Intrarift fault fabric, segmentation, and basin evolution of the Lake Malawi (Nyasa) Rift, East Africa

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ABSTRACT

The Lake Malawi (Nyasa) Rift, in the East African Rift System (EARS), is an ideal modern analogue for the study of extensional tectonic systems in low strain rate settings. The seismically active rift contains the 700-m-deep Lake Malawi, one of the world’s oldest and largest freshwater lakes with one of the most diverse endemic faunal assemblages on Earth. Modern and reprocessed legacy multi-channel seismic-reflection data are constrained by velocity information from a wide-angle seismic experiment to evaluate variability in extension, segmentation, and timing of fault development along the 550-km-long rift zone. Fault geometries and patterns of synrift sediment fills show that the Lake Malawi Rift is composed of three asymmetric rift segments, with intervening accommodation zone morphologies controlled by the degree of overlap between segment border faults. Most extension occurs on the basin border faults, and broadly distributed extension is only observed at one accommodation zone, where no border fault overlap is observed. Structural restorations indicate a weakly extended rift system (~7 km), with diminishing values of extension and thinner rift fill from north to south, suggesting a progressively younger rift to the south. There is no evidence of diking, sill injection, or extrusions within the synrift fill of the Lake Malawi Rift, although the volcanic load of the Rungwe magmatic system north of the lake and related subsidence may explain the presence of anomalously thick synrift fill in the northernmost part of the lake. The thickest synrift depocenters (~5.5 km) are confined to narrow 10- to 20-km-wide zones adjacent to each rift segment border fault, indicating concentration of strain on border faults rather than intrarift faults. Intrarift structures control axial sediment delivery in the North and Central rift segments, focusing sediment into confined areas resulting in localized overpressure and shake diapirs. The asymmetric, basement-controlled relief was established early in rift development. When overprinted with frequent high-amplitude hydroclimate fluctuations, which are well documented for this basin, the resulting highly variable landscape and lake morphometry through time likely impacted the diverse endemc faunas that evolved within the basin. New seismic-reflection data, augmented by wide-angle seismic data and age constraints from drill core, offer the most highly resolved 3D view to date of latest Cenozoic extensional deformation in East Africa and provide a foundation for hazards analysis, resource assessments, and constraining deformation in a low strain rate, magma-poor active rift.

INTRODUCTION

Divergent plate boundaries are separated along strike into discrete segments that have been well described on mid-ocean ridges and in late-stage continental rifts (e.g., Macdonald et al., 1988; Taylor et al., 1995). These segments vary in length, width, and internal structural fabric depending on several factors, including strength of the continental lithosphere (Ebbing et al., 1991), antecedent heterogeneities, and preexisting crustal structures (Dunbar and Sawyer, 1989; Versfelt and Rosendahl, 1989; Corti et al., 2007; Brune et al., 2017) and the degree of magmatic involvement in rifting processes (e.g., Baker, 1986; Morley, 1994; Hayward and Ebinger, 1996; Ebinger and Casey, 2001; Corti et al., 2007; Muirhead et al., 2016). The linkage behavior of discrete rift segments, in the form of accommodation zones or transfer zones, may also be influenced by these same factors, and different linkage geometries may produce structures of markedly varying morphologies (e.g., Rosendahl, 1987; Morley et al., 1990). The sequential evolution of both the rift bounding and intrarift faults dictates the surface expression of rift zones, adjacent uplifted footwall mountain ranges, and zones of intrarift subsidence, which may be filled with thick sequences of synrift deposits and at times be occupied by large tectonic lake basins, sometimes for the life history of the rift zone (e.g., Tercelin et al., 1988).

The East African Rift valley is the iconic earth surface expression of the largest continental rift system on Earth, with components that reveal varying degrees of extension, from classic examples of mature rifting and incipient sea floor spreading (e.g., Bastow and Keir, 2011) through to embryonic rifting and limited basinal subsidence in areas such as the Okavango Rift (e.g., Kinabo et al., 2008). The Lake Malawi (Nyasa) Rift (Fig. 1) occupies the southern extension of the western branch of the East African Rift System (EARS), part of the system that has experienced relatively low amounts of strain and is characterized by low magma inputs into the upper crust, compared to the eastern branch of the rift (Baker, 1988; Morley, 1994; Hayward and Ebinger, 1996; Wright et al., 2006; Muirhead et al., 2019). The role of extensional tectonics in the region has been essential in producing a long-lived lake basin renowned for its biodiversity and endemism.
Structure of the Lake Malawi (Nyasa) Rift, East Africa

(REINTHAL, 1993). Lake Malawi itself plays a prominent role in the evolution of the rift, as most of the synrift fill in the basin accumulated subaquously; given the thick sedimentary section in the rift (ROSENDAHLM., 1992) and considerable organic-rich sediments, it is considered prospective for commercial quantities of hydrocarbons (MACGREGOR, 2015). Because nearly the entire rift zone is covered by one of the world’s largest lakes, it is possible to use marine seismic methods to image and assess the developmental history and structure of the rift.

The structure of the offshore Lake Malawi Rift was investigated previously using marine multichannel seismic-reflection methods (e.g., SPECHT AND ROSENDHALL, 1989; ROSENDHALL ET AL., 1992); however, the earlier basin-scale imaging was limited to profiles acquired with a small airgun source, an analog hydrophone array, limited navigational control that used pre-GPS technology, and data collection off of a small (13 m) underpowered vessel. Earlier studies used images generated only from short reflection offsets (<1500), 1980s-era processing capabilities, limited velocity constraints, and no ground-truth information from scientific drill cores. Here we integrate newly acquired offshore seismic-reflection data, reprocessed legacy seismic-reflection data, new wide-angle seismic-reflection, and seismic-refraction data acquired using lake-bottom seismometers and geochronology from scientific drill cores to examine the overall rift segmentation, evolution, and internal structural fabric of the Lake Malawi Rift (Fig. 2). These integrated data sets allow an unprecedented assessment of one of the world’s largest active intracontinental rifts, including detailed segmentation geometry and history, intrarift structure, and the spatial and temporal variations in extensional strain, both along and across strike. The new and legacy reprocessed seismic-reflection data presented here are processed through pre-stack depth migration and use velocity constraints from the wide-angle seismic data acquired with lake-bottom seismometer (LBS) data (ACCARDO ET AL., 2018; SHILLINGTON ET AL., 2020) to improve imaging and assess the character of the most deeply subsided parts of the rift. For the first time, our new work presents the synrift basement, intrarift normal faults, and border fault geometries in depth, rather than two-way travel time (TWTT) or in depth from over-simplified TWTT-depth transformations, providing a harmonized basin-wide perspective of basement structural relief and fault fabric along the full length of the Lake Malawi Rift. Depth processing of seismic-reflection data enables quantitative estimates of extension using area-balanced structural restoration methods. We compare orientations of intrarift faults, basin-bounding border faults, and onshore lineaments from a shuttle radar topography mission (SRTM) digital elevation model (DEM) to characterize the influence of regional terranes and terrane boundaries on rift architecture. This new basin-scale perspective, combined with age constraints from drill core, is the most highly resolved 3D view to date of late Cenozoic extensional deformation in East Africa over a full rift zone and provides a new basis for hazards analysis, resource assessments, and understanding extensional deformation in a low strain rate, magma-poor active rift system.

