

# LARGE-SCALE FLEXURING AND ANTITHETIC EXTENSIONAL FAULTING ALONG A NASCENT PLATE BOUNDARY IN THE SE AFAR RIFT

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Short title : Structure of a nascent plate boundary in SE Afar

## ABSTRACT

New structural data from the SE Afar margin in Djibouti leads us to discriminate two recent (<1 Ma) extensional fault networks between the Afar accreted crust, and the South Danakil Block to the east. Emphasis is placed on the N-S-oriented Makarassou fault system which dissects the prominent westward- (riftward-)facing topographic flexure between the two structural domains. The most striking characteristic of the Makarassou fault belt is a closely-spaced network of continentward-dipping extensional faults, bounding domino blocks of 3-1 Ma tilted lavas of the Stratoid series. The Makarassou fault-flexure system is interpreted as an extensional faulted monocline that developed in response to differential subsidence and crustal downwarping of the Afar magmatically-accreted transitional crust. Large-scale flexuring and associated structures along the eastern flank of the Asal-Manda Inakir incipient plate boundary are regarded as indicative of a nascent volcanic rifted margin in SE Afar.

## Introduction

Since the recognition of volcanic rifted margins (VRMs) in the 1980's (see Coffin and Eldhom, 1994, for a review), the continent-ocean transition at VRMs is known to be characterized by a typical style of crustal deformation and magmatic construction. Diagnostic structures at VRMs comprise oceanward-thickening wedges of flood basalts displaying a large-scale flexure, facing towards the ocean, and further dissected by a network of continentward-dipping extensional faults (Mutter, 1984). The resulting seaward-dipping reflector sequences (SDRS) pass laterally into oceanic crust (White and McKenzie, 1989). Generally, the continent-ocean transition at VRMs is either partly under water, as along

35 modern ocean margins, or severely eroded within older exposed continental margins  
36 (Klausen, 2009). Therefore, complete cross-strike transects of VRMs are rarely observed,  
37 hence leading to uncertainties about, for example, the isostatic *versus* tectonic origin of the  
38 overall fault-flexure pattern (Palmason, 1980; Nielsen and Brooks, 1981), or the timing and  
39 duration of brittle strain with respect to the rifting and breakup events. These structural issues  
40 are discussed here in the context of the SE Afar margin, where a magmatic fault-flexure  
41 system is exceptionally exposed along the Asal active rift (Fig. 1) and interpreted as a  
42 possible analog to a nascent VRM.

43

#### 44 **SE Afar rift context**

45 The network of still-active tectono-magmatic axes that propagated since 3 Ma  
46 throughout the Afar depression, ahead of the Red Sea and Aden oceanic ridges, form onshore  
47 incipient plate boundaries between Arabia, Somalia and Nubia (Fig. 1B) (Mohr, 1989). In SE  
48 Afar, the inland prolongation of the Aden ridge is outlined by the <1 Ma northerly-  
49 propagating Ghoubbet-Asal and Manda-Inakir en echelon subrifts (Manighetti et al., 1998).  
50 This modern rift axis cuts through the 3-1 Ma-old Stratoid flood basalts (Barberi and Varet,  
51 1977) that cover most of the thin (18-22 km) and transitional crust of the Afar depression  
52 (Dugda and Nyblade, 2006). The SE Afar magmatically-accreted domain is flanked to the  
53 east by the South Danakil uplifted block *via* a prominent riftward-facing topographic scarp  
54 representing the SE Afar margin (Fig. 1). The latter is further dissected by the N-S-trending  
55 Makarassou fault system (MFS), which is generally regarded as a transfer zone linking the  
56 Ghoubbet-Asal and Manda-Inakir subrifts (Tapponnier and Varet, 1974). Mechanisms of rift  
57 propagation in SE Afar have been extensively discussed by Manighetti et al. (1998), but never  
58 addressed in terms of uplift process. The role of vertical tectonics during the recent  
59 development of the SE Afar margin is emphasized in the present work from the 3D-  
60 morphostructural analysis of the Asal-South Danakil area.

