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Flip-flop detachment tectonics at nascent passive margins in SE Afar

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Abstract: We propose a two-stage tectonic evolution of SE Afar in Djibouti leading to the complex development of highly asymmetric conjugate margins. From *c*. 8.5 to *c*. 2 Ma, an early mafic crust developed, associated in the upper crust with synmagmatic growth faults dipping dominantly to the SW. After an erosional stage, a new detachment fault system developed from *c*. 2 Ma with an opposite sense of motion (i.e. to the NE), during an amagmatic extensional event. In the Asal area, break-up occurred after *c*. 0.8 Ma along the footwall of an active secondary detachment fault rooted at depth above the lithospheric necking zone. This evolution suggests that flip-flop detachment tectonics is developed during extension at passive margins, in connection with the dynamics of the melting mantle and the associated magma plumbing of the crust.

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Detachment faults are thought to play a significant role in accommodating extension at passive continental margins (e.g. Lavier & Manatschal 2006; Reston & McDermott 2011). In contrast to faults associated with domino-type tectonics, detachment faults are low-angle (dip <30°) normal faults that detach the hanging wall (upper plate) from the footwall along a detachment-rooted listric or planar 'break-away' fault (e.g. Spencer 1984; Faure & Chermette 1989). The theoretical space created as a result of the detachment may be initially accommodated by a downward roll-over flexure generally cut by synthetic secondary normal faults (e.g. Lister & Davis 1989). Alternatively, the space may be accommodated by a compensation graben with antithetic normal faults depending on the initial geometry of the break-away fault (Faure & Chermette 1989). When the detachment fault offset increases, the tectonic denudation is compensated for by isostatically driven uplift and arching of the lower plate (Spencer 1984). This warping could be associated with an intense 'rolling-hinge' deformation of the lower plate, exhuming the slip surface as well as deeper levels such as the lower crust or lithospheric mantle (e.g. Wernicke & Axen 1988; Axen & Bartley 1997; Lavier & Manatschal 2006; Reston & McDermott 2011). Some studies suggest that the dynamics of extension could be more complex at passive margins, notably when the mantle is melting during extension (Geoffroy 2005). There is clearly a need to use natural observations to obtain better constraints on the pattern of crustal deformation and its evolution through time.

The concept of 'conjugate passive margins', which record long-term stretching and thinning leading to plate break-up, has so far never been applied to the SE Afar extensional domain. In the following, lithosphere break-up is understood as a failure affecting the whole lithosphere (lack of strength in the lithosphere; e.g. Kusznir & Park 1987) associated with the focusing of mantle melting and subordinate tectonic activity along a new plate boundary. New structural data extracted from remote sensing imagery (Landsat Enhanced Thematic Mapper Plus (ETM+), and corresponding digital elevation model (DEM)), and further calibrated by field observations, lead us to identify an asymmetric conjugate pattern in Djibouti that involves incipient margins evolving from a magma-rich to a magma-poor environment over a period of at least *c*. 8 Ma. The proposed kinematic model is illustrated by a sub-crustal-scale transect that highlights the role of a two-stage extensional detachment fault system, with opposing senses of motion through time.

Geological setting

The Afar depression (Fig. 1) is a key area for understanding the mechanisms of active plate break-up in a magma-rich context (e.g. Ayele *et al*. 2009). However, we have only a poor understanding of the tectonic processes that led to lithospheric thinning and stretching between Africa–Arabia and Somalia–Arabia.

The eastern Afar rift in Djibouti is an extensional faulted area extending from the Gobaad–Abhe discontinuity in the SW to the Danakil continental block in the NE (Fig. 1). Much of the depressed Afar rift domain is covered by the Neogene Stratoid Volcanic Series (Barberi & Varet 1977). The Stratoid floor is further dissected by a narrow and active en echelon tectonomagmatic axis, extending between the Ghoubbet–Asal and the Manda Inakir segments (referred to below as GAMI) (Fig. 1). The presence of oceanic-type lithosphere in SE Afar is documented beneath only the Asal axis, based on petrogenetic studies of its <1 Ma old volcanic rocks, which suggest relatively shallow melting in the depth range of 40–80 km (Pinzutti *et al*. 2013). Outside the currently active segments, seismic refraction and receiver function data recorded throughout eastern and central Afar suggest the existence of a 20–26 km thick crust of transitional character, comprising a continental lower crust intensively intruded by magma (e.g. Makris & Ginzburg 1987; Dugda & Nyblade 2006; Hammond *et al*. 2011).

