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East African weathering dynamics controlled by vegetation-climate feedbacks

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ABSTRACT

Tropical weathering processes hold important linkages to global biogeochemistry, as well as landscape evolution including in the East African rift valley. We disentangle the influences of climate change and terrestrial vegetation on chemical weathering intensity and erosion at Lake Malawi using a long sediment record. Fossil pollen, micro-charcoal, particle size, and mineralogy data affirm that the types of allochthonous clays accumulating in deepwater within the lake is controlled by feedbacks between climate and hinterland forest composition. Patterns of particle size are also best explained by vegetation change, through feedbacks with dynamic lake levels, wildfires, and erosion.

We develop a new conceptual source-to-sink framework that links lacustrine sedimentation to hinterland vegetation in tropical rifts. Our analysis suggests that climate-vegetation interactions and their coupling to weathering and erosion could threaten future food security. In addition, the results hold implications for accurately predicting petroleum play elements in continental rift basins.

INTRODUCTION

Weathering affects all biogeochemical cycles and is key to critical zone dynamics. Chemical and physical weathering have been shown to impact soil stability/erosion, with potential effects on carbon transport, sediment loading, and nutrient cycling. On human timescales, weathering changes may place fisheries and potable water supplies at risk of sediment pollution (Alin et al., 1999). On longer (10^5-10^7 yrs) timescales, these processes link rock decay and sediment transport in hinterlands with stratal development in basins and underpin source-to-sink sedimentary models (Romans et al., 2015). Thus, knowledge of weathering and erosion across different timescales provides a framework for many applications, from soil conservation to forward modeling sediment composition and the occurrence of petroleum play elements.

The importance of modern biosphere-geosphere interactions on weathering has been highlighted in experimental watershed studies (Dunne, 1979; Drever, 1994; Berner and Cochran, 1998). For example, interactions between biotic and abiotic systems have been studied at the Luquillo Critical Zone Observatory (e.g., Zimmerman et al., 1995; White et al., 1998). However, the Luquillo forest represents an end-member tropical landscape, and outcomes from this system may not be broadly applicable to other tropical environments. Further, observational records are frequently too short to capture information relevant to global change or source-to-sink problems in ancient sedimentary basins (Einsele and Hinderer, 1998). By contrast, most studies of weathering in deep time have focused on feedbacks associated with climate or orogenesis (Lee et al., 2015), and the lack of long vegetation records biases models that incorporate climate alone. Moreover, paleoecological records suggest climate plays an indirect role mediated through vegetation change, such as the influence of rainfall seasonality on vegetation composition or disturbance (Ivory et al., 2014). Thus, biological mediation in weathering processes has been called the most “provocative, important, and testable” hypothesis of the next decade (Brantley et al., 2011). This same shortcoming was identified by the basin analysis community, as a paucity of paleovegetation data sets limits the accuracy of predictive sediment modeling (Heins and Kairo, 2007).

Here we use multiple proxies from Lake Malawi drill cores to examine the relationships among climate, vegetation, and sedimentation over climatic and biogeographic cycles beginning at ~100ka (Scholz et al., 2007). As vegetation in the Lake Malawi watershed is sensitive to changes in both rainfall and seasonality, the integration of sedimentological and palynological data afford an opportunity to investigate weathering patterns in response to rainfall amount and vegetation semi-independently.

BACKGROUND

Lake Malawi occupies a series of alternating N-S oriented half-graben basins (Fig. 1). Bedrock is dominated by Proterozoic basement (migmatitic gneisses) with localized outcrops of Cenozoic alkaline volcanics and Mesozoic sedimentary rock to the north and west of the lake (Fig. 1; Persits et al., 1997). Lowland soils are dominated by pellic vertisols and mollic andosols, whereas the mountains have lithosols, chromic cambisols, and dystric regosols (U.N.-FAO, 1998). The lake is situated at the southern limit of the Intertropical Convergence Zone (ITCZ; Fig. 1). Mean annual precipitation (MAP) has a strongly decreasing N-S gradient, ranging from 2400 to 800mm/yr, with a single rainy season in November-April.

