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Large-to Local-Scale Control of Pre-Existing Structures on Continental Rifting: Examples From the Main Ethiopian Rift, East Africa

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In the Main Ethiopian Rift (East Africa) a complex tectonic history preceded Tertiary rifting creating pre-existing discontinuities that influenced extension-related deformation. Therefore, this area offers the opportunity to analyze the control exerted by pre-existing structures on continental rifting at different scales. In this paper we present an overview of such an influence. We show that at a large scale (up to ~800–1,000 km) rift localization has been controlled by a lithospheric-scale inherited heterogeneity corresponding to a Precambrian suture zone, separating two different lithospheric domains beneath the plateaus surrounding the rift. The inherited rheological differences between these two lithospheric domains, as well as the presence of pre-existing lithospheric-scale transversal structures, largely controlled the along-axis segmentation and symmetry/asymmetry of different, ~80–100 km-long rift segments. Inherited transversal structures also controlled the development of off-axis volcano tectonic activity in the plateaus surrounding the rift. At a more local scale (<80 km), inherited fabrics controlled the geometry of normal faults and the distribution and characteristics of rift-related volcanism. These observations document a strong control exerted by pre-existing structures on continental rifting at all different scales.

Keywords: continental rifting, extensional tectonics, East African Rift System (EARS), Main Ethiopian Rift (MER), pre-existing structures, tectonic inheritance

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INTRODUCTION

Continental rift systems normally develop within a previously deformed lithosphere in which the distribution, architecture and evolution of deformation may be strongly influenced by pre-existing structures. Indeed, inherited mechanical heterogeneities (from the lithospheric scale, e.g., suture zones, to the upper crustal scale, e.g., foliations, shear zones, folds, faults, dykes) either weaker or stronger than the surrounding material, are able to significantly influence the pattern, propagation and overall evolution of continental rifts (e.g., Rosendahl, 1987; Dunbar and Sawyer, 1989; Smith and Mosley, 1993; Vauchez et al., 1998; Morley, 1999; Corti, 2012; Buiter and Torsvik, 2014; Purcell, 2017; Will and Frimmel, 2017).

Many extensional settings suggest such a control, including the North Sea (Bell et al., 2014; Phillips et al., 2019), the Rhine graben system (e.g., Schumacher, 2002; Michon and Sokoutis, 2005; Edel et al., 2007), the Tertiary rifts of Thailand (Morley et al., 2004; Pongwapee et al., 2019) and, finally, the East African Rift System (Chorowicz, 2005; Vétel and Le Gall, 2006; Corti et al., 2007;

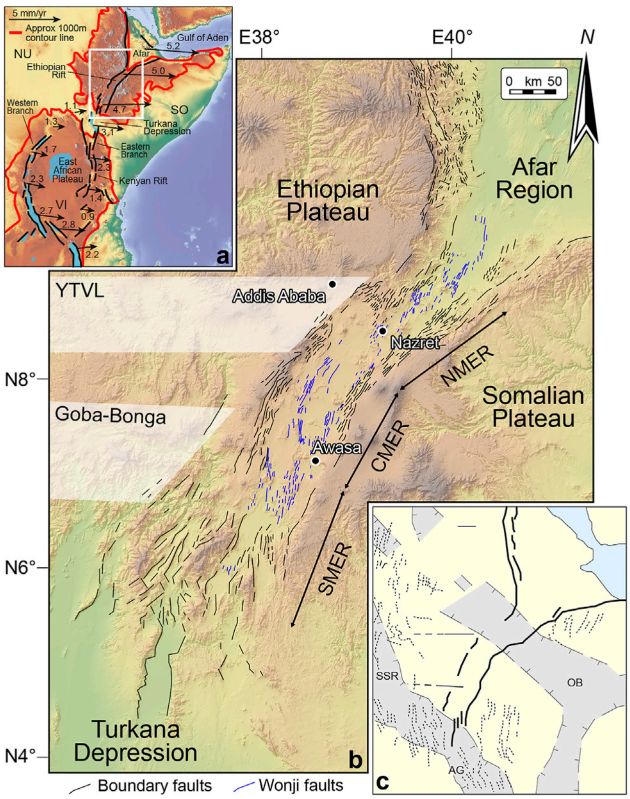

FIGURE 1 | Tectonic setting of the Main Ethiopian Rift. **(A)** Present-day plate kinematics of the East African Rift (modified from Corti et al., 2019). Black arrows show relative motions with respect to a stable Nubian reference frame; values besides arrows indicate motion in mm/yr. NU: Nubian plate; SO: Somalian plate; VI: Victoria microplate. **(B)** Main rift-related faults differentiated in Boundary and Wonji (axial) faults; indicated is the subdivision in the different segments: Northern MER (NMER), Central MER (CMER), Southern MER (SMER). Whitish pattern indicates the transversal lineaments of Yerer-Tullu Wellel (YTVL) and Goba-Bonga. **(C)** Inherited structures in Ethiopia (modified from Korme et al., 2004; Gani et al., 2009). Dashed lines indicate NE-SW- to N-S-trending basement foliations; solid lines illustrate E-W structures, corresponding to the main transversal lineaments affecting the rift; greyish pattern represents NW-SE-trending structures corresponding to sedimentary Mesozoic basins (AG: Anza graben; OB: Ogaden basin; SSR: South Sudan rifts).

Brune et al., 2017). Furthermore, several works show that many rifts developed in different, successive extensional phases (Whipp et al., 2014; Deng et al., 2017; Phillips et al., 2019; Wu et al., 2020), with normal faults formed during initial extensional events exerting a strong control on the structural architecture developed during the later rifting phases (Bell et al., 2014; Duffy et al., 2015; Henstra et al., 2015, 2019; Deng et al., 2018; Wang et al., 2021). Such a control exerted by early normal faults on structures formed during later extension is also supported by crustal and lithospheric scale analogue models (e.g., Corti et al., 2007; Sokoutis et al., 2007; Autin et al., 2013; Molnar et al., 2017, 2019, 2020; Zwaan and Schreurs, 2017; Maestrelli et al., 2020; Wang et al., 2021; Zwaan et al., 2021a).

The Main Ethiopian Rift (MER), in the East African Rift System (EARS), offers the possibility to analyse the control at different scales of pre-existing structures on rifting. Ethiopia has been indeed affected by several tectonic events that preceded Cenozoic rifting, from complex Precambrian phases of collision to extension during the Mesozoic (e.g., Korme et al., 2004; Chorowicz et al., 1994; Abbate et al., 2015 and references therein). This long tectonic history created pre-existing structures that controlled the development of the Ethiopian sector of the EARS from a regional to a local scale; the control of these mechanical heterogeneities (which are defined at different scales in the following sections) is the focus of this review paper.

TECTONIC SETTING

The MER is the northernmost portion of the EARS, extending from the Afar region in the north, to the Turkana depression in the south (**Figure 1**). This region of rifting results from active extension between the Nubia and Somalia Plates (e.g., Ebinger, 2005; Corti, 2009), with geodetic measurements indicating that extension is currently occurring in a roughly E-W direction at rates of ~4–6 mm/yr (e.g., Bendick et al., 2006; Saria et al., 2014; Birhanu et al., 2016). Extension in the northern EARS, Gulf of Aden and the Red Sea occurred contemporaneously with, and after, an intense phase of flood basalt volcanism at ~32–30 Ma (Wolfenden et al., 2004), which possibly resulted from upwelling of the African Superplume (e.g., Ritsema et al., 1999), although more complex scenarios have been recently proposed (e.g., Chang et al., 2020).

The MER is subdivided into three main sectors: Northern MER (NMER), Central MER (CMER) and Southern MER (SMER) (**Figure 1**). These sectors differ in terms of age and pattern of deformation, volcanic activity and lithospheric characteristics (e.g., Mohr, 1983; WoldeGabriel et al., 1990; Hayward and Ebinger, 1996; Bonini et al., 2005; Corti, 2009).

In the NMER, significant tectonic activity is localised at the rift axis along a belt of Pleistocene-Holocene volcano-tectonic structures, the so-called Wonji Fault Belt (WFB, e.g., Mohr, 1962; Boccaletti et al., 1998; Ebinger and Casey, 2001). The WFB is characterized by swarms of short, closely-spaced faults with minor vertical displacement, with associated focused volcanic activity and magma intrusion (e.g., Boccaletti et al., 1998; Tommasi and Vauchez, 2001). Large-offset boundary faults defining prominent marginal escarpments in this rift sector are interpreted to have accommodated deformation in the Mio-Pliocene, but they have been deactivated during the Pleistocene (e.g., Wolfenden et al., 2004; Casey et al., 2006; Keir et al., 2006). Voluminous magma intrusion beneath the axial WFB since 2 Ma caused important modifications of the composition, thermal structure and rheology of the crust/lithosphere in this rift sector (e.g., Beutel et al., 2010; Daniels et al., 2014). As a result, a combination of magma intrusion and normal faulting accommodates extension in this rift sector (e.g., Keranen et al., 2004; Dugda et al., 2005; Mackenzie et al., 2005; Keir et al., 2006; Bastow et al., 2010).