From global positioning system (GPS) and interferometric synthetic aperture radar (InSAR) data, the separation of the Arabia and Somalia plates along the nascent GAMI oceanic spreading axis, ahead of the westerly propagating Aden–Tadjoura oceanic ridge (Manighetti *et al*. 1997), is known to occur at an average rate of $16 \pm 1\,mm\,a^{-1}$, perpendicular to the Asal rift axis (e.g. Vigny *et al*. 2007; Fig. 1).

Post-Stratoid extension through NE-dipping detachment faults

The volcanic stratigraphy adopted here for the Stratoid formation agrees with previous studies (Gasse *et al*. 1987), which distinguish a Lower series (*c*. 3.3–2.2 Ma) and a thin Upper series (*c*. 2.2–2 Ma).

Post-Stratoid architecture

The predominantly basaltic floor of the SE Afar rift in Djibouti comprises the extensive Stratoid series and the <0.8 Ma volcanic rocks

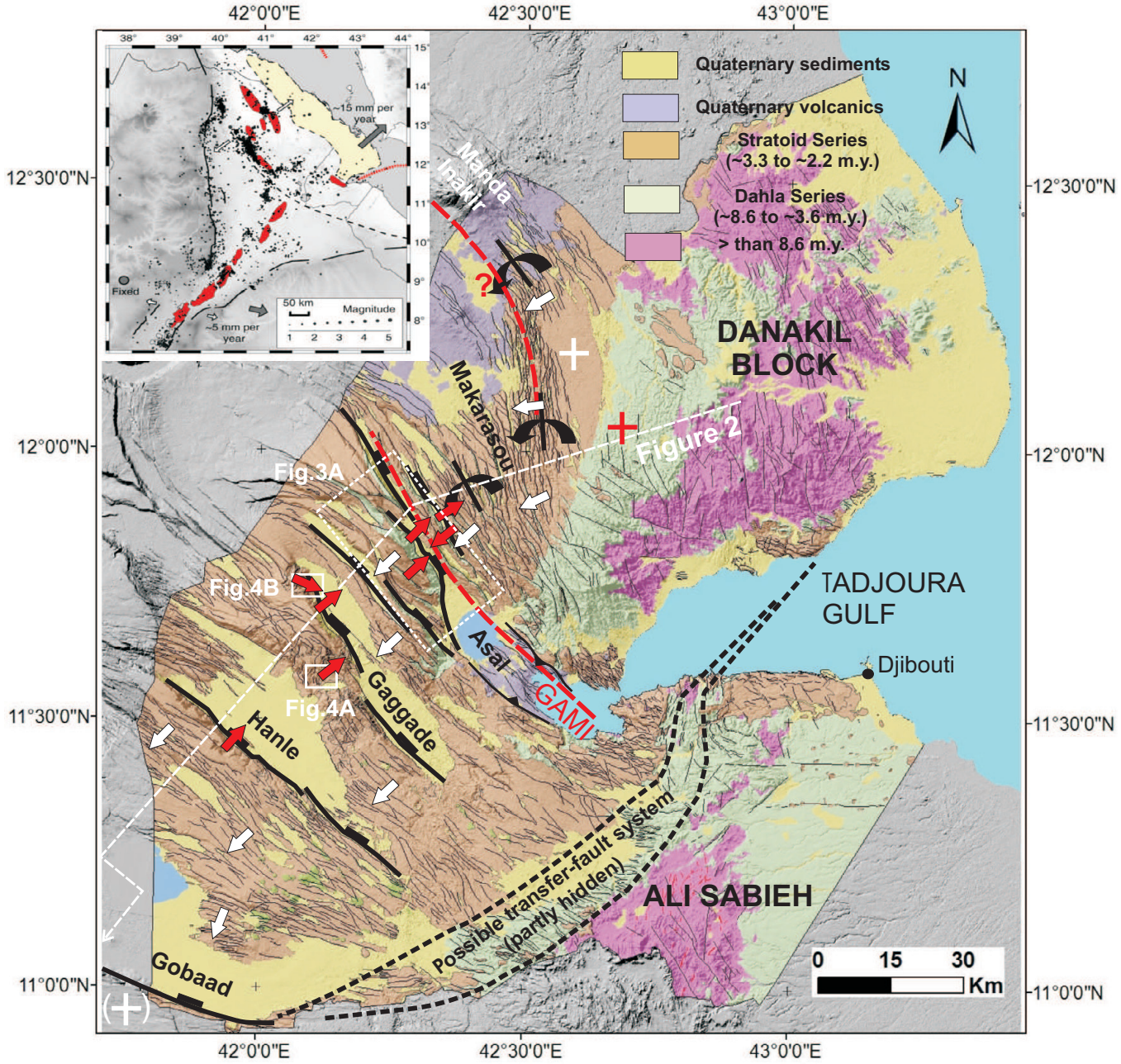


Fig. 1. Simplified geological map of Djibouti overlain on Shuttle Radar Topography Mission (SRTM)-based DEM, showing location of section (Fig. 2), satellite image (Fig. 3a) and field observations (Fig. 4a and b). Red and white arrows indicate the trend of dip of the Dahla–Lower Stratoid and Upper Stratoid series, respectively. Crosses indicate horizontal layers. Black bars and curved arrows indicate axis and dip of upper-crustal flexures, respectively. Inset shows seismicity (10/2001 to 02/2003) and Quaternary or active magmatic segments in the Afar depression, after Keir *et al*. (2011).