61

#### 62 **The South Danakil-Asal rift system**

63 Our structural study of the SE Afar margin is primarily based on 3D-morphostructural  
64 data supplied by both Landsat ETM+ (resolution 15 m) and ASTER (60 x 60 km) satellite  
65 images. ASTER digital elevation models (resolution 15 m) allow estimates of (1) fault and  
66 lava dips, and (2) minimum vertical fault displacement from surface offsets along individual  
67 fault scarps. Fault lengths, deduced from map traces, are underestimated because of the loss  
68 of resolution below 15 m of vertical offset. Extensive field investigations did not permit the

69 observation of fault surfaces with slip criteria, because the lower parts of fault scarps are  
70 systematically concealed by slope deposits, whereas their exposed upper sections usually  
71 follow basaltic columnar jointing that rarely preserves the fault slip plane.  
72 Field measurements were mostly devoted to calibrating fault and lava dips, estimated from  
73 ASTER cross-profiles. The timing and magnitude of syn- to post-Stratoid regional uplift are  
74 deduced from the spatial distribution, thickness variations and elevation of the Stratoid basalts  
75 along the SE Afar margin.

76 The mapped extent of the Stratoid flood basalts on the western flank of the South  
77 Danakil block suggests a two-stage uplift history which started in pre-Stratoid times with  
78 initiation of the proto-Danakil block as a NE-plunging asymmetrical dome (Fig.  
79 1A). Pronounced uplift is assumed to have continued in syn- to post-Stratoid times, in  
80 combination with subsidence of the Afar accreted crust to the west. The resulting crustal-scale  
81 downward bending occurred synchronously with the emplacement of the Stratoid basalts as a  
82 volcanic wedge thickening westwards from a few 10's m on the Asa Gayla plateau, up to 100  
83 m in the Makarassou fault belt, and > 1200 m in the Asal rift (Fig. 1C) (Zan et al., 1990).  
84 Ongoing uplift of the proto-South Danakil block in post-Stratoid times caused the ~800 m  
85 elevation of the initially horizontal Stratoid basalts towards the Day Mountains (Fig. 1A). The  
86 onset of uplift might be as young as 125 kyr, by correlation with the Middle Pleistocene  
87 conglomeratic fans that currently fringe the foot of the South Danakil range in the Tadjoura  
88 coastal plain (Fig. 1B) (Gasse and Fournier, 1983).

89 During the last 3 Ma, the SE Afar margin recorded several episodes of extensional faulting in  
90 various tectonic settings. The westernmost edge of the proto-South Danakil block (present-  
91 day Asa Gayla plateau) developed as a >10 km-wide half-graben-like structure, filled with a  
92 probably thin sequence of Stratoid basalts ( $S_2$ ), and bounded to the east by an inferred  
93 submeridian master fault (Fa on Figs. 1B and 1C). Uplift and erosion events in the footwall  
94 block to the east are currently expressed by discrete inliers of deeply incised Lower Stratoid  
95 basalts ( $S_1$ ), resting horizontally on top of Dalha substratum volcanics. Two younger  
96 extensional events finally led to the present-day fault arrangement along the SE Afar margin.  
97 The <1 Ma Ghoubbet-Asal-Manda-Inakir en echelon subrift pattern along the subdued part of  
98 the margin is not detailed here (see Manighetti et al., 1998). More interestingly for the present  
99 issue is the structural development of the Makarassou fault system in the upper part of the SE  
100 Afar topographic scarp.

