A review of tectonic models for the rifted margin of Afar: implications for continental break-up and passive margin formation

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Frank Zwaan[1], Giacomo Corti[2], Derek Keir[1,3], Federico Sani[1]

1) Dipartimento di Scienze della Terra, Università degli Studi di Firenze, Via G. La Pira, 4, 50121 Florence, Italy
2) Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse, Via G. La Pira, 4, 50121 Florence, Italy
3) School of Ocean and Earth Science, University of Southampton, Southampton SO14 3ZH, United Kingdom

ORCIDs:

Frank Zwaan	https://orcid.org/0000-0001-8226-2132
Giacomo Corti	https://orcid.org/0000-0001-7399-4438
Derek Keir	https://orcid.org/0000-0001-8787-8446
Federico Sani	https://orcid.org/0000-0001-8832-1471

Corresponding author: F.Zwaan (frank.zwaan@geo.unibe.ch)

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Abstract

The Afar region represents a unique opportunity for the study of ongoing rift development and the various phases of continental break-up. In this work we discuss the geological and geomorphological characteristics of the Western Afar Margin (WAM) and the various scenarios proposed for its evolution. A drastic decline in topography and crustal thickness from the Ethiopian Plateau into the Afar Depression, as well as a series of marginal grabens and a general presence of antithetic faulting characterize the WAM. Present-day extension is mostly accommodated at the rift axis in Afar, yet the margin is still undergoing significant deformation.

Models for the evolution of the WAM involve either isostatic loading effects due to erosion, rifting-induced block rollover, large-scale detachment fault development or crustal flexure due to lithospheric stretching or magmatic loading. This wide variation of potential mechanisms for WAM development may reflect a general structural variation along the margin and in Afar, involving different stages of rift formation and possibly indicating two distinct pathways leading to continental break-up.

In order to better understand the rifting mechanisms and to fully exploit the research potential of the region, further assessment of the WAM and its relation to Afar will be necessary. The findings of such future work, combined with data from rifts and passive margins from around the globe will be of great importance to assess the processes involved in continental breakup and to better constrain the sequence of events leading from initial rifting to break-up and oceanic spreading.

1. Introduction

One of the crucial processes in plate tectonics is the rifting and eventual breaking up of continents, followed by the opening of a new ocean basin with a passive continental margin on either side. Rifts and passive margins have been studied extensively for economic reasons, in particular for their vast oil and gas reserves (e.g. Levell et al. 2011; Zou et al. 2015), their rich archives on global environmental change (e.g. Haq et al. 1987; Catuneanu et al. 2009; Kirschner et al. 2010; Catuneanu & Zecchin 2013) and their associated natural hazards (Brune 2016). Yet the structural evolution of continental break-up and the processes involved remain poorly understood (e.g. Peron-Pinvidic et al. 2013). The main reasons involve accessibility: significant parts of (aborted) rifts or passive margins are generally situated deep below sea level and relevant structures are often covered by thick sequences of clastic sediments and evaporites (Divins 2003; Brune 2016), thus posing significant challenges for scientists and exploration geologists alike (e.g. Argent et al. 2000; Law et al. 2000; Oakman 2005; Levell et al. 2011; Jones & Davison 2014).

The Afar region, which forms the triple junction between the East African, Red Sea and Gulf of Aden rift systems (Fig. 2), provides geologists with a unique research opportunity, as it represents one of the rare locations where active continental break-up and the on-going transformation from rifts to passive margins can be examined on land (Varet 2018). In recent years, much attention has focused on understand mechanisms and time scales of magma injection in the rift axis of Afar, where phases of intense volcanism and focussed seismicity occur along discrete segments of the rift axis (e.g. Wright et al., 2005; Barnie et al., 2016; Daniels et al., 2014), interpreted as embryonic spreading centres (e.g. Barberi et al. 1970, Barberi & Varet 1977; Hayward & Ebinger 1996; Ebinger et al. 2010, Fig. 2a). By contrast, the margins of the Afar rift remain poorly studied.

This review paper is mainly focused on the Western Afar Margin (WAM, Figs. 1, 2), which represents a major fault zone separating the Afar Depression from the Ethiopian Plateau and marks a drastic reduction in topography (from 2500-3000 m to 800-100 m and locally below sea level, Mohr 1983, Figs. 1, 4) and crustal thickness (from ca. 40 km down to 23-16 km, Makris and Ginzburg, 1987; Hammond et al. 2011). A remarkable series of basins (referred to as “marginal grabens”, Mohr 1962, Fig. 2b) associated with pervasive antithetic faulting aligns along the rifted margin. These fault-bounded basins, a unique feature for along rifted margins, are tectonically active, posing severe seismic hazards to the local population (Gouin 1979; Ayele et al., 2007).

Previous authors have proposed various contrasting structural models to explain the evolution and architecture of the WAM, from rollover structures due to a large-scale detachment faults (e.g. Tesfaye & Ghebreab, 2013), erosion-induced isostatic adjustment (Mohr 1962) to lithospheric flexure caused by magmatic loading (e.g. Wolfenden et al. 2005). It is clear that the development of the WAM is linked to lithospheric extension, yet to date no scientific consensus has been reached over which processes govern the system.

The aim of this paper is therefore to provide an overview of the various concepts proposed for the structural evolution and architecture of the WAM and its marginal grabens, how these concepts relate to the available field evidence and how they may fit in the large-scale evolution of Afar. We furthermore propose strategies and techniques to improve our knowledge of the area in order to better understand rift and passive margin evolution.

2. Regional geological setting

Afar forms a triangular zone of highly extended lithosphere with a relatively low surface topography, locally even below sea level. Afar is bordered by the Ethiopian Plateau to the west, the Somalian Plateau to the south (Mohr 1983) and the Danakil and Ali-Sabieh/Aïsha Blocks to the NE and east (Kidane 2015, Fig. 2). From the east, the Gulf of Aden enters Afar at the Gulf of Tadjura, initiating continental break-up there (e.g. Makris & Ginzburg 1987; Manighetti et al. 1997; 1998). In the north, the Red Sea oceanic spreading system steps laterally over the Danakil Block into the Gulf of Zula and northern Afar. From there, the Danakil Depression and its continuation to the SE represent the second arm of the current Afar triple junction (Fig. 2, inset). Along the axis of this rift zone deformation, earthquake activity and volcanism are currently localized along discrete magmatic segments where a significant proportion of extension occurs by magma intrusion indicating imminent break-up (e.g. Barberi et al. 1970, Barberi & Varet 1977; Hayward & Ebinger 1996; Ebinger & Casey 2001; Wright et al., 2006; Ebinger et al. 2010). The Danakil rift links up with the Gulf of Aden structures through a series of en-echelon and overlapping grabens in central and eastern Afar (e.g. Abbate et al. 1995; Manighetti et al. 1998, 2001; Muluneh et al. 2013; Doubre et al., 2007; Pagli et al. 2019). The continental Main Ethiopian Rift in the south forms the third rift branch, and is separated from the Red Sea-Gulf of Aden system by the Tendaho-Goba'ad Discontinuity (e.g. Wolfenden et al. 2004, Fig. 2).

The development of Afar initiated with the eruption of extensive flood basalts during a ca. 1 Ma interval around 30 Ma (Hoffman et al. 1997), an event associated with the arrival of one or multiple mantle plumes between 30-40 Ma (Rooney et al. 2011; 2013; Rooney 2017). These basalts, referred to as the trap series, cover a peneplain surface that extends into Yemen and that is characterized by laterites, indicating a long period of tectonic stability at low elevation (Abbate et al. 2015). The emplacement of the traps was followed by the onset of rifting in Afar after 29 Ma, separating the Nubian and Arabian plates (Ukstins et al. 2002; Bosworth et al. 2005; Wolfenden et al. 2005, Figs. 1, 2). In the Gulf of Aden, extension started earlier at ca. 35 Ma, whereas rifting in the Red Sea only began at ca. 23 Ma (Szymanski et al. 2016; Leroy et al. 2010; Purcell 2017 and references therein). This NW-ward propagation of rift initiation is likely related to the counterclockwise rotation of the Arabian plate due to collision in the Mediterranean and subduction in the Makran (Fig. 1), whereas rift location was likely controlled by mantle plume emplacement and/or structural inheritance (Smith et al, 1993; Bellahsen et al. 2003; ArRajehi et al. 2010; Molnar et al. 2017, 2018; Koptev et al. 2018).

Continental rifting was followed by oceanic spreading around 17.6 Ma or even 20 Ma at the easternmost sector of the Gulf of Aden and subsequently progressed westward (Manighetti et al. 1997; d'Acremont et al. 2006; 2010; Autin et al. 2010; Fournier et al. 2010; Leroy et al. 2010). Seafloor spreading in the central and southern Red Sea is dated at around 5 Ma (Bosworth et al. 2005; Cochran 2005; Augustin et al. 2014 and references therein), but may have initiated as early as 12 Ma (Izzeldin 1987). In Afar, by contrast, oceanic spreading has not yet been fully established. We also observe a decreasing trend in the age of earliest rift-related volcanism from north to south within Afar, suggesting that extension locally propagated southward until ca. 11 Ma (Zanettin & Justin-Visentin 1975; Wolfenden et al. 2005; Ayalew et al. 2006).

Around this time the Main Ethiopian rift developed in the south of Afar forming the third arm of the current triple junction (Wolfenden et al., 2004, Figs. 1, 2), although the Somalian plate possibly started moving away from the Nubian plate as early as 16 Ma (DeMets & Merkouriov 2016). This late development of the Main Ethiopian rift, which in contrast to the other rift arms is still in its continental phase and possibly propagated to the SW, away from Afar (Bonini et al. 2005; Corti 2009; Abebe et al. 2010b), supports the notion that Afar should not be seen as an example of a classic RRR-triple junction (e.g. Barberi et al. 1972; Varet 2018). Furthermore, the Danakil block, which is strongly extended and was previously a part of the Red Sea rift valley floor (Morton and Black 1975; Collet et al. 2000; Redfield et al. 2003), started an anticlockwise rotation associated with the development of the Danakil Depression due to a rift jump of the Red Sea rift axis into Afar around 11 Ma (e.g Eagles et al. 2002; McClusky et al. 2010). The Danakil Block thus became an additional conjugate margin to the WAM, next to the larger Yemen margin. Strain partitioning between the rifts on both sides of the microplate (Fig. 2) may have contributed to the protracted break-up in Afar. In the meantime, the Ali-Sabieh/Aïsha block underwent a simultaneous clockwise rotation (Kidane 2015).

As extension continued within this complex tectonic environment, deformation generally shifted from the WAM to the rift axes, possibly in a stepwise succession reflected in three distinct volcanic phases (Zanettin & Justin-Visentin 1975, Wolfenden et al. 2005). During this process, magmatism and deformation became highly focuses along discrete segments that were established at ca. 2 Ma (e.g. the Wonji Fault belt in the Main Ethiopian Rift and the Danakil Ridge in the Danakil Depression, Mohr 1967). These magmatic segments developed around the same time as Gulf of Aden system started propagating into Afar through the Gulf of Tajura (Bosworth et al. 2005; Geoffroy et al. 2014) and can be considered the loci of embryonic oceanic spreading centres, and the focus of ongoing continental break-up processes (e.g. Barberi et al. 1970, Barberi & Varet 1977; Hayward & Ebinger 1996; Ebinger & Casey 2001; Ebinger et al. 2010).

3. The Western Afar Margin

3.1. General tectonic characteristics

The WAM, which stretches roughly N-S following a sigmoidal trace between ca. 9°30'N-14°N, marks a sharp decline in topography, from 3000-3500 m to ca. 500 m, or even below sea level in the northernmost parts of Afar (Fig. 2). This decrease in altitude is accompanied by a decrease in crustal thickness from some 40 km below the Ethiopian Plateau to 26 km in southern Afar, down to 15 km or less in the Danakil Depression (Makris and Ginzburg, 1987; Bastow and Keir, 2011; Hammond et al., 2011). The margin is characterized by normal faulting and tilted blocks, as well as the presence of unique marginal grabens (e.g. Abbate & Sagri, 1969; Justin-Visentin & Zanettin 1974; Beyene & Abdelsalam, Abbate et al. 2015; Corti et al. 2015a; Stab et al 2016, Figs. 1-4a-c) and ongoing seismic activity (e.g. Gouin 1970, 1979; Ayele et al., 2007; Craig et al., 2011; Goitom et al., 2017; Illsley-Kemp et al., 2018, Fig. 2).

3.2. Antithetic faulting and tilted fault blocks

The structural architecture of the WAM is dominated by a pervasive style of antithetic normal faulting (i.e. normal faults dipping away from the rift basin, here to the west) and the widespread occurrence of eastward tilted fault blocks with dips increasing towards Afar (Baker et al. 1972, Fig 5a-d). In the Arabati area for instance (i.e. the WAM east of Dessie, Fig. 2) the margin consists of 1-5 km wide fault blocks that are increasingly tilted eastward, from 10° to 35°, although much higher inclinations are recorded in the Afar Depression to the NE (Mohr 1983; Stab et al. 2016). Similar observations are reported by Abbate &

Sagri (1969), who found fault blocks dipping 30-40 degrees to the NE and faults dipping 60˚-70˚ the SW in the area north of Dessie (Figs. 1, 5a-c). Also, feeder dikes from the pre-rift trap basalts are tilted in the same fashion (Abbate & Sagri 1969, Justin-Visentin & Zanettin 1974). It is worth noting that dike swarms tend to be parallel to the margin (Mohr 1971; Megrue et al. 1972), although Barberi et al. (1974) stress the presence of transverse dikes and lineaments, as well as the general right-stepping en-echelon offset of the transition between the WAM and the Afar Depression (Fig. 2).

Wolfenden et al. (2005) report a similar situation between Dessie and the southern end of the WAM: synthetic faults and westward tilted strata west of the marginal grabens versus antithetic faulting with eastward dipping blocks on the Afar side. Dips are similar to those reported to the north (10˚-45˚). Note that antithetic faulting is to some extent also present in the easternmost section of the Southern Afar Margin (SAM) (Tesfaye et al. 2003, Fig. 2), that is otherwise dominated by synthetic (i.e. northward) normal faulting (Fig. 5e). Other examples of antithetic faulting are found SE of the Danakil Block (Figs. 1, 5f, Le Gall et al. 2011), as well as on the Yemen-Red Sea margin (Davison et al. 1994, 1998; Geoffroy et al. 1998). Yet no large and well-defined marginal grabens as observed along the WAM occur in these areas (Fig. 2, section 3.3).

3.3. Marginal grabens

Next to the antithetic faulting and associated tilted fault blocks, the WAM harbours a series of remarkable fault-bounded basins. The names and extend of these basins are not always clearly defined, as different authors use different names for different (sub)basins, which is especially confusing in the northernmost part of the WAM. The situation is not improved by the fact that place names written in the Ethiopian alphabet are commonly not readily transferable in the latin alphabet (Gouin, 1979) and have changed over time for political reasons. An attempt to summarize basin definitions, we present the nomenclature in table 1 and coarse basin extents are outlined in Fig. 3. In the following we tend to follow the convention proposed by Abbate et al. (2015) and Williams (2016). Note that the Damas graben (Tesfaye & Ghebreab, 2013), which shares the characteristics of the other marginal grabens, is not strictly part of the WAM, but is situated at the Red Sea margin and linked to the Buia graben by a transfer zone (Drury et al. 2006, Figs. 2, 3). Also, the status of the Buia graben as a marginal graben can be contested, as it practically forms the continuation of the Danakil rift axis (Figs. 1, 2).