along the GAMI axis (Fig. 1). Pre-Stratoid basalts, corresponding mainly to the *c*. 9–4 Ma Dalha series, are largely exposed in the Danakil and Ali Sabieh boundary ranges to the east, and to a lesser extent at the base of a number of fault scarps NE of the study area (Fig. 1). The Upper Stratoid series occurs in tilted fault blocks (Figs 1 and 2), whose orientation rotates gradually clockwise from the east–west-trending Gobaad half-graben to the NW–SE-oriented troughs of Hanle, Gaggade and Asal. Because of scarp erosion, the dip of the dominantly dip-slip master faults is poorly constrained. Most of this master fault network recorded >1 km vertical throws (Manighetti *et al*. 2001), hence resulting in a cumulative post-Stratoid extension that is assumed not to exceed 9% throughout SE Afar (Gupta & Scholz 2000). The exposed hanging-wall infill is almost exclusively composed of syntectonic sediments <1 km in thickness (Fig. 1). East–west-trending newly formed and active normal faults cross-cut the half-graben sedimentary infill. These structures are synchronous with a lateral-slip reactivation of the master faults, formed in response to the *c*. 10° clockwise rotation recorded throughout SE Afar (e.g. Courtillot *et al*. 1984; Manighetti *et al*. 2001).

Detachment-type tectonics

NE of the GAMI axis, the Stratoid basalts onlapping onto the western edge of the Danakil range are downflexed and intensely faulted