In the CMER and SMER, the large boundary faults are well developed and less eroded than in the Northern MER, and geological, geodetical and seismicity data indicate that they still accommodate significant extension (Gouin, 1979; Keir et al., 2006; Pizzi et al., 2006; Agostini et al., 2011; Kogan et al., 2012; Molin and Corti, 2015; Corti et al., 2020). This occurs together with a decrease in the amount of extension taken up by axial Wonji faults, which are considered to be in an incipient stage of development in the CMER, but almost absent in the SMER (e.g., Ebinger et al., 2000; Agostini et al., 2011). Similarly, the volume of Quaternary volcanism decreases southwards and the volcano-tectonic activity within the rift is sparse in the SMER and limited to the rift margins.

All these variations of the distribution and characteristics of the tectonic and magmatic activity along the rift axis have been interpreted to reflect a transition from initial rifting in the SMER, with marginal deformation and rift morphology dominated by faulting, to more advanced rifting stages in the NMER, where prominent axial intrusion, dyking and related normal faulting testify a phase of magma-assisted rifting that precedes continental break-up (e.g., Kendall et al., 2005).

The several tectonic events that affected Ethiopia since the Precambrian created different sets of inherited structures that exerted an important control on Cenozoic rifting and can be classified into three main groups (**Figure 1C**; e.g., Korme et al., 2004): 1) Rift-parallel or subparallel structures (NE-SW- to N-S-trending) are mainly related to deformation connected to the closure of the Mozambique Ocean during the Proterozoic and to a suture zone which formed in relation to this event. 2) Roughly E-W structures correspond to Neoproterozoic weaknesses (e.g., faults, fractures) sub-parallel to the trend of the Gulf of Aden. 3) NW-SE-trending structures correspond to sedimentary basins (e.g., Ogaden basin, Anza graben, South Sudan rifts) and associated normal faults formed during Mesozoic extension, which in turn likely reactivated pre-existing Precambrian major crustal weakness zones.

CONTROL OF PRE-EXISTING LITHOSPHERIC WEAKNESSES ON RIFT LOCALISATION

Along with other processes (e.g., magma intrusion), the presence of large-scale zones of weakness such as ancient suture zones (e.g., Buiter and Torsvik, 2014), whose rheology is different from the surrounding regions, facilitates deformation of a continental lithosphere which would be otherwise too strong to be deformed by the available tectonic forces (e.g., Buck, 2004). This is why rift structures typically localise within pre-existing zones of weakness at a lithospheric scale, which tend to strongly favour extensional deformation (e.g., Dunbar and Sawyer, 1989; Buiter and Torsvik, 2014).

Previous studies in the MER based on geophysical data suggest that initial rift location has been controlled by a lithospheric-scale, up to ~800-1000 km-long, pre-existing Precambrian suture (**Figure 2**; e.g., Gashawbeza et al., 2004; Bastow et al., 2005; Daly et al., 2008; Keranen and Klemperer, 2008; Keranen et al., 2009; Cornwell et al., 2010; Purcell, 2017), resulting from the closure of the Mozambique Ocean and accretion of East to West Gondwana.

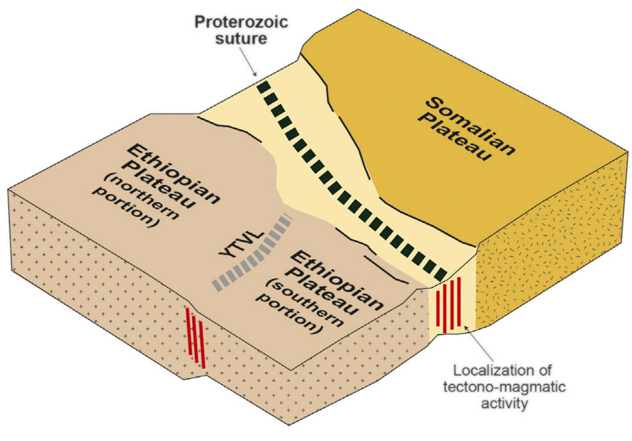

FIGURE 2 | Pre-rift lithospheric domains and location of Cenozoic volcano-tectonic activity in the MER (modified from Keranen and Klemperer, 2008). Cenozoic extension follows the rheological boundaries between two distinct Proterozoic basement terranes, underlying the Ethiopian and Somalian plateaus; this lithospheric weakness zone corresponds to an ancient suture zone (see text for details).

Ophiolites composing this suture zone have been dated between 880 and 690 Ma (Kroner et al., 1992; Claesson et al., 1984; Pallister et al., 1988). The existence of such a suture zone, which puts in contact 870 Ma Neo-Proterozoic juvenile crust with 2 Ga Archean basement (Kazmin et al., 1978; Vail, 1983; Berhe, 1990; Stern et al., 1990; Stern, 1994, 2002; Abdelsalam and Stern, 1996), is supported by differences in crustal/mantle properties between the Ethiopian and Somalian plateaus surrounding the rift. Several geophysical data (crustal thickness and bulk crustal Vp/Vs ratios, resistivity from magnetotelluric data, arrival-time body-wave tomographic models and effective elastic plate thickness) indicate indeed a strong and homogenous Somalian plateau, which contrasts with the more heterogeneous Ethiopian plateau composed of a strong and thick northern portion and a thinner and weaker southern portion (**Figure 2**; e.g., Corti et al., 2018a and references therein). The reactivation of this weakness zone is interpreted to have occurred at the eastern margin of the upwelling mantle plume, not above its center (e.g., Bastow et al., 2008), as documented in other flood basalt provinces (e.g., Deccan, Greenland, Parana, Central Atlantic; Courtillot et al., 1999). Magmatic activity and melt upraising through the upper mantle and crust may have promoted thermal and mechanical weakening of the continental lithosphere, possibly contributing its extension-related deformation (e.g., Díaz-Alvarado et al., 2021). The curved plan-view geometry of this inherited weakness significantly influenced the trend of the Cenozoic faulting (e.g., Mohr, 1962; Kazmin et al., 1980), with a variation from roughly N-S-trending in the south to roughly NE-SW-trending in the North. This resulted in an along-axis variation of the kinematics of rifting, from orthogonal in the southern MER to moderately oblique in the northern MER (Keir et al., 2015; Erbello et al., 2016), which had a major control on the segmentation and structural architecture of the rift (Corti, 2008). Notably, the

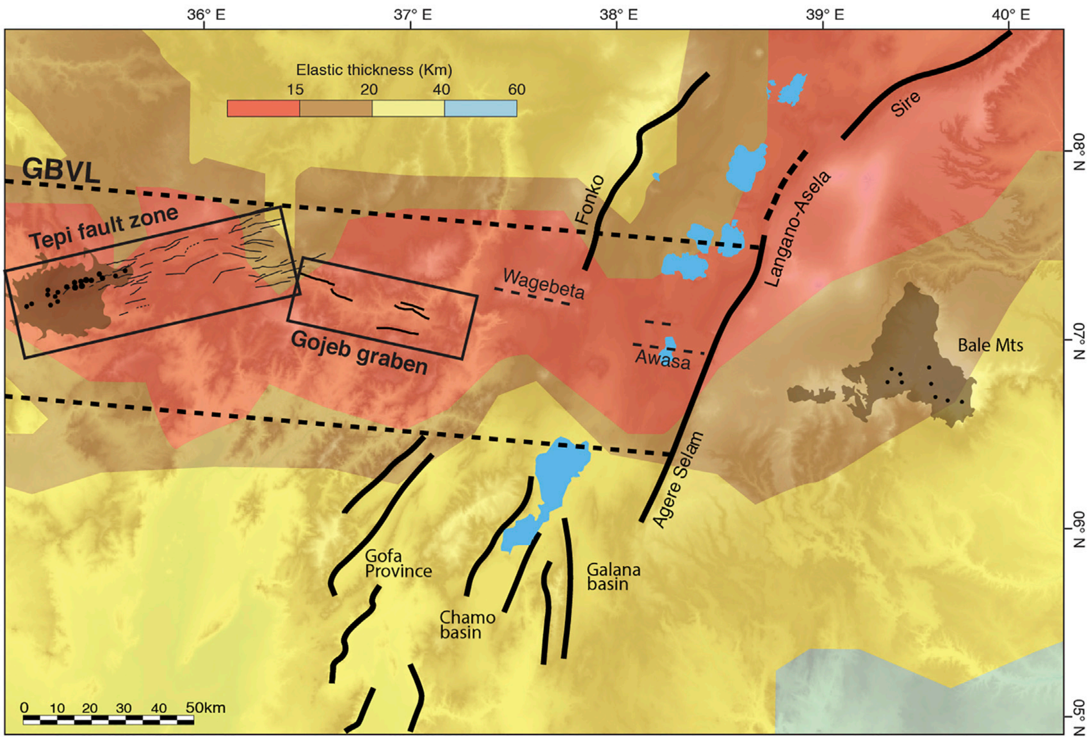

FIGURE 3 | Structural scheme of the Goba Bonga lineament (from Corti et al., 2018b) superimposed on a map of the elastic thickness of the lithosphere (Te), modified after Pérez-Gussinyé et al. (2009). Low Te values (<10–15 km) are observed in a narrow region extending in a roughly E-W direction in the region corresponding to the extent of the Goba Bonga lineament.

reactivation of an inherited weak zone oblique to the plate motion vector is able to impose a local reorientation of the extension direction at the rift margins, as illustrated in below **Section 6**.

