

DeepCHALLA: Two Glacial Cycles of Climate and Ecosystem Dynamics from Equatorial East Africa

by Dirk Verschuren, Daniel O. Olago, Stephen M. Rucina, Peter O. Odhengo, on behalf of the ICDP DeepCHALLA Consortium

doi:10.2204/iodp.sd.15.09.2013

Scientific Rationale in Relation to Scientific Themes of the ICDP Workshop

Documenting the geographical variation of past climate change and the structure of its temporal variability is critical for understanding how various external climate forcings, on inter-annual to orbital timescales, are translated into regional climate variability. Long climate records from tropical and sub-tropical continental regions provide a particularly important complement to the polar ice-core records, as they are crucial to resolving long-standing questions about the relative importance of tropical and high-latitude climate processes in generating spatial patterns in climate. This high priority is exemplified by completed International Continental Scientific Drilling Program (ICDP) lake-drilling projects in South and Central America (e.g., Titicaca, Peten Itza) and Africa (e.g., Bosumtwi, Malawi).

One specific geographical area where long continental climate records are still notably scarce is the inter-tropical zone near the equator, where twice-annual passage of tropical convective activity known as the Intertropical Convergence Zone (ITCZ) creates a bimodal seasonal rainfall regime of two wet seasons and two dry seasons. Equatorial East Africa is perhaps the most appropriate region to pursue this equatorial record, because here seasonal ITCZ migration spans the widest latitude range in the world, and hence atmospheric dynamics associated with Northern and Southern Hemisphere monsoon systems most strongly interact. Specifically, these systems are the northeasterly monsoon bringing rainfall during Northern Hemisphere autumn–winter, and the southeasterly monsoon bringing rainfall during its spring–summer.

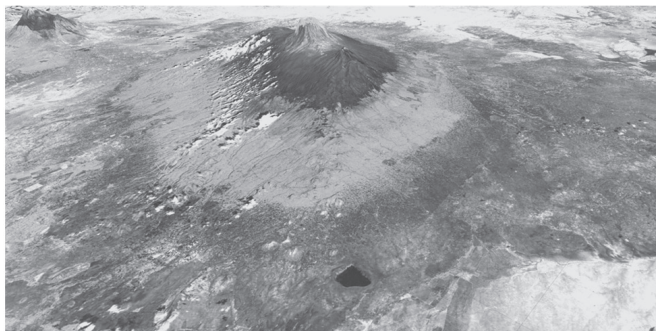


Figure 1. Lake Challa occupying a volcanic caldera, of 2.7 km diameter, at 840 m elevation on the lower east slope of Mt. Kilimanjaro, viewed from the southeast; gray shading reflect vegetation zones.

An extraordinarily well-suited location for an ICDP lake-drilling project near the equator would be Lake Challa (3°S, 36°E), a 4.2-km², 94-m-deep crater lake situated at 840 m altitude near Mt. Kilimanjaro (Fig. 1) in eastern equatorial Africa. From 10 to 13 September 2012, twenty-five scientists from eight countries joined twenty-three colleagues and government representatives from Kenya at an ICDP-funded workshop in Nairobi and Taveta to develop the scientific objectives of an ICDP deep-drilling project on Lake Challa (DeepCHALLA), and to discuss technical and logistical issues concerning both the recovery of this sedimentary archive and the establishment of a lake-system monitoring program.

The workshop started with a full day of formal presentations at the National Museums of Kenya on the aims and structure of ICDP itself and the DeepCHALLA project (Fig. 2). In addition, high-resolution (3.5-kHz GeoPulse) seismic data collected in 2005 were used to identify preferred and alternative drilling sites where the profundal sediment stratigraphy is continuous and complete (Fig. 3). On the second day the group visited Lake Challa, where a lively discussion developed on the equipment and logistics



Figure 2. Clockwise: [A] Group photo of participants in the ICDP DeepCHALLA workshop, in front of the Louis Leakey Auditorium of the National Museums of Kenya, host of the workshop. [B] Dr. Gerald Haug presenting the ICDP program. [C] Opening speech by Dr. Idle Omar Farah, Director General of the National Museums of Kenya.

required to successfully drill the lake's sediment record. Lake Challa is a relatively difficult ICDP target site in terms of access with heavy instrumentation, but this is compensated by quiet lake-surface conditions and the relatively shallow depth of sub-bottom drilling (~210 m; Fig. 3) from an anchored platform. On day three in Taveta, technical presentations were provided by invited scientists. The discussions elaborated the scientific work program and revealed new synergies between different proxies and analytical methods to more reliably reconstruct past climate and ecosystem components. In the final morning session, a strategy was developed for financing of the project via formal collaborations between teams working jointly on particular portions of the project, followed by discussion of outreach and knowledge-transfer opportunities. The workshop ended with an overview of the project consortium, which includes thirty-four principal investigators from eleven countries, of which six are ICDP member countries.

