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Left-lateral strike-slip tectonics and gravity induced individualisation of wide continental blocks in the western Afar margin

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Key words: Western Afar margin, Strike-slip motion, Gravity tectonic, Releasing bend basin, Alps, Briançonnais

RESUME

Le long de la marge Ouest Afar se trouve une série de bassins allongés N-S qui n'ont pas été pris en compte dans le modèle géodynamique de l'ouverture de l'Afar au Néogène (rotation anti-horaire du bloc Danakil, fixé à l'Afrique au nord et à l'Arabie au sud). Des images SAR ERS-1 et un Modèle Numérique de Terrain nous ont permis de cartographier les structures affectant la marge. Les bassins ont été initialisés par des mouvements décrochants senestres orientés N-S. Plus tardivement, de larges blocs crustaux se sont détachés gravitairement de la marge. Notre carte et des observations structurales de terrain complémentaires mettent en évidences trois phases tectoniques. 1) Au début du Miocène, un mouvement décrochant senestre a initialisé des pré-bassins à la faveur de courbures le long des failles. Ce mouvement senestre implique que le bloc Danakil n'était pas fixé à l'Afrique par son extremité septentrionale lors de l'ouverture de l'Afar, mais il a coulissé vers le nord. 2) Cette phase initiale a été suivie par une phase d'extension diffuse régionale, orientée NO-SE, qui est lié à l'ouverture du Rift Ethiopien. 3) Au Pliocène-Quaternaire, les grands blocs crustaux se sont détachés et ont glissé gravitairement vers l'Afar. Ces blocs ont une position au sein de la marge et des dimensions similaires à des blocs crustaux se trouvant fréquemment dans les marges passives comme par exemple le bloc Briançonnais dans les Alpes Occidentales.

ABSTRACT

In the western margin of the Afar there occurs a series of N-S elongated basins. In the reconstruction of the Afar opening in Neogene time (anti-clockwise rotation of the Danakil block, with attachment points onto Africa and Arabia) the formation of these basins has been overlooked. Using radar satellite imagery (SAR ERS-1) and a Digital Elevation Model (DEM), we mapped some of the structures along the margin. The basins were initiated by N-trending left-lateral motion. Later, wide (60 km) continental blocks were detached from the Afar margin. Based on remote mapping and field structural analysis, we propose three tectonic events. 1) Early- to mid-Miocene, N-S trending sinistral motion initiated the Borkena and other pre-basin structures at releasing bends of N-striking faults. This sinistral transcurrent movement implies that the Danakil block was not fixed to Africa at this time but was moving northward. 2) A NW-trending regional diffuse extension related to the evolution of the Ethiopian rift. 3) Pliocene-Quaternary motion toward the Afar of the wide crustal blocks induced by detachment and gravity forces. These wide blocks are similar in size and location inside the margin scheme to other crustal blocks frequently found at passive margins (e.g., Briançonnais block in the Western Alps).

Introduction

The Afar triangle is the triple junction of the Red Sea, Gulf of Aden and Ethiopian Rift, three boundaries separating Nubia (Africa), Arabia and the Somalian block (Fig. 1a). The ocean-continent transition zones bounding the Afar triangle are young and can be regarded as type-examples of the early stages of passive margin evolution. They are poorly known and have been explained (Sichler 1980) in the frame of simple rigid anti-clockwise rotation of the Danakil block relative to Africa with the Danakil block kept fixed to Africa in the north and to Arabia in the south (Fig. 2b). Interpreting the fault distribution in the Afar, Souriot & Brun (1992) supported this idea. The model implies that the western margin is extensional and the southern one transtensional with a right-lateral strike-slip component.

The western Afar margin features a series of N-S oriented basins (Fig. 1b), bordered by faults and filled with sediments of at least Pliocene-Quaternary age (Kazmin 1972). They are separated from the Afar by a continuous line of large continental blocks, 500 km long and 60 km wide. These blocks are well exposed and we have analyzed them tectonically by radar satellite imagery and Digital Elevation Model (DEM) interpretation, to constrain the geometry of deformation, and field structural measurements, to constrain mechanisms. We propose that the blocks result from transtensional left-lateral strike-slip motion along the N-trending margin, followed by gravity induced movements.

