Strain Localization and Migration During the Pulsed Lateral Propagation of the Shire Rift Zone, East Africa

Folarin Kolawole[1,1], Travis Vick[2,2], Estella A Atekwana[3,3], Daniel A Laó-Dávila[4,4], Aristides Costa[2,2], and Brett M Carpenter[2,2]

[1]BP Exploration
[2]University of Oklahoma
[3]University of California, Davies
[4]Oklahoma State University

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Abstract

We investigate the spatiotemporal patterns of strain accommodation during multiphase rift evolution in the Shire Rift Zone (SRZ), East Africa. The NW-trending SRZ records a transition from magma-rich rifting phases (Permian-Early Jurassic: Rift-Phase 1 (RP1), and Late Jurassic-Cretaceous: Rift-Phase 2 (RP2)) to a magma-poor phase in the Cenozoic (ongoing: Rift-Phase 3 (RP3)). Our observations show that although the rift border faults largely mimic the pre-rift basement metamorphic fabrics, the rift termination zones occur near crustal-scale rift-orthogonal basement shear zones (Sanangoe (SSZ) and the Lurio shear zones) during RP1-RP2. In RP3, the RP1-RP2 sub-basins were largely abandoned, and the rift axes migrated northeastward (rift-orthogonally) into the RP1-RP2 basin margin, and northwestward (strike-parallel) ahead of the RP2 rift-tip. The northwestern RP3 rift-axis side-steps across the SSZ, with a rotation of border faults across the shear zone and terminates further northwest at another regional-scale shear zone. We suggest that over the multiple pulses of tectonic extension and strain migration in the SRZ, pre-rift basement fabrics acted as: 1) zones of mechanical strength contrast that localized the large rift faults, and 2) mechanical 'barriers' that refracted and possibly, temporarily halted the propagation of the rift zone. Further, the cooled RP1-RP2 mafic dikes facilitated later-phase deformation in the form of border fault hard-linking transverse faults that exploited mechanical anisotropies within the dike clusters and served as mechanically-strong zones that arrested some of the RP3 fault-tips. Overall, we argue that during pulsed rift propagation, inherited strength anisotropies can serve as both strain-localizing, refracting, and transient strain-inhibiting tectonic structures.

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Kindly contact Folarin Kolawole (folarin.kol@gmail.com or f.kolawole@columbia.edu) with any feedback that you may have.

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Folarin Kolawole[1,2]*, Travis Vick[3,4], Estella A. Atekwana[5], Daniel A. Laó-Dávila[6], Aristides G. Costa[3], and Brett M. Carpenter[3]

[1]BP Exploration, Houston, TX 77079
[2]Lamont-Doherty Earth Observatory at Columbia University, Palisades, NY 10964
[3]School of Geosciences, University of Oklahoma, Norman OK 73019
[4]Department of Geophysics, Colorado School of Mines, Golden, CO 80401
[5]Department of Earth and Planetary Sciences, University of California, Davis, CA 95616
[6]Boone Pickens School of Geology, Oklahoma State University, Stillwater, OK 74078

Corresponding Author: folarin.kol@gmail.com

Key Points:

- Multiphase rifting in the Shire Rift Zone (SRZ) transitioned from earlier magma-rich phases (RP1 & 2) to the currently active magma-poor phase (RP3)
- Surface and subsurface data suggest a pulsed lateral SRZ propagation with transient rift-tip stagnation at/near rift-orthogonal basement shear zones
- Inherited intra-basement structures served as both strain-localizing and temporary strain-inhibiting tectonic elements during the rift propagation

Keywords: Continental extension, Multiphase rifting, Strain localization, Strain migration, Structural inheritance

Abstract

We investigate the spatiotemporal patterns of strain accommodation during multiphase rift evolution in the Shire Rift Zone (SRZ), East Africa. The NW-trending SRZ records a transition from magma-rich rifting phases (Permian-Early Jurassic: Rift-Phase 1 (RP1), and Late Jurassic-Cretaceous: Rift-Phase 2 (RP2)) to a magma-poor phase in the Cenozoic (ongoing: Rift-Phase 3 (RP3)). Our observations show that although the rift border faults largely mimic the pre-rift basement metamorphic fabrics, the rift termination zones occur near crustal-scale rift-orthogonal basement shear zones (Sanangoe (SSZ) and the Lurio shear zones) during RP1-RP2. In RP3, the RP1-RP2 sub-basins were largely abandoned, and the rift axes migrated northeastward (rift-orthogonally) into the RP1-RP2 basin margin, and northwestward (strike-parallel) ahead of the RP2 rift-tip. The northwestern RP3 rift-axis side-steps across the SSZ, with a rotation of border faults across the shear zone and terminates further northwest at another regional-scale shear zone. We suggest that over the multiple pulses of tectonic extension and strain migration in the SRZ, pre-rift basement fabrics acted as: 1) zones of mechanical strength contrast that localized the large rift faults, and 2) mechanical 'barriers' that refracted and possibly, temporarily halted the propagation of the rift zone. Further, the cooled RP1-RP2 mafic dikes facilitated later-phase deformation in the form of border fault hard-linking transverse faults that exploited mechanical anisotropies within the dike clusters and served as mechanically-strong zones that arrested some of the RP3 fault-tips. Overall, we argue that during pulsed rift propagation, inherited strength anisotropies can serve as both strain-localizing, refracting, and transient strain-inhibiting tectonic structures.

1 INTRODUCTION

The extensional deformation and break-up of the continental lithosphere often occur over multiple phases of stretching (Keep and McClay, 1997; Bergh et al., 2007; Mohriak and Leroy, 2013; Bell et al., 2014; Phillips et al., 2019a). Multiphase rifts may experience a rotation in extension direction between the different phases, leading to the geometrical modification of the earlier-established fault systems (Duffy et al., 2017; Bell et al., 2014; Henstra et al., 2015). Also, multiphase rifts commonly show evidence of complex patterns of spatial migration of strain and depocenters between the different phases, associated with the abandonment and later reactivation of the early rift faults, and/or creation of new fault systems (Ebinger et al., 2000; Bell et al., 2014; Brune et al., 2014; Ford et al., 2017; Fazlikhani et al., 2020). These processes facilitate the overall progressive growth of multiphase rift basins by the deepening, lengthening, and/or widening of the basin, demonstrated by an increase in the extent of the deformation.

As continental extension initiates, rift basins may attain significant width and length during the earliest phase of extension (e.g., Modisi et al., 2000; Rotevatn et al., 2018) and crustal strength properties may influence the lateral propagation of the rift tip (Van Wijk and Blackman, 2005). However, the recurrence of extension with prolonged inter-rift periods or decreased stretching rates could heal the mantle-lithosphere, and facilitate depocenter abandonment and migration of strain to an outboard zone of unrifted crust (e.g., Braun, 1992; Naliboff and Buiter, 2015). This outward migration of the crustal deformation leads to a progressive enlargement of the brittle deformation field, with associated crustal subsidence and rift-related sedimentary and/or volcaniclastic accumulation (Mohriak and Leroy, 2013; Naliboff and Buiter, 2015; Ford et al., 2017; Gawthorpe & Leeder, 2000).

Here, we examine the longstanding question of how evolving continental rifts propagate over multiple phases of tectonic extension, especially in the case of juvenile (stretching stage; low beta factor) rift settings. We explore this problem in the Shire Rift Zone (SRZ), East Africa (Figure 1a), which is one of the basins that experienced all the known phases of Phanerozoic extensional tectonics that affected the region. The NW-trending SRZ is located between the southern tip of the Malawi Rift, the Lower Zambezi Rift, and Urema Graben, and extends

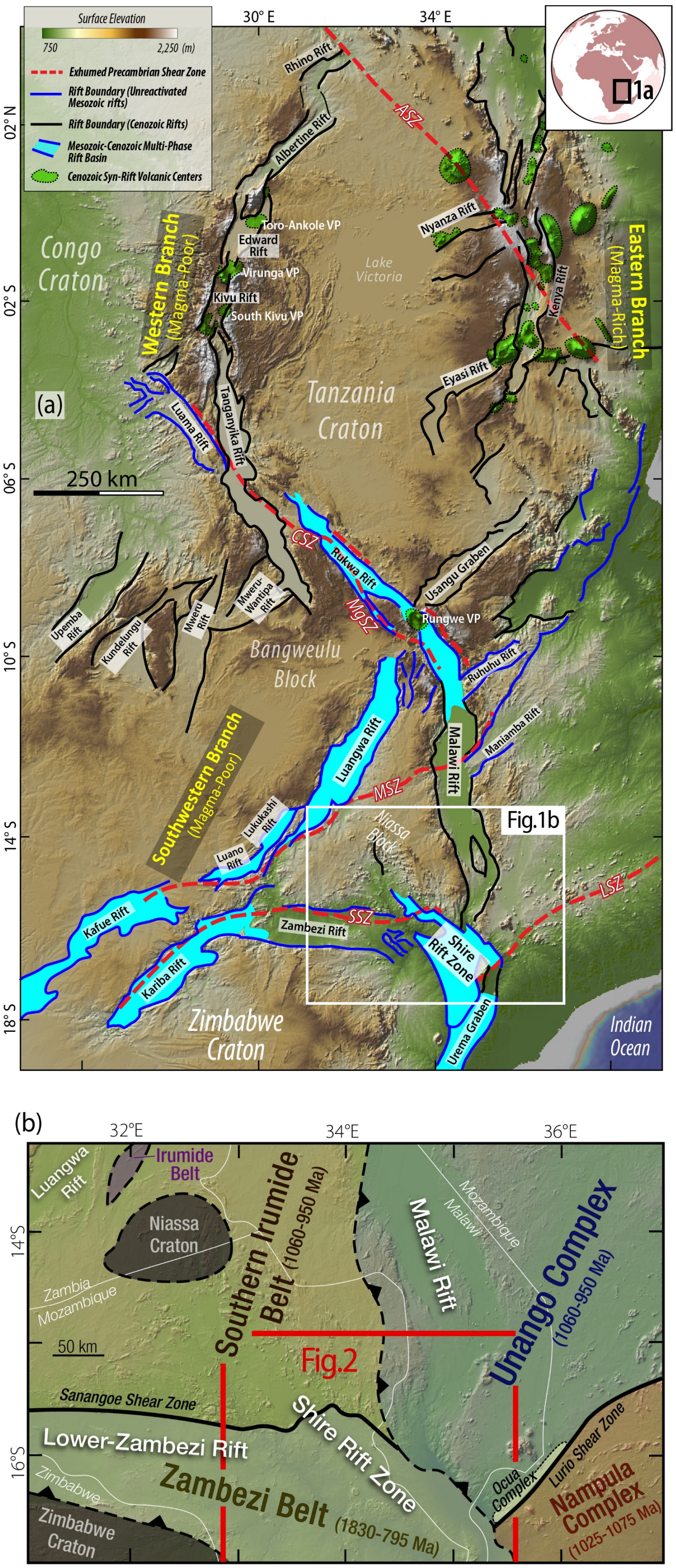

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Figure 1. Regional tectonic setting. (a) Global Multi-resolution Topography (GMRT) digital elevation model (DEM) hillshade map of Eastern Africa showing the various segments of the East African Rift, and major Precambrian basement shear zones in the region (modified after Daly et al., 1989, Castaing, 1991; Delvaux, 1989; Fritz et al., 2013; Heilman et al., 2019). ASZ: Aswa Shear Zone, CSZ: Chisi Suture Zone, LSZ: Lurio Shear Zone, MgSZ: Mughese Shear Zone, MSZ: Mwembeshi Shear Zone, SSZ: Sanangoè Shear Zone. The blue polygons extend across rift segments with records of multiphase (Mesozoic-Cenozoic) extension and are not indicative of the part of the rift that was active during a particular phase of extension. GMRT source: Ryan et al. (2009). The GMRT base map is obtained from GeoMapApp. (b) Generalized map of the Precambrian basement terranes in the region of the Shire Rift (modified after Hargrove et al., 2003; Westerhof et al., 2008; Fritz et al., 2013). Although there is no clearly defined single shear zone separating some of the tectonic blocks (as indicated by dashed black lines), the Sanagngoe and Lurio shear zone terrane boundaries are well defined and constrained in field studies (Barr and Brown, 1987; Bingen et al., 2009). Sawtooth pattern on dashed lines indicates thrust relationship between the flanking terranes or basement blocks (after Westerhof et al., 2008).

across the political boundaries of Malawi and Mozambique (Figure 1b). The rift zone, which developed within an exhumed Precambrian metamorphic crystalline basement (Figure 2), exhibits excellent surface exposure of rift fault escarpments (Figure 3a), the pre-rift intra-basement fabrics along the rift margins (Figures 3b-c), and multiphase syn-rift sedimentary sequences within the rift basin and hanging walls of the rift-bounding faults (Figures 3a, 3d-e).

We integrate field structural measurements, aeromagnetic data, digital elevation model (DEM) hillshade maps, and published field and borehole data to investigate multiphase rifting in the SRZ. Our study presents an updated structure of the rift zone, highlighting the patterns of strain migration and how the rift transitioned from magma-rich rifting into magma-poor rifting over three phases of tectonic extension. Also, the study presents evidence suggesting that pre-rift crustal structures (and those inherited in earlier rift phases) may influence rift evolution by playing the contrasting roles of 1.) weak, exploitable structures that promote strain localization, and 2.) resisting structures that transiently arrest or refract the lateral propagation of rift segments and associated faults.

2 GEOLOGICAL SETTING

Eastern Africa has experienced multiple phases of extensional tectonic deformation in the Phanerozoic Eon (e.g., Delvaux, 1989; Castaing, 1991; Chorowicz, 2005). These rifting phases include the Permian – Early Jurassic (Karoo) rifting event herein referred to as rift-phase 1 (RP1), a Late Jurassic - Cretaceous rifting event (rift-phase 2, RP2), and the current Cenozoic phase of tectonic extension known as the ‘East African Rift System’ (rift-phase 3, RP3). Some of the RP1 basins, among which is the SRZ, were reactivated during RP2, and again reactivated in RP3 (Figure 1a; Delvaux, 1989; Castaing, 1991; Daly et al., 2020). The SRZ is a NW-trending rift basin, flanked to the north by the N-trending Malawi Rift, to the west by the E-trending Zambezi Rift, and to the south by the NNE-trending Urema Graben (Figure 1a). Although the SRZ has been included as part of the Malawi Rift in some older literature (e.g., Ebinger et al., 1987), following Castaing (1991), we distinguish the SRZ and its sub-basins based on the distinct NW-SE trend of their border faults, onlapping syn-rift sequences, and the basement-highs at the zones of interaction between the rifts (Kolawole et al., 2021b). Each of the flanking rift segments, excluding the Urema Graben, are separated from the SRZ by a zone of exposed or shallowly-buried pre-rift basement, distinguishing the SRZ as a distinct tectonic element in the region (Castaing, 1991; Kolawole et al., 2021b).

