DATA MINE

Acquisition of a Unique Onshore/Offshore Geophysical and Geochemical Dataset in the Northern Malawi (Nyasa) Rift

by Donna J. Shillington, James B. Gaherty, Cynthia J. Ebinger, Christopher A. Scholz, Kate Selway, Andrew A. Nyblade, Paul A. Bedrosian, Cornelia Class, Scott L. Nooner, Matthew E. Pritchard, Julie Elliott, Patrick R. N. Chindandali, Gaby Mbogoni, Richard Wambura Ferdinand, Nelson Boniface, Shukrani Manya, Godson Kamihanda, Elifuraha Saria, Gabriel Mulibo, Jalf Salima, Abdul Mruma, Leonard Kalindekafe, Natalie J. Accardo, Daud Ntambila, Marsella Kachingwe, Gary T. Mesko, Tannis McCartney, Melania Maquay, J. P. O'Donnell, Gabrielle Tepp, Khalfan Mtelela, Per Trinhammer, Douglas Wood, Ernest Aaron, Mark Gibaud, Martin Rapa, Cathy Pfeifer, Felix Mphepo, Duncan Gondwe, Gabriella Arroyo, Celia Eddy, Brian Kamoga, and Mary Moshi

ABSTRACT

The Study of Extension and maGmatism in Malawi aNd Tanzania (SEGMeNT) project acquired a comprehensive suite of geophysical and geochemical datasets across the northern Malawi (Nyasa) rift in the East Africa rift system. Onshore/offshore active and passive seismic data, long-period and wideband magnetotelluric data, continuous Global Positioning System data, and geochemical samples were acquired between 2012 and 2016. This combination of data is intended to elucidate the sedimentary, crustal, and upper-mantle architecture of the rift, patterns of active deformation, and the origin and age of rift-related magmatism. A unique component of our program was the acquisition of seismic data in Lake Malawi, including seismic reflection, onshore/offshore wide-angle seismic reflection/refraction, and broadband seismic data from lake-bottom seismometers, a towed streamer, and a large towed air-gun source.

SCIENCE MOTIVATION AND EXPERIMENT SUMMARY

The primary scientific goal of the Study of Extension and maGmatism in Malawi aNd Tanzania (SEGMeNT) project is to examine the emergence and early evolution of two fundamental features of all divergent plate boundaries: magmatism and segmentation. Magmatism accommodates a significant percentage of plate separation at most midocean ridges and late-stage continental rifts. Likewise, transform faults demarcate discrete spreading segments in midocean ridges, which are broadly characterized by more robust magmatism at their centers than at their edges (Macdonald *et al.*, 1988; Lin *et al.*, 1990). Well-developed magmatic and tectonic segmentation is also observed in late-stage continental rifts and new ocean basins (Taylor *et al.*, 1995; Ebinger and Casey, 2001; Keir *et al.*, 2009), but little is known about the controls on the initiation and development of magmatism and segmentation in immature rifts. Our project is focused on addressing the following questions:

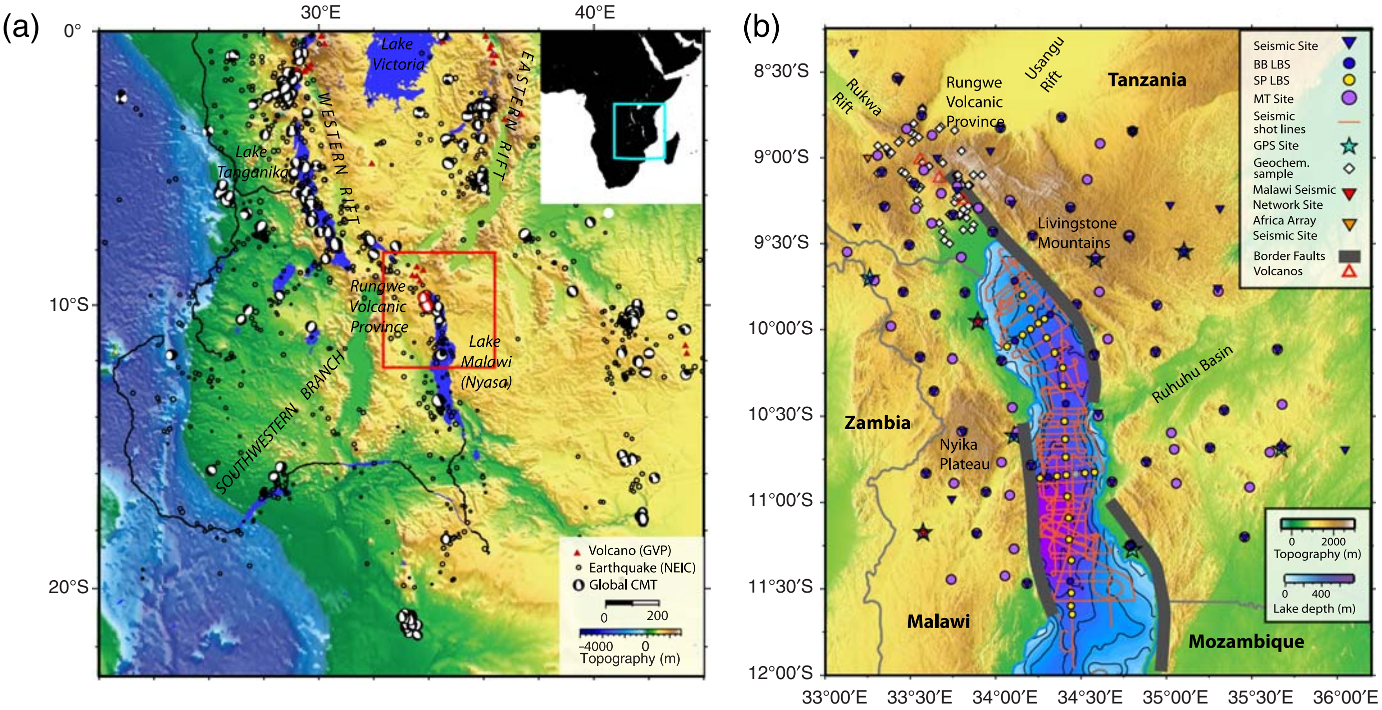
- When, where, and why does magmatism initiate in rifts, and what is its role in accommodating extension?
- What controls the development of tectonic segmentation in early-stage rifts? How is it manifested in 4D patterns of magmatism and deformation?

To address the questions above, we acquired an integrated geophysical and geochemical dataset across the northern Malawi (Nyasa) rift in the southern part of the East Africa Rift system (EARS). Our team included universities and geological surveys in the United States, Malawi, and Tanzania. The following datasets were acquired as a part of the SEGMeNT project: onshore/offshore active and passive seismic data, long-period and wideband magnetotelluric (MT) data, continuous Global Positioning System (GPS) data, and geochemical samples. This is the first integrated geophysical and geochemical dataset acquired across and within any of the great African rift lakes that can constrain rift architecture and processes at a range of scales.