CONTROL OF LARGE-SCALE TRANSVERSAL STRUCTURES ON OFF-AXIS DEFORMATION, RIFT INTERACTION AND LINKAGE

Transversal Lineaments and Off-Axis Deformation

The MER is characterised by the occurrence of major transversal lineaments, which affect the rift floor and the plateaus surrounding the rift valley (**Figure 1**; e.g., Abebe Adhana, 2014 and references therein). Specifically, the main structures correspond to the roughly E-W to WNW-ESE-trending Yerer-Tullu Wellel and Goba Bonga volcano-tectonic lineaments (**Figure 1**, **Figure 3**), causing deformation and volcanic activity to extend for hundreds of kilometres into the southern portion of the Ethiopian plateau and marking the transition between the different MER sectors. At a regional scale, these transversal structures have been interpreted to reflect the reactivation of inherited Neoproterozoic weaknesses roughly parallel to the trend of the Gulf of Aden (e.g., Abbate and Sagri, 1980; Abebe et al., 1998; Korme et al., 2004; Abebe Adhana, 2014; Corti et al., 2018b). As explained below, geophysical data support indeed the influence of inheritance on the development of these structures. The Yerer-Tullu Wellel lineament corresponds to a significant gradient in the thickness of the crust and marks the boundary between the northern and southern portions of the Ethiopian Plateau (**Figure 2**; Keranen and Klemperer, 2008). The P wave velocity model of Bastow et al. (2008) in its 75 km depth slice shows discrete low velocity anomalies that extend from the rift valley into the Ethiopian Plateau, beneath the Yerer-Tullu Wellel and Goba Bonga lineaments (see their **Figure 7**). A combination of a thermal anomaly and partial melting in response to asthenospheric upwelling and decompression, in turn related to localized lithospheric extension and thinning, best explains these low velocity anomalies beneath the two transversal lineaments (e.g., Bastow et al., 2010; Gallacher et al., 2016). The Goba Bonga lineament is also characterised by lower values of the elastic thickness of the lithosphere (T_e; Pérez-Gussinyé et al., 2009), which shows a decrease from values of up to 40 km beneath the Ethiopian plateau to values of 10–15 km (Pérez-Gussinyé et al., 2009) in a narrow E-W domain corresponding to the transversal structure (see **Figure 3**). These zones of thinned crust or lithosphere beneath the Yerer-Tullu Wellel and Goba Bonga lineaments were possibly caused by either inherited lithospheric thinned regions or by syn-rift extension exploiting pre-rift weakness zones. Overall, this indicates a pre-rift, structural control on the current structure of the lithosphere (Corti et al., 2018a).

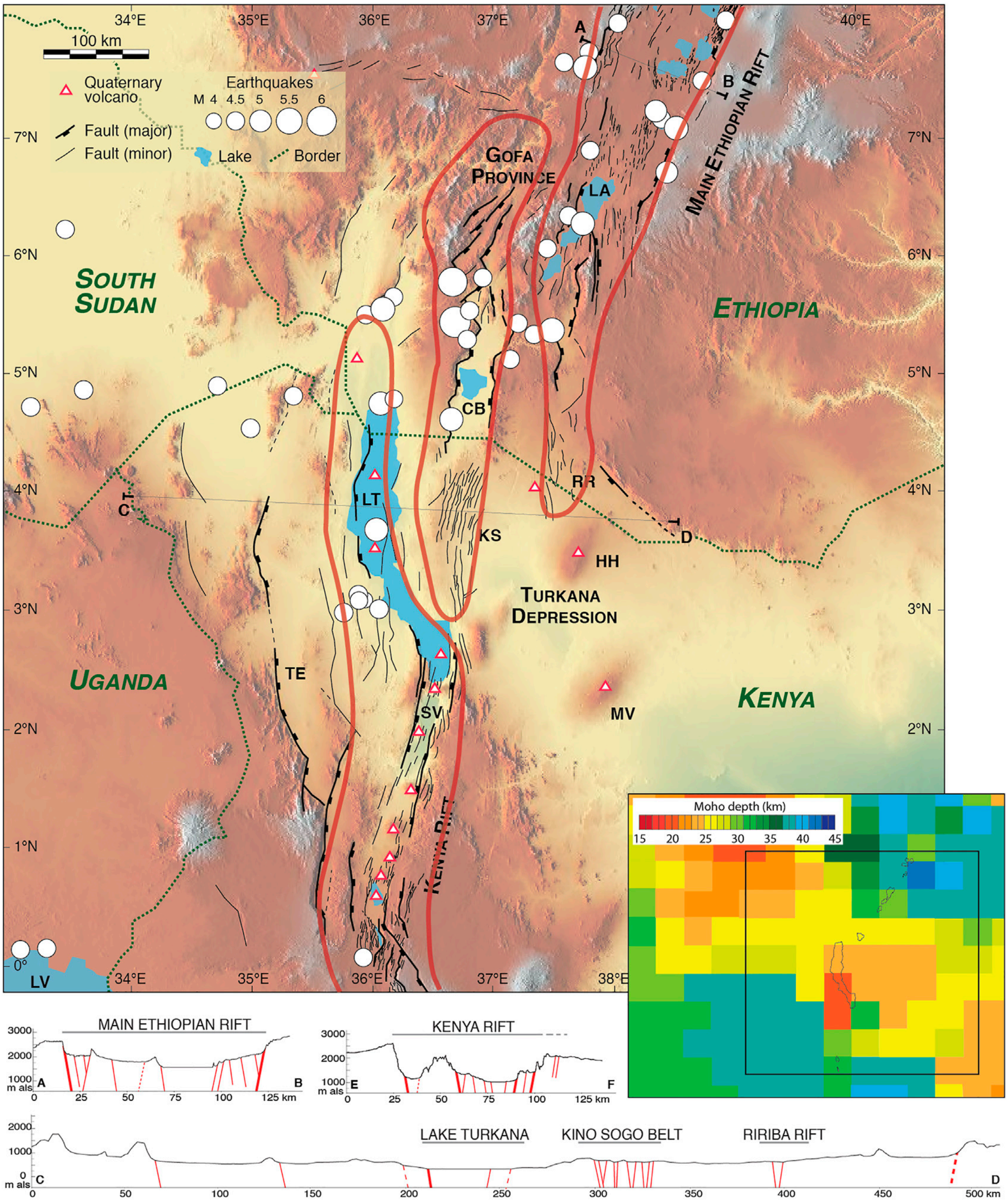

FIGURE 4 | Tectonic setting of the Turkana depression and surrounding regions, with Quaternary faults, seismicity and Quaternary volcanoes superimposed on a SRTM (Nasa Shuttle Radar Topography Mission, 30 m resolution) digital elevation model (modified from Brune et al., 2017). CB: Chew Bahir basin; HH: Hurri Hills; KS: Kino Sogo belt; LA: Lake Abaya; LT: Lake Turkana; LV: Lake Victoria; MV: Marsabit volcano; RR: Ririba Rift; SV: Suguta Valley; TE: Turkwell Escarpment. Areas encircled by red lines are the main deformation domains. Inset in the bottom right shows the crustal thickness in the region (from Benoit et al., 2006). Also illustrated are simplified cross sections highlighting the different architecture and distribution of deformation in the Turkana depression with respect to the Kenyan and Ethiopian rifts.

Rift Interaction and Linkage

At its southern termination, the MER interacts with the Kenya Rift within the Turkana depression, a low-land where deformation, seismic activity and Pleistocene-Holocene volcanism are distributed over a width of more than 450 km (**Figure 4**; e.g., Ebinger et al., 2000). Within this anomalously wide region of ongoing tectonic and magmatic activity, extension is accommodated by numerous small normal faults with limited vertical displacement. This is in striking contrast with the narrow rift valleys to the north and south, characterized by a typical rift valley morphology dominated by large fault escarpments and boundary faults with large vertical displacement. Previous studies have suggested an influence of the Mesozoic-Early Paleogene