The marginal grabens follow the curving N-S trend of the WAM, which is ca. N-S between 13-14° N, NNE-SSW between 14°-12°30'N, NNW-SSE between 14°30'N-10°N (or even 9°30'N, Wolfenden et al. 2005). However, individual basins are oriented ca. NNW-SSE and arranged in a right-stepping pattern, although the Robit graben and the northern part of the Kobo graben have a NNE-SSW orientation (Fig 2). This general NNW-SSE orientation is oblique to the overall trend of the margin, but roughly parallel to the rift axis in Afar and may be due to the reactivation of a Neoproterozoic (Pan-African) tectonic grain, possibly in combination with oblique extension (e.g. Baker et al. 1972; Drury et al. 1994; Chorowicz et al. 1999; Talbot and Ghebreab 1997; Ghebreab and Talbot 2000). Transfer zones with complex fault structures link up the marginal grabens into a continuous system that covers most of the WAM.

The marginal grabens themselves are some 10-20 km wide and several tens of km in length, although at various places they are poorly developed and various small (sub)basins can be distinguished (Fig. 2). The sedimentary infill consists of alluvial deposits of at least Pliocene-Quaternary age (e.g. Kazmin 1972; Chorowicz et al. 1999). In the Buia graben to the north, these deposits can be up to 550 m thick (Ghinassi et al 2015; Sani et al. 2017). In contrast, sediment thicknesses in the Borkenna graben to the south are limited (Abbate et al. 2015). However, there is a general lack of data on the thickness, type and age of the sediments in the marginal grabens and no seismic sections or well logs are published (Tesfaye and Ghebreab, 2013), so that there are little constraints on the timing of basin formation.

As pointed out by Mohr (1978), the altitude of the marginal graben floors increases towards the south, a feature well visible on topographic sections (Fig. 4). In the northernmost graben (Garsat), the basin floor lies at ca. 500 m, whereas the basin floor of e.g. the Hayk and Borkenna grabens are situated at ca. 1500 m altitude. The sections also nicely illustrate that in the north, the distance between the marginal grabens and the plateau margin amounts to various tens of kilometres (Fig. 4a, b). This distance decreases towards the south so that the Borkenna graben lies immediately adjacent to the margin (Fig. 4e), which is in line with a southward propagation of rifting (e.g. Wolfenden et al. 2005; Ayalew et al. 2006); the older northern part of the WAM seemingly experienced more erosion and associated retreat of the plateau margin (Zanettin & Justin-Visentin 1975).

It is worth stressing that although the antithetic faulting typical for the margin can to a degree be observed at different locations in the region (see section 3.2), the presence of such well-developed marginal grabens are to our knowledge a unique feature of the WAM.

3.4. Seismicity

Afar exhibits a high degree of seismic activity of magnitudes up to ~M6.5, that pose significant direct and indirect hazards (Gouin 1979; Abebe et al., 2010a). Most of these earthquakes can be linked to the (developing) spreading centres in the Afar Depression, the Red Sea, Gulf of Aden and Main Ethiopian Rift (Fig. 2). However, an important belt of seismic activity occurs along the WAM and numerous significant seismic events have been recorded in the area (e.g. Gouin 1970, 1979; Ayele et al., 2007; Craig et al., 2011; Goitom et al., 2017; Illsley-Kemp et al., 2018).

The first historical account of an earthquake in Ethiopia occurred in the northern part of the WAM in 1431-1432 (Gouin, 1979). This has been followed by reports of several 10s of significant earthquakes in the 15^{th} - 20^{th}centuries (Gouin, 1979). Notable events are the swarm of earthquakes during 1841-1842 which triggered a landslide that destroyed Ankober, and the 1961 earthquake swarm which destroyed Majete and caused significant damage to Karakore (Gouin, 1979). The National Earthquake Information Centre (NEIC) provides constraints on earthquakes >M4 since 1973. The catalog shows earthquakes distributed along the WAM, indicating that the whole margin is still actively deforming (Tesfaye & Ghebreab 2013, Fig. 2)

Moment tensor inversion of globally recorded waveforms suggests most earthquakes are less than 10 km depth, though some earthquake do occur down to ~20 km (e.g. Craig et al., 2011). This depth distribution is consistent with that determined using local seismic networks (Illsley-Kemp et al., 2018; Keir et al., 2006). Earthquake focal mechanisms are mostly of normal faulting type with the majority of T-axes scattered by +- 40 degrees either side of N95 degrees (e.g. Illsley-Kemp et al., 2018; Craig et al., 2011; Ayele et al., 2007). A few strike slip earthquakes are also observed (Illsley-Kemp et al., 2018).

These recurring seismic events pose severe risks to the population living in the agriculturally attractive marginal grabens and along the plateau scarps of the WAM, especially due to the presence of steep, easily destabilized slopes (e.g. Abebe et al., 2010a; Meaza et al. 2017 and references therein). The ongoing tectonic activity along the western margin of Afar also suggests that not all the extension has been focused to the rift axis (Illsley-Kemp et al., 2018). Therefore, the rifted margin of Afar has not yet evolved into a true "passive" margin (Fig. 2).

The driving force for deformation and earthquake generation remains unclear. Perhaps a simple explanation for the ongoing seismic activity is that deformation is not yet fully localized along the Afar spreading axes. Consequently, the WAM is not yet a true passive margin and a more distributed mode of extension may be preserved, causing earthquakes along the WAM. Evidence from the Red Sea (Pallister et al. 2010; Ebinger et al. 2010) shows that even after break-up "passive" margins can remain subject to deformation. It is also proposed that stress focusing along the WAM caused by a gradient in crustal thickness, magmatic loading of the rift, as well as sedimentary loading within the rift and the marginal grabens may play a role in focusing extensional stresses (e.g. Wolfenden et al. 2005; Tesfaye & Ghebreab 2013), but little data to support these hypotheses is available. For instance, most earthquake locations and depths are not constrained to a sufficient resolution required to link an event to a specific fault.

Exceptions to this are recent analysis from the Garsat and Abala area, which suggests that seismicity is concentrated along the antithetic eastern boundary fault of the marginal graben system (Illsley-Kemp et al. 2018). In addition, the surface deformation of the 1961 Karakore seismic events was concentrated along the eastern boundary fault of the Borkenna graben (Gouin 1979). When examining the marginal grabens in more detail, it often appears that the eastern boundary fault scarps are characterized by fresher, steeper and less eroded morphology than their western counterparts, where the fault trace may even be absent (Figs. 2, 3). This likely reflects a more intense, recent fault activity on the eastern, antithetic faults. However, the 1500-2000 m decrease in altitude between the Ethiopian plateau and the marginal graben floors (Figs. 2, 4) indicate that the western boundary faults have accommodated major subsidence in the more distant past.

4. Models for the development of the structural architecture along the WAM

Below we present an overview of the various tectonic mechanisms proposed for the development of the structural framework of the WAM, which are subsequently linked to the tectonic evolution of the Afar and the Red Sea rift. Early models involve erosion of the plateau margin (Mohr 1962) or block "rollover" due to crustal creep (Black et al. 1972). Other authors have suggested that extension in Afar is principally accommodated by large-scale detachment faulting (e.g. Morton and Black 1975; Chorowicz et al. 1999; Tesfaye & Ghebreab 2013, Stab et al. 2016). Alternative models involve marginal flexure (Abbate and Sagri 1969), possibly triggered by magmatism during the development of Afar (e.g. Wolfenden et al. 2005). In the following sections we aim to describe the main aspects of each of the proposed tectonic models as well as their implications and predictions, summarized in Table 2 and Fig. 6.

4.1. Erosion of the plateau margin

In an early paper, Mohr (1962) proposed that the Borkenna Graben in the southern section of the WAM may have formed simply due to isostatic compensation after material was removed by erosion of the plateau margin (Fig. 7a-d). According to the model, post-trap extension caused rifting. Subsequent erosion and crustal readjustment formed the eastern boundary fault, followed by the western boundary fault. Although the author states in a later publication, without further explanation, that the model is not realistic (Mohr 1967), its merit is that it does take into account buoyancy effects due to surface processes. Next to erosion, sedimentary (or magmatic) infill and loading of the marginal grabens may affect tectonics along the WAM as well (Tesfaye and Ghebreab 2013), which is known to have an important effect on rift tectonics (e.g. Burov & Cloetingh 1997; Burov & Poliakov 2001; Corti et al. 2013; Zwaan et al. 2018).

4.2. Crustal creep and margin overturn models

Black et al. (1972) suggested that brittle deformation along the Afar margins may be controlled by underlying (lower) crustal creep during extension (Fig. 7e, f). However, which parameters control whether faulting is synthetic or antithetic remains unclear. Kazmin et al. (1980) and Zanettin & Justin-Visentin (1975) consider the possibility that all faulting is initially synthetic, after which the easternmost fault blocks are so far rotated towards Afar that fault throw is reversed and the previously synthetic faults become antithetic. A mechanism other than continued tectonic thinning to explain this massive margin overturn is however not provided.

4.3. Interacting normal (detachment) fault models

In a subsequent paper, Morton and Black (1975) proposed two more elaborate models in which synthetic and antithetic faults (in the case of the WAM eastward and westward dipping faults, respectively) may interact, leading to the formation of a marginal graben in a rollover fault setting (Fig. 7g-h). In this view, the first option is a scenario dominated by a large antithetic (detachment) fault and a marginal graben (i.e. a “compensation graben”, Faure & Chermette 1989) forms due to minor synthetic faulting. The other option involves a large synthetic (detachment) fault and a graben forming due to secondary antithetic faults. In both models, deformation is strongly focused along the detachment fault and the basinward part of the crust is dominated by antithetic faulting. Note however, that the timing of synthetic fault initiation is different in both cases (Fig. 7g-h). Block rotation is suggested to increase towards Afar as a result of enhanced extension towards the rift axis.

4.3.1. Two-phase eastward dipping detachment model I (Tesfaye & Ghebreab 2013)

Tesfaye and Ghebreab (2013) suggest an eastward dipping detachment model for Afar (Fig. 8a, b). The authors based the analysis primarily at the northernmost part of the WAM next to the Gulf of Zula (e.g. Drury et al. 1994; Talbot and Ghebreab 1997; Ghebreab and Talbot 2000, Fig. 8c). The WAM is interpreted as the original breakaway zone along pre-existing Neoproterozoic (Pan-African) weaknesses (Fig. 8a), now marked by its strong decline in topography and crustal thickness. After a first phase of asymmetrical deformation during which the marginal grabens were formed, the current situation is one of symmetrical stretching (Fig. 8b). Within this context, the northernmost marginal grabens, which are situated closest to the Afar rift axis, would be the oldest and most evolved structures (Tesfaye & Ghebreab 2013). Their low altitude (even below sea level) is due to the strongly thinned crust in the northern Afar (<15 km versus 26 km to the south, Makris and Ginzburg, 1987; Bastow & Keir 2011, Hammond et al. 2011). Such a topographic decline towards the north can also be observed along the (northern) Danakil block, which is interpreted as a core complex exhumed along a large-scale detachment (Talbot and Ghebreab 1997). The marginal grabens are then associated with the large-scale detachment fault and although not specifically stated by the authors, must as such be part of a rollover structure (Fig. 8).

The idea that the oldest grabens are found in the north fits with the observation that volcanism and associated rifting initiated in the northern part of the WAM and propagated southward (Zanettin and Justin-Visentin 1975; Wolfenden et al. 2005; Ayalew et al. 2006). A problem however, may be the actual presence of the main detachment. Although such structures are reported from Eritrea, their existence is contested by Abbate et al. (2002), arguing that there is no field evidence to support a large-scale detachment. Other authors have dated detachment structures in the area back to the Neo-proterozoic Pan-African orogeny (Ghebreab et al. 2005). If present and of the correct age, an early eastward dipping detachment could account for the proposed large initial deformation along the western boundary faults. The proposed shift to symmetric stretching would have produced the current tectonic setting with the western boundary faults relatively abandoned and eroded (Fig. 8a, b). Unfortunately, the authors do not provide a clear mechanism for the change to this second phase, yet their schematic (Fig. 8b) does incorporate seaward dipping reflector (SDR) development and therefore seems to suggest a marginal flexure mechanism for the more recent development of the WAM (see 4.4). Furthermore Tesfaye & Ghebreab (2013) propose the oldest age for (full) marginal graben development of all models (Table 2). Early marginal graben development is perhaps not impossible, but no graben infill of this age has been found and it may not fit with the flexure model (e.g. Kazmin 1972; Chorowicz et al. 1999; Wolfenden et la. 2005).

4.3.2. Two-phase eastward dipping detachment model II (Chorowicz et al. 1999)

Chorowicz et al. (1999) proposed a model somewhat similar to the Tesfaye and Ghebreab (2013) model in that it involves large eastward dipping detachments, yet it incorporates multiple phases of deformation associated with the motion of the Danakil block (Fig. 9). By means of radar imagery combined with fieldwork in the Borkenna graben area, the authors interpret an initial phase of sinistral oblique extension in the early to middle Miocene due to a general N20˚ extension (Fig. 9a). The strike-slip deformation reactivated Pan-African weaknesses leading to the formation of proto-marginal grabens as releasing bends along the whole of the WAM (Fig. 9a). A subsequent minor phase of diffused NW-SE extension seems to fit with deformation in the Main Ethiopian Rift to the south that formed around 11 Ma (Wolfenden et al. 2004). The final deformation phase concerns the Pliocene-Quaternary and involves eastward motion and opening of the marginal grabens due to gravity-induced detachment of large crustal blocks along the WAM as the Danakil block rotates away and Afar opens (Fig. 9b-d).

Chorowicz et al. (1999) are so far the only authors invoking initial oblique extension during the formation of the WAM, yet such a motion is required given the plate geometries and the rotation pole location of the Arabian plate (Smith 1993). The opening of the Main Ethiopian Rift is indeed supposed to have taken place in Miocene times (ca. 11 Ma, Wolfenden et al. 2004) and the rotation of the Danakil block is a well-established and currently active phenomenon, although the exact amount and timing of this rotation is disputed (Collet et al., 2000; Eagles et al 2002; McClusky et al. 2010; Kidane et al. 2015).

There are however some objections to the Chorowicz et al (1999) model. Wolfenden et al. (2005) have criticized the choice of fieldwork area since most of the data are gathered to the north of the Borkenna graben, in the Dese-Bati accommodation zone that links the Borkenna graben with the Hayk graben to the north. Therefore, the oblique extension may be measured on faults that link the marginal grabens, and may not be representative of the regional kinematics of the WAM. Furthermore, Wolfenden et al. (2005) argue that the marginal grabens probably developed in later stages of Afar formation (see also section 4.4). But since the age of the basins is poorly constrained, early to middle Miocene age basin initiation remains a possibility. Yet the question remains how significant the proposed first phase of deformation was since it except for Collet et al. (2000), none of the plate reconstruction efforts have felt the need to explicitly include it.

