

Methods

Drill core MAL05-1B was collected from the central basin of Lake Malawi in 2005 (Fig. 1; 11°18'S, 34°26'E; 592m water depth). Further details of the core site and age model are provided in Scholz et al. (2011a; 2011b), Lyons et al. (2011), Lyons et al. (2015), and Ivory et al. (2016). This study focuses on a 53-meter core section (61-114 mblf).

All samples were processed using standard methods, with the addition of *Lycopodium* spores (Faegri and Iverson, 1989) and were sieved at 10 microns. Samples were taken every ~30 cm, with a target temporal resolution of ~300 years. Pollen samples were taken at the same depths as those for particle size and clay mineralogy and were processed following the standard methods of Faegri and Iverson (1989). More details about sample preparation and pollen identification can be found in Ivory et al. (2012). Vegetation groupings presented in this study are based on biomes of White (1983) as well as prior pollen studies within the watershed by Debussk (1994) and Vincens et al. (2007). Between 300-500 grains were counted per sample, with the exception of the six uppermost samples, which range from 17-149 grains/sample due to extremely low pollen concentrations. 227 pollen taxa and five freshwater algae were identified using the African Pollen Database and atlases of pollen morphology (Maley, 1970; Bonnefille, 1971a, 1971b; Bonnefille and Riollet, 1980). Pollen percentages were calculated against a sum of all pollen and spores less undeterminable grains, aquatics (*Cyperaceae*, *Typha*, *Nymphaea*, *Polygonum senegalense*-type, *Ottelia*, *Laurembergia*) and undifferentiated bryophytes, which were calculated separately (Fig. 4). Pollen diagrams were drawn using Tilia (Grimm, 1990), and zonation was determined by constrained cluster analysis using CONISS (Grimm, 1987). The percentage values presented in the results section are average percentages for a subzone unless otherwise specified. Pollen nomenclature follows Vincens et al. (2007a), and pollen taxa assemblages described here are based on biomes outlined by Vincens et al. (2006) for East African vegetation and used in previous studies in this watershed (Vincens et al. 2007b; Ivory et al., 2012). Tropical seasonal forest is the total of *Moraceae*, *Macaranga*-type, *Celtis*, and *Trema*-type *orientalis*, and afro-montane is *Podocarpus*, *Olea*, *Ericaceae*

undifferentiated, *Myrica*, *Juniperus*-type, *Faurea*-type, and *Ilex mitis*. Miombo woodland is only represented by *Brachystegia* and *Uapaca* in summary figures as this is the highest-dispersing, most indicative taxon in this vegetation type.

Particle size analysis (sand: >4-62.5 μm ; silt: 3.9-62.5 μm ; clay: < 3.9 μm), was conducted on the terrigenous fraction of the core MAL05-1B samples using a Malvern laser-diffraction particle size analyzer coupled to a Hydro 2000S dispersion bench at the University of Arizona. Absorption and obscuration, the two most important variables for particle size analysis by laser-diffraction (Sperazza et al., 2004), produced low residual values on the Mastersizer when optimized at ~0.6 and 15-20%, respectively (Ivory et al., 2014). Samples were stirred at 3425 rpm and sonicated at 85% for 1 minute prior to and during measurements. To avoid flocculation of clays, individual aliquots of sediment were suspended in a dilute solution of sodium hexametaphosphate and placed on a wrist-action shaker for several days prior to the analysis. Each sample was measured four times, and we present our data as the average of these measurements. Prior to analysis, sediment sub-samples were subject to chemical digestions in order to remove organic matter, biogenic silica, and carbonate, following the methodology detailed in Ivory et al. (2014). Visual examination of smear slides confirmed the removal of biogenic components, and we estimate that refractory biochemical materials highly-resistant to chemical attack constituted <2.0% of the sub-samples.

Detrital clay minerals in lake sediments provide evidence for the alteration of watershed parent lithologies by physical (disintegration) and chemical (compositional alteration) weathering processes. Quantitative mineralogy was determined using powder x-ray diffraction (XRD) and the computer program RockJock v.11 (Eberl, 2003). Samples were micronized using a McCrone mill, spiked with a corundum standard, then scanned from 5-65 degrees 2θ (0.02 degree step) with a Scintag X-1 XRD system at the USGS in Denver. Diffraction patterns were input into RockJock, which determines the weight percent of pre-selected minerals using a peak fitting routine and a library of mineral standard