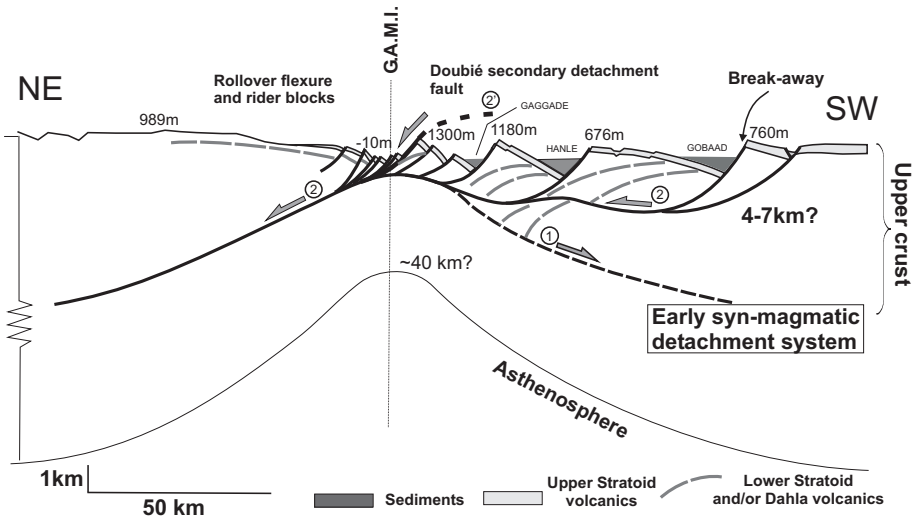


Fig. 2. Deep transect of the SE Afar rift–margin system, extrapolated from surface structural dataset (location shown in Fig. 1). Asthenosphere depth after Pinzutti *et al*. (2013). Vertical scale applies to only the upper crust. Numbers refer to the stages of development of the two-stage extensional fault system. The basal geometry of the late-stage detachment system (2) is speculative, and is based on the topography of the upper crust and published analogous examples and concepts (e.g. Spencer 1984; Lister & Davis 1989).

toward the Asal axis along the Makarassou fault belt (Tapponnier & Varet 1974; Le Gall *et al*. 2011; Fig. 1). This flexure has a complex 3D geometry, further complicated by a dense extensional fault network comprising north–south-trending antithetic structures that post-date NW–SE-oriented features (Fig. 1). According to recent dating of the basalts, the onset of flexuring occurs during the time interval from 1.8 to 0.8 Ma (Le Gall *et al*. 2011).

Whereas the fault network along the GAMI volcano-tectonic axis displays steeply dipping fault planes (*c*. 70° at ground surface), a different geometry is observed along the shallow master fault (<40°) that extends over a distance of *c*. 20 km in a prolongation of the Asal fault system (Doubié Fault in Figs 1–3). The footwalls of the Gaggade and Doubié faults are abnormally high compared with those to the SW (*c*. 300 m; Figs 2 and 3a). The mean vertical velocity inferred from InSAR data over 10 years shows an active uplift of the footwall area of the Doubié Fault and also, fundamentally, the Makarassou flexure (Peltzer *et al*. 2007). The domed footwall of the Doubié Fault culminates at *c*. 1650 m, displaying an overall convex-shaped morphology that is further dissected by high-angle faults (Figs 2 and 3a, b). This fault exhumes the Miocene Dahla series (Figs 1 and 3d). Because of the relative freshness of its fault scarp and the very thin basin infill (Fig. 3d), the shallow dip of the Doubié Fault is confidently regarded as a primary and recent low-angle fault feature, instead of resulting from the erosion of an initially steeper fault plane (Fig. 3). An upward flattening of the fault is inferred (Fig. 3c and d), but could alternatively be interpreted as the locking-up of a rotated fault (now dipping 17° ± 3°) by a steeper fault dipping 40° ± 3° fault, a geometry elsewhere suggested by Reston (2005). According to our interpretation, the Makarassou flexure probably represents a post-magmatic roll-over structure developed in the hanging wall of the Doubié detachment (Figs 2 and 3). Significantly, the foot of the flexure is cut by several faults limiting rider blocks (Figs 2 and 3a, b) (e.g. Choi & Buck 2012), which appear to be seismically active and potentially correlated with a basal shear (Peltzer *et al*. 2007). To the NW, the Doubié Fault is segmented along-strike, displaying a steeper dip (Fig. 3a).