Modern sediments are dominantly medium to fine-grained sands within 1–2 km of deltas, whereas finer particles occur in water deeper than ~30 m (Dolozi et al., 2011). However, coarse-grained sediments are documented in all depositional environments, due to gravity flows or lake current winnowing around islands (Soreghan et al., 1999). Clay mineralogy studies show smectite, kaolinite, and illite present, in rank order, with a marked increase in smectite southward, suggesting a linkage between dry climate and smectite abundance (Kalindekafe et al., 1996).

Malawi vegetation is largely constrained by rainfall and rainfall seasonality (Ivory et al., 2014). In the lowlands, both forests and woodlands dominate (White, 1983). Open-canopy Zambezian miombo woodlands grow in areas of highly seasonal rainfall. Closed-canopy tropical seasonal forests occur in areas with shorter dry season and moister edaphic conditions. Above 1500m asl, closed-canopy afromontane forests are dominant with extensive high elevation grasslands (White, 1983).

METHODS

A previous study of weathering from Lake Malawi showed that vegetation and fire frequency were strong controls on chemical weathering and erosion (Ivory et al., 2014). However, it is unknown if these processes differ over multiple climate cycles. To investigate these relationships, we used fossil pollen, terrigenous grain size, and clay mineralogy from core MAL05–1B (11°18′S, 34°26′E; 359m depth; Fig. 1). This 90kyr, 52m interval (62–114meters below lake floor [mblf]) was divided into parasequences based on lithofacies stacking patterns (Supplementary Methods). Over the studied interval, three parasequences occur that represent cyclic lake-level change (Fig. 2). Parasequence one (P1), the oldest transgression-regression cycle, occurs from 114 to 90mblf (180–140ka), parasequence two (P2) from 90 to 77mblf (140–123ka), and parasequence three (P3) from 77 to 62mblf (123–93ka). The age model for the core suggests that the transition from the Penultimate Glacial to the Last Interglacial Period occurs at the end of P2, such that only P3 occurs during the Last Interglacial Period (Scholz et al., 2007; Ivory et al., 2016).

RESULTS AND DISCUSSION

Long-term Weathering and Vegetation

The vegetation record displays trends that are mirrored in the parasequences. Profundal lithofacies at each parasequence base are coeval with hinterland forest phases (Fig. 2; Supplementary Figure). The upper portions of the parasequences are comprised of shallow water lithofacies and semi-arid vegetation. The data suggest that forest expansion occurred when rainfall was high (100% modern rainfall; Lyons et al., 2011), and the lake was at highstand. Very reduced rainfall (–61% from modern) resulted in lake level regression and caused forest collapse and replacement by discontinuous semi-arid bushland (Fig. 2). Thus, three forest expansion and retreat cycles are recorded.

Forest composition during wet periods differs in each parasequence. During the P1 and P2 forest phases which occurred during the Penultimate Glacial, highland and lowland forest, as well as miombo woodland, were abundant (Fig. 2). In contrast, during

P3 which occurred during the Last Interglacial, only highland forest and miombo woodland expanded, suggesting more open lowland vegetation. Previous work has documented similar assemblages when MAP was near modern but the dry season length is ~6 months, suggesting that a change in seasonality resulted in the difference in the P3 vegetation composition (Ivory et al., 2014).

Low charcoal concentrations suggest infrequent fires during the semi-arid phases of all parasequences (Fig. 2). Similar East African vegetation communities today show infrequent fires despite aridity as a result of discontinuous vegetation (Makishima, 2005). Although charcoal concentrations are higher during all forest phases, maximum values are sustained only during the P3 forest phase, when open woodland dominated.