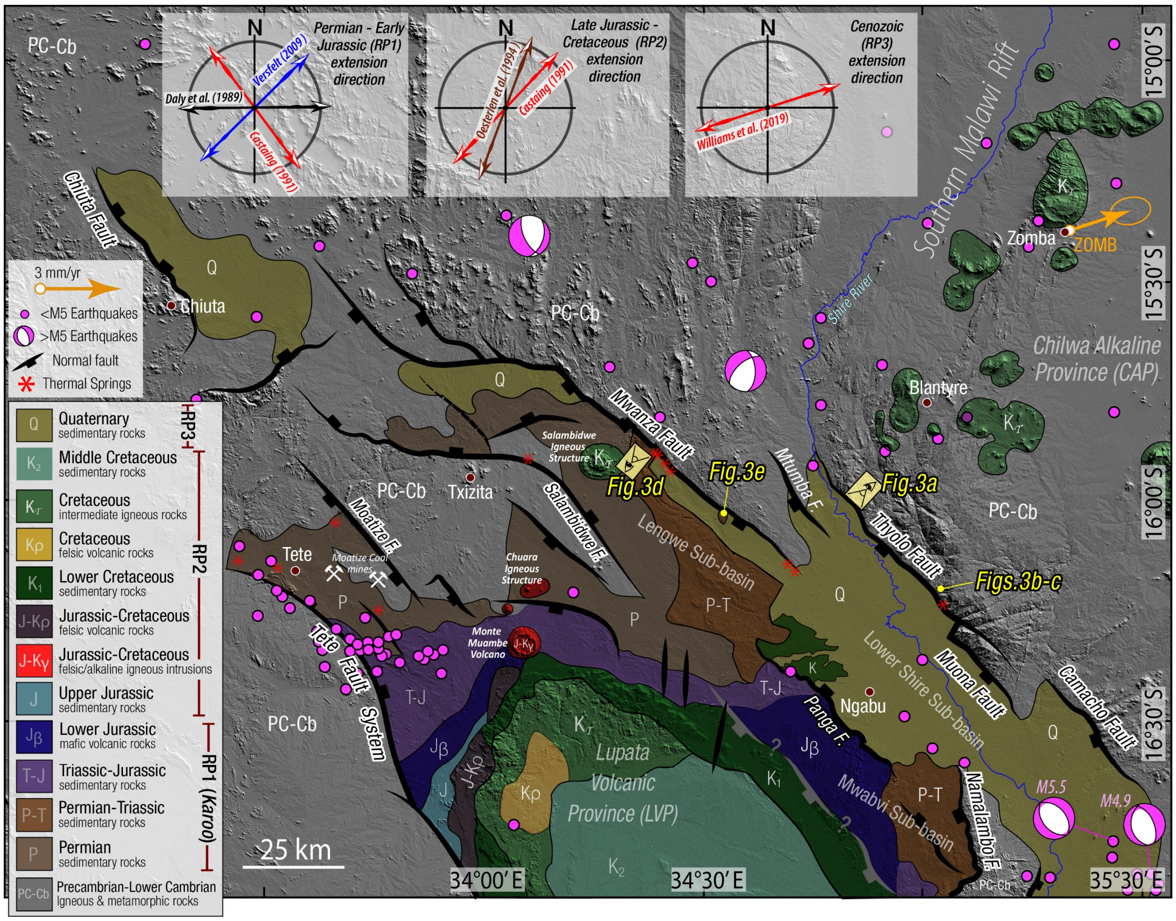


Figure 2. Geologic setting of the Shire Rift Zone. (a) Geologic Map of the Shire Rift Zone overlaid on Shuttle Radar Topography Mission (SRTM) digital elevation model. The map is compiled from Cooper and Bloomfield (1961), Habgood et al. (1963), Habgood (1973), Choubert et al., (1988), Bennett (1989), Castaing (1991), Chisenga et al. (2018), Nyalugwe et al. (2019a). *Top insets* show the inferred RP1 and RP2 regional extension directions from previous studies (Daly et al., 1989; Castaing, 1991; Oesterlen and Blenkinsop, 1994; Versfelt, 2009). The RP3 regional extension direction (Williams et al., 2019) was calculated from earthquake focal mechanism inversion. The orange arrow (ZOMB) represents the RP3 GNSS vector and velocity solution (with 95% uncertainty ellipse) for southern Malawi, from Stamps et al. (2018). Thermal springs are from Procesi et al. (2015), Njinju et al. (2019b), and Addison et al. (2021). Earthquakes are compiled from United States Geological Survey earthquake catalog, Williams et al. (2019), and Stevens et al. (2021). Note that seismicity in the Tete region is associated with coal mining operations in the Moatize coal mines Stevens et al. (2021).

2.1 The Pre-Rift Precambrian Basement

The SRZ extends along the tectonic boundaries separating four distinct Precambrian mobile belts and terranes (Figure 1b), which include the Southern Irumide Belt (1060 - 950 Ma), Zambezi Belt (1830 - 795 Ma), the Unango Complex (1060 - 950 Ma), and the Nampula Complex (1025-1075 Ma) (Hargrove et al 2003; Fritz et al., 2013). These mobile belts are composed of Paleoproterozoic-Mesoproterozoic crust which has been reworked and overprinted by contractional structures and igneous intrusions of the Neoproterozoic Pan African Orogeny. Overall, the mobile belts are dominated by schists, amphibolite and granulitic gneisses, and deformed granites, granodiorites, syenites, gabbro, and anorthosites (e.g., Figures 3b-c; Barr and Brown, 1987; Fritz et al., 2013).

Several field studies have revealed the presence of prominent crustal- and lithospheric-scale shear zones and sutures separating these basement terranes. These shear zones include the E- to ENE-trending Sanangoe Shear Zone (SSZ) separating the Southern Irumide Belt and Zambezi Belt (e.g., Barr and Brown, 1987; Kröner et al., 1997; Evans et al., 1999; Westerhof et al., 2008), and the NE-trending Lurio Shear Zone (LSZ) (Bingen et al., 2009; Sacchi et al., 2000; Westerhof et al., 2008) which defines the boundary between the Unango and Nampula Complexes (Figures 1a-b). The SSZ deformation is a 3 - 8 km wide zone of thrust duplexes and associated cataclasites (Barr and Brown, 1987), defining a crustal-scale south-dipping thrust boundary between two Proterozoic basement terranes: 1) the Tete Province to the south, within which the E- to ENE-trending gneisses, pelitic schists, and quartzites have been pervasively intruded by gabbroic plutons and anorthosites of the Tete Complex, and 2) the Luia Group Terrane to the north, which hosts gneisses, granulites and Charnockites (Barr and Brown, 1987; Evans et al., 1999). Based on the regional clustering patterns of deformed Proterozoic and Mesozoic alkaline rocks and carbonatites, it was inferred that the SRZ exploited a Late Proterozoic suture zone (Burke et al., 2003).

2.2 Multiphase Phanerozoic Rifting

The SRZ, which extends ~264 km along-strike and ~134 km in width (maximum width in the southeast), is defined by an area of fault-bounded syn-rift sedimentary and volcaniclastic sequences (Figure 2). The rift zone has undergone three distinct phases of

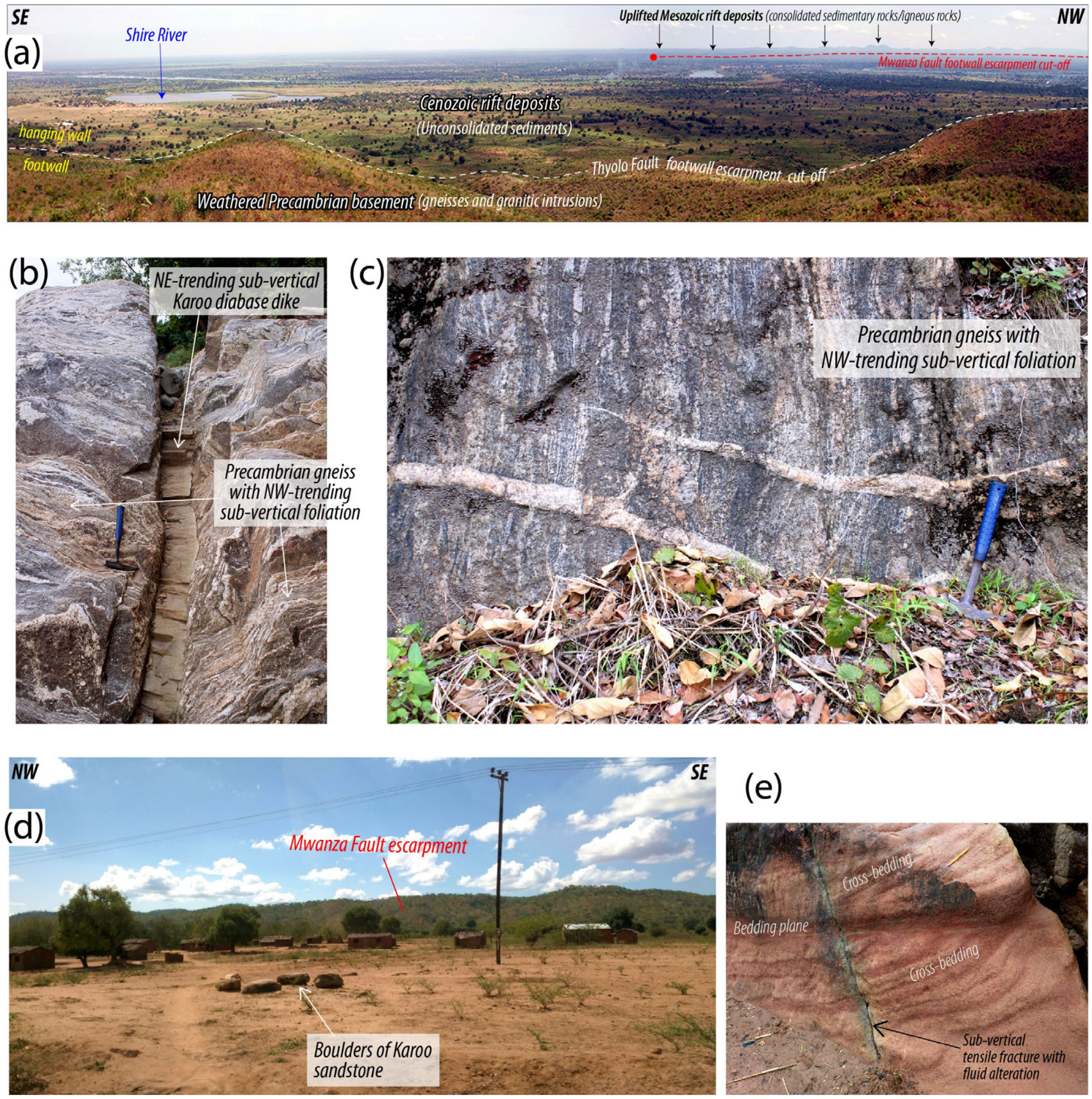


Figure 3. (a) Landscape photograph overlooking the Lower Shire River valley of the Shire Rift, looking southwest from the top of the Thyolo Fault escarpment (see location in Figure 2a). (b - c) Outcrops of Precambrian gneissic basement along the footwall of the Thyolo Fault showing NW-trending sub-vertical foliation. In Figure 3c, a sub-vertical NE-trending Jurassic diabase dike crosscuts the metamorphic foliation of the Precambrian gneiss host rock. (d) Landscape photograph looking northeast from the hanging wall of the Mwanza Fault. (e) Photograph of Karoo sandstone outcrop in the hanging wall of the Mwanza Fault. Also, see the locations of Figures 3b-e in Figure 2.

extension in post-Precambrian times (Figure 2; Castaing, 1991). The first episode of rifting (RP1), popularly known as the "Karoo" rifting episode, began in the Permian and ended in the Lower Jurassic (Castaing, 1991; Delvaux, 1989). This initial phase of extension established large >150 km-long basin-bounding master faults (border faults) which include the SW-dipping Mwanza and Namalambo Faults to the northeast and a NE-dipping fault system (herein referred to as the 'Tete Fault System') to the southwest (Figure 2; Castaing, 1991). The early phase syn-rift fill is dominated by sedimentary sequences deposited in sub-basins defined by grabens and half grabens (Figures 2, 3d-e; Habgood, 1963; Choubert et al., 1988; Castaing, 1991). Among these RP1 sub-basins, only the Lengwe and Mwabvi domains have been studied in detail due to the widespread outcrops of the syn-rift units in Southern Malawi (Figure 2; Habgood, 1963; Castaing, 1991). RP1 was concluded by the emplacement of igneous centers and diabase dike swarms across the basin in the Early Jurassic, known as the Stormberg vulcanicity (e.g., diabase dike in Figure 3b; Habgood et al., 1963, 1973; Woolley et al., 1979). Studies of RP1 rifting in the region inferred contrasting orientations of regional extension direction (Figure 2 insets). Versfelt (2009) and Daly et al. (1989, 1991) proposed an E- to NE-extension direction, based on a broad kinematic interpretation of regional transtension driven by north-directed far-field compression from the south during the Gondwanide Orogeny (Daly et al., 1991; Trouw and De Wit, 1999). Whereas Castaing (1991) inferred a NW-extension direction, based on the presence of NE-trending Late RP1 Stormberg dike swarm in the Shire Rift Zone, assuming a dike-orthogonal dilatant opening direction (e.g., Fig. 3b).

The second phase of extension (RP2) was relatively short-lived, occurring between the Middle Jurassic and the Cretaceous (Castaing, 1991). RP2 extension was associated with the reactivation of the RP1 faults, voluminous expulsion of volcanic material and relatively minor clastic deposition and are well-documented in the southwestern (Lupata Volcanic Province, LVP), southeastern (Mwabvi sub-basin), and northeastern parts of the basin (Salambidwe Igneous Structure in the Lengwe sub-basin) (Castaing, 1991; Choubert et al., 1988). The magmatic activities also extended into areas outboard of the basin, particularly the Chilwa Alkaline Province (CAP; Figure 2; Cooper and Bloomfield, 1961; Nyalugwe et al., 2019a). The Cretaceous-age dikes are alkaline in composition with a set trending NE and another set trending NW (Castaing (1991). Although the stress inversion of slickenside striations obtained along major faults in the Lengwe and Mwabvi sub-basins show a 'post-Karoo' NE-SW mean extension direction, assuming a dike-orthogonal dilatant opening direction, Castaing (1991) proposed an initial minor NW-extension, but dominant NE-extension direction for RP2. Based on strain analysis of slickenside striations and fault plane orientations in Late RP1 and RP2 syn-rift units within the nearby Zambezi Rift (see Fig. 1a), Oesterlen and Blenkinsop (1994) inferred an NNE-regional extension direction.

The third phase of extension (RP3) is associated with the currently active East African Rift System. In the region of the SRZ, RP3 is thought to have begun in the Late Tertiary (Delvaux, 1989) or Quaternary (Castaing, 1991), and is associated with localized deposition of Quaternary sediments in the Lower Shire Valley of southern Malawi (Figures 2 and 3a; Castaing, 1991; Chisenga et al., 2019) and the Chiuta area of Mozambique (Figure 2; Choubert et al., 1988; Castaing, 1991). Although the RP1 and RP2 tectonic extension in the SRZ were associated with widespread volcanism (magma-rich rifting), RP3 is non-magmatic. The Quaternary Lower Shire depocenter (also known as “Shire Graben” or “Lower Shire Graben”) is bounded to the east by a system of SW-dipping normal faults which consist of the Thyolo (Figure 3a), Muona, and Camacho Faults, and to the west by the Panga Fault (Figure 2). The Panga Fault is interpreted to have initially developed within the hanging wall of the Mwanza border fault during RP1 but had been reactivated in post-RP1 times marked by the brecciation of a Late RP1 dolerite dike contained within the fault zone (Habgood, 1963; Castaing, 1991). In the Chiuta area, which is the northwesternmost sub-basin in the SRZ, the west-bounding fault, herein referred to as “the Chiuta Fault”, represents the border fault in this part of the rift zone (Figure 2).

The SRZ exhibits a thinned lithosphere and elevated heat flow relative to the rift flanks (Njinju et al., 2019a, 2019b). The RP3 regional extension direction is ENE- to E-W and is responsible for several recent >Mw4 earthquakes in the basin (Figure 2; Williams et al., 2019). Geodetic velocity solutions for the region show strain rates of ~2.2 mm/yr (Figure 2; Stamps et al., 2018; Wedmore et al., 2021), and a geomechanical analysis shows that the RP3 eastern border faults are favorably oriented for reactivation in the regional stress field (Williams et al., 2019). Although the broad geologic history of the SRZ has been identified in previous studies (Habgood, 1963; Castaing, 1991), the major structural domains and associated structural elements, the patterns of strain localization and migration, and mechanics of rift propagation over its multiphase history remain unknown.

3 DATA AND METHODS

We integrated field observations from this study and previous studies, digital elevation model (DEM) hillshade maps, intra-basinal borehole penetration logs, and aeromagnetic data to generate an updated tectonic and structural framework for the SRZ, allowing us to evaluate its multiphase rifting history.

To create an updated geologic map of the SRZ, we compile published geological maps (Cooper and Bloomfield, 1961; Habgood, 1973; Habgood et al., 1963; Choubert et al., 1988), which document field observations of the surficial geology across the rift basin and surrounding areas. The compilation allows us to constrain the rift-related lithological units and the spatial extents of the sub-aerial exposures and locations of juxtaposition against the Precambrian basement. We integrated the published legacy geologic maps with subsurface data from borehole penetrations (where available in the basin) and observations from aeromagnetic fabric patterns beneath the rift basin deposits.