TECTONIC BACKGROUND

The northern Malawi (Nyasa) rift in the Western Branch of the EARS is an excellent locality to examine the early stages of rifting in strong, cold lithosphere; only a small amount of stretching has occurred (< 15%; Ebinger, 1989). Sparse constraints suggest that the extension is proceeding relatively slowly at ~3.5 mm/yr (Stamps *et al.*, 2008). The length scales of border faults, the flexure associated with faulting (Ebinger *et al.*, 1991), the occurrence of deep seismicity (Jackson and

doi: 10.1785/0220160112



▲ **Figure 1.** (a) Southern part of East Africa rift system with topography from Shuttle Radar Topography Mission (SRTM; Farr *et al.*, 2007), Centroid Moment Tensors from the Global Centroid Moment Tensor (Global CMT) project (Ekström *et al.*, 2012), earthquakes from the National Earthquake Information Center (NEIC), and volcanoes from the Smithsonian Volcanism Program (Global Volcanism Project, 2013). The 2009 Karonga earthquake sequence is indicated with lighter colored symbols. Box shows location of study area in (b). Inset shows Africa with location of (a) shown with a box. (b) Data acquisition map for the Study of Extension and maGmatism in Malawi aNd Tanzania (SEGMeNT) project with topography from SRTM (Farr *et al.*, 2007) and lake depth from Lyons *et al.* (2011). Key defines symbols. Circles with gray outlines show lake-bottom seismometers (LBSs) that were lost or had no data. Lake depth contoured at 100 m. The color version of this figure is available only in the electronic edition.

Blenkinsop, 1993; Foster and Jackson, 1998), and the inference of mafic lower crust (Nyblade and Langston, 1995) suggest that rifting is occurring in relatively strong lithosphere. Volumetrically minor volcanism is observed in this region, providing a serious test for recent models that require intrusive magmatism to initiate rifting in cold strong continental lithosphere (Buck, 2004). Strikingly, the only surface expressions of magmatism in the western rift occur in accommodation zones between discrete segments rather than in segment centers (Fig. 1a), in clear contrast to midocean ridges and mature rifts. The Rungwe volcanic province, the most southerly volcanism in the EARS, occurs in a complex accommodation zone between the northern basin of Lake Malawi, the Rukwa rift, and the Usangu basin (Fig. 1b). Seismic tomography with existing sparse seismic data indicates a localized low-velocity zone in the mantle below Rungwe (O'Donnell *et al.*, 2013), and isotopic analyses of recent volcanic rocks suggest a deep plume-influenced source, at least for the youngest magmatism (Hilton *et al.*, 2011). However, the original cause of magmatism, the distribution of elevated temperatures and magma at depth beneath the Malawi rift, and the relationship between magmatism and extension remain unknown.

The Malawi rift exhibits pronounced tectonic segmentation, which is defined in the upper crust by ~100-km-long border faults (Ebinger *et al.*, 1987; Specht and Rosendahl, 1989; Flannery and Rosendahl, 1990; Fig. 1b). The border faults are often thought to account for most of the cumulative extension (Specht and Rosendahl, 1989) and host many of the earthquakes. However, a number of intrabasin faults are present as well. The occurrence of a sequence of earthquakes in 2009 with magnitudes up to M_w 6 on one or more west-dipping intrabasin faults near Karonga in northern Malawi clearly indicates that some of these faults remain active (Biggs *et al.*, 2010; Fagereng, 2013; Macheyeki *et al.*, 2015; see Fig. 1a for locations).

The absolute timing of the onset of extension in the Malawi rift and magmatism in the Rungwe volcanic province and their relative timing with respect to one another are poorly known. Although relatively little total extension has occurred, some authors suggest that rifting or magmatism could have started as early as 24 Ma (Roberts *et al.*, 2012).

Finally, and very importantly, the rifting process is associated with significant seismic and volcanic hazards for the densely populated rift valley (e.g., Fontijn *et al.*, 2011; Hodge *et al.*, 2015). The long border faults within thick strong crust may be capable of producing $M_w \sim 8$ earthquakes (Jackson and Blenkinsop, 1997; Hodge *et al.*, 2015). As demonstrated by the Karonga earthquake sequence (Biggs *et al.*, 2010; Fagereng, 2013; Macheyeki *et al.*, 2015), active intrabasin faults also pose a hazard to people living near the lakeshore; such faults could potentially be associated with near-field tsunamis.

DATA ACQUISITION

To address these science questions, the SEGMeNT experiment aims to constrain several fundamental characteristics of the northern Malawi rift:

- 3D patterns of cumulative deformation and magmatism with depth through the crust and upper mantle and along multiple rift segments and the Rungwe volcanic province;
- variations in active deformation along and across the rift, encompassing the full width of deformation;
- origin and age of magmatism in the Rungwe volcanic province.

To provide this critical information, we acquired a suite of geophysical and geochemical observations across the northern Malawi rift between 2012 and 2016 (Fig. 1b). Given that the core of the Malawi rift is covered by the ~70-km-wide, ~650-km-long Lake Malawi, it was necessary to collect data in and around the lake. The collection of multiple seismic datasets in Lake Malawi is a unique part of our project. We summarize each component below.

