soil chemistry on 18 islands spread across the Delta (Figure 1a). In the region of 200 auger holes were drilled and approximately a thousand soil samples were chemically analyzed. About 60 water samples were analyzed for major ions and the conductivity of over 200 water samples was measured. Extensive vegetation surveys were also carried out.

This research indicated that plants, particularly trees growing on islands, are an important agent for water loss. Transpiration by vegetation lowers the water table beneath islands (Figures 1b and 1c), causing a continuous flow of water toward the islands and the progressive accumulation of dissolved salts in the groundwater beneath islands (Figure 1d). The precipitation of calcium carbonate and silica from the groundwater in the subsurface

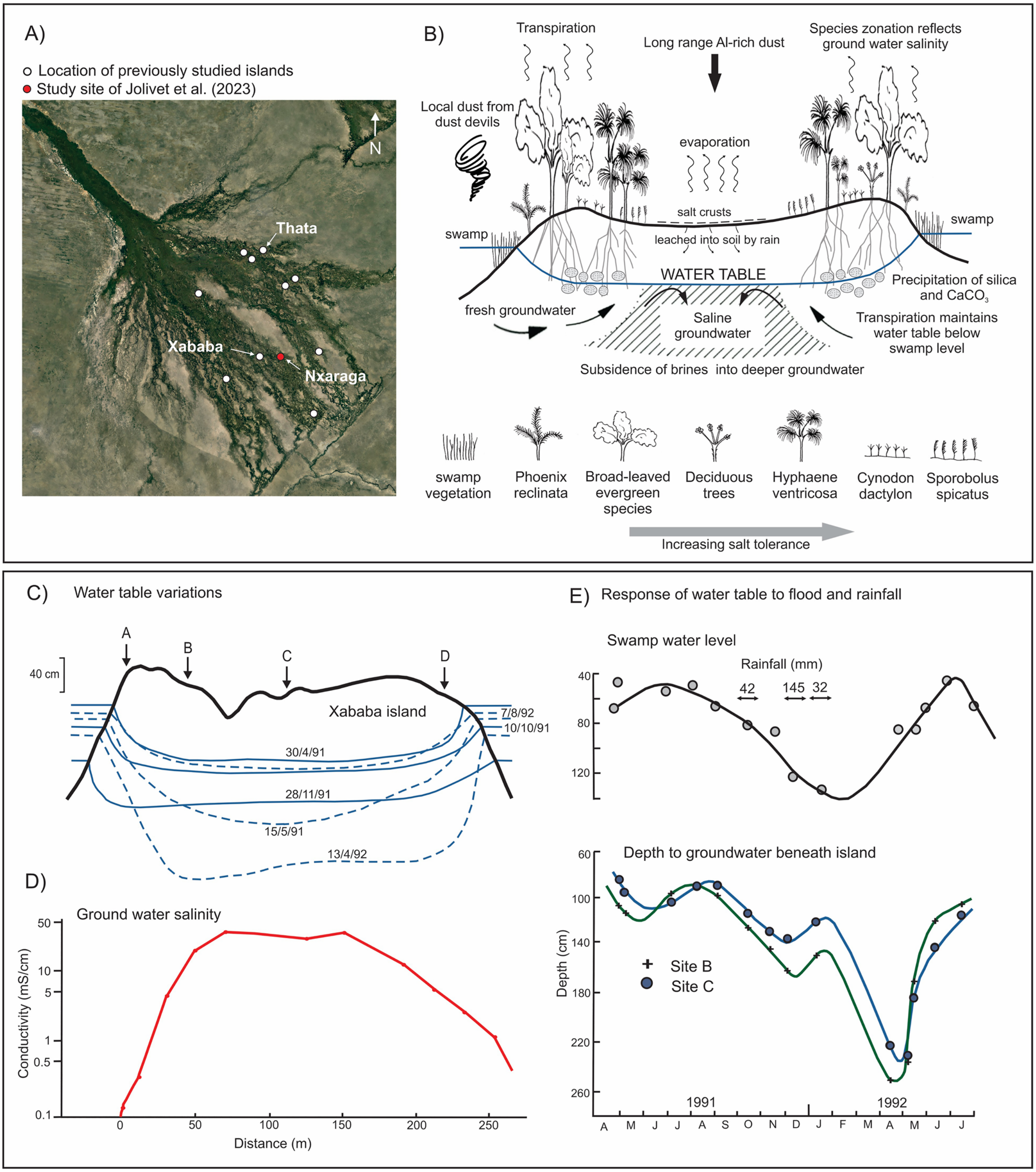

Figure 1. (a) Google image showing the locations of Nxaraga Island and the islands studied by McCarthy and co-workers; (b) Diagram summarizing the model of island growth and saline water disposal developed by McCarthy and co-workers; (c) Variations in the depth to the water table at Xaxaba Island over the 1991–1992 flood cycle; (d) Conductivity of the ground water beneath Xaxaba Island; (e) Variation in depth to the water table at two sites on Xaxaba Island (see panel (a) for locations) over the 1991–1992 flood cycle.

soils of islands presents a significant aggradational process, contributing up to 30%–40% of the total volume of islands (McCarthy et al., 2012). This process is responsible for the gently rolling topography of the Delta. The accumulation of sodium bicarbonate in the ground water makes it sufficiently dense to cause the downward advection of the saline water into an inferred deeper saline groundwater reservoir (Figure 1b), thereby preventing the development of saline surface water (McCarthy, 2006). Pronounced salinity gradients in the shallow groundwater between island fringes and interiors (Figure 1d) are reflected in the zonation of vegetation species on islands because of their differing tolerance to salt (Ellery et al., 1993; Figure 1b). Sodium bicarbonate accumulates in the residual groundwater, eventually rising to levels that are toxic to plants, so much so that island centers are generally barren of vegetation. In the center of islands, this groundwater