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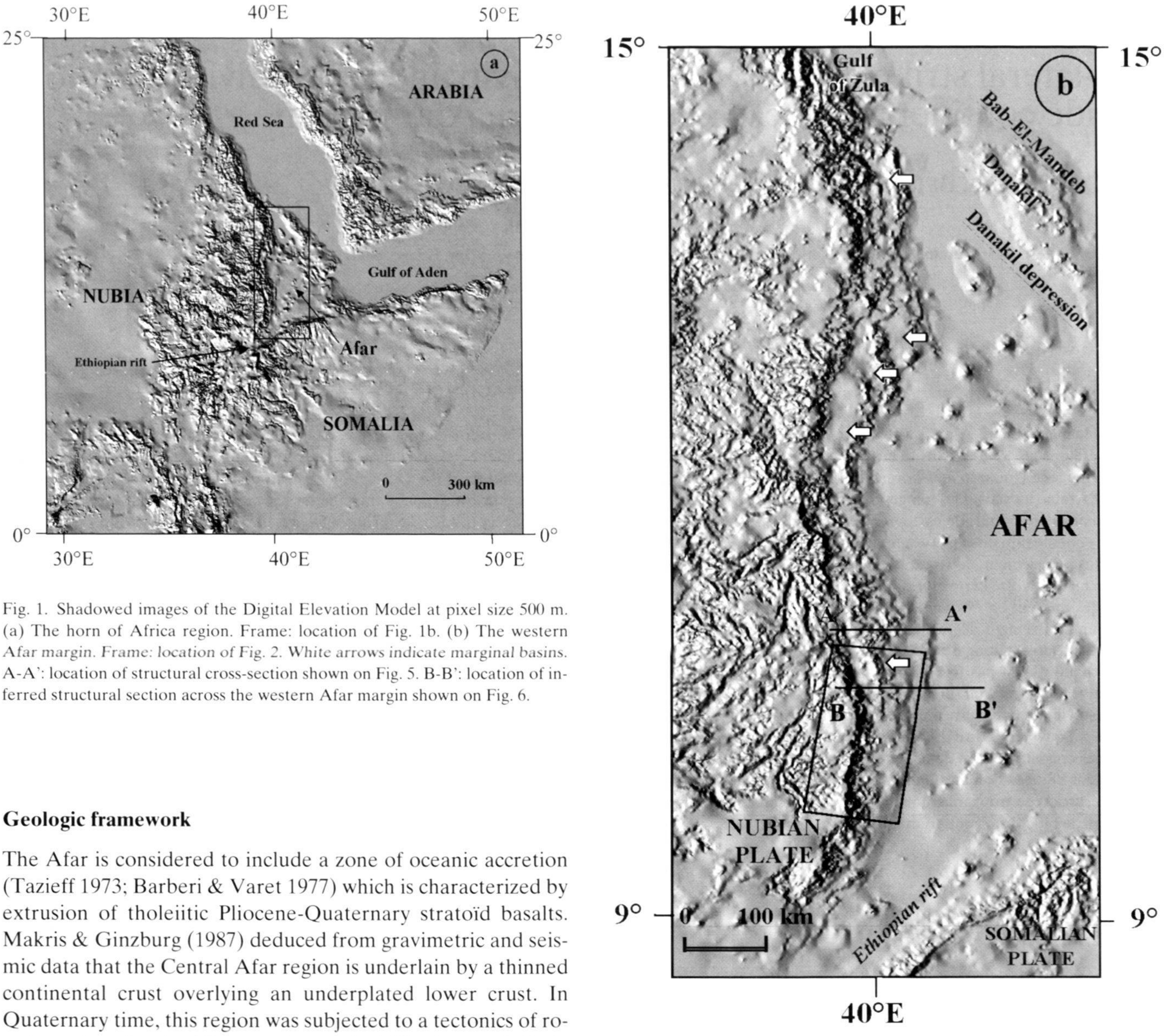

Fig. 1. Shadowed images of the Digital Elevation Model at pixel size 500 m. (a) The horn of Africa region. Frame: location of Fig. 1b. (b) The western Afar margin. Frame: location of Fig. 2. White arrows indicate marginal basins. A-A': location of structural cross-section shown on Fig. 5. B-B': location of inferred structural section across the western Afar margin shown on Fig. 6.

Geologic framework

The Afar is considered to include a zone of oceanic accretion (Tazieff 1973; Barberi & Varet 1977) which is characterized by extrusion of tholeiitic Pliocene-Quaternary stratoïd basalts. Makris & Ginzburg (1987) deduced from gravimetric and seismic data that the Central Afar region is underlain by a thinned continental crust overlying an underplated lower crust. In Quaternary time, this region was subjected to a tectonics of rotating micro-blocks (Tapponnier et al. 1990; Acton & Stein 1991).

The Afar is bordered by three passive margins mainly formed of Paleogene trapp series overlying Mesozoic and Neoproterozoic basement. The Paleogene trapps correspond to four major volcanic units with 1,200 m total thickness. From bottom to top, the trapp units are composed by the ante-Oligocene Ashangi Basalt, the Oligocene Aiba Basalt (34–30 Ma), the Oligo-Miocene Alaji Basalt and Rhyolite (32–16 Ma) and the Oligo-Miocene Termaber Basalt (26–20 and 15–13 Ma) (Zanettin et al. 1980).

The Southern Afar margin is an elevated rift shoulder at the border of the Somalian block. The Danakil block, forming the northern margin, is on the southwest bordered by the Danakil depression and cut on the northeast by the Bab-El-Mandeb straits (Fig. 2a). The shape and size of the Danakil block is conceived by assuming that exposed Panafrican crystalline basement and Jurassic rocks extend beyond the area of visible outcrops (Burek 1970; Tazieff et al. 1972; Le Pichon & Francheteau 1978). Anti-clockwise rotation of the Danakil block was 23°E since the Miocene, of which 11°E occurred since the Pliocene, and is responsible for the Afar opening (Sichler 1980).