## 102 **Structure of the Makarassou fault/flexure system**

103 The NS-trending structures of the Makarassou fault system extend through the western  
104 flank of a prominent asymmetrical topographic range that culminates at 1800 m to the south,  
105 in the Day Mountains, and slopes down, both northwards at 300 m in the Dorra plain, and  
106 more abruptly westwards at <100 m in the Asal-Manda-Inakir rift floor (Fig. 1A). On the  
107 Landsat ETM+ satellite image in Fig. 2A, the Makarassou fault system is a 70 km-long fault  
108 belt that cuts the frontal part of the Stratoid basaltic wedge. It comprises two adjoining fault  
109 subdomains, each 5 km wide, with contrasting structural styles. The high-density fault  
110 subdomain to the east encloses a dense network of anastomosed and sigmoidal faults, about 5  
111 km long on average. It is separated from the tabular Stratoid basalts of the Asa Gayla plateau  
112 *via* the highly segmented fault Fb in Fig. 1C. Fault arrangement is more regular in the western  
113 subdomain where four wider blocks are bounded by linear, and less segmented faults, >15 km  
114 in length. There, the westerly-tilted Stratoid surfaces show remnants of NW-SE (Asal-type)  
115 structures that are sharply cut, and thus post-dated, by the submeridian Makarassou bounding  
116 faults (Fig. 2C). The northern termination of the Makarassou fault belt in the Dorra plain (Fig.  
117 1B) is locally sealed by undeformed Manda Inakir basalts, >0.87 Ma in age (in Vellutini et al.,  
118 1995).

119 The ~40 km-long transect in Fig. 1C cuts at high angle the widest exposed section of the  
120 Makarassou fault system. Topography is dominated by a westerly-facing monoclinial flexure  
121 that lowers the Stratoid surface to about 900 m, from the Asa Gayla plateau down to the Asal  
122 rift floor. The hinge line of the Makarassou flexure approximately coincides with the NS-  
123 trending trace of fault Fb (Fig. 2A). The two fault subdomains correspond to a  
124 marked shallowing of topography westwards, with a flexure gradient decreasing from ~1°/km  
125 to <0.5°/km. However, the most specific attribute of the Makarassou faults is the easterly  
126 (outward) dip of 21 extensional structures (out of a total of 29). With the exception of  
127 marginal horst-graben structures in the crestal zone to the east, the antithetic fault network  
128 occurs strictly through the downflexed part of the cross-section (Fig. 1C). The resulting  
129 inward-dipping Stratoid blocks are arranged in a domino configuration, with a mean spacing  
130 of ~500 m, and rotated lava dips as high as 30°, in the upper and steepest part of the flexure  
131 (Fig. 2B). Mean fault block width increases, up to 1 km, in the western subdomain,  
132 concomitant with decreasing lava dips (10° in average). Average fault dip is about 70°E, and  
133 remains nearly constant across-strike. Topographic fault scarps extracted from the ASTER 3D  
134 models indicate vertical fault throws in the range 20-700 m, with a mean value of 105 m.

135

136 **Kinematic model and discussion**

137 From the new dataset above, the SE Afar margin is inferred to comprise two distinct  
138 extensional fault networks that differ in terms of geometry, timing and kinematics. The Asal-  
139 Manda-Inakir fault pattern bounds NW-SE-oriented en echelon horst/grabens, orthogonal to  
140 the N30°E regional extension (e.g. Jestin et al., 1994), in the Afar depressed axis. In contrast,  
141 the Makarassou extensional fault network is typically characterized by : (1) its spatial  
142 association with a riftward-facing monoclinial flexure, (2) its outward-dipping attitude, away  
143 from the rift axis, (3) its NS orientation, parallel to the flexure axis, and oblique to the  
144 regional extension, and (4) its relatively young age with respect to the Asal structures.  
145 Most of these structural features display striking similarities with those of coastal flexures  
146 involving SDRS-type magmatic prisms along VRMs (Mutter, 1984). However, one specific  
147 aspect of the Makarassou fault-flexure system is the lack of exposed mafic dyke swarms, but  
148 these latter probably exist at depth, beneath the Stratoid fissural-type basalts.  
149 These analogies lead us to evaluate whether the models applied to nascent VRMs could be  
150 valid for the SE Afar volcano-tectonic pattern. Given the location of the Makarassou flexure  
151 along the western edge of the Asa Gayla plateau, i.e. close to the hinge line marking the limit  
152 of pronounced lava thickness towards the magmatically-accreted rift domain, we infer that  
153 magma-assisted processes acted as driving forces for riftward-facing flexuring along the  
154 western flank of the South Danakil block. By analogy with the isostatic model of Palmason  
155 (1980), it is suggested that crustal downwarping along the SE Afar margin was the flexural  
156 response to differential loading of the magmatically-accreted crust during the Stratoid (3-1  
157 Ma), and even Dalha (8-4 Ma), flood basalt activity (Fig. 3C). Additional parameters are  
158 thought to have interacted during flexuring, and to be responsible for the finite geometry of  
159 the Makarassou fault-flexure system. Its NS orientation, oblique to the regional extension, is  
160 believed to have followed preexisting structural fabrics. Indeed, the extensional rejuvenation  
161 of inherited submeridian faults, such as those cutting the Mablás volcanics to the east, likely  
162 accounts for the inferred syn-Stratoid bounding fault Fa (Figs. 1C and 3A). A steep and  
163 similarly-trending weakness zone (Fb) is suspected to occur at depth, beneath the hinge line  
164 of the flexure, further west. This resulted in an extensional monocline, analogous to those  
165 developed above the upward-propagating tip of a blind normal fault (Willsey et al., 2002).  
166 Dominantly dip-slip displacement, down to the west, and probably >500 m, likely occurred  
167 along the steep discontinuity Fb, in order to accommodate part of the downflexed bending of  
168 the Stratoid sequences at the surface. Assuming that the Makarassou flexure nucleated above