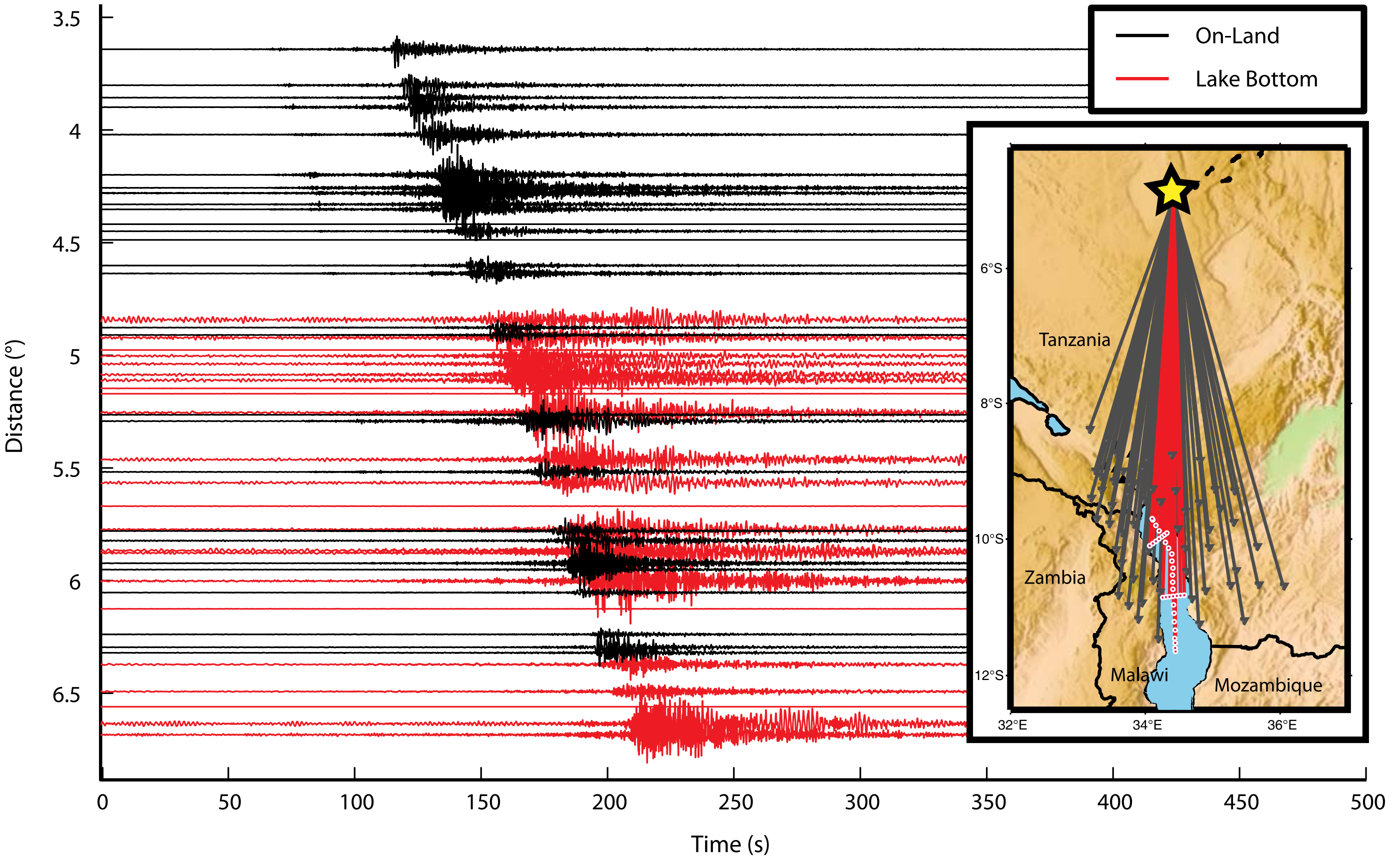
Onshore/Offshore Broadband Seismic Array

The goals of this component of the SEGMeNT project are to record local seismicity to constrain patterns of deformation in the rift, and to record ambient noise and local, regional, and teleseismic earthquakes for seismic imaging of crustal and upper-mantle structure inside and outside the rift. The passive seismic network is composed of 63 stations spanning a ~350 km × 250 km footprint encompassing the northern two segments of the Malawi rift and the Rungwe volcanic province (Fig. 1b). This network includes 43 broadband onshore seismic stations, 14 onshore intermediate-period stations, and 7 broadband (BB) lake-bottom seismometers (LBSs). Most of the onshore seismic equipment is from the Incorporated Research Institutions for Seismology-Program for the Array Seismic Studies of the Continental Lithosphere (IRIS-PASSCAL) instrument center. Sensors include CMG 3Ts, STS-2s, and Trillium 40s. RefTek RT130 dataloggers recorded data at 50 samples per second at 39 stations in Tanzania, and Quanterra Q330 loggers recorded at 100 samples per second for 15 stations in Malawi. These stations were complemented by one AfricaArray station in Tanzania (MBEY), and two stations of the recently established Malawi national network operated by the Malawi Geological Survey department (KARM, VWZM). Data from these stations have been archived with the SEGMeNT network for the duration of the experiment. Onshore stations were deployed in two phases: 15 stations were deployed around the Rungwe volcanic province in August 2013, and the remaining stations were deployed in June–July 2014. We serviced the stations every 3–6 months, and recovered all stations in October–November 2015. Field teams typically included one to two U.S. scientists or students and one to two Tanzanian or Malawian scientists or students, who used 4WD field vehicles to reach sites. Access to the sites was highly variable, with some sites requiring long drives on very rough roads. Deployments were staged from temporary field centers in Karonga and Mzuzu in Malawi and from Mbeya, Njombe, and Songea in Tanzania. We deployed the stations near schools, hospitals, and churches. Besides being advantageous for the security of the stations, this deployment strategy provided excellent opportunities for education and public outreach (Fig. 2d).

The Scripps Institution of Oceanography Institutional Instrument Contributor within the Ocean Bottom Seismograph Instrument Pool supplied seven BB LBSs that were deployed in Lake Malawi. To our knowledge, this is the first time that LBSs were placed within any of the African rift lakes. The Scripps BB LBSs have Trillium 240 seismometers, a differential-pressure recorder and sampled at 100 samples per second. To use these instruments in freshwater, the normal burn-wire release systems- which rely on the conductivity of salt water- were replaced with a new release system developed for this project by the Scripps ocean-bottom seismometer (OBS) group and called the Multi Environment Low-power Trigger (MELT) release. This system uses a plastic-like polymer that melts when heated, but can be reformed at lower temperatures (see Data and Resources). We chose the sites with water depths >230 m for all instruments to improve noise characteristics and to minimize danger to the instruments from fishing. All stations were deployed in February 2015 using the F/V *Ndunduma*, a fishing vessel operated by the Malawi Fisheries Department. The instruments were lowered over the side using the *Ndunduma*'s trawl winch (Fig. 2a). The working conditions were challenging due to the limited deck and lab space and the use of a simple low-tonnage boom for deployments, and hence required significant improvisation and creativity from our team. We staged the cruise from the Chilumba port in southern Lake Malawi, >250 km south of the field area, because this is the only port in Malawi with a gantry crane capable of moving containers. For this same reason, Chilumba was also the chosen port for mobilization for the active-source work (see the Offshore Active-Source Seismic Experiment section). Instruments were recovered during a 3-day cruise in late October 2015 using the M/V *Chilembwe*, which is operated by Malawi Shipping Company/Mota Engil and was briefly used as a fast ferry. The advantages of the *Chilembwe* for our program were that it could make up to 23 kt, has a large deck space, and a small articulated crane capable of handling the heavy broadband equipment, whereas the disadvantage was that there were not enough cabins for the ship's crew and the science party.

The overall data quality from the onshore/offshore seismic deployment is high, with excellent coherence between onshore and LBS recordings (e.g., Fig. 3). Failures of several RefTek GPS clocks resulted in timing uncertainty during the time interval July–November 2013 (Rungwe stations only). One BB LBS (304B) had a bad flash disk and failed to record any data (indicated with gray circle in Fig. 1b), and another BB LBS had problems with the horizontal channels. Malawi network stations KARM and VWZM had equipment problems that were fixed during the course of the experiment. A handful of the

▲ **Figure 2.** Pictures from various components of data acquisition. (a) Deployment of broadband LBS in Lake Malawi from the F/V *Ndunduma* by Ernest Aaron, Mark Gibaud, and Martin Rapa (out of frame). (b) Recovery of outer sections of 1500-m-long streamer aboard the M/V *Katundu* by science party and ship's crew. (c) Patrick Chindandali (Malawi Geological Survey Department) acquiring MT data. (d) Godson Kamihanda (Geological Survey of Tanzania) describes seismic station to high-school students. (e) Nelson Boniface (University of Dar es Salaam) and Gary Mesko (LDEO) acquiring samples from Rungwe volcanic province. (f) M/V *Katundu* in port in Chilumba following mobilization The color version of this figure is available only in the electronic edition.