**GEOLoGICAL BACKGROUND**

The Lake Malawi Rift is a late Cenozoic extensional system located at the southern end of the magma-poor western branch of the East African Rift System (EARS) (Fig. 1) (ROSENDHALL, 1987; MACGREGOR, 2015). It is composed of several rifted half-graben...
segments, each 100–200 km in length, linked by accommodation or transfer zones that partition strain along strike. Pronounced rift-induced active subsidence, combined with a favorable hydroclimate results in hydrologic overfilling of the rift valley. At more than 550 km long and 700 m deep, Lake Malawi ranks behind only Lake Tanganyika in terms of depth, and Lakes Tanganyika and Victoria with respect to area, among African lakes. The modern lake covers most of the rift valley, and only limited outcrops of synrift deposits are observed in the northwestern part of the system. Major border faults define the margins of much of the rift (Specht and Rosendahl, 1989), and faulted lake coastlines are prominent, especially in the northern half of the rift (Fig. 1).

The rift zone is positioned at the confluence of several ancient geological terranes and is aligned with or crosscuts important continental-scale shear zones (e.g., Daly, 1988; Versfelt and Rosendahl, 1989; Chorowicz, 2005; Fritz et al., 2013). The majority of the outcropping bedrock within the rift or within the lake catchment is Proterozoic in age (Fig. 3) and is related to a series of East Africa–wide orogenic and collisional events associated with the East African orogen (Fritz et al., 2013). To the west of the rift lake are primarily greenschist-facies rocks of the Mesoproterozoic Irumide Belt. Paleoproterozoic rocks of the Ubendian belt are positioned mainly to the north and northeast of the Lake Malawi Rift. Lithologies within this belt include gneisses, schists, granulites, granite, and gabbros. To the southwest in Malawi and to the west into Mozambique are mainly granulite- to amphibolite-facies metamorphic rocks of the southern Irumide Belt, of Mesoproterozoic to Neoproterozoic age.

Juxtaposing the Irumide and Southern Irumide terranes to the west of the Malawi Rift is the Mwembeshi Shear Zone (Fig. 3), a major continental-scale deformation that is interpreted as extending across most of southern African and terminating near the Malawi Rift (Versfelt and Rosendahl, 1989; Fritz et al., 2013; Brown et al., 2014). Across the lake and rift valley from this major lineament to the east in Mozambique is the Maniamba Trough, a Permo-Triassic sedimentary basin affiliated with the Karoo system (Kreuser et al., 1990). Modest escarpments, up to ~400 m high, bound this older sedimentary basin. In southwestern Tanzania immediately to the east of Lake Malawi is the Ruhuhu Trough, another Karoo-age basin, which also is easily identified by its lower relief relative to the adjacent crystalline rocks (e.g., Wopfnner, 2002; Fig. 3). At this same latitude, near Chilumba, Malawi, are outcropping Karoo rocks that contain abundant coal beds (Yemane et al., 1989). Seismic-refraction data suggest the presence of pre-rift, Karoo sediments beneath the lake between these onshore expressions (Accardo et al., 2018). Cretaceous “Dinosaur Beds” also outcrop on the northwestern margin of Lake Malawi (Dixey, 1937; Colin, 1990) and may extend north into Tanzania (Dixey, 1937; Roberts et al., 2010). Limited synrift deposits of Cenozoic age are present on the most northwesterly margin of Lake Malawi. These include the fossil-rich Pliocene Chiwondo Beds (Lüdecke et al., 2016) as well as Pleistocene deposits. Intrusive rocks of late Jurassic and early Cretaceous age occur within the catchment of the Lake Malawi Rift, and in southern Malawi include carbonatites and feldspathoid syenites of the Chilika Alkaline Province (Eby et al., 1995). Along the rift axis to the north of the lake is the Rungwe Volcanic Province (Fig. 3), one of two prominent volcanic systems in the rift’s western branch. The Rungwe Volcanic Province is a late Cenozoic extrusive system that includes the Rungwe volcano, which erupted in the Holocene (Fontijn et al., 2010) and has an active magmatic-hydrothermal system at depth (de Moor, 2013). It is underlain by a prominent low-velocity zone in the upper mantle (Accardo et al., 2017, 2020; Grijalva et al., 2018).

Legacy offshore seismic-reflection data enabled initial observations of the sedimentary and structural framework of the Lake Malawi Rift; however, earlier models of rifting and segmentation relied heavily on tectono-geomorphic expression of onshore footwall uplifts. Early offshore single-channel imaging (Rosendahl and Livingston, 1983; Ebinger et al., 1987) revealed that substantial thicknesses of sediment underlie the lake and suggested the importance of rift segmentation for controlling patterns of sediment accumulation. Pioneering efforts by Project PROBE between 1985 and 1987 led to the collection of 3500 km of regional multichannel seismic data that helped characterize the segmentation and intrarift structures and stratigraphy (Fig. 2) (Scholz et al., 1989; Specht and Rosendahl, 1989; Flannery and Rosendahl, 1990); these early results also implied a relationship between half-graben polarity and preexisting rift structures (Versfelt and Rosendahl, 1989). Subsequent high-resolution surveys helped to further constrain the intrabasinal structure and stratigraphy of the offshore part of the rift (Scholz, 1995; Soreghan et al., 1999; Mortimer et al., 2000).
et al., 2007; McCartney and Scholz, 2016). Recent airborne magnetic surveys and onshore geological observations provide insights into rift structure on its margins (Laô-Dávila et al., 2015; Dawson et al., 2018; Kolawole et al., 2018), and in the southern extension of the rift onshore, show that active faults generally follow the trends of Precambrian fabrics (Laô-Dávila et al., 2015). The segmentation framework of Laô-Dávila et al. (2015) utilized observations of lake coastline faults to identify seven segments in the part of the rift covered by Lake Malawi; the work presented herein tests their hierarchical segmentation model by examining offshore fault displacements, synrift sediment accumulation, and fault-controlled basement subsidence.

Much of the western branch of the rift is known for exceptionally deep large earthquakes (Foster and Jackson, 1998; Craig et al., 2011), a consequence of crustal thicknesses up to 45 km (Hodgson et al., 2017; Borrego et al., 2018) with inferred mafic lower crust (Julia et al., 2005). Indeed the Malawi Rift has also experienced considerable seismicity recently, though possibly more on intrarift structures than the border faults (Biggs et al., 2010; Ebbing et al., 2019). Evidence for late Pleistocene and Holocene extension comes from displacements on the lake floor in some places (Ng’ang’a, 1993; Lyons et al., 2011; Shillington et al., 2020) and growth fault analyses from high-resolution, single-channel reflection seismic data (McCartney and Scholz, 2016). Regional geodetic studies suggest that current extension is progressing at 1–3 mm/year, mainly in an E-W direction across the central and southern part of the western rift branch (Saria et al., 2014; King et al., 2019). Rift-associated magmatism has accompanied extension in the eastern branch of the rift, especially in Ethiopia and Kenya (e.g., Mechlie et al., 1994; Keir et al., 2006; Muirhead, 2015), but in the western branch, volcanism is mainly observed in two localities: the Virunga Volcanic Province in the Kivu Rift and the Rungwe Volcanic Province north of Lake Malawi (Furman, 2007). Receiver function studies indicate possible lower-crustal magma intrusion in the southern Tanganyika Rift (Hodgson et al., 2017). Whereas seismicity has generally been inferred to be associated with border-fault deformation in the western branch, in northern Malawi, recent seismicity investigations also reveal pervasive normal- and oblique-slip earthquakes on intrarift structures in the hanging wall (Ebbing et al., 2019; Gaherty et al., 2019).