patterns (including amorphous or poorly crystalline components common in lake sediments, such as kerogen and diatoms). Assuming minimal deviation from standard patterns and proper sample preparation, the measurement error ascribed to RockJock is $\pm 5\%$. RockJock has been applied with success in a number of Quaternary environments, as well as in Reynolds Cup competitions for quantitative mineralogy (Eberl, 2003). Because clay minerals are a focus of this study, we also assessed several samples from each parasequence in the MAL05-1B using qualitative XRD methods (Moore and Reynolds, 1989). Oriented mounts were prepared using the modified filter-peel method of Pollastro (1982), and clay minerals were identified using the guidelines of Hillier (2002). This step also served to validate RockJock inputs. In our interpretation of clay mineralogy, we used the ratio of kaolinite to smectite (K/S) as a proxy for chemical weathering intensity, which has been used in similar studies in Africa (Pastouret et al., 1978; Lézine et al., 2005). Kaolinite is produced by leaching in tropical regions marked by high rainfall (Birkeland, 1984). Smectite is typical of tropical semi-arid regions and points to increased rainfall seasonality, as it frequently forms during the dry season from the concentration of chemical elements transported to downstream areas by runoff (Chamley, 1989; Weaver, 1989). We interpret elevated percentages of micas (illite plus chlorite) to reflect soil formation strongly influenced by physical weathering processes (Thiry, 2000). Our interpretations follow the findings on modern clay mineral distribution and environmental gradients presented in Kalindekafe et al. (1996).

Lithofacies

Modern sedimentary studies of Lake Malawi (Scott et al., 1991; Ellis et al., 2015) have demonstrated that strong contrasts exist among sediments deposited in profundal versus littoral environments, which are attributed to water depth, thermo-and oxycline position, light penetration, and hydrodynamic energy. Thus, due to variability in lake level, tectonics, or landscape evolution (Bohacs et al., 2001; Carroll et al., 2006), we describe lacustrine lithofacies that stack into meter-to-dekameter scale

parasequences. These parasequences reflect time transgressive Waltherian successions that juxtapose deposits of laterally-adjacent depositional environments vertically.

Lithofacies characteristic of profundal environments (deposited when the core site was situated in deep water and inferred to reflect lake level highstand) included laminated to massive black silty clays or silty diatom oozes. By contrast, lithofacies diagnostic of littoral environments (shallow water, associated with lake level lowstand) included laminated to massive, tan calcareous muds with variable silt content. Ostracodes were present in most littoral deposits, and mollusk shell hash was encountered near the top of parasequence two (P2); both attested to the presence of an oxygenated benthic environment. Although evidence of lake floor desiccation was absent, the massive, mottled clayey silts atop parasequence three (P3) (~61-64 m.b.l.f) represent deposition during a megadrought that impacted much of Africa (Scholz et al., 2007; McGlue et al., 2008). Thickness patterns among the parasequences are similar (~15 m each), with profundal intervals about twice as thick as littoral intervals.

Compelling evidence for gravity flow processes affecting the core site exists at different intervals in the record. Thin (3-12 cm) sandy or silty event beds with sharp bases were present in profundal deposits within P2 (Supplemental Figure DR1). We interpret these features as waning flow deposits of low-concentration turbidity currents, approximately equivalent to Bouma Tc, Td and Te beds in marine settings. Such features have been encountered previously in Lake Malawi strata and are known to produce minor erosion of the lake floor (Johnson and Ng'ang'a, 1990; Barry et al., 2002). A much thicker (~128 cm) gravity flow deposit was encountered near the base of P3. This deposit consisted of massively-bedded clayey sand with weak normal grading and a sharp basal contact. Above this contact, abundant outsized clasts of blue mud float within the sandy matrix; the long axes of many of these clasts are oriented sub-vertically. We interpret this feature to have been deposited by a debris flow. Sandy debrites have previously been documented in Lake Malawi within deepwater basin-plain fill facies (Soreghan et al., 1999; Wells et al., 1999). Alternatively, the deposit may represent a turbidite (approximately equivalent to a Bouma Ta) of unusual thickness.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Barry, S.L., Filippi, M.L., Talbot, M.R. and Johnson, T.C., 2002. Sedimentology and geochronology of Late Pleistocene and Holocene sediments from northern Lake Malawi. In *The East African Great Lakes: Limnology, Palaeolimnology and Biodiversity* (pp. 369-391). Springer Netherlands.

Berger, W.H. and Parker, F.L. (1970). Diversity of planktonic Foraminifera in deep sea sediments. *Science*, 168, 1345–1347.