is drawn to surface by capillary action, causing the precipitation of efflorescent crusts of sodium bicarbonate (mainly in the form of trona; McCarthy et al., 1986). The salt is extremely soluble, and is regularly re-dissolved and washed back into the groundwater by rainwater, further enhancing the downward advection of the saline water. Figure 1b provides a summary of the processes involved. This model has been subject to rigorous testing by a number of researchers, which has included geophysical imaging and quantitative modeling of subsiding brine plumes (Bauer et al., 2006; Bauer-Gottwein et al., 2007), and has been widely accepted (e.g., Milzow et al., 2009; Ramberg & Wolski, 2008).

2. Critique of the Jolivet et al. Model

Jolivet et al. (2023) propose an alternative hydrological model for the Okavango. Their model is based on chemical and mineralogical analyses of samples from six auger holes drilled on Nxaraga Island and is augmented with trace element water chemistry data from the same holes by Dauteuil et al. (2021). Nxaraga Island is located at the lower fringe of the permanent swamp (Figure 1a). The Jolivet model is analyzed below.

Using groundwater and soil samples collected from the auger holes and surface water from the adjacent Boro channel and floodplain, Jolivet et al. (2023) propose that there are two non-connected aquifers beneath the Delta; an upper aquifer hosted in sand-rich sediment and an underlying confined deeper aquifer which contains a relatively high proportion of clay material. They propose that the interaction between sediment, water and organic matter in the confined aquifer explains the geochemical enrichment of the water beneath islands, although the actual chemistry involved is not discussed. In contrast, analyses of numerous water samples collected along transects across islands by McCarthy and co-workers have shown that rather than two discrete types, the salinity of groundwater varies continuously by about three orders of magnitude, from about 40 mg/L close to channels to several thousand mg/L beneath islands (e.g., Figure 1d). Moreover, groundwater salinity is concentrically zoned beneath and around the islands, with the highest concentration in the center (McCarthy et al., 2012). The notion that there are two populations of groundwater is incorrect.

