Knickpoint Morphotectonics of the Middle Shire River Basin: Implications for the Evolution of Rift Interaction Zones

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Abstract

Tectonic and paleo-environmental reconstructions of rift evolution typically rely on the interpretation of sedimentary sequences, but this is rarely possible in early-stage rifts where sediment volumes are low. To overcome this challenge, we use geomorphology to investigate landscape evolution and the role of different forcing mechanisms during basin development. Here, we focus on the humid Middle Shire River basin, located within the zone of progressive interaction and linkage between the southern Malawi Rift and Shire Rift Zone, East Africa. We used a digital elevation model to map knickpoints and knickpoint morphologies in the Middle Shire River basin and examined the relationships with pre-rift and syn-rift structures within the rift interaction zone. The main axial stream, Shire River, descends steeply, 372 m over a 50 km distance, across exposed metamorphic basement along the rift floor, exhibiting a strongly disequilibrated longitudinal elevation profile with both ‘mobile’ and ‘fixed’ knickpoints. In particular, we identify two clusters of mobile knickpoints, which we interpret as associated with baselevel fall events at the downstream end of the exposed basement that triggered knickpoint migration through the fluvial network since at least the Mid. Pleistocene. We infer that after the integration of the axial stream across the Middle Shire Basin, the knickpoints migrate upstream in response to fault-related subsidence in the Shire Rift Zone. Conversely, the fixed knickpoints are interpreted to reflect local differential bedrock erodibility at lithologic contacts or basement-hosted fault scarps along the basin floor. The results suggest that Middle Shire basin opening, associated with rift linkage, is likely a recent event (at least Mid. Pleistocene) relative to the Late Oligocene activation of Cenozoic rifting in the East African Rift’s Western Branch. These findings support the hypothesis that the Western Branch developed from the gradual propagation, linkage, and coalescence of initially nucleated distinct rift basins.

Keywords: Knickpoints, Malawi Rift, Rift Interaction Zones; Tectonics

Introduction

Landscape evolution is a complex process where quasi-equilibrium is maintained by a range of factors but particularly tectonism (Ebinger and Scholz, 2011; Burbank and Pinter, 1999) and climate (Tiercelin, 1990; Hartshorn et al., 2002; Bookhagen et al., 2005; Ferrier et al., 2013). In tectonically-active areas such as the East African Rift System (EARS), landscapes are highly dynamic, resulting in the interaction of various geomorphological processes (Bailey et al., 2000; Gawthorpe and Leeder, 2000; Flores-Prieto et al., 2015), including the progressive adjustment of the drainage networks to tectonic surface deformation. However, the interaction of climate and tectonics also complicates the process of environmental reconstruction, particularly in environments where suitable proxies are not available (Moore et al., 2009).

Early-stage rifts, where crustal thinning is minimal and magmatic systems are yet to develop (Ebinger et al., 2004; Chenin et al., 2018), are important for understanding the development of continental rifts as they set up the location of continental breakup margins. However, although seismic reflection datasets, commonly available in rifted margins, provide excellent images of the syn-rift stratigraphy, the typical low sediment volumes of early-stage rifting inhibit detailed investigation and paleoenvironmental reconstruction in these settings. Thus, active early-stage rift zones, such as the humid rift basins along the Western Branch of the East African Rift System, present an excellent opportunity to explore the salient geomorphic structure and landscape evolution peculiar to early-stage rifting. In such settings, geomorphic indicators such as drainage patterns, channel geometry, river behavior, knickpoints, and slope attitudes provide insights into the interactions between active crustal deformation and landscape evolution (e.g., Vita-Finzi, 2012; Castillo et al., 2013; Kent et al., 2021; Gallen and Fernández-Blanco, 2021; Molin and Corti, 2015; Jiang et al., 2016).

Knickpoints are inflection points in longitudinal river profiles that demarcate a sudden change in river steepness steep sections along an otherwise smooth concave river profile, and are among some of the most widely used geomorphic features for the reconstruction of fluvial basin evolution and for the isolation of the roles of different forcing mechanisms (e.g. Phillips et al., 2010). Knickpoints can vary in form from short and discrete changes in river gradient (e.g. single waterfalls) to longer, higher-gradient segments extending for many kilometers also called knickzones (Whipple et al., 1999; Crosby and Whipple, 2006; Kirby and Whipple, 2012).Knickpoint formation is often triggered by a relatively sudden drop in river baselevel or change in baselevel fall rate that propagates throughout a fluvial network causing a transient response in the landscape (Castillo et al., 2013). However, the origins of knickpoints are not unique and can include tectonic movements, Quaternary glaciations, river captures, and local baselevel changes due to differential erosion between rocks of different competencies (Crosby and Whipple, 2006; Marrucci et al., 2018; Gallen et al., 2013; Gallen, 2018). Similar to other geomorphic proxies, the factors controlling knickpoint evolution may not always be independent or mutually exclusive (Boulton et al., 2014).

In this study, we investigated the mechanisms of landscape evolution in the humid Middle Shire River basin, hosted within a zone of tectonic interaction between the southern Malawi Rift and the Shire Rift Zone (Figures 1c-d). The study area is located along the Western Branch of the East African Rift system, where several studies hypothesize a model of rift growth by an initial nucleation of distinct rift basins that gradually linked together (Ebinger et al., 1989; Nelson et al., 1992; Corti et al., 2007; Heilman et al., 2019; Kolawole et al., 2021; Jess et al., 2021). However, the details of landscape evolution within actively deforming rift interaction zones (RIZs) needed to test this hypothesis remain a longstanding knowledge gap. The Middle Shire's position between the southern Malawi Rift and Shire Rift Zone, and its youthful nature, as indicated by the sparseness of syn-rift deposits (Williams et al., 2022), indicates that it is an ideal natural laboratory for understanding how continental rifts progressively evolve in space and time.

We perform a geomorphic analysis by utilizing drainage pattern geometry and knickpoints to investigate the morphotectonics of the Middle Shire River basin. In doing so, we show how the axial stream morphology is guided by syn-rift faults, pre-existing basement lithological contacts, and changes in baselevel at the downstream end of the rift interaction zone. We then use features associated with the latter process to provide quantitative constraints on the possible timing of rift propagation and linkage across the rift interaction zone. The results of this study, therefore, advance the understanding of the spatio-temporal evolution of rift segment interaction and landscape evolution in continental rift zones.

2 The Middle Shire River Basin

2.1 Location and Hydrology

The study area is located in southern Malawi between latitudes 15^{o} 30’ S and 16^{o} 00’ S and bounded by the Malawi-Mozambique border to the west (approximately longitude 34^{o}30’ E) and longitude 35^{o} 00’ E to the east (Figures 1). The hydrology of southern Malawi is dominated by the Shire River, Malawi’s largest river, and Lake Malawi’s single outlet to the Zambezi River (Figure 1b, although it should be noted that ~90% of annual water loss from Lake Malawi is through evaporation (Drayton et al., 1984)). The river is critical to the country’s socio-economic development as it supports irrigated agriculture and electricity generation. Electricity in Malawi is predominantly hydro-generated, with about 80% being produced from the Middle Shire section of the river (Taulo et al., 2015).

The Shire River is geographically divided into three main sections (Figure 1b), the Upper Shire (the northernmost segment), the Middle Shire, and the Lower Shire (the southernmost segment). The Upper Shire River runs from Lake Malawi at Mangochi (ca. 485 m above mean sea level (amsl)) to the Matope area (ca. 472 m amsl), following an arcuate bend in the Malawi Rift as it transitions from the NNW-trending Makanjira Graben to the NNE-SSW trending Zomba Graben (Figures 1b and c; Dulanya et al., 2017; Wedmore et al., 2020a; Williams et al., 2019, 2021). Along this section, the Shire River flows over unconsolidated alluvium and colluvium (Shela, 2000) and is characterized by meanders with a high sinuosity index (~1.17; Kolawole et al., 2021), reflecting the low topographic gradient (15 m) of the 130 km-distance between Mangochi and Matope. This lower gradient is also reflected by records of the Upper

Shire silting up in the early 20thcentury, and causing the upper 65 km section of the river to temporally flow back into Lake Malawi (Dixey 1924).

The boundary between the Upper and Middle Shire sections is where the river crosses the ENE-dipping Mlungusi Fault (Wedmore et al., 2020a) at Matope (ca. 472 m amsl, Figures 1b-d). At this point, the Shire River flows through a series of rapids and gorges that have recently been incised through basement rock to Chikwawa Town (at ca. 100 m amsl), thus losing a height of nearly 380m over a distance of 50 km. This very steep gradient relative to the Upper Shire section results in a considerably lower sinuosity index (~1.04; Kolawole et al., 2021).

The Middle Shire River is characterized by erosion and narrow steep-sided river sections reflecting recent incision (Bloomfield and Garson, 1965a; Lister, 1967; Kolawole et al., 2021). A number of prominent rivers, some of which are tributaries of the Shire River, originate in the Middle Shire section, including the Lisungwe and Wamkurumadzi Rivers. These rivers have made deep incisions into the surrounding country rocks and reflect active denudational processes in the area. The course of the Lisungwe River in the area close to the Middle Shire section is deeply incised, occurring at a lower altitude than the Middle Shire River section. The differences in vertical heights between the two rivers in the Middle Shire section range from about 100 m near Matope to about 20 m near its confluence with the Shire River. Geological structure played a major role in the hydrology of this section in that the Shire and Lisungwe Rivers are fault-controlled for most of their parts (Bloomfield, 1965; Bloomfield and Garson, 1965a). Geomorphological evidence acquired from drainage morphology seems to suggest that there has been drainage network reorganization that affected a number of rivers and streams whose watercourses have been redirected into or away from the Middle Shire since the Late Cretaceous/Early to Mid-Tertiary (Tweddle et al., 1979; Bloomfield and Young, 1961).