**METHODS**

### Seismic-Reflection Data

As a part of the multidisciplinary Study of Extension and magmatism in Malawi and Tanzania (SEGMeNT project, an international team conducted an offshore seismic experiment on Lake Malawi in March and April 2015 using the M/V Katundu, a local container vessel temporarily converted into a geophysical survey vessel. Both seismic-reflection (common mid-point) and wide-angle reflection and refraction data were collected, and details of acquisition parameters are provided in Shillington et al. (2016) and in the Supplemental Document. New reflection data, totaling ~2000 line-km, were acquired using a 500–1540 in³ airgun array and a digital seismic streamer with up to 1500-m-long active section, resulting in 30- to 60-fold data. Wide-angle reflection and refraction data were collected using lake-bottom seismometers recording all shots fired from the vessel (Shillington et al., 2016; Accordo et al., 2018). An active navigation system used differential GPS for all positioning. In figures and maps, these lines are denoted with 15-###.

Legacy seismic-reflection data (Fig. 2) (Rosendahl, 1987; Flannery and Rosendahl, 1990; Scholz et al., 1989; Specht and Rosendahl, 1989) were originally acquired between 1985 and 1987 using a marine streamer with a 1450-m-long offset, 960-m-long active section, and an airgun source array of 40–120 in³, resulting in ~500 line-km of 24-fold data. Legacy data were reprocessed in 2016 by ION Geophysical, and interpreted along with new SEGMeNT data (please see Supplemental Document (footnote 1, Section 4: Legacy Data Processing and 5: Seismic Data Interpretation and Integration)). The legacy data were acquired in the pre-GPS era, and positioned using the transit satellite system, radar, and deduced reckoning. These data aid in constraining the geometry of intrarift normal faults below the lake. In figures and maps, these lines are indicated with 86-### or 87-### annotations.

### Data Processing and Data Integration

New multichannel seismic-reflection data collected during the SEGMeNT project were processed though post-stack Kirchhoff time migration, and included wave equation multiple removal (WEMR) and surface-related multiple elimination (SRME). Selected SEGMeNT profiles presented here were processed through pre-stack depth migration and utilized velocity information independently derived from the lake-bottom seismometer data (Accordo et al., 2018) as well as velocities determined from common midpoint (CMP) velocity analyses in the upper synrift sedimentary section. Legacy seismic data were reprocessed by ION Geophysical, through pre-stack depth migration (PSDM), and also using wave equation multiple removal (WEMR) and surface-related multiple elimination (SRME) routines. A full summary of processing routines is presented in the Supplemental Document (footnote 1, Section 4: Legacy Data Processing). Interactive seismic interpretations, including basement and fault mapping, were carried out using Landmark DecisionSpace™ interpretation software. Seismic profiles were initially interpreted in the time domain, and interpretations were compared with depth profiles and adjusted iteratively. The synrift basement surface and fault heaves were interpreted in time and then depth-transformed using a 3D velocity brick generated from pre-stack time migration (PSTM) velocities. Mapping and contouring algorithms used a least-squares gridding approach that excluded fault heaves; complete parameters are included in Supplemental Document (footnote 1, Section 5: Seismic Data Interpretation and Integration). Key stratigraphic surfaces used in section restorations were determined by examining stratigraphic relationships using standard seismic stratigraphic techniques (Vail et al., 1977). The stratigraphic framework presented here follows previous nomenclature (Scholz et al., 1989; Flannery and Rosendahl, 1990; Lyons et al., 2011), although given the improved profile density and

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**Supplemental Document.** Provides additional background to methodologies used for analyses presented in main paper. Presents background information on SEGMeNT Project; summary of seismic data acquisition parameters; SEGMeNT data processing and legacy data reprocessing details; seismic data interpretation and integration methods; GIS analysis of local relief in the rift; expanded summary of structural restoration methods; summary of volcanic load estimates and methods; summary of the lineament analyses; and discussion of the age of the Malawi Rift. Please visit https://doi.org/10.1130/GES.8.12323264 to access the supplemental material, and contact editing@geoscience.org with any questions.
data fidelity, some fault and stratal surface interpretations reveal radically different patterns than prior mapping efforts.

**Structural Restorations**

To calculate total extension in each of the identified Lake Malawi Rift segments (North, Central, and South Basins; see interpretation sections below), a selected depth-converted profile from each basin was balanced and restored using an area-conservation approach (Gibbs, 1983; Rowan and Kligfield, 1989). Structural restorations of depth-converted profiles were completed using the Lithotec™ structural restoration software. Stratigraphic architecture and fault geometry beneath the lake are constrained by seismic-reflection data interpretations from the SEGMeNT and legacy data sets. Footwall uplifts within the Western Branch of the East African Rift System follow the shape of the long-wavelength topography (Ebinger et al., 1991), and the regional elevation and pin-point is defined as the location where this long-wavelength uplift decays away. We constrain the regional elevation and pin point for each restoration using the ETOPO30 DEM in the Central and South Basins and the 90 m Shuttle Radar Topography Mission (SRTM) DEM in the North Basin. The SRTM data are down-sampled to the same resolution (~1 km) as ETOPO30 for consistency; this resolution is adequate to capture long-wavelength structure.

Cross sections are orientated parallel to the modeled regional extension directions for Lake Malawi from Delvaux and Barth (2010) in the North Basin, and Sarria et al. (2014) in the Central and South Basins; these extension directions are also rift-normal (i.e., perpendicular to border-fault orientation). The 2D restorations assume plane strain; thus, if sections do not balance, this is attributed to (1) a component of deformation occurring through out-of-plane motion and/or (2) erroneous interpretations (Gibbs, 1983, 1984; Groshong, 2006) or flawed depth conversions. Thus, we project our seismic interpretations into the regional extension directions. Stratal surfaces from previous studies (Scholz et al., 1989; Fianney and Rosendahl, 1990; Lyons et al., 2015) provide the relative time progression of deformation in each rift segment.

Sections are restored using the vertical simple-shear kinematic model of Gibbs (1983, 1984), which is considered to be a good geometrical approximation of distributed brittle deformation at the cross-section scale within unconsolidated and well-bedded sediments (Rowan and Kligfield, 1989). We conserve area within fault blocks during the restoration process, whereas the area of section beneath the brittle basement is not required to remain constant and may freely flow into and out of the plane of view (Schultz-Ela, 1992).

We first account for the deeply eroded footwalls of the rift-bounding faults and any missing section (lighter-gray areas, see detailed methods section in Supplemental Document [footnote 1], Section 7: Structural Restorations). We then kinematically restore slip on the intrarift fault population for the uppermost synrift sequence, using each fault’s footwall cutoff as a local “pin.” Next, we kinematically restore slip on the border faults for the uppermost synrift sequence to the regional datum, defined by the updip intersection of the border fault plane and the far-field, long-wavelength topography. The uppermost synrift sequence is then removed, and the remaining synrift section is decompacted. Finally, we correct the section for the flexural iso-static response to the unloading of the synrift sequence (full method, including compaction procedure, in Supplemental Document [footnote 1], Section 7: Structural Restorations, Fig. S3). The processes described above are then repeated for the remaining synrift sequences down to the base of the synrift section. These methods require the restoration of the rift flank topography and the removal of the water column during the first step of the restorations, because we are restoring the sections to a flat datum rather than balancing a section to the Moho, which would necessitate making undue assumptions about deeper crustal and mantle processes. We are not implying that there is an absence of rift flank topography or the absence of a lake throughout rift history. Instead, because there are no controls on the paleo-rift flank topography, or the tectonic paleo-lake depth with respect to the “regional” datum, we decline to constrain it in our restorations. This implicitly results in zero accommodation space in the basin. Therefore, the observed border-fault configuration and basin subsidence during the restored stages do not represent the exact rift configuration at this time. These simplified rift-stage scenarios, however, have no impact on the final extension measurements.