By using a conserved element as a tracer to monitor the evolution of groundwater composition (Na in this case), McCarthy and co-workers have demonstrated that the variations in groundwater chemistry are systematic and reflect the progressive saturation of solutes as water is lost by transpiration (McCarthy et al., 1993). Silica saturates first, followed by magnesium calcite. Silica and calcite precipitate in the near-surface soils, causing swelling and hence island growth (McCarthy et al., 2012). Sodium content (as bicarbonate) increases progressively beneath the islands to the point where the water becomes sufficiently dense to induce gravitational advection into the subsurface. One of these descending plumes has been imaged using geophysical methods by Bauer and co-workers. During the hot summer months, saline groundwater which has risen to surface evaporates, leaving efflorescent crusts on the soil surface.

Jolivet et al. (2023) are of the opinion that the near surface sediment which forms the islands is stratified, with discrete clay- and sand-rich layers. They suggest the clay-rich layer beneath the island extends laterally beneath the floodplain, although the auger holes they drilled in the floodplain did not intersect this presumed layer. The distribution of Al_2O_3, a proxy for clay, has been examined in several of the studies carried out by McCarthy and co-workers (e.g., McCarthy & Ellery, 1994, 1995; McCarthy et al., 1986, 1991, 1993; McCarthy, Ellery, & Dangerfield, 1998; McCarthy & Metcalfe, 1990). None of these studies have revealed a stratigraphic break between an upper sand layer and a lower clay-rich layer. Deeper boreholes (ca. 100 m) drilled into Thata Island (Figure 1a) island also found no evidence of different sedimentary layers (Bauer, 2004). Rather, the Al_2O_3 content of islands is highly variable and is often associated with termite mounds. Petrographic examination of termite mound material suggests that termites selectively gather fine material, including clay, amorphous silica and calcite, which they mix with body fluids and use as a mortar in the construction of their termitaria (McCarthy

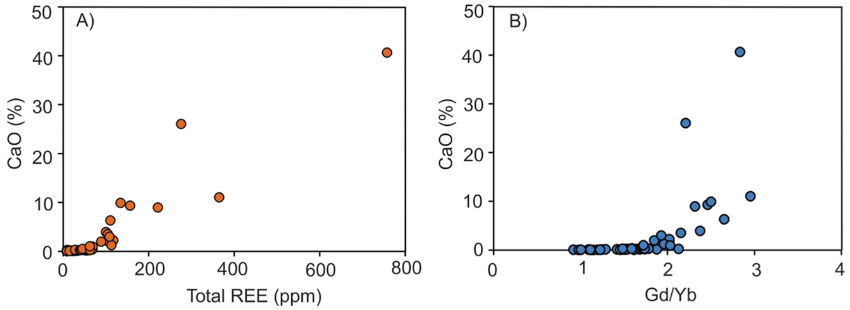

Figure 2. The relationship between CaO content, a measure of the calcite abundance and (a) total REE abundance and (b) the Gd/Yb ratio.

et al., 1986). The normal sandy soils in the Delta lack cohesion, so the use of this mortar is essential in the construction of termitaria.

The major source of Al is probably airborne dust (Humphries et al., 2014; Krah et al., 2004), much of which appears to originate in the adjacent Makgadikgadi playa lakes, as indicated by $^{87}Sr/^{86}Sr$ ratios (Humphries et al., 2020). Much of this dust is probably eluviated into the subsurface soil, where it can be collected by termites. The mortar material is recycled during weathering and erosion of the mounds, but gradually becomes locally concentrated as clusters of termite mounds expand into ever larger islands (McCarthy, Ellery, & Dangerfield, 1998). Termites cannot construct termitaria on seasonal floodplains. However, the distribution of water across the Okavango Delta constantly changes due to the blockage and failure of upstream distributary channels (McCarthy et al., 1992). The implication of this is that large regions of the floodplain may revert to dry land and remain so for decades (McCarthy et al., 2003), during which time termites are able to colonize the dry surfaces.