In the Lower Shire section, the Shire River meets the Mwanza River, which originates from the west near the border with Mozambique and flows along the Karoo-reactivated Mwanza Fault (e.g.Castaing 1991; Moore et al., 2007; Figure 1b). It may therefore reflect the original course of the Shire River prior to its linkage with the Upper Shire. The Lower Shire Section is characterized by a low gradient (~1 m elevation over 5 km distance), ox-bow lakes, meanders, and high sinuosity index (~1.28; Kolawole et al., 2021), similar to the Upper Shire section. Across this section, the Shire River flows southeast across the hanging-wall of the Thyolo Fault (Wedmore et al., 2020b) into a broad floodplain past Chikwawa Town and towards its confluence with the Zambezi River in Mozambique.

2.2 Climate

Malawi has two main seasons; a cool dry season between May and October with a mean temperature of ~13 °C in June and July, and a hot wet season between November and April, where the mean temperature ranges between 30 and 35 °C (Nicholson et al., 2014). Rainfall is variable depending on altitude, ranging from 600 mm/yr on the rift valley floors to 1600 mm/yr in mountainous areas. The climate of the region is largely influenced by the seasonal migration and intensity of the intertropical convergence zone (ITCZ), a low-pressure belt within the Congo basin caused by tropical high-pressure belts over both the Indian and Atlantic Oceans (Nicholson, 2001;

Nicholson et al., 2014) and the Congo Air Boundary (CAB), controlled by sea-surface temperature (SST) anomalies such as the Indian Ocean Dipole (IOD) and El Niño/ Southern Oscillation (ENSO) system (Abram et al., 2007; Saji et al., 1999).

General circulation models have shown that African climates are highly sensitive to high latitude glaciations (de Menocal, 1995; Gasse et al., 2008; Clark et al., 2009; Stone, 2014). For example, the Pleistocene-Holocene climate generally shows a succession of wet-dry cycles driven by global and regional circulation that affect the region with various patterns and intensities (e.g.Gasse, 2000; Filippi and Talbot, 2005; Thomas et al., 2009; Boxclaer et al., 2012). Although the climate in the region is extremely variable, lake sediment cores from Lake Malawi, which forms the main catchment basin of the Shire River, have shown generally stable climate regimes for the last 75 ka (Scholz et al., 2007, 2011). This is unlike the140-70 ka BP period which was characterized by megadroughts around 135–105 and 105–75 ka BP (Scholz et al., 2007, Konecky et al., 2011; Beuning et al., 2011).

2.3 Paleogeography

Paleoclimate reconstructions show that the level of Lake Malawi has been highly variable since the Mid-Pleistocene (800-900kyr) with lowstands of up to 600m (Lyons et al., 2015, Ivory et al., 2016). However, over the last 75 ka of relative climate stability, the lake level has been relatively stable with consistent highstand conditions (levels 0-100 m below modern lake level; Scholz et al., 2007; Lyons et al., 2015).

The timing at which the Upper and Middle sections of the Shire River became an established connected river corridor and as Lake Malawi's main outlet are uncertain. The South Basin of Lake Malawi, which feeds the river, is thought to have evolved in the

Late Miocene – Mid. Pliocene (Scholz et al., 2020). Based on paleoenvironmental changes in Lake Malawi, Ivory et al. (2016) suggest that it was not until 800 Ka that the Shire River became Lake Malawi's main outlet. However, units of yellow to brown medium- to coarse-grained sands ranging in thickness from a few metres to hundreds of metres, known as the Chipalamawamba Beds, have been mapped in the vicinity of Lake Malombe (Figure 1a,b) and were dated to be Early – Mid. Holocene (van Boxclaer et al., 2012). The stratigraphic characteristics of these syn-rift deposits (van Boxclaer et al., 2012) suggest a lacustrine to riverine environment, interpreted to have been deposited during the development of the Shire River as Lake Malawi's outlet (van Boxclaer et al., 2012). Therefore, it is unclear if the Upper Shire began to drain Lake Malawi in the Mid-Pleistocene (~800 Ka) as suggested by Ivory et al. (2016) or the Early-Middle Holocene as suggested by van Boxclaer et al. (2012). The Lower Shire River is probably the oldest section of the Shire River which may have developed during the Permo-Triassic (Karoo) or Cretaceous phases of rifting in the Shire Rift Zone, associated with the Gondwana fragmentation (Castaing, 1991; Kolawole et al., 2022 preprint).

2.4 Geology and Tectonic Setting of Southern Malawi

2.4.1 The Precambrian Basement

The Middle Shire River Basin sits on a crystalline basement that is comprised of Proterozoic metamorphic rocks of both igneous and sedimentary parentage (Figure 2). These metamorphic rocks form part of the Southern Irumide orogenic belt (Mesoproterozoic age) that underwent amphibolite-granulite facies metamorphism during the Pan-African Orogeny (~800-450 Ma.; Kröner et al., 2001; Fritz et al., 2013; Manda et al., 2019). Typical assemblages include various gneisses and charnockitic granulites of the Unango Terrane, part of the Mozambique Belt (Fullgraf et al., in press), with some intercalations of pelitic schists and paragneisses, calc-silicate rocks and marbles. Various orthogneissic rocks, including granitoid and basic orthogneisses, are associated with ring complexes found in the area (Bloomfield, 1958a; Bloomfield and Garson, 1965a, b; Walshaw, 1965; Evans, 1965; Habgood and Walshaw, 1965; Habgood, 1963; Morel, 1958). A prominent marble horizon is found along the amphibolite-granulite facies contact for nearly 40 km and forms a useful marker horizon of the boundary between these lithological units (Carter and Bennett, 1973).

2.4.2 Phanerozoic Geology and structural History

Structural studies in the south Malawi area indicate three main successive rift phases: the Karoo (NW-SE extension), the Cretaceous (NE-SW extension) and Cenozoic East African Rift System (ENE-WSW extension; Castaing, 1991; Wedmore et al. 2021). A sequence of Permian-Triassic sediments was deposited during Karoo rifting in the Lower Shire Graben (Habgood 1973, Castaing, 1991), but there is no evidence of Mesozoic sediments in the Upper and Middle Shire. In the Lower Jurassic, NE-SW striking Stormberg dolerite dykes were emplaced (Castaing, 1991) and then followed by a distinct period of upper Jurassic-Lower Cretaceous alkaline magmatism, which occurred throughout southern Malawi and is referred to as the Chilwa Alkaline Province (CAP; Bloomfield, 1965; Castaing, 1991; Dulanya, 2017; Eby et al., 1995; Woolley, 2001). Rocks of the CAP include syeno-granites, carbonatites, agglomerates, foidolites and associated alkaline dykes (Woolley, 2001) and are widespread within the study area where they have a general ENE parallel strike to the Ntembwe Fault (Bloomfield and Garson, 1965a). Within the Lower Shire section, Cretaceous sandstones and marls belonging to the Lupata Group rest unconformably above the Karoo Group (Figure 2; Habgood and Walshaw, 1963; Habgood, 1965; Dixey, 1924).

2.5 Active Faulting and Quaternary Geology in the Middle Shire River Basin

Geodetic models suggest that the southern Malawi Rift is currently accommodating 0.5-2 mm/yr ENE-WSW -oriented extension between the Rovuma and San Plates (Stamps et al., 2018; Wedmore et al., 2021). Rift-scale earthquake focal mechanism stress inversion also indicates a regional ENE-WSW-trending minimum compressive stress, although, at the scale of individual faults, local stress rotations are possible (Williams et al., 2019). The tectonic style of the Middle Shire is dominated by a set of curvilinear rift faults striking NW to N that extend northwards from the Lower Shire Graben Rift Zone to the Southern Malawi Rift's Zomba Graben (Figure 3; Kolawole et al., 2021). These are intersected by an orthogonal set of fractures with a NE-strike. The kinematics and geometry of these fractures are unclear, and the NE-striking fractures may be linked to the Karoo dolerite dyke emplacement, pre-existing metamorphic fabrics, poorly developed southwestward extension of the Zomba Graben faults, or extensional segments of a potential transverse NE-striking strike-slip fault in the Zomba Graben such as the Ntembwe Fault (Bloomfield and Garson, 1965a; Dulanya, 2017; Figure 3).

The Middle Shire River links the Zomba Graben and Lower Shire Graben (Ebinger et al., 1989; Lao-Davila et al., 2015; Dulanya et al., 2017; Williams et al., 2019; 2021; Wedmore et al., 2020a; Wedmore et al., 2020b; Kolawole et al., 2021). The two grabens represent distinct rift sub-basins of which the former is in the Malawi Rift, oriented NNE, sits at a higher elevation, and hosts only Cenozoic syn-rift deposits; whereas the latter is in the Shire Rift Zone, oriented NW-SE, and hosts both Mesozoic and Cenozoic syn-rift deposits (Chisenga et al., 2019; Kolawole et al., 2022 preprint). The Lower Shire section of the rift is currently active with deformation hosted on reactivated Karoo faults (Castaing 1991; Chisenga et al., 2018; Wedmore et al., 2020b).