To provide an updated fault map of the rift zone, we first compiled fault lineaments from the legacy geologic maps and previous studies in various parts of the rift (Choubert et al., 1988; Castaing, 1991; Chisenga et al., 2018; Wedmore et al., 2020). These previous studies mostly mapped faults from surface topographic scarps and outcrops but lack information on the buried fault segments. Also, the mapping of potential buried faults from linear gradients in a bouguer gravity grid covering the Malawi part of the basin (Chisenga et al., 2018) is subject to the low resolution of the gravity data and lacks geological constraints. To update the fault maps, we delineated additional fault segments using the vertical derivative of the available aeromagnetic grids across the basin (Figures S1a-c). Although our fault mapping mostly consists of buried faults and buried extensions of exposed faults interpreted from filtered aeromagnetic maps, we also interpreted additional surface-breaking fault segments from topographic hillshade maps (see Figure S2). Below, we provide the details of the field data collection, borehole data, and aeromagnetic datasets, and data analysis techniques used in the study.

3.1 Field Data

We conducted a field campaign in the Malawi part of the SRZ, covering the footwall and hangingwall areas of the Thyolo-Muona and Mwanza border fault systems (Figures 3a-e). In the exposures of the pre-rift gneissic basement along the footwalls of the rift border faults, we collected field measurements of the strike and dip of the metamorphic basement fabrics (i.e. foliation; n=39 along Mwanza Fault's footwall, and n=229 along Thyolo-Muona Fault's footwall). Along the footwall of the Thyolo-Muona Fault, where Mesozoic diabase dike intrusions are ubiquitous across the basement (e.g., Figure 3b), we collected field measurements of the strike and dip of the dikes where possible (n=50). We present the 3-dimensional (3D) structural datasets as equal-area stereographic projections of poles to planes with 2-interval Kamb contours. We augment our field measurements along the Thyolo-Muona Fault's footwall with datasets previously collected by the Geological Survey of Malawi and published in Habgood et al. (1973). The Geological Survey of Malawi structural dataset consists of strike/dip of gneissic foliation (n=191), and map-view traces of diabase dikes which we digitized and from which we automatically extracted 2,086 strike measurements of dike segments using ArcMap.

3.2 Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM)

In the less-studied sub-basins of the Shire Rift Zone, in combination with aeromagnetic data (see section 3.5), we utilized 1 arc-second (30 m spatial resolution) Shuttle Radar Topography Mission (SRTM) DEM hillshade maps to delineate surface traces of normal faults. In areas where the aeromagnetic data used in this study is of lower resolution (e.g., NW and SE termination zones of Shire Rift), we mapped the topographic lineaments in the DEM hillshade maps of basement exposures as supporting independent data on the trends of the basement metamorphic fabrics.

3.3 Aeromagnetic Data

For the mapping of buried fault segments, dikes, and buried volcanic centers, and the modeling of the depth-to-magnetic basement, we utilize two aeromagnetic datasets: a lower resolution (2 km spatial resolution) regional grid covering the entire basin (both the Malawi

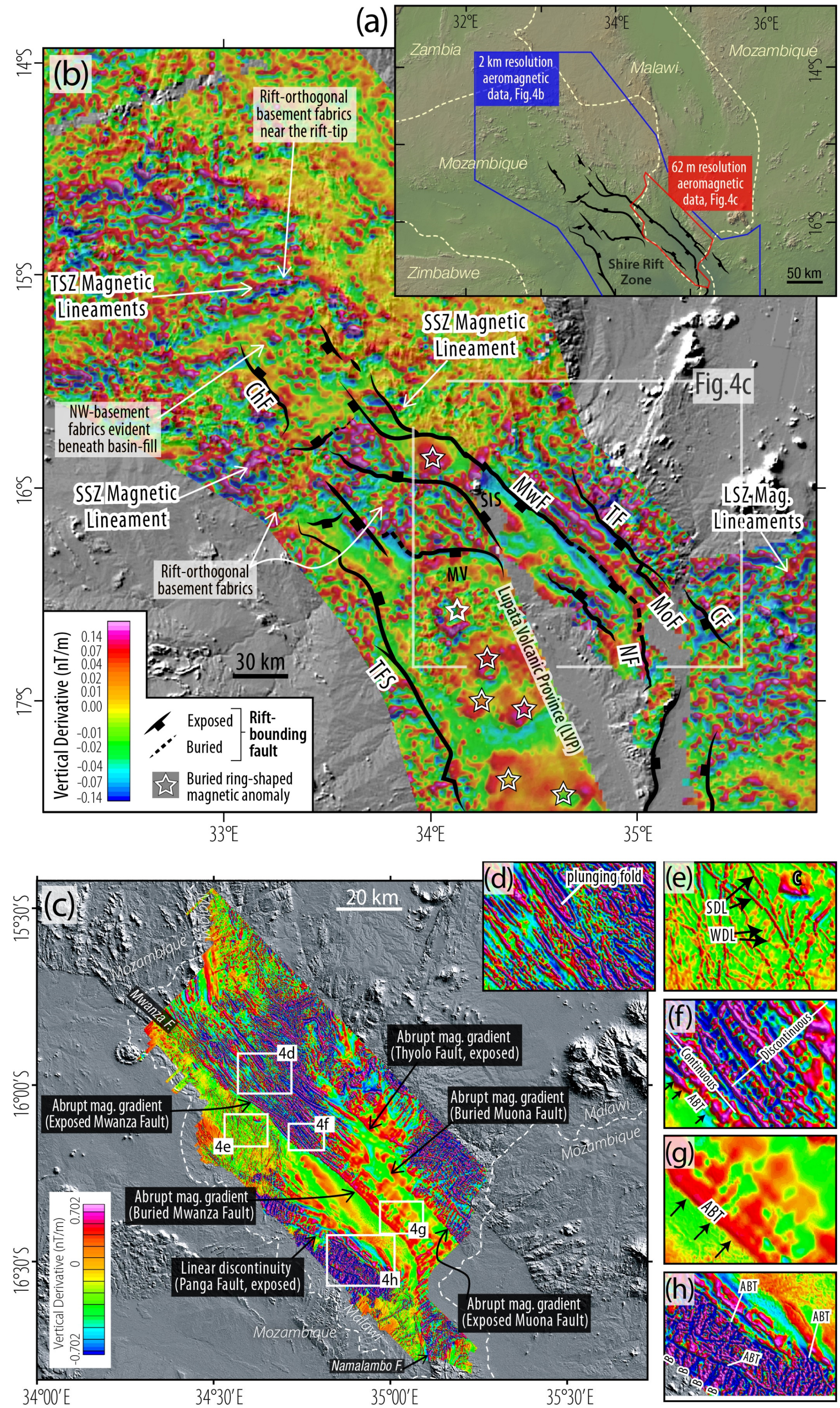

(a)
32°E
34°E
36°E
14°S
16°S
Zambia
Malawi
Mozambique
Mozambique
Zimbabwe
2 km resolution aeromagnetic data, Fig.4b
62 m resolution aeromagnetic data, Fig.4c
Shire Rift Zone
50 km
(b)
14°S
15°S
16°S
17°S
Rift-orthogonal basement fabrics near the rift-tip
TSZ Magnetic Lineaments
SSZ Magnetic Lineament
Fig.4c
NW-basement fabrics evident beneath basin-fill
ChF
SSZ Magnetic Lineament
SIS
MwF
TF
LSZ Mag. Lineaments
Rift-orthogonal basement fabrics
MV
Lupata Volcanic Province (LVP)
MoF
CF
NF
TFS
30 km
Vertical Derivative (nT/m)
0.14
0.07
0.04
0.02
0.01
0.00
-0.01
-0.02
-0.04
-0.07
-0.14
Exposed
Buried
Rift-bounding fault
Buried ring-shaped magnetic anomaly
33°E
34°E
35°E
(c)
15°30'S
16°00'S
16°30'S
20 km
Mozambique
Mwanza F.
4d
Abrupt mag. gradient (Thyolo Fault, exposed)
Abrupt mag. gradient (Exposed Mwanza Fault)
4e
4f
Abrupt mag. gradient (Buried Muona Fault)
Malawi
Mozambique
Abrupt mag. gradient (Buried Mwanza Fault)
4g
Vertical Derivative (nT/m)
0.702
0
-0.702
Linear discontinuity (Panga Fault, exposed)
4h
Abrupt mag. gradient (Exposed Muona Fault)
Mozambique
Malawi
Namalambo F.
34°00'E
34°30'E
35°00'E
35°30'E
(d)
plunging fold
(e)
SDL
WDL
(f)
Continuous
Discontinuous
ABT
(g)
ABT
(h)
ABT
ABT
ABT
B
B
B
B

Figure 4. Aeromagnetic datasets. (a) Regional hillshade topography map (same as Fig. 1b) showing the coverage of the aeromagnetic datasets used in the study. (b) 1st vertical derivative of the regional-scale pole-reduced aeromagnetic grid (2 km spatial resolution) covering the Shire Rift and surrounding areas. CF: Camacho Fault, ChF: Chiuta Fault, LSZ: Lurio Shear Zones, MoF: Muona Fault, MV: Monte Muambe Volcano, MwF: Mwanza Fault, NF: Namalambo Fault, SIS: Salambidwe Igneous Structure, SSZ: Sanangoe Shear Zones, TSZ: Techigoma Shear Zone. The delineation of the shear zones (LSZ and SSZ) is constrained by field observations in Barr and Brown (1987); Sacchi et al. (2000), Kroner et al. (1997), Bingen et al. (2009), Fritz et al. (2013). (c) 1st vertical derivative of the higher-resolution pole-reduced aeromagnetic grid (62 m spatial resolution) covering only the Malawi part of the rift basin. Salient aeromagnetic fabric patterns observable in the high-resolution aeromagnetic map include: (d) Broad clusters of parallel, elongate magnetic fabrics in the exposed basement (i.e. basement metamorphic foliation). (e) Cross-cutting discrete magnetic-high lineaments enclosed by magnetic-low anomalies (i.e. mafic igneous dikes in sedimentary strata). 'SDL': Strong discrete lineament (shallow dike), 'WDL': Weak discrete lineament (deep-seated dike), 'C': Discrete magnetic-high ring-shaped anomaly (ring intrusion or sill?). (f) Mesh pattern fabrics in the exposed basement (i.e. metamorphic foliation overprinted by cross-cutting mafic dikes). (g) Mesh pattern fabrics in the buried basement (i.e. buried part of the basement exposed in Figure 3f). (h) Compact linear bands of chaotic magnetic fabrics (i.e. exposed or shallowly buried mafic volcanic deposits). The fabric becomes diffused northeastward as the depth of burial of the volcanic flows increases. 'B': compact band, 'ABT': abrupt magnetic gradient (i.e. normal fault). See Figures S1a-c for unfiltered and uninterpreted versions of the aeromagnetic grids. The unfiltered total magnetic intensity grids of these vertical derivative maps are in supplementary figures S1a-c.

and Mozambique sections) and surrounding areas (Figures S1a-b, 4a-b), and a higher resolution (62 m spatial resolution) grid covering only the Malawi section of the basin (Figures S1c, 4a, and 4c). The regional dataset (Figure S1a) consists of a grid of merged aeromagnetic field data acquired in the 1970s and 1980s from countries in southern Africa (source: South Africa Development Community, SADC aeromagnetic data, provided by Council for Geoscience, South Africa). This regional data includes a legacy Malawi aeromagnetic grid which has a resolution of ~250 m spatial resolution and was acquired in 1984/1985 with a 120 m terrane clearance and 1 km-spaced NE-SW flight lines (Figure S1b; Kolawole et al., 2018). The 62 m-resolution Malawi aeromagnetic data (Figure S1c) was acquired in 2013 (source: Geological Survey Department of Malawi; Nyalugwe et al., 2019b) with 80 m terrane clearance along NE-SW lines with a line spacing of 250 m.

3.4 Borehole Data

To investigate the subsurface stratigraphy in the RP3 Lower Shire Sub-basin, we assessed available lithologic logs from borehole penetrations below the Quaternary sediments, which are documented in Habgood (1963) and Habgood et al. (1973) (Figure S3a-b). There is no known documentation of well penetration beneath the Quaternary sediments in the RP3 Chiuta Sub-basin. Therefore, to infer the dominant basin fill of the Chiuta Sub-basin, we relied on published surficial geologic maps, aeromagnetic fabric analysis, and lateral variations in DEM hillshade surface roughness patterns across the sub-basin.

3.5 Structural Interpretation from Aeromagnetic Data

Although structural deformation is commonly expressed as 'abrupt' gradients in aeromagnetic grids, the distinct magnetic character and expressions of basement-rooted fault traces, cross-cutting mafic dike intrusions, dike-intruded fault zones, and exhumed metamorphic terrane fabrics can be distinguished (Jones-Cecil et al., 1995; Modisi et al., 2000; Kinabo et al., 2007, 2008; Grauch & Hudson, 2007; Kolawole et al., 2018; 2017; Heilman et al., 2019). The total magnetic intensity (TMI) aeromagnetic data is a grid of magnetic anomalies produced by a combination of the magnetic susceptibility of the sources, the depth to the top of the magnetic sources, and the steepness of the contacts between distinct magnetic bodies [e.g., Grauch & Hudson, 2007, 2011]. However, due to the vertical offset and lateral juxtaposition of layers of strongly contrasting magnetic properties across steep fault planes, derivative-filtered aeromagnetic grids can resolve both buried and surface-breaking normal faults that offset the primary magnetic units. Similarly, the lateral alternation of mafic and felsic mineral banding in gneissic rocks (metamorphic basement fabrics), and mafic dikes cross-cutting gneissic basement are resolvable by derivative aeromagnetic grids which allows the delineation of their large-scale trends (Kinabo et al., 2007, 2008; Kolawole et al., 2018; Heilman et al., 2019; Lemna et al., 2019). Thus, the aeromagnetic datasets covering the SRZ allow us to delineate the rift-related faults (sub-aerial and subsurface), buried and sub-aerial magmatic structures (dikes and ring-shaped intrusions), and pre-rift basement fabrics within the Shire Rift and along its margins.

However, before structural interpretation, we first pole-reduced (RTP) the total magnetic intensity (TMI) aeromagnetic datasets to correct for the skewness of the magnetic field due to the proximity of the study area to the equator (Baranov, 1957; Arkani-Hamed, 1988). Here, we preferred RTP correction over equator-reduction (RTE) because the RTP correction produced a grid with better alignment of fault-related gradients with their geologic sources in areas where the surface breaking fault traces provide geologic constraints (see Kolawole et al., 2018). After RTP correction, we applied a vertical derivative filter to the TMI-RTP data to better resolve the structure-related gradients in the grids (Figures 4b-h) (e.g., Ma et al., 2012; Kolawole et al., 2017; 2018; Heilman et al., 2019). Following a systematic characterization of the aeromagnetic patterns observable in the 2013 Malawi aeromagnetic grid (Figures 4d-4h), we identified distinct patterns herein referred to as 'aeromagnetic facies', which allow a better interpretation of the structural character of the associated magnetic sources. To assess the orientation of basement foliation and mafic dikes in the SRZ, independent of the collected field measurements (see section 3.1), we digitized and measured the trend of the aeromagnetic anomaly lineaments corresponding to the structures constrained by published geologic map of the basement structures (Habgood et al., 1973). In the Mozambique part of the SRZ where a lower-resolution aeromagnetic data is available (Figure S1), we supplemented aeromagnetic mapping with the digitization and trend measurement of topographic lineaments representing basement fabrics.

Further, we calculated the frequency-azimuth distribution of the measured lineament trends within the relevant segments of the rift zone. For multimodal distributions, we divided the data into their modal sets using the frequency minima. For both unimodal and multimodal plots, we calculated the circular vector mean and 95 % confidence interval for the modal sets using the method of Mardia and Jupp (2009). Note that the magnitude of the confidence interval is dependent on the number of sample data used. All frequency-azimuth plots present in this study are area-weighted.

3.6 Estimation of Depth-to-Magnetic Basement

Along the SRZ, we estimated the depth-to-magnetic basement in two sub-basins where a widespread accumulation of Quaternary-age sediments is most widespread and prominent. These sub-basins are in the Chiuta Fault hanging wall and the Lower Shire Graben (Thyolo-Muona Fault hanging wall) with extensions into the Mwanza Fault hanging wall (Figure 2). In the Chiuta area, which is in Mozambique, we utilized the available 2 km-resolution regional aeromagnetic grid (Figures S1a and 4b). Whereas, in the Lower Shire Graben, located in Malawi, we utilized the original (unmerged) Malawi part of the legacy regional grid (Figure S1b). Our preference for the unmerged legacy Malawi aeromagnetic grid for source-depth estimation is due to its moderate resolution and suppression of high-frequency noise (e.g., related to intra-sedimentary mafic dikes).