The N-S trending western Afar margin at the border of the Nubian plate includes the Northwestern Ethiopian Plateau which lies at a mean elevation of 3,400 m (Fig. 1b and 2a). The Pliocene-Quaternary elongated basins found in the western Afar margin are etched in the Oligo-Miocene volcanic rocks. They are separated from the Afar by a continuous line of large

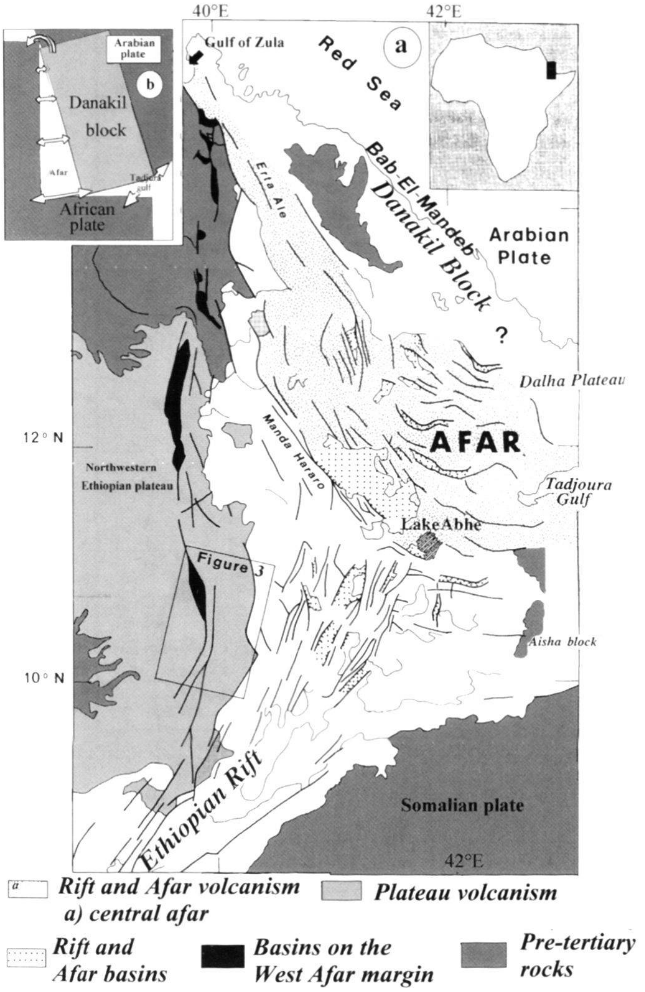

Fig. 2. (a) Structural map of the Afar region. (b) Model of the Afar opening (crank-arm model from Sichler 1980), redrawn from Souriot & Brun (1992).

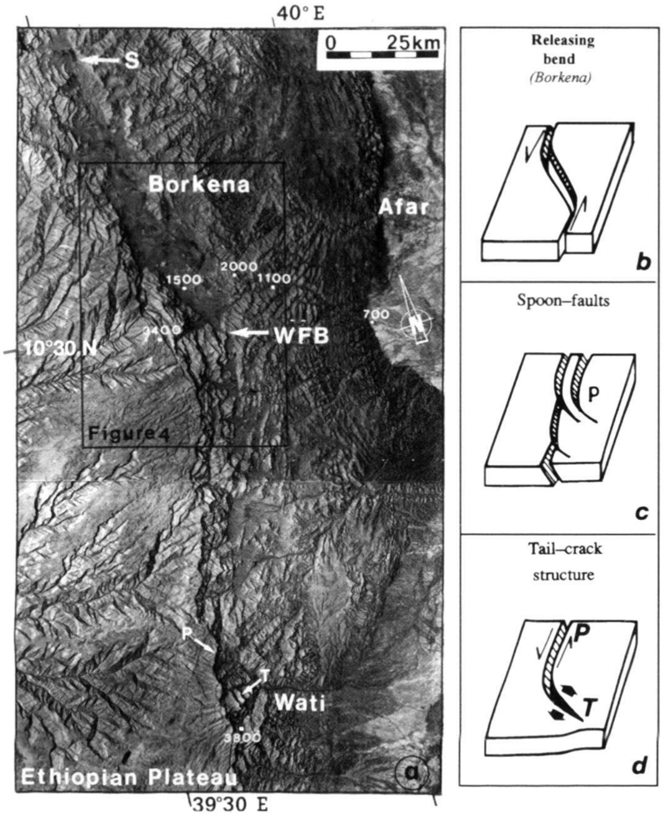

Fig. 3. (a) Mosaic of SAR ERS-1 scenes, acquired 29/06/93, covering the southwestern margin of the Afar and the Borkena graben. Abbreviations: P, first-order fault; T, second-order fault. (b) Sinistral releasing bend opening that initialised the pre-basin. (c) Spoon-fault arrangement. (d) Tail-crack model.