The Middle Shire section does not have well-developed basins for sediment deposition, which could be useful for disentangling its paleoenvironmental and tectonic history (Dulanya, 2017). Quaternary sediments are rare and thin (<100 m thick) in the Middle Shire area; however, assorted fluvio-lacustrine superficial deposits are present along major drainage features (Dulanya, 2017; Bloomfield and Garson, 1965a) and could provide evidence of the recent paleoenvironmental history of the area where they are present. Unconsolidated fluvial deposits previously described as black cotton clays (Morel, 1958) occur in an area about 5 km southwest of the Lisungwe-Shire River confluence covering an area of ca. 25 km^2 (Figure 2). The outcrop is elongated ~NNW-SSE, generally parallel to the strike direction of the prominent rift-related faults in the area. Despite the minimal late Cenozoic sedimentary record, the Middle Shire section possesses some remarkable geomorphotectonic features such as rapids, falls and gorges, which we investigate here for paleoenvironmental reconstructions.

3. Methodology

In erosional landscapes, the shape of river profiles largely dictates topographic relief (e.g. Mackin, 1948; Morisawa, 1962; Gilbert, 1877). It has been shown that graded, equilibrated river profiles exhibit a power law scaling between local channel slope (S) and upstream contributing drainage area (A) (Morisawa, 1962; Flint, 1974; Kirby and Whipple, 2012), given by:

$$S = k_s A^{-\theta} \qquad \textit{(equation I)}$$

where θ is the concavity index and k_s is the channel steepness index.

Because empirically calculated values of θ and k_s covary, a reference concavity index (θ_{ref}) of ~0.45, typical of graded river profiles, allows for the calculation of the normalized steepness index (k_{sn}) and the comparison of channel steepness across different drainage areas.

Simplified versions of the detachment-limited stream power model, which is appropriate for approximating long-term incision in bedrock channels, can be solved to arrive at a similar expression to equation 1. The detachment-limited stream power model simulates bedrock incision, E, as (Howard, 1994; Whipple and Tucker, 1999):

$$E = KA^m S^n \qquad \textit{(equation 2)}$$

where K is an erodibility coefficient and m and n are positive constants that reflect aspects of basin hydrology, channel hydraulic geometry, and incision process, among other phenomena (Whipple, 2004). Equation 2 can be solved for local channel slope to show:

$$S = (E/K)^{1/n} \mathrm{A}^{\text{-m/n}} \qquad \textit{(equation 3)}$$

Comparison of equations 1 and 3 suggests that k_s or k_{sn} = $(E/K)^{1/n}$ and $\theta = -m/n$. Noting that incision rates respond to rock uplift rates, at steady-state (E=U), these relationships suggest that k_{sn} is a sensitive recorder of the spatial and temporal patterns of incision rate and by association rock uplift rate (Snyder et al., 2000; Wobus et al., 2006; Anoop et al., 2012; Kirby and Whipple, 2012) but could also be affected by choice of the DEM (Boulton and Stokes, 2018) which could be a source of error in our work.

Typical values of m and n vary widely, but their ratio is typically between ~0.3 and 0.7 (Snyder et al., 2000; Wobus et al., 2006; Kirby and Whipple, 2012), and some studies have shown that concavity index (e.g., m/n) increases with tectonic activity (Harel et al., 2016; Seybold et al., 2021) and decreases with increasing aridity (Harel et al., 2016; Chen et al., 2019). Regardless of these variations, the general consistency of the m to n ratio among numerous natural landscapes suggests that these parameters covary. The n parameter has been more widely studied than the m parameter, and in natural settings generally varies between 0.5 and 4 but might be as high as 7 (DiBiase and Whipple, 2011; Royden and Perron, 2013; Lague, 2014; Harel et al., 2016; Gallen and Wegmann, 2017; Gallen and Fernández-Blanco, 2021). Despite the wide range of reported values, most estimates of n are between 1 and 2. For simplicity, later analyses conducted in this study assume that n = 1, but we recognize the limitations of this assumption.

The erodibility parameter, K, has been shown to vary over approximately 5 orders of magnitude (e.g., Stock and Montgomery, 1999; Harel et al., 2016). Variations in this parameter depend on a number of factors, including rock strength, climate, and sediment characteristics.

3.1 Stream profile extraction

We used a Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) with a spatial resolution of 30 m to extract longitudinal stream profiles, performed using the MATLAB-based Topotoolbox (Schwangart and Scherler, 2014). The absolute vertical accuracy of the SRTM 30 m DEM is ≤16 m, and a relative accuracy is ≤10 m (Hensely et al., 2001). Apart from the stream profiles, this toolbox also generates flow directions, watershed boundaries and identifies knickpoints (Shahzad and Gloaguen, 2011a, b).The channel network was defined as portions of the landscape draining ≥1 km^2. Elevation and drainage area extracted from the river network was then used to identify breaks in longitudinal channel slope as potential knickpoints (e.g. Zhang et al., 2017).

3.2 Knickpoint and knick zone mapping

Several computer-based algorithms have been developed based on the *S*-*A* power law relationships, useful for knickpoint mapping and analysis (e.g. Hayakawa and Oguchi, 2006; Wobus et al., 2006; Gonga-Saholiariliva et al., 2011; Queiroz et al., 2015; Zahra et al., 2017; Neely et al., 2017). In this work, we adopted the approach by Schwangart and Scherler (2014) because it closely mimics the early definitions of knickpoints (Gailleton et al., 2018). Knickpoints are identified along the longitudinal profiles of river tributaries using the *Knickpointfinder* function in TopoToolbox (Schwangart and Scherler, 2014). This is an iterative, automated procedure that identifies knickpoints as pronounced convex sections that separate concave equilibrium profiles in a DEM. The procedure achieves this by regressing linear segments of the streams in log *S*–log *A* space to provide a channel steepness index (k_s) calculated from the upstream drainage area (1,000,000 km^2) using the DEM and concavity (θ = 0.45) (Hack, 1957; Kirby and

Whipple, 2001; Snyder et al., 2000). Specifically, offsets between the actual river profile and a fitted concave-upward profile are identified as potential knickpoints (Stolle et al., 2019).Once these potential knickpoints are identified, we calculate normalized steepness index values, which are useful for the identification of true from false anomalies (knick zones), assuming the river profile was decreasing monotonously or not (Schwangart and Scherler, 2020).

3.3 Chi (χ) Analyses

Although the method described above is useful for extracting geomorphic parameters, the noise inherent in DEMs may mask some features of interest. For this reason, a statistical technique for quantifying the spatial variation called the chi (χ) analysis (Mudd et al., 2014) may be preferable. The χ-parameter is calculated as the path integral along the channel of the inverse of drainage area (*A(x))* raised to the *m* to *n* ratio (i.e., θ_{ref}) (Perron and Royden, 2013):

$$\chi = \int_{x_b}^{x} \left(\frac{A_o}{A(x)}\right)^{\frac{m}{n}} dx$$

(equation 4)

where A_o is an arbitrary reference drainage area used to give chi units of meters. This parameter can be used to examine the geometry of channels assuming that incision is equal to uplift where the slope of a χ-elevation plot is proportional to k_{sn} (Perron and Royden, 2013; Mudd et al., 2014). The technique has the advantage of allowing for the comparison of the steepness of channels across basins of different sizes, and it is less subject to topographic noise than slope-area analysis because the only inputs required are the drainage area and the elevation along the channel (Mudd et al., 2014).

These differences in χ-values are used as an indication of which catchment basin is losing (lower χ-values on one side of the divide) or gaining (higher χ-values) catchment depending on either side of the divide (Willett et al., 2014). A disequilibrium state is found where χ-values along rivers flowing in opposite sides of the drainage divide are not equal. A stable state is formed where the χ-values are almost equal. Therefore χ-maps have been used to show the growth and decay of drainage basins and have become a useful tool for understanding divide migration or equilibrium and disequilibrium conditions in catchment basins (Willett et al., 2014). Furthermore, we also used the χ-values to determine the fluvial response time, τ, by assuming *n* in the stream power model is 1:

$$\tau = \frac{\chi}{K^{*} {A_0}^{m/n}}$$

(equation 5)

The fluvial response time is then used to estimate knickpoint ages and migration rates from a common baselevel, which for our analyses is defined by the downstream 'mouth' of Middle Shire River near Chikwawa (Figure 6). Most of the published erodibility data present in the southern Africa region relates to loose soils and not derived for hard competent rocks like the ones for the study area (e.g.Vargas and Omuto, 2016; Gyamfi et al, 2016;Songu et al., 2021; Breetzke et al., 2013; Laker, 2004; Smith, 1999; Mughogho, unpublished). In this work, we used A_0= 10^6 km^2 and a range of erodibility

(K) values of ~$2x10^{-6}$ to $3x10^{-6}$, which were estimated by Jess et al. (2020) using thermochronology and river profile modelling for a roughly comparable rock type and climate from the Ruwenzori mountains farther north within the East African Rift system. In the absence of local constraints, we assume that these values are roughly representative of comparable rock units in the Middle Shire.