It is commonly observed that systems of steep normal faults dipping in the same direction are kinematically coupled with basal shear zones (e.g. Lister & Davis 1989; Hayman *et al*. 2003). Considering the whole SE Afar area, the very homogeneous dip trend (north to NE) of the recent (<1.8 Ma) normal fault network strongly favours the existence of a top-to-NE basal shear, along which most faults may sole out at depth (Fig. 2). Its break-away line probably occurs along the Abhe fault to the SW, beyond which the plateau basalts are almost unaffected by post-Stratoid tilting (Figs 1 and 2). We propose that the Doubié Fault acted as an active secondary detachment (e.g. Spencer 1984) that merges into the slightly up-domed part of the basal shear plane beneath the Asal axis, hence bounding the upper plate of the margin (Fig. 2).

Mio-Pliocene volcano-tectonic evolution

No studies have addressed the rift history predating the onset of the eruption of Upper Stratoid Series in SE Afar. The corresponding geological records correspond to the poorly exposed Dalha Basalts and the acidic–mafic volcanic rocks of the Lower Stratoid Series.

Our preliminary field investigations, combined with the interpretation of satellite imagery, highlight a major intra-Stratoid angular unconformity. The Upper Stratoid basalts, which are gently tilted to the SW, unconformably overlie much steeper lavas, including the Dalha series (Fig. 3c and d), which generally face NE (Figs 1–4). According to the few available dating results (Gasse *et al*. 1987), this unconformity was formed at 2 ± 0.2 Ma. By removing the post-Stratoid SW tilt of *c*. 10°, we can infer that the initial NE dip of the underlying volcanic pile was as steep as 40–50°. When extrapolating such a steep dip along the *c*. 100 km structural transect studied here, we clearly need to invoke the existence of major SW-facing synmagmatic faults to achieve a reasonable thickness for the entire volcanic wedge (Fig. 2). Such a fan-like volcanic geometry disappears NE of the southern segment of the GAMI axis (Figs 2 and 3a), where the thin Upper Stratoid series seems to be concordant with the underlying Dahla Formation (Le Gall *et al*. 2011). The main synmagmatic growth fault is thus inferred to occur close to the GAMI axis (Fig. 2). Although the kinematic transport direction is locally towards the ENE (and not to the NE, an effect probably owing to a lateral transfer zone), we can clearly observe a detachment-type synmagmatic growth fault belonging to this early extension along the scarp of the Gaggade Fault (Fig. 4b; location shown in Fig. 1).

Margin models

From the above observations, we can apply an entirely new crustal-scale structural model to the SE Afar rift, in the light of concepts dealing with lithospheric extension at continental passive margins (Fig. 5).