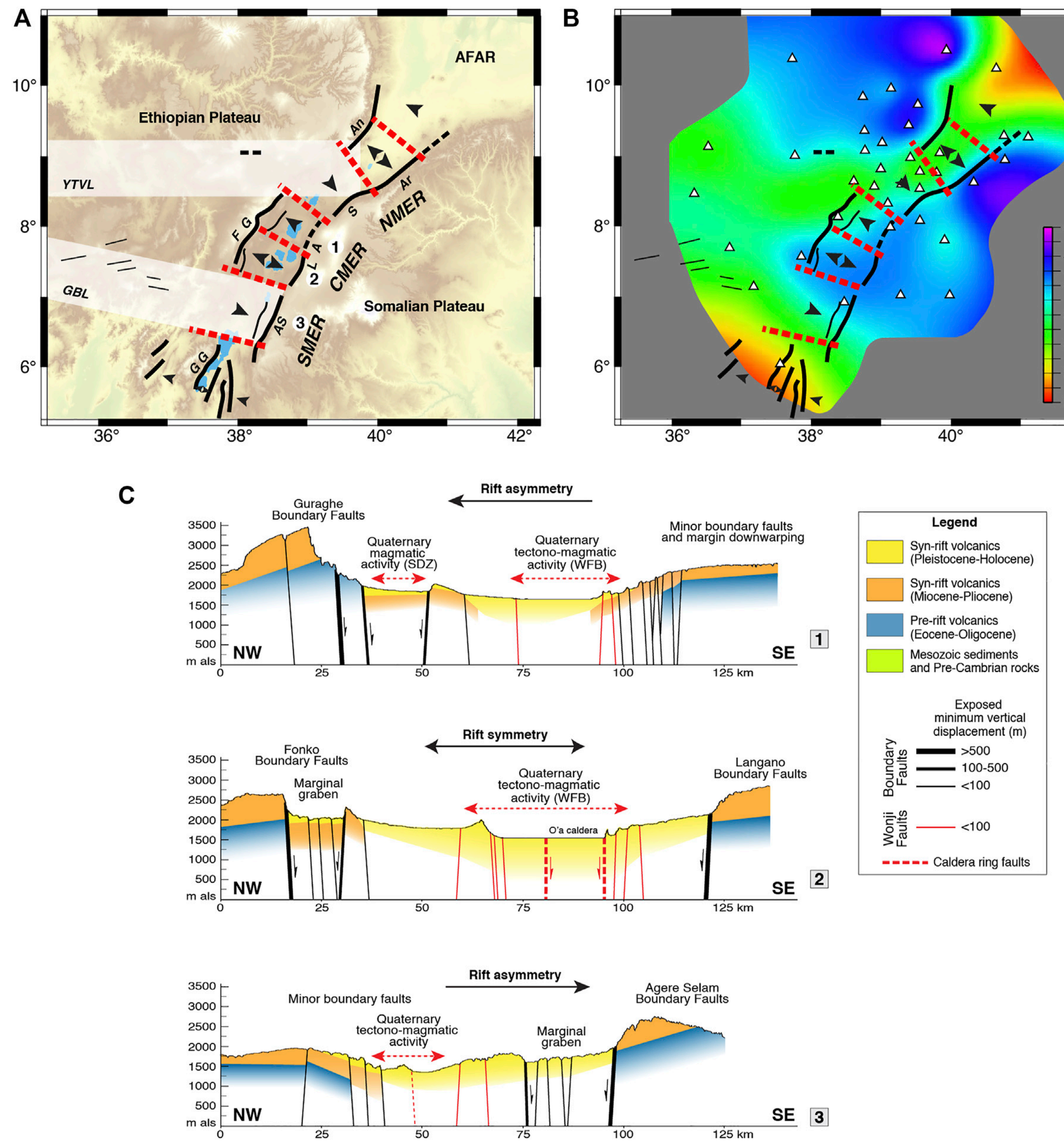

FIGURE 5 | Along-axis variations in the structure of the Main Ethiopian Rift (modified from Corti et al., 2018a). **(A)** Interpreted variations in rift symmetry and polarity: single arrows indicate the polarity of the different rift sectors; double arrows indicate symmetry of rifting. Whitish boxes indicate the hypothesised plan-view extent of the transversal structures: Yerer-Tullu Wellel (YTVL) and Goba-Bonga (GBL) volcano-tectonic lineaments. Rift segments labelled as NMER: Northern MER; CMER: Central MER, SMER: Southern MER. Other labels indicate the main rift escarpments as follows, An: Ankober; Ar: Arboye; AS: Agere Selam; FG: Fonko-Guraghe; GG: Gamo Gidole; LA: Langano Asela; S: Sire. **(B)** Map of depth of the Moho in the MER, modified after Keranen et al. (2009). **(C)** Simplified geological profiles across different sectors of the MER, with vertical exaggeration of x10. WFB: Wonji Fault Belt; SDZ: Silti Debre Zeit volcanic belt.

tectonic phase on the later extensional deformation related to the EARS (e.g., Brune et al., 2017; Corti et al., 2019; Emishaw and Abdelsalam, 2019): the location of the diffuse Cenozoic tectono-magmatic activity has been likely controlled by the presence of a wide region of thinned crust, trending NW-SE and resulting from Mesozoic extension (Anza graben, South Sudan rifts; **Figure 4**). More specifically, the anomalously wide rift zone is likely caused by the N-S direction of propagation of the Main Ethiopian and Kenya rift systems into this NW-SE-trending region of thinned crust and stronger mantle lithosphere (e.g., Brune et al., 2017). In this region, the Kenyan and Ethiopian rift valleys are left-laterally deflected away from one another, avoiding a direct linkage to form a thoroughgoing N-S depression (Brune et al., 2017). Therefore, the presence of pre-existing transversal structures has a

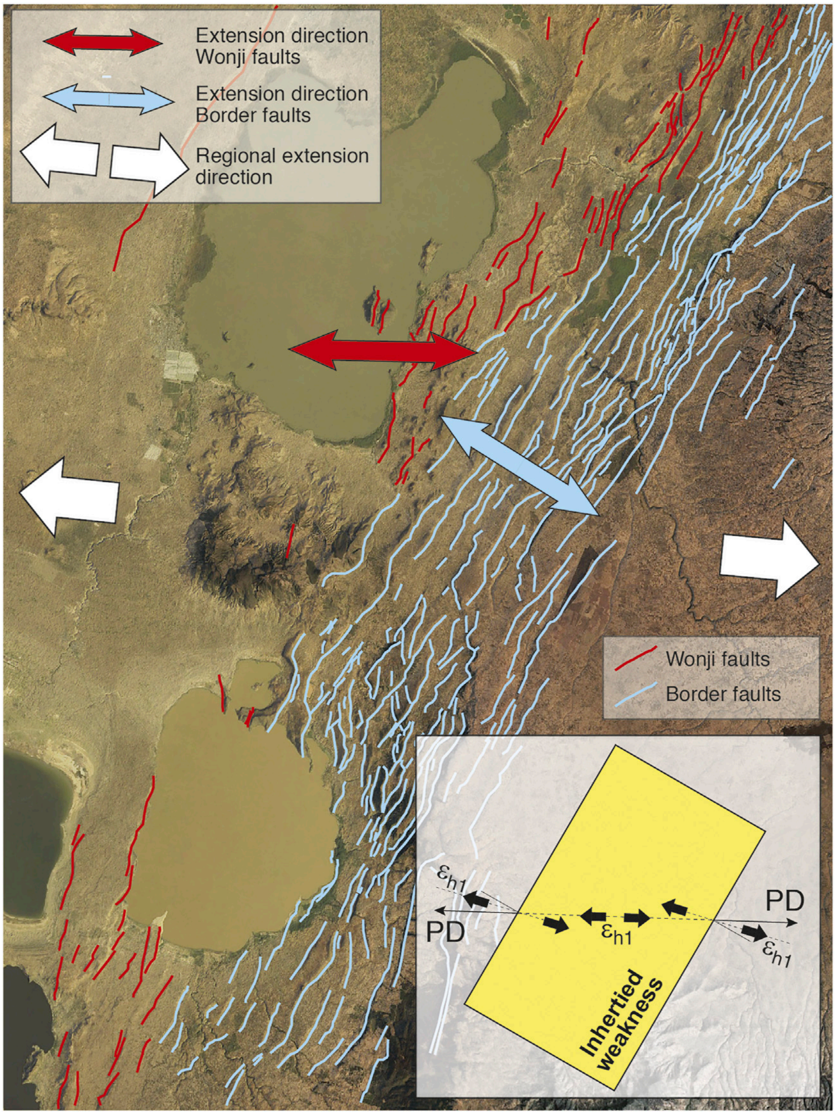

FIGURE 6 | Reorientation of the extension direction at the Asela-Langano margin. The local direction of extension at boundary and internal faults is indicated with light blue and red arrows, respectively; the regional direction of extension is illustrated with the big white arrows. Inset in the bottom right shows the relationship between the rift trend (or its perpendicular), the regional direction of extension (or plate divergence, PD) and the trend of the greatest horizontal principal strain (εh_1) in the different portions of the oblique rift (modified from Corti et al., 2020).

strong influence on the interaction and linkage of major rift segments.

CONTROL OF PRE-EXISTING STRUCTURES ON RIFT SEGMENTATION AND SYMMETRY

Recent studies in the MER (e.g., Corti et al., 2018a) have shown that the pre-rift structure of the Ethiopian and Somalian plateaus at two sides of the reactivated ancient suture zone has a major control on rift architecture and segmentation.

The eastern margin of the MER, where the lithosphere beneath the Somalian Plateau is strong and homogeneous (e.g., Keranen and Klemperer, 2008; Corti et al., 2018a), is characterised by the presence of a more or less continuous system of large boundary faults (**Figures 1**, **5**). Conversely, the western margin shows significant along-axis variations, with segments marked by large boundary faults (Ankober, Fonko-Guraghe, Gamo-Gidole) alternating with sectors characterised by flexures, with gentle monoclines dipping towards the rift axis (**Figures 1**, **5**). This has been interpreted to reflect a more heterogeneous and complex structure of the Ethiopian plateau lithosphere than the Somalian, with the Ethiopian plateau characterised by a strong northern portion and a southern

