A PROTO-VOLCANIC MARGIN ALONG THE ASAL RIFT. THE MAKARASSOU FAULT SYSTEM, DJIBOUTI.

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ABSTRACT

The Makarassou fault system (MFS) is a 40 x 70 km submeridian structure connecting the Asal and Manda Inakir active-recent rift axes, in Eastern Afar. Its previous interpretation as a transform fault structure is challanged on the basis of new structural field data and interpreted satellite images. The MFS involves 3-1 Ma-old basalts of the Stratoid series which onlapped Dalha basalts in the Asa Gayla plateau to the E, ie. on the southern part of the Danakil range. The overall structure of the MFS is dominated by a westerly-dipping monoclinal flexure, downflexed toward the Asal rift axis. It is further disssected by a dense network of extensional faults, dipping consistently outwards, to the E. Lava dips, as steep as 30°, locally occur in individual highly-rotated fault blocks. The causal mechanims of extensional flexuring along the Makarassou are assigned to isostatic loading caused by the >5 km-thick wedge of Stratoid and Dalha basalts that accummulated since 6 Ma beneath the Asal rift. The inward accummulation of mafic material, together with extensional and flexural strain, both resemble the pattern of Seaward Dipping Reflector Sequences that typically develop along volcanic rifted margins, worldwide. The structural interpretation of the MFS as outlining a nascent volcanic rifted margin along the eastern flank of the Asal-Manda Inakir rifted zone is consistent with available geochemical and geophysical records of the mafic crust flooring the Afar depression.

Keywords: East Afar, Makarassou fault belt, extensional flexure, Stratoid basalts, proto-volcanic margin.

INTRODUCTION

The Afar depression involves a number of large-scale fault-bounded blocks and transfer/transform structures (Barberi and Varet, 1977) that developed since less than 3 Ma, in the onshore prolongation of the Red Sea and Aden oceanic ridges (Fig. 1) (Laughton, 1966 ; Manighetti et al., 1998). One of these transform structures was assumed to lie along the Makarassou fault system (MFS), connecting the Asal and Manda Inakir active rift segments (AMIR) in Eastern Afar (Fig. 1) (Tapponnier and Varet, 1974 ; Courtillot et al., 1974). These early interpretations, based on fault map arrangement, and further compared to results of experimental modelling, are challenged in the present work from new structural data. Interpretation of field-calibrated ASTER satellite images suggest that the 3D-architecture of the MFS shares striking similarities with those of large-scale extensional flexures, typically developed along volcanic rifted margins (e.g. Brooks and Nielsen, 1982 ; Dessai and Bertrand, 1995 ; Geoffroy et al., 1998 ; Klausen, 2009). The new flexural model applied here to the MFS lends further support to the commonly accepted concept of the AMIR axis as forming an embryonic oceanic region (Barberi and Santacroce, 1980 ; Mohr, 1989 ; Dugda and Nyblade, 2006).

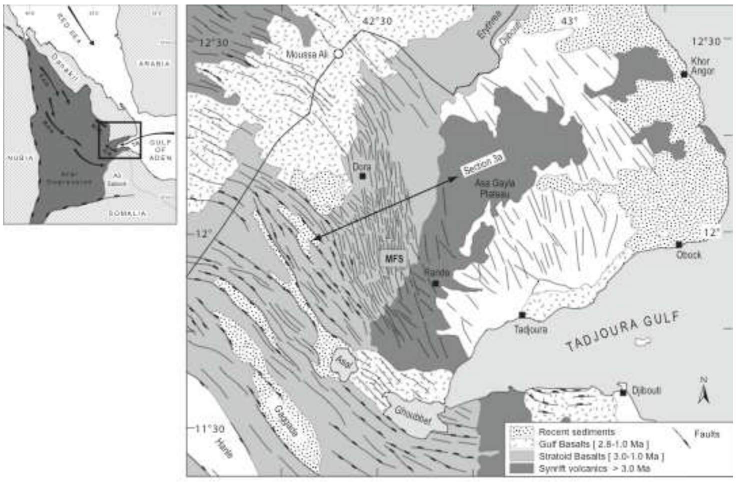

Figure 1: Simplified geological map of the Asal rift and the South Danakil range. The trace of the cross-section in Figure 2a is drawn. Top left inset shows location of Afar Triangle. The unstretched domains during the last 3 Ma are cross-ruled.