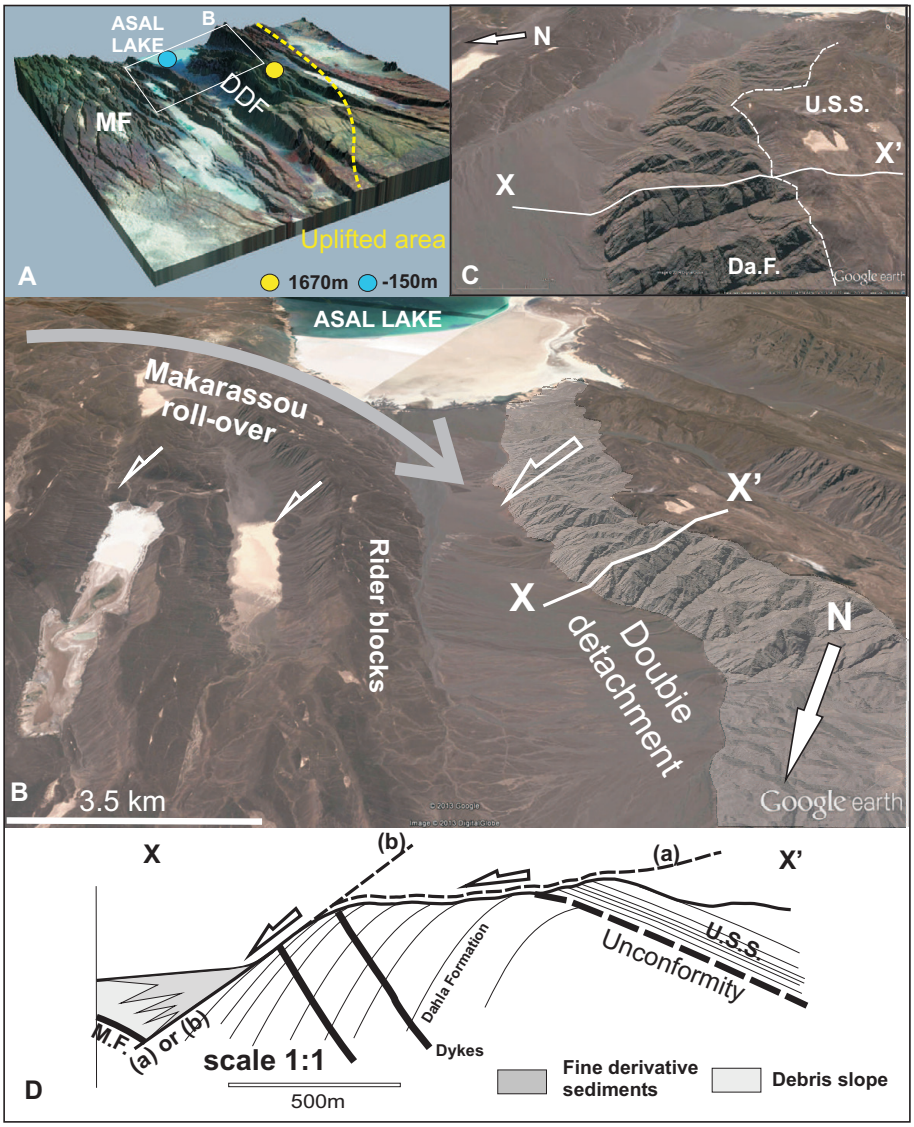


Fig. 3. (**a**) A 3D Landsat view of the Doubié detachment fault (DDF) and rider blocks developed on the lower part of the Makarassou flexure (MF). Location shown in Figure 1. (**b**) The Doubié detachment fault (in grey) and Makarassou roll-over close to the Asal Lake (location shown in Fig. 4a) (Image: © Google, 2014DigitalGlobe, 2014Cnes/ Spot Image). (**c**) Detail of the Doubié Fault (Image looking to the SE: © Google, 2014DigitalGlobe, 2014Cnes/Spot Image). Dashed white line indicates discordance of the Upper Stratoid Series (U.S.S.) dipping to the SW over the eroded Dahla Formation (Da.F.) dipping to the NE. Location of XX′ cross-section shown in (**d**) is indicated. (**d**) XX′ cross-section (location shown in (**b**) and (**c**)) with different geometries for the DDF: either (a) (one single low-dipping fault convex upward) or successively (a) (clockwise rotated early low-dipping fault) followed by (b) (low-dipping fault).

Synmagmatic stages (Fig. 5a and b)

During an early synmagmatic stage, from *c.* 8–9 Ma (or even earlier) to *c.* 2 Ma, the SE Afar domain was a volcanic-type passive margin, recording a strong and localized lithospheric stretching and thinning, coeval with mantle melting. Crustal thinning was probably balanced by the accretion of mafic magmas at different depths, leading to the formation of a transitional-type crust. This stage was associated with the formation of syntectonic volcanic wedges in the upper crust sharing the same characteristics and significance as seaward-dipping reflector (SDR) prisms observed on volcanic passive margins. SDRs are usually regarded as synrift structures, analogous to roll-over anticlines over detachment-type faults dipping toward the continent (e.g. Geoffroy 2005). In the extensional zone studied here, there is no accurate information on either the exact geometry or the number of inferred SDR wedges. The location of the corresponding SW- to south-dipping synmagmatic faults also remains to be clarified (Figs 2 and 5a). Because the SDR wedge pattern does not seem to extend NE of the GAMI axis, it is suggested that, during this stage, the Danakil range, as well as the area SW of GAMI, could have acted as a lower plate and as a tectonized magmatic upper plate, respectively. According to our model, most of the lithospheric thinning was probably concentrated along the proto-GAMI axis. However, further studies, including continuing deep geophysical surveys, would be required to characterize the overall geometry of this major extensional deformation of the SE Afar crust. This stage of tectonic and magmatic evolution, which probably spanned at least 7 Ma, clearly ended *c.* 2 Ma ago, with a transient period of erosion and peneplanation predating the extrusion of the Upper Stratoid basalts (Fig. 5b). The erosion is thought to have been maximal along the GAMI axis where the Lower Stratoid series are missing (see Doubié section in Fig. 3d).