The principal objective of the DeepCHALLA project is to acquire high-resolution and accurately dated proxy data of continental climate and ecosystem change near the Equator over at least one complete glacial-interglacial cycle (150,000 years), with an aim towards extracting the complete record spanning >250,000 years. Such a climate record would encompass the entire known existence of modern humans (*Homo sapiens*) in East Africa.

Lake Challa's proximity to the Indian Ocean ensures that the Congo Air Boundary (CAB), the mostly north-south oriented zone of convection between Atlantic and Indian Ocean moisture sources, is always located to the west. Consequently, the Lake Challa region is little impacted by the climatic effects of changes in tropical Atlantic thermohaline circulation, through which signatures of northern hemisphere glaciation are transferred to the adjacent low-latitude continents (Verschuren et al., 2009). This Atlantic influence extends well into the eastern half of the African continent to the Ethiopian highlands and western portions of the East African Plateau (Tierney et al., 2011); therefore, only in the far east of equatorial Africa can we expect to find a climate history relatively unaffected by a strong northern high-latitude signature. DeepCHALLA thus presents unique opportunities to further scientific understanding of long-term climate change within the inter-tropical zone.

Origin and Development of the DeepCHALLA Project

DeepCHALLA is a follow-up initiative to the CHALLACEA project (2005–2008), which used a suite of 22-m hammer-driven piston cores to reconstruct climate and environmental history near the East African equator over the past 25,000 years. CHALLACEA was funded via the EuroCLIMATE program of the European Science Foundation (ESF), and was executed by six principal investigators from four European countries (Belgium, Denmark, Germany, and The Netherlands), plus associate partners in Canada, Kenya, the U.K., and the U.S.A. The project proved highly successful, due partly to the exceptionally well-constrained chronological framework (Blaauw et al., 2011) and partly to integration of a large number of sedimentological, geochemical, isotopic, and biological proxies, permitting highly detailed palaeoenvironmental reconstructions and a level of proxy cross-validation that is usually elusive. While CHALLACEA's principal and associate investigators constitute the logical core of the DeepCHALLA collaborative effort, the ICDP exploratory workshop provided the opportunity to solicit involvement from researchers with relevant expertise not presently available in the consor-