Furthermore, Chorowicz et al. (1999) predict large downfaulted crustal blocks to the east of the WAM (Fig. 10). There is however no evidence of such structures as illustrated by the Moho depth in the area (Stab et al. 2016 and references therein, Fig. 10). Yet the effects of lower crustal intrusion, as reported by Mohr (1983) and Stab et al. (2016) may hide the westward dipping faults, if present. On the other hand, the eastward dipping detachment faults should account for most of the active deformation and seismicity, which does not seem to be the case.

4.3.3. Westward dipping detachment model

In contrast to the models involving an eastward dipping detachment, Stab et al. (2016) propose a westward dipping detachment model, which is also adopted by Ayalew et al. (2018). On the base of geochronological analysis (K-Ar and U-Th-Sm)/He) combined with balanced cross-sections along a NE-SW trajectory starting north of the Borkenna graben and reaching into Afar (Fig. 10), the authors infer an initial Mio-Pliocene distributed extension followed by localized detachment faulting in the Pliocene. Numerous westward-dipping faults are interpreted to root at a mid-crustal shear zone and to accommodate significant crustal thinning. Such westward dipping detachments are also proposed by Talbot and Ghebreab (2000) based on field observations from Eritrea, yet these structures may date back to the Neoproterozoic (Ghebreab et al. 2005).

Although Stab et al. (2016) do not specifically focus on marginal graben formation and antithetic faulting, they do include these features in their structural evolution scheme (Fig. 10). A “proto-marginal graben” structure would have formed during the early phase of distributed deformation. Only when rifting began localizing along the large-scale detachments rooting in the lower crust, Afar started subsiding and the WAM would have undergone flexure and antithetic faulting (Fig. 10). Magmatic underplating is needed to account for the apparent surplus of lower crust (as also stated by Mohr 1983). No further details on margin formation are provided by the authors, but the concept of flexure is further explored below (section 4.4).

The Stab et al. (2016) westward detachment model could thus induce marginal flexure, accounting for antithetic faulting and marginal graben formation. However, the similarity between their large-scale extension model and the second marginal graben mechanism involving a rollover structure due to a westward detachment as proposed by Morton & Black (1975, Fig. 7h) is of interest as well. The development of the marginal grabens due to a westward dipping detachment would for instance explain the apparent focus of active deformation on the eastern boundary faults. Also the possible absence of a clear western boundary fault along parts of the margin would fit with this model, since a detachment fault might as easily produce a rollover anticline without the formation of a compensation graben. Yet we must also stress that the Stab et al. (2016) model is more complex than the compensation graben model proposed by Morton & Black (1975), since the location of the main detachment fault with respect to the marginal graben differs in both cases (Figs. 9b, 12). A complication for both these concepts however is that one would expect the hanging wall, in this case the Ethiopian plateau to be downthrown along the detachment, thus being lower with respect to the Afar footwall block, which is clearly not the case (Figs. 5, 10).

4.3.4. Flip-flop detachment model

Based on observations in SE Afar, Geoffroy et al (2014) propose a “flip-flop tectonic” model, involving a switch from a south-westward dipping detachment to a north-eastward dipping detachment system (Fig. 11). The authors report opposing dips in lower and upper Stratoid units that indicate a reversal of detachment direction around 2 Ma, due to a shift in mantle and magmatic activity associated with the propagation of the Gulf of Aden spreading ridge into Afar.

This model is based on analysis in the SE of Afar, an area that is strongly affected by oblique extension due to the rotation of the Danakil Block (Souriot & Brun 1992). It is also ambiguous whether these results can or should be extrapolated to the WAM. However, if so, it may infer a relatively old marginal graben initiation on the western edge of the extensional domain, represented by minor antithetic faulting with respect to the regional detachment (Fig. 11a). Following the tectonic shift at ca. 2 Ma (Fig. 11b), the early fault became part of the new detachment system, in which the marginal grabens could have continued developing in a compensation graben form (Fig. 11c). The Geoffroy et al. (2014) model only concerns the last 8 Ma, so that it does not provide a complete scenario for the development of Afar (Fig. 6).

4.4. Marginal flexure models

In contrast to the fault-dominated mechanisms in the previous section, Abbate and Sagri (1969) suggest that the structures of the WAM were formed as a result of crustal flexure to compensate for the relative increased subsidence in Afar (Fig. 12). As specified by Kazmin et al. (1980), such a flexure would cause tensile forces and deformation would lead to antithetic faulting (Fig. 12a, b). Abbate and Sagri (1969) propose two options for the WAM. The first is a simple flexure causing antithetic faults and the formation of a marginal graben at the top of the flexure, similar to a “key stone” in an arc, adjacent to the plateau margin (Fig. 12c, c’). The second involves an additional synthetic normal fault towards Afar to account for the significant topographic drop between the Ethiopian Plateau and the Afar Depression (Fig. 12c’). Field evidence of such an additional fault has been reported (e.g. Mohr 1972; Abbate et al. 2015), yet various other studies suggests that faulting is predominantly antithetic until further into the Afar rift floor and that the Afar units simply onlap on the tilted blocks (e.g. Mohr 1983; Stab et al. 2016, Fig. 4d). Also timing of fault activation and graben formation is not specified. Still it seems that a certain amount of flexural subsidence may be necessary to start brittle failure (Kazmin et al. 1980, Acocella et al. 2008, Fig. 12).

The simple flexure concept proposed by Abbate & Sagri (1969, Fig. 12c) elegantly explains the development of antithetic faults without the problems associated with large eastward detachment faults as described previously. Ongoing flexure would also explain the continued seismicity and fresh fault scarps along the antithetic marginal graben boundary faults (Gouin 1979, Illsey-Kemp et al., 2018, Fig. 3), with no need to maintain significant activity along the synthetic boundary faults.

Such marginal flexure was initially thought to be caused by outward flow of magma from large magma chambers below the sagging rift around 14 Ma (e.g. Kazmin et al. 1980), and a similar process also occurs on a smaller scale in the grabens of the central Afar (Acocella 2010). More recently however, Wolfenden et al. (2005) propose that magmatic loading can be the driving force for marginal flexure (Fig. 13a). Due to its position on a hot spot, Afar is a highly volcanic region and crustal magma injection may increase the density of the crust, which subsequently subsides. Similar magmatic loading and flexure are also reported from the SE margin of the Danakil Block (Le Gall et al. 2011, Fig. 13b) and has been numerically modeled (Corti et al. 2015b, Fig. 13c). Flexure of the WAM is suggested to be a result of increasingly focused magmatic loading along the current spreading axis in Afar in the last magmatic stage (8 Ma-present), as deformation and associated magmatic activity are interpreted to have migrated from the rift edges towards the rift axis during three magmatic phases (ca. 29-26 Ma, 15-8 Ma and 8 Ma-present, Zanettin & Justin-Visentin 1975, Wolfenden et al. 2005).

This magma-loading scenario implies that the marginal grabens are of relatively young age, similar to those of the Pliocene to Recent sediments found in them so far (e.g. Abbate et al. 2002, 2015; Sani et al. 2017). Still, the current apparent absence of older sediments does not exclude an older age for the marginal grabens, as such older sediments might either be covered by younger units or removed by erosion. In fact, Zanettin & Justin-Visentin (1975) and Mohr (1983) suggest flexure and marginal graben formation to have occurred early on, i.e. pre-Pliocene and possibly as early as 19 Ma, which is more in line with the afore-mentioned magma-escape scenario.

Yet, the young basin age inferred from the magma loading scenario would be in accordance with the notion that significant flexure might be necessary to develop faults (e.g. Kazmin et al. 1980, Fig. 12a, b) and even more to develop marginal grabens. It is for instance proposed that Oligocene-early Miocene lithospheric flexure was only much later followed by marginal graben formation in Pliocene-Quaternary times (Mohr 1986). Possibly, the presence of marginal grabens is an expression of extreme flexure as a combined result of the significant uplift of the Ethiopian Plateau and the strong subsidence in Afar. The former has been estimated to be some 2000 m, although the timing is highly debated (Corti 2009; Abbate et al. 2015 and references therein). The latter is difficult to estimate, but the decrease in crustal thickness from 40 below the Ethiopian Plateau to 25 or even 15 km in Afar (Ebinger et al. 2010; Hammond et al. 2011) must have resulted in significant subsidence there.

Wolfenden et al. (2005) furthermore claim that deformation along the WAM, or rather in their Borkenna and Robit graben study area (Fig. 2b), is fully controlled by magmatism and they suggest that current seismicity is due to the strong crustal thickness variations along the WAM. By contrast, Stab et al. (2016), who worked on a profile crossing just north of the Wolfenden et al. (2005) study area (S9 in Figs. 2, 3b), invoke dominant mechanical deformation and infer magmatic underplating to fill in the gaps in the lower crust left over in their mass balances. It is therefore challenging to unify the magmatic loading effects as described by Wolfenden et al. (2005) to the westward detachment model proposed by Stab et al. (2016).

Note however that crustal flexure during rifting and passive margin formation is observed along various magmatic passive margins, and is associated with the development of thick sequences of magmatic layers, seaward-dipping reflectors (SDR), in e.g. East Greenland, Norway, the South Atlantic and the Deccan margin of India (Buck 2017; Paton et al. 2017). It would therefore be possible to study ongoing SDR formation in Afar, as well as the underlying tectonic processes (Wolfenden et al. 2005; Corti et al. 2015b; Paton et al. 2017, and references therein).

5. Discussion

Above we presented a series of distinct mechanisms for the development of the WAM and how these fit in large-scale models for the evolution of the Afar Depression. In Table 2 and Fig. 6 we summarize these and the associated predictions that can be tested in the field. Below we discuss the current limits to our understanding of Afar, how the current interpretations of Afar fit in a more global perspective and possible strategies for future work to exploit its full scientific potential.

5.1. Comparison with models for global rift and passive margin evolution

Since the Afar region provides a unique opportunity to study continental break-up processes, it is important to reflect on how the area may compare to generalized end member models of rifting. Here we link the various rift models for Afar to either the classical pure shear model in which lithospheric stretching is accommodated symmetrically by viscous deformation and high-angle normal faulting (e.g. McKenzie 1978, Fig. 14a), asymmetric simple shear models involving a low-angle lithospheric-scale detachment fault (e.g. Wernicke 1985, Fig. 14b), and the magma-controlled rifting model in which magmatic processes and diking account for the observed extension in a rift system (e.g. Buck 2004, 2006). Since most authors do not specifically link their models for the WAM to lithospheric-scale processes, we also produce a proper classification (Table 2), combined with a summarizing overview of the rift modes reported from the Afar region (Fig. 14d).

Pure shear

The erosion model by Mohr (1962) (Fig. 7a-d) and the block rotation model (Fig. 7f), link best to pure shear stretching, as only high-angle normal faults are implied. The mechanical marginal flexure favoring the presence of only high angle normal faults is also consistent with the pure shear model (Abbate & Sagri 1969, Fig. 12). In this case, relatively little crustal thinning occurs beneath the WAM, and maximum crustal thinning develops beneath the central rift axis in Afar. Also in the Main Ethiopian Rift to the south, which is not yet as developed as the Afar Depression, the geometry and location of upper crustal faults and of crustal thinning with respect to the surface expression of rifting is more compatible with an initially pure shear model (e.g. Corti 2009; 2012, and references therein, Fig. 14d). A continuation of this system into Afar would be consistent with the northward increasing rift maturity trend, including increasing magmatism, as observed in the Main Ethiopian Rift (e.g. Agostini et al. 2011, Fig. 14d).

Simple shear

The detachment models for the WAM involve a simple-shear mode of crustal extension, a type of lithospheric thinning that accounts for the many large-scale detachment structures typical for passive margins (e.g. Lister et al. 1986; Peron-Pinvidic et al. 2013). This is however counter to observations from early stages of rifting in the East African rift (including the Main Ethiopian Rift) where evidence for large scale detachment faults is lacking (Corti 2009; Agostini et al. 2011), and a pure shear model of rifting (with the addition of magma in some regions) seems more likely. A simple solution to this problem is that continental rifting may initiate as pure shear, but evolve to simple shear later in the break-up process (Manatschal 2004, Lavier & Manatschal 2006).

In contrast to Tesfaye and Ghebreab (2013), who propose a simple shear followed by pure shear history in Afar (Fig. 8a, b), Stab et al. (2016) in fact adopt a scenario including an initial phase of pure shear rifting followed by a later phase of simple shear detachment faulting in their structural evolution of Afar (Fig.

10). Such a shift from distributed to localized deformation ultimately leads to continental break-up and mantle exhumation (Manatschal 2004, Lavier & Manatschal 2006) along magma-poor margins and has been interpreted as applicable for breakup in the Gulf of Aden (Bellahsen et al. 2013). By contrast, both pure shear and simple shear structural interpretations have been proposed for the less mature Red Sea basin (Ghebreab 1998 and references therein). The notion that we may currently observe different modes of rifting in both Afar and the Red Sea (Fig. 14d), as expressed by the various contrasting tectonic models proposed for the area (Ghebreab 1998; Table 2), may indicate that (parts of) the Afar region is currently undergoing a transition from pure shear to simple shear rifting. The Afar region could thus provide a perfect natural laboratory to study such shifts of rift style.

Magma-controlled rifting

Both the pure shear and simple shear rift models ignore the effects of magmatism during lithospheric thinning, a factor that is key to the magmatic loading model (Wolfenden et al. 2005). In Afar, lower crustal intrusions have facilitated extension with less crustal thinning than expected from the amount of horizontal extension (Mohr 1983; Bastow and Keir; 2011; Stab et al. 2016) and current deformation in the upper crust is thought by many to largely occur by means of episodic dike intrusion along magmatic segments (e.g. Hayward & Ebinger 1996; Ebinger & Casey 2001; Wright et al., 2006). However, pure magma-controlled rifting (Fig. 14c) does not explain the presence of km-offset faults at the rift margins, the protracted breakup history, nor the significant general crustal thinning we observe in Afar. It therefore is more likely that extension by magma intrusion occurs within a framework of (initial) mechanical rift evolution (e.g. Beutel et al. 2010), a scenario we refer to as “magma-assisted rifting” which may account for the gradual shift of deformation from the rift margins to the axial magmatic centers. Instead of experiencing a shift from pure shear to simple shear, such magma-assisted rifting may allow break-up within a pure shear system (Ebinger 2005), thus avoiding the shift from pure to simple shear rifting that is typical for magma-poor systems (Lavier & Manatschal 2006; Reston 2009).

Pathways to continental break-up

The above assessment leads us to the idea that the various rifting modes observed in the Afar region possibly reflect steps on different pathways towards continental break-up, as summarized in Fig. 15. We infer that rifting may initiate as a pure shear-dominated system. As the rift evolves, significant magmatism can localize deformation along axial spreading centers within a pure shear context (i.e. the Wolfenden et al. 2005 model for Afar). However, when tectonic influences are dominant, we can expect a mechanical control on rifting and a shift from a pure to a simple shear rifting mode (i.e. the Stab et al. 2016 model for Afar). If extension persists, both pathways would eventually lead to strong localization of deformation and continental break-up and the formation of either magma-rich or magma-poor passive margins. These proposed sequences are end members based on data from the Afar region, but they may provide a relevant framework for the interpretation of rifts and rifted margins worldwide.