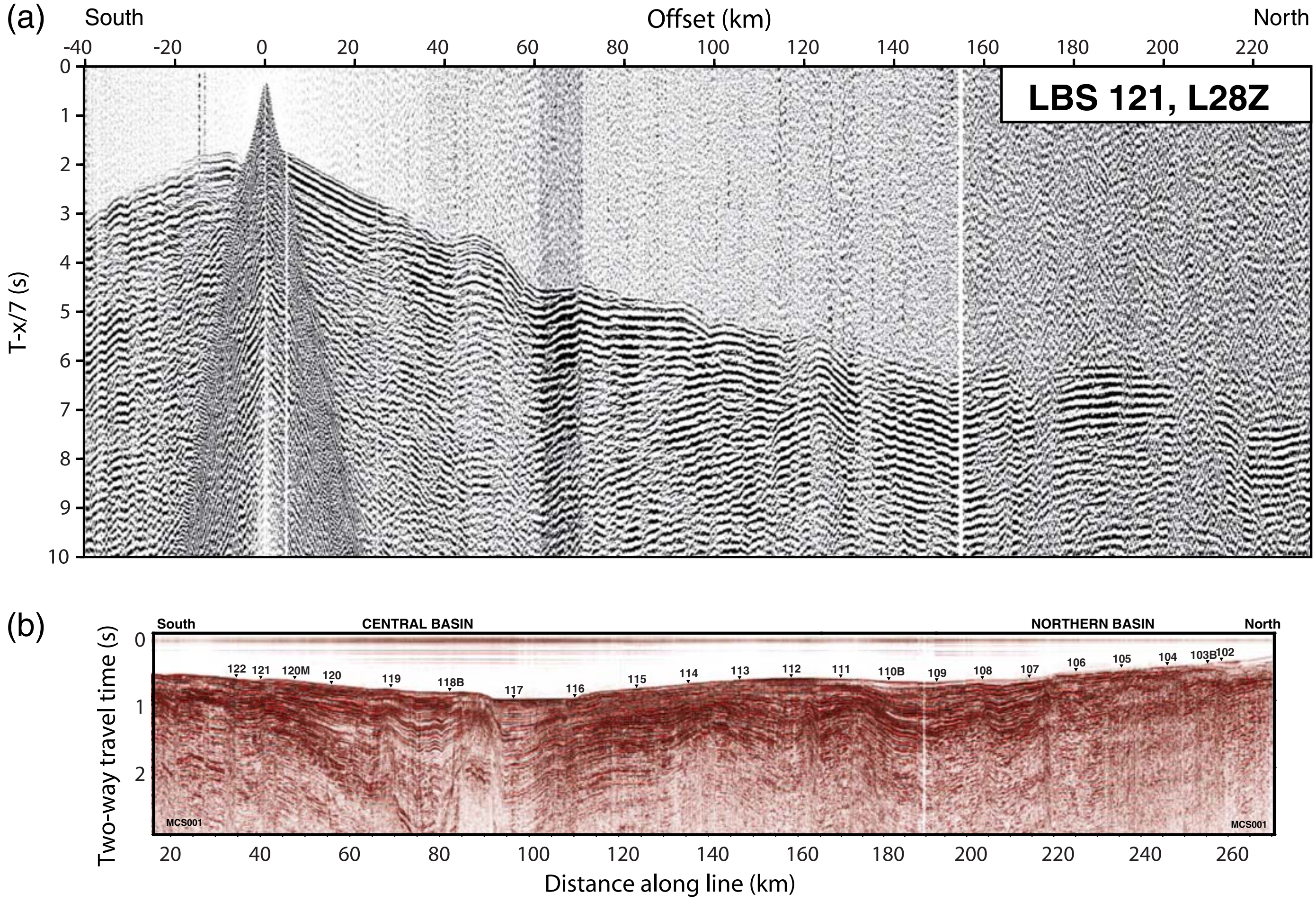
▲ **Figure 3.** Example of seismograms recorded on the vertical channels of land stations (black) and lake-bottom stations (lighter colored symbols) from the SEGMeNT project from an M_w 4.3 event at a depth of 14.9 km located 105 km northwest of Dodoma, Tanzania. The color version of this figure is available only in the electronic edition.

PASSCAL stations experienced data logger and/or sensor failures. However, given the conditions, the overall data return is excellent, with a network uptime of 96.3%. This number does not include the lost short-period (SP) LBS (see following section), which was never archived, or periods of time with compromised timing or data quality.

Offshore Active-Source Seismic Experiment

The objective of the multichannel seismic (MCS) reflection and wide-angle reflection/refraction component is to constrain deformation and magmatism in the crust, from faults and sediments in the basin to overall variations in crustal structure. To enable deep seismic-reflection imaging and long-offset arrivals for refraction work, we required a much larger seismic source than has been used in previous seismic-reflection experiments in Lake Malawi and other African rift lakes (up to 120 inch^3 during the PROBE project, e.g., Rosendahl *et al.*, 1992, and to 15 inch^3 during high-resolution surveys, e.g., Scholz *et al.*, 1993). Active-source data acquisition with a large air-gun array requires significant deck space for the streamer reel, compressors to supply compressed air to the array, lab space for prepping or repairing equipment and monitoring acquisition, and generators to power the compressors, labs, and other gear. Identifying a ship in Lake Malawi that was in good working order with sufficient deck space to hold all of our equipment proved to be a long, but ultimately successful, odyssey that led us to the container ship M/V *Katundu*. Like the *Chilembwe*, this ship was operated by Malawi Shipping Company/Mota Engil. Extensive planning and a 1-month-long refit of the M/V *Katundu* in the Chilumba port in southern Lake Malawi were required to transform this ship into an active-source seismic vessel. The mobilization was an extraordinarily complex undertaking that involved placing and welding six containers, two generators, a streamer winch, and a fuel tank onto the deck of the *Katundu* (Fig. 2b,f). The source was a series of G-guns from Geological Survey of Denmark and Greenland/Aarhus University in Denmark, and the streamer was a $\sim$1500-m-long Hydroscience digital streamer with 12.5-m channel spacing from Syracuse University. Additional equipment to support the seismic source was provided by the Geological Survey of Canada. An unconventional towing strategy was conceived and implemented due to the absence of aft deck space, requiring us to deploy gear from midships (Fig. 2b).