Rift context and methodology

On the map and cross-section of Figs. 1 and 2a, the MFS extends as a ca. 70 x 40 km submeridian fault belt that involves the 3.3-1.3 Ma Stratoid Basalts between the Asa Gayla volcanic plateau to the east, and the AMIR subsiding active axis to the west. The Stratoid faulted basalts give way westwards into younger rift volcanics, related to the AMIR disconnected right-stepping subrifts that propagated onshore, in the time-span 900-140 kyr, ahead of the Aden ridge (Manighetti et al., 1998). To the east, the Stratoid Basalts onlap a >800 m-thick pile of little deformed, and slightly tilted, older flood basalts of the 9.0-3.8 Ma Dalha Fm in the Asa Gayla plateau. The latter rest unconformably over 14.7-9.7 Ma Mablas acidic rocks which constitute the bulk of the South Danakil range. Further east, younger volcanic rocks of the Ribta (3.5 Ma) and Gulf Basalts (2.8-1.0 Ma) series lie over part of the coastal plain, at the foot of paleo-fault scarps following the eastern edge of the South Danakil range.

From field-calibrated ASTER satelitte imagery (15m vertical resolution), and corresponding digital elevation models, the structure of the exceptionally well exposed MFS is depicted, both in map-view and on a 25 km-long cross-section through its widest part. Vertical fault displacement is measured as minimum values from surface offsets along individual fault scarps, whilst fault lenghts, deduced from map traces on the ASTER image, are underestimated because of the lost of resolution below 10-15 m of vertical offset. Cumulate extension recorded by the MFS is estimated by summing individual fault heaves along the studied cross-section. Markers for sens of fault displacement have not been observed, because the lower parts of fault scarps are systematically concealed by slope deposits, whereas their exposed upper sections usually follow basaltic columnar jointing that rarely preserves the fault slip plane.

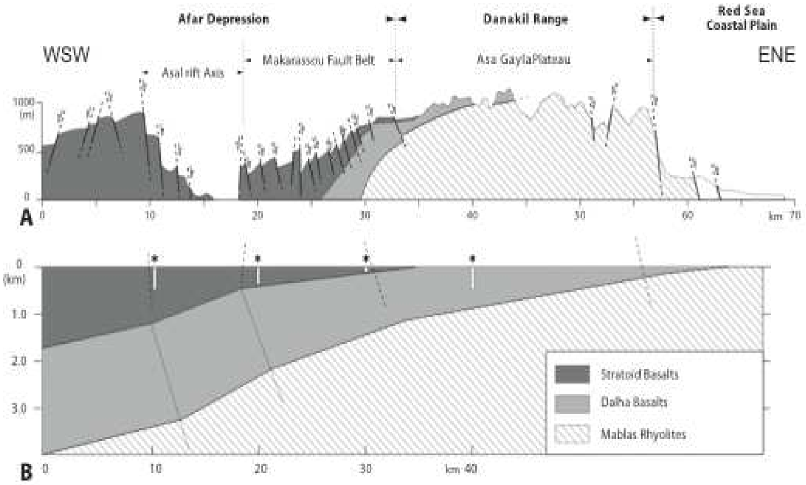

Figure 2: A. Structural section crossing the eastern side of the Afar depression from the Asal rift axis to the South Danakil horst and the Obock coastal plain. The Makarassou fault belt occurs close to the eastern edge of a rifward-thickening flood basalt package, involving the Dalha and Stratoid series. Volcanic thicknesses at depth are extrapolated from exposed sections. Vertical exaggeraration ~10. B. Restored 2D-sectional geometry (prior to extensional faulting) showing the wedge-shaped geometry of the 9.0-1.3 Ma Dalha-Stratoid flood basalt succession.