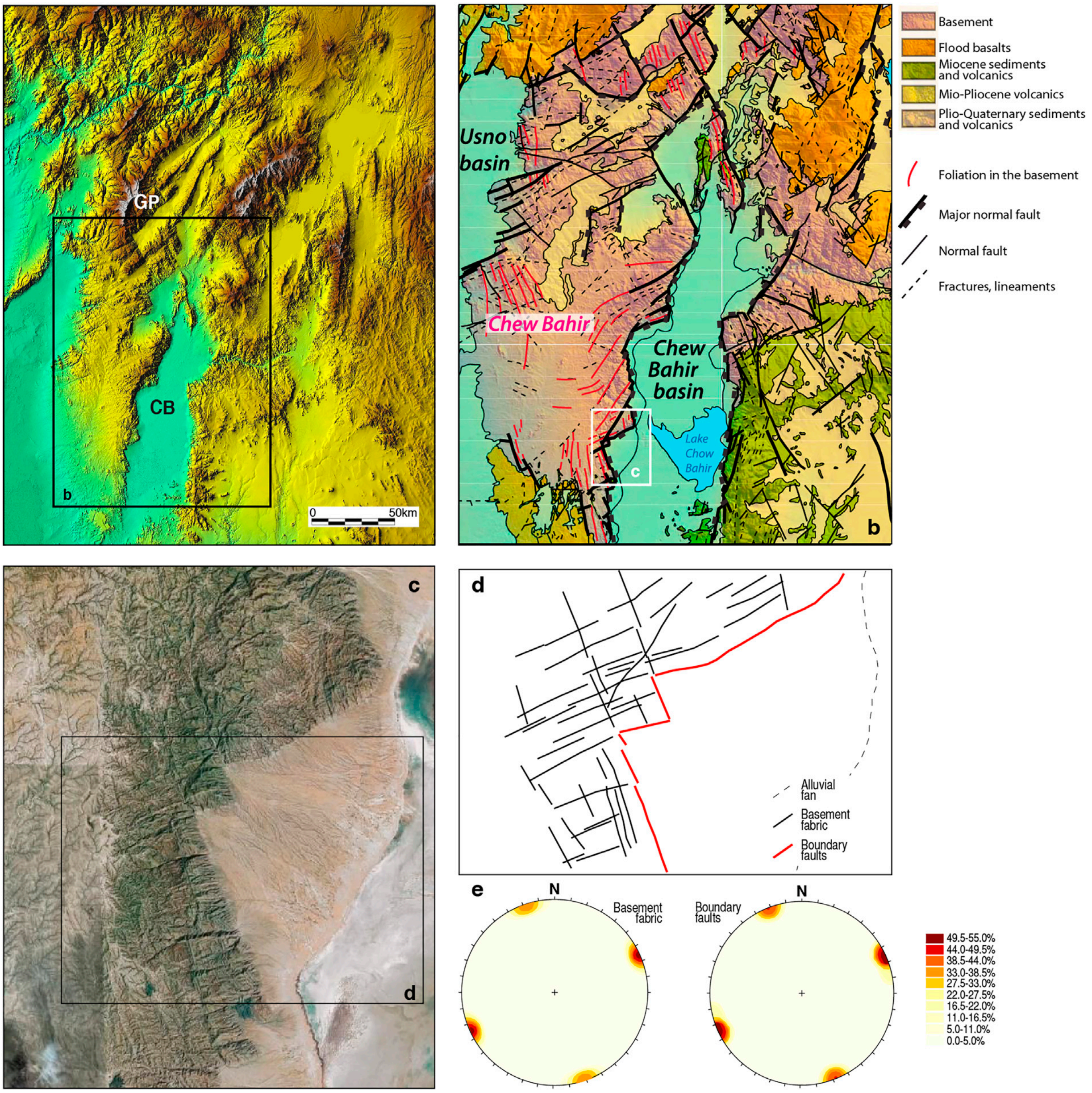

FIGURE 7 | (A) Digital elevation model (NASA-SRTM) of southern Ethiopia. CB: Chew Bahir; GP: Gofa province. **(B)** Geological map of the Chew Bahir basin and surrounding areas, illustrating the pattern of foliation on the basement. **(C)** Typical angular pattern of boundary faults of the Chow Bahir basin (see text for details); **(D)** structural sketch. **(E)** Distribution of inherited basement fabrics and boundary faults, illustrated as plots of weighted fault azimuths. Note the similarity between the trend of basement fabrics and that of boundary faults, supporting that the development of the latter is strongly influenced by basement inherited weaknesses. Panels **(A)**, **(C)**, **(D)**, **(E)** modified from Corti (2009); panel **(B)** modified from Philippon et al. (2014).

portion with a thinner and weaker crust (**Figure 5**; e.g., Keranen and Klemperer, 2008). This southern portion is marked by the presence of the E-W Yerer-Tullu Wellel and Goba Bonga volcano-tectonic lineaments (**Figure 5**). Where these pre-existing weaknesses intersect the rift at a high angle, major boundary faults are absent from the western margin and are instead replaced by gentle flexures; this, together with well-developed faults on the eastern side, gives rise to an overall asymmetry of the rift (**Figure 5**). Instead, where large boundary faults characterise the western margin, the rift is symmetric (**Figure 5**). Notably, southeast of Addis Ababa, the eastern rift margin is characterised by a prominent shift to the East, which occurs in spatial coincidence with the Yerer-Tullu Wellel volcano-tectonic lineament (**Figures 1**, **5**). This coincidence has been interpreted to reflect an influence exerted by the E-W-trending pre-existing weakness on the plan-view geometry of the rift valley at this latitude (e.g., Korme et al., 2004).

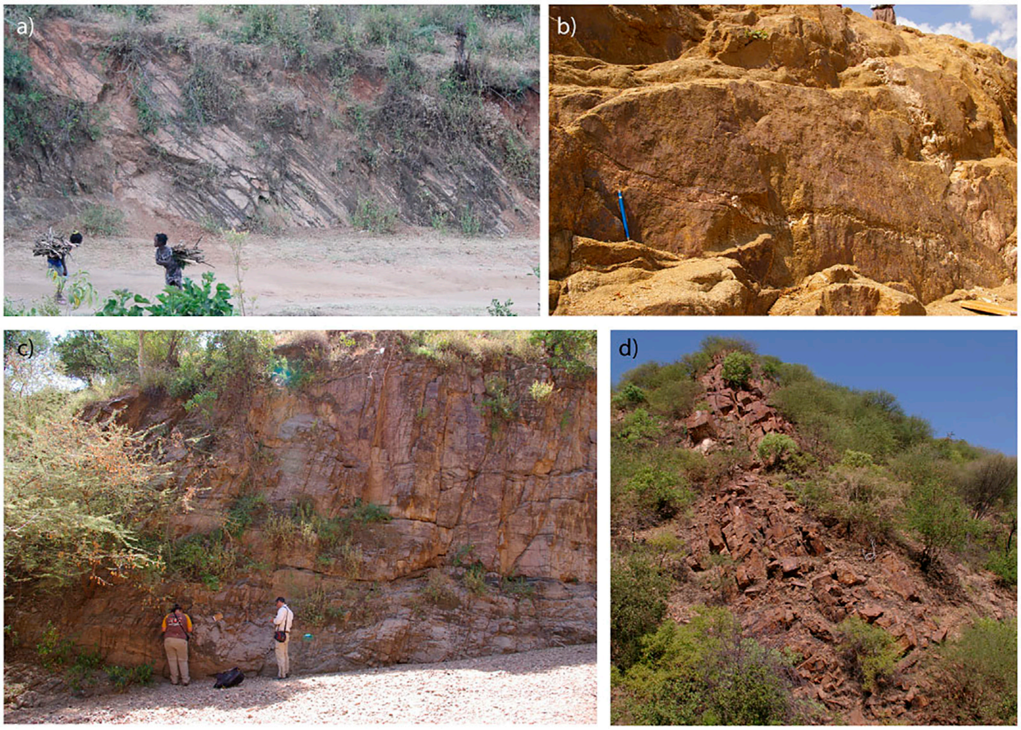

FIGURE 8 | Field examples of structures affecting the Precambrian basement in the southern MER: **(A)** magmatic foliation and **(B)** Cenozoic fault plane affecting basement and cutting quartz vein and aplitic dike in the Gofa province; **(C)** System of sub parallel fractures reactivated and associated to a major normal fault (not visible of the left) in the Chew Bahir basin; **(D)** basement foliation sub parallel to the major fault plane delimiting the Chew Bahir basin.

In summary, the above observations indicate that the MER is characterized by a segmentation strongly controlled by the inherited lithospheric structure, which results in 80–100 km-long rift segments with alternating symmetric/asymmetric basins.

CONTROL OF PRE-EXISTING STRUCTURES ON LOCAL-SCALE FAULT GEOMETRY AND ARCHITECTURE

Pre-existing structures have a significant influence on the geometry and segmentation of extension-related normal faults at a more local (<80 km) and shallower scale. The architecture and kinematics of boundary faults at the margins of the CMER and NMER are strongly influenced by the oblique inherited weakness described in **Section 3**. The boundary faults are at surface en-echelon arranged and oblique to both the pre-existing weakness (i.e., the rift trend) and the orthogonal to the regional plate motion vector; they trend orthogonal to the local direction of extension (**Figure 6**; Corti et al., 2013; Philippon et al., 2015). Inversion of fault-slip data and detailed analysis of fault kinematics in analogue models of oblique rifting indicate indeed a pure dip-slip motion on these faults, in which (given the oblique orientation with respect to the extension direction) a strike-slip component of motion could be expected (Corti et al., 2013; Philippon et al., 2015). This documents a reorientation in the extension direction at the margins of the rift, where the local extension direction does not correspond to the regional plate divergence, resulting in a pure dip-slip motion in an overall oblique kinematics (e.g., Morley, 2010; Corti et al., 2013; **Figure 6**).