5.2. Towards a better understanding of the WAM and Afar

As discussed in the previous sections, the various options to explain widespread antithetic faulting and marginal graben formation along the WAM predict wildly different structures and all have pros and cons. Based on the current knowledge, it seems that the magma loading model by Wolfenden et al. (2005) and the detachment model by Stab et al. (2016) fit best with the available data from Afar and global scenarios for continental break-up (Table 2, Figs. 6, 14, 15). However, a major problem is that the initial observations on which these models are based are rather limited. Justin-Visentin & Zanettin (1974) and Zanettin & Justin-Visentin (1975) point out that most of the early fieldwork on the WAM was concentrated along the ca. E-W road between Dessie and Bati (S3, Fig. 3b), since it was the only place allowing to observe a full transect of the margin and many later field campaigns have focused there as well (e.g. Chorowicz et al. 1999; Mohr et al. 1983; Rooney et al. 2013; Stab et al. 2016). Although this particular area is easily accessible, it is a transfer zone between two marginal grabens (Hayk and Borkenna, section S3 trace, Fig. 3b) and may thus not be representative for a typical WAM section (Mohr 1971; Wolfenden et al. 2005).

Other structural field studies were concentrated in Eritrea (e.g. Drury et al. 1994, Fig. 8c) are also taken as representative for the whole margin (Tesfaye & Ghebreab 2013). Next to the fact that the interpretation of rift-related detachment faults is contested (see section 3.3.1) and that the area is far north and may not even be considered truly part of the WAM, it is questionable whether one can simply extrapolate the observations from one section of the WAM to explain the whole margin (e.g. Mohr 1971). It is not uncommon that rift structures have significant variations along strike and the WAM is already known to have a different topographic profile, lithology, crustal thickness and rift initiation age from north to south, as well as a different strike in its southernmost sector (see section 2). Furthermore, Zanettin and Justin-Visentin (1975) note the possibility that the typical antithetic faulting of the WAM may be due to superficial basement-controlled deformation in the massive Trap basalts; where the latter are eroded and the basement is exposed (mostly in the northern part of the WAM), a simpler geology with less defined structures seems to dominate (Fig. 2a). New analogue experiments may shed more light on this topic (e.g. Holland et al. 2006; Kettermann et al. 2018).

Furthermore, the complex tectonics of the Afar Depression, including significant lower crustal intrusion, the rotation of the Danakil Block leading to the formation of the current Danakil conjugate margin instead of the older Yemen margin, as well as the late opening of the Main Ethiopian Rift to the south, probably caused quite significant structural variations from north to south. Any comprehensive explanation for the development of the WAM and its links to the regional tectonic evolution should account for that. Yet a margin-wide structural interpretation on which such a model could be based is lacking at the moment. We therefore recommend a thorough structural assessment of the WAM, in order to determine which faults are dominant and what their orientations are, to characterize marginal graben size and geometries. Here, geomorphological analysis may help to determine (relative) ages of fault activity and earthquake analysis could help to determine current fault activity (e.g. Illsley-Kemp et al. 2018). An additional objective should be to obtain reflection seismic sections calibrated by borehole data along the WAM, which would provide invaluable data to constrain fault geometries and slip histories in depth, the results of which could subsequently be compared to the structures interpreted on seismic data from mature passive margins.

Other important information that is currently poorly constrained concerns the age and thickness of the sediments in the marginal grabens, as well as the architecture of the basin infill. The oldest known units are of Pliocene age and there may be up to 550 m of sedimentary infill (e.g. Abbate et al. 2015; Sani et al. 2017), but no well logs or reflection seismic data are available to verify if there are yet older units or deeper depocenters and how the sediments relate to the faults. The age of the marginal grabens, their structural architecture and their tectono-sedimentary features, which may be keys to determine which model for the WAM is correct, thus remain obscure.

A further question is the amount of deformation needed to generate antithetic faulting and/or a marginal graben, i.e. how much stretching for the detachment models and/or how much (relative) subsidence in case of marginal flexure. In this context, it would also be useful to not only determine the subsidence Afar has undergone (e.g. Bastow et al., 2018), but also the significant uplift of the rift shoulder (the Ethiopian Plateau) and whether these vertical motions occurred in one event or in steps. The latter remains highly debated (Abbate et al. 2015 and references therein).

The uncertainties surrounding the geological history of the WAM provides interesting opportunities for future laboratory experiments or numerical simulations. Few studies formally model the dependence of rift evolution on rheology and structure of the lithosphere, but instead present conceptual models that attempt to reconcile with geophysical and structural data. Future work may for instance assess the influences of lithospheric rheology, such as pre-existing (Pan-African) tectonic weaknesses, the presence and thickness of a ductile lower crust, the degree of brittle-ductile coupling, but also of surface processes and magmatism on margin development. These parameters are known to influence rift systems (e.g. Brun et al. 1999; Corti et al. 2003, 2004; Hardy et al. 2018; Burov & Cloetingh 1997; Burov & Poliakov 2001; Zwaan et al. 2018; 2019) and by running such models, it would be possible to get an impression of the relative importance of the various factors may have affected the WAM at various stages of its evolution.

6. Conclusion

The Afar region represents a unique tectonic setting, allowing the study of ongoing rift development and various stages of continental break-up. In this paper we present an overview of the geological and geomorphological characteristics of the Western Afar Margin (WAM) and the various scenarios that have been previously proposed for its evolution. The margin is characterized by a steep decline in topography and crustal thickness from the Ethiopian Plateau into the Afar Depression, as well as a series of marginal grabens and a general presence of antithetic faulting. Although rifting is shifting to the rift axis, significant deformation is still occurring along the margin.

Models for the evolution of the WAM involve either isostatic loading effects due to erosion, rifting-induced margin overturn, large-scale detachment fault development or crustal flexure due to lithospheric stretching or magmatic loading. This wide variation of potential mechanisms for WAM development may reflect a general structural variation along the margin and in the Afar region, involving different stages of rift formation and possibly indicating two distinct pathways leading to continental break-up.

Yet we must stress that in order to better understand the system and to fully exploit the research potential of the region, further assessment of the WAM and its relation to the Afar will be necessary. Important questions are for instance which boundary faults are active and what the full stratigraphy and their structural architecture in the marginal grabens is. Reflection seismic and well data would be of great help, but more practical approaches could include earthquake analysis and fieldwork, as well as analogue and numerical modeling. The findings of such future work, combined with data from rifts and passive margins from around the globe will be of great importance to improve our understanding of the processes involved in continental breakup and to better constrain the sequence of events leading from initial rifting to oceanic spreading.

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Tables

Marginal graben name (this study)	Named after	Reference	Alternative marginal graben name	Reference
*Damas**	Damas river	Drury et al. (2006); Tesfaye & Ghebreab (2013)		
*Buia***	Town of Buia	Abbate et al. (2015); Williams (2016)		
Garsat	Garsat plain	Abbate et al. (2015); Williams (2016)	Maglala-Renda-Coma	Mohr (1967), Tesfaye & Ghebreab (2013)
			Garsat-Simbileli	Hagos et al. (2016)
Abala	Town of Abala	-		
Raya***	Wordiya (district) of Raya Azebo	Williams (2016)		
Teru	Wordiya (district) of Teru	Abbate et al. (2015)	Dergheha-Sheket	Mohr (1967), Tesfaye & Ghebreab (2013)
Kobo	Town of Kobo	Abbate et al. (2015); Williams (2016)	Guf Guf	Mohr (1967), Tesfaye & Ghebreab (2013)
			Azebu Gallo (northern part)	Mohr (1967)
			Kobbo (southern part)	Mohr (1967)
Hayk****	Lake/town of Hayk	Abbate et al. (2015); Williams (2016)	Menebay-Hayk	Mohr (1967), Tesfaye & Ghebreab (2013)
Borkenna	Borkenna river	Abbate et al. (2015); Williams (2016) and various other works		
Robit	Town of Shewa Robit	Williams (2016)	Robi	Mohr (1967), Gouin (1979)
			Ayete	Wolfenden et al. (2005)

Table 1. Overview of nomenclature applied to the fault-bounded basins along the WAM, for locations see Figs. 1 and 2.

* The Damas graben does not align the WAM (Figs. 1 and 2), but is considered a marginal graben by Tesfaye & Ghebreab (2013)

** The Buia graben forms the continuation of the Danakil rift axis and may therefore not be considered a true marginal graben (Fig 2).

*** The name "Raya graben" is perhaps poorly chosen, since the northern part of the Kobo basin is often referred to as the "Raya valley" by hydrologists and geographers (e.g. Fenta et al. 2015), and the Raya graben is actually situated outside of the wordiya of Raya Azebo. We however lack an acceptable alternative name.

**** The name "Hayk graben" is poorly chosen, as the city of Mesra and not the city (or lake) of Hayk are situated in the main regional depocenter (Mesra plain, Fig. 3). Also, the basin extent is poorly constrained in previous works, since the Mesra plain only forms a small part of a much larger sigmoidal graben structure that cuts into the Ethiopian plateau Stab et al. (2016, Fig. 3). Yet for reasons of consistency with previous literature, we maintain the term “Hayk graben” and use it to refer to this large graben structure.

Deformation mechanism	Potential model for the evolution of the WAM (and Afar)	Rift mode	Marginal graben initiation	Currently dominant marginal graben boundary fault	Main challenges to model
A. Erosion (Mohr 1962, Fig. 7a-d)	Extension/rifting and rift shoulder erosion (Mohr 1962, Fig. 7a-d)	?	Late Miocene?	Both?	Local model, rejected by author (Mohr 1967)
B. Margin overturn (Kazmin et al. 1980; Zannetin & Justin-Visentin 1975, Fig. 8e-f)	Lower crustal creep due to (symmetric?) tectonic extension (Black et al. 1972, Fig. 8e-f)	Pure shear? (Fig. 14a)	?	Eastern boundary fault	Unclear mechanism, incomplete scenario
C. Detachment fault & rollover – **C1. Eastward dipping (detachment) fault** (e.g. Morton & Black 1975, Fig. 7g)	Initial eastward dipping detachment followed by distributed extension (Tesfaye & Ghebreab 2013, Fig. 8)	Simple shear, followed by pure shear (Fig. 14b)	Near start of extension: ca. 29 Ma	Eastern boundary fault?	Presence and age of initial detachment debated, unclear mechanism for WAM development, very early marginal graben development
	Sinistral oblique extension followed by an eastward dipping detachment due to gravitational collapse (Chorowicz et al. 1999, Fig. 9)	Pure shear (?) followed by simple shear (Fig. 14b)	Releasing bends phase: Miocene Margin collapse phase: Pliocene-Quaternary	Western boundary fault	No clear evidence for active westward dipping detachment faults
	Flip-flop tectonics: minor initial eastward faulting followed by major eastward detachment (Geoffroy et al. 2014, Fig. 11)	Simple shear (Fig. 14b)	?	Western boundary fault	Not clear if directly relevant to WAM, no description of early rift phases, no clear evidence for active westward detachment faults
C. Detachment fault & rollover – **C2. Westward dipping (detachment) fault** (Morton & Black 1975, Fig. 9h)	Distributed extension followed by westward dipping detachments (Stab et al. 2016, Fig. 8)	Pure shear, followed by simple shear (Figs. 12, 14a, b)	Early "proto marginal graben" development: ca. 25 Ma True WAM development: Pliocene, ca. 5 Ma	?	Hanging wall of detachment (Ethiopian Plateau) is situated higher than footwall (Afar), early development of marginal grabens
D. Marginal flexure (Abbate & Sagri 1969, Fig. 12)	Marginal flexure with eastward dipping fault between the WAM and Afar (Abbate & Sagri 1969, Fig. 12c')	Pure shear? (Fig. 14a)	?	Eastern boundary fault	Eastward dipping fault not (always) present
	Early marginal flexure (Zanettin & Justin-Visentin 1975; Mohr 1983), potentially due to depleting magma chambers below Afar (Kazmin 1980)	Pure shear? (Fig. 14a)	Pre-Pliocene (ca. 19 Ma)	Eastern boundary fault?	Early development of marginal grabens, mechanism poorly constrained
	Magmatic loading and progressive migration of deformation to rift axis (Wolfenden et al. 2005, Fig. 13)	Pure shear (Fig. 14a)	After tectonic shift to rift axis: ca. 2 Ma	Eastern boundary fault	Based southernmost WAM, 2D model
	*Distributed extension followed by westward dipping detachments and flexural rollover (Stab et al. 2016, Fig. 8)**	*Pure shear, followed by simple shear (Figs. 12, 14a, b)*	*Early "proto marginal graben" development: ca. 25 Ma True WAM development: Pliocene, ca. 5 Ma*	*Eastern boundary fault*	*Hanging wall of detachment (Ethiopian Plateau) is situated higher than footwall (Afar), Early development of marginal grabens*

Table 2. Overview of mechanisms for the formation of the WAM structural architecture with associated models for the evolution of Afar and the associated crustal extension mode, as well as predictions that can be tested in the field.