Using equation 4, the rate of knickpoint migration (*r*, in meters/year) can be estimated (equation 5) by the ratio of the knickpoint distance ***d*** from the point of propagation to its response time, given by:

$$r = \frac{d}{\tau}$$

(Equation 6)

The results obtained from these analyses have later been used for the interpretation of regional landscape evolution and correlations with the other spatial data, such as geological structures and precipitation that may be influencing knickpoint formation in the area (Fielding et al., 1994; Bookhagen and Burbank, 2006; Scotti et al., 2014; Azañón et al., 2015). In our study, we mark the base level location at the mouth of the Middle Shire River (at coordinate 16.09^{o} S, 34.86 ^{o} E which has an elevation of 70 m asl). Although the downstream mouth of the Middle Shire section receives inflow from both the Upper Shire and Middle Shire catchments (Figure1c), we restricted the upstream drainage area (A_o) used for our calculations to the Middle Shire river catchment. This approach was taken because taking the Upper Shire catchment into consideration would include the whole Lake Malawi catchment basin (Figure 1b).The inclusion of the whole Lake Malawi catchment basin presents a problem as it creates an unreasonably large catchment area for the Middle Shire section. Thus, for our analysis, we treat the Middle Shire as an independent catchment, and we account for the uncertainties that this imposes on our estimates in the discussion part of this text (sections 5.4 and 5.5).

4 Results

4.1 Knickpoint Analysis

Results from the stream profile extraction (Figures 2, 3a-c) generally show a spatial correlation of knickpoints with fractures e.g. major faults, lithological units, metamorphic fabric and dykes (Figure 2, 3c).

We note here the following sequence in the spatial distribution of the knickpoints from the Upper to Lower Shire sections (Figures 3b, c):

i.) From its contact with the Upper Shire segment at Matope, the first major knickpoint is at Murchison Falls (locality **i** on Figure 3b) with other knickpoints at Toni and Nachimbeya (locality **ii** on Figure 3b). The section between Matope and Mbinjewananda Rapids (located at **iii** on Figure 3b) roughly follows a NNE-SSW trend along the tectonic/lithologic boundary between the amphibolite and granulite facies suite characterized by a marble as a marker horizon between these two metamorphic suites (Figure 2). This boundary has also recently been described as the probable margin of the Southern Irumide and the Unango terranes (Fullgraf et al., in press). It appears that in this section, the course of the Shire River is largely controlled by geological features such as metamorphic fabrics e.g. foliation and some fractures ii.) Between Mbinjewananda Rapids and the Shire River's confluence with the Lisungwe River, the former migrates away from the amphibolite-granulite contact and follows a SW-trend controlled by a mixture of fractures and various dykes. Along this section, the Shire River flows over two knickpoints (Nkula and Tedzani Falls, localities **iv** and **v** respectively in Figure 3b).

iii.) From its confluence with the Lisungwe, the Shire River switches to a largely SE trend, influenced by various fractures including the Lisungwe and Thyolo Faults and NE-SW to NW-SE striking geologic fabrics (Bloomfield and Garson 1965).Two knickpoints have formed either side of where the Shire River flows across an aplite dyke at Mpatamanga (localities **vi** and **vii** on Figure 3b).

iv.) A tectonic knickpoint has formed where the Shire River flows over the Thyolo fault near Chikwawa (locality **viii** at Kapichira on Figure 3b).

While we recognize that some of the knickpoints in the study area are likely static and associated with local features (i.e., faults or lithological contacts), we hypothesize that those that do not spatially correlate with these features might be mobile and related to periods of elevated based level drop at the base of the bedrock channels draining the Middle Shire. To test the hypothesis that pulses of incision are communicated throughout fluvial networks (Crosby and Whipple, 2006), we must first isolate static from presumably transient knickpoints. We test this using the chi analysis and the river response time analysis, which can determine if there are knickpoint sets that cluster in chi-elevation or τ-elevation space. These clusters within this parameter space are significant because knickpoints migrate at the same rate vertically (so they will stay at the same elevation if originating from the same base level fall event) and, assuming uniform erodibility, will also migrate at the same rate in chi.

4.2 *χ*- analysis

From our analysis of the χ-plot (Figure 4) it can be observed that χ-values along specific stream channels emanating from the same drainage divide but constituting different catchment basins are different. From our analysis, the *χ*-plot (Figure 4) shows different states of drainage divides, with most near the rift shoulders, and the Middle-to-Upper Shire boundary in a state of disequilibrium (unequal χ-values on the opposite sides of a drainage divide) compared to the drainage divide between the Middle Shire and Lisungwe, which are in a steady-state (almost equal χ-values on the opposite sides of a drainage divide). The histograms of knickpoint χ and elevation (Figure 5) show a large spread (mean of ca. 110,000 and standard deviation of ca. 53,000 χ) of the data ranging from ca. 17,000-265,000 χ occurring at altitudes of ca. 100 – 1400m asl (mean of about 700m asl with a standard deviation of 290m asl). However, we distinguish two main knickpoint clusters in the χ-elevation distribution plots (Figure 5) whose main characteristics are summarized in Table 1. This result is important because mobile knickpoints migrate at the same rate vertically and in *χ*-space provided spatially uniform rock uplift and erodibility (Niemann et al., 2001; Royden and Perron, 2013). The results for the modeled knickpoint migration rates in the Middle Shire River basin (Figures 6a and d), show values ranging between 0.06 to 2.0 m yr^{-1} for different erodibility values (Figure 6a and d). Overall, the lower migration rates (<0.65 m yr^{-1}) dominate the NW and SE margins of the basin, coinciding with the outer border fault zones, including the footwall areas of the Thyolo Fault. Whereas the highest migration rates (0.65–2.0 m yr^{-}

^{1}) occur mostly along and in the vicinity of the Middle Shire River channel along the basin axis.

The clustering indicates two broad time intervals i.e.ca. 51,000 – 124,000 years BP and ca. 99,000-210,000 years BP (Figures 6b and e) for the timing at which each set of knickpoint were formed.

Table 1: Knickpoint response times and their K-values for the two clusters

5 Discussions

5.1 Local drainage dynamics

The chi analysis map (Figure 4) shows that the drainage divides in the rift shoulder areas to the NW of Tedzani and near Blantyre together with the intrabasin area to the east of Matope are in a state of disequilibrium. These areas show that their drainage divides are migrating towards the axial stream of the Middle Shire River section. To the contrary, the axial stream of the Middle Shire section between Matope and Kapichira Falls covered by the Middle Shire and Lisungwe drainage divides are in a steady state. The clustering shown in the chi-elevation plots (Figure 5) also supports the idea that some tectonic activity is within the rift shoulder areas to the NW and SE. These observations suggest that most of the tectonic strain is accommodated in the axial region of the basin, which is consistent with previous fault mapping, rift morphology, and scarp offset distributions in this region (Wedmore et al., 2020a; Kolawole et al., 2021).

5.2 Knickpoints and formation mechanisms

Consistencies in the location and form of knickpoints suggest a systematic response is responsible for their spatial distribution in the Middle Shire basin. The rapid incision in the Middle Shire area and localization of clusters in some sections of the border faults lead us to hypothesize that most of the strain in the region is localized within the axis of the Shire River where the river might be responding to baselevel fall associated with slip along the Thyolo Fault.

We identified both static and mobile knickpoints in the study area. The former are related to various faults, lithological contacts and metamorphic fabric, while the latter coincide with the outer border fault zones, including the footwall areas of the Thyolo Fault and the intrabasin faults near Matope (Figures 3 and 4). The locations of the static knickpoints suggest that these knickpoints are responding to variations in erodibility resulting in the formation of a step-like topography along the river pathways as is the present case in the course of the Middle Shire. The mobile knickpoints form two distinct clusters in chi-elevation space (Figure 5) and strongly support the notion that these knickpoints were triggered in response to baselevel fall events associated with tectonic perturbations along a fault downstream of the Middle Shire and cascade upstream through the fluvial network. The Thyolo Fault is the most prominent and fastest slipping fault downstream of the Middle Shire (Wedmore et al., 2020b; Williams et al., 2021), and so is most likely responsible for this baselevel fall. We do not rule out the possibility of contributions from tectonic subsidence in the active rift basins further downstream, such as the Nsanje graben (northern extension of the Urema Graben in central Mozambique; Dulanya, 2017). However, that the base level position near the Thyolo fault does explain the mobile knickpoint pattern well (i.e. clustering in χ-elevation space, Figures 5, 6a and c).

5.3 Migration Rates and Timing of formation of the Mobile Knickpoints

Knickpoint modeling across the Middle Shire basin shows that the highest migration rates (Figures 6b and e) occur primarily along and in the vicinity of the Middle Shire axial stream channel and near the Thyolo Fault. This probably explains the proximity to the propagation centre (base level location) and that the basement rocks in the axial region of the Middle Shire river are being dismembered faster than in the other parts of the Middle Shire basin (i.e. rift shoulder).