To perform an automatic calculation of depth-to-the top of the magnetic basement, we used the Source Parameter Imaging™ (SPI™) transform of the aeromagnetic grid (Thurston and Smith, 1997; Smith et al., 1998). The SPITM technique assumes a step-type source model and produces spatially distributed source depth-solutions that are independent of magnetic declination, inclination, strike, dip, and remanent magnetization. The transform first computes the tilt derivative, and the total horizontal gradient of the tilt derivative (local wavenumber, K). For a step source model, the Kmax-1 represents the depth to the magnetic source where Kmax is the peak value of the local wavenumber based on a simple Blakely test (Blakely and Simpson, 1986). Following standard practice, to minimize the noise from shallow sources, we applied a Hanning filter to the K grid before calculating the source depths. The gridding of the depth solutions assumes a 2-layer model such the SPI map represents the average depth to the top of the shallowest magnetic basement. Source depth estimations from aeromagnetic data generally have an accuracy of about ±20 % (Gay, 2009), thus, they provide a coarse approximation of lateral variation of depth to the top of the magnetic basement beneath the rift sedimentary deposits.

4 RESULTS

4.1 Structural Compartmentalization of the Shire Rift Zone (SRZ)

The updated fault map of the SRZ (Figure S2), integrated with the existing geologic map of the basin (Figure 2), provides information on the structure and sub-basinal compartmentalization of the rift zone. The large-scale rift architecture is defined by a NW-trending basin that bifurcates northwestwards into two 20-25 km-wide grabens, both of which are bound by large fault systems (Figure 5a). Based on the distribution and ages of rift-related sedimentary and volcaniclastic units within the confines of these faults (Figure 2), we identify seven sub-basins (Figure 5b). These sub-basins include five magmatic sub-basins: Lengwe, Mwabvi, Moatize, Monte-Muambe, and Lupata, which host RP1 and RP2 volcano-sedimentary sequences; and two non-magmatic sub-basins: Lower Shire and Chiuta where widespread RP3 Quaternary sedimentary cover is localized (Figures 2 and 5b). The

Lupata Sub-basin hosts a major Mesozoic volcanic zone, the Lupata Volcanic Province (LVP). The LVP and the Salambidwe Igneous structure define the main intra-rift igneous zones, and the Chilwa Alkaline Province (CAP) defines an off-rift syn-rift igneous province.

Basin-scale rift-orthogonal topographic profiles (profiles P1 to P3; Figures 5a-b) show that the most-prominent topographic-highs in the SRZ are the southwestern and northeastern flanks of the Chiuta Sub-basin, the Salambidwe Igneous Structure, the eastern flank of the Lengwe Sub-basin, and the eastern flank of the Lower Shire Sub-basin. However, the escarpment height of the border fault zones (Figures 5c-e) is largest in the southwestern margin of the Chiuta Sub-basin (~696 m) and in the northeastern margin of the Lower Shire Sub-basin (~708 m), and smallest in the northern margins of the Lengwe Sub-basin (<200 m) and the southwestern margin of the Lupata Sub-basin (66 m). Along the entire rift, the border faults with the greatest escarpment height are the Chiuta Fault and the Thyolo-Muona Fault system.

At the northwestern tip of the SRZ (Chiuta Sub-basin), the rift morphology defines a graben geometry in which the basin asymmetrically tilts gently westwards towards the Chiuta border fault (profile P1, Figure 5c). At the central part of the rift zone (profile P2, Figure 5b), the rift morphology highlights the western and eastern rift bifurcations (Moatize and Lengwe Sub-basins), separated by a basement block, which we herein refer to as 'the Txizita Horst' (after 'Txizita town' in Figure 2). In the southeast, the SRZ is widest, defined by a ~134 km-wide basin in which the western and central areas (Lupata and Mwabvi Sub-basins) are elevated relative to the far eastern areas (Lower Shire Sub-basin) (profile P3, Figure 5c). Although the Quaternary sediments of the Lower Shire Sub-Basin onlap the Mesozoic sequences in the Lengwe and Mwabvi Sub-basins, a major boundary between the Mwabvi and Lower Shire is marked by the NE-dipping Panga Fault such that the Mwabvi is in the SW and Lower Shire in the NE. The surface morphology of the Lower Shire Sub-basin reflects a graben morphology in which the basin asymmetrically tilts eastwards towards the Thyolo-Muona-Camacho border fault system. However, all the aeromagnetic grids over the Lower Shire Graben (e.g., Figures S1a-c) and depth-to-basement map (see section 4.2.1) show that this sub-basin is further compartmentalized into a deeper SW section and shallower NE section by the buried southeastern continuation of the Mwanza Fault

4.2 Subsurface Structure of the Active Sub-Basins in the Shire Rift Zone

In the SRZ, the sub-basins that host widespread accumulations of Quaternary sediments are inferred to be active in the current phase of rifting in eastern Africa. Although the most prominent of these sub-basins are the Lower Shire and Chiuta Sub-basins (Figure 2), we also note that the northern and southern Lengwe Sub-basin show evidence of partial reactivation (see partial Quaternary sediment cover in Figure 2). An understanding of the first-order subsurface structure of the two prominent RP3 sub-basins is critical for elucidating the multiphase evolution of the SRZ.

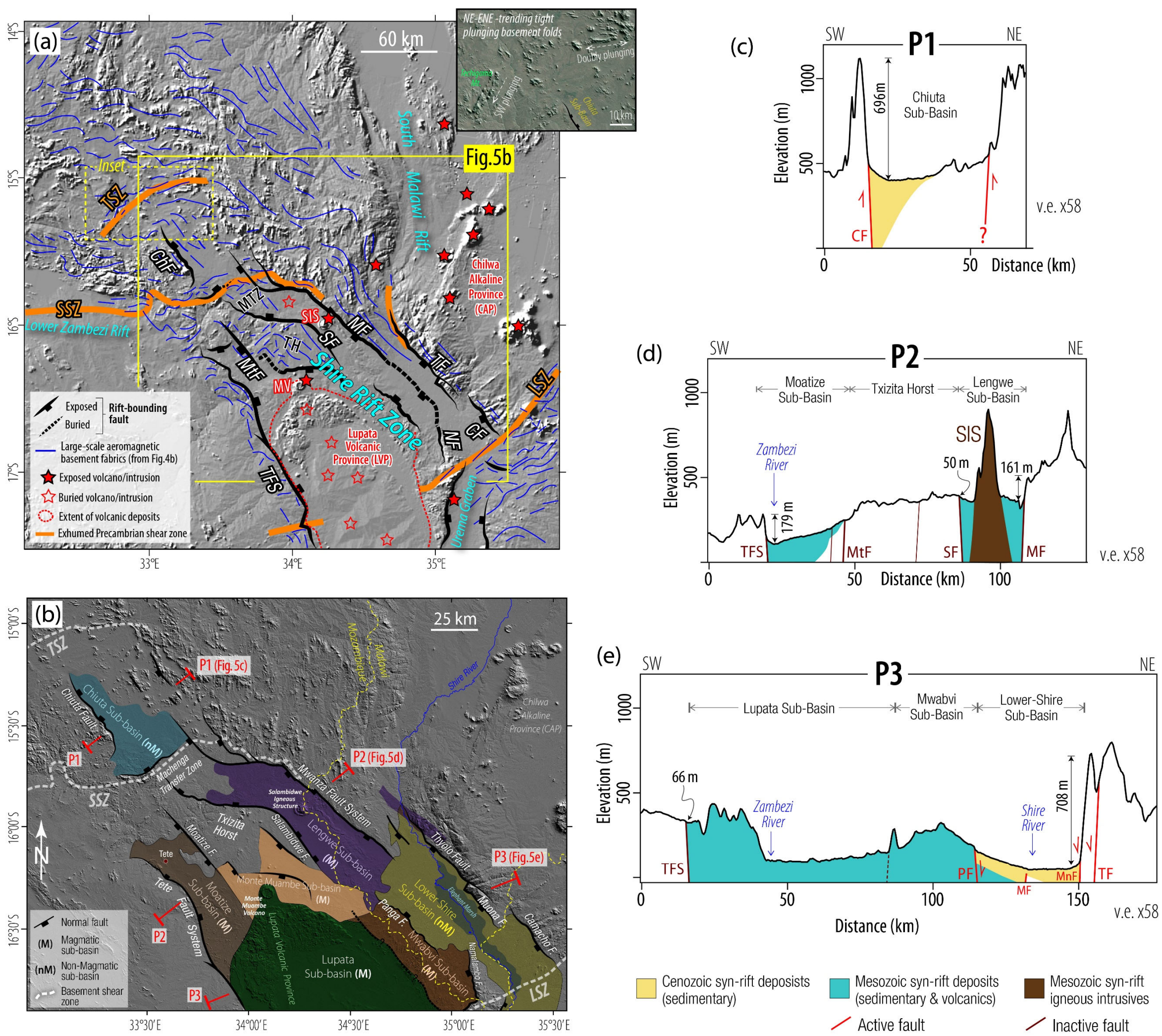


Figure 5. New Interpretation of the Large-Scale Structure of the Shire Rift Zone. (a) Hillshade digital elevation model overlaid with interpretations of the filtered regional aeromagnetic data. Open and filled red stars are Mesozoic (RP1-RP2) igneous centers. CF: Camacho Fault, ChF: Chiuta Fault, LSZ: Lurio Shear Zone,

MDC: Mulata Dike Cluster, MF: Mwanza Fault, MtF: Moatize Fault, MV: Monte Muambe Volcano, NF: Namalambo Fault, SF: Salambidwe Fault, SIS: Salambidwe Igneous Structure, TF: Thyolo Fault, TFS: Tete Fault System, TH: Txizita Horst, TSZ: Techigoma Shear Zone. The location, geometry, and extents of the Lurio and Sanangoe Shear Zones are after Barr and Brown (1987); Sacchi et al. (2000), Kroner et al. (1997), Bingen et al. (2009), Fritz et al. (2013). The Techigoma Shear Zone is delineated in this current study based on its character as a distinct high-amplitude aeromagnetic lineament separating terranes of different fabric trends (Figure 2b), collocated with satellite-scale, plunging tight folds (inset showing Google Earth map). (b) Map showing the Shire Rift extents and sub-basin compartmentalization based on fault scarp continuity and published distribution of the syn-rift sedimentary and volcanic deposits (Figure 2; Choubert et al., 1988). LM: Lake Mbenje, LSV: Lurio Shear Zone, SSZ: Sanangoe Shear Zone. (c - e) Rift-perpendicular topographic profiles (see Figure 5b for profile transects).

4.2.1 Depth to Magnetic Basement

The Lower Shire Sub-Basin:

The spatial distribution of depth-to-magnetic basement estimates beneath the Lower Shire (Figure 6a) shows larger depths in the hanging walls of the Mwanza-Namalambo Fault System compared to the hanging walls of the Thyolo-Muona Fault System. The results show that along the Mwanza Fault's hanging wall, the magnetic basement depths range between ~900 m and 2.4 km and attain a maximum of ~2.7 km at locations within both the exposed and buried sections of the fault. The hanging wall of the Namalambo Fault exhibits shallower depths than that of the Mwanza Fault but attains a maximum depth of 2.4 km along its southern section. Whereas, relative to the Mwanza-Namalambo Fault, the magnetic basement in the hanging wall of the Thyolo-Muona Fault defines a broad 'shelf' area with depths mostly ranging between 600 m and 1.2 km but records a maximum of ~1.4 km near the central areas of the hanging wall.

Overall, the hanging wall of the Mwanza Fault features broader and deeper zones of basement-lows compared to the Thyolo-Muona Fault hanging wall which shows smaller zones of basement-lows with moderate depths, separated by NW and NE-trending basement-highs. Thus, although the hanging walls of Mwanza and Thyolo-Muona synthetic border fault systems are covered by widespread Quaternary syn-rift sedimentary deposits (Figures 2 and 5e), the subsurface basement structure reveals significant contrast in the magnitudes of subsidence of the magnetic basement across the border faults.

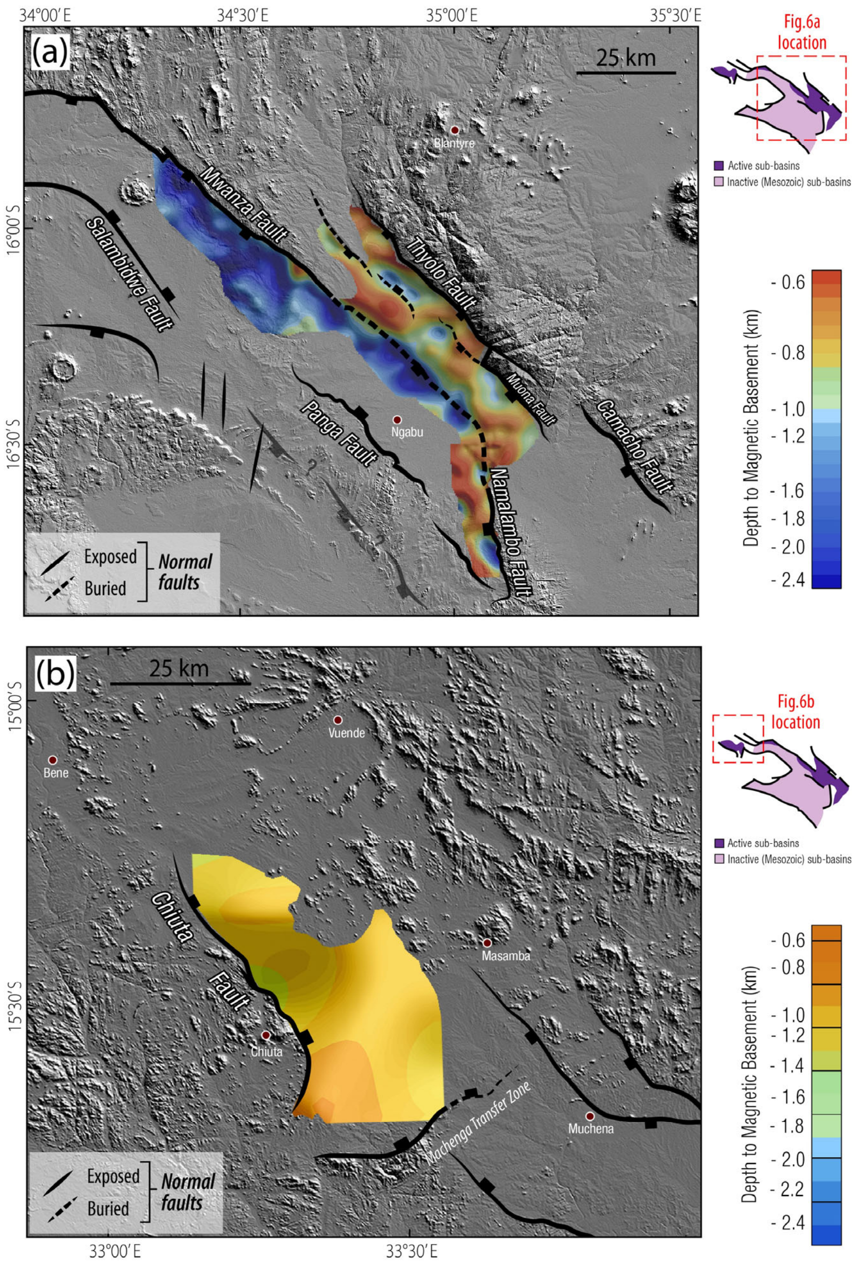


Figure 6. Depth-to-Magnetic Basement in the active (i.e., Cenozoic) Sub-Basins. (a) Depth-to-magnetic basement map of the Lower Shire sub-basin (and part of the Lengwe Sub-basin), overlaid on Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) hillshade map. The top of RP2 volcanic sequences is inferred to represent the magnetic basement in the hanging wall of the Mwanza-Namalambo Fault (Domains 1 & 2 in Fig. 7c). Whereas the top of the pre-rift metamorphic basement most likely represents the magnetic basement to the northeast of the Mwanza Fault (Domains 3-4 in Fig. 7c). (b) Depth-to-magnetic basement map of the Chiuta sub-basin, overlaid on SRTM-DEM hillshade map. Here, due to a lack of evidence on the presence of Mesozoic volcanics in this sub-basin, the top of the pre-rift metamorphic basement is inferred to represent the magnetic basement. Note that the Lower Shire sub-basin depth map shows a higher resolution than that of the Chiuta sub-basin because of the relatively higher-resolution aeromagnetic data in the Lower Shire sub-basin (see Figs. 3b-c).