Jolivet et al. (2023) and Dauteuil et al. (2021) proposed that the groundwater beneath floodplains and islands are hydrologically separate. However, several studies have demonstrated there is a complete evolutionary link between fresh groundwater beneath the floodplain and saline water beneath islands as mentioned above (e.g., McCarthy & Ellery, 1994, 1995; Figures 1c and 1d). Moreover, there is complete physical connectivity, as numerous water table depth measurements across islands and floodplains have demonstrated. Although continuous, the island and floodplain groundwater do not mix because groundwater moves by laminar flow and, unlike surface water, flows down pressure gradients rather than topographic gradients. During a long-term monitoring study at Xaxaba, 12 km west of Nxaraga (Figure 1a), groundwater was monitored for 17 months in the period 1991–1992 (Figures 1c and 1e). Heavy rains were experienced in the rainy season which produced a distinct rise in the water table (Figures 1c and 1e). This indicates that the groundwater is directly connected to surface ingress and is not a confined aquifer as proposed by Jolivet et al. (2023). The arriving floodwater sinks vertically into the ground and the groundwater level ahead of the flood rises up in response (Figure 1c). The saline water beneath islands therefore rises and falls seasonally, but lateral movement is minimal. The rate of change of salinity below island centers is thus very slow (Figure 1d) and may even achieve a steady state condition, reflecting a balance between evapotranspirative enrichment in salt content and density-driven downward advection of the resulting brine. In this way, islands act as solute sinks in the landscape, connecting shallow saline groundwater with a deeper saline groundwater reservoir of the kind discussed by McCarthy, Bloem, and Larkin (1998). In contrast, the hydrological model proposed by Jolivet et al. (2023) cannot account for the fate of solutes in the Okavango.

Rare earth element (REE) abundances form a key component of the argument put forward by Jolivet et al. (2023). However, little is known about the behavior of REEs in environments like the Okavango. Ground water beneath islands is typically saturated with respect to calcium carbonate and silica, which precipitate in island soils. The precipitation of these minerals, particularly calcite, is likely to result in the fractionation of REEs. Experimental studies have demonstrated that REEs are strongly partitioned into calcite by substituting for Ca^{2+} in the crystal lattice and through adsorption (e.g., Voigt et al., 2017; Zhong & Mucci, 1995). The partitioning of REEs between calcite and aqueous solution generally decreases systematically with atomic number (Voigt et al., 2017). In Figure 2, we plot data collected by Jolivet et al. (2023) to demonstrate the influence of calcite (represented by CaO) on the concentration and fractionation of REEs in soils from Nxaraga Island. Samples containing high concentrations of CaO are enriched in REEs (Figure 2a) and exhibit clear fractionation of the

Gd/Yb ratio (Figure 2b), reflecting the varying ability of REEs to incorporate into the solid phase (log $D^{\mathrm{Gd}} = 3.4$ vs. log $D^{\mathrm{Yb}} = 1.9$). We suggest that this process is responsible for the distinctive concave REE concentration patterns Jolivet et al. (2023) observed in the island subsurface samples they analyzed. Rather than indicating the presence of two non-connected aquifers, the differing REE patterns observed in sediment samples from Nxaraga Island reflects the preferential fractionation of REEs into calcite, which precipitates as a consequence of evapotranspiration.

We are of the opinion that Jolivet et al. (2023) have insufficient data to suggest revisions to the current understanding of the functioning of the Okavango hydrological and sedimentological system. Their paper is well-referenced, but unfortunately the authors don't seem to have appreciated the significance of the contents of many of the cited paper for their Nxaraga study area. The Okavango Delta is probably the most thoroughly understood of the world's arid zone wetlands, and further understanding will only be obtained by large-scale interdisciplinary research.