STRUCTURAL ANALYSIS OF THE MFS

On the DEM in Fig. 1b, the MFS is a fan-shaped fault belt, partly concealed to the NW, in the Dorra plain, by Holocene alluvial sediments and Pleistocene volcanics of the Moussa Ali volcanoe. To the east, the MFS comprises a narrow (20 km-wide) NS-trending belt of closely-spaced and colinear faults that swing counterclockwise to the NW, towards the Moussa Ali volcanic center, whilst merging into N130°-oriented Asal-type faults to the south. Fault strike rotates slightly (<10°) counterclockwise in the western part of the MFS, concomitantly to increasing fault spacing. There, wider fault-bounded blocks sharply cut, and thus post-date, N130°E Asal-type horst-graben structures extending continuously further west in the AMIR domain.

The 25 km-long structural cross-section in Fig. 2a cuts at high angle the MFS in its central part. It exhibits a westerly-dipping monoclinal flexure that lowers the exposed surface of the Stratoid Basalts to about 900 m, from the Asa Gayla plateau down to the Alol rifted zone to the west, with a regional dip of ~10°. The westerly-facing warp is dissected by a dense network of extensional faults, facing dominantly to the east (27 over a total of 38 faults), with an average dip of 70-80° (Fig. 3a). Their nearly consistent outward attitude (with respect to the Asal rift axis) is the most significant attribute of the entire MFS network. Antithetic faults, and associated asymmetric horsts structures are present at the two extremities of the cross-section, and those occurring to the west, i.e. in the fan-shaped faulted subdomain, are Asal-type N130°E structures. Monoclinal flexuring is strictly focused on a 15 km-long high density fault section, enclosing a network of closely-spaced extensional faults, dipping exclusively to the east (F_{9-25}). The width of the resulting faulted blocks increases westwards from 480 m (F_{9-18}) to 700 m (F_{18-25}) (Figs. 3a and 4). Lava dips, as steep as 30° in highly rotated individual blocks (Fig. 3a), contrast with the regional dip of 10° of the envelop surface.

The spatial association of high tilt angles and closely-spaced faulted blocks typically characterizes high-strained extensional zones. Assuming that flexuring along the MFS took place at a late stage of the 900-140 kyr period (see above), in agreement with the involvement of <0.9 Ma-old volcanics of the Moussa Ali edifice (Piguet and Vellutini, 1991) into the curved extremity of the MFS to the north, indicates a minimum long-term cumulative extension rate of ca. 6 mm/yr. The finite geometry of the MFS thus results from the conjugate effects of large-scale flexuring an outward-verging extensional faulting, which are both characteristic structures of nascent volcanic margins. That leads us to discuss the tectonic *versus* isostatic origin of flexuring and associated structures along the MFS, as classically addressed about most volcanic rifted margins worldwilde.