Birkeland PW, (1984) *Soils and Geomorphology*. Oxford University Press, Oxford. 310 pp.

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. *Lake basins through space and time: AAPG Studies in Geology*, 46, pp.3-34.

Bonnefille, R., 1971. *Atlas des pollens d'Ethiopie: Pollens actuels de la basse vallee de l'omo, recoltes botaniques 1968*. Adansonia.

Bonnefille, R., 1971. *Atlas des pollens d'Ethiopie. Principales espèces des forêts de montagne. Pollen Spores*, 13(1), pp.15-68.

Bonnefille, R. and Riollot, G., 1980. *Pollens de savanes d'Afrique Orientale*. Paris: Editions du Centre National de la Recherche Scientifique, 140.

Carroll, A.R., Chetel, L.M. and Smith, M.E., 2006. Feast to famine: Sediment supply control on Laramide basin fill. *Geology*, 34(3), pp.197-200.

Chamley H (1989) *Clay sedimentology* (Vol. 623) New York: Springer-Verlag. 623 pp

DeBusk, G.H., 1994. Transport and stratigraphy of pollen in Lake Malawi, Africa.

Eberl, D.D. (2003). User's guide to RockJock -- A program for determining quantitative mineralogy from powder X-ray diffraction data: U.S. Geological Survey Open-File Report 2003-78, 47 p.

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. *Geological Society of America Special Papers*, 515, pp.SPE515-02.

Fægri, K. and Iverson, J., 1989. *Text Book of Pollen Analysis*. John Wiley and Sons, New York, ISBN 0, 471(92178), p.5.

Gajewski, K., Lézine, A.M., Vincens, A., Delestan, A., Sawada, M., and the African Pollen Database, 2002. Modern climate–vegetation–pollen relations in Africa and adjacent areas. *Quaternary Science Reviews* 21, 1611–1631.

Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geosciences* 13, 13–35.

Grimm, E., 1990. TILIA and TILIAGRAPH: PC spreadsheet and graphic software for pollen data. INQUA Holocene Working Groups on data-handling methods. *Newsletter* 4, 5–7.

Hillier, S., 2002. Quantitative analysis of clay and other minerals in sandstones by X-ray powder diffraction (XRPD). *Clay Mineral Cements in Sandstones: Special Publication*, 34, pp.213-251.

Ivory, S.J., Lézine, A.M., Vincens, A. and Cohen, A.S., 2012. Effect of aridity and rainfall seasonality on vegetation in the southern tropics of East Africa during the Pleistocene/Holocene transition. *Quaternary Research*, 77(1), pp.77-86.

Ivory SJ, McGlue MM, Ellis GS, Lézine A-M, Cohen AS, and Vincens A (2014) Vegetation Controls on Weathering Intensity during the Last Deglacial Transition in Southeast Africa. *PLoS ONE* 9(11): e112855. doi:10.1371/journal.pone.0112855

Ivory, S. J., Blome, M. W., King, J. W., McGlue, M. M., Cole, J. E., and Cohen, A. S. (2016). Environmental change explains cichlid adaptive radiation at Lake Malawi over the past 1.2 million years. *Proceedings of the National Academy of Sciences*, 113(42), 11895-11900.

Johnson, T.C. and Ng'ang'a, P., 1990. Reflections on a rift lake. *Lacustrine basin exploration: Case studies and modern analogs*. *Am. Assoc. Petroleum Geologists Mem*, 50, pp.137-150.

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.

Lézine AM, Duplessy JC, and Cazet JP (2005) West African monsoon variability during the last deglaciation and the Holocene: Evidence from fresh water algae, pollen and isotope data from core

KW31, Gulf of Guinea. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 219: 225–237. doi: 10.1016/j.palaeo.2004.12.027

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*, 303(1), pp.20-37.

Lyons, R.P., Kroll, C.N. and Scholz, C.A., 2011. An energy-balance hydrologic model for the Lake Malawi Rift Basin, East Africa. *Global and Planetary Change*, 75(1), pp.83-97.

Lyons, R.P., Scholz, C.A., Cohen, A.S., King, J.W., Brown, E.T., Ivory, S.J., Johnson, T.C., Deino, A.L., Reinthal, P.N., McGlue, M.M. and Blome, M.W., 2015. Continuous 1.3-million-year record of East African hydroclimate, and implications for patterns of evolution and biodiversity. *Proceedings of the National Academy of Sciences*, 112(51), pp.15568-15573.