Synsedimentary and break-up stage (Fig. 5c)

During this late stage, mantle melting was mainly localized along the GAMI proto-oceanic axis, whereas the early stage volcanic passive margins developed into a pair of conjugate non-volcanic margins with a major change in dip (and probably location) of the detachment faults (Figs 2 and 5c). This recent and short deformation event lasted for less than 1.1 Ma. It is associated with minor stretching (8–10%) and, accordingly, with bulk deformation rates higher than $2.8 \times 10^{-15}\,s^{-1}$. At this stage, the Danakil block formed the upper plate of a pair of well-defined and strongly asymmetrical non-volcanic

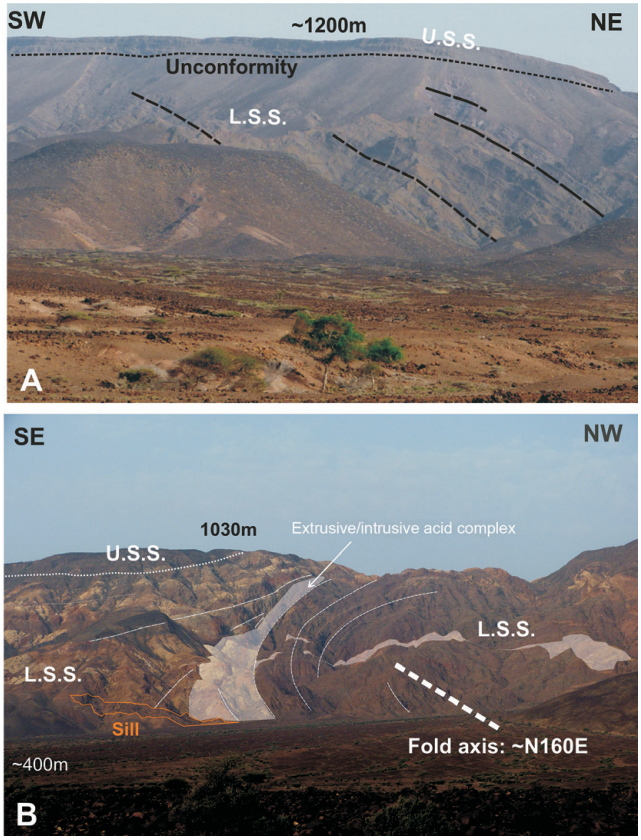


Fig. 4. (**a**) Unconformity of the Upper Stratoid Series (U.S.S.) over the Lower Stratoid Series (L.S.S.) dipping to the NE (location shown in Fig. 1). Height of cliff in background is *c*. 800 m. (**b**) Syn-L.S.S. detachment-type tectonics with kilometre-scale rollover anticline (location shown in Fig. 1). The L.S.S. formation is folded over a subhorizontal hidden growth fault. The upper part of the L.S.S., mainly acidic, displays a syntectonic fan-like geometry. The displacement along the fault was ENE oriented. U.S.S. are discordant at the top.