The response times for the mobile knickpoints suggest they initiated between 51,000 to 210,000 years BP (Table 1) with two main clusters identified. We interpret that the older cluster (~99,000 and 210,000 years BP; Figures 6b-c, e-f) possibly corresponds to an earlier phase of increased slip rate along the Thyolo Fault during the Late to Middle Pleistocene, and that the second cluster corresponds to a another phase of increased slip rate along the fault (younger cluster timing of ~51,000 to 124,000 i.e. Late Pleistocene; Figures 6-c, e-f). Regardless of the interpretation of the older and younger clusters of mobile knickpoints, the fact that this record of slip rate perturbations along the Thyolo Fault exists in the Middle Shire basin implies an at least Mid. Pleistocene connection between the Middle Shire and Lower Shire basins. However, the exclusion of the Upper Shire catchment from the defined Middle Shire drainage area (A_o) in our analysis implies a possible overestimation of the knickpoint response times and underestimation of the migration rates.

We acknowledge that this age estimate is sensitive to the erodibility constant *K* and this parameter, which is sensitive to the local climate and can only be inferred for southern Malawi. However, varying the full range of *K* values used in this calculation, as obtained from Jess et al., 2021 (i.e., between $2x10^{-6}$ and $3x10^{-6}$), does not substantially change the age estimates (Figure 6).Temporal variations in *K* may also exist in southern Malawi due to the occurrence of megadrought between 135 – 75 ka in the region (paleoclimate records in Lake Malawi sediment cores; Scholz et al., 2007). In these periods, lower incision rates of the bedrock rivers (due to reduced discharge and drainage area) would have decreased the rate of knickpoint retreat. Hence, our estimates of knickpoint migration rate represent an upper bound in the Middle Shire basin, and so basin linkage in southern Malawi could be slightly older than the Mid. Pleistocene (see equations 5 and 6). We infer that spatial variations in climate might explain some of the scatter in the knickpoint clusters.

We also acknowledge that there could have been some complexity in the spatiotemporal sequence of opening of the Middle Shire basin (i.e., north to south integration of the Shire River network), such as an initial opening of the Middle Shire to the Upper Shire prior to its linkage with the Lower Shire section, thus introducing some uncertainties into our age estimates. However, our interpretation of events is supported by syn-rift paleo-lake sediments at the southern end of the Zomba Graben including the Matope Beds and yet-to-be buried bedrock along the rift floor south of the Matope beds, suggesting a previously dammed southern-end of the Upper Shire segment (Bloomfield and Garson, 1965; Dulanya, 2017; Kolawole et al, 2021). Furthermore, an overall southward propagation of long-term basin development at the scale of the Malawi Rift is consistent with previous studies (Scholz et al., 2020).

5.4 Implications for Rift Interaction and Linkage in Southern Malawi

We are thus able to propose a possible sequence of evolution of rift linkage and basin opening across the Middle Shire area (Figures 7a-b). Prior to the onset of East African Rifting in southern Malawi, the Upper and Middle Shire River sections were likely elevated basement regions relative to the Shire Rift Zone, which hosts the Lower Shire River, as only the latter experienced Karoo extension and subsidence (Bloomfield 1965; Habgood, 1973; Castaing, 1991). It has been suggested that prior to Cenozoic rifting in southern Malawi, the Upper Shire river might have flowed eastward into the Lake Chilwa basin, now located on the eastern rift flank (Figure 1c; Dixey, 1939).Considering the presence of more developed rift faulting and considerable syn-rift sediment deposits in the Upper Shire section (Malombe and Zomba grabens) relative to the Middle Shire area where both are lacking, rift basin development in the Upper Shire region likely preceded the propagation of rifting across the Middle Shireregion. The Upper Shire rift faults may have developed relatively quickly (Plio-Pleistocene) to form a rift axis that channeled the axial Shire River southwards from Lake Malawi.

Thus, prior to the integration of the Upper and Lower Shire into a through-going trunk stream, the region of the Middle Shire River was an elevated unrifted basement that restricted flow in a closed-drainage system, and that at times may have resulted in paleo-lake formation in the Zomba Graben (Paleo-lake Matope; Figure 7a). This is represented by the presence of Cenozoic lacustrine clays and distinct large-scale beach gravel deposits described as the Matope Beds which directly overlie the basement in the Zomba Graben (exposed on the footwall of the Mlungusi Fault; Bloomfield, 1965; Bloomfield and Garson 1965; Dulanya, 2017; Wedmore et al., 2020a). During this period, the predominant drainage along the Lower Shire section would have been the lower section of the Shire and Mwanza Rivers (Figure 7a; e.g. Moore et al., 2007), and the Lisungwe and Wamkurumadzi Rivers probably flowed eastwards (e.g. Bloomfield and Young, 1961; Bloomfield and Garson, 1965; Tweddle et al., 1979).

Subsequently, subsidence and tectonic movements along the Thyolo Fault in the Shire Rift Zone, and interactions with the southward propagating faults of the Southern Malawi Rift (e.g., Zomba, Lisungwe, and Chingale Step faults) led to surface deformation of the Middle Shire by the localization of rift interaction zone(RIZ)-breaching faults (Kolawole et al., 2021). Progressive faulting and erosion of the bedrock of the subsiding Middle Shire area resulted in the opening of the upper parts of the Middle Shire and re-routing of the course of the Shire River into a south-flowing axial stream leading to the linkage of the Zomba and Lower Shire basins (Figure 7b).

Within the bedrock stream network of the Middle Shire River, the southwest course of the northern part of the axial stream is parallel to the surrounding border and intrabasin faults of the Zomba Graben, whose geometry is strongly influenced by exploitation of basement metamorphic fabrics that are well oriented relative to regional EAR extension direction (Figure 7b; Mortimer et al., 2016; Williams et al., 2019; Kolawole et al., 2021). The southern half of the axial stream follows a southeast course, parallel to the trend of Thyolo Fault and a network of RIZ-breaching faults (Figure 7b) which also follow NW-trending basement fabrics (Wedmore et al., 2020b; Kolawole et al., 2021). Minor deviations in the course of the Shire River downstream are influenced by other NE-trending fractures or lithological units, such as the aplite dyke at Mpatamanga gorge. Hence, the pre-existing basement fabrics have strongly influenced the brittle deformation and rift linkage between the Zomba and Lower Shire grabens.

Knickpoints are inherently transient features, particularly for rivers like the Shire with large drainage areas (Holland and Pickup, 1976; Crosby and Whipple, 2006; Hodge et al., 2020).In the bedrock drainage basin of the Middle Shire River, the preservation of multiple knickpoints across tectonic and lithologic discontinuities that we document here, and the Mid. to Late Pleistocene knickpoint response time suggest that the integration of the Middle and Lower Shire River sections is recent relative to the Oligocene-Miocene initiation of rifting in the region (Roberts et al., 2012; Ojo et al., 2022a). We note that the estimated ages of linkage is a lower bound considering that knickpoint formation must have occurred after basin linkage and that knickpoint migration rate may have been lower during well-documented Late Pleistocene (135-75 ka) megadrought period in the region (Scholz et al., 2007). Nevertheless, the results provide a minimum quantitative constraint on the timing of rift linkage between the southern Malawi Rift and Shire Rift Zone across the Middle Shire basin, which was only speculated on in previous studies of the Middle Shire RIZ (Dulanya et al., 2017; Kolawole et al., 2021).

More broadly, the results imply that the East African Rift western branch initiated and developed as distinct basins that have gradually linked together since the Late Oligocene rift activation in the region (Kolawole et al., 2021; Jess et al., 2021). We suggest that the tectonic processes associated with the interaction and linkage of the Southern Malawi Rift and Shire Rift Zone facilitated the integration of the axial stream across the Middle Shire Basin. After rift linkage and starting in the Mid. Pleistocene, the knickpoints progressively began to migrate upstream in response to pulses of baselevel fall downstream of the Middle Shire River. This baselevel fall events are associated with active tectonic subsidence in the Lower Shire Graben, driven by slip along the Thyolo Fault.

6 Conclusions

Landscape evolution responds to different forcing mechanisms at play in different parts of the Earth. In this study, we investigated the geomorphic evolution of the Middle Shire river basin in south Malawi, a bedrock river network which developed within a zone of rift interaction and linkage between the ~NNE-NNW-trending southern Malawi Rift and the NW-trending Shire Rift Zone. Despite its lack of well-developed basins with thick sediments, we utilize knickpoint mapping of bedrock rivers along the rift zone from a Digital Elevation Model (DEM) and analyze their associated geomorphic characteristics.

Our results show that the axial stream (Middle Shire River) exhibits a strong disequilibrated longitudinal profile, and although inherited basement lithologic boundaries and faults modulate some of the knickpoint locations, there exist mobile knickpoints that are migrating upstream from through the river network due to base level fall events downstream in the Shire Rift Zone. We estimate a Mid. Pleistocene age for the oldest knickpoints in the network, representing a lower bound on the timing of integration of the Middle and Lower Shire River sections and rift linkage between the southern Malawi Rift and Shire Rift Zone, relative to the Oligocene-Miocene initiation of rifting in the region.

More broadly, the results are consistent with the hypothesis that the East African Rift western branch has developed by the gradual propagation, linkage and coalescence of initially nucleated distinct rift basins. Further, the results show that the morphotectonic evolution of actively subsiding erosional rift floors in zones of recent rift segment linkage are influenced by inherited basement structures and syn-rift structures.

