Landscape and lakescape evolution: source-to-sink study of geomorphic, tectonic, climatic, and vegetation interactions in a tropical rift basin (Lake Malawi)

Ramon Arrowsmith[1], Andrew S. Cohen[2], Scott Robinson[1], Marina B. Foster[1], Sarah J. Ivory[2], Arjun Heimsath[1], and Kelin Whipple[1]

1. Arizona State University, 2. The University of Arizona

Landscape changes within a watershed involve interacting processes that operate on disparate time-scales. Although the relief produced by tectonism establishes the template for the conveyance of eroded materials to sedimentary basins, the relative rates and transitions among surface processes are modulated in time and space by climate with its associated influences on vegetation and soil production. A source-to-sink examination of how geomorphology, tectonism, climate, and vegetation interact would be invaluable to further our understanding of climate/tectonic interactions. Unfortunately, appropriate field laboratories, where watershed/tectonic evolution can be directly coupled to a receiving basin that captures and faithfully records the history of landscape evolution are rarely available (e.g., GeoPrisms, 2010; NRC, 2010).

The Lake Malawi basin, in the western branch of the East African Rift System (EARS) provides an excellent opportunity for an integrated study of landscape (geomorphology and vegetation communities) and lakescape (bathymetry, tectonics, sediment delivery and provenance) evolution in a rift basin (Fig. 1). The lake and its watershed comprise half graben segments of alternating polarity bounding a closed sedimentary basin (Ebinger et al., 1987) containing a deep lake with a paleoenvironmental history that is accessible through cores from deep drilling (Scholz et al., 2006; Fig. 2). The interaction between the footwall escarpments along the ~N-S rift axis and the regional climate system, largely driven by seasonal migration of the Intertropical Convergence Zone (ITCZ), results in a complex but interpretable variation of microclimates, which in turn affect vegetation and, presumably, erosion patterns (Figs 1-3). Through time, this interaction occurs against a dynamic backdrop of extraordinary regional climate variability, with orbitally forced precipitation changes driving that have resulted in dramatic lake level decreases ofas much as 600m (Scholz et al., 2007; Cohen et al., 2007).

Large lakes create their own weather through moisture recycling, and modeling results suggest these "lake effects" in Africa (e.g., Yin and Nicholson, 1998) are accentuated during the dry season. At Malawi, this occurs in the austral winter when strong southeasterly winds prevail along the ~N-S oriented lakes.

We have developed a conceptual model for an elongate rift lake with multiple half-graben segments which predicts: **First**, in any lake basin with a strong asymmetry in prevailing wind run (mean velocity x duration along the lake fetch), we expect strong precipitation, vegetation, and erosion anomalies at both the leeward lake end and associated with topographic barriers to low elevation airflow. **Second**, precipitation, vegetation, and erosion should vary (high to low) from the leeward to windward sides of barriers, even over very short distances (tens of km). **Third**, axial margins of the lake will be wet at the windward end and dry at the leeward end. Finally, for the tropics, this asymmetry is strongest near the N and S ends of the ITCZ belt where the seasonal contrast of wind speed and orientation are strongest (e.g., Lake Malawi; Fig. 1).

During drier climates (which follow eccentricity-modulated precession cycles, Scholz et al., 2011b), when lakes are shallower and smaller, these precipitation, vegetation, and erosion asymmetries disappear (Fig. 3). The much reduced fetch and water sources for evaporation produces little or no "lake effect" on the surrounding watersheds. Consequently, we expect more homogeneous vegetation, erosion or sediment input patterns to the basin between the windward and leeward sides of footwall escarpment topographic barriers.

This general model of climatology and tectonic interactions conforms to observations of within-basin microclimatologic variability associated with the underlying tectonics and geomorphology of the Malawi rift basin, and with other basins within the EARS. Footwall escarpments of the half-graben segments create small mountain ranges that intersect the regional (and periodically moisture laden) winds. These ranges rise to as much as 1500m above the lake surface, generating considerable precipitation along the mountain fronts facing the lake. Striking differences in precipitation occur over very short distances between lakeshore areas adjacent to or farther from these precipitation traps (Cohen et al., 2012; Figs. 2-3). Furthermore, these areas of higher precipitation are asymmetrically organized around the Lake Malawi basin, such that the southern promontories or south-facing coastlines of half-graben footwall uplifts as well as the volcanic Rungwe Mountains that lie at the north axis of the basin, windward relative to the strong southeasterly winds, display the highest precipitation anomalies. The major difference in the precipitation pattern for these regions is that they receive rainfall in the form of recycled moisture through most of the dry season. Conversely, the promontories and escarpment coastlines facing the weaker northeasterly winds (and the south end of the lake) receive only regional precipitation during the rainy season, resulting in less mean annual precipitation and longer dry seasons.