Maley, J., 1970. Contributions a l'etude du Bassin tchadien Atlas de pollens du Tchad. *Bulletin du Jardin botanique national de Belgique/Bulletin van de Nationale Plantentuin van Belgie*, pp.29-48.

McGlue, M. M., Lezzar, K., Cohen, A., Russell, J., Tiercelin, J.-J. et al., 2008, Seismic records of late Pleistocene aridity in Lake Tanganyika, tropical East Africa: *Journal of Paleolimnology*, v. 40, p. 635-653.

New, M., Hulme, M. and Jones, P., 2000. Representing twentieth-century space-time climate variability. Part II: Development of 1901-96 monthly grids of terrestrial surface climate. *Journal of Climate*, 13(13), pp.2217-2238.

Pastouret L, Chamley H, Delibrias G, Duplessy JC, and Thiede J (1978) Late Quaternary climatic changes in western tropical Africa deduced from deep-sea sedimentation off Niger Delta. *Oceanol Acta* 1: 217–232.

Pollastro, R. M. (1982). A recommended procedure for the preparation of oriented clay–mineral specimens for X-ray diffraction analysis. U.S. Geological Survey Open File Report, pp. 71–82.

Scholz, C.A., Johnson, T.C., Cohen, A.S., King, J.W., Peck, J.A., Overpeck, J.T., Talbot, M.R., Brown, E.T., Kalindekafe, L., Amoako, P.Y. and Lyons, R.P., 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*, 104(42), pp.16416-16421.

Scholz, C.A., Cohen, A.S., Johnson, T.C., King, J., Talbot, M.R. and Brown, E.T., 2011. Scientific drilling in the Great Rift Valley: the 2005 Lake Malawi Scientific Drilling Project—an overview of the past 145,000 years of climate variability in Southern Hemisphere East Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 303(1), pp.3-19.

Scholz, C.A., Talbot, M.R., Brown, E.T. and Lyons, R.P., 2011. Lithostratigraphy, physical properties and organic matter variability in Lake Malawi Drillcore sediments over the past 145,000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 303(1), pp.38-50.

Scott DL, Ng'ang'a P, Johnson TC, and Rosendahl BR (1991) High-resolution acoustic character of Lake Malawi (Nyasa), East Africa, and its relationship to sedimentary processes. *Special Publication of the International Association of Sedimentologists* 13: 129–145. doi: 10.1002/9781444303919.ch7

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 analysis. *Journal of Sedimentary Research*, 69(4).

Sperazza, M., Moore, J. N., and Hendrix, M. S. (2004). High-Resolution Particle Size Analysis of Naturally Occurring Very Fine-Grained Sediment Through Laser Diffraction. *Journal of Sedimentary Research*, 74(5), 736-743.

Thiry M (2000) Palaeoclimatic interpretation of clay minerals in marine deposits; an outlook from the continental origin. *Earth Sci Rev* 49: 201–221. doi: 10.1016/s0012-8252(99)00054-9

Vincens, A., Bremond, L., Brewer, S., Buchet, G. and Dussouillez, P., 2006. Modern pollen-based biome reconstructions in East Africa expanded to southern Tanzania. *Review of Palaeobotany and Palynology*, 140(3), pp.187-212.

Vincens, A., Garcin, Y. and Buchet, G., 2007. Influence of rainfall seasonality on African lowland vegetation during the Late Quaternary: pollen evidence from Lake Masoko, Tanzania. *Journal of biogeography*, 34(7), pp.1274-1288.

Vincens, A., Lézine, A.M., Buchet, G., Lewden, D. and Le Thomas, A., 2007. African pollen database inventory of tree and shrub pollen types. *Review of Palaeobotany and Palynology*, 145(1), pp.135-141.

Weaver CE (1989) *Clays, muds, and shales*. Elsevier. 818 pp.