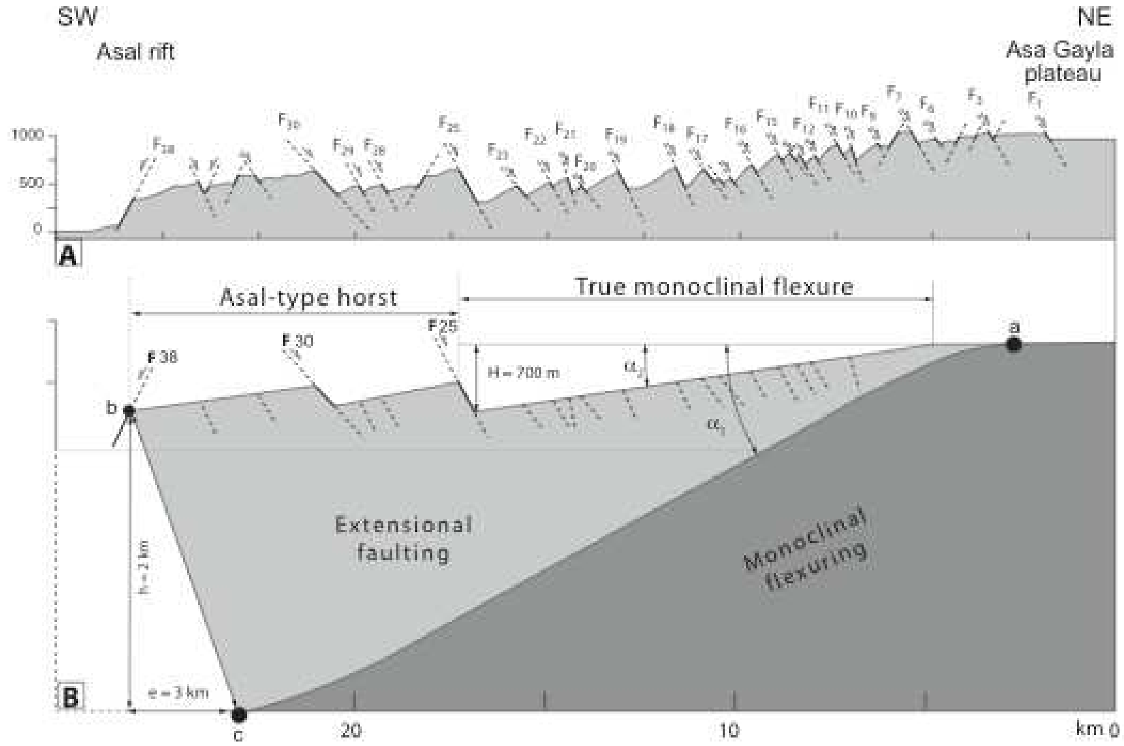

Figure 3: A. Structural cross-section of the Makarassou fault belt showing inward-dipping Stratoid blocks, arranged in a domino style, and bounded by a network of closely-spaced extensional faults dipping dominantly inward, toward the Asal rift axis. Numbers refer to individual faults identified from ASTER data interpretation. B. Structural sketch illustrating the respective role of flexuring and faulting during the development of the MFS on the eastern side of the Asal rifted zone. The envelop surface of the exposed Stratoid Basalts is used as a reference. Extensional faulting resulted in (1) the shallowing (estimated at 2 km) of the downflexed surface (from AC to AB) and (2) nearly 3 km of cumulate extension.

CAUSAL MECHANISMS OF THE MFS FLEXURE

The volcano-stratigraphic cross-section in Fig. 2b shows the restored architecture of the Dalha and Stratoid trap series, prior to the Makarassou flexuring event. The two basaltic successions are seen to thicken dramatically westwards through the South Danakil-Asal transition zone. The thickness of the Dalha Basalts increases from ca. 200 m in the coastal plain, up to >800 m over the Asa Gayla plateau, and > 1 km in the Doubye rift axis, north Asal (Vellutini, 1990). A much thicker sequence of Dalha Basalts might have once floored the Afar depression further west, in relation to a marked thinning of the Afar lithosphere in the time-period 8-3 Ma (Vellutini, 1990). Thickness distribution of the Stratoid basaltic cover also varies from a few 10’s m on the western flank of the Asa Gayla plateau, up to >100 m throughout the MFS, >250 m north of the Asal rift (Gasse et al., 1985), and >1300 m in Central Afar (Barberi and Varet, 1975).