169 a steep weakness zone satisfactorily accounts for (1) its relative tightness (~10 km) with  
170 respect to its total length, and (2) its concave profile, with higher flexure gradients in its upper  
171 part.

172 The discontinuity Fb is believed to have once breached the monocline along a surface  
173 breaking zone, currently outlined by the crestal horst-graben pattern. The network of  
174 antithetic normal faults, splaying upwards into the immediate hangingwall of fault Fb,  
175 resemble those directly observed, or obtained experimentally, in extensional monoclines  
176 (Withjack et al., 1990; Kaven and Martel, 2007). But, their nucleation and development in the  
177 downflexed Stratoid lava pile were probably controlled by volcanic structures, as follows.  
178 Provided that the wedge-shaped pile of initially horizontal (Dalha-Stratoid) lava flows rotated  
179 westwards, towards the axis of the active magmatic zone, during early flexuring, the cooling  
180 joint pattern, known to generally act as tension fractures under tensile stress (Forslund and  
181 Gudmundsson, 1992 ; Le Gall et al., 2000), likely evolved from an initially vertical attitude to  
182 an easterly-inclined position with time (Fig. 3B). The decreasing dip attitude of the joint  
183 pattern at depth resulted in a listric-shaped joint trajectory which might have later triggered  
184 nucleation of normal faults, dipping away from the subsiding rift axis to the west, once  
185 submitted to the N30°E-directed extension.

186 The isostatic, instead of tectonic, model proposed here for the Makarassou flexure is  
187 reinforced by the fact that structural evidence are currently absent for a continentward-facing  
188 detachment underlying the Stratoid wedge, as argued in the 'roll-over anticline' model  
189 applied to SDRS prisms elsewhere (Geoffroy et al., 1998). Furthermore, the constant and  
190 steeply-dipping attitude of extensional faults throughout the Makarassou flexure is at odds  
191 with highly rotated hangingwall structures, typically developed above the frontal part of a  
192 detachment (McKlay, 1996).

193 From the age of pre- (3-1 Ma) and post-flexuring (>0.87 Ma) basalts, the maximum duration  
194 of the Makarassou flexure is ~2Ma, i.e. as similarly stated for others VRMs (Lenoir et al.,  
195 2003 ; Klausen, 2009). Such a short time span suggests that regional strain rates were  
196 relatively high during flexuring along the SE Afar margin, probably in relation with  
197 anomalous thermal gradients at depth.

198 The magma-driven vertical tectonics and riftward-facing flexuring that operated during the  
199 last 3 Ma, along the eastern flank of the Asal-Manda Inakir future plate boundary, are  
200 confidently regarded as the structural expression of an incipient VRM in SE Afar. The inferred  
201 embryonic stage of continental breakup is in agreement with previous assessments about the  
202 transitional type of the Stratoid flood basalt series, and the thinned character of the Afar crust.