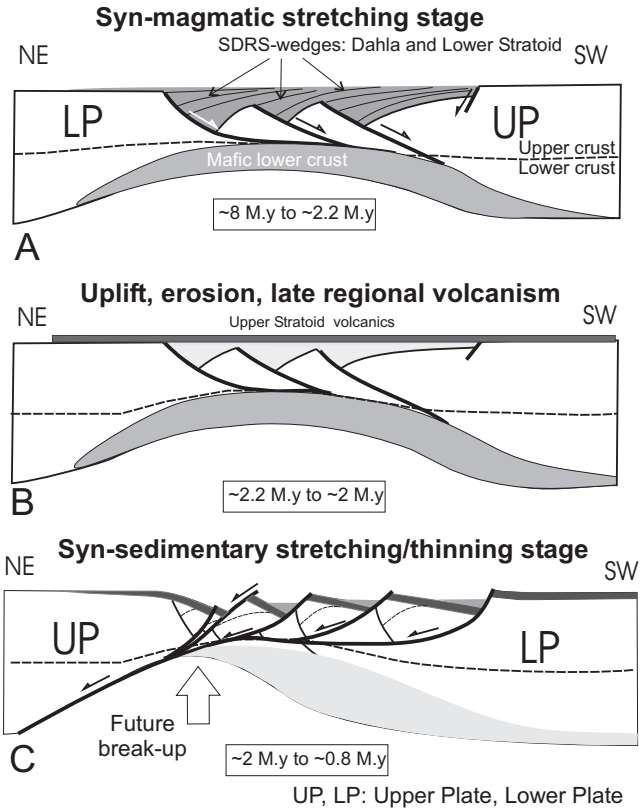


Fig. 5. Sequential development of the SE Afar incipient margin over the last 9 Ma, along a NE–SW crustal transect. (**a**) Volcanic margin stage coeval with extrusion of Dahla–Lower Stratoid Series, and emplacement of a mafic lower crust at depth. (**b**) Transient stage of uplift, erosion and extrusion of the (unconformable) Upper Stratoid Series. Maximum of erosion is thought to have occurred along the (future) GAMI axis. (**c**) Pre-breakup event with detachment-type tectonics. The early synmagmatic structures (see (**a**)) are only partly indicated.

passive margins, the upper plate being located NE of GAMI, and the lower plate farther to the SW. Apart from the very small volumes of fissural volcanic rocks erupted in the time-interval *c*. 1.6–1 Ma, this deformation was coeval with the development of synrift half-graben basins filled with lacustrine evaporites, fine detrital sediments and diatomites (Gasse *et al*. 1987).

Concluding remarks

Although expressed by opposite fault geometries, the two successive extensional events identified here form part of a two-stage continental extensional system associated with the continuing propagation of the Aden–Tadjoura oceanic axis to the NW (Manighetti *et al*. 1997). Reston & McDermott (2011) first suggested that detachment faults may change their polarity several times during the process of mantle exhumation at non-volcanic passive margins. Detachment faults accommodating the exhumation of mantle at ultraslow-spreading ridges have recently been shown to undergo a flip-flop tectonic evolution, with a possible link between discrete mantle melting events and changes in polarity (Sauter *et al*. 2013). However, the geodynamic evolution of SE Afar further suggests a radical and sudden change in lithosphere behaviour during continental extension, involving a long-term and widespread magmatic stage followed by synsedimentary break-up when mantle melting is concentrated along the future oceanic axis. This tectonic evolution suggests that the mantle dynamics not only changes rapidly with time but also exerts a first-order control on the lithospheric rheology, either directly (e.g. thermal weakening effects of small-scale convection; see Gac & Geoffroy 2008) or indirectly (magmatism in the crust). It is also noteworthy that the geometry of the late and rapid stage of non-magmatic extension triggered the location of the break-up axis and the onset of oceanic crust accretion. From *c*. 0.8 Ma onwards, the GAMI axis represents the earliest stage of oceanization, with the development of an active oceanic-type volcano-tectonic segment bounded by conjugate high-angle faults (e.g. De Chabalier & Avouac 1994; Doubre *et al*. 2007).

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