Following mobilization, we conducted three cruises to acquire active-source data. Two cruises were aboard the F/V *Ndunduma* to deploy and recover 27 SP LBS provided by the Scripps



▲ **Figure 4.** Example of receiver gather from (a) LBS 121 with shots from along-strike profile shown with (b) a water-velocity FK-migrated brute stack of coincident seismic reflection data from MCS001/001C. LBS positions indicated with triangles and numbers. The color version of this figure is available only in the electronic edition.

Instrument Center for the wide-angle reflection/refraction experiment. These instruments have a three-component geophone and a hydrophone sampling at 200 samples per second. The SP LBSs were deployed during the same cruise as the BB LBS in February 2015 using the boom of the *Ndunduma*, as described in the previous section. Two trips were required from Chilumba to deploy the instruments because there was not space for all 34 instruments on the *Ndunduma*. All SP and BB LBSs were deployed for the duration of the active-source seismic cruise aboard the M/V *Katundu* (see following paragraphs). These instruments employed the same MELT releases as the BB LBS described in the previous section. The SP LBSs were recovered with the F/V *Ndunduma* during a second cruise in April 2015, which also required multiple trips. One SP LBS 102 could not be recovered from the lake bottom (gray circle at northern end of lake in Fig. 1b), and voltage problems rendered the hydrophone recordings of nine SP stations unusable. Otherwise, the data quality was high (e.g., Fig. 4). We observed refractions and wide-angle reflections at all shot-receiver offsets (> 200 km) on most instruments. Besides recording the active-source experiment, the SP LBS also recorded local seismicity.

Following the mobilization and the deployment of the LBS, we conducted a successful 29-day cruise aboard the M/V *Katundu* from 8 March to 5 April 2015, during which we acquired ~2000 km of MCS reflection data with a variety of acquisition parameters and fired the air-guns along an additional ~1500 km of lines at longer (250 m) shot intervals to be recorded by LBS and land seismometers (Fig. 1b). The science party comprised members from project partner institutions in the United States, Malawi, and Tanzania. Personnel from the Malawi Department of Fisheries were present for environmental monitoring and assisted in communicating with fishing communities onshore. The MCS lines included a series of dip and strike profiles in the northern and central basins intended to be orthogonal to structures or well suited for along-strike correlations (Fig. 1b). Several sets of acquisition parameters were tested during the cruise to optimize the trade-offs between source volume, shot interval, and recording time with the goal of reflection imaging of the top of basement and structures in the deep sediments and upper crust, and refraction imaging of the entire crust and uppermost mantle. We used a streamer up to 1500 m long with a group interval of 12.5 m and a sample rate of 2 ms. We used shot volumes between 500 and 1540 inch^3 at a pressure of 135 bar, shot intervals of 25–50 m, and recording times of 6–14 s.

We also shot a series of profiles intended as sources for refractions and wide-angle reflections to be recorded on seismometers deployed on the lake bottom and onshore (Fig. 1b). For OBS shooting, we used a volume of 2580 inch^3 firing at a pressure of 180 bar at a longer shot spacing of 250 m to avoid previous shot noise for long-offset recordings. We also fired the air-guns at larger shot intervals (and at larger volumes when possible) during turns and streamer deployments, recoveries, and repairs to provide additional ray coverage for wide-angle reflection/refraction study.

The cruise aboard the *Katundu* was divided into four legs by port calls to refuel/re-provision and for repairs/replacements of equipment. This part of the program came with numerous challenges: our streamer was struck by lightning (twice!), our seismic gear became tangled with fishing gear, and we experienced failures in nearly every piece of equipment needed for our operation, including both generators providing power for the operation. However, we were able to overcome the majority of these challenges thanks to the extraordinary tenacity and creativity of our excellent technical crew, ultimately leading to a very successful cruise. The data quality from both the MCS and OBS work is very high (Fig. 4).

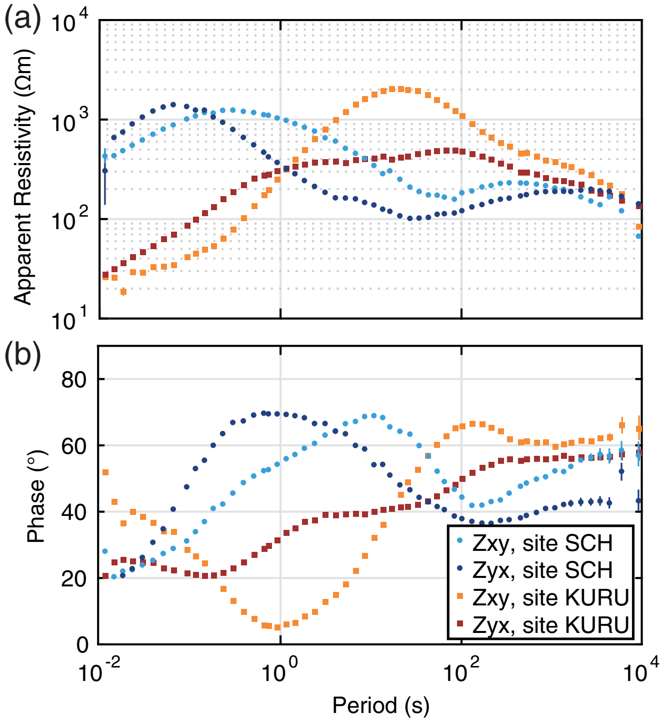
MT Dataset

The goal of the MT component of the project is to image crustal and lithospheric structure across the rift system. MT data image electrical conductivity of the Earth, which is a distinct and complementary physical property to what seismic imaging provides. In particular, MT data are much more sensitive to magma and fluids than seismic data and are therefore essential to the goal of constraining the distribution of magmatism along and across the rift. Combined interpretation of MT and seismic data also provides better resolution of lithospheric temperature and composition than is possible with one methodology alone.