Detrital clay minerals in the strata consist of smectite, kaolinite, illite, and chlorite, in rank order (Supplementary Methods). Kaolinite, an indicator of intense chemical weathering, reached high values (≥15% of clays) during highstands. By contrast, smectite, common in less altered tropical soil profiles, reached high percentages during lowstands (Fig. 2). This pattern was especially clear in P3, where smectite was routinely >25% in lowstand sediments. The highest kaolinite to smectite (K:S) ratio occurred in P2, suggesting very intense chemical weathering (Pastouret et al.,1978; Lézine et al., 2005). Much less variability is present in illite, associated with strong physical weathering, although the highest values occurred during the P3 and P2 lowstands (Hillier, 1995).

Detrital grain size provides indications of storage release from deltas, hinterland transport distance, and sub-lacustrine depositional processes (Ivory et al., 2014). With the exception of a thicker (~128 cm) mass wasting deposit at the base of P3 and two thin turbidites in P2, sand content is low. High silt:clay occurs at each parasequence base, although coarsening varied. P3 contained the coarsest profundal lithofacies (mean silt:clay of 2.9), whereas the silt:clay in P1 and P2 was lower (Fig. 2). A trait common to all three parasequences was that lowstand lithofacies contained very fine-grained sediments, with the exception of mottled megadrought silt beds at the top of P1.

Conceptual Model of Vegetation and Weathering

These parasequence relationships suggest that on long time scales, variations in chemical weathering intensity are not adequately explained by rainfall or temperature forcing alone. Water levels at Lake Malawi respond to effective precipitation, resulting in three parasequences defined by wet-dry cycles (Fig. 2; Supplementary Figure). If temperature or rainfall were the most direct control on weathering, the parasequence clay mineral suites should mirror the wet-dry cycles. Although all lowstands share similar indicators of reduced chemical weathering, clay mineral variability during the highstands hints at the potential for differing critical zone dynamics. The kaolinite contents during the P2 (~14.4 +/– 5%) and P1 (~13.0 +/–5%) highstands were relatively high in comparison to the P3 highstand (~11.4 +/–5%). As the P2/P3 boundary is associated with a glacial-interglacial transition, if weathering were strongly controlled by rainfall and temperature, higher temperatures and monsoon enhancement over the transition should enhance chemical weathering and kaolinite delivery. However, kaolinite concentrations are greater during both parasequences which occur during the cooler/drier glacial period.

Instead, we interpret forest composition as a critical control on weathering intensity. During the P1 and P2 highstands, dense lowland and highland forest was present as a result of high rainfall and low seasonality. In contrast, during P3, a long dry season limits lowland forest expansion. In modern forested watersheds, vegetation density and composition are linked to organic acid abundance in soils, which catalyze chemical reactions leading to the rapid breakdown of aluminosilicates (Blum et al., 2002). The link between vegetation and weathering is further supported by high abundances of smectite and grass pollen, as well as low silt:clay, in lowstand deposits, which indicate that opening of the lowland landscape reduces leaching and the efficacy of sediment transport (Fig. 2).

The terrigenous grain size pattern is also best explained by linkages to vegetation composition. Highest silt:clay values are recorded during highstand forest phases (Fig. 2). Furthermore, there are differences in grain size among highstands, such that the P3 highstand exhibits a higher average silt:clay. This suggests that when open woodland dominates, conditions are conducive to hinterland sediment flushing, as less rainfall is intercepted by the open canopy. Furthermore, low ground cover and root networks on the landscape are less effective at retaining infiltrated moisture (Roering et al., 2010). Thus, seasonal rivers with flashy discharge transport sediment-laden water to lake margin deltas, which transform into hyperpycnal flows, capable of delivering a high silt:clay sediment into deepwater. A similar mechanism is responsible for transporting terrestrial organic matter to deep environments (Ellis et al., 2015).