* marginal flexure as part of a detachment model

Images

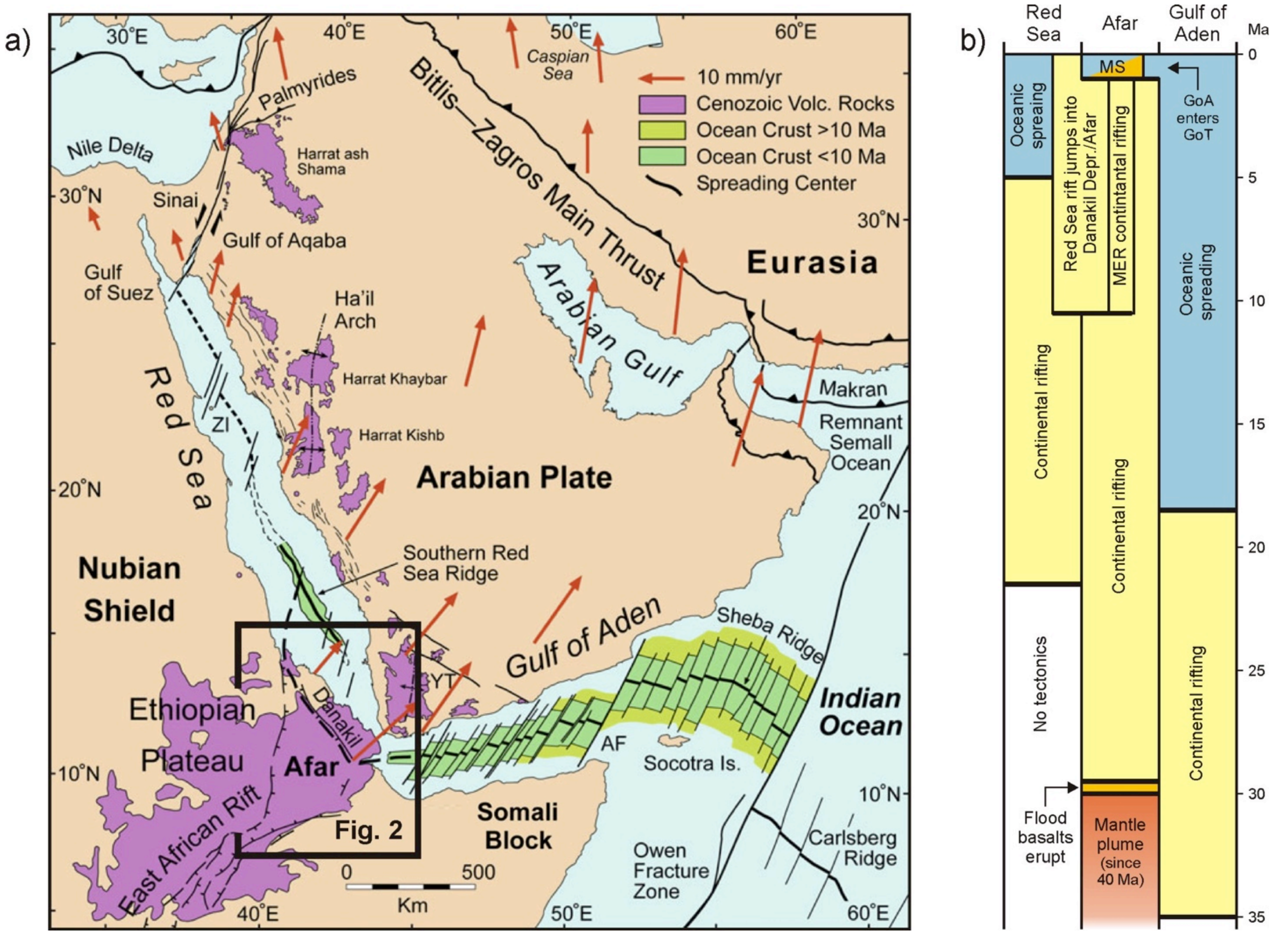

Fig. 1. (a) Tectonic setting of Red Sea-Afar-Gulf of Aden rift system (Modified after Bosworth 2015). Note the westward decreasing width of the oceanic crust as a result of the rotation of the Arabian plate. (b) timeline of main tectonic events in the Red Sea-Afar-Gulf of Aden rift system (see text for details) GoA: Gulf of Aden, GoT: Gulf of Tajura, MS: magmatic segments, MER: Main Ethiopian Rift, MS: magmatic segments.

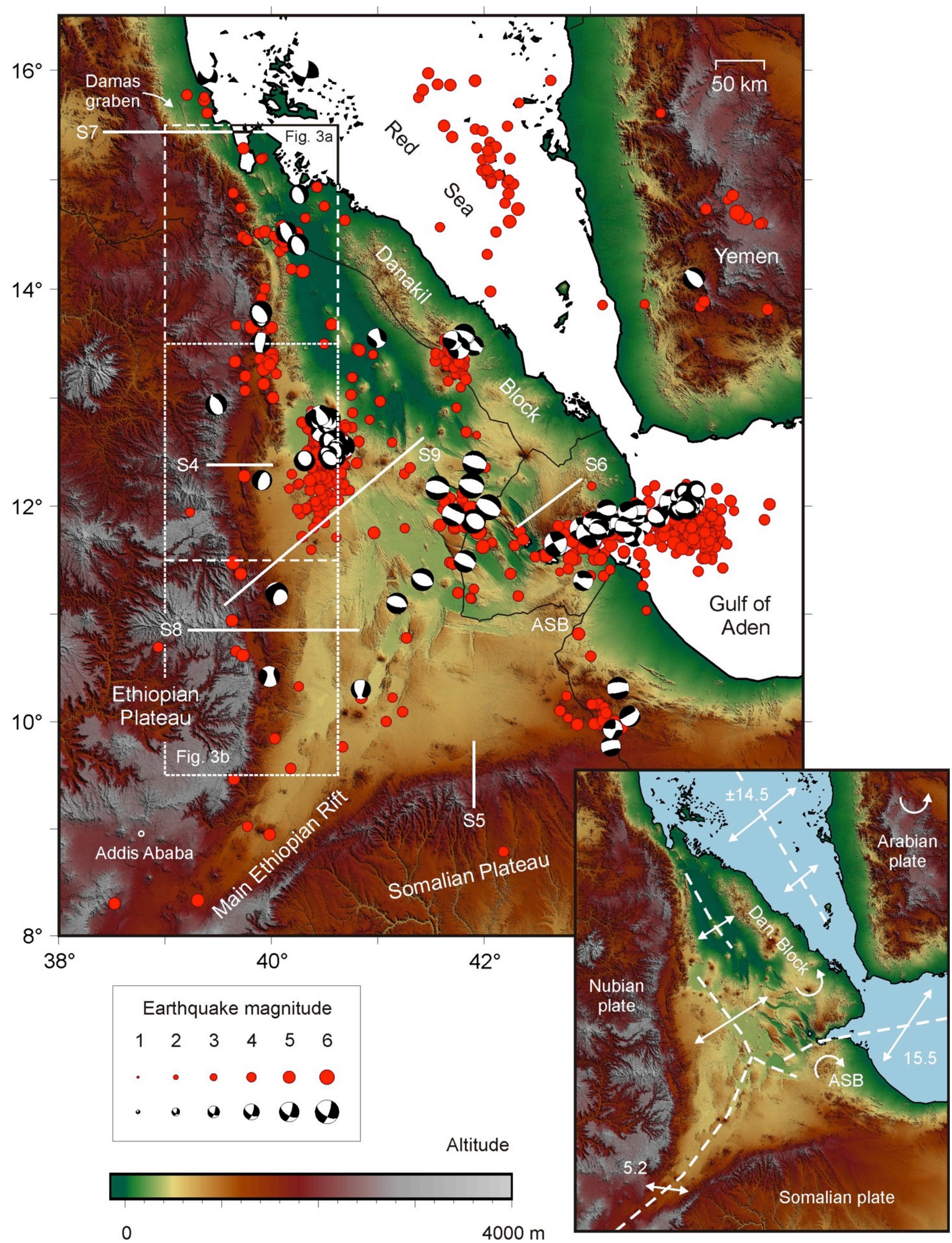

Fig. 2. Afar Depression in East Africa and the location of the Western Afar Margin (WAM). Red dots indicate historic earthquakes from the 1973-2018 NEIC earthquake catalogue. White lines indicate the location of geological sections. Focal mechanisms are derived from the GCMT catalogue (Dziewonski et al. 1981; Ekström et al. 2012). Inset: current tectonic setting, including spreading directions (mm/y) and

block rotations (McClusky et al. 2010; ArRahjehdi et al. 2010; Saria et al. 2014; Kidane 2015). ASB: Ali-Sabieh/Aïsha Block, DD: Danakil Depression, GoT: Gulf of Tajura, TGD: Tendaho-Gobaad Discontinuity. Topography is derived from ASTER data (30 m resolution). ASTER GDEM is a product of NASA and METI (Japan).

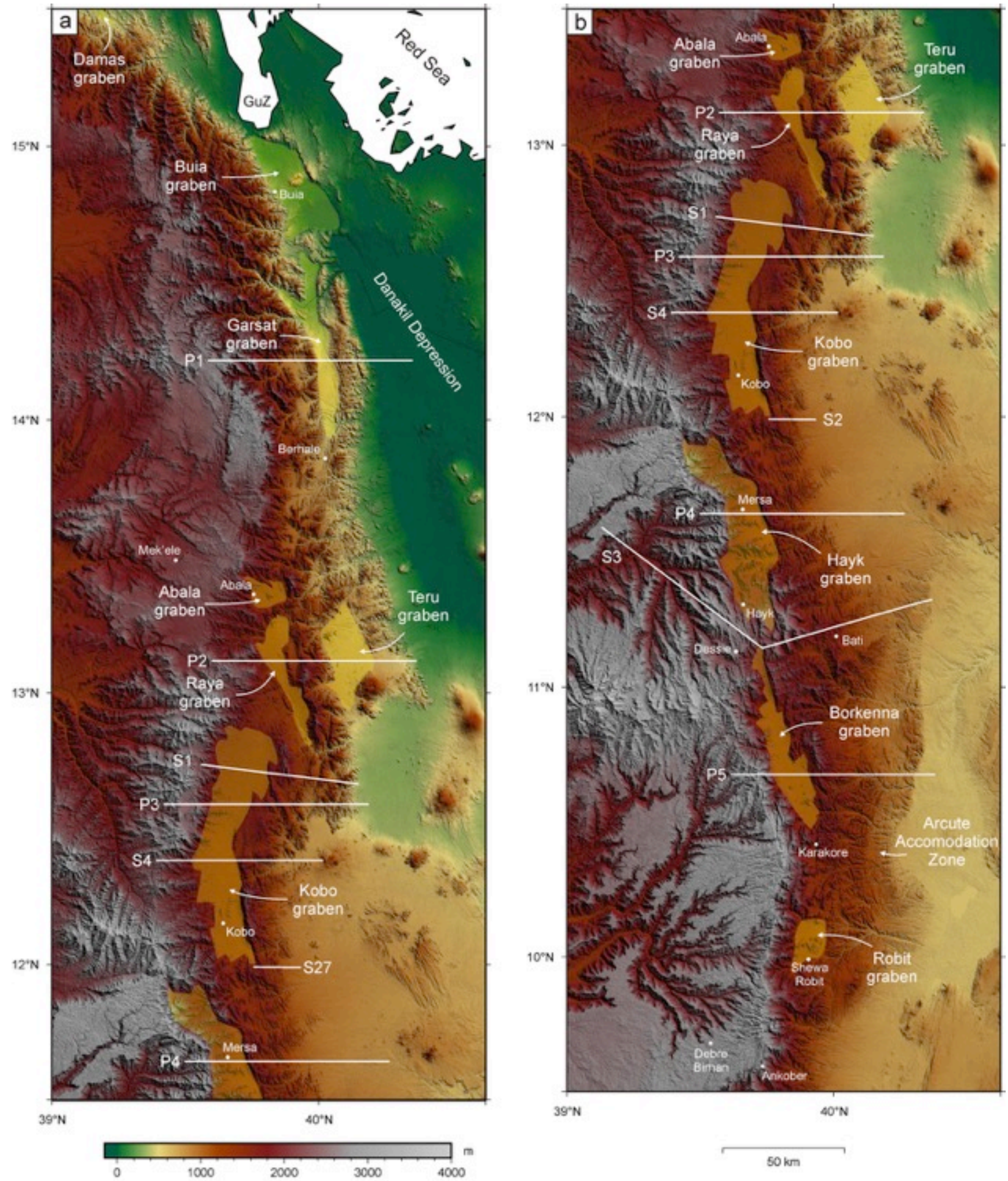

Fig. 2. Overview of basin locations along the Western Afar Margin (WAM). Transparent yellow polygons indicate the extents of the marginal grabens. White lines follow the traces of topographic profiles P1-5 and geological sections (S1-3, 9) as presented in Figs. 3 and 5. Note that the location of section S2 is

poorly constrained. For locations of (a) and (b) see Fig. 2. GuZ: Gulf of Zula. Background topography is derived from ASTER data (30 m resolution). ASTER GDEM is a product of NASA and METI (Japan).

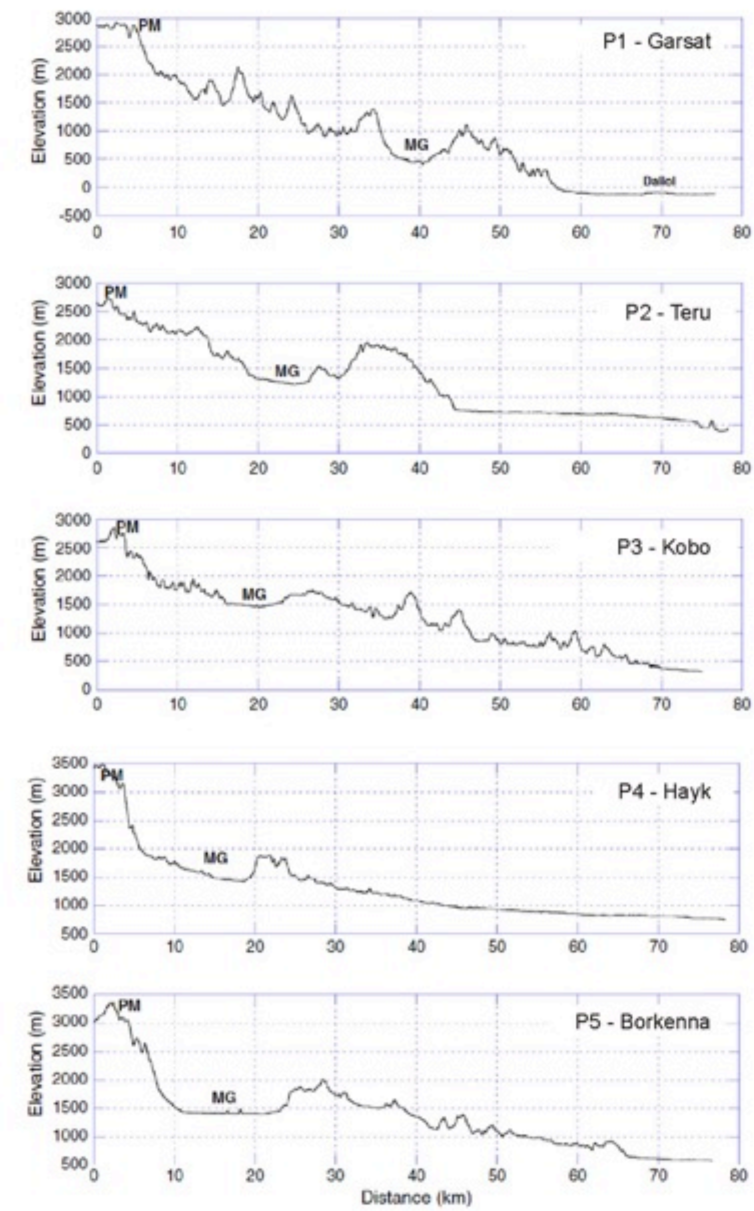

Fig. 4. Topographic profiles across the WAM. PM: plateau margin, MG: Marginal graben. For locations see Fig. 3. Modified after Tesfaye and Ghebreab (2013).