**Lineament Analyses**

Lineaments on the uplifted Malawi Rift flank were analyzed using 30 m SRTM DEM to compare to the interpreted intrarift normal fault patterns in the lake subsurface. Following the methodology of Muirhead et al. (2019), linear surface features were enhanced visually by calculating the second derivative of the elevation data of the 30 m SRTM DEM. Surface lineaments within 75 km of the lake shoreline, which occur within mapped Proterozoic terranes, were characterized as representing basement fabrics if they had lengths >10 km and no visible scarp, so as not to falsely characterize recently active faults as these structures. Because these structural features do not exhibit scarps, they form as long, linear ridges or valleys. Our mapped structures were binned into northern, central, and southern segments, then compared with inherited basement fabrics observed in aeromagnetic data (e.g., Laô-Dâvila et al., 2015) and field studies (Ring, 1994; Wheeler and Karson, 1994).

**SEGMENTATION AND INTRARIFT DEFORMATION IN THE MALAWI RIFT**

New images of the Lake Malawi Rift allow us to assess the sequential activity of border and intrasaginal faults in seismic-reflection data, using observed fault displacements and subsidence-controlled stratal thickness variations. The integration of new and legacy multichannel seismic (MCS) data, coupled with velocity constraints from both refraction and pre-stack time-migrated (PSTM) velocity analyses, allows for quantitative estimates of fault geometries and displacements, basement subsidence, and stratigraphic sequence volumes over
time. Whereas the rift segmentation into numerous components has been reported previously (e.g., Ebinger et al., 1987; Specht and Rosendahl, 1989; Laó-Dávila et al., 2015), the analyses from the new data integration show that there are three main half-graben basins or dip domains that accommodate the strain and subsidence in the basin, rather than five to seven segments (e.g., Ebinger et al., 1991; Laó-Dávila et al., 2015). Moreover, in each of the three rift segments identified (the North, Central, and South Basins), extension and basin subsidence has mainly focused on border faults. Whereas other scarps, such as on the east side of the Central Basin, are observed onshore (Fig. 2), and have been interpreted as border faults (Ebin- ger et al., 1987; Laó-Dávila et al., 2015), subsurface data reveal comparatively limited subsidence adjacent to these structures and thus indicate that they have not accumulated significant total extension and are not border faults defining rift segmentation. Below we characterize deformation within each of the dip domains, and we also characterize the linkage behavior of the accommodation zones between the North and Central Basins and Central and South Basins.

MCS Results and Interpretation—North Basin

A total of ~1100 line-km of offshore multichannel seismic-reflection data are available for analysis of basin deformation in the North Basin (Fig. 2), which extends from the Chilumbwa peninsula to the lake’s northern tip and beyond. Basin physiography onshore is dominated by the Livingstone Mountains and border fault on the Tanzania shoreline (Fig. 2), with more than 1500 m of relief above the lake surface; offshore is a 600-m-deep, asymmetric basin adjacent to the Tanzania shoreline. The western margin of the basin is a flexural ramp.

The base of the synrift section, interpreted as pre-rift basement, is observed on many profiles in the basin, consisting of a low-frequency and high-amplitude, two- to three-cycle reflection on new and legacy-reprocessed data. Marked increases in seismic velocities are observed across the basement (Fig. 4); independently generated refraction velocities (Accardo et al., 2018) indicate basement velocities in excess of 6000 m/s at a depth of <2 km below lake surface datum on the crest of some intrarift fault footwall blocks (Fig. 5). Basement-reflection mapping across the basin allows for a 3D rendering of normal fault geometry, displacement, configuration, and orientation across the basin (Fig. 5A; see also Supplemental Mapping Files). A maximum of 7.7 km of vertical throw is observed on the Livingstone fault, between the footwall crest and observed hanging-wall basement (Fig. 6), broadly consistent with refraction results of Accardo et al. (2018) and Shillington et al. (2020). Fault-plane reflections are observed on four legacy profiles, indicating fault dips of ~60°. There is considerable along-strike variability in total basement subsidence along the rift. The maximum basement subsidence is observed near the south-central part of the Livingstone fault hanging wall (Fig. 5), adjacent to the fault (see profile 15-102, Fig. 6). At the lake’s northernmost tip, another major depocenter is observed on the two northernmost seismic profiles (Figs. 5 and 6), indicating more than 5 km of basement subsidence and synrift fill.

The northern part of the North Basin is characterized by distributed extension on three major and several lesser west-dipping synthetic intrabasinal faults (Shillington et al., 2020), several of which displace the lake floor up to 15 m in some localities (Figs. 5 and 6). Maximum basement displacement of ~2.8 km is observed on these intrarift faults, which vary in strike from NW-SE to NNW-SSE. At the footwall cutoffs of these intrarift faults, basement shallows to within ~700 m of the lake floor (~1100 m below lake surface datum), effectively isolating parts of the North Basin into discrete basins with limited stratigraphic continuity between them (Figs. 5 and 6). In the southern part of the North Basin, the intrarift extension focuses onto a single synthetic intrarift fault (Shillington et al., 2020). Although the border fault strikes NW-SE in the north and central parts of the basin, in the south part of the North Basin, it strikes N-S or NNW-SSE. The maximum synrift sediment accumulation of ~5.5 km observed in the south part of the basin is localized to a narrow region parallel to main basin border fault (Fig. 5). See Shillington et al. (2020) for a more detailed description of North Basin faulting.

The Livingstone fault continues onshore beyond the lake to the NNW for more than 50 km (Fig. 5), thus forming one of the longest rift segments in the East African Rift System (>170 km total length). Whereas most border faults in the East Africa rift accumulate maximum displacement near the fault centers (e.g., Rosendahl, 1987; Karp et al., 2012; Muirhead et al., 2019), the Livingstone fault exhibits a more complex subsidence pattern, with the deepest depocenter positioned where there is a
change in fault azimuth in the south-central part of the North Basin and the other at the northern tip of the lake (Fig. 5). The ~5 km of synrift sediment observed at the northernmost end of the North Basin within the lake also probably extends onshore, as suggested from reports of commercial seismic-reflection and potential field data collected during proprietary onshore studies (Thornton, 2015). Additional subsurface data from onshore areas north of the lake are required to fully evaluate the evolution of this major structure. However, the observed bimodal depocenter geometry is interpreted as produced by (1) major subsidence near the fault center (south-central main depocenter), as well as (2) by volcanic loading from the Rungwe Volcanic Province (see Discussion).

There is a considerable along-strike contrast in intrabasinal fault fabric from the central part of the North Basin to its southern end. In the north and central part of the basin multiple intrabasinal normal faults strike NNW-NW, and several of those are oblique to the Livingstone border fault. In the southern part of the North Basin, a single NNW-striking intrabasinal fault is parallel to the Livingstone border fault in this area, and may be better aligned with the regional extension direction (Shillington et al., 2020). The intrabasinal faults in the basin exhibit considerable relief on the modern lake floor, and the marked thinning onto the footwalls of these structures at all stratigraphic levels (e.g., Fig. 6) suggests this relief has been long-lived. Modern lake-floor channels that are confined by these faults extend more than 40 km (Ng’ang’a, 1993; Scholz, 1995) into the deeper parts of the North Basin, and the structures guided sediment into the deep part of the basin for much of its history.