The Chiuta Sub-Basin:

The results (Figure 6b) show that the magnetic basement generally deepens southwestwards towards the Chiuta Fault, attaining a maximum depth of ~1.4 km. To the southeast, the basement first shallows up to ~1 km before deepening slightly to ~1.2 km along a NE-trending, NW-dipping fault that terminates the sub-basin against the 'Machenga Transfer Zone'. Due to the absence of borehole penetration data in the Chiuta sub-basin, the lateral variation in our depth-to-magnetic basement estimate provides the first insight into the subsurface structure of the sub-basin.

4.2.2 Basement and Stratigraphic Architecture of the Lower Shire Sub-Basin

The Quaternary deposits in the Lower Shire Sub-basin overlap with the Mesozoic syn-rift deposits of the Lengwe and Mwabvi Sub-basins (Figure 2). Thus, with illustrations in Figures 7a and 7b, we describe here our observations of the basement and syn-rift architecture of the Lower Shire Sub-basin relative to those of its bounding sub-basins.

The Mwabvi Sub-basin is dominated by RP1 volcano-sedimentary units with no known accumulation of Quaternary (RP3) sediments (Domain-1 in Figure 7a). The Lengwe Sub-basin is also dominated by the RP1 units but hosts minor accumulations of RP3 sediments (Figure 2) in the northern segments of the Mwanza Fault (Domain-2 in Figure 7b). Along the northern Mwanza Fault, the syn-rift sequences are directly juxtaposed against the Precambrian metamorphic basement exposed in the footwall of the fault (Domain-3 in Figure 7b). However, towards the southeast, the cover of RP3 sediments in Domain-2 is more widespread and dominates the surficial extents of the domain.

Integration of all available information from independent datasets provides insight into the syn-rift stratigraphic architecture and lateral variation in the origin of the magnetic basement across the Lower Shire Sub-basin. These datasets include field observations (Figures 3a-c), basin-scale surficial geological map compilation (Figure 2), litho-logs from boreholes that penetrate below the Quaternary sedimentary cover (S3a-b and Table S1), and aeromagnetic fabric patterns (Figures 4c-h). First, these datasets show that the RP1-RP2 volcano-sedimentary units of the Mwabvi Sub-basin have been faulted and buried beneath RP3 sediments on the hanging wall of the Panga Fault (Domain-1 and -2 in Figure 7c).

Second, borehole logs and the aeromagnetic fabric patterns show that the RP1-RP2 volcanic rocks do not extend into the footwall of the buried Mwanza Fault segments (Figures 7c, S3a-b; Table S1). Also, the logs from boreholes in the areas between the Mwanza Fault and Thyolo Fault show no evidence for the presence of RP1 or RP2 sedimentary rocks beneath Quaternary sediments as the unconsolidated sediments directly overlie the gneissic basement (Figure S3a; Table S1). The magnetic structure of the Lengwe Sub-basin where mafic dikes have intruded the Mesozoic sedimentary sequences (Figure 7b) is different from that of the hanging wall of the Thyolo-Muona Fault system where high-amplitude anomalies are sparse and are of long-wavelengths. This suggests that there is no magnetic fabric pattern defining mafic diking of the sedimentary sequences overlying the gneissic basement in the hangingwall of the Thyolo Fault (Domain-3 in Figure 7c).

Additionally, beneath the Cenozoic cover of the Thyolo-Muona Fault hanging wall, the aeromagnetic map reveals a long-wavelength, low-frequency gradient that is parallel to- and extends northeastwards from the NE surface termination of the Muona Fault (Figure 4c). We describe this gradient as representing a buried (non-surface-breaking) segment of the Muona Fault. Based on these observations, we present an updated and comprehensive structural map of the Shire Rift, showing the previously mapped features and those mapped in this study (Figure 8).

4.2.3 Basement and Stratigraphic Architecture of the Chiuta Sub-Basin

The absence of high-resolution aeromagnetic data over the Chiuta Sub-basin does not permit a detailed structural interpretation. However, a key observation here is that aeromagnetic lineaments corresponding to a continuation of basement metamorphic fabrics beneath the rift-fill are visible along the axis of the Chiuta Sub-basin (Figure 4b). This is consistent with observations in other juvenile rift basins in Eastern Africa where the shallowly buried metamorphic basement is directly overlain by non-magnetic unconsolidated sediments (Kinabo et al., 2007; Kolawole et al., 2018),

4.3 Pre-Rift Basement Metamorphic Fabrics of the Shire Rift Zone (SRZ)

In the areas of exposed basement along the SRZ, aeromagnetic facies representing the basement metamorphic fabrics (gneissic foliation) are defined by tight clusters of parallel, elongate magnetic lineaments that show folded geometries along their strike (e.g., Figure 4d). We herein refer to this aeromagnetic pattern as the 'basement metamorphic fabric' or 'basement fabric'. Also, during our field visit, where possible, we collected strike and dip measurements of the basement foliation to independently compare with the broader-scale measurements from aeromagnetic grids. Below, we summarize the results of the frequency-azimuth distribution of the mapped basement fabrics observed along the SRZ (Figures 9a-g).

4.3.1 The Mwanza and Thyolo-Muona Border Faults and Environs

Along the Mwanza Fault, the frequency-azimuth distribution of the basement fabric (Figure 9bi) shows a dominant NW-SE trend with a 140° mean trend that is sub-parallel to the fault trend (~136°). This is consistent with our field measurements of the basement foliation (stereographic projection inset in Figure 9bi). Along the Thyolo-Muona Fault system, the mapped aeromagnetic metamorphic fabrics also show a prominent NW-SE trend with a mean of 123° (Figure 9ci), which is consistent with field measurements (128°), both being parallel or sub-parallel to the fault trend (~131°). We also note that along both the Mwanza and Thyolo Faults, the average dip magnitude and dip direction of the basement fabrics are strongly correlated with those of the faults (see stereographic contours and poles to fault planes in Figures 9bi and 9ciii).

4.3.2 Txizita Horst

In the absence of high-resolution aeromagnetic data over the Txizita Horst, we map basement fabrics in both the low-resolution SADC aeromagnetic grid (Figures 4b, 5a) and the topographic relief map (red lines in Figure 9a). The frequency-azimuth distributions of the metamorphic fabric lineaments in both datasets (Figure 9di-ii) show a multimodal distribution with consistent dominant sets trending ENE to NE (~079° from aeromagnetics, ~069° from topographic relief) and NW-SE (~132° from aeromagnetics, 145° from topographic relief). The plots also show a minor N to NNE set (~011° from aeromagnetics,

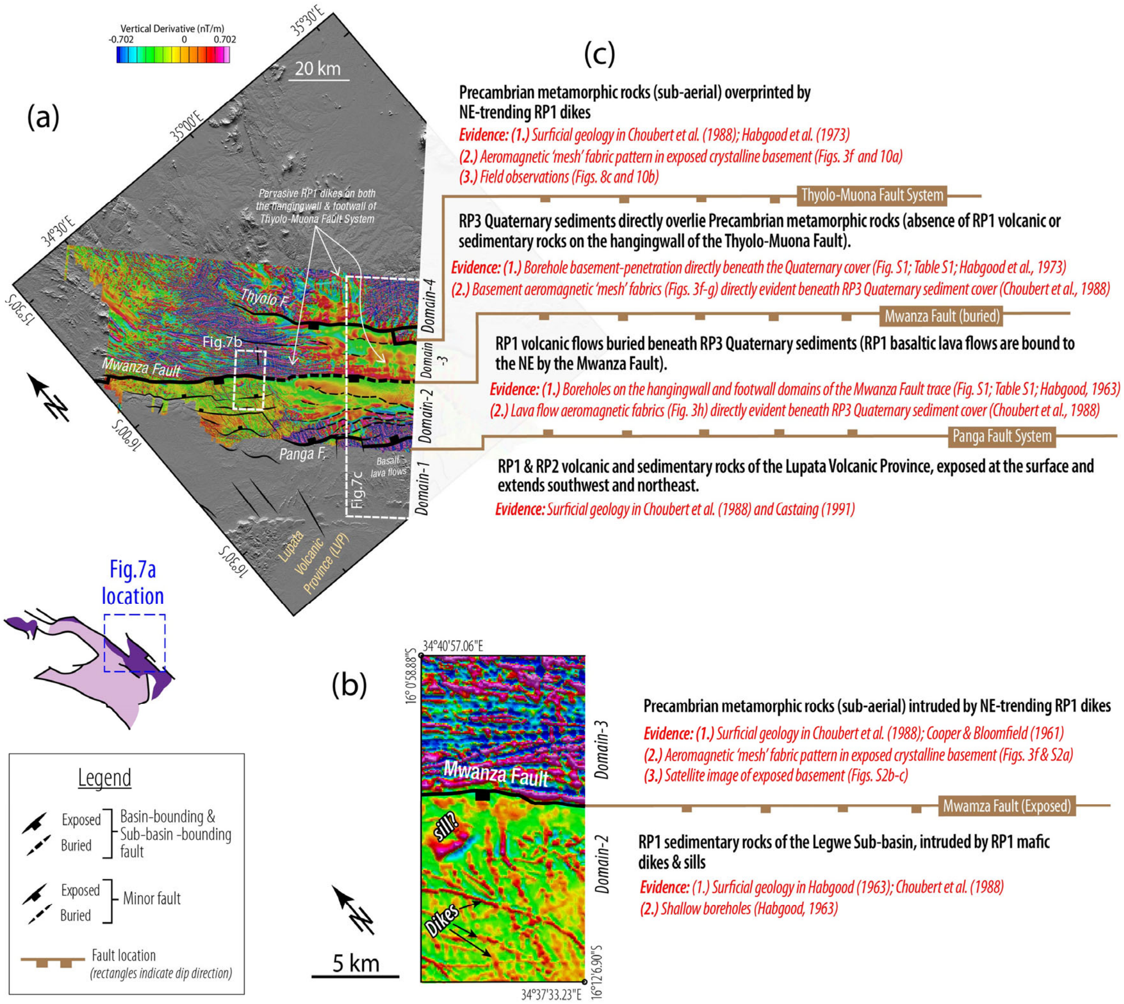
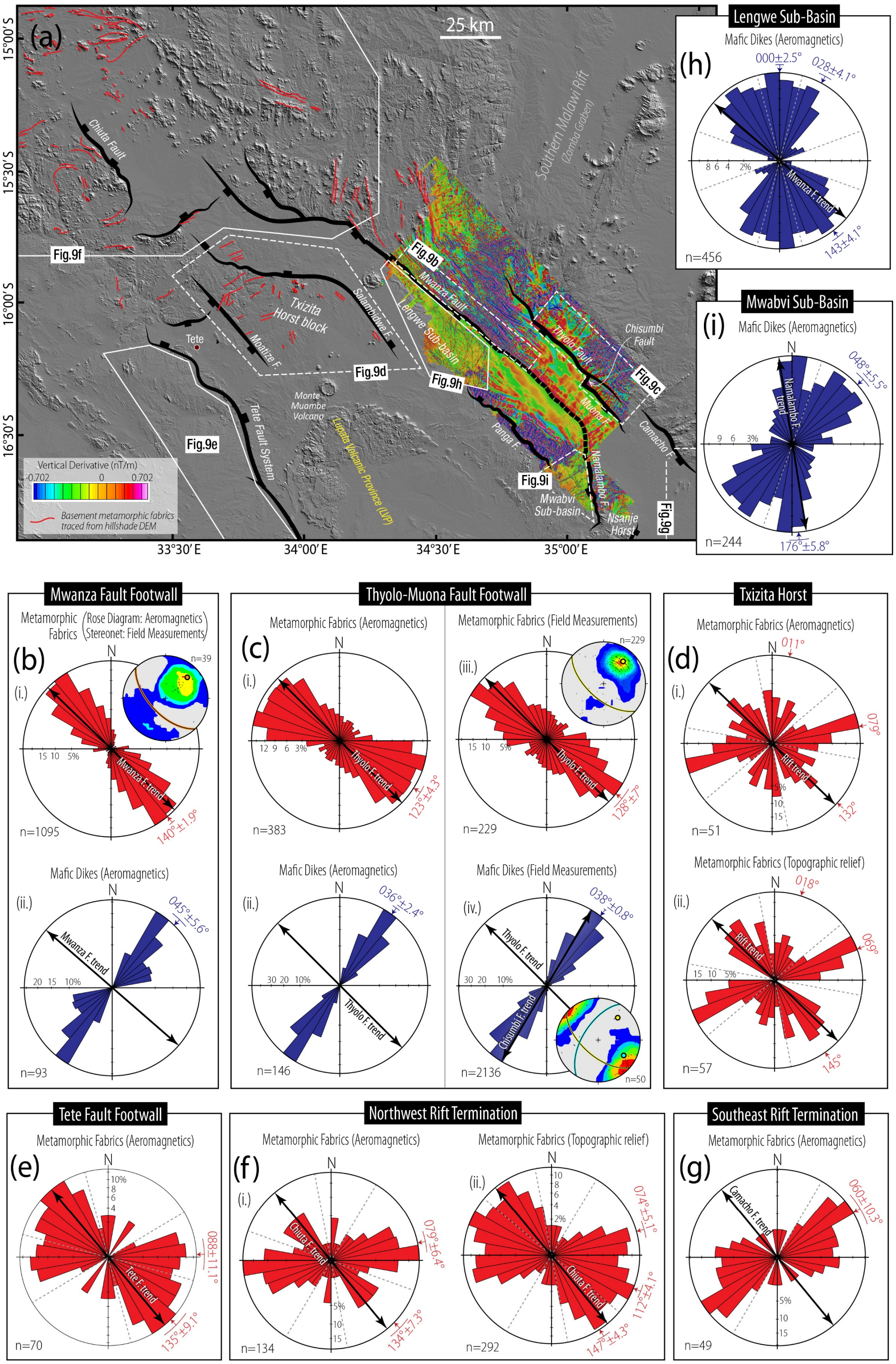


Figure 7. Borehole and magnetic fabric constraints on the relative timing of strain localization in the Lower Shire sub-basin. (a) Map covering parts of the Lengwe and Lower Shire sub-basins (same map in Figure 3c). (b) Zoomed-in map of the eastern portion of the Lengwe Sub-basin (see location in inset sketch map). The interpretations of the distinct magnetic domains (bold black texts in Figures 7b and 7c) are constrained by multiple independent datasets and observations (italicized red texts). In Figures 7b and 7c, the referenced borehole locations and associated data are provided in Supplementary Figures S3a-b and Supplementary Table S1.