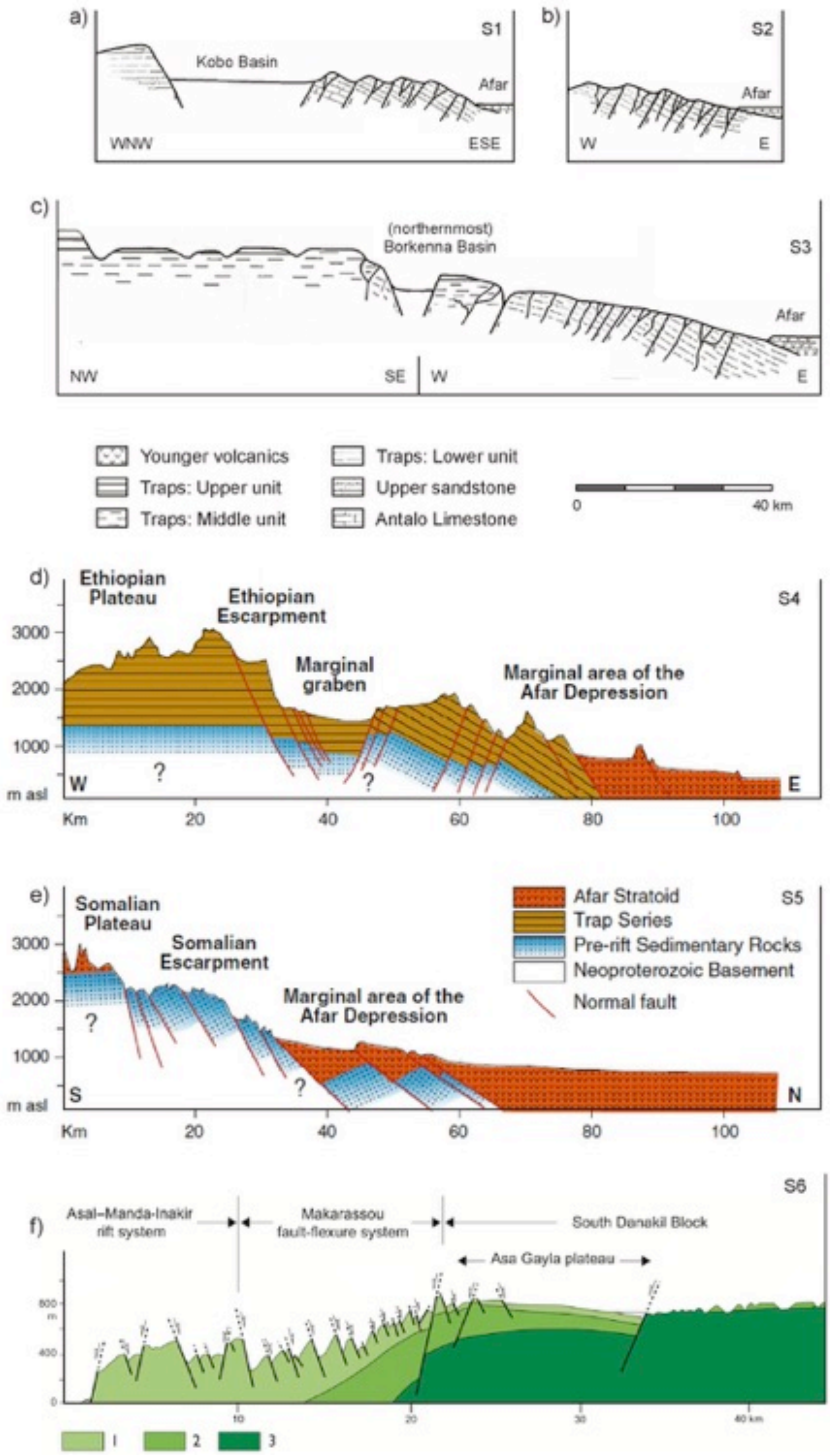

Fig. 5. Interpreted geological sections across the margins of Afar. (a) Section S1 in the northern Kobo basin, near Corbetta. (b) Section S2 in the transfer zone between the Kobo and Hayk graben. (c) Section S3 at the northern end of the Borkenna graben, near Dessiè. Modified after Abbate & Sagri (1969). (d) Section S4 through the Kobo graben. Modified after Beyene & Abdelsalam (2005) and Corti et al. (2015a). (e) Section S5 through the Somalian margin near Dire Dawa, showing the typical synthetic faulting style. Modified after Beyene & Abdelsalam (2005) and Corti et al. (2015a). (f) Section S6 near the southern tip of the Danakil Block. 1 and 2: S_1 and S_2 Stratoid basalts, respectively, 3: Dalha basalts. Modified after Le Gall et al. (2011). For section locations see Figs. 2 and 3.

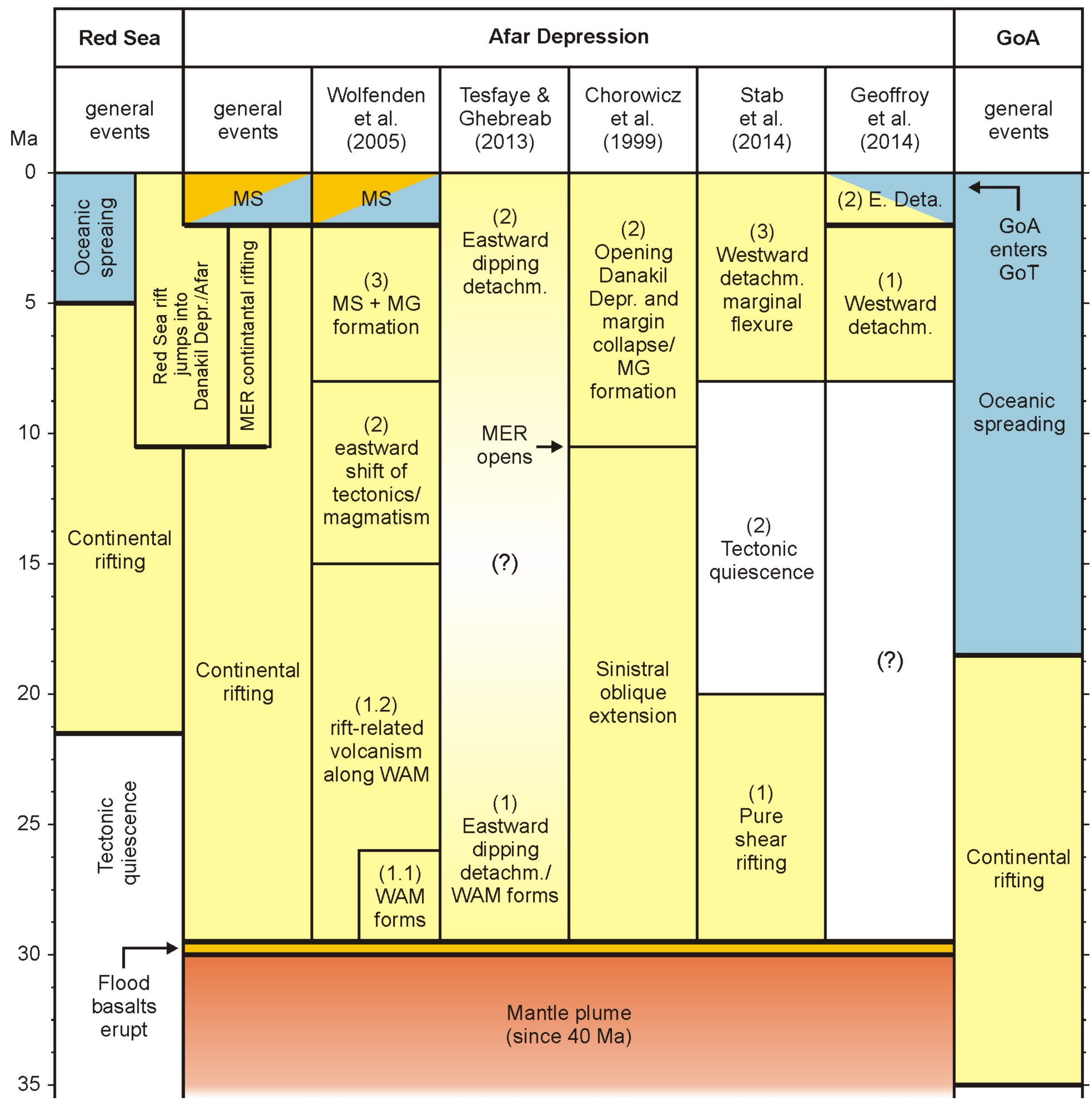

Fig. 6. Overview of relative timing of tectonic events in the Afar region, compared with selected models for the evolution for the WAM and Afar. See text for details. GoA: Gulf of Aden, GoT: Gulf of Tajura, MG: marginal graben, MS: magmatic segments. Compare with Fig. 1.

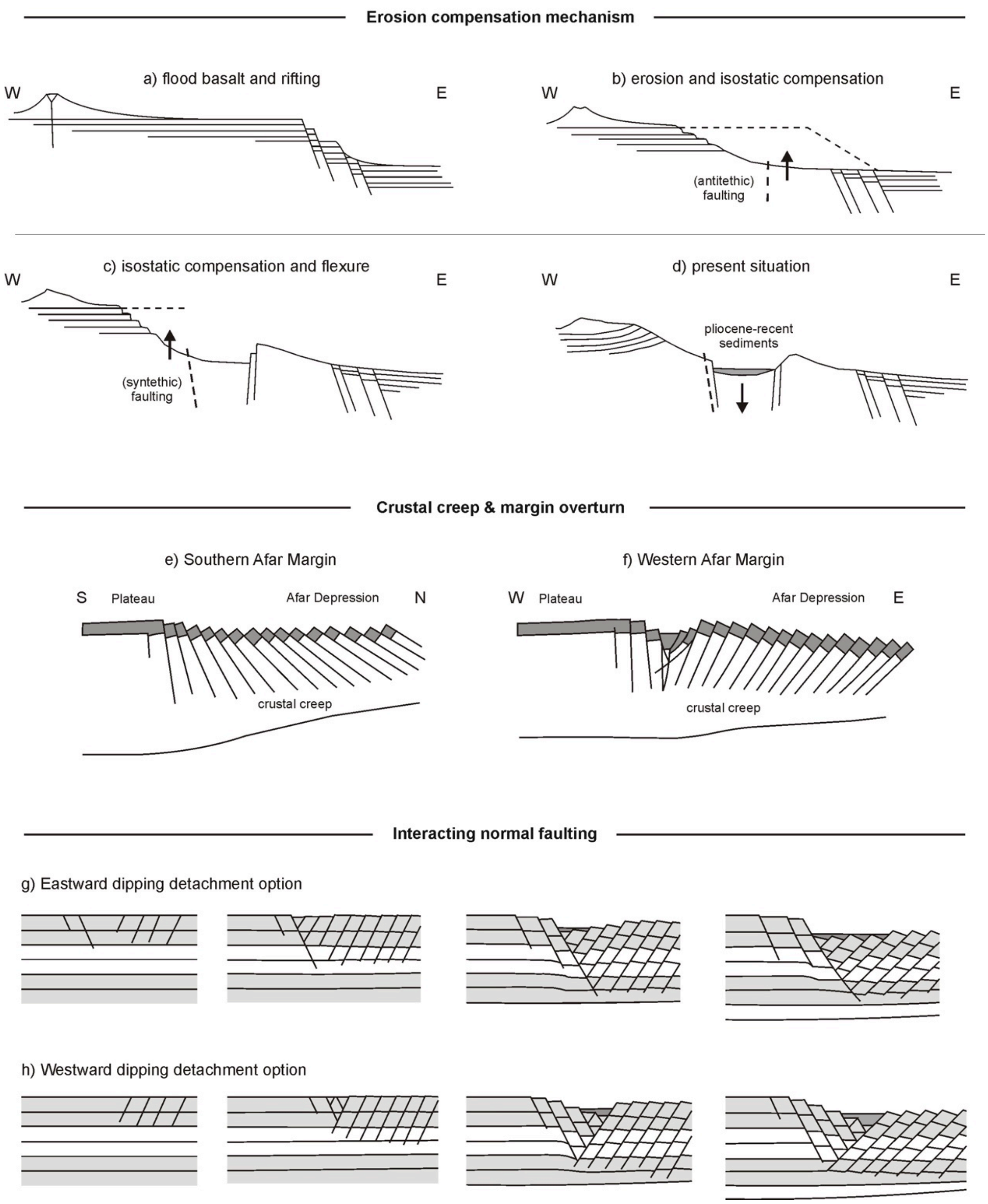

Fig. 7. Potential mechanisms for the formation of the WAM structural architecture. (a-d) Erosion compensation model as proposed by Mohr (1962). (a) Main Miocene " post-trap" rifting. (b) Denudation causes lithospheric strain and fracturing along A-A' (as in the present Kobo graben). (c) Further readjustment induces faulting along B-B'. (d) Final structure. Image redrawn after Mohr (1962). (e-f) Schematic sections depicting crustal structures along the margins of Afar, interpreted as a result of crustal creep (a) near Dire Dawa (Southern Afar Margin, SAM, analogue to S5, Fig. 5e) and (b) in the region of Maychew (WAM, analogue to S4, Fig. 5d). The transition from synthetic to antithetic faulting could have been caused by a massive margin overturn (Kazmin et al. 1980; Zanettin & Justin-Visentin 1975). Redrawn after Black et al (1972). (g-h) Models of marginal graben formation due to the interaction of synthetic and antithetic faults along the developing WAM. (a) Situation involving a dominant eastward (synthetic) fault and (b) a dominant westward (antithetic) fault. Redrawn after Morton and Black (1975).

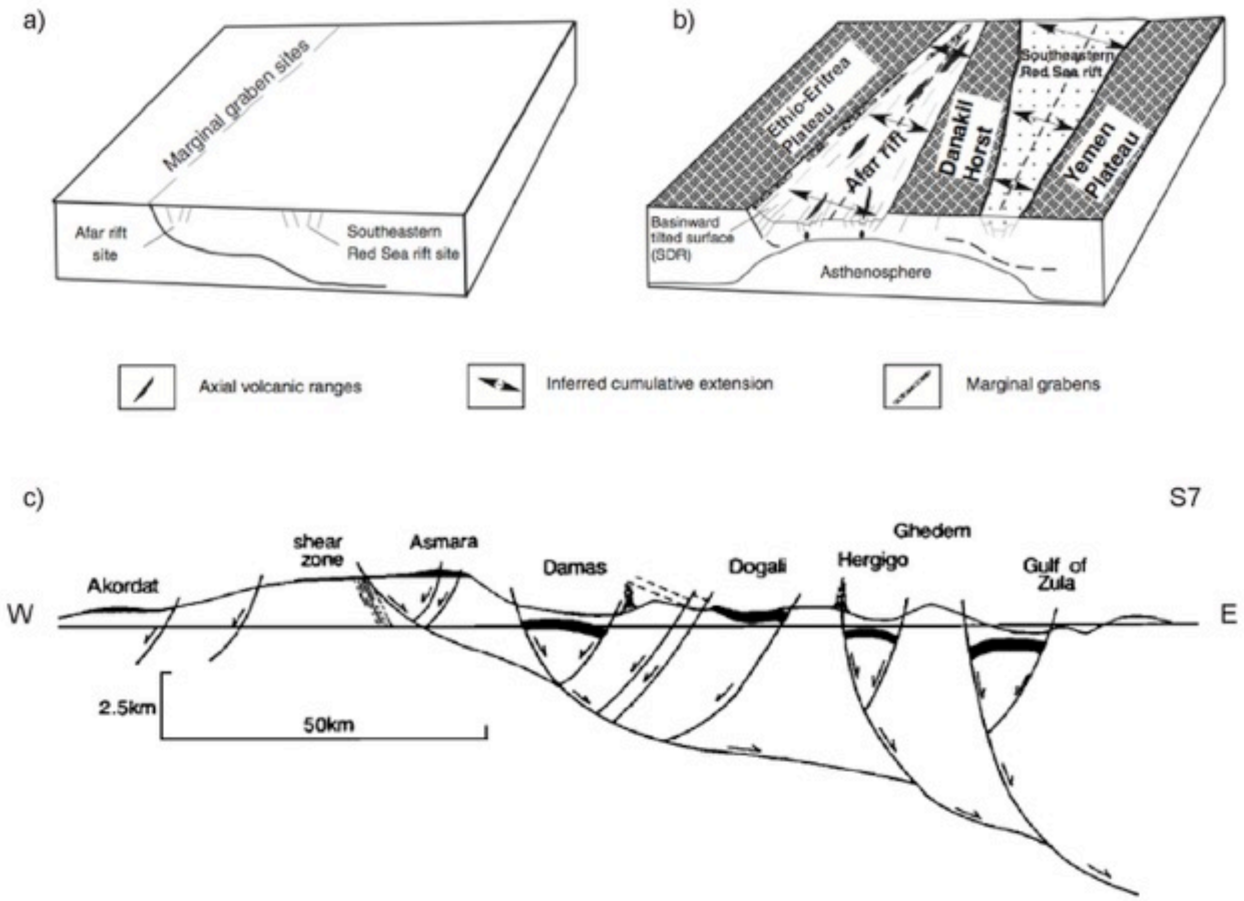

Fig. 8. (a-b) Development of Afar according to Tesfaye and Ghebreab (2013), involving an initial detachment fault dominated system, followed by a phase of more distributed extension. (c) Interpreted section S7 showing an eastward dipping detachment in the Damas area (northernmost WAM), for location of section see Fig. 3a. Modified after Drury et al. (1994) and Tesfaye and Ghebreab (2013).