Examples of an important control of inherited structures like fractures, faults, foliations, and dikes on the geometry of individual faults or fault segments are evident in the Gofa Basin and Range and in the Chew Bahir basin, in southern Ethiopia (**Figures 7**, **8**). In these regions, large boundary faults are typically highly segmented, with many short interacting segments characterised by sharp changes in orientation giving rise to zig-zag geometries and angular patterns (e.g., Moore and Davidson, 1978; Vétel et al., 2005; Vétel and Le Gall, 2006). Typically, the orientation of the boundary fault segments mimics the trend of foliations or mylonite zones indicating a strong control exerted by pre-existing basement structures (**Figures 7**, **8**; Moore and Davidson, 1978). Faults parallel to the extension direction are related to reactivation of basement fabrics rather than to recent transcurrent faults (Moore and Davidson, 1978; Philippon et al., 2014).

A similar control has been suggested by recent works in the Ririba rift, at the southern termination of the Ethiopian Rift (Corti et al., 2019). In this rift, besides the angular fault pattern and the parallelism between faults and inherited fabrics, the main boundary faults are characterised by an anomalously low displacement/length ratio (i.e. long faults have very low displacement) and by displacement/length (D-L) curves (with flat top profiles, low-end gradients and low D-L ratio values) typical of a 'constant length model' of fault growth (see Supplementary Fig. 4 in

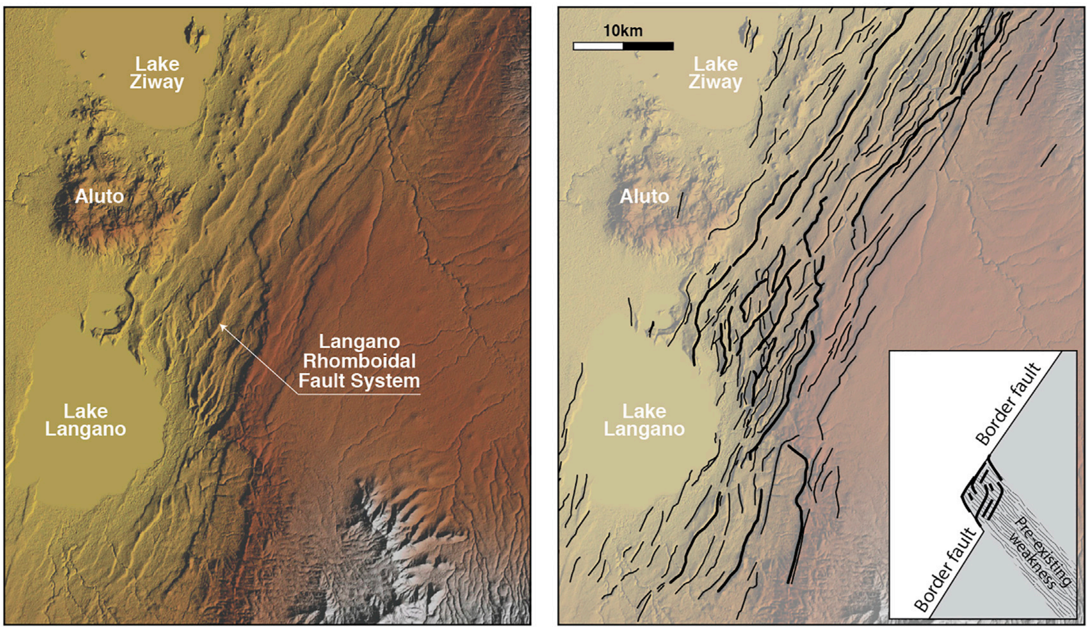

FIGURE 9 | Digital elevation model (NASA-Shuttle Radar Topography Mission, SRTM 30 m resolution; left panel), and faults superimposed onto a SRTM digital elevation model (right panel) of the Langano Rhomboidal Fault System. Inset in the bottom right shows a schematic representation of the possible influence of a NW-SE-trending inherited weakness on the fault pattern. See text for details.

Corti et al., 2019). This growth model is representative of reactivated fault systems in which fault lengths are inherited from underlying structures and established almost instantaneously on geological timescales, as also suggested for the nearby Kino Sogo fault belt in Kenya (Vétel et al., 2005; Vétel and Le Gall, 2006).

Another typical example is the Langano (or Haroresa) Rhomboidal Fault System (Le Turdu et al., 1999), located East of Lake Langano (**Figure 9**). In this area, the NE-SW-trending Asela-Langano escarpment curve to acquire a NW-SE trend and the interaction between NE-SW and NW-SE-trending structures give rise to a complex pattern of normal faults, with typical S- or Z-shaped plan-view geometries (**Figure 9**). This pattern and the curvature of the escarpment have been suggested to be controlled by a major NW-SE pre-existing crustal weakness zone, roughly parallel to the trend of the Red Sea (e.g., Korme et al., 2004). The existence of such pre-existing transverse structure close the Lake Langano is also supported by gravity data (Korme et al., 2004) which evidence the presence of NW-SE graben below the rift depression. A similar example of control on the local-scale fault pattern of inherited structures includes NW-SE faults East of Addis Ababa (Wolenchiti area) defining a NW-SE-trending graben filled by Pleistocene diatomite deposits (Korme et al., 2004).

CONTROL OF PRE-EXISTING STRUCTURES ON THE DISTRIBUTION VOLCANISM

Many examples in the MER document a strong control exerted by pre-existing structures on the distribution of volcanic vents and edifice geometries. In the Ririba rift, at the southern termination of the MER, the Quaternary volcanic fields are aligned in a NE-SW direction and show no apparent relationship with the N-S-trending Pliocene boundary faults of the rift (**Figure 10**) therefore indicating that these structures do not exert a control on the pathways of magma ascent. This volcanism aligns parallel with regional, NE-SW/NNE-SSW-trending pre-existing lineaments (such as the Buluk Fault Zone in **Figure 10**) suggesting that the distribution of volcanic centres may have been controlled by these major deep inherited structures (e.g., Vétel and Le Gall, 2006; Corti et al., 2019; Franceschini et al., 2020). Magma ascent along these pre-existing structures may have been caused by abandonment of the Ririba rift and consequent deactivation of the main rift faults, and a stress re-organization due to gradients in crustal thickness (Franceschini et al., 2020). This resulted in buoyancy forces causing a local stress field with maximum horizontal stress orthogonal to the Turkana depression, enabling the uprising and emplacement of magma along NE-SW pre-existing structures. At a more local scale, the distribution of vents and their preferential directions of elongation (within individual volcanic fields) suggest a second-order control by inherited basement fabrics (Franceschini et al., 2020), as documented by the above-mentioned angular networks of minor normal faults observed in the area. Overall, the Ririba example supports that major, lithospheric-scale inherited structures may represent zones of crustal weakness that magma can exploit during its ascent, controlling the volcanic spatial and temporal evolution, volcanic morphology, magma volume, and eruptive dynamics (e.g., Le Corvec et al., 2013; Wadge et al., 2016).

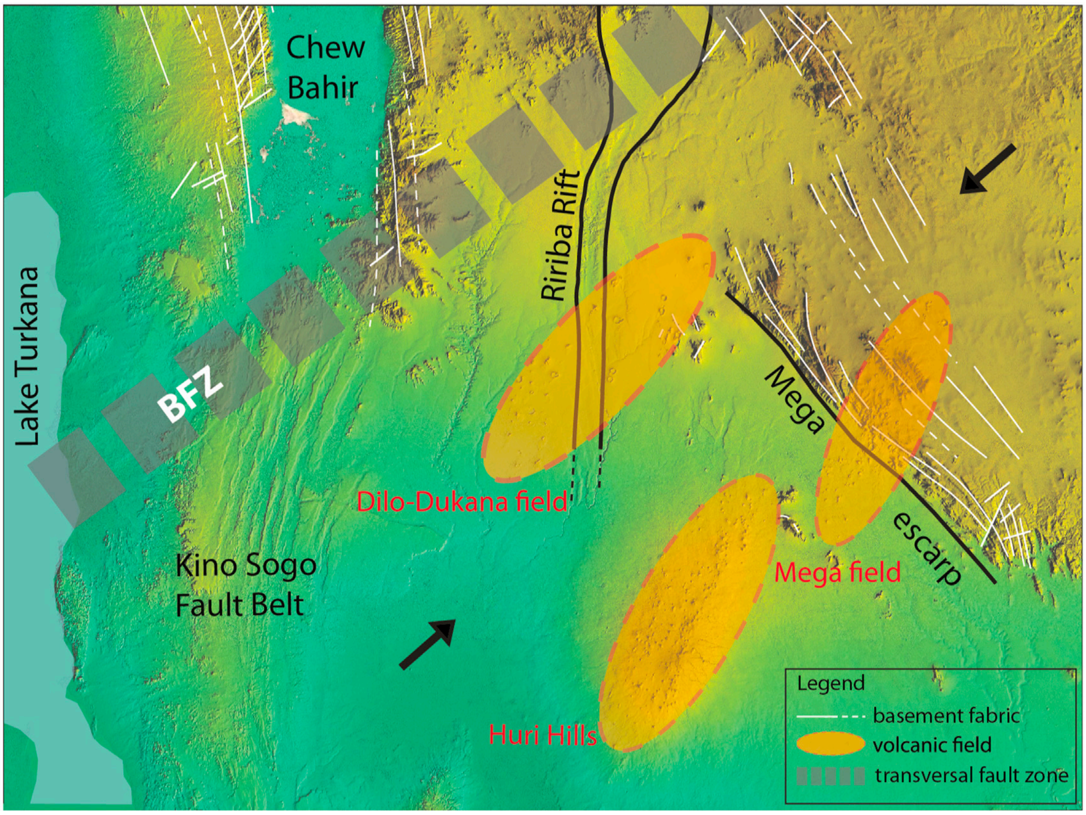

FIGURE 10 | Schematic relations between the distribution of the Quaternary volcanic fields of Dilo, Mega and Huri Hills (orange ellipses) and major inherited structures (dashed lines in the figure) such as the BFZ (Buluk Fault Zone), modified from Franceschini et al. (2020). Black arrows schematically indicate the main compressive stress resulting from buoyancy forces in the area related to variations in crustal thickness and topography. See text for details.