**MCS Results—Accommodation Zone, North and Central Basins**

The linkage zone between the North and Central Basins accommodates strain resulting from the switch from a west-dipping border fault in the north, to an east-dipping border fault system on the west side of the Central Basin, where most strata dip to the west (Figs. 5–7). These two major facing border faults both strike ~N-S in this region and overlap by ~25 km (Accardo et al., 2018). The morphology of the accommodation zone between the Central and North Basins is a broad, deeply subsided, transverse fault-related fold (Schlische, 1995), with synrift sediments within the accommodation zone thinning to a minimum of ~3.5 km over the crest of the structure (Fig. 5B) (Accardo et al., 2018). The reduction in footwall relief at the southern end of the Livingstone Mountains fault allows the Ruhuhu River, draining the largest catchment in the rift, to deliver the largest volumes of water and sediment into the lake at this location (Wells et al., 1999). Wide-angle refraction data indicate an interval with velocities of 3.75–4.5 km/s below the synrift section; these velocities were interpreted to arise from pre-rift sediments (Accardo et al., 2018; Fig. 4).

**MCS Results—Central Basin**

The Central Basin extends for more than 150 km north to south, and is defined primarily by its faulted western coastline and border fault (Figs. 5A and 7). The maximum observed footwall relief along the coastline is 1300 m above the adjacent lake surface datum. Approximately 1200 line-km of 2015 and legacy seismic-reflection data are available to constrain the border fault and intrarift fault geometry in the Central Basin (Figs. 2 and 5). The maximum basin subsidence adjacent to the western border fault is ~5.5 km below the modern lake surface (Figs. 5A and 7), and MCS data show stratal dips to the west. Much less subsidence is observed along the eastern margin, with a maximum of 1.4 km below lake surface datum (Fig. 5A).

The western border fault system is composed of a primary fault that forms the Lake Malawi coastline
and an offshore submerged fault in the north positioned inboard of the primary coastal fault, forming a major relay ramp ~14 km wide and 48 km long, expressed on the lake floor as a platform in water depths of ~100–400 m (Fig. 5A and 7). The secondary border fault is recently active, with ~150 m of lake floor relief in some areas (Fig. 7).

Within the Central Basin along the rift axis is a series of connected, elongate, and in some areas, complexly deformed intrarift highs (Figs. 5A and 7). Synrift basement shallows to as little as 250 m below the lake floor in some areas of these highs (e.g., Figs. 5A and 5B), and the structures produce observable bathymetric relief (Fig. 2). Synthetic and antithetic intrarift normal faults with up to 1.5 km of basement relief form asymmetric horsts in some localities, whereas in other parts of the intrarift, high antithetic faults with varying degrees of displacement generate the basement relief (Figs. 5A and 7). Extending along the rift axis for more than 115 km, the intrarift highs confine the main sediment pathways to the western part of the basin, including focusing deep subaqueous channels (Soreghan et al., 1999). In the most deeply subsided part of the Central Basin, synrift basement is ~5.5 km below the lake surface datum, but this region of maximal subsidence is limited to a small fraction of the basin and positioned between the border fault and central intrarift high (Figs. 2 and 7).

Within the sedimentary section beneath the deep basin plain (Figs. 2, 5, and 7), where we observe maximum subsidence and sediment accumulation in this basin (Figs. 5A and 5B), a series of diapirs are observed; these diapirs extend upward through the sedimentary section to within ~300 m of the lake floor. Covering an area of ~130 km², the structures are generally reflection-free, with low-amplitude upper surfaces, and lack gas chimneys in the sections above them. Based upon seismic character and velocities comparable to what is observed in the synrift section, we interpret these structures as shale diapirs. A total of 13 diapirs are observed, each rooted in the middle or lower part of the sedimentary section (Fig. 7). Strata adjacent to individual diapirs thin next to each feature and overlying strata thin ~10% above each diapir (Fig. 7). Several diapirs are positioned adjacent to the intrarift high described above. At the southern end of the border fault system, where border fault displacement is diminished, the basin transitions from a zone of border-fault–focused extension and subsidence to zone of distributed extension across a series of mainly west-dipping intrarift normal faults where the lake is widest (~90 km).

Refraction velocities derived from lake-floor seismometers indicate a zone of velocities intermediate between the synrift sedimentary section and the inferred crystalline basement in several areas (Accardo et al., 2018). This section of intermediate velocities, ~3.75–4.5 km/s in the refraction data, is...
observed extending from the southeasternmost end of the North Basin, across the accommodation zone between the North and Central Basins, and into the northwestern part of the Central Basin (Accardo et al., 2018). Clear basal synrift reflections are observed in the North Basin and southern Central Basin, and this synrift “basement” in the North Basin is coincident with the velocity boundary described by Accardo et al., 2018. However, across the accommodation zone between the North and Central Basins, and in the deep parts of the northwestern and west-central parts of the Central Basin, well-defined synrift “basement” reflections are not observed. There we use the refraction velocity change to guide our interpretations of synrift basement on the MCS data. Notably, there is no change in reflectivity, no high-amplitude reflection, or stratal discordance observed between the synrift section and the deeper sediment package in northern Central Basin.

This zone of intermediate velocities is positioned adjacent to the Permo-Triassic Karoo Ruhuhu rift (Kreuser et al., 1990) on the east side of the lake (Fig. 3) and similar-aged rocks on the western margin of the lake (Yemane et al., 1989). Given the extent of these older rift deposits, we infer that an older rift sedimentary section is present at depth in Lake Malawi in this region, as proposed by Accardo et al. (2018). The lack of definitive synrift basement reflections in the deeper parts of the Central Basin MCS data prevents an unambiguous interpretation of the pre- or earliest-rift deposits. This limited imaging of deeper packages may be a consequence of steep stratal dips in many localities, stacked desiccation horizons produced during Pleistocene lake lowstands (Scholz et al., 2007; Lyons et al., 2015; Johnson et al., 2016), and/or a limited impedance contrast between the synrift and pre- or earliest rift sedimentary packages.

**MCS Results—Accommodation Zone, Central and South Basins**

The south end of the Central Basin, near the accommodation zone between the Central and South Basins, is a wide area of distributed extension, rather than a zone of narrowly focused subsidence observed over much of the basin, and

![Figure 7](image-url)