Futher, we observe stark differences among the style of deposition in P2 and P3. Posamentier and Kolla (2003) noted that regression events, steep slopes, and sand in shelf-margin staging areas are prerequisites for sand in deepwater marine settings. At Lake Malawi, our stratal record indicates that gravity flows occurred during lake level highstands. It is plausible that a threshold was crossed from P2 to P3 that provided the conditions necessary to explain the coarser grain size trend. We suggest that this threshold was a change to strongly unimodal rainfall seasonality that altered both vegetation and hinterland fluvial dynamics. By analogy, Fraticelli (2006) observed that delta progradation along the Texas coast occurred when severe droughts denuded coastal plain vegetation preceding major floods. The P2 littoral deposits mark an important transition in the record, when dry season length increased and tropical evergreens became spatially restricted. This transition conditioned a change in weathering and erosion dynamics, which is unequivocally the result of the establishment of open canopy miombo woodlands.

Furthermore, wildfires were most pronounced when the hinterland was dominated by open woodlands (Fig. 2). Microcharcoal abundances in P1 and P2 suggest only modest fire activity, consistent with abundant evergreens, suggesting that fire is not a key feedback on erosion during these intervals. In contrast, fires served as a strong positive feedback on sediment flushing in P3. Within low moisture open canopy woodlands, dry season winds are an effective mechanism for spreading and sustaining fire. Wildfires destroy root networks and reduce hillslope stability, leading to higher occurrences of post-fire debris flows and sediment yields (Moody et al., 2013).

These trends observed over tens of thousands of years are confirmed by a principal components analysis, which shows covariance between vegetation and sedimentology (Supplementary Methods), and are in agreement with patterns identified in a shorter Lake Malawi record (Ivory et al., 2014). Combining these data sets, we constructed a conceptual model describing patterns of vegetation-weathering-climate interactions (Fig. 3). Expansion of trees occurred when rainfall was high. However, dense lowland forest occurs only during short dry seasons, while woodland predominates during longer dry seasons. Although woodland and forest occur under similar total rainfall, dense forests lead to reduced wildfires, more intense chemical weathering, and moderately silty detritus. When long dry seasons preclude dense forests, the open vegetation is amenable to more variable weathering and common fires, which condition the landscape for mass wasting and sands and silt in deepwater. By contrast, when rainfall is low, discontinuous semi-arid vegetation is fuel-limited, resulting in few fires. The sparse vegetation leads to fine-grained detrital sediments that are smectite and illite-rich, suggesting very reduced chemical weathering and a transport-limited landscape.

CONCLUSIONS AND IMPLICATIONS

We show that feedbacks between vegetation and climate are critically important to weathering and sediment accumulation. In studies of both deep time and modern watersheds, it is clear that sediment generation, erosion, and phytogeography are linked in complex ways (Torres-Acosta et al., 2015). We demonstrate that across Quaternary timescales a strong and direct influence of vegetation composition and structure on weathering intensity exists in the tropics that has far-reaching implications.

First, these interactions could have impacts on sustainable development. If greater rainfall variability spurs an opening of natural vegetation, such as for P3, our results suggest that soil stability could suffer. Critically, degradation harms not only crops, but fisheries as well. For example, at Lake Tanganyika, sediment pollution alters the aquatic food web and the potential for healthy fish yields, which is relied upon for protein and income (Alin et al., 1999; Cohen et al., 2016). Today most paleo-environmental change studies consider climate change as the primary driver of weathering regime alteration

(Harris and Mix, 1999). However, if vegetation and climate have a complex interdependence, it will be critical to consider vegetation in developing management strategies. This is particularly true in areas where land-use decouples vegetation from climate, as rapid changes to weathering might be expected due to vegetation clearance alone.

On geological timescales, tropical rifts are an important component of the global petroleum endowment. Productivity, preservation, and dilution are the key controls on developing petroleum source rocks (Bohacs et al., 2000). Our results indicate that dilution of organic-rich profundal sediments could be affected by hinterland vegetation patterns in balanced-filled rifts like Lake Malawi. Higher silt:clay over long timescales could impact source-rock quality for conventional and unconventional petroleum systems (Katz and Lin, 2014). The Lake Malawi data also suggests that the accuracy of sediment composition forward models used for petroleum reservoir prediction hinges on accounting for vegetation dynamics (Heins and Kairo, 2007).