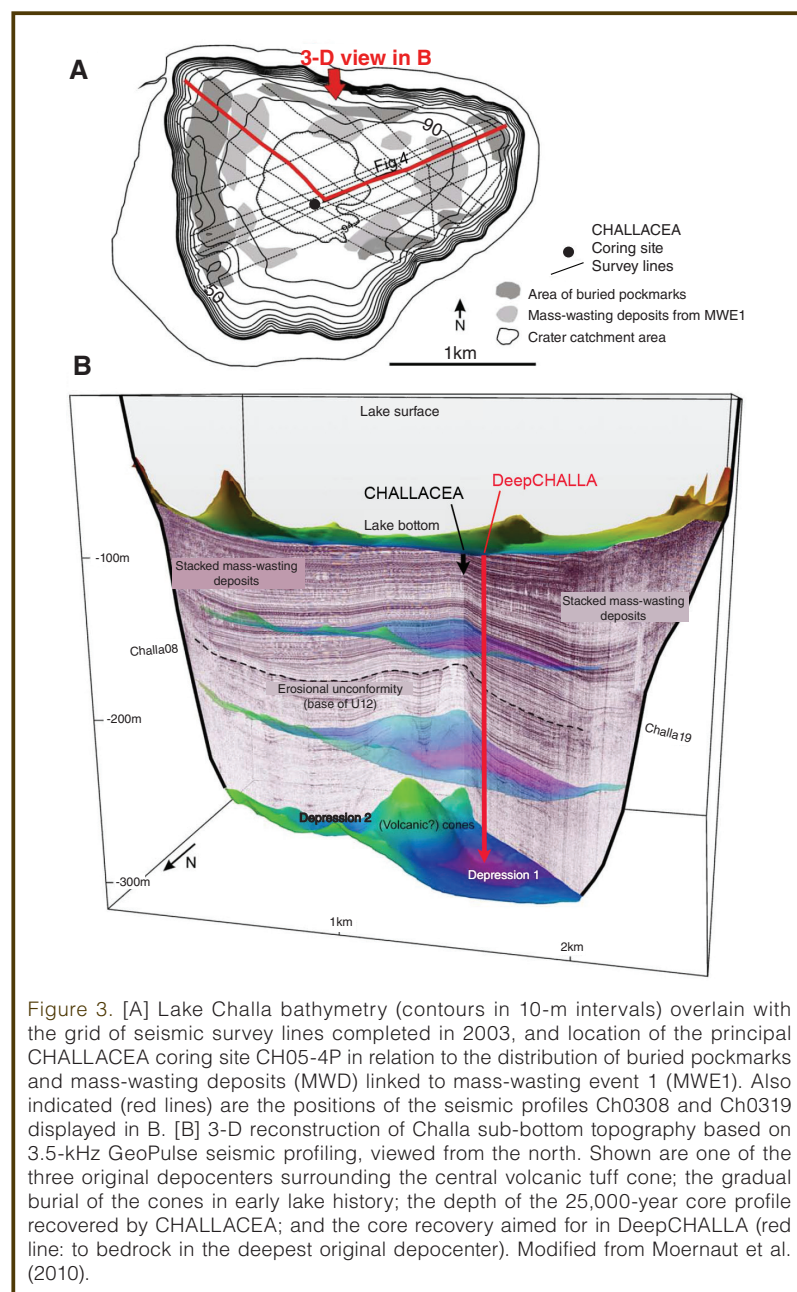


Figure 3. [A] Lake Challa bathymetry (contours in 10-m intervals) overlain with the grid of seismic survey lines completed in 2003, and location of the principal CHALLACEA coring site CH05-4P in relation to the distribution of buried pockmarks and mass-wasting deposits (MWD) linked to mass-wasting event 1 (MWE1). Also indicated (red lines) are the positions of the seismic profiles Ch0308 and Ch0319 displayed in B. [B] 3-D reconstruction of Challa sub-bottom topography based on 3.5-kHz Geopulse seismic profiling, viewed from the north. Shown are one of the three original depocenters surrounding the central volcanic tuff cone; the gradual burial of the cones in early lake history; the depth of the 25,000-year core profile recovered by CHALLACEA; and the core recovery aimed for in DeepCHALLA (red line: to bedrock in the deepest original depocenter). Modified from Moernaut et al. (2010).

tium, such that the expanded consortium covers all the research niches that recovery of the complete Lake Challa sediment record will generate.

Previous Investigations and State of the Art

The long lake records produced by ICDP projects in Africa and South America, plus excellent palaeodata extracted from South American and East Asian speleothems (Cruz et al., 2005; Wang et al., 2008), show that northern and southern tropical regions experienced anti-phased 23,000-year-long moisture-balance cycles. This supports the idea that on orbital timescales the mean annual position of the ITCZ and associated tropical monsoon rainfall mostly responded to precession-driven changes in low-latitude summer insolation (Ruddiman, 2006). The ICDP records from tropical Africa (Cohen et al., 2007; Scholz et al., 2007) also

revealed the occurrence of African mega-droughts during the period of incipient glaciation—Marine Isotope Stage (MIS) 5a-d—compared to which the iconic Last Glacial Maximum (LGM) drought may have been quite modest, at least in certain parts of the continent. Geophysical surveying of profundal lacustrine deposits in Lake Challa by the CHALLACEA project produced an exquisite seismic-reflection stratigraphy of lake-level changes over the last 150,000 years (Moernaut et al., 2010). In itself this seismic record (Fig. 4) has sufficient detail already to constrain important aspects of the long-term moisture-balance history of equatorial East Africa, including signatures of local drought during MIS 6 (Peak Penultimate Glaciation), MIS 5a-d (African mega-drought), and MIS 2 (LGM). A striking observation is that near-constant high lake level (inferred moist climate conditions) prevailed between about 98,000 and 20,000 years ago, interrupted only by eight short-lived dry spells, five of which match the timing of Heinrich events 2 to 6. These data demonstrate the high quality of the Lake Challa sediment record with regard to temporal continuity and the stability of sedimentation rates.