*Figure 7 Five pre-stack depth-migrated profiles from the Central Basin of the Lake Malawi Rift. West-dipping synrift fills are controlled by subsidence on the east-dipping border fault. Profile 86-820 reveals 10-15 km-wide relay ramp on the western margin where border fault strain is accommodated between both the onshore (coastal) border fault and the offshore border fault. All profiles show a series of interconnected intrarift highs, which, in many localities, have undergone complex deformation, not fully resolved in the 2D seismic data set. The western deep depocenter also hosts a series of diapirs interpreted as shale mobilization due to pronounced sediment loading and overpressure, in the confined main depocenter. The southernmost profile shows a broad zone of normal fault blocks characteristic of the distributed extension observed at the south edge of the Central Basin. This distributed strain may in part have occurred because of an along-strike gap between the Central and South Basin border faults, unlike the accommodation zone between the North and Central Basins that developed in part because of overlap of facing border faults.*
characteristic of much of the rift along strike. This zone of distributed extension corresponds with the widest part of Lake Malawi (~90 km). MCS profiles that image the broadly rifted region show a zone of eight intrarift normal faults, synthetic to the main basin-bounding fault, with as much as 1 km of vertical throw, and spaced ~2–8 km apart (Figs. 5 and 7). Several of these faults displace the modern lake floor, indicating ongoing extension in the area. All strata observed in this area of the southern part of the Central Basin dip W to NW, consistent with a westward-dipping domain of the entire 150-km-long Central Basin. The eastern lake shoreline (~11°–12°S) is characterized by a fault escarpment that rises ~1000 m above the lake surface, but the sub-basins in this region all dip westward away from this escarpment; this lakeshore fault therefore does not define a separate rift segment, in contrast to previous inferences based on onshore topographic analyses (e.g., Ebinger et al., 1987; Laõ-Dávila et al., 2015). We surmise this is instead relict relief that predates the latest phase of Malawi Rift extension. The linkage area between the Central and South Basins is a zone of relatively low relief. Rather than forming a broad apron and transverse fold, as in the case of the accommodation zone between the North and Central Basins, this accommodation zone forms a narrow graben with a maximum of ~3 km of sediment accumulation. Unlike the North Basin–Central Basin accommodation zone, where there is ~25 km of along-strike overlap, there is instead a gap of ~30 km between the Central and South Basin border-fault systems, which may further allow for a broadly extended region and a wide rift to develop in this area. Accordingly, this broadly rifted zone is a consequence of a segmentation linkage geometry of opposite-facing half-graben basins (e.g., divergent transfer zone of Morley et al., 1990) but with no overlap, and aspects of this geometry are consistent with some analogue models of orthogonal rifting (e.g., Paul and Mitra, 2013).

MCS Results and Interpretation—South Basin

Approximately 1400 line-km of legacy seismic-reflection data are available to constrain the southern part of the Malawi Rift (Figs. 2, 5, and 8). SEGMeNT seismic-reflection and refraction data were not acquired in this part of the rift; profiles are widely spaced (~10 km or more, Fig. 2), and the velocity constraints are limited to reflection data sets here, compared to the Central and North rift segments. Accordingly, this part of the lake was examined using only legacy Project PROBE data sets, including those recently reprocessed.

The South Basin is the longest dip domain in the rift and extends from the area just north of Likoma Island southward 300 km beyond the southern end of the lake (e.g., Jackson and Blenkinsop, 1997) (Fig. 2). Most extension is accommodated by a series of linked border faults observed just offshore of the eastern shoreline (Figs. 5 and 8), rather than defined by faulted coastlines with high rift shoulders, as is the case with the two northern rift segments (Fig. 5). Maximum subsidence below datum in the South Basin is 4.5 km (Fig. 8). The maximum sediment accumulation in the South Basin of 4 km is observed in a localized area adjacent to the eastern border fault (see Fig. 8, profiles 87-948 and 87-956), although accumulations in the long, linear depocenters are typically on the order of 2 km (Fig. 5B). Unlike the southern end of the Central Basin, the main west-dipping, synthetic intrarift faults are limited in the South Basin, with maximum throws of 1.3 km, and are best observed on Profile 86-844 and on adjacent

Figure 8. Four pre-stack depth-migrated seismic profiles from the South Basin of Lake Malawi. These profiles, along with the basement structure contour map (Fig. 5A), show the comparatively simple offshore intrarift fault fabric of that basin. Note that the linked faults that form the border fault system are offset from the coastline, which in most localities is not defined by high rift shoulder escarpments as is the case of the Central and North Basins of the lake.
profiles (e.g., Fig. 8). At the southern end of the South Basin, the lake bifurcates into western and eastern arms (Fig. 2). The main zone of extension and fault-associated subsidence is located along a fault that defines the western arm (Figs. 5A and 8), and includes a foothill on the Cape Maclear peninsula (Fig. 2). The eastern arm of the lake holds a maximum of ~950 m of synrift sediments, although synrift fill is typically <500 m. The lake’s western arm contains a maximum of 1.9 km of synrift fill. Whereas large escarpments up to ~600 m above the lake surface are located adjacent to the southeastern arm of the lake (Fig. 5A), stratal dips in the southernmost part of the lake are to the east, consistent with the overall easterly dip domain that characterizes this southern segment.

Balanced Section Restorations and Extension Estimates

Area-balanced restorations of depth-converted seismic profiles coupled to regional digital elevation models allow assessment of total upper-crustal extension and schematic basin evolution over time. We use stratal surfaces identified in the seismic data and following previous work (Scholz et al., 1989; Flannery and Rosendahl, 1990; Lyons et al., 2011) to provide constraints on the area balance for the synrift section. In the North Basin, profile 15-002 is positioned near the center of the basin, near the area of maximum basement subsidence; across this profile we measure 7.0 km of total extension (Fig. 9A, ~89.1 km present-day length, compared to ~82.1 km restored length).

In the Central Basin, we restore profile 15-262, positioned E-W at the south-central part of the basin. This is the area that has experienced the maximum observed subsidence in the Central Basin, and accordingly represents the maximum values of extension in this part of the Lake Malawi Rift. Three stratal surfaces are restored, including the 1.3 m.y. surface representing the approximate base of the 2005 scientific drill hole in Lake Malawi, a deep unconformity surface between the Nyasa and Baobab sequences (Flannery and Rosendahl, 1990), and the interpreted synrift basement surface (Fig. 9B). This restoration yields a total extension of 6.7 km expressed over an original profile length of 83.5 km.

In the South Basin, profile 87-956 was restored using a similar approach as above. Notably the lowermost depositional sequence observed in the Central Basin is not observed in the South Basin (Flannery and Rosendahl, 1990), and accordingly that step is not included here. This restoration (Fig. 9C) uses an original regional line length of 53 km, and the restoration yields an extension value of 3.7 km, with most extension accommodated by the eastern margin border fault.

Lineament Analyses

The orientations of lineament trends in basement terranes identified in the 30-m SRTM DEM are presented as rose plots for the different rift segments (Fig. 10). All observed lineaments within 75 km of Lake Malawi are located within the Ubendian-Usagaran, Irumide, South Irumide, Txitonga, and Unango basement terranes (e.g., Fig. 3). Our data suggest that two dominant fabrics are present at a regional scale within these terranes, trending NW-SE and NNE-SSW. These prevailing lineament trends also exhibit a north to
southern transition. The North Basin is dominated by the NW-trending fabric, the Central Basin exhibits a primary NNE-trending and secondary NW-trending fabric, and NNE-trending lineaments prevail in the South Basin. These regional-scale, basement fabric trends are also locally observed in aeromagnetic and field data sets. For example, field measurements of fractures, foliations, and shear zones in Ubendian-Usagaran Belt rocks in the uplifted footwall of the Rukwa border fault and in the Karonga region of the North Basin dominantly trend NW-SE (Ring, 1994; Wheeler and Karson, 1994; Kolawole et al., 2018). These lineaments also parallel magnetic lineaments from aeromagnetic surveys on the western side of the North Basin in the Irumide terrane (Laõ-Dávila et al., 2015; Dawson et al., 2018; Kolawole et al., 2018), the latter of which are interpreted to represent the steeply dipping foliations of the 550–580 Ma Mughese shear zone (Ring, 1994; Dawson et al., 2018). Based on these associations, it appears that the Precambrian terranes that form the basement rocks of the Malawi Rift and catchment bedrock retain the expression of original discrete structures and penetrative fabrics that are observable on a landscape scale through digital elevation models. Therefore, we make the simple assumption that these linear surface features are controlled by inherited crustal fabrics and thus can shed light on the influence of preexisting structures on rift fabric when compared with our newly mapped faults.