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REFERENCES CITED

Alin, S., et al., 1999, Effects of landscape disturbance on animal communities in Lake Tanganyika, East Africa: Conservation Biology, v. 13, p. 1017–1033, doi:10.1046/j.1523-1739.1999.96476.x.

Berner, R.A., and Cochran, M.F., 1998, Plant-induced weathering of Hawaiian basalts: Journal of Sedimentary Research, v. 68, p. 723–726, doi:10.2110/jsr.68.723.

Blum, J.D., Klaue, A., Nezat, C.A., Driscoll, C.T., Johnson, C.E., Siccama, T.G., Eagar, C., Fahey, T.J., and Likens, G.E., 2002, Mycorrhizal weathering of apatite as an important calcium source in base-poor forest ecosystems: Nature, v. 417, p. 729–731, doi:10.1038/nature00793.

Bohacs, K.M., Carroll, A.R., Neal, J.E., and Mankiewicz, P.J., 2000, Lake-basin type, source potential, and hydrocarbon character: An integrated sequence-stratigraphic geochemical framework, *in* Gierlowski-Kordesch, E. H., and Kelts, K. R., eds., Lake basins through space and time: American Association of Petroleum Geologists Studies in Geology, v. 46, p. 3–34.

Brantley, S.L., et al., 2011, Twelve testable hypotheses on the geobiology of weathering: Geobiology, v. 9, p. 140–165.

Cohen, A.S., Gergurich, E.L., Kraemer, B., McGlue, M.M., McIntyre, P., Russell, J.M., Simmons, J., and Swarzenski, P., 2016, Climate warming reduces fish production and benthic habitat in Lake Tanganyika, one of the most biodiverse freshwater ecosystems: Proceedings of the National Academy of Sciences of the United States of America, v. 113, p. 9563–9568, doi:10.1073/pnas.1603237113.

Dolozi, M.B., Kalindekafe, L.S., Ngongondo, C., and Dulanya, Z., 2011, A comparative analysis of the distribution, composition and geochemistry of surface sediments in the Linthipe and Songwe River Deltas of Lake Malawi: Journal of African Earth Sciences, v. 60, p. 93–105, doi:10.1016/j.jafrearsci.2011.02.002.

Drever, J.I., 1994, The effect of land plants on weathering rates of silicate minerals: Geochimica et Cosmochimica Acta, v. 58, p. 2325–2332, doi:10.1016/0016-7037(94)90013-2.

Dunne, T., 1979, Sediment yield and land use in tropical catchments: Journal of Hydrology (Amsterdam), v. 42, p. 281–300, doi:10.1016/0022-1694(79)90052-0.

Einsele, G., and Hinderer, M., 1998, Quantifying denudation and sediment–accumulation systems (open and closed lakes): Basic concepts and first results: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 140, p. 7–21, doi:10.1016/S0031-0182(98)00041-8.

Ellis, G.S., Katz, B.J., Scholz, C.A., and Swart, P.K., 2015, Organic sedimentation in modern lacustrine systems: A case study from Lake Malawi, East Africa, *in* Larsen, D., et al., eds., Paying Attention to Mudrocks: Priceless!: Geological Society of America Special Paper 515, p. 19–47, doi:10.1130/2015.2515(02).

Fraticelli, C.M., 2006, Climate Forcing in a Wave-Dominated Delta: The Effects of Drought–Flood Cycles on Delta Progradation: Journal of Sedimentary Research, v. 76, p. 1067–1076, doi:10.2110/jsr.2006.097.

Harris, S.E., and Mix, A.C., 1999, Pleistocene precipitation balance in the Amazon Basin recorded in deep sea sediments: Quaternary Research, v. 51, p. 14–26, doi:10.1006/qres.1998.2008.