Analysis of two independent paleohydrological proxies in the cored upper portion of the Lake Challa sediment sequence (Verschuren et al., 2009) revealed that over the past 25,000 years, rainfall variability in easternmost equatorial Africa followed a hybrid pattern of those typically documented for the northern and southeastern African tropics. Some millennial-scale climate events of high northern-latitude origin impacted strongly on East Africa, such as the Younger Dryas cold episode which is recorded as a severe drought between 13,000 and 11,650 years ago. Overall, however, Challa's moisture-balance history predominantly reflects longer-term variation in low-latitude insolation. Noting that wet and dry episodes alternated at half-precessional (~11,500-year) intervals, Verschuren et al. (2009) suggested that the region enjoyed high rainfall when peak summer insolation over either northern or southern subtropical Africa strengthened southeasterly or northeasterly monsoon flow advecting moist air from the Indian Ocean. Dry climate conditions prevailed between 20,500 and 16,500 years ago and between 8500 and 4500 years ago, when neither monsoon was strong and a minimum in local March or September insolation caused the ensuing rain season to wither.

The clear expression of this characteristically equatorial signature at Lake Challa is attributed to the unique combination of the site's position east of the CAB and the strongly bimodal rainfall seasonality of this semi-arid equatorial region. Also, in this system both the seismic stratigraphy of lake-level fluctuation and the Branched Isoprenoid Tetraether