(a)
25 km
15°00' S
15°30' S
16°00' S
16°30' S
33°30' E
34°00' E
34°30' E
35°00' E
Chiuta Fault
Fig.9f
Fig.9b
Fig.9d
Fig.9h
Fig.9c
Fig.9e
Fig.9i
Fig.9g
Txizita Horst block
Moatize F.
Sabambowa F.
Mwanza Fault
Lengwe Sub-basin
Thyolo Fault
Muona F.
Tete
Tete Fault System
Monte Muambe Volcano
Lupata Volcanic Province (LVP)
Southern Malawi Rift (Zomba Graben)
Chisumbi Fault
Camacho F.
Panga F.
Nsanje Horst
Namalambo F.
Mwabvi Sub-basin
Vertical Derivative (nT/m)
-0.702 0 0.702
Basement metamorphic fabrics traced from hillshade DEM
Lengwe Sub-Basin
Mafic Dikes (Aeromagnetics)
(h)
000±2.5°
028±4.1°
143±4.1°
Mwanza F. trend
n=456
Mwabvi Sub-Basin
Mafic Dikes (Aeromagnetics)
(i)
048°±5.5°
176°±5.8°
Namalambo F. trend
n=244
Mwanza Fault Footwall
Metamorphic Fabrics
Rose Diagram: Aeromagnetics
Stereonet: Field Measurements
(b)
(i.)
n=39
140°±1.9°
n=1095
Mafic Dikes (Aeromagnetics)
(ii.)
045°±5.6°
n=93
Thyolo-Muona Fault Footwall
Metamorphic Fabrics (Aeromagnetics)
(c)
(i.)
123°±4.3°
Thyolo F. trend
n=383
Metamorphic Fabrics (Field Measurements)
(iii.)
n=229
128°±7°
Mafic Dikes (Aeromagnetics)
(ii.)
036°±2.4°
n=146
Mafic Dikes (Field Measurements)
(iv.)
038°±0.8°
Chisumbi F. trend
n=2136
n=50
Txizita Horst
Metamorphic Fabrics (Aeromagnetics)
(d)
(i.)
011°
079°
132°
Rift trend
n=51
Metamorphic Fabrics (Topographic relief)
(ii.)
018°
069°
145°
n=57
Tete Fault Footwall
Metamorphic Fabrics (Aeromagnetics)
(e)
088°±11.1°
135°±9.1°
Tete F. trend
n=70
Northwest Rift Termination
Metamorphic Fabrics (Aeromagnetics)
(f)
(i.)
079°±6.4°
134°±7.3°
Chiuta F. trend
n=134
Metamorphic Fabrics (Topographic relief)
(ii.)
074°±5.1°
112°±4.1°
147°±4.3°
n=292
Southeast Rift Termination
Metamorphic Fabrics (Aeromagnetics)
(g)
060°±10.3°
Camacho F. trend
n=49

Figure 9. Structural trends of inherited basement fabrics (foliation) and syn-rift igneous dikes. (a) Shuttle Radar Topography Mission (SRTM) DEM hillshade map of the Shire Rift Zone overlaid with vertical derivative aeromagnetic map of the Malawi part of the rift. The red lines represent topographic expressions of basement fabrics around the rift (providing independent information on pre-rift basement fabrics, see Figs. 9d & 9f); (b - c) Azimuth-frequency distribution of basement metamorphic fabrics and mafic dikes along the footwall of (b) the Mwanza Fault, and (c) the Thyolo-Muona Fault System; (d - g) Frequency-azimuth distribution of metamorphic fabrics within the Txizita Horst block (9d), footwall of the Tete Fault System (9e), and the northwestern (9f) and southeastern (9g) rift terminations zones; (g - h) Frequency-azimuth distribution of mafic igneous dikes in the Lengwe (9h) and Mwabvi sub-basins (9i). Insets of stereographic projections (equal-area) represent poles to planes with 2 interval Kamb contours, and great circles with colored halos represent the Mwanza Fault plane (136°/60° in 9bi), Thyolo Fault plane (131°/60° in 9ciii-iv), and Chisumbi Fault (211°/60° in 9civ). The 60° dip of fault planes is obtained from previous field observation along the Thyolo Fault (Wedmore et al., 2020). In Fig. 9ciii, the rose and stereographic projection both consist of a combination of field measurements collected during our field visit (n=38) and those previously collected by the Malawi Geological Survey (n=191; Habgood et al., 1973). Whereas, in Fig. 9civ, although the rose plot includes a combination of our field measurements (n=50) and those in Habgood et al. (1973) (n=2086), the stereographic projection consists only of our field measurements as the dip of dikes were not reported in Habgood et al. (1973). Black dashed lines in rose plots represent frequency minima used for modal set grouping and calculation of circular vector mean for the modal sets.

~018° from topographic relief). The NE-trending fabrics appear to dominate most of the horst, whereas the NW-trending, which set is parallel to the rift trend, is primarily localized at the center and along the northeastern margin of the horst in the footwall of the Salambidwe Fault (Figures 4b, 5a, 9a).

4.3.3 The Tete Border Fault and Environs

Since the basement fabrics are poorly expressed in the topographic relief map (Figure 9a), we only obtain measurements of basement fabrics from the regional aeromagnetic grid (Figures 4b, 5a). The result shows a very prominent NW-SE trend (~135°) which is sub-parallel to the trend of the Tete Fault system (Figure 9e). However, we also observe a secondary set in the data which trends E-W (~088°) and is collocated with a kink in the trend of Tete Fault's trace (Figure 5a).

4.3.4 The Rift Termination Zones

At regional-scale, within the northwestern rift termination zone (i.e., vicinity of the Chiuta Sub-basin), the available aeromagnetic grid shows that the basement fabrics are characterized by multimodal trends (Figure 9fi-ii) in which an ENE trend (~079° from aeromagnetics, ~074° from topographic relief) and NW-SE (134° from aeromagnetics, ~147° from topographic relief) trend are most prominent. The NW-SE fabric set is parallel to the trend of the Chiuta Fault (~137°). Whereas at the southeastern rift termination zone (SE tip of the Camacho Fault; Figure 9a), the basement is dominated by NE-SW -trending fabrics with a mean trend of ~060° (Figure 9g), which are sub-orthogonal to the Camacho Fault trend (~140°).

4.4 Syn-Rift Magmatic Structures in the Shire Rift Zone

Observations during our field visit (e.g., Figure 3b) and a compiled surficial geologic map of the SRZ (Figure 2) raise the need to explore the patterns and distribution of syn-rift diking and ring-shaped igneous structures that dominate the rift zone. The aeromagnetic fabric patterns and lineament 'types' observable in the filtered aeromagnetic grids include: 1) Broad clusters of parallel, elongate high-frequency, high-amplitude short-wavelength magnetic fabrics in exposed basement (Figure 4d), representing sub-vertical basement metamorphic foliation observable in field outcrops (Figures 3b-c); 2) Discrete cross-cutting lineaments of high-amplitude short-wavelength character enclosed by longer-wavelength magnetic-low anomalies, representing mafic igneous dike intrusions within sedimentary sequences in Lengwe and Mwabvi Sub-basins (e.g., Figure 4e) observable in exhumed Mesozoic syn-rift outcrops and boreholes (Habgood, 1963), among which lineament sets show different amplitudes indicative of different emplacement depths, here in described as "strong discrete lineaments, 'SDL'" (shallower dikes?) and "weak discrete lineaments, ‘WDL’" (deep-seated dikes?); 3) Broad zones of high-amplitude mesh pattern fabrics in exposed basement (Figure 4f), representing metamorphic foliation overprinted by cross-cutting mafic dikes observable in field exposures (Figures S4a-c); 4) Broad zones of low-amplitude mesh pattern fabrics in intra-basinal areas of Quaternary-age sedimentary cover (Figure 4g), occurring as the buried lateral continuation of the metamorphic basement hosting cross-cutting mafic dikes (i.e. fabric type #3 buried beneath unconsolidated alluvial sediments); and 5) Broad zones of compact linear bands of chaotic high-amplitude high-frequency magnetic fabrics (Figure 4h) collocated with exposed or shallowly buried Mesozoic basaltic flows in the Mwabvi Sub-Basin (Figure 2; Habgood, 1963).

The basalt-related magnetic fabrics are cur and truncated by a system of sub-parallel rectilinear abrupt gradients that correspond to faults (e.g., Panga Fault, observable in the field and in topographic relief map; Figures 2, 4c). Also, the amplitude of the basalt-related magnetic anomalies decreases northeastward towards the Mwanza Fault as the depth of burial of the volcanic flows increases. Overall, in eastern SRZ in Malawi where high-resolution aeromagnetic data is available (Figures 4a and 4c), we mapped and analyzed the dike-related magnetic lineaments. In other parts of the rift zone where lower-resolution aeromagnetic data is the only available subsurface data (Figures 4a and 4b), we show the presence and distribution of prominent ring-shaped magnetic anomalies and describe their associations with surface igneous complexes in the rift.

4.4.1 Lengwe and Mwabvi Sub-Basins

The high-resolution aeromagnetic data reveal the presence of a more complex network of cross-cutting dike-related magnetic lineaments in the Lengwe Sub-basin than in the Mwabvi Sub-basin (Figures S5a-b). The frequency-azimuth distribution of the Lengwe dikes (Figure 9h) is multimodal with three dominant sets trending N-S (~000°), NNE-SSW (~028°), and NW-SE (~143°). The NW-SE dike segments are generally sub-parallel to the intrabasin faults, the Mwanza border fault, and the overall rift trend (Figure S5).

In the southern section of the Mwabvi Sub-basin where the dikes are observable, the data (Figure 8i) shows only two dominant sets which include a N-S (~176°) and NE-SW (~048°) trend. The N-S trending dike segments are parallel to the strike of the Namalambo Fault representing the border fault in that part of the basin (Figure S5b). Whereas the NE-trending dikes, some of which extend across the border fault, are parallel to the trend of the basement fabrics in the Namalambi Fault footwall (LSZ and surrounding fabrics at the SE rift termination zone; Figure 5a). Further, some of the NE dikes that extend across the Namalambo Fault are collocated with the zone of burial of the northern tip of the Namalambo Fault, and en-echelon transverse offsets of the fault beneath the Quaternary cover ('T' in Figure S5b).

4.4.2 Mwanza and Thyolo-Muona Border Fault Footwalls

In the footwall of the Mwanza Fault, the dikes show a dominant (unimodal) NE-SW trend, ~045° (Figures 9bii, S4a-c). Similarly, on both the footwalls and hanging walls of the Thyolo-Muona Fault system, the dikes show a prominent unimodal trend of ~036° (Figures 9cii, 10a-b), consistent with field measurements in their footwalls (~038°; Figure 9civ and stereographic projection). Our field measurements (stereographic contours in Figure 9civ) show that in dip view, the dikes occur in a conjugate set with some dipping to the NW and others to the NE. Although the Thyolo and Muona Faults are sub-orthogonal to the dikes, the Chisumbi Fault (~031°) strikes parallel to the dikes and shows strong alignment in dip magnitude and direction with the NW-dipping dike set (see pole to Chisumbi Fault plane in Figure 9civ).

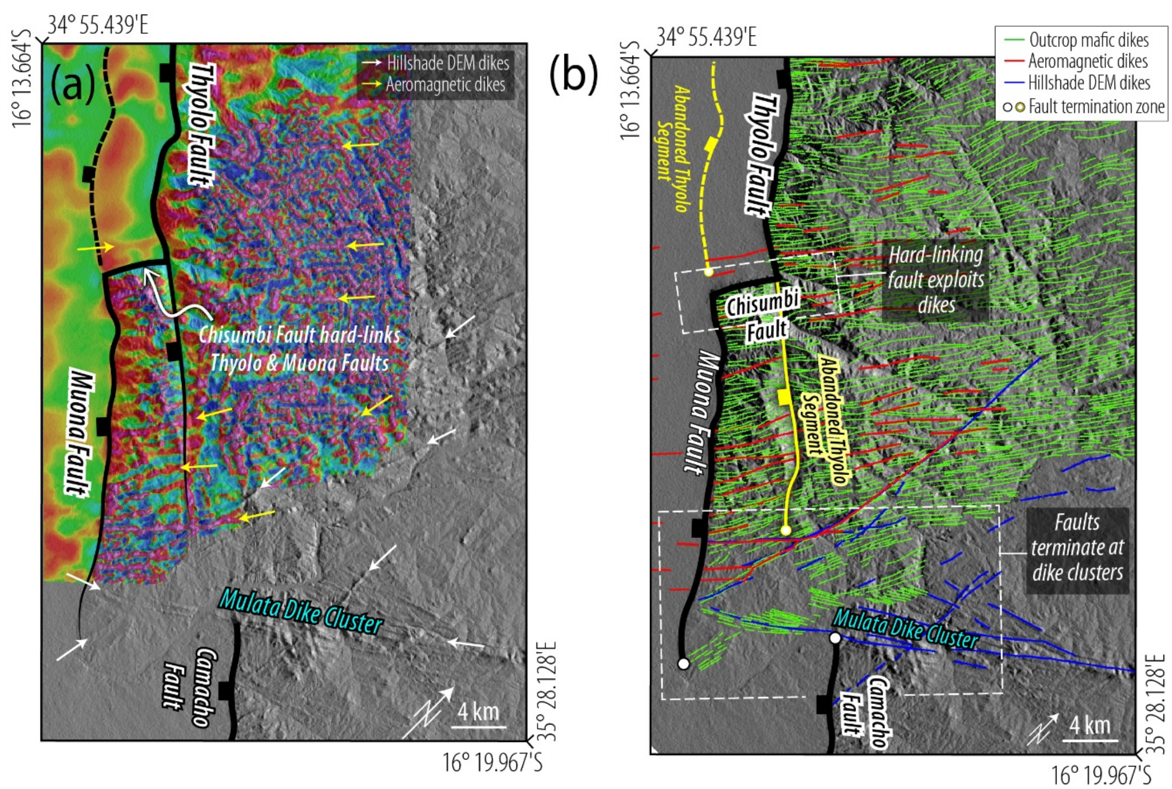


Figure 10. Relationships between the rift border faults and the early phase (RP1-RP2) mafic dikes. (a) Filtered aeromagnetic map (location: SE half of polygon "Fig. 9c" in Figure 9a) showing aeromagnetic dike lineaments (yellow arrows) and topographic expression of dikes (white arrows); (b) Map of same area in Figure 10a, showing the interpreted mafic dike aeromagnetic lineaments (red lines), SRTM hillshade dike lineaments (blue lines), and those from published field mapping (green lines; Habgood et al., 1963).

4.4.3 Lupata Volcanic Province (LVP)

The regional aeromagnetic grid shows that both the Monte Muambe Volcano (MV) and Salambidwe Igneous Structure (SIS) are characterized by prominent ~10 km-wide ring-shaped magnetic-high anomalies (Figure 4b). South of the Monte Muambe Volcano, we identify several similarly-sized ring-shaped high-amplitude magnetic anomalies (with 7.5 – 19 km diameters) distributed over a distance of 140 km (Figures 4b and 5a). These ring-shaped anomalies do not correspond to any distinct surface topographic feature. However, the anomalies delineate a NW-trending belt along the rift axis.

5 DISCUSSION

5.1 New Interpretation of the SRZ Architecture

Although the broad geologic history of the SRZ has been previously identified (Castaing, 1991), only the Lengwe, Mwabvi, and Lower Shire depocenters were distinguished while the rest of the basin was referred to as the Middle Zambezi Valley (Castaing, 1991, Chisenga et al., 2019). Thus, the detailed structure, rift basin compartmentalization, and the associations with the phases of extension are not known. The extent and distribution of fault-bounded Mesozoic and Cenozoic sedimentary and volcaniclastic deposits in the Shire Rift (Figure 2) represent a multiphase rift zone with compartmentalization (Figure 5b) that is facilitated by complex brittle and magmatic deformation (Figure 8). Based on the integration of surficial geology (Figure 2) and structural interpretations from filtered aeromagnetic datasets, we identified seven structural domains within the basin, which include the Lower Shire, Mwabvi, Lengwe, Monte Muambe, Moatize, Chiuta, and Lupata Sub-Basins (Figure 5b).

Based on the presence of basement-sedimentary magmatic intrusions, volcanic deposits, and timing of magmatic activities in the SRZ, we characterized the sub-basins into magmatic and non-magmatic categories. Considering that the Lupata Sub-Basin houses the Lupata Volcanic Province (LVP) where multi-phase rejuvenation of widespread intra-rift volcanism localized during RP1-RP2, we suggest that this sub-basin likely hosts some of the richest information on multiphase early-stage magmatic rifting, yet it remains poorly understood. Also, the spatial extents of syn-rift sequences across the SRZ (Figures 2) suggest that the Lengwe, Mwabvi, Moatize, and Monte Muanbe Sub-basins were established and most active during RP1 (Figure 11a). Late-RP1 magmatic plumbing of the rift appears to be basin-scale (Castaing, 1991). However, RP2 tectonic activities largely involved the focusing of intra-rift volcanism in the LVP, the Salambidwe area of the Lengwe Sub-basin, and localization of off-rift magmatism outboard of the evolving rift (Chilwa Alkaline Province, CAP; Figures 2, 8, 11b).

5.1.1 Possible Cenozoic Establishment of the Lower-Shire and Chiuta Sub-Basins

As is the case in many onshore basins in East Africa, the lack of surface-to-basement wells limits the understanding of the spatiotemporal rift propagation at the segment scale. A similar challenge arises here in the SRZ, where available legacy boreholes only sampled shallow depths in the Chiuta and Lower Shire Sub-basins. However, based on the most up-to-date compilation of surface and subsurface data on the SRZ, we infer the most probable rift history of the two sub-basins with the most widespread accumulations of RP3 deposits.