203

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210

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272 **Figure captions**

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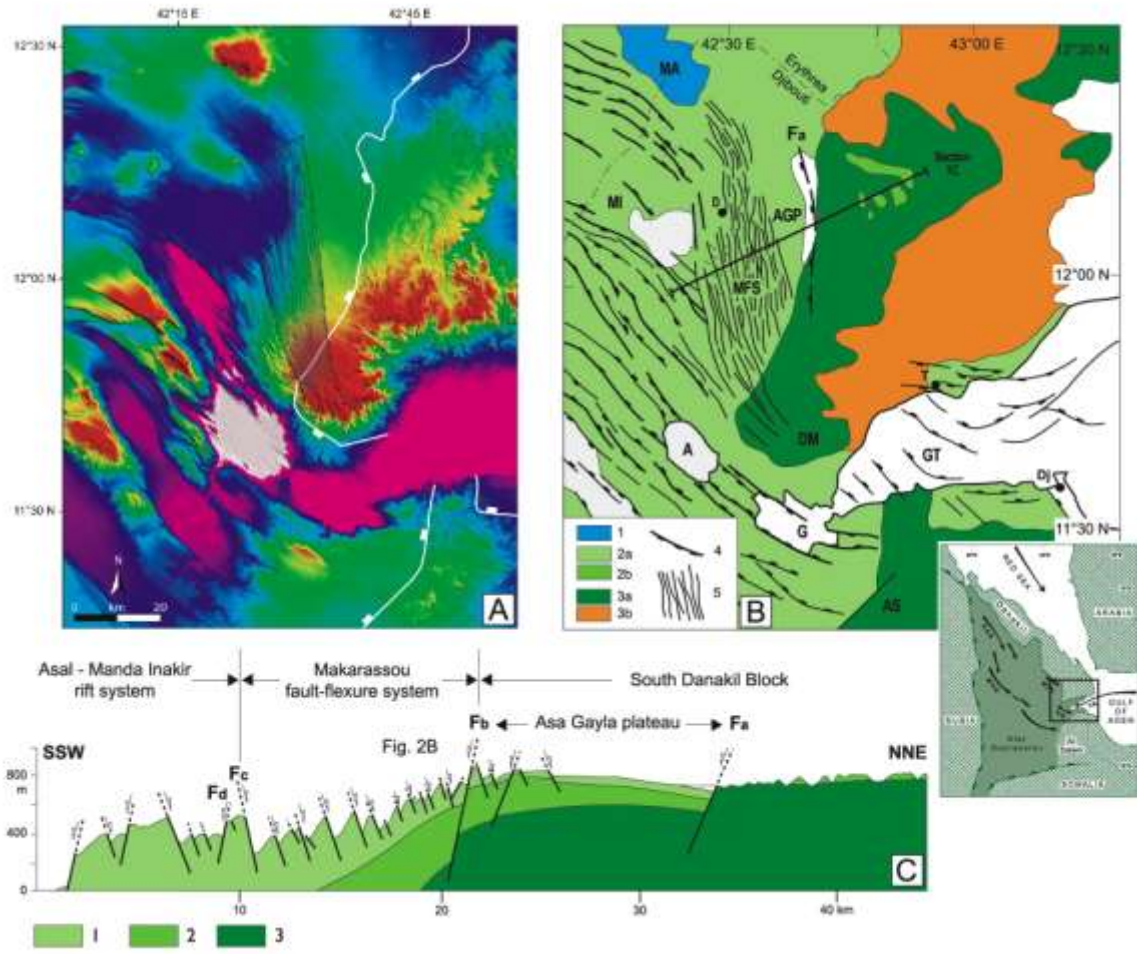
274 Fig. 1A. ASTER digital elevation model of the SE Afar rift in Djibouti (vertical resolution 15  
 275 m). Topography ranges from -150 m (Asal) up to 1800 m (Day Mountains). See  
 276 nomenclature in Fig. 1B. The white line shows the limit of Stratoid basalts (onshore).  
 277 Ticks are inside the volcanic area. Note its obliquity with respect to the South Danakil  
 278 reliefs. Fig. 1B. Structural sketch of the SE Afar margin in Djibouti. 1. Moussa Ali  
 279 volcanics ; 2a. 3-1 Ma Stratoid and Gulf basalts; 2b. Lower Stratoid basalts; 3. >3 Ma  
 280 synrift volcanics, 3a. Dalha basalts, 3b. Mablbas Fm. ; 4. Main faults, 5. Makarassou  
 281 fault system. A., Asal ; AGP., Asa Gayla plateau ; AS., Ali Sabieh ; D., Dorra ; Dj.,  
 282 Djibouti ; DM., Day Mountains ; G., Ghoubbet ; GT., Gulf of Tadjoura ; MA., Moussa  
 283 Ali volcano ; MFS., Makarassou fault system ; MI., Manda Inakir; T., Tadjoura. Trace  
 284 of section 1C is drawn. Inset shows accretionary axes in the Afar Triple junction. 1C.  
 285 Structural cross-section of the central part of the Makarassou fault system. Topography  
 286 is extracted from the ASTER DEM. 1 and 2. S<sub>1</sub> and S<sub>2</sub> Stratoid basalts, respectively. 3.  
 287 Dalha basalts. Vertical exaggeration ~4. Location in Fig. 1B.