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FIGURES

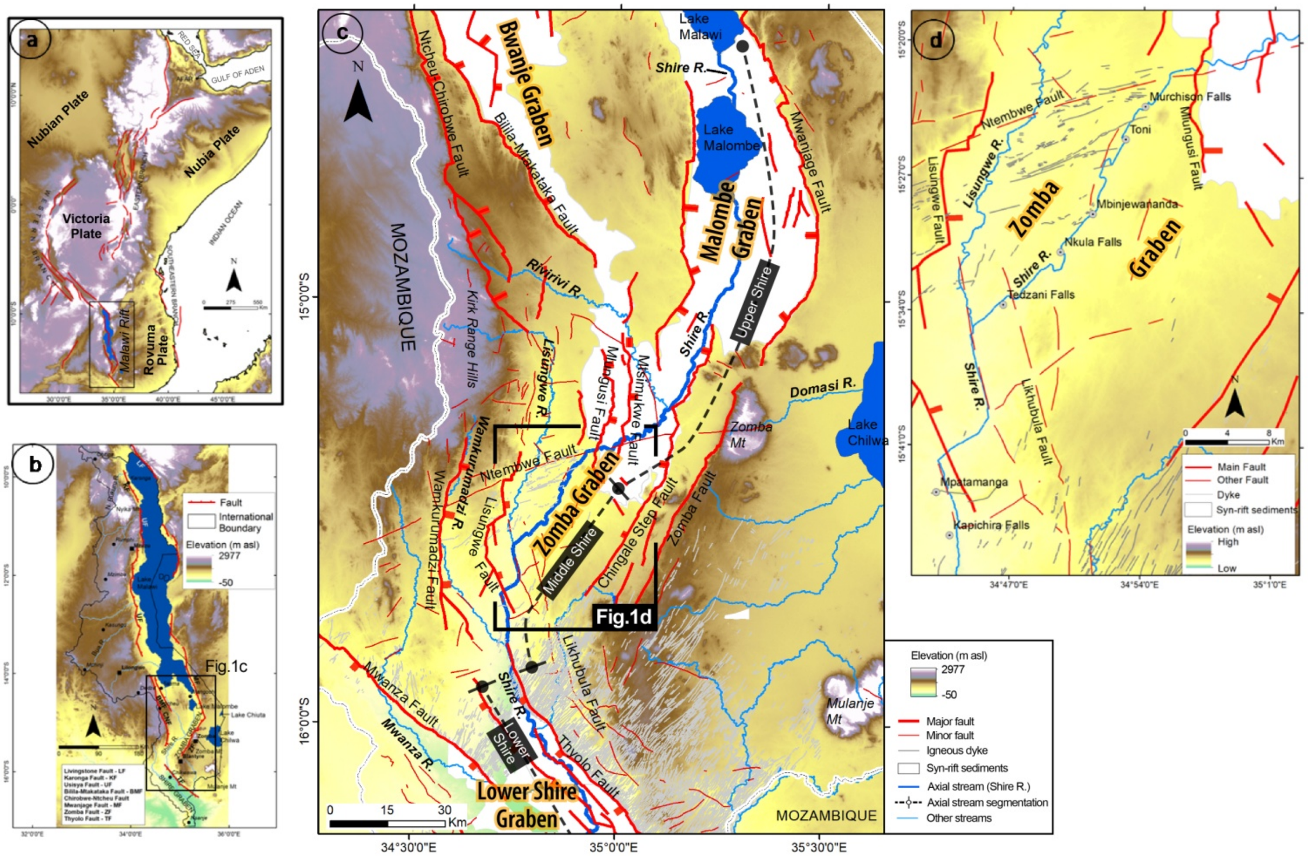

Figure 1. The position of Malawi on the African continent (a) with the main tectonic features (adopted from Chorowicz, 2005); TheMalawi Rift (b) overlaid on an 30m-resolution SRTM DEMshowing the main geomorphological and tectonic features; The study area (c) showing the Shire River and the major tectonic elements (modified after Williams et al, 2022) and; (d) Some falls and rapids in the Middle Shire River section and the associated topographical and structural features.

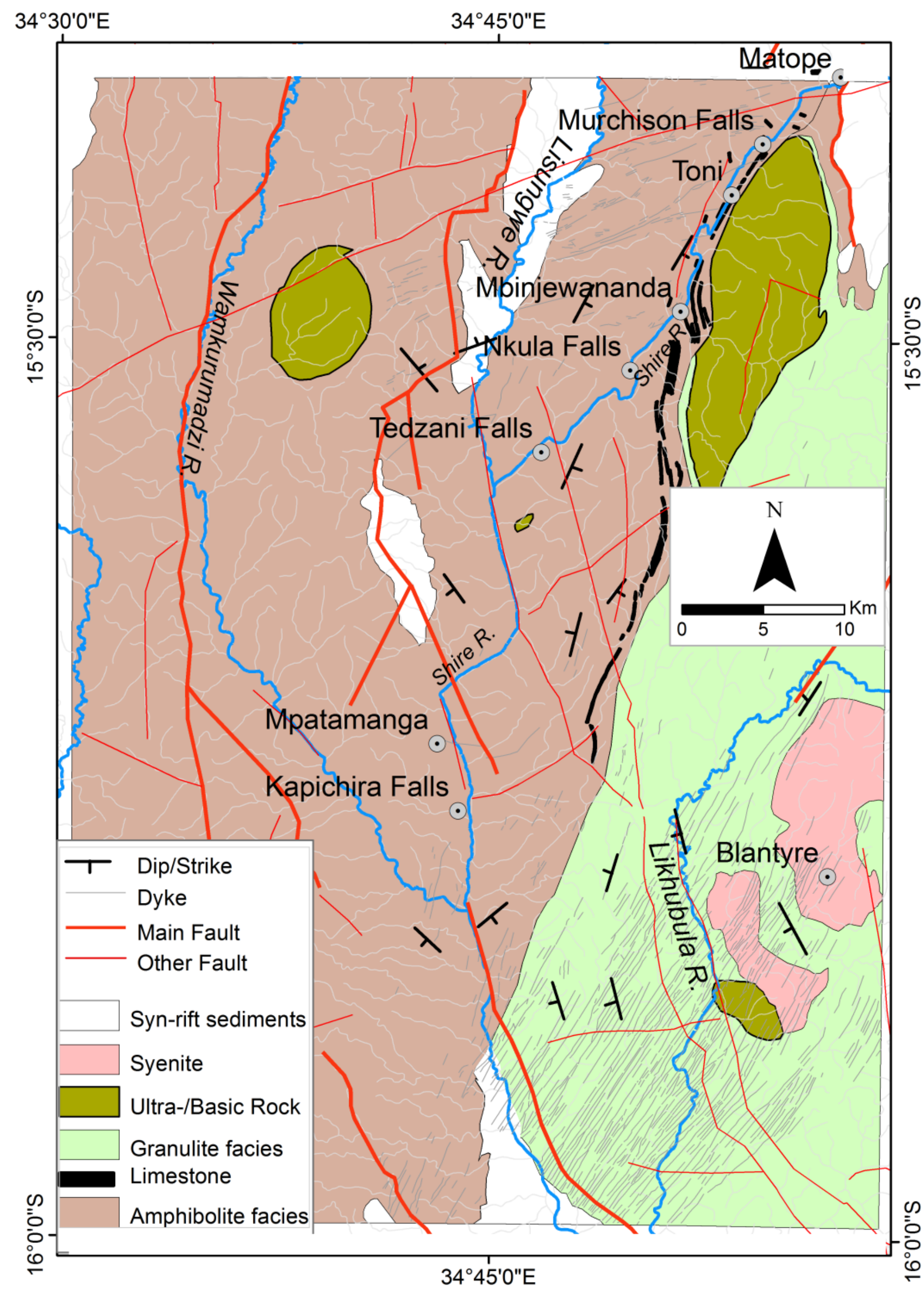

Figure 2. Detailed geology of the study area (modified after Habgood and Wa 1965; Bloomfield and Garson, 1965; Evans, 1965; Habgood, 1963; Coope Bloomfield, 1961; Morel,