MT data were collected across the same footprint as the onshore seismic deployment (Fig. 1b). We collected both long-period data, which can image deep into the upper mantle, and wideband data, which provide better crustal resolution. Wideband data were collected for at least 1 day using Electromagnetic Instruments, Inc. (EMI) MT24LF data loggers coupled with EMI induction coil sensors, whereas long-period data were collected for at least 7 days, and typically 14 days, using NIMS data loggers and fluxgate magnetometers from Narod Geophysics. Electric field measurements were made using nonpolarizable $Ag/AgCl_2$ electrodes and ∼100-m-long dipoles. All instruments were loaned by the U.S. Geological Survey. We had three key criteria for site selection. The first was to avoid cultural noise, such as power lines, or features that cause the sensors to vibrate, such as roads or milling machines. We sought to avoid such features, which was often difficult because the field area is densely populated. The second was to avoid galvanic distortion. Surface features such as steep topography, riverbeds and abrupt changes in soil type can distort the electric field measurements; so we looked for site locations that were large enough to deploy the electric dipoles while avoiding such features. The third was that we required station locations that could be easily guarded to ensure instrument safety. We buried all instrumentation (including cables) at all sites to help keep them hidden from view. With these criteria in mind, we deployed 52 collocated wide- and long-period stations at close proximity to the onshore seismic stations. Generally, we were able to deploy the station within the same school, church, or hospital that housed the seismic station; where this was not possible, we found an alternate site at most a few kilometers away. In addition, we deployed 30 stand-alone wideband stations in the gaps between the long-period stations in order to improve lateral resolution. In total, data was collected at 56 sites in Tanzania and 26 sites in Malawi (Fig. 1b). Acquiring these data required two exceptionally long field seasons by an individual field team: 2 months in 2013 and 4 months in 2014. In general, only one to two stations could be deployed each day due to long driving times between stations and the time required to find a suitable site and gain permission for deployment. In almost all cases, two or more stations were synchronously recording, to assist in signal/noise separation via remote-reference processing. Although cultural noise was encountered at some sites, the ionospheric and magnetospheric sources of signal upon which the MT method relies were strong during both the 2013 and 2014 surveys. In general, high-quality data were collected, with well-defined wideband (long-period) impedance data to 1000 s (10,000 s). Figure 5 shows a comparison between sounding curves from station KURU, located on the eastern side of Lake Malawi (Nyasa), and station SCH, located on the western side of the lake. Strong variations in the data at periods shorter than 100 s provide an indication of complex conductivity structure within and surrounding the rift basin.

GPS and Interferometric Synthetic Aperture Radar (InSAR)

The goal of the GPS and InSAR component of SEGMeNT is to constrain deformation associated with active rifting and volcanism in our study area, which will strongly complement the seismicity information provided by the seismic array. InSAR data are collected over the region infrequently by most satellites, and some satellites have made no useful observations. But sufficient data from several satellites exist to observe ground deformation—principally from the European Space Agency's Envisat and Sentinal-1 satellites and the Japanese Space Agency's ALOS-1 satellite (Biggs *et al.*, 2010; Hamiel *et al.*, 2012). The GPS network includes 12 continuous GPS stations deployed in Malawi, Tanzania, and Zambia (Fig. 1b). Ten of these stations were installed between July 2012 and March 2013 by U.S., Tanzanian, and Malawian scientists along with UNAVCO engineers, and two stations were deployed in Zambia in March 2013 by Zambian partners and UNAVCO engineers. This network is complemented by nearby AfricaArray stations in Malawi (MZUZ), Tanzania (MBEY and MTVE), and Zambia (KASM). The SEGMeNT GPS stations have Trimble receivers (either NetR9 or NetR8) and Trimble Zephyr GNSS Geodetic II antennas. Sites were chosen near schools, hospitals, churches, national parks, and other secure locations, and guards



▲ **Figure 5.** Comparison of magnetotelluric impedance data from two sites: SCH (on western side of Lake Malawi) and KURU (on eastern side of Lake Malawi). (a) Apparent resistivity, and (b) impedance phase. The color version of this figure is available only in the electronic edition.

have been hired for the duration of the experiment. Several GPS and seismic stations were collocated during the deployment of the onshore broadband seismic array. Monumentation varies with local conditions; antenna mounts include stainless steel masts attached to bedrock, threaded rods attached to concrete pillars, and building mounts that bolt directly to rooftops.

Four of these stations are located outside the core footprint of the seismic/MT experiment to ensure that we encompass the full width of deformation zone, including across the seismically active southwest branch of the EAR and the intervening craton, which lies to the west of the Malawi rift (Fig. 1). All GPS stations are still active and are being serviced every 6 months by Malawian, Tanzanian, and Zambian collaborators. Vandalism at the Isoka (ISOK) Zambia station and Kifanya (KFNY) Tanzania station has resulted in loss of some data at those sites, but both have since been repaired. Campaign measurements were also made during July 2012 at Iringa (IRI2) and Makambako (MAK2) in Tanzania and future measurements are being considered. Data are made publicly available immediately after collection through the UNAVCO archive; users of these data need to abide by the UNAVCO Data and Attribution Policies (Pritchard *et al.*, 2012) and should contact the Principal Investigator before using unpublished data in a scientific publication.

Geochemistry

The objective of the geochemical portion of the SEGMeNT program is to determine the origin and evolution of magmas at Rungwe volcanic province. The timing and geochemistry of magmatism is essential to understand the role of magmatism in early-stage rifts as well as how this relationship evolves as extension, particularly lithospheric thinning, matures. A secondary goal is to better characterize the mantle source(s) in both a regional and global context through geochemical and isotopic fingerprinting.

During a 5-week-long field campaign in July–August 2012, a team of U.S. and Tanzanian scientists and students collected 117 volcanic rock samples (total weight of 550 kg) from the Rungwe volcanic province for analysis (Figs. 1b and 2e). The team focused on sampling distal flows and edifices to obtain and geochemically constrain the earliest eruptions in the sequence. Samples were described in the field to evaluate freshness and note any phenocrysts.

SUMMARY AND FUTURE WORK

The acquisition of the geophysical and geochemical datasets described above was enormously successful, albeit challenging, and has produced a unique dataset for understanding the early stages of continental rifting. Analyzing and integrating these data will enable the development of a complete picture of this early-stage rift and extract valuable constraints on continental rifting processes. We expect that our study will strongly complement previous, ongoing, and future studies in this and other parts of the EAR, including the Project for Rift Initiation Development and Evolution (PRIDE) (Bufford *et al.*, 2012; Leseane *et al.*, 2015; Yu *et al.*, 2015).

DATA AND RESOURCES

The data acquired by the Study of Extension and maGmatism in Malawi aNd Tanzania (SEGMeNT) program are being archived at the appropriate databases described below. The Global Positioning System (GPS) data are open now, and the other datasets will be open following the customary two-year moratorium.

- Active and passive seismic data from onshore/offshore network: Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC; doi: 10.7914/SN/YQ_2013; http://www.fdsn.org/networks/detail/YQ_2013/, last accessed August 2016).
- Seismic reflection data: Marine Geoscience Data System (http://www.marine-geo.org/index.php, last accessed August 2016).
- GPS data: UNAVCO (http://www.unavco.org/data/doi/doi:10.7283/T5J38QW6, last accessed August 2016).
- MT data: U.S. National Geoelectromagnetic Facility (ngf.oregonstate.edu) archive located at the IRIS-DMC (www.iris.edu, last accessed August 2016).
- Geochemistry: Samples are International Geo Sample Number (IGSN) registered and are to be made searchable at http://www.earthchem.org/portal (last accessed August 2016).
- The Multi Environment Low-power Trigger (MELT) release (https://scripps.ucsd.edu/news/new-invention-advances-

freshwater-seismology-research, last accessed August 2016).