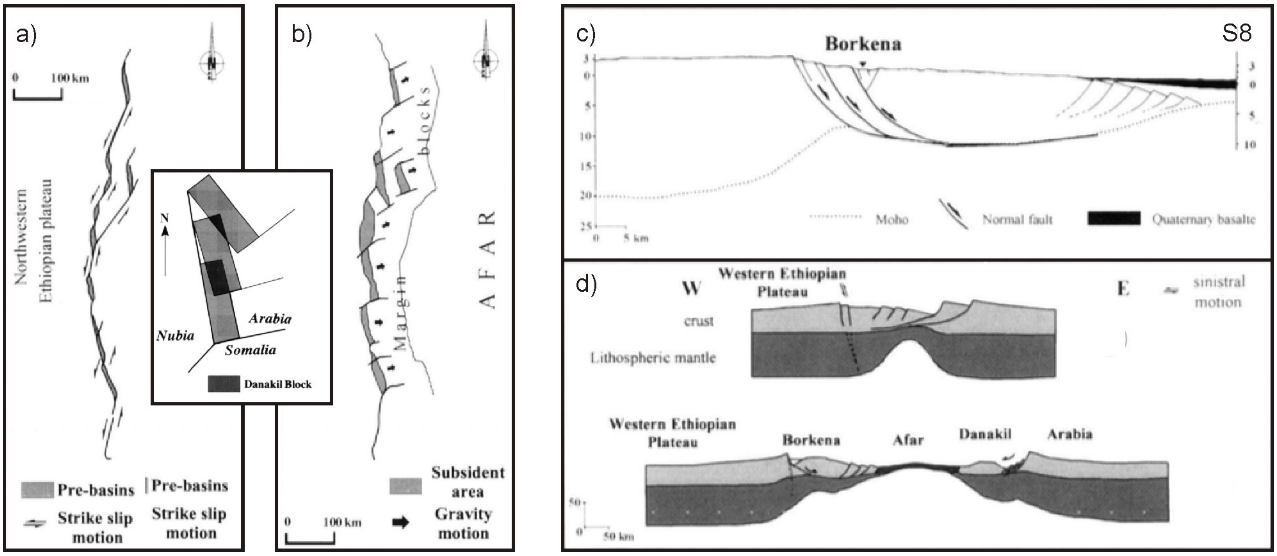

Fig. 9. Evolution of the WAM and its marginal grabens according to Chorowicz et al. (1999). (a) Sinistral strike-slip phase (early to middle Miocene) and (b) gravitational collapse, both in map view. Inset between (a) and (b): schematic map view of the translation and rotation of the Danakil Block. (c) Interpreted section S8 through the Borkenna graben with an eastward dipping detachment system. For section location see Fig. 2. (d) Schematic section view depicting the evolution of the lithosphere and the marginal grabens during the first and last phases of WAM development. Image modified with permission from the Swiss Geological Society.

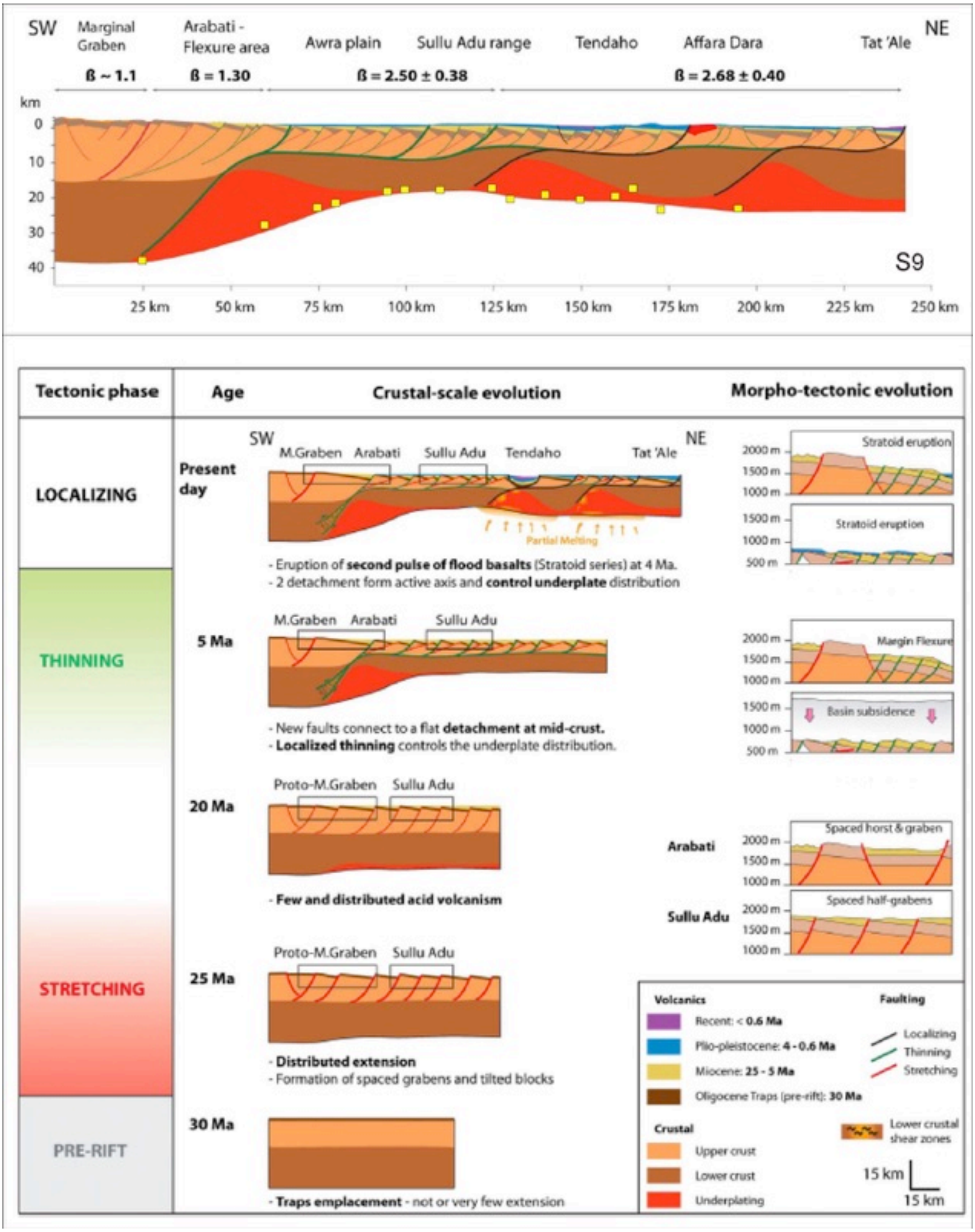

Fig. 10. Interpretation of section S9 trough the WAM (above) and Afar, as well as its supposed structural evolution (below). Yellow squares indicate receiver function Moho depth after Hammond et al. (2011) and Reed et al. (2014). For section location see Fig. 2. Image modified after Stab et al. (2016).

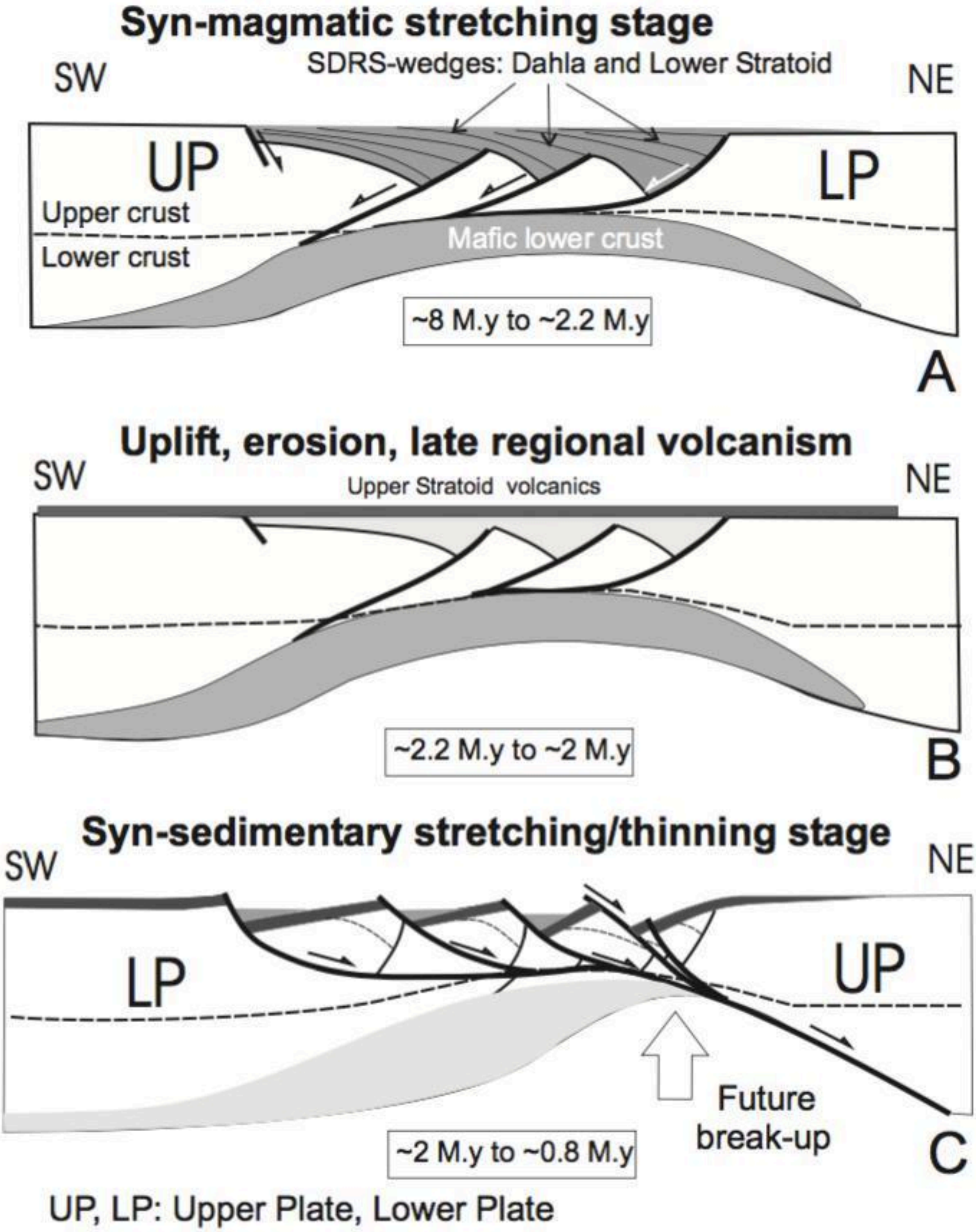

Fig 11. Flip-flop tectonic model for the SE Afar over the last 8 Ma as proposed by Geoffroy et al (2014). (**a**) Volcanic margin stage coeval with extrusion of Dahla–Lower Stratoid Series, and mafic lower crustal intrusion. (b) Transitional phase involving uplift, erosion and extrusion of the Upper Stratoid Series. (c) Pre-breakup detachment-type tectonics. The early structures shown in (a) are only partly indicated. Image modified after Geoffroy et al. (2014).

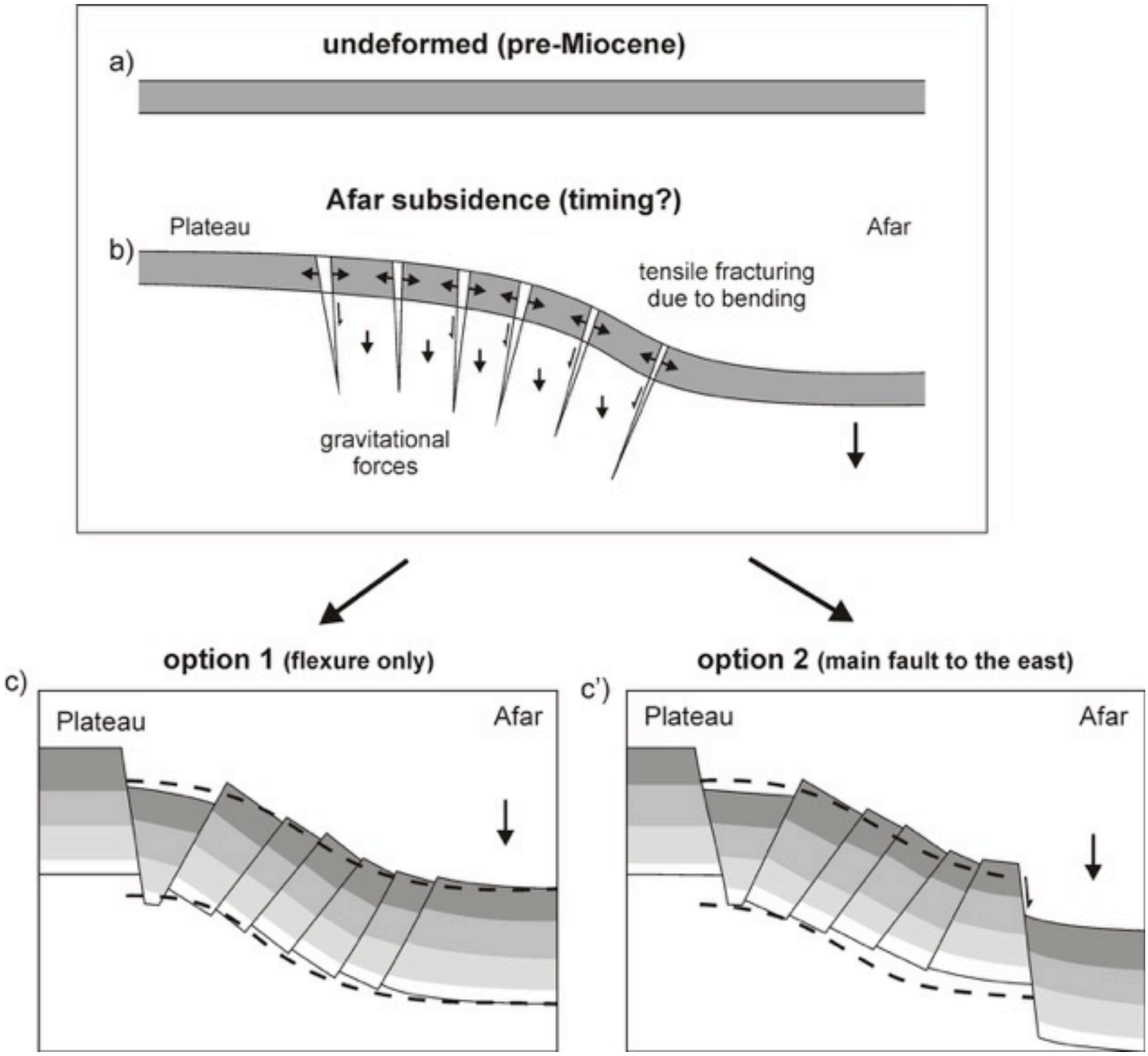

Fig. 12. (a-b) Development of antithetic faults due to flexure (Kazmin et al. 1980). (c, c') two types of flexure proposed for the WAM by Abbate and Sagri (1969). (c) depicts a simple monocline with the marginal graben block acting as a keystone, (c') shows the same structure, with and additional synthetic fault between the WAM and Afar.