(~500 km long, ~60 km wide) blocks. This line commences in the vicinity of the Ethiopian rift in the south and continues to the Gulf of Zula in the north (Fig. 1b). These marginal basins, bordered on the east by elongated blocks, have not been considered in the previous models explaining the initial Afar opening by simple motion of the Danakil block.

SAR ERS analysis

Radar imagery is an appropriate mean for observing landforms and neotectonic structures (Chorowicz et al. 1995). We have used SAR ERS-1 (Synthetic Aperture Radar, European Remote Sensing Satellite number 1) scenes (Fig. 3a) to analyse the geometry of the Borkena basin. Radar beams light the scene from ESE with an angle of 23°E to the vertical. The image is shown in negative to emphasise structures. The analysis was performed at 1:250,000 with 25 m pixel size. The morphologic surfaces facing the illumination appear dark, those facing away are bright. The radar illumination creates a foreshortening effect (relief distortion) which sometimes creates a false impression of dipping planes, as can be observed at the foot of the Ethiopian Plateau where the slope is darker because it is steeper. A series of thin upright curved banks can be seen there. They seem to be subvertical or dip W. In reality, geological cross-sections (Zanettin et al. 1978) show that layers dip towards the Afar.

From west to east, the SAR image features the edge of the Northwestern Ethiopian Plateau, the escarpment zone [narrow in the south and wide in the north] and the Afar plain. The N160°E-trending Borkena basin is part of the escarpment zone. This graben is bordered along its western side by E-fac-

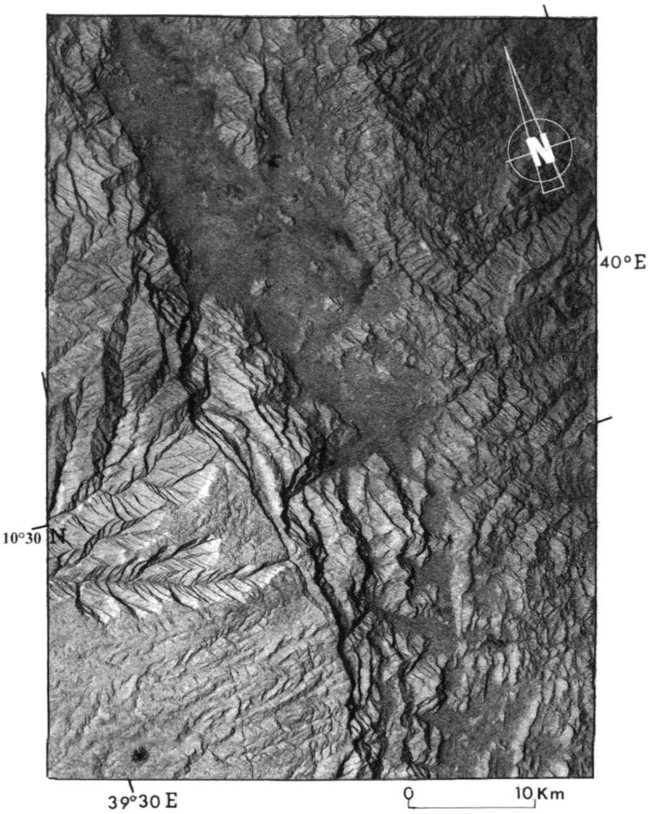

Fig. 4. Window of the SAR ERS-1 image of the Borkena basin (see frame in Fig. 3a).

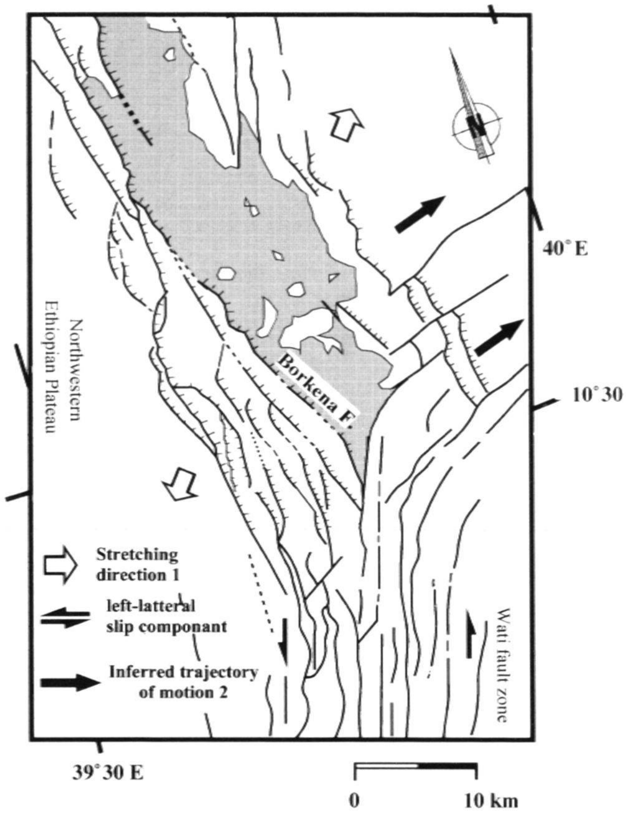

Fig. 5. Structural interpretation of Fig. 4.

ing N160°E-striking fault scarps across which the elevation drops ~2000 m. These faults progressively connect southward with others oriented N20°E which we term the Wati fault zone (e.g., P). Some faults of this system show a curved southward termination. The geometric pattern is that of successive spoon-shaped faults (P in Fig. 3c). Similar second-order faults (T) end on the Wati volcano (Figs. 3a and d). We interpret that T-faults terminate as open fissures from which lava was extruded. In this model the volcano is rooted at the end of a fault that opened in a tail-crack fashion (Fig. 3d). The geometry of this tail-crack feature and of the spoon-shaped faults imply a component of sinistral slip along the Wati fault zone.