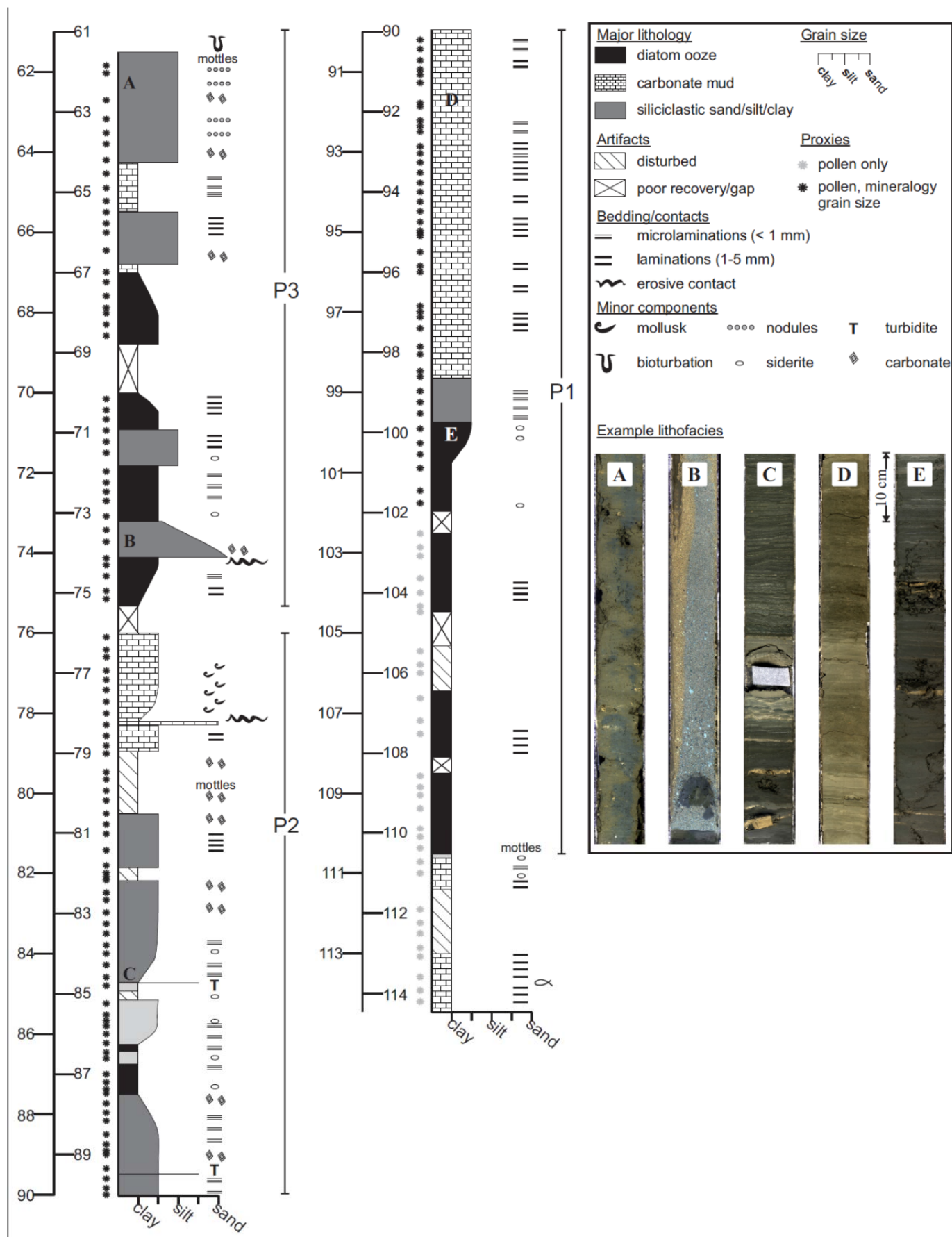
Wells, J.T., Scholz, C.A. and Soreghan, M.J., 1999. Processes of sedimentation on a lacustrine border-fault margin: interpretation of cores from Lake Malawi, East Africa. *Journal of Sedimentary Research*, 69(4).

White F (1983) *Vegetation of Africa—a descriptive memoir to accompany the Unesco/ AETFAT/UNSO vegetation map of Africa*. Natural Resources Research Report XX. UNESCO, Paris, France.