Data Availability Statement

New data were not created through this research. The arguments described in this paper are based on previously published data sets cited in-text.

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References

Bauer, P. (2004). *Flooding and salt transport in the Okavango Delta, Botswana: Key issues for sustainable wetland management* (Unpublished PhD thesis). ETH Zurich.

Bauer, P., Supper, R., Zimmermann, S., & Kinzelbach, W. (2006). Geoelectrical imaging of groundwater salinisation in the Okavango Delta, Botswana. *Journal of Applied Geophysics*, *60*(2), 126–141. https://doi.org/10.1016/j.jappgeo.2006.01.003

Bauer-Gottwein, P., Langer, T., Prommer, H., Wolski, P., & Kinzelbach, W. (2007). Okavango Delta islands: Interaction between density-driven flow and geochemical reactions under evapo-concentration. *Journal of Hydrology*, *335*(3–4), 389–405. https://doi.org/10.1016/j.jhydrol.2006.12.010

Dauteuil, O., Jolivet, M., Dia, A., Murray-Hudson, M., Makati, K., Barrier, L., et al. (2021). Trace metal enrichments in water of the Okavango Delta (Botswana): Hydrological consequences. *Geochemistry, Geophysics, Geosystems*, *22*(5), e2021GC009856. https://doi.org/10.1029/2021gc009856

Ellery, W. N., Ellery, K., & Mccarthy, T. S. (1993). Plant distribution in islands of the Okavango Delta, Botswana: Determinants and feedback interactions. *African Journal of Ecology*, *31*(2), 118–134. https://doi.org/10.1111/j.1365-2028.1993.tb00526.x

Humphries, M. S., Benitez-Nelson, C. R., Bizimis, M., Ralph, T. J., Larkin, Z. T., & McCarthy, T. S. (2020). Dust provenance and its role as a potential fertilizing agent for the Okavango Delta, Botswana. *Earth Surface Processes and Landforms*, *45*(8), 1705–1716. https://doi.org/10.1002/esp.4840

Humphries, M. S., McCarthy, T. S., Cooper, G. R. J., Stewart, R. A., & Stewart, R. D. (2014). The role of airborne dust in the growth of tree islands in the Okavango Delta, Botswana. *Geomorphology*, *206*, 307–317. https://doi.org/10.1016/j.geomorph.2013.09.035

Jolivet, M., Dauteuil, O., Dia, A., Davranche, M., Pierson-Wickmann, A.-C., Barrier, L., et al. (2023). Highly contrasted geochemical pattern in sediments of the Okavango Delta, Botswana driven by dust supply, hydrological heritage and biogeochemical reactions. *Geochemistry, Geophysics, Geosystems*, *24*(6), e2023GC010978. https://doi.org/10.1029/2023gc010978

Krah, M., McCarthy, T. S., Annegarn, H., & Ramberg, L. (2004). Airborne dust deposition in the Okavango Delta, Botswana, and its impact on landforms. *Earth Surface Processes and Landforms*, *29*(5), 565–577. https://doi.org/10.1002/esp.1051

McCarthy, J. M., Gumbricht, T., McCarthy, T., Frost, P., Wessels, K., & Seidel, F. (2003). Flooding patterns of the Okavango Wetland in Botswana between 1972 and 2000. *Ambio*, *32*(7), 453–457. https://doi.org/10.1579/0044-7447-32.7.453

McCarthy, T. S. (2006). Groundwater in the wetlands of the Okavango Delta and its contribution to the structure and function of the ecosystem. *Journal of Hydrology*, *320*(3–4), 264–282. https://doi.org/10.1016/j.jhydrol.2005.07.045

McCarthy, T. S., Bloem, A., & Larkin, P. A. (1998). Observations on the hydrology and geohydrology of the Okavango Delta. *South African Journal of Geology*, *101*, 101–117.