**DISCUSSION**

Extension and Segmentation of the Malawi Rift

Previous studies characterized the Lake Malawi Rift as broken into numerous discrete rift segments (Ebinger et al., 1987; Specht and Rosendahl, 1989; Laõ-Dávila et al., 2015), mainly upon the basis of fault scarps identified on digital elevation models. However, in the absence of extensive subsurface information, those studies were limited in their capacity to fully characterize deep fault structure and fault-driven stratal dip domains and thickening that are representative of tectonic extension and subsidence over the life history of the rift. New reflection and reprocessed legacy seismic-reflection data, combined with velocity information from a wide-angle seismic data, necessitate a revised segmentation model for the Malawi Rift, based upon stratal dips, intrarift normal fault fabric, and synrift sedimentary fill. We observe that three major border-fault systems accommodate most subsidence and extension in the Malawi Rift (Figs. 5–8 and 11), producing three distinctive dip domains within the lake. Although separated into subbasins in some areas by synthetic intrarift faults or intrarift basement highs, the dip domains have the general form of three large half-graben basins with limited sediment accumulations on the flexural or shoaling margins. Limited subsidence and extension is observed adjacent to escarpments on the eastern margin of the rift in Mozambique and southern Tanzania (Figs. 5A and 5B), which were previously interpreted as border faults (Ebineger et al., 1987). Whereas the observed onshore escarpments other than the border faults may be active zones of deformation today, the offshore subsurface data presented here suggest that over the
full, time-averaged history of the rift, those other escarpments played limited roles in accommodat-
ing extension.

Structural restorations of pre-stack depth-mi-
gated profiles from the three major rift segments described above confirm that the Lake Malawi Rift is a low-strain region of EARS, and our analyses produce values broadly consistent with prior estimates (Ebinger et al., 1987; Specht and Rosendahl, 1989) though with better precision on account of use of depth versus time seismic sections informed by previously unavailable velocity constraints. The structural balancing of the PSDM profiles also shows a progressive reduction in the absolute amount of extension, with values of 70, km, 6.7 km, and 3.7 km observed in the North, Cen-
tral, and South Basins, respectively. The estimates of diminished amounts of upper-crustal extension in the southern segment are consistent with modern geodetic observations, where average plate velocities diminish from ~2.2 mm/yr in the north to 1.4 mm/yr in the southern part of the rift (Saria et al., 2014). The stratigraphic sequence architecture of the respective basins, with the deepest sequence apparently missing in the South Basin (Flannery and Rosendahl, 1990), and the overall thinner syn-
 rift section in the south (Figs. 5, 11, and 12), is also consistent with interpretations of a younger rift to the south. This simple progression fits the observed data, though because of the presence of a deeper sequence in the Central and North Basins, we cannot rule out a lengthier and/or much earlier phase of extension in the Malawi Rift such as is documented in Rukwa (e.g., Roberts et al., 2012) or Turkana (e.g., Ragon et al., 2019). The South Basin synrift fill has not been drilled and dated. However, by analogy with the deep Lake Malawi Drilling Project Central Basin drill site, which has an age of 1.3 million years at the core base (380 m subbottom; Lyons et al., 2015), we estimate a likely Pliocene maximum age for the oldest sediments in the South Basin. The amount and distribution of brittle deformation from this study broadly agree with what is known about bulk crustal extension. Receiver functions and velocity models based on wide-angle seism-
ic data indicate modest crustal thinning focused beneath the basins of the Malawi Rift, with little

Volcanic Loading and Anomalous Subsidence

in North Basin

In addition to the primary depocenter in the south-central part of the North Basin, immediately adjacent to the Livingstone Basin (Shillington et al., 2020), an anomalously thick accumulation of
sediment is observed in the MCS data at the northern tip of the North Basin, and is also observed in refraction data (see line 86-802, Fig. 6, and northernmost tip of North Basin structure-contour and sediment thickness maps, Fig. 5; Accardo et al., 2018). The observed thickening and apparent increase in tectonic subsidence toward the northern border fault tip appears counterintuitive, given that fault throw profiles are classically elliptical, with maximum throw at the fault center and tapering to zero at the fault tips (Walsh and Watterson, 1988; Dawers, 1993). Sediment accumulation toward the northern end of this basin may either be (1) a consequence of local volcanic loading in this area from the ~2950-m-high Rungwe volcano, which has a summit situated ~84 km northwest of this zone of localized subsidence, or (2) an anomalous and asymmetric displacement profile along the border fault, with significant fault displacement at its northern tip. As discussed below, this region of increased sediment accumulation theoretically sits within the zone of flexural subsidence for the Rungwe volcano, and thus we favor the former explanation.

In the Virunga Province (Rwanda and Democratic Republic of Congo), volcanic loading is estimated to have produced greater than 1 km of subsidence in the Kivu rift (Wood et al., 2017), even for conservative values of the volcanic load (e.g., 1-km-high edifices). Turcotte and Schubert (2014) show that the area of subsidence for an elastic plate impacted by a vertical load will be determined primarily by the thickness ($T_e$) and elastic properties ($E$, $v$) of the subsiding elastic layer. Using relations in Turcotte and Schubert (2014) and elastic properties from Shillington et al. (2020) ($T_e = 38$ km, $E = 2–4$ Gpa, $v = 0.25$), the estimated distance from the summit of Rungwe volcano to the flexural forebulge (i.e., radius of the subsiding region) is calculated to range between 78 and 93 km and extends into the northernmost part of the North Basin, thus supporting the potential role of volcanic loading in enhancing local subsidence at the northern end of the Malawi Rift (see also Supplemental Document, Section 8: Analysis of Rungwe Volcanic Load).

**Influence of Preexisting Structures**

Numerous studies have considered the influence of preexisting structures in rifts, from the...
We observe the North Basin and northern part of the Central Basin (Accardo et al., 2018). However, we use new constraints on the architecture of the Malawi Rift and preexisting lineaments to evaluate the influences of two major preexisting structures that crosscut the rift at accommodation zones and of basement fabric in Proterozoic terranes on border faults and intrarift faults. The two main accommodation zones and segment linkage zones in the Malawi Rift coincide with major ancient terrane boundaries: the Mwembeshi Shear Zone crosses the rift between the Central and South Basins of the lake, and the Karoo Rift crosses the rift at the accommodation zone between the North and Central Basins. The observation of an extensive deep zone of intermediate velocity strata in southern part of the North Basin and northern part of the Central Basin provides the first direct evidence that earlier rift deposits (Karoo and Cretaceous–early Cenozoic rift deposits) may underlie the Malawi Rift (Fig. 4, Accardo et al., 2018). From the MCS data presented here alone, it is not clear if those ancient structures offer a mechanistic control on rift segmentation; determining the roles of these older structures requires further assessment of lower crust and mantle anisotropies to assess the pervasiveness of trends observed in the upper crust. The consistently long border faults bounding the three segments suggest that the dominant control on segmentation is lithospheric strength (Ebinger et al., 1991). However, crosscutting structures may have exerted a secondary control. The skewed offset profile on the Livingstone fault may be partially explained by pinning the lengthening of the Livingstone fault by the Ruhuhu Basin (Shillington et al., 2020).