The southern end of the Borkena basin is marked by the main scarp (WFZ in Fig. 3a) of the Wati fault zone, progressively connecting northward with the N160°E-trending eastern border of the basin. Similarly, the northern end of the basin is formed by a line of fault scarps (S) oriented N20°E, the same orientation as the Wati fault zone. The western escarpment of the basin connects with the (S) line. We interpret that the Borkena pre-basin was formed at releasing bend of the ~N20°E trending fault system (Fig. 3b). This interpretation is consistent with a component of sinistral slip along the Wati fault zone.

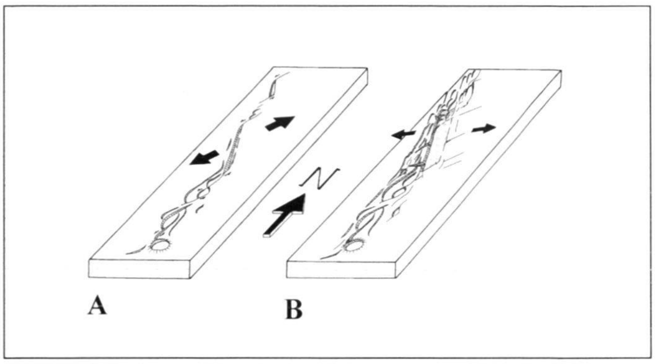

Fig. 6. Model of Borkena graben structuration A) Initial releasing bend with NNE direction of divergent motion. B) Enlargement of the graben due to the E-W extension

The Wati fault zone is the southern termination of the western Afar margin block and basin system. An enlargement of the radar image shows details of the area of termination (Figs. 4 and 5). The western escarpment is strongly faulted, with N160°E major faults including the Borkena fault. The

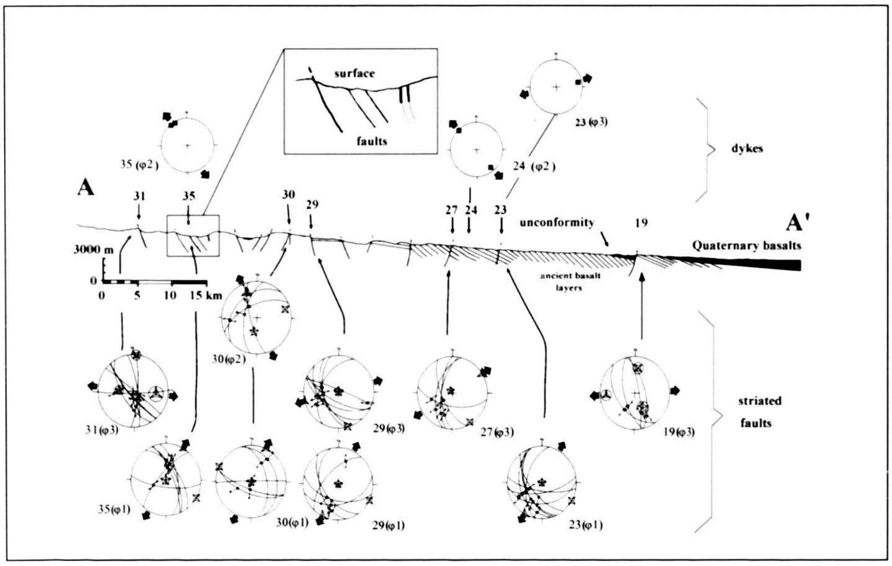

Fig. 7. Structural cross-section, located A A' in Fig. 1b. Fault traces (great circles) and striations (arrows) are plotted on Schmidt diagrams (lower hemisphere). Small black square is pole to dike plane and indicates divergent motion. Star is computed direction of σ1, quadrangle of σ2 and triangle of σ3. Numbers refer to sites of structural analysis. Thick arrows show the directions of extension.

faults face E and bound W-dipping tilted blocks of the Northwestern Ethiopian Plateau. The Borkena fault turns and connects with the Wati fault zone, forming the south corner of the basin. The eastern border of the basin is a stratigraphic contact but the eastern shoulder is bounded by smaller normal faults, dipping E, which define W-dipping tilted blocks. This geometry is that of an asymmetric basin, with the Borkena fault being the main detachment fault and the eastern basin shoulder the corresponding roll-over structure.