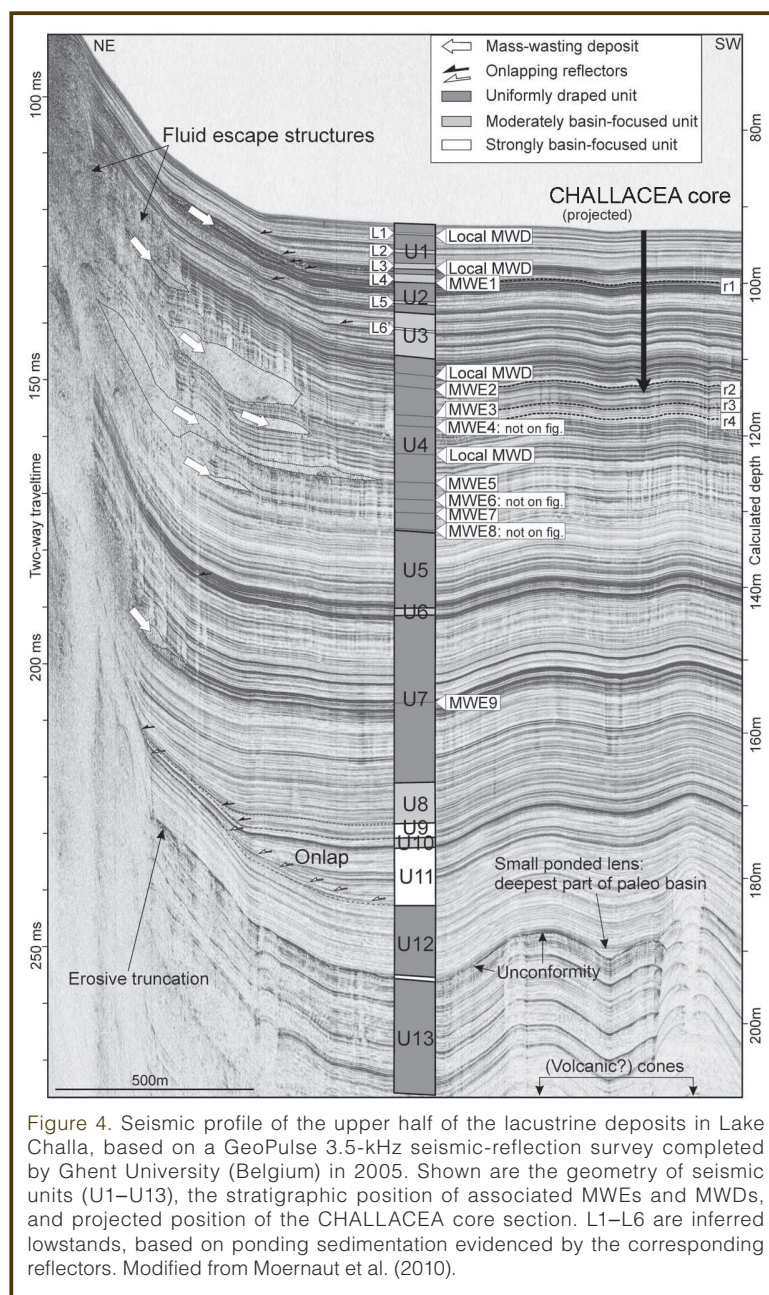


Figure 4. Seismic profile of the upper half of the lacustrine deposits in Lake Challa, based on a GeoPulse 3.5-kHz seismic-reflection survey completed by Ghent University (Belgium) in 2005. Shown are the geometry of seismic units (U1–U13), the stratigraphic position of associated MWEs and MWDs, and projected position of the CHALLACEA core section. L1–L6 are inferred lowstands, based on ponding sedimentation evidenced by the corresponding reflectors. Modified from Moernaut et al. (2010).

(BIT) index of glycerol dialkyl glycerol tetraether (GDGT) membrane lipids preserved in bottom sediments appear to reflect past variation in the amount of annual rainfall.

By contrast, a paleohydrological reconstruction based on the oxygen-isotope ($\delta^{18}\text{O}$) signature of diatom silica, which in this system mainly reflects the duration and severity of the main dry season (Barker et al., 2011), displayed an increasing trend throughout most of the Holocene. Combination of the BIT and diatom $\delta^{18}\text{O}$ records showed how decoupled variation in annual rainfall and seasonal drought controlled long-term variation in the region's savanna fire regimes (Nelson et al., 2012). Comparison of the $\delta^{13}\text{C}$ record of plant leaf-wax alkanes preserved in Lake Challa with the BIT record, the TEX₈₆ record of central African temperature from Lake Tanganyika (Tierney et al., 2008; Sinninghe Damsté et al., 2012), and the ice-core record of atmospheric $p\text{CO}_2$ allowed assessing principal environmental controls on the proportion of regional plants using the C₃ or C₄ photosynthetic pathway (Sinninghe Damsté et al., 2011). These and other studies have demonstrated Lake Challa's status as a tropical climate archive of global significance, and they create confidence that the deeper Lake Challa sediments will reveal a truly unique record of quintessentially equatorial climate change and ecosystem dynamics over glacial-interglacial timescales.

Lake Challa is also the only long climate archive from equatorial Africa with a demonstrated annual rhythm of sediment deposition, allowing reconstruction of high-frequency (inter-annual) climate variability over long periods of time. Our work on this aspect (Wolff et al., 2011) showed that variation in the thickness of annual layers deposited over the past century significantly correlates with historical sea-surface temperatures in the western Indian Ocean and El Niño–Southern Oscillation (ENSO) dynamics in the Pacific Ocean, demonstrating that Lake Challa sediments contain signatures of past regional climate variability with the highest possible time resolution. In this semi-arid tropical region, the magnitude of inter-annual rainfall variability is a primary determinant of agricultural success. Detailed study of this short-term variability and the recurrence time of climate extremes in past time windows with colder and warmer mean climate than today has evident socio-economic value for this water-stressed, densely populated region of equatorial East Africa.

Collection of data on the geology, physical limnology, chemistry, and biology of Lake Challa started with a first surveying trip in September 1999 and now comprises twelve field campaigns. Lake-monitoring efforts were stepped up in November 2006 with the installation of air and water temperature loggers and a sediment trap and with the monthly collection of water-level data and water samples for stable-isotope analysis. The monthly sediment-trap samples provided invaluable information on seasonal variation in phytoplankton composition, carbonate precipitation, min-

eral dust, and organic matter deposition (Barker et al., 2011; Wolff et al., 2011), and on the influx of organic biomarkers derived from a variety of aquatic and terrestrial microorganisms (Sinninghe Damsté et al., 2009). All these data and samples are used to calibrate and validate climate and environmental proxies extracted from the sediment record. We aim to continue this monitoring effort for a total of ten years (2006–2015), i.e., through a full ENSO rainfall cycle.

Scientific Objectives of the ICDP DeepCHALLA Project

The four principal research objectives identified during the workshop are as follows.