The independently derived refraction results are consistent with a deep sedimentary section in the southeastern edge of the North Basin, the accommodation zone between the North and Central Basins, and the northwestern part of the Central Basin (Accardo et al., 2018). However, we observe no marked amplitude anomalies, unconformities, or stratal dip contrasts between the synrift deposits and the lower sedimentary packages (e.g., Fig. 7). Notably, basement reflections are absent or unclear in this part of the basin compared with other parts of the Malawi Rift (see seismic profiles on Fig. 7). Although the MCS imaging is limited below ~4 km depth, the sequences observed in our data are apparently stratigraphically conformable. This would suggest that the main border faults in North and Central Basins may have very long life spans, although it seems unlikely that those structures could have been operative since the Mesozoic. An earlier episode of rifting at 25 Ma is proposed for another part of the western branch, the Rukwa Rift (Robertson et al., 2012), and the deep “pre-rift” sediment package inferred here and in Accardo et al. (2018) could be of this age.

Lineament analyses of Precambrian bedrock terranes reveal no significant alignment with main basin border faults, except at the northern part of the North Basin of the rift, which is recognized in previous studies (Wheeler and Karson, 1989; Ring, 1994; Lao-Davila et al., 2015; Dawson et al., 2018; Kolawole et al., 2018). Whereas deep-seated crustal or mantle anisotropies may indeed govern the locations and evolution of the large border faults, we see no reason to interpret a direct relationship between the older structures and fabrics (e.g., fractures, foliations, and shear zones) and primary structures (i.e., border faults) accommodating extension across much of the basin.

In contrast, preexisting structures could contribute to the considerable variability in intrarift faulting along strike of the rift. Where the main basin border faults strike N-S, orthogonal to modeled regional extension direction (Stamps et al., 2008; Saria et al., 2014), generally one or two primary intrarift faults are observed within each segment. However, two major zones with multiple intrarift faults are observed, suggesting markedly more distributed strain. These zones include (1) the southern part of the Central Basin, close to the accommodation zone with the South Basin near the widest part of the Malawi Rift, and (2) in the northern and central parts of the North Basin, where the border fault strike distinctly NW-SE (Shillington et al., 2020). The distributed strain observed in the latter may partially be a response to the oblique orientation of the rift in this area with respect to the regional extension direction (Saria et al., 2014; Shillington et al., 2020).

Controls on Sediment Pathways

The thickness of sedimentary fill of each rift segment is mainly controlled by the degree of strain accommodated on the main basin border faults, and thick regions of synrift fill are located in relatively narrow zones, 10–20 km wide, adjacent to each border fault (Fig. 5B). Intrarift faults and highs in the North and Central Basins are paramount for orienting sediment delivery systems into deep basins within the rift. In the case of the Central Basin, the confinement of axial channels, both during high lake stages and past low lake intervals (Soreghan et al., 1999; Scholz et al., 2007; Lyons et al., 2015) were important for focusing sediments into the deepest sumps in each basin. The intrarift structures were likely established early in the histories of these rift segments (e.g., McCartney and Scholz, 2016) and consequently are responsible for much higher sediment delivery to localized and most deeply subsided parts of the rift. The deeply subsided parts of the Central Basin are areas of much higher rates of sediment accumulation (Figs. 5B and 7); we speculate that excess sediment load in this confined region also may result in over-pressure (e.g., Swarbrick et al., 2002; Marin- Moreno, 2012), which has mobilized fine-grained siliciclastic strata into shale diapirs (Fig. 7). These narrow axial sedimentary troughs close to the border faults within each rift segment are also the likely areas where synrift lacustrine source rocks may accumulate and be buried to sufficient depths to generate hydrocarbons. Whereas the modern lake covers nearly the entire rift valley, during dry intervals in the Pleistocene, it was repeatedly confined to those narrow depocenters (e.g., Scholz et al., 2007; Lyons et al., 2015; Johnson et al., 2016). The evidence for very thick but narrow troughs presented here suggests that the asymmetric lake basin morphology was established early in the history of the rift, and
since the Miocene, those zones served as arid inter- 
val refugia for the lake’s unique evolving faunas.

**CONCLUSIONS**

- Intrarift structures, border-fault displacements, and half-graben, synrift fill patterns suggest that the Lake Malawi Rift consists of three pri- 
mary dip domains or rift segments. The main 
segment linkage areas or accommodation 
zones show distinctly different morphologies 
that may be a consequence of the distinctive 
overlap geometries between the main border- 
fault systems.

- Intrarift normal fault populations show con- 
siderable along-strike variability in spatial 
density, basement displacements, lake-floor 
and near lake-floor displacements, as well 
as orientations relative to basin-bounding 
faults. Although synthetic faults dominate 
the intrarift population, antithetic structures 
combine with synthetic structures to form 
prominent intrarift highs in the Central Basin.

- Restoration of pre-stack depth-migrated 
profiles shows a weakly extended rift with 
diminished amounts of extension from north 
to south. Sediment thickness diminishes con- 
siderably to the south, and the age of the 
basalt stratigraphic packages is much less than 
to the north, all consistent with a progression of 
extension toward the southern part of the rift.

- No direct evidence of sills, dikes, or magmatic 
extrusives is indicated in the multichannel 
seismic data from the Lake Malawi Rift. How- 
ever, at the northern tip of the rift, we observe 
anomalously deep pre-rift basement and 
anomalously thick synrift sedimentary 
packages. In other parts of the rift, border faults 
show classical elliptical along-strike displace- 
ment geometries, with most subsidence and 
sediment loads at the centers of the border 
fauls. The observed basement geometry in 
the far north is consistent with flexural sub- 
sidence of the elastic plate due to a volcanic 
load emplaced at the Rungwe volcano, with 
the flexural forebulge predicted to range from 
78 to 93 km from the volcano center.

- Lineament analyses of Precambrian bedrock 
terranes reveal no significant alignment with 
main basin border faults, except at the northern 
tip of the North Basin of the rift, but intrarift 
fauls are generally well aligned with lineament 
trends on the rift flanks. Whereas the intrarift 
structures accommodate much less extension 
than what has accumulated on the basin border 
fauls, the intrarift faults may be controlled by 
the ancient Proterozoic structural trends.

- Synrift sediments are concentrated in relatively 
10–20-km-wide depocenters in each 
half-graben rift segment and are positioned 
shortly after the main basin border faults. The 
restriction of the thick sediment packages to the 
border-fault margins in each basin has import- 
ant implications for hydrocarbon prospectivity 
in the basin, because it suggests relatively 
narrow regions for hydrocarbon source-rock 
maturation, relative to the full expanse of the 
rift and lake. Moreover, the limited extent of 
intrarift geometry plays an important role in orienting 
anticlines and lake morphometry during past 
arid intervals, which would have had profound 
impacts on endemic aquatic faunas in the basin.

- Intrarift faults that strike parallel to the bor- 
der faults and the rift axis show considerable 
basement and lake-floor displacements in the 
North and Central Basins. This axial fault 
geometry geometry plays an important role in orienting 
siliciclastic sediment delivery into the deep 
parts of the North and Central Basins, result- 
ing in excess sediment loading and possibly 
overpressure, which have produced shale dia- 
pirs in the deepest part of the Central Basin 
of the Lake Malawi Rift. Nearly all the normal 
fauls observed in Lake Malawi seismic-reflection 
records are rooted in the basement.

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