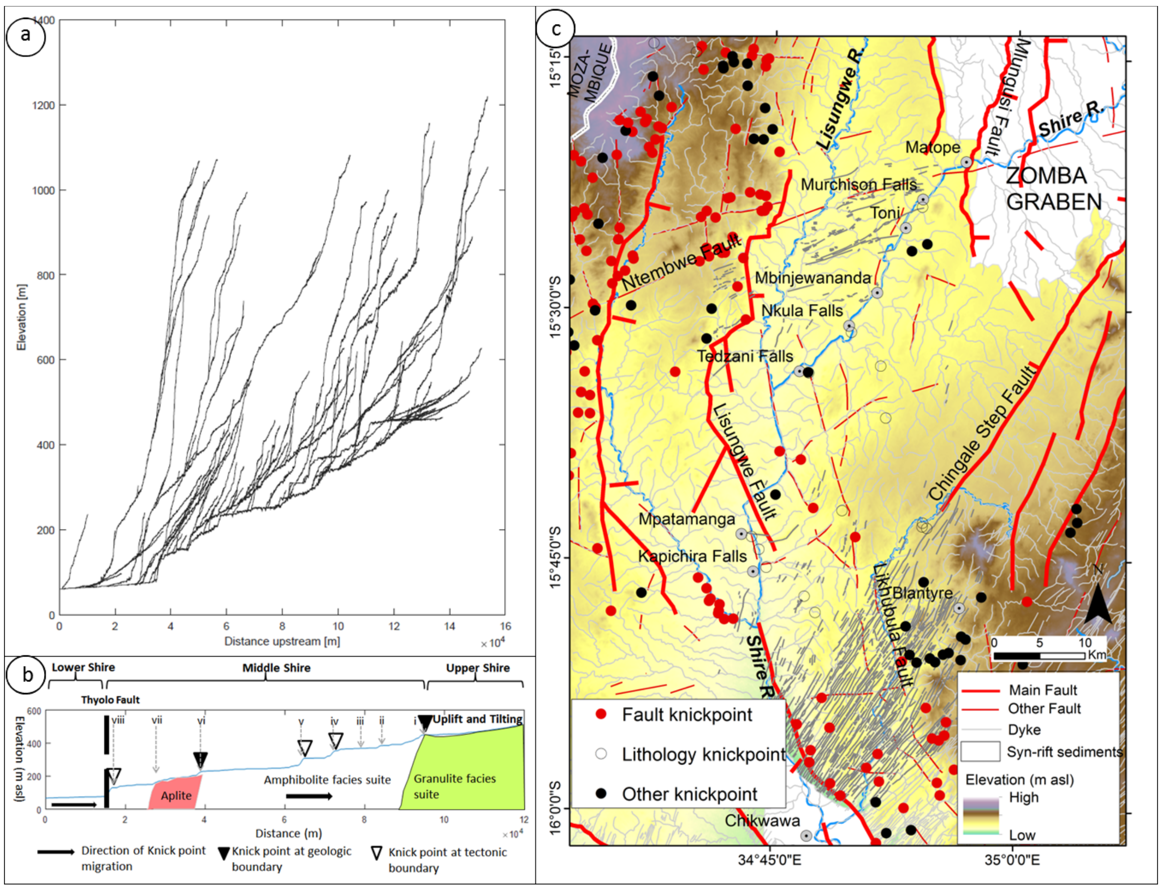

Figure 3. Longitudinal profiles along: (a) the Middle Shire basin (b) the Middle Shire River with various knickpoints (i – Murchison Falls. ii – Toni-NachimbeyaRapids. iii – Mbinjewananda Rapids. iv – Nkula Falls. v –TedzaniFalls. vi – Mpatamanga Gorge. viii – Majete Rapids. viii – Kapichira Falls) and some tectonic and lithological controls associated with

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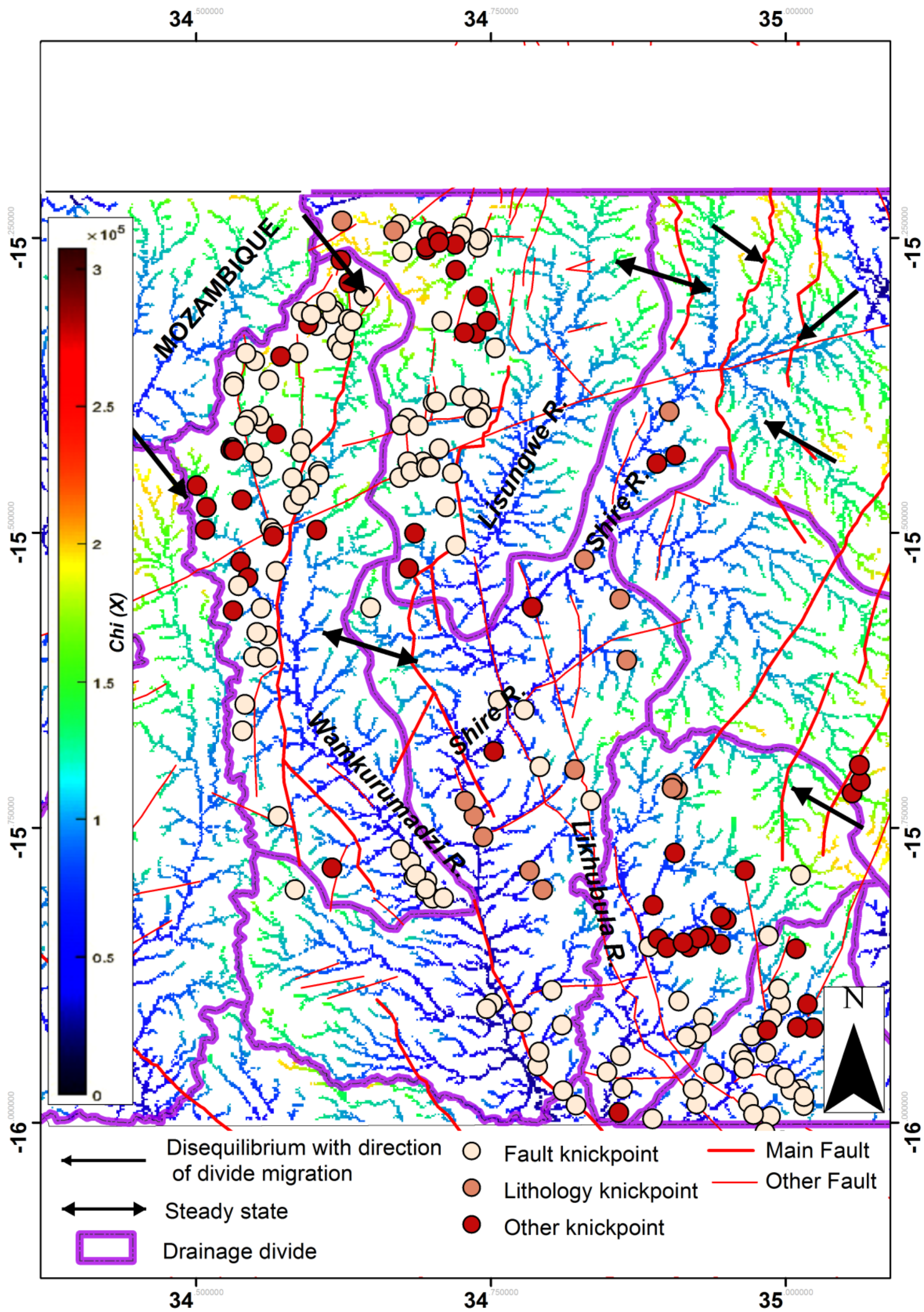

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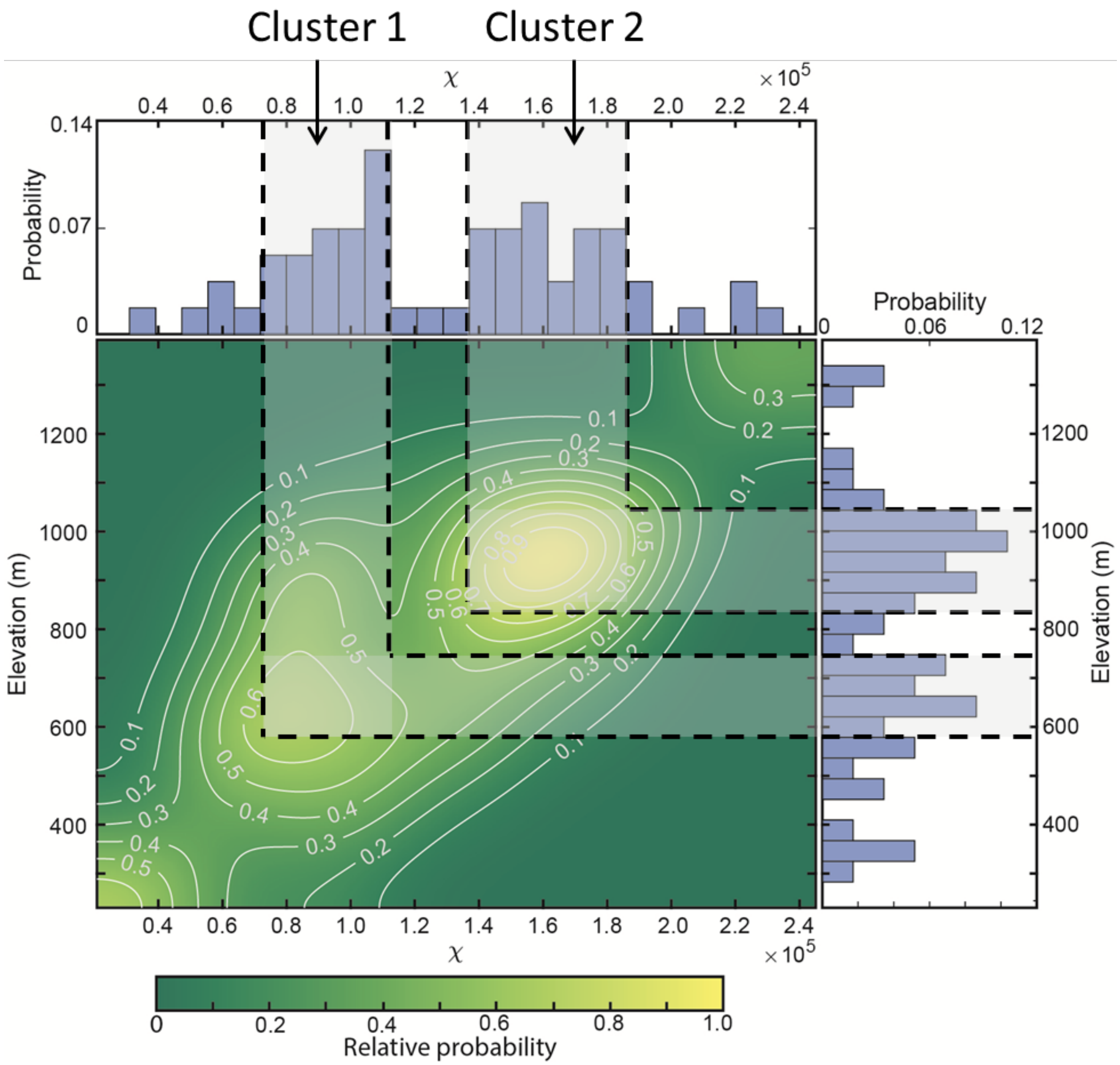
1138 Figure 4. χ-plot of streams in (a) the Middle Shire Basin.