To reconstruct at least one complete glacial-interglacial cycle of tropical monsoon dynamics over the western Indian Ocean, allowing assessment of the equatorial signatures of i) low-latitude insolation forcing vs. long-distance impacts of northern hemisphere and Antarctic glaciation; ii) the MIS 5 African mega-droughts; and iii) inter-annual climate variability and extreme events under a range of different mean climate states. We specifically focus on differentiating the histories of three fundamental aspects of the tropical hydrological cycle: annual rainfall, effective moisture, and the duration/severity of seasonal drought.

To document long-term biodiversity patterns and ecological dynamics of a tropical grassland-woodland ecosystem in response to changes in atmospheric CO₂, temperature, moisture balance, and fire. As we exploit the full range of terrestrial paleoecological proxies available, our results will help explain/predict the present-day/future prevalence of C₃ and C₄ plant species using the photosynthetic pathway in tropical grasslands, and the past/future persistence of biodiversity hotspots in eastern Africa, in particular the montane forest ecosystems of the Eastern Arc Mountains in Tanzania.

To reconstruct the long-term dynamics of a tropical freshwater ecosystem in response to climate-driven changes in water-column temperature and stratification, palaeohydrology, and nutrient budget, with special attention to the colonization of an isolated crater lake by cichlid fish, and their morphological adaptation to long-term variation in available habitat.

To drill to the bottom of the sedimentary infill in Lake Challa (Fig. 3; ~210 m below the lake floor) and determine the age of its caldera, which may help constrain the history of Mt. Kilimanjaro volcanism. Given the >250,000-year paleoenvironmental record contained in Lake Challa, the DeepCHALLA project will show exactly how often, when, and how much the East African landscape has changed throughout the entire existence of modern humans (currently dated at 190,000 years). Specifically, documentation of the magnitude and geographical distribution of severe drought across tropical Africa during MIS 6 and MIS 5 is critical to reconstructing the tempo and mode of their exodus from Africa into Eurasia ~100,000 years ago.