The faults in the northern part of the Wati fault zone turn eastward and cuts the normal faults of the eastern border, forming a transfer fault system. Such a structure is best interpreted assuming two tectonic stages. First N20°E-directed motion of the margin block along the sinistral strike-slip Wati fault zone opened the Borkena pre-basin at a releasing bend (Fig. 6a). This was followed by E-directed motion along the transfer faults inducing major extension in the basin (Fig. 6b). From the image of Fig. 3a, the perception is of 'foundering' of the margin block into the Afar, the transfer fault zone forming the southern limit of the block.

From this analysis of the satellite imagery, we have deduced a model of the deformation with two tectonic events. The model was tested by field data consisting of slip vectors along fault planes and orientation of dikes.

Fault-slip and dike kinematics

In the field, we have measured striated fault planes in volcanic rocks of late Cenozoic age, and the orientation of dikes. We assume that local extension direction is perpendicular to the dikes (Chorowicz et al. 1997; Korme et al. 1997). The microtectonic field data have been collected from 32 representative sites along the west Afar margin, especially along a cross-section normal to the margin (Figs. 7, 9B, 10B and 11B). Major (mapped) fault planes, if observed, are drawn as thick lines on diagrams. (1) If striations were measured on these major fault planes, on stereoplots the horizontal component of the movement coincides with the plunge direction of striations [shown as thick arrow]. Alternatively, (2) if the major fault plane is not exposed, the movement shown on diagrams is derived from smaller faults parallel to the major faults (shown as dashed line). (3) When the site in not located on a major fault, the local paleostress pattern is computed by inversion method and, in this case, used to characterize the local deformation. We discuss below how we have deciphered three different tectonic events.

Geomorphology is a good indicator of active faults. Poorly eroded major scarps attest that some large faults are still active (Fig. 8). The striations on their fault-surface testify to an E-directed motion (i.e., site 31, Fig. 7). We refer to deformation associated with these striations as the φ3-phase, the more recent one.

Geometric relationships between faults, dikes and eroded surfaces have been used to determine relative dating. For instance, along the border of the Afar depression, faulted Quaternary stratoid basalt (black in Fig. 7), dipping E02°E to E09°, overlies an erosion surface below which volcanic rocks dip E22°E to E45°E (lines on Fig. 7). This unconformity attests to at least two tectonic events. The last one (φ3-phase) is shown at site 19 where recent minor faults cutting the Quaternary basalt have striations trending SW and SE. This local deformation, after data inversion, is related to E-W minimum stress, attributed to φ3-phase. In another exemple, at site 35, faults and dikes pre-date the φ3 phase – the present day active phase – because do not displace the old erosion surface (inset in Fig. 7). Dikes are injected along pre-existing faults. These dikes imply a SE-trending divergent motion direction compatible with the φ2–phase. Striation elements along the preexisting

Fig. 8. Exemple of active fault. The Wati fault has a steep scarp and is active. View from the north. Location in Fig. 11.

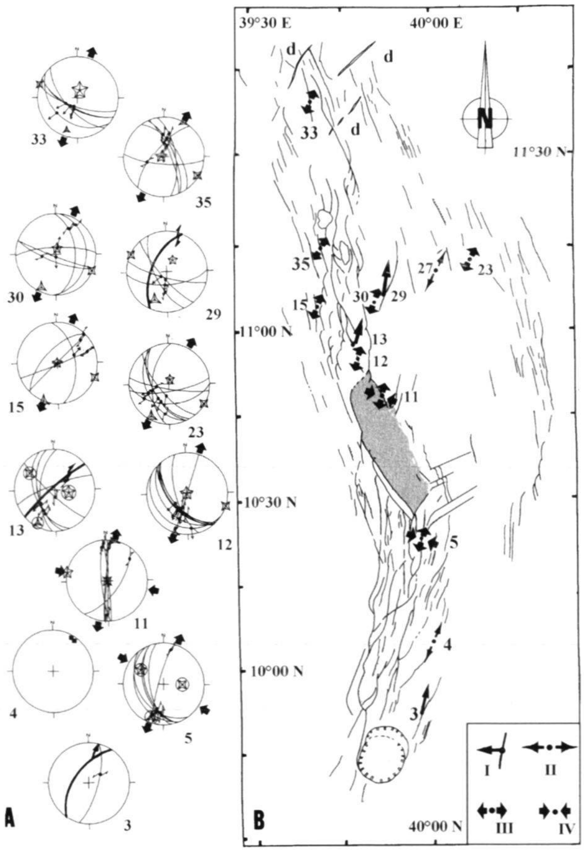

Fig. 9. The oldest tectonic event (φ1-phase). A Fault traces and striations were ploted on Schmidt diagrams. See legend in Fig. 7. Thick arrows show the direction of extension (divergent) or contraction (convergent). B. Fault map drawn from analysis of SAR ERS imagery complemented with analysis of Landsat-MSS images. Numbers are sites of structural analysis. In gray: the Borkena basin. d: dikes observed on Landsat images. I: horizontal projection of striations observed on major (mapped) fault. II: divergent motion direction from dikes. III: σ 3 direction. IV: σ 1 direction.