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1140 Figure 5. Chi-Elevation histogram probability plot and the associated knickpoint clusters.

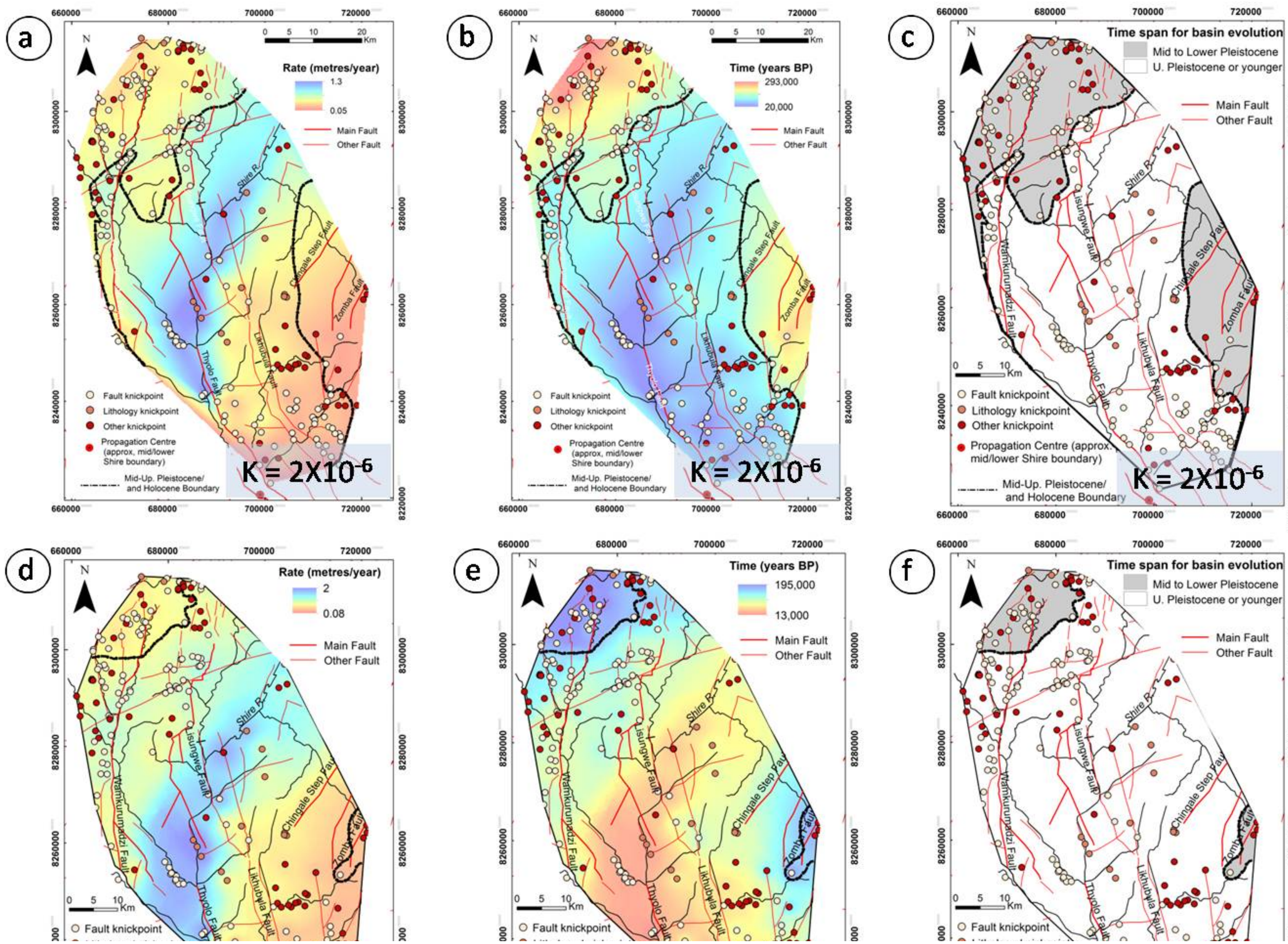
a
b
c
d
e
f
Rate (metres/year)
Time (years BP)
293,000
20,000
195,000
13,000
Time span for basin evolution
Mid to Lower Pleistocene
U. Pleistocene or younger
Main Fault
Other Fault
Fault knickpoint
Lithology knickpoint
Other knickpoint
Propagation Centre (approx. mid/lower Shire boundary)
Mid-Up. Pleistocene/ and Holocene Boundary
K = 2X10-6
Shire R.
Chingale Step Fault
Zomba Fault
Thyolo Fault
Likhubula Fault
Lisungwe Fault
Mwankurumadzi Fault
Km

Figure 6. Knickpoint rates (a and d), response times (b and e) from different erodibility values (according to Jess et al., 2021) and time spans for basin evolution (c and f) in the Middle Shire section. The legend for the knickpoints only describes our observations of knickpoint associations, and that fault and lithology-related knickpoints are interpreted as 'static knickpoints' and 'others' are interpreted to be 'mobile knickpoints

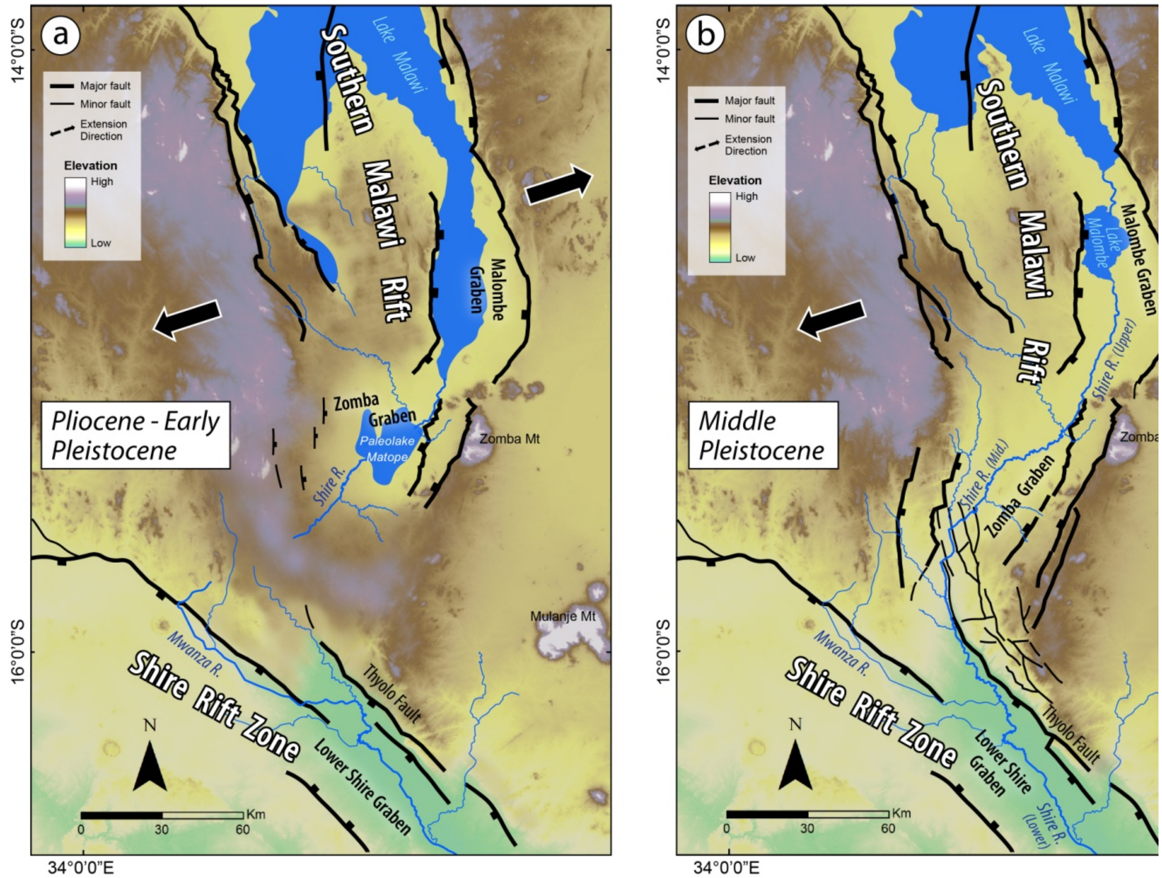

Figure 7. Hypothetical paleographical reconstruction of the Middle Shire rift inte zone from(a) the Pliocene-Early Pleistocene to(b)the Middle Pleistoceneand pı day, connecting the Zomba Graben (in Southern Malawi Rift) and the Lower Graben (in Shire Rift Zone), after Dulanya (2017),Kolawole et al. (2021, 2022); a et al. (2022a,b).