The half graben asymmetry of the basins provides a first order template for the drainage network. This includes steep and short drainages developed on the footwall rift flanks, long lower gradient hanging wall rivers, and large drainage basins wrapping around the ends of the rift segments and entering the basin in the accommodation zones or adjacent hanging wall platform margins(Figs 2-3). The lake level controlled orographic precipitation operates on this template, promoting variable vegetative vigor and soil development in the spatial gradients of our conceptual model. We predict that the orographic precipitation will drive increased erosion rates during high lake stands along the windward promontories.

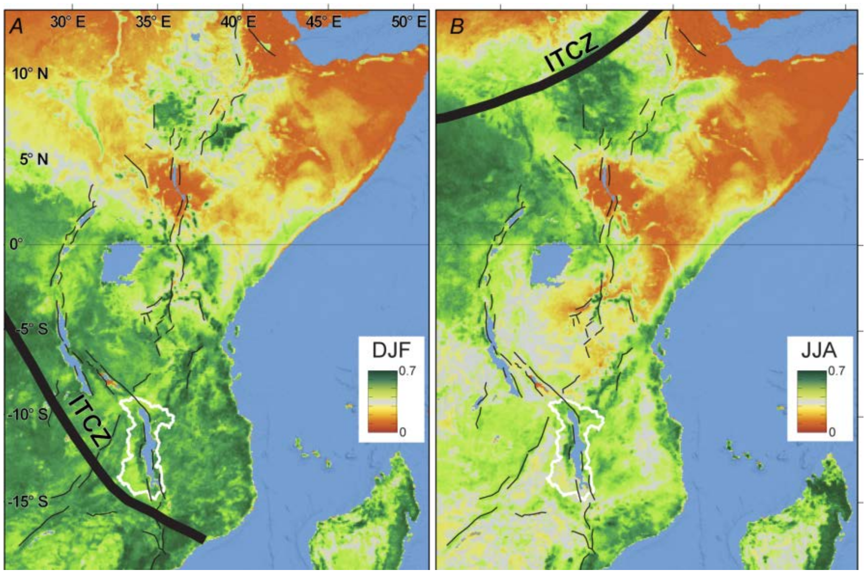

Figure 1. Annual cross equatorial migratio of the ITCZ (A: austral summer, December- January-February (DJF) and B: austral wint June-July-August (JJA)) drives variation in precipitation and airflow, which when combined with temperature and orograph produces a seasonal vegetation response (NDVI from Tucker, et al., 2005). Small bla lines indicate active faults of the East Afric Rift. White polygon outlines Lake Malawi watershed (see Figs. 2 & 3).

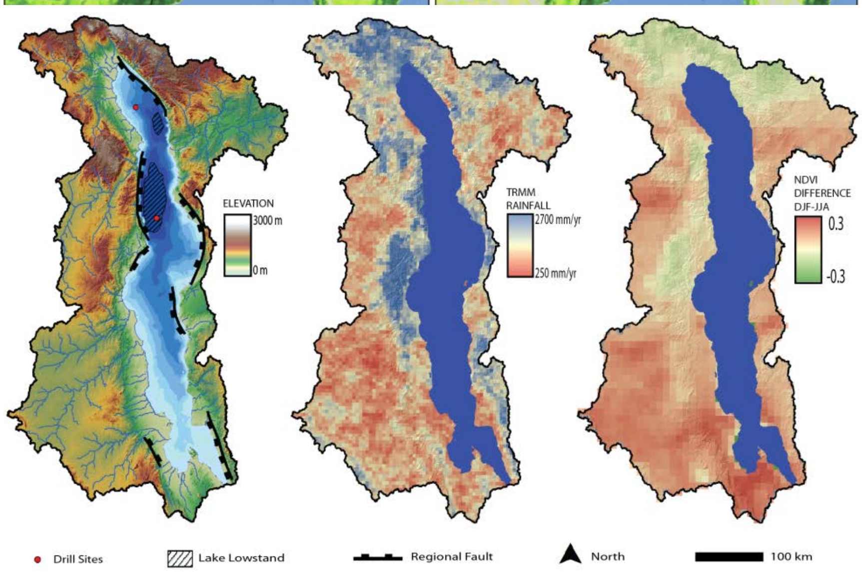

Figure 2. Maps of the Lake Malawi watershed (Fig. 1 white polygon). Left topography and bathymetry with maj half graben faults. Hachures indicate t lake extent at >500 m lowstand. Red dots are scientific drill sites (Scholz, et al., 2011a). Fig. 3A,B locations are red squares. Middle: TRMM rainfall (Bookhagen, in review) shows increas moisture along western central basin and north side of northern basin (compare with Fig. 3). Right: DJF-JJA difference in 1980-2000 8km NDVI (Tucker et al., 2005; Ivory, in press) shows enhanced greenness in austral winter (JJA) in areas corresponding to high TRMM values.