In a recent compilation, Maestrelli et al. (2021) suggested that at least some calderas in the MER (e.g., Fantale, Kone, Gedemsa and Corbetti) may have experienced a tectonic control exerted by pre-existing faults reactivated during the collapse (i.e., fault-controlled caldera rim; **Figure 11**). Furthermore, Acocella et al. (2002) hypothesized a control exerted by inherited structures, reactivated during rift extension, on the localization for Fantale, Kone and Gedemsa calderas. In this regard, Lloyd et al. (2018) suggested the presence of a E-W deep rooted inherited structures controlling the localization and the structural setting of the Corbetti Caldera. As supported by Corti et al. (2018b), this structure may be related to the regional-scale Goba Bonga lineament.

Previous works have also suggested the influence of inherited structures on the development of off-axis (or flank) volcanoes (**Figure 12**). Such volcanic edifices are located in the plateaus surrounding the rift, in an off-axis position with respect to the tectonic depression; a classic example of this volcanism is the Galama range, located in the Somalian plateau (**Figure 12**). Different models of magma generation and/or migration have been applied to explain the development of such volcanism (e.g., Bonini et al., 2001; Maccaferri et al., 2014; Chiasera et al., 2018). However, in most of the different models, the final uprising of magma at shallow crustal levels, resulting in the alignment of dikes and scoria cones in an area of thicker crust, has been related to ascending mafic dikes exploiting pre-existing basement faults and fractures slightly oblique to the rift margins (Mohr and Potter, 1976; Chiasera et al., 2018). Off-axis volcanism is also associated with pre-existing E-W lithospheric structures corresponding the Yerer-Tullu Wellel and Goba Bonga transversal lineaments (Abebe Adhana, 2014; Corti et al., 2018b).

DISCUSSIONS AND IMPLICATIONS FOR REACTIVATION OF PRE-EXISTING STRUCTURES DURING CONTINENTAL RIFTING

Understanding how the pre-existing structure of the continental lithosphere influences rifting is of primary importance, as it may have an impact on several aspects of the rifting process and its outcomes. These may include the potential architecture (e.g., symmetry/asymmetry) of resulting passive margins, the possible segmentation of oceanic domains and transform faults separating them, the characteristics (length, depth extent, segmentation) of seismogenic faults (with implications for maximum magnitude of earthquakes), the distribution, volumes, and dynamics of

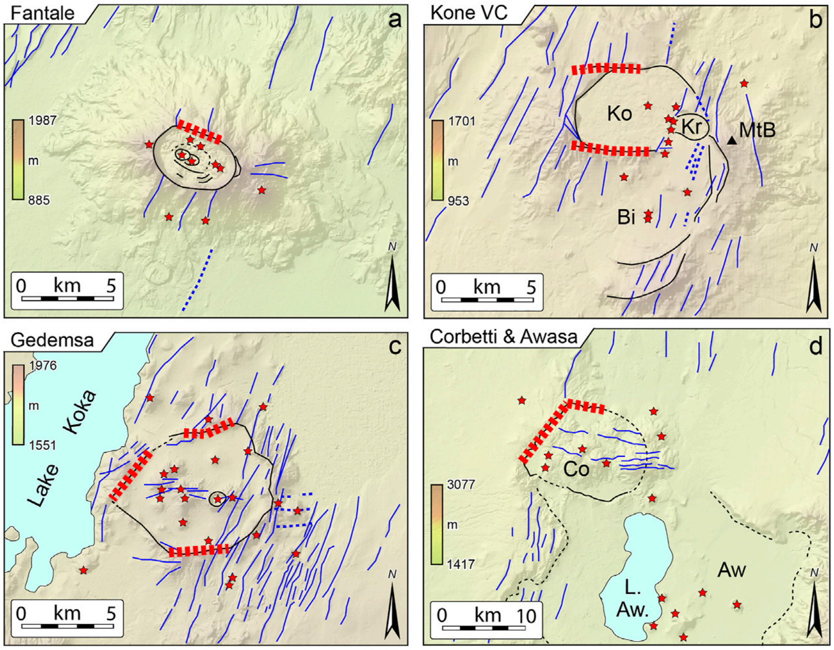

FIGURE 11 | Structural control on collapsed caldera margin at **(A)** Fantale, **(B)** Kone Volcanic complex (KVC), **(C)** Gedemsa and **(D)** Corbetti. Red dashed lines indicate caldera ring faults controlled by inherited structures reactivated during the collapse. Red stars mark volcanic emission points (modified from Maestrelli et al., 2021). Ko: Kone caldera; Kr: Korke caldera; Bi: Birenti caldera; MtB: Mount Birenti; Co.: Corbetti; L. Aw, Lake Awasa; Aw: Awasa caldera remnants.

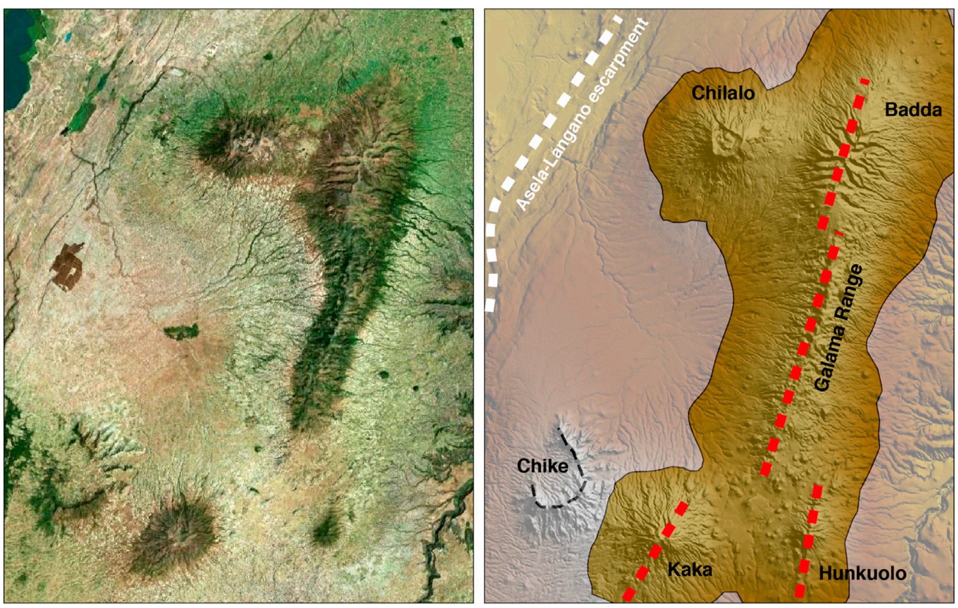

FIGURE 12 | Satellite image (left) and main off-axis volcanoes (right) in the Somalian Plateau. Red dashed lines indicate the trend of inherited fabrics that possibly feed the volcanoes.

associated volcanism (influencing volcanic risks and geo-resources such as geothermal energy). Because of this, the relationship between the Proterozoic crustal/lithospheric framework and the pattern of rift-related structures in East Africa has attracted considerable debate over the last decades (see Purcell, 2017).

Examples from the MER provide useful insights into this debate. Specifically, these examples document a significant