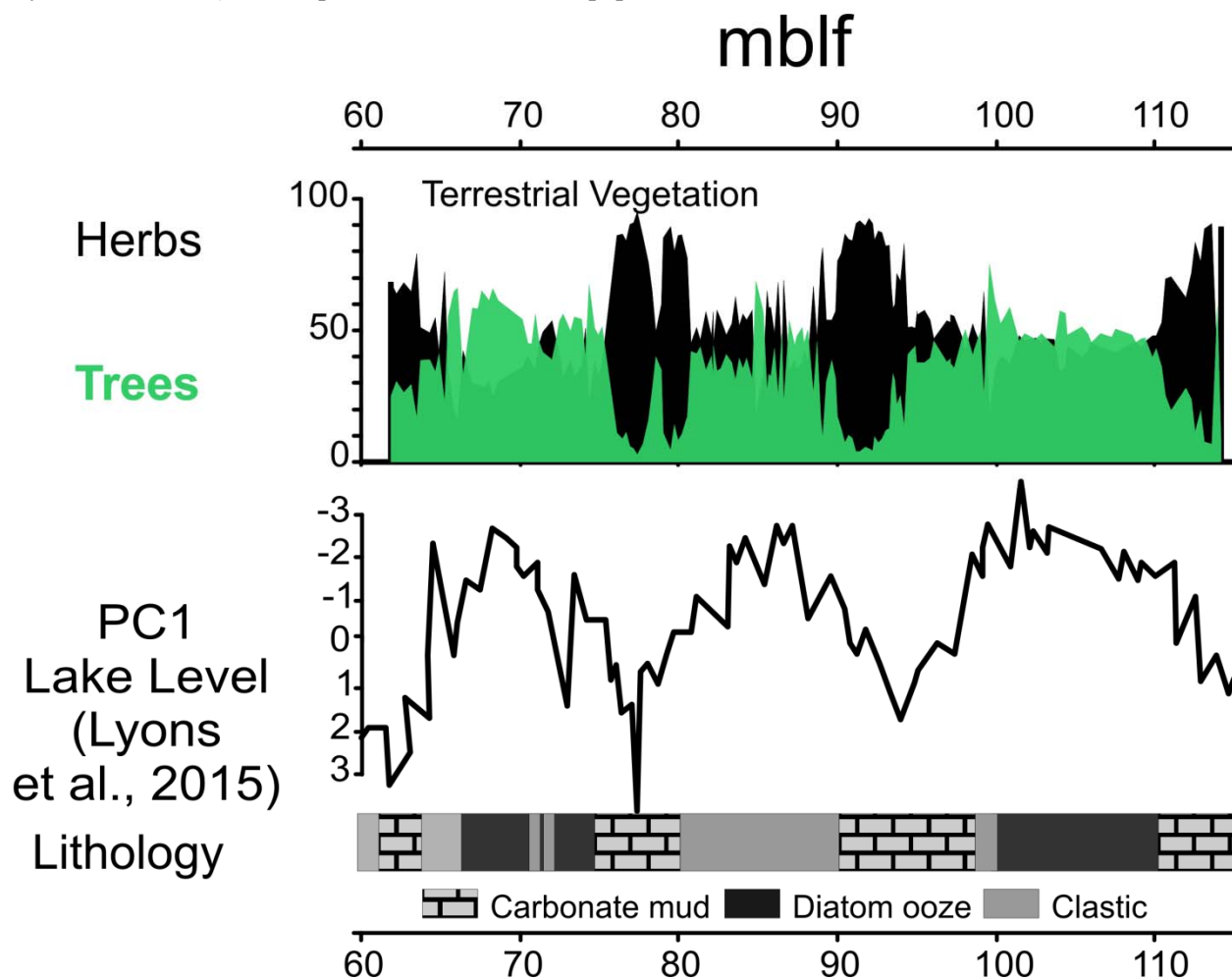
SUPPLEMENTARY FIGURES

Supplementary Figure DR1.

Stratigraphy of the Lake Malawi scientific drill core 1B, ~61-114 meters below low floor. The section consists of three parasequences (P1-P3); each parasequence is comprised of lithofacies that stack in an upward shoaling motif. Vertical facies variability reflects the sensitivity of the deepwater coring site to lake level changes. All lithofacies contain allochthonous siliciclastic and biogenic components, which were separated chemically to facilitate particle size and palynological analysis. (A) Massive mottled silts, associated with deposition during a profound lake level lowstand. (B) Sand-rich mass wasting deposit with clay rip-up clasts; this facies is uniquely associated with open canopy woodland pollen. (C) Laminated silty clay with turbidite and siderite nodules. Thin turbidites occur in highstand deposits of P2. (D) Laminated calcareous mud commonly deposited during lake level lowstands; this facies is associated with low kaolinite:smectite and abundant fine detrital particle sizes, illite, and grass pollen. (E) Silty diatom ooze; this facies is associated with high relative kaolinite:smectite and closed canopy forest pollen.



Supplementary Figure DR2. Tree and herb pollen percentages with lake level reconstruction (based on Lyons et al., 2015) for the period discussed in the paper.



Supplementary Figure DR3. Principal components analysis of all sedimentological, mineralogical, and paleoecological indicators from core MAL05-1B used in this analysis. Biplot shows that the facies associated discussed in Figure 2 of the manuscript are backed up by ordination analysis.