Bloomfield (1958), Cooper and Bloomfield (1961), and Habgood (1963) documented the presence of ~1.2 km-wide hydrothermal alteration zone along the escarpment and footwalls of the Mwanza Fault and Namalambo Fault. The alteration zones are characterized by unbroken silicic and calcite hydrothermal veins with associated epidote and pyrite mineralization, and they preserve evidence of multiple episodes of fluid alteration (Bloomfield, 1958). Along the Namalambo Fault zone, the veins crosscut both the Precambrian basement and brecciated RP1 diabase intrusions (Bloomfield, 1958). Based on the observed cross-cutting relationship and the large-scale 'unbroken' structure of the veins, this pervasive hydrothermal event has been interpreted to have occurred during the Late Cretaceous rifting activity (RP2). However, field observations along the Thyolo-Muona Fault zones show no evidence of fluid alteration (this study, and others: Williams et al., 2019; Wedmore et al., 2020), suggesting that the fault zones did not undergo the same hydrothermal events observed along the Mwanza and Namalambo Faults. These observations suggest that the Thyolo-Muona Fault System was likely not established until the RP3.

The absence of Mesozoic volcanic rocks in the hanging wall of the Thyolo-Muona border fault suggests that the Lower Shire Sub-basin was most likely not established as a major depocenter during the magmatic RP1-2 rift phases (Figures 7a-c, 11c). Also, in the other on-shore Eastern Africa rift basins that accommodated RP1-RP2 rifting and have been reactivated in the Cenozoic, outcrops of the Mesozoic syn-rift units have been documented along their uplifted flexural margins (e.g., Rukwa Rift, Luangwa Rift, Northern Malawi Rift; Bennett, 1989; Ring 1995; Delvaux, 2001; Kolawole et al., 2018; Daly et al., 2020). However, in the uplifted flexural margins of the Chiuta Sub-basin and hanging walls of the Thyolo-Muona Fault, outcrops of RP1-RP2 sedimentary rocks are absent. Also, the magnetic anomaly pattern in the hanging walls of the Thyolo and Muona Faults (see Figure 7a) primarily exhibits long-wavelength anomalies of buried metamorphic fabrics crosscut by mafic dikes, both confined to the crystalline basement beneath the sedimentary cover (Figures 4f-g). Whereas, in the hanging wall of the Mwanza and Namalambo faults where RP1-RP2 syn-rift sequences are widespread, the magnetic fabric pattern is dominated by discrete magnetic-high short-wavelength lineament anomalies of mafic dikes that intruded the syn-rift sedimentary sequences (Figures 4e, S5a-b; also see field and borehole observations in Habgood, 1963; Castaing et al., 1991). In essence, the Thyolo-Muona fault hanging wall lacks the presence of sedimentary sequences with intruded mafic dikes.

The modeled depth-to-crystalline-basement in the Chiuta Sub-basin and Thyolo-Muona Fault hanging wall (Figures 6a-b) generally shows <1.5 km depth, which is consistent with basement depths in the nearby southern Malawi Rift (maximum of 1.6 km) where an absence of Mesozoic rifting has been similarly inferred (Scholz et al., 2020; Williams et al., 2021). At regional scales, geodetic stretching rates generally decrease towards the euler pole of plate rotation, such that within a sub-region of contemporary rifting such as the Shire Rift Zone and Southern Malawi Rift, crustal stretching rates can be assumed to be relatively uniform spatially (~2.2 mm/yr; Stamps et al., 2018; Wedmore et al., 2021). Thus, if both the southern Malawi Rift and Lower Shire Graben have experienced tectonic extension for the same length of time, the maximum throws on the active border faults should be relatively similar, assuming a uniform time-averaged crustal stretching rates across the sub-region. Therefore, the similarity of maximum border fault throws in southern Malawi Rift to those of the Chiuta Sub-Basin and Thyolo-Muona Fault hanging wall, given by maximum depth-to-basement along the border faults, suggests that the three areas are likely coeval.

Dixey (1925) also noted the absence of RP1 and RP2 syn-rift sediments in the Lower Shire Sub-basin (i.e., in the area between Mwanza Fault and Thyolo-Muona Fault) and speculated on ~400 m Jurassic-age uplift event (immediately after RP1) and additional ~1.2 km Late Miocene-age localized uplift event (after RP2) within the sub-basin that could have led to the erosion of both the RP1 and RP2 syn-rift deposits immediately after each rift phase. These speculations are problematic considering that 1) the suggested magnitude of post RP1 uplift implies that the Lower Shire area (i.e., Mwanza Fault's footwall) did not experience significant tectonic subsidence during RP1, and 2) results from thermochronology studies in the area does not support the occurrence of a localized uplift, but rather a regional-scale Paleogene tectonic uplift (Daszinnies et al., 2008; Ojo et al., 2020 *in review*). The studies show the occurrence of regional Eocene-age uplift associated with the initiation of East African Rift System (Daszinnies et al., 2008) and Late Cenozoic footwall uplift along the Thyolo Fault (i.e., RP3 rift border faulting; Ojo et al., 2020 *in review*).

Coal deposits are known to preserve excellent records of maximum paleotemperatures that they have been exposed to (e.g., Hunt et al., 2002; Singh et al., 2007). Geochemical analyses of the Karoo-age (RP1) coal seams of the Lengwe-Mwabvi Sub-basins show approximate carbon content of 75.7 % and volatile matter of ~25 % on a dry ash free basis (Habgood, 1963). These values indicate orthobituminous coals of high to medium volatile bituminous rank, corresponding to victrinite reflectance of ~0.9 - 1.5 % (Hunt et al., 2002; Suárez-Ruiz & Crelling, 2008). Assuming an average geothermal gradient (25-30 °C/km in continental crust) and normal burial-and-exhumation paths, these RP1 coal-rich units would have been buried to about ~3 - 4 km depths to attain the estimated thermal maturity level (Bjorlykke, 1989) prior to exhumation. However, such a simple burial-and-exhumation history cannot be assumed here considering the RP1 and RP2 magmatic events and associated intrusions into the coal-rich syn-rift sequences (Habgood, 1963; Figs. S5a-b) and the strong thermal maturation effects of such extraneous heat sources on coal deposits (e.g., Stewart et al., 2005; Singh et al., 2007). Therefore, we infer that the exhumed RP1 units in the Lengwe-Mwabvi Sub-basins (adjacent to the Lower Shire Sub-basin) were likely only buried to depths much shallower than 4 km prior to their Cenozoic exhumation.

We acknowledge that it is still possible that the current locations of the Chiuta Sub-basin and Thyolo-Muona Fault's hanging wall area hosted syn-rift Mesozoic depocenters that were eroded off at sometime between the Cretaceous and Cenozoic rift phase. However, such depocenters may have been significantly smaller and shallower (diffused rifting?) than those hosted and preserved in the other sub-basins with widespread outcrops of RP1-2 deposits: Lengwe, Mwabvi, Moatize, Monte-Muambe, and Lupata Sub-basins. Therefore, we argue that that the Chiuta Fault and the Thyolo-Muona Fault Systems were likely not established as major syn-rift depocenters along the SRZ until the RP3. Thus, it is still possible that isolated pockets of small RP1-RP2 sedimentary deposits may be preserved at the deepest parts of these major RP3 sub-basins, but would require a future basement-penetrating drilling campaign to confirm. Also, we emphasize that unlike the RP1-RP2 strain accommodation in the SRZ that recorded pronounced magma-assisted rifting, the RP3 strain accommodation in the rift zone is not magma-assisted.

5.2 Pulsed Rift Propagation in the SRZ: Multiphase Strain Migration and Sub-Basin Abandonment

The absence of major RP1-RP2 depocenters in the Chiuta Sub-basin and Thyolo-Muona Fault's hanging wall suggests that the RP1-RP2 rift deformation and subsidence were largely confined to the region bounded by the Mwanza-Namalambo Fault to the northeast and the Tete Fault to the southwest. To the northwest, the RP1-RP2 rift bifurcates and appears to have terminated at or near the intersection of the rift with the Senangoe Shear Zone. To the southeast, the rift-bounding Namalambo Fault also terminates at the Lurio Shear Zone. However, the localization of the Chiuta Sub-basin to the northwest of the Sanangoe Shear Zone in RP3 suggests that the Cenozoic rifting in the SRZ recorded a resurgence of lateral along-trend propagation of the rift basin. The absence of RP3 tectonic activity in the LVP and surrounding sub-basins suggests that this previously active magmatic domain of the rift was largely abandoned after RP2, and strain has migrated further northwest and east/northeast of the basin. The RP3 rift-orthogonal strain migration into the margin of the older basin led to the development of the Lower Shire Graben.

This sequence of temporal rift evolution describes a pulsed pattern of lateral rift propagation in which continuous lateral propagation of the tip of an active rift is stalled for a considerable period, after which rift lengthening resumes (Courtillot 1982; Van Wijk and Blackman, 2005). However, questions arise as to the forcing mechanism behind the large-scale abandonment of the RP1-RP2 basin and rift-orthogonal strain migration into the northeastern rift margin. Strain migration during multiphase rifting is not uncommon in the tectonic records of rifted continental margins and failed continental rifts (e.g., Braun, 1992; Bell et al., 2014; Fazlikhani et al., 2020). In the SRZ, the Mesozoic phases of rifting were accompanied by voluminous basaltic magmatism (Figures 2 and 11; Castaing et al, 1991), and gravity modelling reveal the possible presence of sub-crustal intrusive bodies beneath the SRZ-related RP2 igneous provinces (Njunju et al., 2019b).

Therefore, an explanation for the basin abandonment and strain migration could be a possible strengthening (healing) of the crust and lithospheric mantle beneath the early-phase sub-basins, facilitated by a prolonged inter-rift period between RP2 and RP3 after the RP1-RP2 magma-assisted crustal thinning. This inference is supported by lithospheric-scale rift models (e.g., Braun, 1992; Naliboff and Buiter, 2015). Braun (1992) argued that the absence of RP3 reactivation in the RP1-RP2 rift basins flanking the northern Malawi Rift (Ruhuhu and Maniamba Rifts; Figure 1a) is due to inter-rift lithospheric healing, such that relatively unstretched regions of the mobile belts served as strain concentrators in the RP3. The integrated crustal strength of the magmatic RP1-RP2 rift zone may likely have surpassed that of the surrounding areas (Naliboff and Buiter, 2015), such that the initiation of Cenozoic crustal stretching (RP3) favored the migration of strain into the surrounding areas. We note that although other magmatic RP1-2 rifts in the region such as the Zambezi Rift also show a similar style of large-scale post-RP2 abandonment, the border faults of the Luangwa Rift are experiencing RP3 reactivation (Daly et al., 2020). However, it is also not yet clear if inter-RP2-3 lithospheric healing also controlled the absence of resurgent magmatic rifting in the RP3 along the SRZ, considering that the basin was largely magmatic in the previous phases of extension.

5.3 Inheritance of Weakening Structures: Strain Localization Through the Exploitation of Intra-Basement Weak Zones

5.3.1 Early-Phase (RP1) Border Faulting

If the Mwanza-Namalambo and Tete Faults are the main Mesozoic border faults of the SRZ, based on the present-day surface locations of the faults and exposures of syn-rift basin-fill, we estimate that the RP1 basin is a NW-trending rift basin that bifurcates northwestwards into two 20-25 km-wide branches, covering a total of ~17,299 km^2 areal extent over a length of ~200 km (Figures 5b, 11a). The branches are also confined by 'inner' border faults, Moatize, and Salambidwe Faults, which juxtapose the rift-fill against the pre-rift basement of the Txizita Horst (Figure 5d).

Along the eastern rift shoulder, the Mwanza Fault's strike and dip show strong alignment with those of the underlying pre-rift basement metamorphic fabrics (Figures 9b, 11a). In the northern Lengwe Sub-basin where the Mwanza Fault rotates counter-clockwise, field observations in Barr and Brown (1987) show that the fault is collocated with- and follows the easternmost segment of the crustal-scale Precambrian Sanangoe Shear Zone (SSZ). Likewise, the Salambidwe Fault is parallel to the trends of the basement fabrics (Figures 4a, 9a). However, to the SE, the N-trending Namalambo border fault cuts across the NE-trending basement fabrics of the Lurio Shear Zone (LSZ), except for its southernmost tip which rotates clockwise and follows the trend of the basement fabrics (Figure 5a; Bloomfield, 1958). We note that the southernmost part of the Namalambo Fault bends into a NE trend which parallels the LSZ (Figures 4b, 5a). Along the western rift shoulder, the northernmost sections of the Tete Fault trend parallel to aeromagnetic basement fabrics (Figures 4b and 9e), which is consistent with observations in published geologic maps (Choubert et al., 1988). Whereas, the Moatize Fault, the inner border fault of the Moatize rift branch, appears to crosscut the metamorphic basement fabrics (Figures 4b, 5a, 9a). Overall, based on these observations, we suggest that that the RP1 eastern border fault (Mwanza Fault) exploited the pre-rift basement fabrics along most of its length, whereas the western border fault (Tete Fault) partially exploited the basement fabrics.

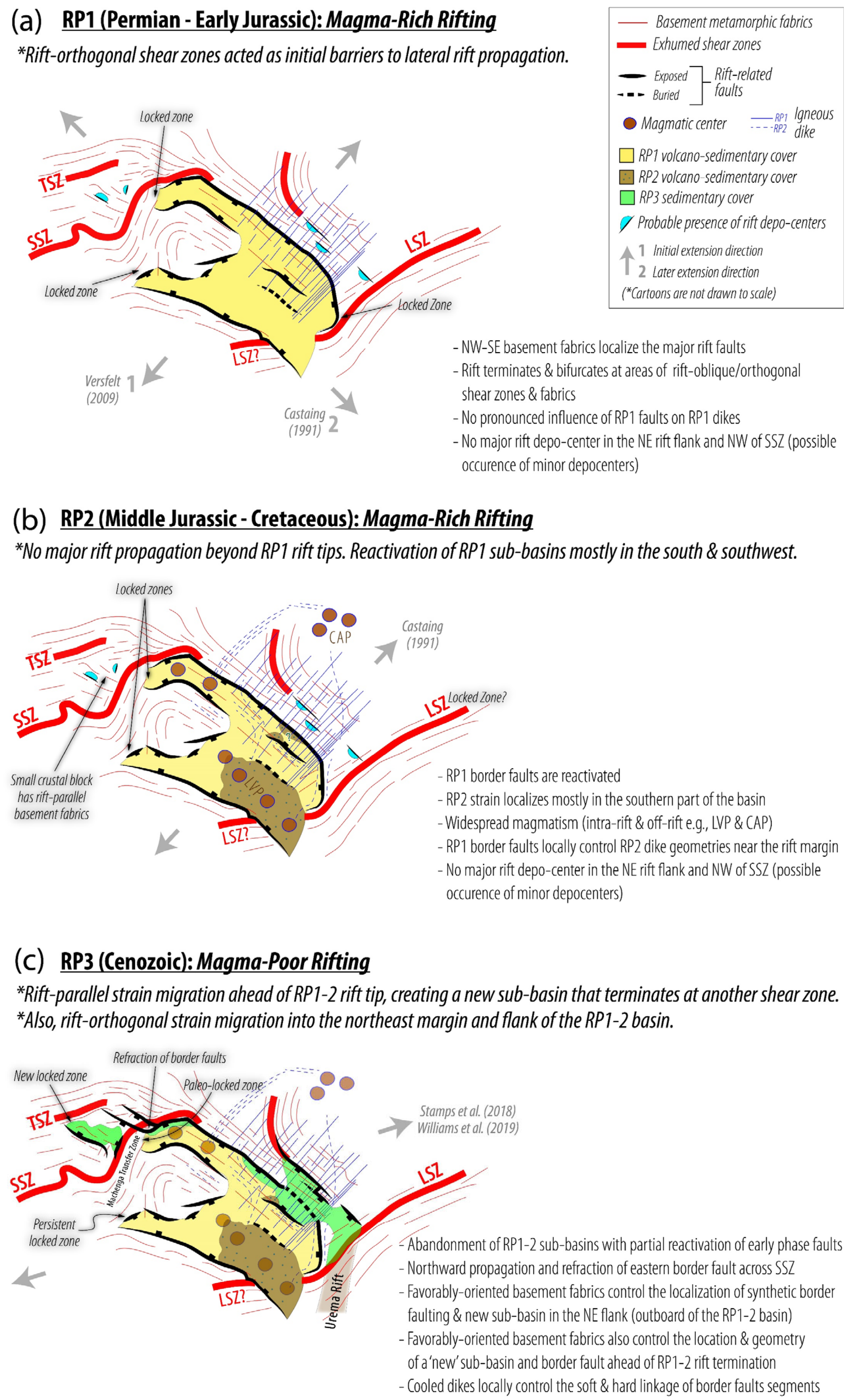


Figure 11. Cartoons summarizing the multiphase evolution and strain migration in the Shire Rift Zone, based on observations in this study. LSZ: Lurio Shear Zone, MDC: Mulata Dike Cluster, SSZ: Sanangoè Shear Zone.