A wedge-shaped volcanic succession, >2-3 km thick, is thus assumed to have accumulated in the time range 9.0-1.3 Ma, at the transition between the proto-South Danakil horst and the Asal trough. It cannot be definitely ascertained whether the thickest volcanic accummulation, and corresponding attenuated and/or underplated crust at depth, were focussed along the AMIR and Manda Hararo axial ranges (Manighetti et al., 1998), or filled the entire Afar depression. In any case, the MFS flexure developed along the western edge of the Asa Gayla plateau, i.e. close to the hinge line marking the limit of pronounced lava thickness towards the active rifted domain. That is supported by aeromagnetic data from Eastern Afar (Courtillot et al., 1980) that show the trace of the MFS following the transition zone between an oceanic-type magnetic domain to the west (AMIR), and a continental-type (quiet) magnetic domain to the east (Danakil range).

The inward-dipping accummulation of mafic material erupted along the eastern edge of the AMIR resembles magmatic prisms, known as Seaward Dipping Reflector Sequences along most volcanic margins worldwide (see review by Coffin and Eldhom, 1992). The dyke swarms typically observed along volcanic margins are missing in the MFS, at the present erosion level, but they probably exist at depth beneath the Stratoid fissural-type flood basalts.

The accumulation of a km’s-thick wedge of flood basalts along the South Danakil/AMIR transition zone leads us to envisage the key-role of isostatic loading on large-scale flexuring along the MFS, the old Dalha basaltic sequences being progressively depressed by weight of younger overlapping series (Stratoid) during volcanic deposition. The role of tectonic forces during flexuring cannot be totally ruled out. But, structural and geophysical evidence are currently missing for the presence of a large-scale antithetic detachment underlying the MFS, as commonly evoked in the roll-over anticline model applied to many volcanic margins (Nielsen and Brooks, 1981 ; Barton and White, 1997 ; Geoffroy et al., 1998).

The origin of the antithetic extensional fault network in the MFS is more satisfactorilly explained, using shear failure criterion, and applying the model of fault formation proposed by Forslund and Gudmundsson (1992) to the South Iceland rift. Assuming that the wedge-shaped pile of initially horizontal lava flows rotated westwards, towards the axis of the active magmatic zone, the cooling joint pattern, prone to act as tension fractures under tensile stress, evolved from an initially vertical attitude to an easterly-inclined position with time. The decreasing dip attitude of the joint pattern at depth resulted in a listric-shaped joint trajectory which might have later triggered the development of antithetic normal faults, dipping away from the subsiding rift axis to the west, once submitted to the N30°E horizontal extension. The obliquity of the submeridian MFS to regional extension might be partly explained by assuming its isostatic, instead of tectonic, origin.

CONCLUSIONS

ASTER satellite image interpretation, calibrated by field observations, leads us to interpret the Makarassou fault system, SE Afar, as an extensional faulted corridor, superimposed on a large-scale inward- (riftward-)facing flexure, involving the 3-1 Ma-old Stratoid basaltic trapp series. This monocline structure is assumed to result from isostatic adjustment related to the overloading of a >3 km-thick magmatic accumulation, composed of Dalha basalts and younger Stratoid lavas, at the transition between the South Danakil plateau and the Asal-Manda Inakir rifted domain to the East. The flexuring and outward-verging extensional faulting documented in the present work along this narrow transition zone are tectonic processes typically recorded by volcanic rifted margins, at an early stage of continental breakup. Our interpretation of the MFS as the shallow structure of a proto-volcanic margin fits with the kinematic model proposed by Wolfenden et al. (2005) for the conjugate West Afar margin (Fig. 1a). Once combined, these two structural works demonstrate the symmetrical 2D-architecture of the twin proto-volcanic margins, immediatly prior to, or even at an incipient stage of, plate separation between Nubia and Somalia.

ACKNOWLEDGMENTS

Funding and support from CERD (Study and Research Center of Djibouti) is appreciated. Dr Mohamed Jalludin, Director of CERD, is warmly thanked for his constant interest for the geological works carried out in Djibouti since many years by our team from Brest university.

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