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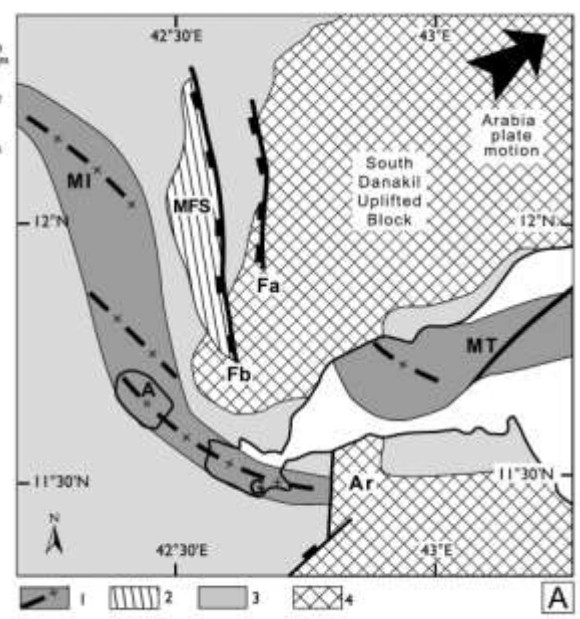
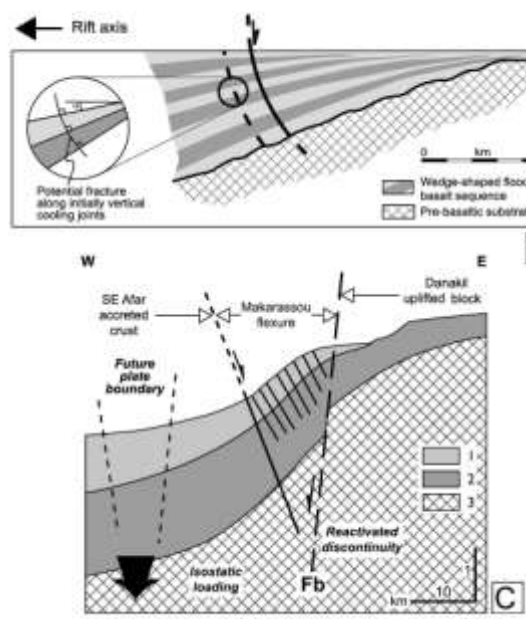
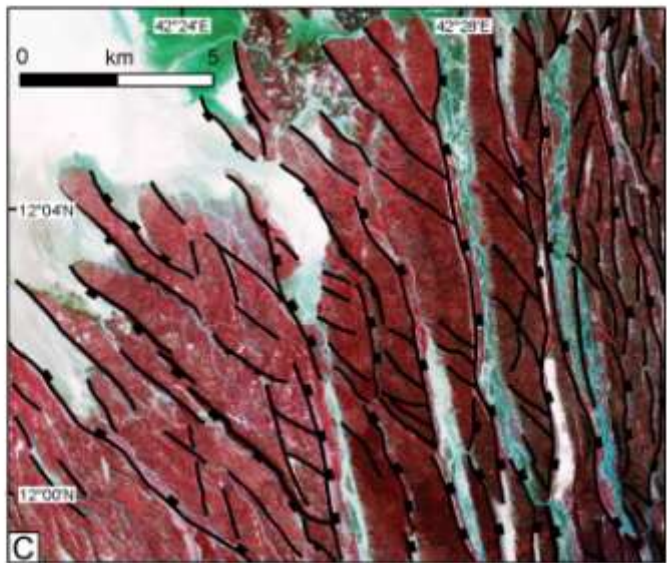
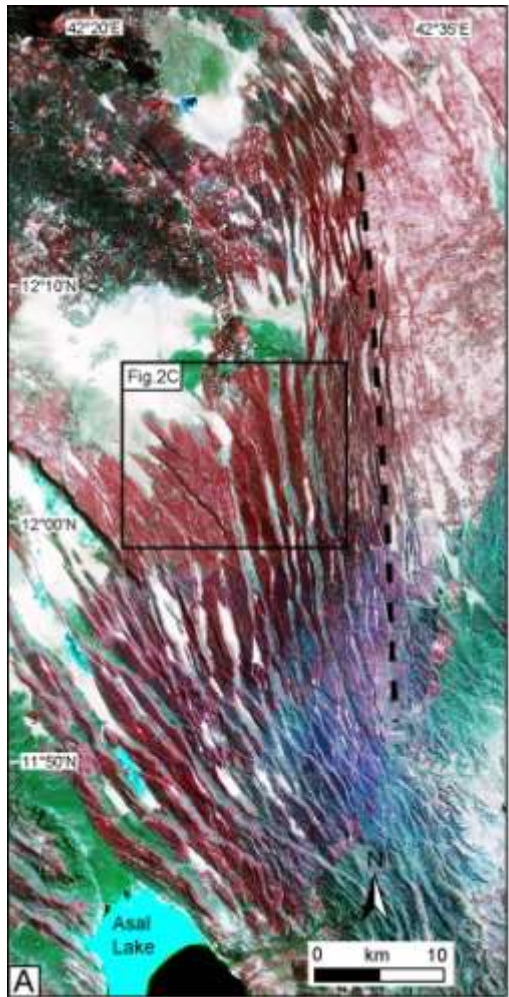
289 Fig. 2A. Map trace of the Makarassou fault belt on the eastern flank of the Asal-Manda Inakir  
 290 rift framework (Landsat ETM+ image, 15 m resolution). The dashed black line is the  
 291 trace of the flexure hinge line, close to the trace of fault Fb. 2B. Field view of a closely-  
 292 spaced network (~500 m) of three Stratoid tilted blocks (dip ~15°W), bounded by  
 293 easterly-facing extensional faults. View looking south. The main fault scarp in the back  
 294 is about 150 m high. Location in Fig. 1C. 2C. Focussed view of the Landsat ETM+  
 295 image (in Fig. 2A) showing Makarassou submeridian normal faults cutting NW-SE-  
 296 trending Asal horst-graben structures.

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Fig. 3A. Sketch structural map of SE Afar emphasizing the role of inherited NS discontinuities on (1) the propagation of the Aden and Ghoubbet-Asal-Manda-Inakir incipient plate boundaries, and (2) initiation of the corresponding volcanic rifted margin (Makarassou belt). 1. <1 Ma rifted zones ; 2. Makarassou flexure ; 3. Onshore distribution of 3-1 Ma Stratoid and Gulf basalts; 4. Pre-Stratoid volcanics. A. Asal ; Ar. Arta ; G. Ghoubbet ; MFS. Makarassou fault system ; MI. Manda Inakir ; MT. Maskali transform. 3B. Conceptual model for the origin of outward-dipping extensional faults in wedges of flood basalts. 3C. Development of riftward-flexuring and antithetic extensional faulting along the SE Afar margin, as a consequence of magma-driven isostatic loading, and reactivated heterogeneities. 1. Stratoid basalts (3-1 Ma); 2. Dalha basalts (8-4 Ma); 3. Volcanic substratum (>8 Ma).



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