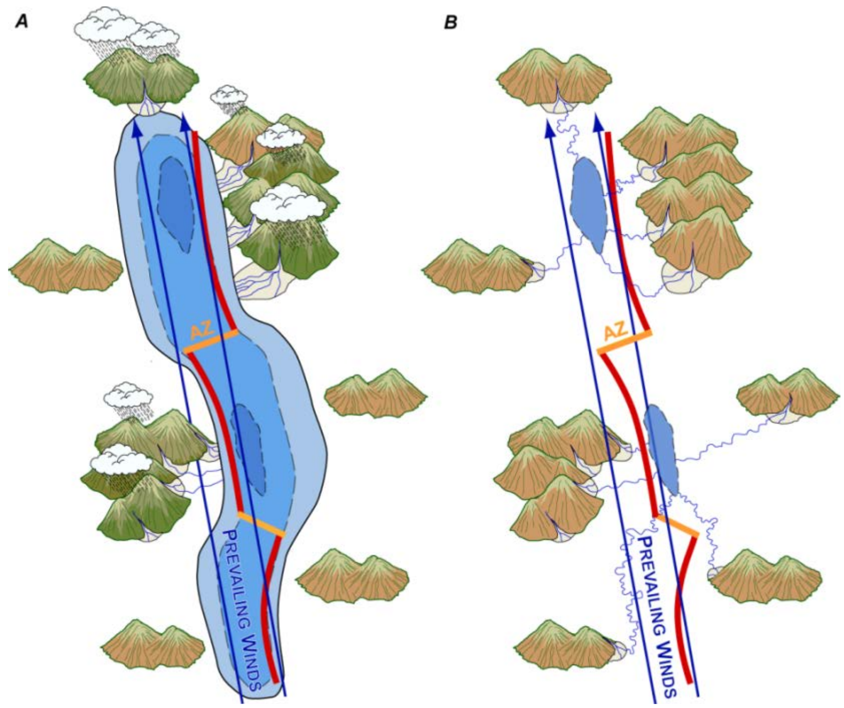

Figure 3. Prevailing southerly winds gather moisture as they move over a high stand lake (A). Orographic precipitation is enhanced on the windward sides of the protruding footwalls of the alternating half graben segments. When the lake is low (B), available moisture and the orographic effect is limited. In addition, the drainage network must extend over the dry lake floor to the restricted lowstand basins. Red lines are the principal half graben faults and are connected by accommodation zones (AZ).

References

Cohen, A.S., Stone, J.R., Beuning, K.R.M., Park, L.E., Reinthal, P.N., Dettmar, D., Scholz, C.A., Johnsor, T.C., King, J.W., Talbot, M.R., Brown, E.T., and Ivory, S.J., 2007, Ecological consequences of early Late Pleistocene megadroughts in tropical Africa: Proceedings of the National Academy of Sciences of the United States of America, v. 104, p. 16422-16427.

Cohen, A.S., Arrowsmith, R., Ivory, S.J., Robinson, S., Foster, M., Whipple, K., and Heimsath, A., 2012, Climatic and tectonic interactions in the East African rift system: The view from the Lake Malawi basin: Magmatic Rifting and Active Volcanism Conference, Addis Ababa, Ethiopia, Abstracts with Programs, p. 20.

Ebinger, C.J., Rosendahl, B.R., Reynolds, D.J., 1987, Tectonic model of the Malawi rift, Africa: Tectonophysics, v.141, p.215-235.

GeoPrisms, 2010, GeoPrisms Science Plan, http://www.geoprisms.org/images/stories/documents/DSP/GeoPRISMS_DSP_ALL_hires.pdf.

Ivory, S.J., Cohen, A.S., and Lezine, A.-M., (in press), Effect of aridity and rainfall seasonality on vegetation in East Africa during the Late Pleistocene: Quaternary Research.

National Research Council (NRC), 2010, Landscapes on the edge: New horizons for research on the Earth's surface, http://www.nap.edu/catalog.php?record_id=12700.

Scholz, C.A., Cohen, A.S., Johnson, T.C., King, J.W., Moran, K., 2006, The 2005 Lake Malawi scientific drilling project: Scientific Drilling, v.2, p.17-19.

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.O., Lyons, R.P., Shanahan, T.M., Castaneda, I.S., Heil, C.W., Forman, S.L., McHargue, L.R., Beuning, K.R., Gomez, J., and Pierson, J., 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.

Scholz, C.A., Cohen, A.S., and Johnson, T.C., 2011a, Southern hemisphere tropical climate over the past 145ka: Results of the Lake Malawi. Scientific Drilling Project, East Africa: Palaeogeography Palaeoclimatology Palaeoecology, v. 303, p. 1-2.

Scholz, C.A., Cohen, A.S., Johnson, T.C., King, J., Talbot, M.R., and Brown, E.T., 2011b, 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, v. 303, p. 3-19.

Tucker, C.J., Pinzon, J.E., Brown, M.E., Slayback, D.A., Pak, E.W., Mahoney, R., Vermote, E.F., and El Saleous, N., 2005, An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data: International Journal of Remote Sensing, v. 26, p. 4485-4498.

Yin, X.G., and Nicholson, S.E., 1998, The water balance of Lake Victoria: Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, v. 43, p. 789-811.