ACKNOWLEDGMENTS

Funding for this program was provided by the National Science Foundation (NSF) through Awards EAR-1109293, 1109302, 1109512, 1110882, and 1110921, and by Lamont-Doherty Earth Observatory of Columbia University. Acquisition of this large and complex dataset would not have been possible without the support from communities in our study area, national and regional governmental entities in Malawi, Tanzania, and Zambia, and administrative and technical support from institutes, companies and geological surveys in the United States, Malawi, Tanzania, Denmark, and Canada. We gratefully acknowledge the captains and crews of the *Katundu*, *Ndunduma*, and *Chilembwe*, the drivers of field vehicles, and the many other people who assisted in data acquisition onshore. We particularly wish to acknowledge Jim Normandeau and others at UNAVCO; Noel Barstow, Jackie Gonzales, and others at the Incorporated Research Institutions for Seismology (IRIS) Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center; Jeff Babcock and others at the Scripps Institution of Oceanography Institutional Instrument Contributor within the Ocean Bottom Seismograph Instrument Pool; Marius Lengkeek, Ben Millson and Rory MacDonald at Lengkeek Vessel Engineering, Inc.; Christian Marcussen at the Geological Survey of Denmark and Greenland; Alcides Pessoa, Carlos Lima, Jose Denis, Roberto Ferraira, and others at Malawi Shipping Company/Mota Engil; Noormohamed and Navida Abdoul at Arya Logistics; Aly and Hamida Lalji at Kanji Lalji Ltd.; David Mosher at the Geological Survey of Canada; Majura Songo at University of Dar es Salaam; and Jim and Joyce McGill. Finally, we thank Kasey Aderhold, Jared Peacock, Associate Editor Zhigang Peng, Danielle Sumy, and an anonymous reviewer for helpful comments that improved this contribution. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES

Biggs, J., E. Nissen, T. Craig, J. Jackson, and D. P. Robinson (2010). Breaking up the hanging wall of a rift-border fault: The 2009 Karonga earthquakes, Malawi, *Geophys. Res. Lett.* **37,** L11305, doi: 10.1029/2010GL043179.

Buck, W. R. (2004). Consequences of asthenospheric variability on continental rifting, in *Rheology and Deformation of the Lithosphere at Continental Margins*, G. D. Karner, B. Taylor, N. W. Driscoll, and D. L. Kohlstedt (Editors), Columbia University Press, New York, New York, 1–30.

Bufford, K. M., E. A. Atekwana, M. G. Abdelsalam, E. Shemang, K. Mickus, M. Moidaki, M. P. Modisi, and L. Molwalefhe (2012). Geometry and faults tectonic activity of the Okavango rift zone, Botswana: Evidence from magnetotelluric and electrical resistivity tomography imaging, *J. Afr. Earth Sci.* **65,** 61–71.

Ebinger, C. J. (1989). Tectonic development of the western branch of the East African rift system, *Geol. Soc. Am. Bull.* **101,** 885–903.

Ebinger, C. J., and M. Casey (2001). Continental breakup in magmatic provinces: An Ethiopian example, *Geology* **29,** no. 6, 527–530.

Ebinger, C. J., G. D. Karner, and J. K. Weissel (1991). Mechanical strength of extended continental lithosphere: Constraints from the western rift system, East Africa, *Tectonics* **10,** no. 6, 1239–1256.

Ebinger, C. J., B. R. Rosendahl, and D. J. Reynolds (1987). Tectonic model of the Malaŵi rift, Africa, *Tectonophysics* **141,** 215–235.

Ekström, G., M. Nettles, and A. M. Dziewonski (2012). The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes, *Phys. Earth Planet. In.* **200/201,** 1–9.

Fagereng, A. (2013). Fault segmentation, deep rift earthquakes and crustal rheology: Insights from the 2009 Karonga sequence and seismicity in the Rukwa–Malawi rift zone, *Tectonophysics* **601,** 216–225.

Farr, T. G., E. Caro, R. Crippen, R. Duren, S. Hensley, M. Kobrick, M. Paller, P. Rodriguez, P. Rosen, L. Roth, *et al.* (2007). The shuttle radar topography mission, *Rev. Geophys.* **45,** RG2004, doi: 10.1029/2005RG000183.

Flannery, J. W., and B. R. Rosendahl (1990). The seismic stratigraphy of Lake Malawi, Africa: Implications for interpreting geological processes in lacustrine rifts, *J. Afr. Earth Sci.* **10,** no. 3, 519–548.

Fontijn, K., G. G. J. Ernst, C. Bonadonna, M. A. Elburg, E. Mbede, and P. Jacobs (2011). The ~4–ka Rungwe Pumice (south-western Tanzania): A wind-still Plinian eruption, *Bull. Volcanol.* **73,** 1353–1368.

Foster, A. N., and J. A. Jackson (1998). Source parameters of large African earthquakes: Implications for crustal rheology and regional kinematics, *Geophys. J. Int.* **134,** 422–448.

Global Volcanism Project (2013). *Volcanoes of the World, v. 4.4.3*, Venzke, E. (Editor), Smithsonian Institute.

Hamiel, Y., G. Baer, L. Kalindekafe, K. Dombola, and P. Chindandali (2012). Seismic and aseismic slip evolution and deformation associated with the 2009–2010 northern Malawi earthquake swarm, East African rift, *Geophys. J. Int.* **191,** 898–908.

Hilton, D. R., S. A. Halldórsson, P. H. Barry, T. P. Fischer, J. M. de Moor, C. J. Ramirez, F. Mangasini, and P. Scarsi (2011). Helium isotopes at Rungwe Volcanic Province, Tanzania, and the origin of East African plateaux, *Geophys. Res. Lett.* **38,** doi: 10.1029/2011GL049589.

Hodge, M., J. Biggs, K. Goda, and W. Aspinall (2015). Assessing infrequent large earthquakes using geomorphology and geodesy: The Malawi rift, *Nat. Hazards* **76,** 1781–1806.

Jackson, J., and T. Blenkinsop (1993). The Malawi earthquake of March 10, 1989: Deep faulting within the East African rift system, *Tectonics* **12,** no. 5, 1131–1139.

Jackson, J., and T. Blenkinsop (1997). The Bilila-Mtakataka fault in Malawi: An active, 100-km-long, normal fault segment in thick seismogenic crust, *Tectonics* **16,** no. 1, 137–150.

Keir, D., I. J. Hamling, A. Ayele, E. Calais, C. Ebinger, T. J. Wright, E. Jacques, K. Mohamed, J. O. S. Hammond, M. Belachew, *et al.* (2009). Evidence for focused magmatic accretion at segment centers from lateral dike injections captured beneath Red Sea rift in Afar, *Geology* **37,** no. 1, 59–62.

Leseane, K., E. A. Atekwana, K. L. Mickus, M. G. Abdelsalam, and E. M. Shemang (2015). Thermal perturbations beneath the incipient Okavango rift zone, northwest Botswana, *J. Geophys. Res.* **120,** no. 2, 1210–1228.