Table 1. List of tectonic indicators cutting each other and used for relative dating of tectonic events. Grey indicates older event. Measurements are sorted by sites and consist in dike dip and strike or fault orientation and striation pitch. All measurements – except site 35 – were taken along active scarps and the last tectonic indicators (striation or dike) were attributed to φ 3, the active tectonic event. Older -inactive- features were attributed to φ2 or φ1 on the basis of their compatibility with NW-trending (φ2) or N-trending (φ1) extension direction.

Site	Dike trend	Fault strike & dip and striation pitch	NNE-SSW 1	NW-SE 2	E-W 3
4	125 90		OLDER		
		15 E75 S86			ACTIVE
5		18 W66 N74		OLDER	
		18 W66 S74			ACTIVE
		00 W80 S70	OLDER		
		00 W80 N62			ACTIVE
6		32 W66 N84		OLDER	
		32 W66 S85			ACTIVE
7		139 NE 72 W35		OLDER	
		139 NE72 SE70			ACTIVE
11		145 SW48 SE26		OLDER	
	155 SW 65				ACTIVE
26	140 90		OLDER		
	015 W 60				ACTIVE
27	105 E 30		OLDER		
	170 W 70				ACTIVE
28	030 E 85			OLDER	
	155 W 75				ACTIVE
29		25 W58 N10	OLDER		
		25 W58 S44			ACTIVE
35		95 S75 W58	OLDER		
	060 90			MORE RECENT	

TABLE 1

faults and other compatible faults indicate NNE-motion which we interpret to be the earliest φ1 event (Table 1). At site 30, the erosion surface is also not displaced. Two sets of striated faults are consequently relatively ancient and have been attributed to φ1 and φ2 respectively. At site 23, a dike related to φ3 cuts the fault set which we assign to φ1 (NNE extension). At site 24, dikes leveled by an erosion surface yield SE-extension (φ2-phase).

Clear cross-cutting relationships of dikes and faults were also used for assigning features to the old, intermediate or recent tectonic phases (Table 1). We present two examples. (i) At site 29, two sets of striations were found on an active scarp. The more recent striations show E-NE directed motion (φ3), whereas the oldest (φ1) indicates N-NE motion. (ii) At site 27, small faults showing striations compatible with NE φ3 extension post-date an ancient (φ1) dike.

Where no other means of discrimination was possible, measurements of slip vectors were computed using the R4DT

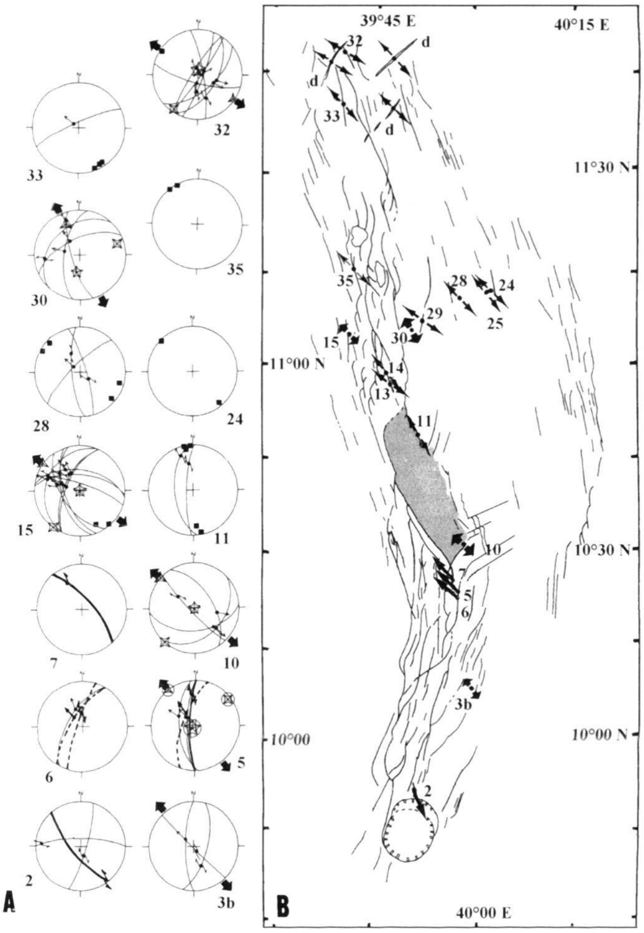

Fig. 10. The intermediate tectonic event (φ2-phase). Same explaination as Fig. 9.