The large-scale alignment of the early-phase border faults with those of the underlying pre-rift basement metamorphic fabrics suggests that the border fault likely exploited the basement fabrics during rift initiation. Due to limited field access, we are only able to assess the 3-D component of the alignment in the Malawi extension of the SRZ. However, our observations along the Mwanza Fault escarpment show a correspondence between the strike, dip magnitude, and dip direction of the basement fabrics with those of the border fault. The gneissic basement foliation along the SRZ border faults constitute planes of mechanical weakness that was exploited by brittle deformation during the early-rift extension (e.g., Donath, 1961; Youash, 1969; Ranalli and Yin, 1990; Morley, 1999, 2010). However, the inferred NW-SE regional extension direction for RP1 (Castaing, 1991) is not compatible with the development of NW-trending faults, and even less likely in a crust with NW-trending pre-rift mechanical anisotropy (Youash, 1969; Morley, 1999). Although Castaing (1991) inferred strike-slip kinematics for the RP1 rifting, the rift structure lacks the map-view rhombic geometry or associated Reidel pattern faulting that is typical of strike-slip and transtensional basins.

Thus, we argue that it is more likely that the SRZ first accommodated a NE-oriented tectonic extension during early RP1, and in late RP1, the rotation of extension direction into a NW-SE direction facilitated an oblique-normal or strike-slip reactivation of the early rift border faults (Figure 11a). This is supported by the Lower Jurassic age (late RP1) of the magmatic diking of the rift (Habgood, 1963) upon which the inference of NW-SE-oriented $\sigma3$ was based. We infer that the basement fabrics could have been favorably-oriented for brittle exploitation by the early rift border faults within the NW-directed early-RP1 extension direction. Such favorably-oriented planes of mechanical weakness in the basement have been noted to facilitate the localization of the early-rift border faults in other Karoo rifts that were coeval with the SRZ (e.g., Rukwa and Luama Rift; Wheeler and Karson, 1994; Kolawole et al., 2021a). This interpretation of basement inheritance is consistent with previous observations in different parts of the SRZ (e.g., Cooper and Bloomfield, 1961; Castaing, 1991; Williams et al., 2019; Wedmore et al., 2020a) and other rift segments of the East African Rift System (Kinabo et al., 2007; Morley, 1999, 2010; Wheeler and Karson, 1989, 1994; Kolawole et al., 2018; Heilman et al., 2019).

5.3.2 Later-Phase (RP3) Border Faulting

The Cenozoic (RP3) sub-basins in the SRZ: the Lower Shire and Chiuta Sub-basins, developed in the hanging walls of border faults with prominent escarpments and along which the RP3 sedimentary rift-fill is thickest (Figures 5c-e, 6a-b). However, we note that although the southern sections of the Mwanza Fault that are buried beneath Quaternary sediments (dashed Mwanza fault trace in Figure 8) do not appear to be active in the current rift phase, the northern sections of the fault have been partially reactivated. This partial reactivation is inferred from the presence of narrow zones of Quaternary sedimentary cover along the northern Mwanza Fault (see Figure 3).

The Thyolo, Muona, Chisumbi, and Camacho faults define distinct segments of a system of synthetic border faults along the Lower Shire Graben (Figures 8, 10a-b). All three segments show side-stepping geometries among which the Thyolo and Muona segments are hard-linked by the Chisumbi segment but soft-linked with the Camacho Fault (Figures 6a-b). The northwesternmost segment, the Thyolo Fault, side-steps basinward to the right and overlaps with the Muona Fault, which extends ~27 km SE and side-steps to the left towards the hinterland where it overlaps with the Camacho Fault (Figure 8). The Camacho Fault terminates to the SE near the NE-trending Precambrian Lurio Shear Zone (LSZ) where the basin geometry rotates from the NW-SE trend into a N-S trending graben and transitions into Urema Graben (Figure 5). These faults are active in the current regional normal faulting stress field (Williams et al., 2019). The large-scale alignment of the Thyolo and Muona faults with the basement metamorphic fabrics suggests that these border fault segments likely localized by exploiting of the basement fabrics at depth (Hodge et al., 2018). It has been proposed that the Thyolo border fault likely exploited a Precambrian terrane boundary that terminates the Unango Complex to the south (Wedmore et al. (2020a). This interpretation of structural inheritance is further supported by the non-optimal orientation of the NW-trending basement fabrics to the current ENE-trending regional extension direction (Williams et al., 2019).

However, we also find evidence of possible control of rift-orthogonal intra-basement structures on the hard- and soft-linkage, and termination of the side-stepping Lower Shire border fault segments. In the hanging wall of the Thyolo Fault, the aeromagnetic grids reveal a magnetic gradient defining a northwestward continuation of the Muona Fault beneath the Quaternary sediments (Figures 10a-b). This buried Muona Fault continuation is truncated and separated from the exposed southeastern section of the fault by the NE-trending Chisumbi Fault which physically connects the exposed Muona Fault to the Thyolo Fault (Figures 10a-b). Similarly, the Chisumbi Fault defines the boundary between the northwestern section of the Thyolo Fault hanging wall with Quaternary cover from the southeastern section where there is no sedimentary cover (Figure 2). Essentially, the Chisumbi Fault breached the relay zone between the Thyolo and Muona Faults sometime after the faults had been established, and hard-linked them together (also see Wedmore et al., 2020a). However, our field data on the strike and dip of the cooled RP1 mafic igneous dikes along the rift shoulder (Figure 9civ) shows an alignment of the Chisumbi Fault with the intra-basement dikes, suggesting that the hard-linkage of the border fault segments was facilitated by the brittle exploitation of the cooled intra-basement dikes (Figure 10b). The mechanical contrast created by the mafic dike contacts could have localized the hard-linking fault segment. This interpretation is also consistent with a recent field study of the Thyolo-Chisumbi-Muona Fault (Wedmore et al., 2020a).

Additional observation of possible brittle deformation localized by the cooled early-phase dikes is shown in the filtered aeromagnetic images along the northern and southern boundaries of the buried ~60 km-long southern section of the Mwanza Fault. The images reveal transverse truncation and offset of the NW-trending fault along the contacts of the NE-trending dike lineaments ("T" in Figures S4c and S5b). These truncations are more pronounced at the northern tip of the Namalambo Fault where the dikes appear to align with and follow the NE-trending basement fabrics along trend (Figure S5b). We interpret that the truncating structures are shallow transverse faults that exploited mechanical anisotropies within the cooled dike swarms (e.g., dike contacts), consistent with observations elsewhere in the North Sea Rift (Phillips et al., 2017). These transverse faults appear as oblique-normal faults that cut the pre-existing well-developed border faults in RP3 (Figure S5b), or served as side-stepping faults (Figure S4c), to accommodate the subsidence of the Lower Shire Graben along the hanging walls of the RP3 border faults as strain has now migrated away from the older Mwanza-Namalambo border fault. Thus, we suggest that the RP3 subsidence and burial of the southern Mwanza Fault, a major long-lived RP1-RP2 border fault of the SRZ is related to both the subsidence of the Thyolo-Muona Fault and Panga Fault hanging walls and subsidiary faulting along the transverse faults. However, we do not rule out a possibility of reactivation of the buried Mwanza Fault segment prior to and after its burial.

At the distal northwest, major border faulting along the SRZ is defined by the Chiuta Fault (Figures 5a and 6b) where the fault and its sub-basin developed within a zone of NW-trending basement fabrics (Figures 4b and 5a). The alignment of the Chiuta Fault with the bounding basement fabrics (Figures 4b, 9a, and 9f) suggests that the nucleation of the fault also exploited the basement fabrics.

5.4 Inheritance of Resisting Structures: Transient Barriers to Continuous Lateral Rift Propagation in the Crust

5.4.1 Rift-Orthogonal Intra-Basement Shear Zones

Based on basement field studies in the northwestern parts of the SRZ (Barr and Brown, 1987; Evans et al., 1999), we suggest that the large-scale bifurcation structure of the SRZ and geometry of its branches are influenced by the crustal-scale ENE-trending Precambrian Sanangoè Shear Zone (SSZ; Figures 1a-b, and 5a-b). Filtered aeromagnetic grids show that the southwestern branch of the SRZ (i.e., the Moatize Sub-basin) terminates at a zone of ENE-trending metamorphic fabrics corresponding to gneisses, schists, and diabase dikes of the underlying Proterozoic basement terrane (fabrics in the northern parts of Txizita Horst in Figures 4b and 9a). Within this zone of termination, the northeastern branch rotates counter-clockwise to the west and the Mwanza border fault splays into two NW-trending segments near its intersection with the SSZ (Figure 5a). Within this region of border fault splay, the basement is exposed, defining a termination of the RP1-RP2 graben along the northeastern branch, and we here-in refer to as the 'Machenga Transfer Zone, MTZ' (see location in Figures 5a-b). Although the Chiuta Sub-basin is localized to the north of the MTZ, its southern bounding fault is oriented ENE-WSW, following the trend of the SSZ (Figure 5b).

Thus, we infer that the initial termination and stagnation of the RP1-RP2 SRZ rift tip was controlled by the SSZ which possibly represented a mechanical barrier to continued early-phase lateral propagation of the rift zone. Also, we note that although in RP3 tectonic strain migrated further northwest of the SSZ, represented by the Chiuta Sub-basin, the RP3 sub-basin also terminates near another zone of ENE-trending basement fabrics with a plunging ductile shear zone (Techigoma Shear Zone, TSZ; Figures 4b, 5a, and 5a inset). Furthermore, we suggest that the establishment of the Chiuta Sub-basin was facilitated by strain localization within an isolated crustal block of NW-trending basement fabrics that is located ahead, but proximal to and colinear with the earlier established RP1-RP2 rift zone. To the southwest, the RP1-RP2 border fault system either terminates at the NE-trending Lurio Shear Zone (Namalambo Fault) or rotates and forms a kink geometry at its intersection with the shear zone (Tete Fault System) (see 'NF ' and 'TFS' geometries in Figure 5a). We also note that the southern tip of the Namalambo Fault rotates clockwise into the NE trend of the shear zone. These exhumed intra-basement shear zones are crustal-scale boundaries between different basement terranes (Barr and Brown, 1987; Kröner et al., 1997; Evans et al., 1999; Bingen et al., 2009). These observations lead us to infer that the rift-orthogonal crustal-scale intra-basement shear zones acted as mechanical barriers that influenced the initial termination of the Shire Rift Zone during RP1 and RP2, and again terminated the newly localized RP3 sub-basin at the northwestern rift tip during the current phase of extension (Figures 11a-c). In essence, these shear zones influenced the pulse pattern of multiphase lengthening of the rift zone.

The NE trend of the shear zones is misoriented for brittle reactivation in the current regional ENE-extension direction, and this 'misorientation' of the mechanical anisotropy created by the shear zones may have damped the stress concentration at the propagating rift tips. However, we suggest that the lateral variation of crustal strength across the shear zones, and the broader rheological domain around the shear zones (e.g., up to 8 km wide zone of metamorphic deformation and gabbroic intrusions along the SSZ) most likely influenced the temporary stagnation of rift tips near the shear zones. This interpretation is consistent with models in Courtillot (1982) which demonstrated that propagating rift tips can become stagnated at strong ribbons of the crust referred to as 'locked zones'. Van Wijk and Blackman (2004) further showed that the lateral propagation of a rift tip is stalled within strong pre-rift continental crust, such that during the stall phase, shear stresses progressively build up near the rift tip to facilitate a later resumption of lateral rift propagation.

In the SRZ, the counterclockwise rotation and splaying of the Mwanza border fault across the SSZ can be interpreted to represent refraction of the propagating border fault during the resumption of rift propagation in RP3. This interpretation is consistent with observations of normal fault splaying across misoriented crustal terrane boundaries along the path of lateral propagation of rift zones in the Great South Basin, New Zealand (Phillips et al., 2019b). Numerical models also demonstrate the temporary stagnation of propagating rift tips at terrane boundaries that are rift-orthogonal and bound terranes of contrasting crustal strength (Phillips et al., 2021). In addition, observations in other areas of early-stage continental rifting show that rift zones and their bounding faults terminate at major rift-oblique/orthogonal basement shear zones, for example, the termination of the Okavango Rift at the Sekaka Shear Zone (Kinabo et al., 2007), and the termination of the Rhino Rift at the Aswa Shear Zone (Figure 1a; Katumwehe et al., 2015; Kolawole et al., 2021b). Another possible example is the termination of the southern Main Ethiopian Rift at a rift-oblique basement terrane (Kounoudis et al., 2021).

5.4.2 Cooled Early-Rift Mafic dikes

In addition to the larger scale influence of intra-basement shear zones on rift termination, we also note that the cooled early-phase (RP1) magmatic plumbing structures of the basement beneath the SRZ may have influenced the arrangement and termination of the later phase (RP3) border fault segments. The cooled early-phase dikes did not only facilitate the hard-linkage, it appears that the dikes also facilitated the soft-linkage of the border fault segments in the Lower Shire Graben (Figures 10a-b). Both the Thyolo and Muona Fault segments terminate to the southeast at a zone of conjugate-pattern dike clusters consisting of N and NW-trending dike sets (see dike clusters in Figures 10a-b). Likewise, the western tip of the Camacho Fault terminates at the Mulata Dike Cluster. We interpret that the inherited early phase dikes posed mechanical barriers to the lateral propagation of each RP3 border fault segment, resulting in the nucleation of multiple synthetic border fault segments that are soft-linked across the zone of conjugate dike cluster.

This may also imply that at this initial stage of development, the maximum lengths of the fault segments are delimited by the inherited cooled dikes.

In summary, during the pulsed or episodic propagation of a rift segment, inherited intra-basement strength anisotropies can act as both strain-localizing and strain-inhibiting tectonic elements within the lithosphere. We suggest that these mechanisms play important roles in the evolution of continental rift segment architecture during the early stages of continental extension.

6 CONCLUSIONS

We investigated the large-scale architecture and evolution of the Shire Rift Zone (SRZ) over the three phases of tectonic extension (RP1, RP2, and RP3) that are recorded in the basin. We compiled and integrated all available surface and subsurface datasets to better understand the pre-rift basement structure, major syn-rift depo-centers (sub-basins), the border fault structure, and their spatiotemporal distribution. Our results show that although the SRZ is characterized by seven major sub-basins, the RP3 (Cenozoic) sub-basins were activated at later phase of rifting. Overall, among the seven sub-basins, five are magmatic (deposition of volcanics and/or igneous intrusion in sedimentary units) and two are non-magmatic. Thus, we infer that the two non-magmatic sub-basins were likely established in RP3, the current phase of rifting, during which the RP1-RP2 sub-basins were largely abandoned, and strain migrated and localized both at the eastern rift margin and ahead of the initial rift termination zone.

We propose that the SRZ propagated in a pulsed manner over the three phases of extension, and we provide evidence suggesting that although the border faults largely exploited the NW-trending basement metamorphic terrane fabrics, the transient stagnation zones of the rift tips during each rift phase were influenced by rift-orthogonal terrane boundary shear zones. In essence, we argue that during the pulsed propagation of a continental rift segment, inherited strength anisotropies can serve as both strain-localizing, refracting, and possibly, temporarilyy strain-inhibiting tectonic elements in the lithosphere.

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DATA AVAILABILITY

The Shuttle Radar Topography Mission (SRTM) dataset used in this study can be freely obtained from the United States Geological Survey database https://earthexplorer.usgs.gov. The southern Malawi Total Magnetic Intensity (TMI) dataset can be freely obtained from the Interdisciplinary Earth Data Alliance (IEDA) at doi:10.1594/IEDA/324860 (Nyalugwe et al., 2019b).

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