Heins, W.A., and Kairo, S., 2007, Predicting sand character with integrated genetic analysis: Geological Society of America. Special Paper, v. 420, p. 345.

Hillier, S., 1995, Erosion, sedimentation and sedimentary origin of clays, *in* Velde, B., ed., Origin and mineralogy of clays: Berlin Heidelberg, Springer, p. 162–219, doi:10.1007/978-3-662-12648-6_4.

Ivory, S.J., McGlue, M.M., Ellis, G.S., Lézine, A.M., Cohen, A.S., and Vincens, A., 2014, Vegetation controls on weathering intensity during the last deglacial transition in southeast Africa: PLoS One, v. 9, p. e112855, doi:10.1371/journal.pone.0112855.

Ivory, S.J., Blome, M.W., King, J., McGlue, M.M., Cole, J., and Cohen, A.C., 2016, Paleoecology links climate change and landscape dynamics with adaptive radiation of cichlids at Lake Malawi: Proceedings of the National Academy of Sciences of the United States of America, v. 113, p. 11895–11900, doi:10.1073/pnas.1611028113.

Kalindekafe, L.N., Dolozi, M.B., and Yuretich, R., 1996, Distribution and origin of clay minerals in the sediments of Lake Malawi, *in* Johnson, T.C., and Odada, E., eds., The Limnology, Climatology and Paleoclimatology of the East African Lakes: Amsterdam, Gordon and Breach, p. 443–460.

Katz, B., and Lin, F., 2014, Lacustrine basin unconventional resource plays: KEY differences: Marine and Petroleum Geology, v. 56, p. 255–265, doi:10.1016/j.marpetgeo.2014.02.013.

Lee, C.T.A., Thurner, S., Paterson, S., and Cao, W., 2015, The rise and fall of continental arcs: Interplays between magmatism, uplift, weathering, and climate: Earth and Planetary Science Letters, v. 425, p. 105–119, doi:10.1016/j.epsl.2015.05.045.

Lyons, R.P., Scholz, C.A., Buoniconti, M.R., and Martin, M.R., 2011, Late Quaternary stratigraphic analysis of the Lake Malawi Rift, East Africa: An integration of drill-core and seismic reflection data: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 303, p. 20–37, doi:10.1016/j.palaeo.2009.04.014.

Makishima, H., 2005, Flora and vegetation of Nachola, Samburu District, northern Kenya: a study of vegetation in an arid land: African Study Monographs, v. 32, Supplement, p. 63–78.

Moody, J.A., Shakesby, R.A., Robichaud, P.R., Cannon, S.H., and Martin, D.A., 2013, Current research issues related to post-wildfire runoff and erosion processes: Earth-Science Reviews, v. 122, p. 10–37, doi:10.1016/j.earscirev.2013.03.004.

Oliva, P., Viers, J., and Dupré, B., 2003, Chemical weathering in granitic environments: Chemical Geology, v. 202, p. 225–256, doi:10.1016/j.chemgeo.2002.08.001.

Persits, F.M., Ahlbrandt, T.S., Tuttle, M.L., Charpentier, R.R., Brownfield, M.E., and Takahashi, K., 1997, Maps showing geology, oil and gas fields and geological provinces of Africa: U.S. Geological Survey Open-File Report 97–470-A.

Posamentier, H.W., and Kolla, V., 2003, Seismic geomorphology and stratigraphy of depositional elements in deep-water settings: Journal of Sedimentary Research, v. 73, p. 367–388, doi:10.1306/111302730367.

Roering, J.J., Marshall, J., Booth, A.M., Mort, M., and Jin, Q., 2010, Evidence for biotic controls on topography and soil production: Earth and Planetary Science Letters, v. 298, p. 183–190, doi:10.1016/j.epsl.2010.07.040.