Lin, J., G. M. Purdy, H. Schouten, J.-C. Sempere, and C. Zervas (1990). Evidence from gravity data for focused magmatic accretion along the Mid-Atlantic ridge, *Nature* **344,** 627–632.

Lyons, R. P., C. A. Scholz, M. R. Buoniconti, and M. R. Martin (2011). Late Quaternary stratigraphic analysis of the Lake Malawi rift, East Africa: An integration of drill-core and seismic-reflection data, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **303,** 20–37.

Macdonald, K. C., P. J. Fox, L. J. Perram, M. F. Eisen, R. M. Haymon, S. P. Miller, S. M. Carbotte, M.-H. Cormier, and A. N. Shor (1988). A new view of the mid-ocean ridge from the behaviour of ridge-axis discontinuities, *Nature* **335,** 217–225.

Macheyeki, A. S., H. Mdala, L. S. Chapola, V. J. Manhica, J. Chisambi, P. Feitio, A. Ayele, J. Barongo, R. W. Ferdinand, G. Ogubazghi, *et al.* (2015). Active fault mapping in Karonga-Malawi after the

December 19, 2009 M_s 6.2 seismic event, *J. Afr. Earth Sci.* **102,** 233–246.

Nyblade, A. A., and C. A. Langston (1995). East African earthquakes below 20 km and their implications for crustal structure, *Geophys. J. Int.* **121,** 49–62.

O'Donnell, J. P., A. Adams, A. A. Nyblade, G. D. Mulibo, and F. Tugume (2013). The uppermost mantle shear wave velocity structure of eastern Africa from Rayleigh wave tomography: Constraints on rift evolution, *Geophys. J. Int.* **194,** no. 2, 961–978, doi: 10.1093/gji/ggt135.

Pritchard, M. E., S. Owen, S. Anandakrishnan, W. E. Holt, R. A. Bennett, P. LaFemina, P. Jansma, I. MacGregor, C. Raymond, S. Schwartz, *et al.* (2012). Open access to PI-led geophysical datasets requires community responsibility, *Eos Trans. AGU* **93,** 243, doi: 10.1029/2012EO260006.

Roberts, E. M., N. J. Stevens, P. M. O'Connor, P. H. G. M. Dirks, M. D. Gottfried, W. C. Clyde, R. A. Armstrong, A. I. S. Kemp, and S. Hemming (2012). Initiation of the western branch of the East African rift coeval with the eastern branch, *Nat. Geosci.* **5,** 289–294.

Rosendahl, B. R., E. Kilembe, and K. Kaczmarick (1992). Comparison of the Tanganyika, Malawi, Rukwa and Turkana rift zones from analyses of seismic reflection data, *Tectonophysics* **213,** 235–256.

Scholz, C. A., T. C. Johnson, and J. W. McGill (1993). Deltaic sedimentation in a rift valley lake: New seismic reflection data from Lake Malawi (Nyasa), East Africa, *Geology* **21,** 395–398.

Specht, T. D., and B. R. Rosendahl (1989). Architecture of the Lake Malawi rift, East Africa, *J. Afr. Earth Sci.* **8,** 355–382.

Stamps, D. S., E. Calais, E. Saria, C. Hartnady, J.-M. Nocquet, C. J. Ebinger, and R. M. Fernandes (2008). A kinematic model for the East African rift, *Geophys. Res. Lett.* **35,** L05304, doi: 05310.01029/02007GL032781.

Taylor, B., A. Goodliffe, F. Martinez, and R. Hey (1995). Continental rifting and initial sea-floor spreading in the Woodlark basin, *Nature* **374,** 534–537.

Yu, Y. Q., K. H. Liu, C. A. Reed, M. Moidaki, K. Mickus, E. A. Atekwana, and S. S. Gao (2015). A joint receiver function and gravity study of crustal structure beneath the incipient Okavango rift, Botswana, *Geophys. Res. Lett.* **42,** no. 20, 8398–8405.

Donna J. Shillington
James B. Gaherty
Cornelia Class
Natalie J. Accardo
Gary T. Mesko
Celia Eddy
Lamont-Doherty Earth Observatory of Columbia University
Palisades, New York 10964 U.S.A.
djs@ldeo.columbia.edu

Cynthia J. Ebinger
Gabrielle Tepp
Earth and Environmental Sciences
University of Rochester
Rochester, New York 14627 U.S.A.

Christopher A. Scholz
Tannis McCartney
Douglas Wood
Department of Earth Sciences
Syracuse University
Syracuse, New York 13244 U.S.A.

Kate Selway[1]
Centre for Earth Evolution and Dynamics
University of Oslo
0316 Oslo, Norway

Andrew A. Nyblade
Marsella Kachingwe
Gabriella Arroyo
Department of Geosciences
Pennsylvania State University
University Park, Pennsylvania 16802 U.S.A.

Paul A. Bedrosian
U.S. Geological Survey
Crustal Geophysics and Geochemistry Science Center
Denver, Colorado 80225 U.S.A.

Scott L. Nooner[1]
Department of Earth and Ocean Sciences
University of North Carolina Wilmington
Wilmington, North Carolina 28403 U.S.A.

Matthew E. Pritchard
Earth and Atmospheric Sciences
Cornell University
Ithaca, New York 14853 U.S.A.

Julie Elliott
Department of Earth, Atmospheric, and Planetary Sciences
Purdue University
West Lafayette, Indiana 47907 U.S.A.

Patrick R. N. Chindandali
Jalf Salima
Felix Mphepo
Duncan Gondwe
Malawi Geological Survey Department
Zomba, Malawi

Gaby Mbogoni
Godson Kamihanda
Abdul Mruma
Geological Survey of Tanzania
Dodoma, Tanzania

Richard Wambura Ferdinand
Nelson Boniface
Shukrani Manya
Gabriel Mulibo
Melania Maquay
Khalfan Mtelela
Brian Kamoga
Mary Moshi
Department of Geology
University of Dar es Salaam
Dar es Salaam, Tanzania

Elifuraha Saria
Daud Ntambila
Department of Geomatics
School of Geospatial Sciences and Technology
Ardhi University
Dar es Salaam, Tanzania

Leonard Kalindekafe
Ndata School of Climate & Earth Sciences
Malawi University of Science and Technology
Limbe, Malawi

J. P. O'Donnell[2]
School of Earth and Environment
University of Leeds
Leeds LS2 9JT, UK

Per Trinhammer
Department of Geosciences
Aarhus University
8000 Aarhus C, Denmark

Ernest Aaron
Mark Gibaud
Martin Rapa
Scripps Institution of Oceanography
La Jolla, California 92037 U.S.A.

Cathy Pfeifer
Incorporated Research Institutions for Seismology (IRIS)
Portable Array Seismic Studies of the Continental Lithosphere
(PASSCAL) Instrument Center
New Mexico Tech
Socorro, New Mexico 87801 U.S.A.

---

[1] Also at Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964 U.S.A.

[2] Also at Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802 U.S.A.