McCarthy, T. S., & Ellery, W. N. (1994). The effect of vegetation on soil and ground water chemistry and hydrology of island in the seasonal swamps of the Okavango Fan, Botswana. *Journal of Hydrology*, *154*(1–4), 169–193. https://doi.org/10.1016/0022-1694(94)90216-x

McCarthy, T. S., & Ellery, W. N. (1995). Sedimentation on the distal reaches of the Okavango Fan, Botswana, and its bearing on calcrete and silcrete (Ganister) formation. *Journal of Sedimentary Research*, *A65*, 77–90.

McCarthy, T. S., Ellery, W. N., & Dangerfield, J. M. (1998). The role of biota in the initiation and growth of islands on the floodplain of the Okavango Alluvial Fan, Botswana. *Earth Surface Processes and Landforms*, *23*(4), 291–316. https://doi.org/10.1002/(sici)1096-9837(199804)23:4<291::aid-esp844>3.0.co;2-a

McCarthy, T. S., Ellery, W. N., & Ellery, K. (1993). Vegetation-induced, subsurface precipitation of carbonate as an aggradational process in the permanent swamps of the Okavango (Delta) fan, Botswana. *Chemical Geology*, *107*(1–2), 111–131. https://doi.org/10.1016/0009-2541(93)90105-r

McCarthy, T. S., Ellery, W. N., & Stanistreet, I. G. (1992). Avulsion mechanisms on the Okavango fan, Botswana: The control of a fluvial system by vegetation. *Sedimentology*, *39*(5), 779–795. https://doi.org/10.1111/j.1365-3091.1992.tb02153.x

McCarthy, T. S., Humphries, M. S., Mahomed, I., Le Roux, P., & Verhagen, B. T. (2012). Island forming processes in the Okavango Delta, Botswana. *Geomorphology*, *179*, 249–257. https://doi.org/10.1016/j.geomorph.2012.08.016

McCarthy, T. S., McIver, J. R., & Cairncross, B. S. (1986). Carbonate accumulation on islands in the Okavango Delta. *South African Journal of Science*, *82*, 588–591.

McCarthy, T. S., McIver, J. R., & Verhagen, B. T. (1991). Groundwater evolution, chemical sedimentation and carbonate brine formation on an island in the Okavango Delta swamp, Botswana. *Applied Geochemistry*, *6*, 577–595. https://doi.org/10.1016/0883-2927(91)90071-v

McCarthy, T. S., & Metcalfe, J. (1990). Chemical sedimentation in the Okavango Delta, Botswana. *Chemical Geology*, *89*(1–2), 157–178. https://doi.org/10.1016/0009-2541(90)90065-f

Milzow, C., Kgotlhang, L., Bauer-Gottwein, P., Meier, P., & Kinzelbach, W. (2009). Regional review: The hydrology of the Okavango Delta, Botswana—Processes, data and modelling. *Hydrogeology Journal*, *17*(6), 1297–1328. https://doi.org/10.1007/s10040-009-0436-0

Ramberg, L., & Wolski, P. (2008). Growing islands and sinking solutes: Processes maintaining the endorheic Okavango Delta as a freshwater system. *Plant Ecology*, *196*(2), 215–231. https://doi.org/10.1007/s11258-007-9346-1

Voigt, M., Mavromatis, V., & Oelkers, E. H. (2017). The experimental determination of REE partition coefficients in the water-calcite system. *Chemical Geology*, *462*, 30–43. https://doi.org/10.1016/j.chemgeo.2017.04.024

Zhong, S., & Mucci, A. (1995). Partitioning of rare earth elements (REEs) between calcite and seawater solutions at 25°C and 1 atm, and high dissolved REE concentrations. *Geochimica et Cosmochimica Acta*, *59*(3), 443–453. https://doi.org/10.1016/0016-7037(94)00381-u