Romans, B.W., Castelltort, S., Covault, J.A., Fildani, A., and Walsh, J.P., 2015, Environmental signal propagation in sedimentary systems across timescales: Earth-Science Reviews, v. 153, p. 7–29, doi:10.1016/j.earscirev.2015.07.012.

Soreghan, M.J., Scholz, C.A., and Wells, J.T., 1999, Coarse-grained, deep-water sedimentation along a border fault margin of Lake Malawi, Africa: Seismic stratigraphic analyses: Journal of Sedimentary Research, v. 69, p. 832–846, doi:10.2110/jsr.69.832.

Scholz, C.A., et al., 2007, East African megadroughts between 135 and 75 thousand years ago and bearing on early-modern human origins: Proceedings of the National Academy of Sciences of the United States of America, v. 104, p. 16416–16421, doi:10.1073/pnas.0703874104.

Torres Acosta, V., Bande, A., Sobel, E.R., Parra, M., Schildgen, T.F., Stuart, F., and Strecker, M.R., 2015, Cenozoic extension in the Kenya Rift from low-temperature thermochronology: Links to diachronous spatiotemporal evolution of rifting in East Africa: Tectonics, v. 34, p. 2367–2386, doi:10.1002/2015TC003949.

United Nations Food and Agriculture Organization, 1988, Soil Map of the World, Revised legend, World Soil Resources Report 60: Rome, Italy, FAO.

White, A.F., Blum, A.E., Schulz, M.S., Vivit, D.V., Stonestrom, D.A., Larsen, M.C., Murphy, S.F., and Eberl, D., 1998, Chemical weathering in a tropical watershed Luquillo Mountains, Puerto Rico: I. Long-term versus short-term weathering fluxes: Geochimica et Cosmochimica Acta, v. 62, p. 209–226, doi:10.1016/S0016-7037(97)00335-9.

Zimmerman, J.K., Aide, T.M., Rosario, M., Serrano, M., and Herrera, L., 1995, Effects of land management and a recent hurricane on forest structure and composition in the Luquillo Experimental Forest, Puerto Rico: Forest Ecology and Management, v. 77, p. 65–76, doi:10.1016/0378-1127(95)03575-U.

FIGURE CAPTIONS

Figure 1. Map of Africa and (A) Lake Malawi hydrology and bathymetry, (B) topography, (C) bedrock geology [Persits et al. (1997)], and (D) modern vegetation. Malawi drill cores (2A and 1B) are indicated with black and red dots. Geology is after Q = Quaternary. Qe = Holocene. Qv = Quaternary igneous. T = Tertiary. K = Cretaceous. JTr = Jurassic and Triassic. Mi = Mesozoic igneous. JC = Jurassic/Carboniferous. TrP = Triassic/Permian. PC = Permian/Carboniferous. pCm = Precambrian.

Figure 2. Vegetation and weathering indicators from drill core MAL05–1B. Weathering indicators are normalized clay mineral percentages and ratio of kaolinite/smectite (K/S). Red and blue shading indicates 3 highstands that differ based on their rainfall seasonality, with red = long dry season, and blue = short dry season.

Figure 3. Conceptual source-to-sink model for hinterland vegetation change in a tropical lacustrine rift setting. Ternary diagrams reflect clay mineralogy (K-I+C-S) and detrital particle size (Si-Sa-Cl) data. (A) Modern Setting, (B) presence of open woodland where many wildfires results in reduced chemical weathering and delivery of less weathered clay minerals to lake and primes landscape for erosion, (C) arid intervals with expansion of desert ecosystems results in deposition of fine grained sediments and less chemically altered clays (gray points = arid intervals, black points = megadrought interval), (D)

expansion of lowland forest results in increased chemical weathering and deposition of more altered clay minerals (gray points = P1, black points = P2).

[1] GSA Data Repository item 2017xxx, xxxxxxxx, is available online at www.geosociety.org/datarepository/2017 or on request from editing@geosociety.org.