References

- Barker, P. A., Hurrell, E. R., Leng, M. J., Wolff, C., Cocquyt, C., Sloane, H. J., and Verschuren, D., 2011. Seasonality in equatorial climate over the last 25,000 years revealed by oxygen isotope records from Mount Kilimanjaro. *Geology*, 39:1111–1114. doi:10.1130/G32419.1
- Blaauw, M., van Geel, B., Kristen, I., Plessen, B., Lyaruu, A., Engstrom, D. R., van der Plicht, J., and Verschuren, D., 2011. High-resolution ¹⁴C dating of a 25,000-year lake-sediment record from equatorial East Africa. *Quat. Sci. Rev.*, 30:3043–3059. doi:10.1016/j.quascirev.2011.07.014
- Cohen, A. S., Stone, J. R., Beuning, K. R. M., Park, L. E., Reinthal, P. N., Dettman, D., Scholz, C. A., et al., 2007. Ecological consequences of Early Late-Pleistocene megadroughts in Tropical Africa. *Proc. Nat. Acad. Sci. U.S.A.*, 104:16422–16427. doi:10.1073/pnas.0703873104
- Cruz, Jr., F. W., Burns, S. J., Karmann, I., Sharp, W. D., Vuille, M., Cardoso, A. O., Ferrari, J. A., Silva Dias, P.L., and Viana, Jr., O., 2005. Insolation-driven changes in atmospheric circulation over the past 116,000 years in subtropical Brazil. *Nature*, 434:63–66. doi:10.1038/nature03365
- Moernaut, J., Verschuren, D., Charlet, F., Kristen, I., Fagot, M., and De Batist, M., 2010. The seismic-stratigraphic record of lake-level fluctuations in Lake Challa: Hydrological stability and change in equatorial East Africa over the last 140 kyr. *Earth Planet. Sci. Lett.*, 290:214–223. doi:10.1016/j.epsl.2009.12.023
- Nelson, D. M., Verschuren, D., Urban, M. A., and Hu, F. S., 2012. Long-term variability and rainfall control of savanna fire regimes in equatorial East Africa. *Glob. Change Biol.*, 18:3160–3170. doi:10.1111/j.1365-2486.2012.02766.x
- Ruddiman, W. F., 2006. What is the timing of orbital-scale monsoon changes? *Quat. Sci. Rev.*, 25:657–658. doi:10.1016/j.quascirev.2006.02.004
- Scholz, C. A., Johnson, T. C., Cohen, A. S., King, J. W., Peck, J. A., Overpeck, J. T., Talbot, M. R., et al., 2007. East African megadroughts between 135 and 75 thousand years ago and bearing on early-modern human origins. *Proc. Nat. Acad. Sci. U.S.A.*, 104:16416–16421. doi:10.1073/pnas.0703874104
- Sinninghe Damsté, J. S., Ossebaar, J., Abbas, B., Schouten, S., and Verschuren, D., 2009. Fluxes and distribution of tetraether lipids in an equatorial African lake: Constraints on the application of the TEX₈₆ palaeothermometer and BIT index in lacustrine settings. *Geochim. Cosmochim. Acta*, 73:4232–4249. doi:10.1016/j.gca.2009.04.022
- Sinninghe Damsté, J. S., Ossebaar, J., Schouten, S., and Verschuren, D., 2012. Distribution of tetraether lipids in the 25-kyr sedimentary record of Lake Challa: Extracting reliable TEX₈₆ and MBT/CBT palaeotemperatures from an equatorial African lake. *Quat. Sci. Rev.*, 50:43–54. doi:10.1016/j.quascirev.2012.07.001
- Sinninghe Damsté, J. S., Verschuren, D., Ossebaar, J., Blokker, B., van Houten, R., van der Meer, M. T. J., Plessen, B., and Schouten, S., 2011. A 25,000-year record of climate-induced changes in lowland vegetation of eastern equatorial Africa revealed by the stable carbon-isotopic composition of fossil plant leaf waxes. *Earth Planet. Sci. Lett.*, 302:236–246. doi:10.1016/j.epsl.2010.12.025
- Tierney, J. E., Russell, J. M., Huang, Y. S., Sinninghe Damsté, J. S., Hopmans, E. C., and Cohen, A. S., 2008. Northern hemisphere controls on tropical southeast African climate during the past 60,000 years. *Science*, 322:252–255.
- Tierney, J. A., Russell, J. M., Sinninghe Damsté, J. S., Huang, Y., and Verschuren, D., 2011. Late Quaternary behavior of the East African monsoon and the importance of the Congo Air Boundary. *Quat. Sci. Rev.*, 30:798–807. doi:10.1016/j.quascirev.2011.01.017
- Verschuren, D., Sinninghe Damsté, J. S., Moernaut, J., Kristen, I., Blaauw, M., Fagot, M., Haug, G. H., and CHALLACEA project members, 2009. Half-precessional dynamics of monsoon rainfall near the East African equator. *Nature*, 462:637–641. doi:10.1038/nature08520
- Wang, Y. J., Cheng, H., Lawrence Edwards, R., Kong, X., Shao, X., Chen, S., Wu, J., Jiang, X., Wang, X., and An, Z., 2008. Millennial- and orbital-scale changes in the East Asian monsoon over the past 224,000 years. *Nature*, 451:1090–1093. doi:10.1038/nature06692
- Wolff, C., Haug, G. H., Timmermann, A., Sinninghe Damsté, J. S., Brauer, A., Sigman, D. M., Cane, M. A., and Verschuren, D., 2011. Reduced interannual rainfall variability in East Africa during the last ice age. *Science*, 333:743–747. doi:10.1126/science.1203724

Authors

Dirk Verschuren, Ghent University, Limnology Unit, K.L. Ledeganckstraat 35, B-9000 Ghent, Belgium, e-mail:dirk.verschuren@UGent.be

Daniel O. Olago, University of Nairobi, Department of Geology, Chiromo Campus, P.O. Box 30197, Nairobi 00100, Kenya, e-mail:dolago@uonbi.ac.ke

Stephen M. Rucina, Palynology and Palaeobotany Section, National Museums of Kenya, P.O. Box 40658, Nairobi 00100, Kenya, e-mail:stephenrucina@yahoo.com

Peter O. Odhengo, Office of the Prime Minister, P.O. Box 74434, Nairobi 00200, Kenya, e-mail:odhengo@yahoo.co.uk

Related Web Links

<http://www.ecology.ugent.be/limno/challacea.htm>

<http://www.esf.org/activities/eurocores/completed-programmes/euroclimate/projects/challacea-fp28.html>

Photo Credit

Fig. 2: National Museums of Kenya.