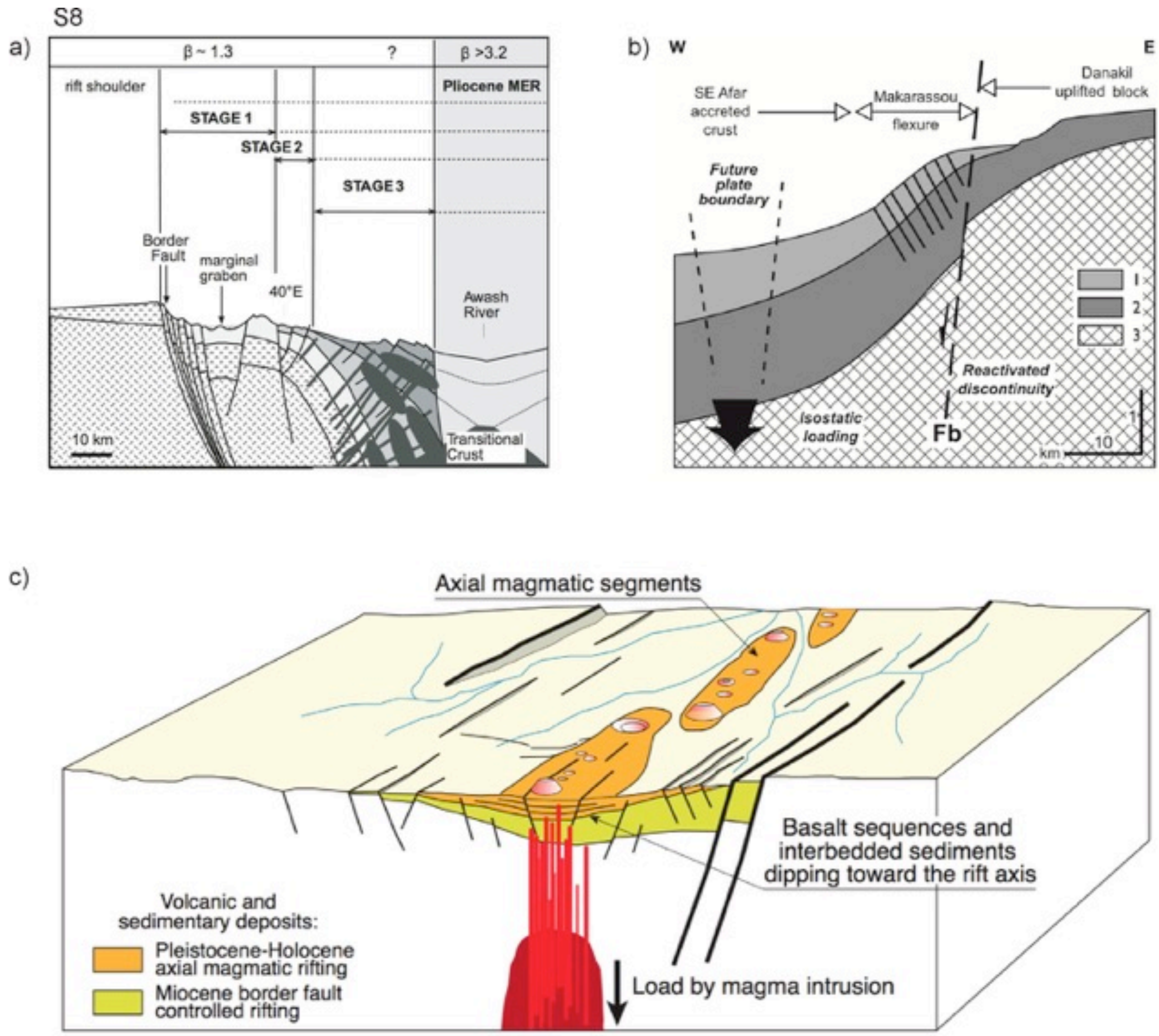

Fig. 13. Examples of magmatic loading and resulting crustal flexure as interpreted in Afar and Main Ethiopian Rift. (a) Section S8 at 10˚50'N in the Borkenna graben area (Modified after Wolfenden et al. 2005). (c) Situation at the southern tip of the Danakil Blok in the east of Afar. 1. Stratoid basalts (3–1 Ma); 2. Dalha basalts (8–4 Ma); 3. Volcanic substratum (>8 Ma). Modified after Le Gall et al. 2011, see also section S6 in Fig. 5f. (c) Flexure developing in the Main Ethiopian Rift, where initial deposition processes are controlled by the rift boundary faults. In a later phase, magma intrusion along the rift axis results in progressive tilting of volcanic and sedimentary strata (Modified after Corti et al. 2015b). For section locations see Fig. 2.

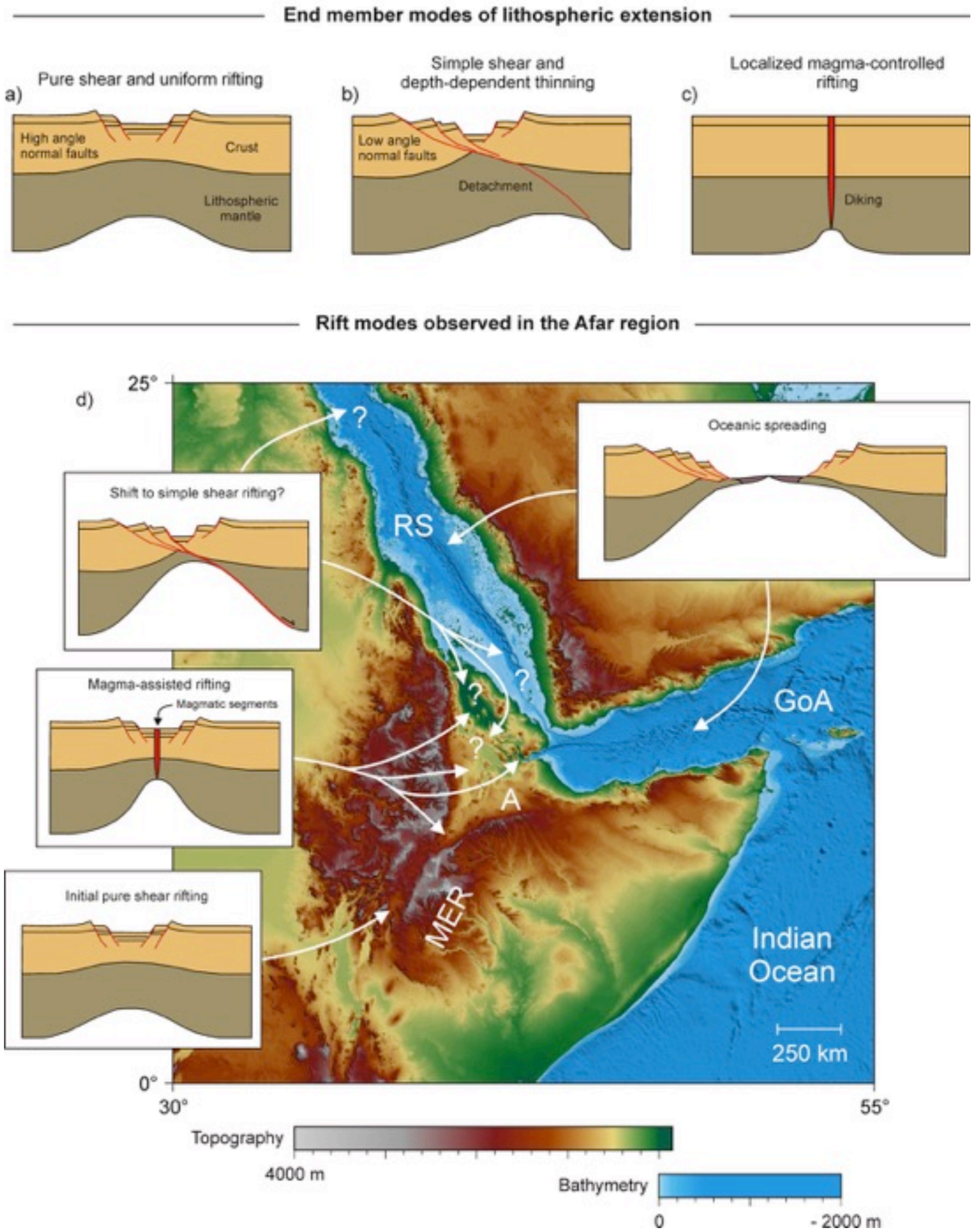

Fig. 14. Schematic overview of (a-c) end-member modes of lithospheric extension as well as (d) rift modes occurring in the Afar region. (a) Pure shear involving symmetric stretching (e.g. McKenzie 1978). (b) Simple shear via a large-scale detachment fault (e.g. Wernicke 1985). (c) Magma-controlled rifting (e.g. Buck 2004, 2006). (d) Distribution of modes in the Afar region. Pure shear rifting occurs in the southern Main Ethiopian Rift (MER), magma-assisted pure shear rifting is dominant in the northern MER and southern Afar (A), and probably active in the Danakil Depression (northern Afar) as well. In the Central Afar, parts of the Red Sea (RS) and the propagating tip of the Gulf of Aden (GoA), a shift from pure to simple shear rifting may be occurring, although the latter location may also be affected by magmatism. Post-breakup oceanic spreading can be observed in the central RS and GoA (e.g. Bosworth et al. 2005). Topography and bathymetry derived from the GEBCO Digital Atlas (IOC et al. 2003).

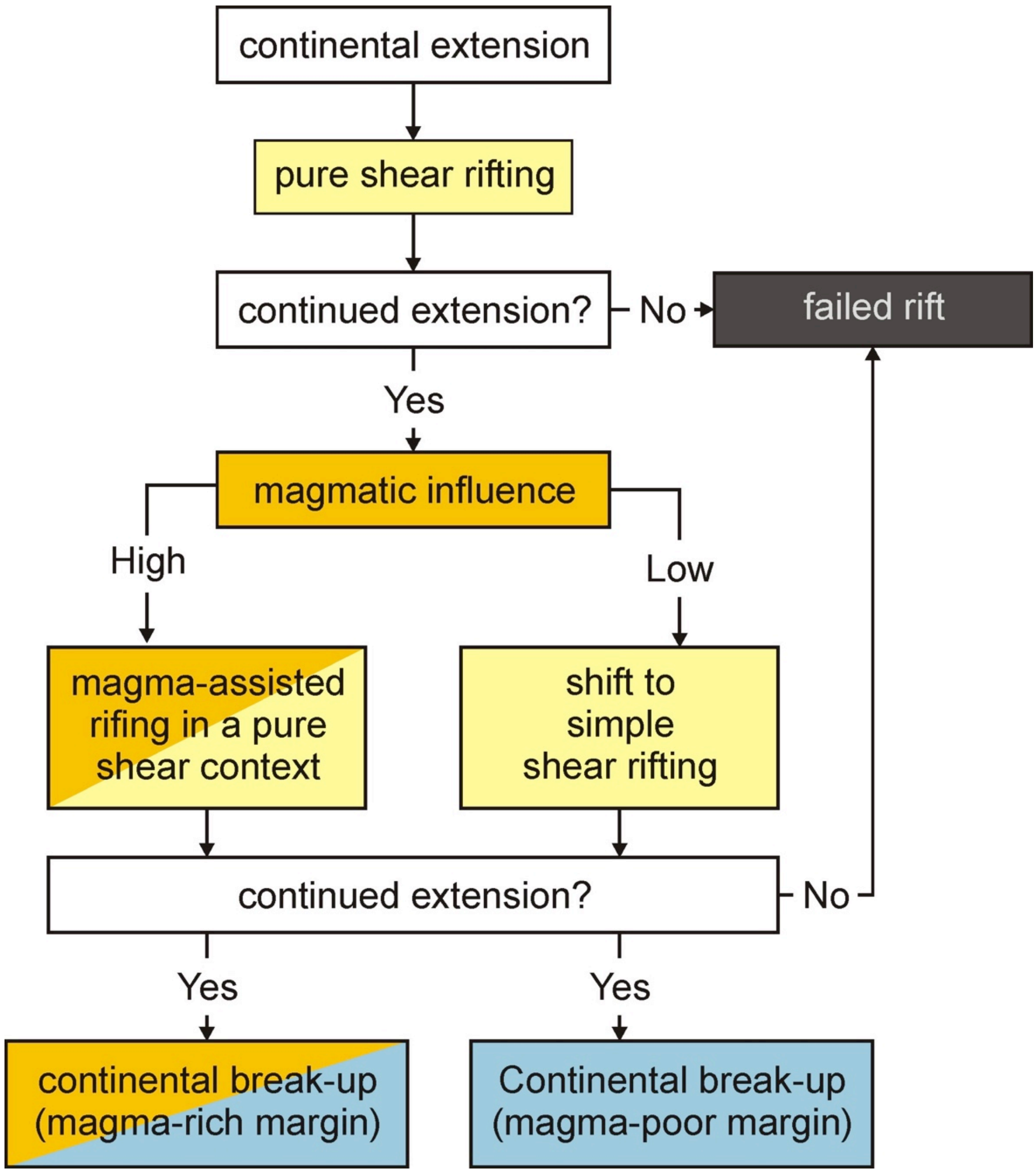

Fig. 15. Flow chart depicting the end member pathways to continental break-up as interpreted from the Afar region. Initial rifting is thought to occur in a symmetric, pure shear mode. Subsequent magmatic influence may control whether a shift to simple shear rifting occurs or not. If extension persists, the system may enter the final continental break-up phase, involving the development of a magma-rich or magma-poor passive margin. However, if extension halts before break-up, the result will be a failed rift.