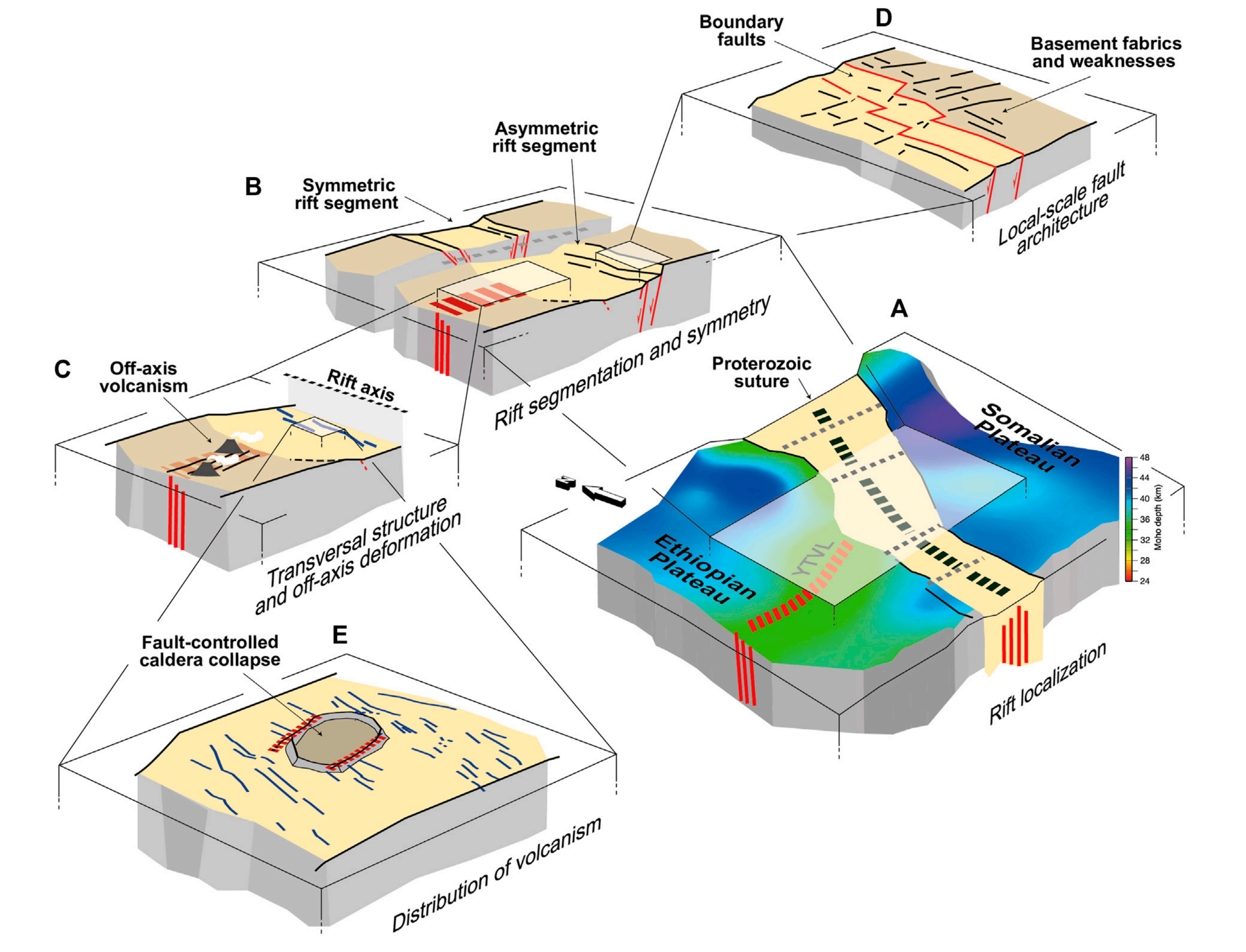

FIGURE 13 | Schematic illustration of the control exerted by inherited heterogeneities at different scales in the MER. From regional-scale to local-scale, we observe: **(A)** Rift localization controlled by Proterozoic suture. YTVL: Yerer-Tullu Wellel transversal structure; **(B)** Rift segmentation and asymmetry induced by large-scale transversal structures; **(C)** Off-Axis volcanism controlled by large-scale transversal structures; **(D)** Local-scale architecture controlled by inherited basement fabrics; **(E)** Distribution and setting of volcanism controlled by local scale-inherited structures.

control exerted by inherited heterogeneities at all different scales, which is illustrated in **Figure 13**.

At a large scale (up to ~800–1,000 km), the localisation of extensional deformation and the plan-view geometry of the rift valley is largely controlled by a NE-SW- to N-S-trending, lithospheric-scale Precambrian suture zone (**Figure 13A**). Suture zones may be indeed weaker than the normal lithosphere, because of processes including increased heat production in the thickened crust and the presence of inherited faults that can weaken the crust (Buiter and Torsvik, 2014). This explains why suture zones are typically reactivated during extension and localize extension-related deformation, as documented in many examples worldwide (see review in Buiter and Torsvik, 2014). In Ethiopia, the along-axis variations in the trend of the suture and the resulting rift valley, determine along-axis differences in the kinematics of rifting, from orthogonal in the southern MER to moderately oblique in the northern MER, which have important implications for rift architecture and evolution (see Keir et al., 2015).

Within the rift, the inherited rheological heterogeneities and different strength of the lithospheric domains surrounding the rift, and the presence of transversal structures, control the interaction between the Ethiopian and Kenyan rift, as well as the along-axis segmentation of the rift valley (**Figure 13B**). Specifically, the strength difference (or similarity) of the lithosphere beneath the plateaus controlled the development of 80–100 km-long rift portions characterised by asymmetry (or symmetry) of the rift valley. Recent analysis from other continental rifts (e.g., Malawi Rift, Upper Rhine Graben; Laó-Dávila et al., 2015; Grimmer et al., 2017) support that along-axis variations in inherited structures (e.g., basement fabrics) have a significant influence on basin architecture and segmentation, and on the characteristics of the rift margins.

Roughly E-W, lithospheric-scale inherited weaknesses control the development of off-axis volcano-tectonic activity in the plateaus surrounding the rift, an activity which may extend hundreds of kilometres away from the rift (**Figure 13C**). Transversal pre-existing structures may have controlled other characteristics of the MER, such as its plan-view geometry and its deflection southeast of Addis Ababa. Similar controls have been described in other regions of East Africa: for instance, the inherited Aswa Shear Zone has been suggested to control rift deflection in northern Kenya and the transfer of strain from the Western Branch to the Eastern Branch of the EARS (e.g., Purcell, 2017 and references therein).

At a local scale (<80 km), pre-existing structures may control the geometry of extension-related normal faults, causing anomalous fault patterns (**Figure 13D**): when controlled by inherited structures, normal faults may deviate from linear to zig-zag or sigmoidal plan-view geometries, with atypical displacement/length (D/L) curves and fault lengths established almost instantaneously on geological timescales (constant length model of fault growth). Examples from other sectors of the EARS (e.g., Malawi) confirm that pre-existing basement fabrics may have an important influence on the architecture of later rift-related faults (e.g., Williams et al., 2019; Wedmore et al., 2020; Kolawole et al., 2021). However, this may not always be the case: other studies have shown that pre-existing weaknesses only locally control border fault geometry at subsurface (e.g., Hodge et al., 2018) or that high-angle normal faults may cut through low-angle basement fabrics (e.g., Ebinger et al., 1989). In the Kenya rift, recent studies (Muirhead and Kattenhorn, 2018) points to a complex time-evolution of inheritance during rifting, with reactivation of pre-existing structures documented to postdate rift initiation and occur in an advanced rifting stage. In this case, later activation of inherited fabrics may reflect a complex contribution by magma-assisted deformation (Muirhead and Kattenhorn, 2018). A time-dependent reactivation of inherited structures has been also documented in other regions of the EARS, such as the Turkana depression of southern Ethiopia and northern Kenya. There, contrarily to what suggested for the Kenya rift, field analyses and seismic reflection data indicate that some NE-SW-trending basement structures have been reactivated during initial rifting but then abandoned during progressive extension, given their non-optimal orientation with respect to the roughly E-W extension direction (Nutz et al., 2021). Similarly, NW-SE-trending faults related to a previous Cretaceous-Early Paleogene extension phase are non-optimally oriented with respect to the roughly E-W extension of Cenozoic rifting. In this case, geodetic observations, and analysis of present-day deformation (Knappe et al., 2020) indicate no reactivation of these pre-existing faults during later extension, as also supported by analogue modelling of extension in the region (Wang et al., 2021). These analogue models indicate that the absence of fault reactivation may be related to a limited development of structures during the early rift phase, with a small volume of crust affected by pre-existing weak zones and a low reduction in strength in the brittle crust, and to their obliquity with respect to the later extension direction. In general, the strength contrast between the undeformed crust and that affected by pre-existing structures and the orientation, size and depth of inherited faults with respect to the extension direction are controlling factors in the reactivation of pre-existing structures as documented in many modelling works (e.g., Bellahsen and Daniel, 2005; Maestrelli et al., 2020; Molnar et al., 2017, 2019, 2020; Osagiede et al., 2021; Samsu et al., 2021; Schori et al., 2021; Wang et al., 2021, Zwaan and Schreurs, 2017; Zwaan et al., 2021a,b).

Inherited structures also control the patterns of migration and emplacement of rift-related magmas (**Figure 13E**), which may at some places show no direct relations to rift related faults and rather cut them. The MER examples support that pre-existing structures may control the spatial and temporal evolution of volcanic activity, its volume and eruptive dynamics, as observed in other parts of the EARS (such as the Chyulu Hills in the Kenya Rift; e.g., Mazzarini and Isola, 2021) and other regions undergoing extension (e.g., Gómez-Vasconcelos et al., 2020).

CONCLUDING REMARKS

We have shown how inherited structures have controlled the development of the MER from regional to local-scale. In general, as typically observed in other rift settings, the influence of inheritance on rift-related deformation is rather obvious at a regional scale, as rift valleys localise within lithospheric-scale weak zones avoiding stronger regions. Similarly, large, lithospheric-scale transversal structures influenced the MER segmentation, symmetry and off-axis volcanic activity. Examples in the MER document a local-scale influence of inherited structures on normal fault geometries and rift-related volcanism. However, comparison with other examples from the EARS suggests that the relations between pre-rift structures and individual rift basins or faults are more complex and several aspects of fault reactivation at a local scale remain enigmatic. These include, among others, the time-space variations of reactivation during rift progression and its dependence on parameters such as: the volume of crust affected by pre-existing weak zones and/or their dimensions, the strength contrast required for their re-use, and their dip and orientation with respect to the extension direction. Additional detailed studies in locations where we can clearly analyse, in 3D, crustal faults and ancient structures are therefore needed to improve our knowledge of these complex relations.

AUTHOR CONTRIBUTIONS

GC conceptualized and wrote the work; FS and DM contributed to the writing.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.