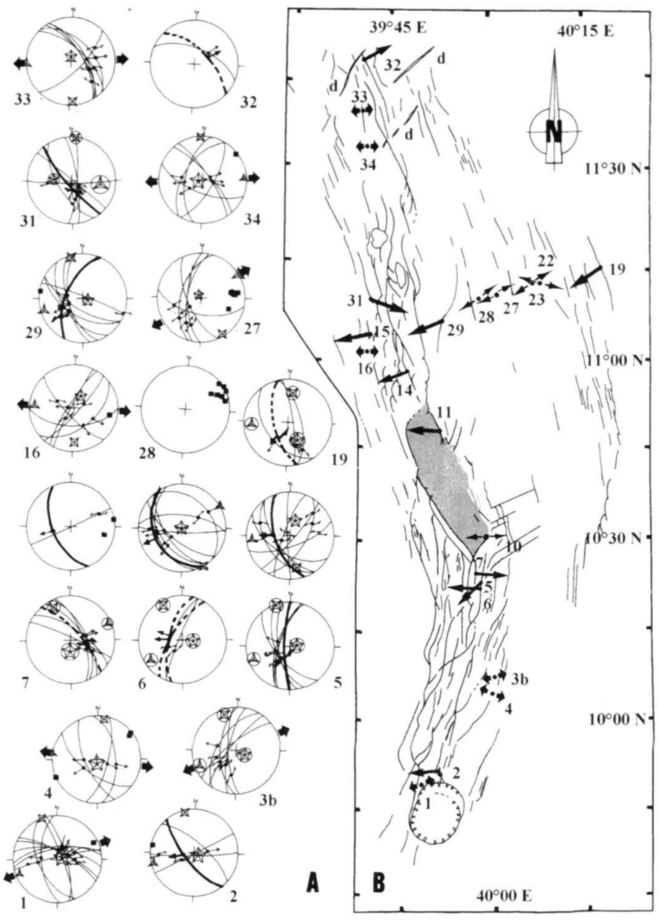

Fig. 11. The latest tectonic event (φ3-phase). Same explaination as Fig. 9.

Angelier's (1984) method to obtain the stress tensors. Only those values of slip vectors showing ANG parameter < 25 were accepted, and assumed compatible with one deformational phase. The other values (ANG parameter > 25) were computed again, and the new σ3 assumed to indicate another deformational phase.

Data were finally sorted into φ1-, φ2- and φ3-phases and plotted on Schmidt diagrams (Figs. 9A, 10A and 11A). Sense of motion on fault planes, divergent motion trends obtained from dike orientations and σ3 trends were drawn separately for each phase on a structural map made from our observations on the SAR ERS imagery completed by faults traces detected on Landsat-MSS images (Figs. 9B, 10B and 11B).

The results are coherent from one site to the next, and over the entire studied area. The model proposed above from interpretation of images (an oldest N20°-directed motion of the margin block along the sinistral strike-slip Wati fault zone, and a latest E-directed motion along the transfer faults) is consistent with interpretation of the field structural data. The N20°-directed motion is phase φ1, the E-directed motion is phase φ3 but a third SE-trending event (φ2) can be characterised. This event is not marked by geomorphic or tectonic features, except by the reactivation of some major faults and possibly tension fractures forming dikes noted on Landsat-MSS images (Fig. 10 B). For this event, we infer a regional diffuse strain related to the NW-SE extension in the Ethiopian rift. The latest tectonic event φ3 is also characterised by contemporary E-W extension of the Afar margin shown by the focal-mechanisms of earthquakes (Kebede & Kulhanek 1991).

Strike-slip and gravity tectonic model

The whole western Afar margin structure is similar to that of the Borkena basin, and we consequently interpret that the style of tectonics occurred along the entire margin. Using the DEM (Fig. 1b), we drew a model of the basins opening

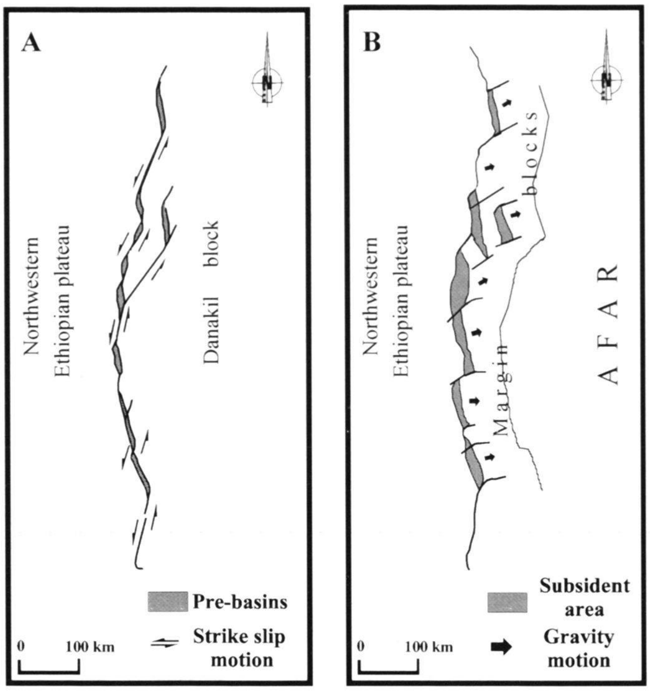

Fig. 12. Interpretation of the DEM of the west Afar margin of Fig. 1B. A) Initial left-lateral strike-slip NNE movement of the Danakil block. B) After opening of the Afar, gravity induced E-directed movement.

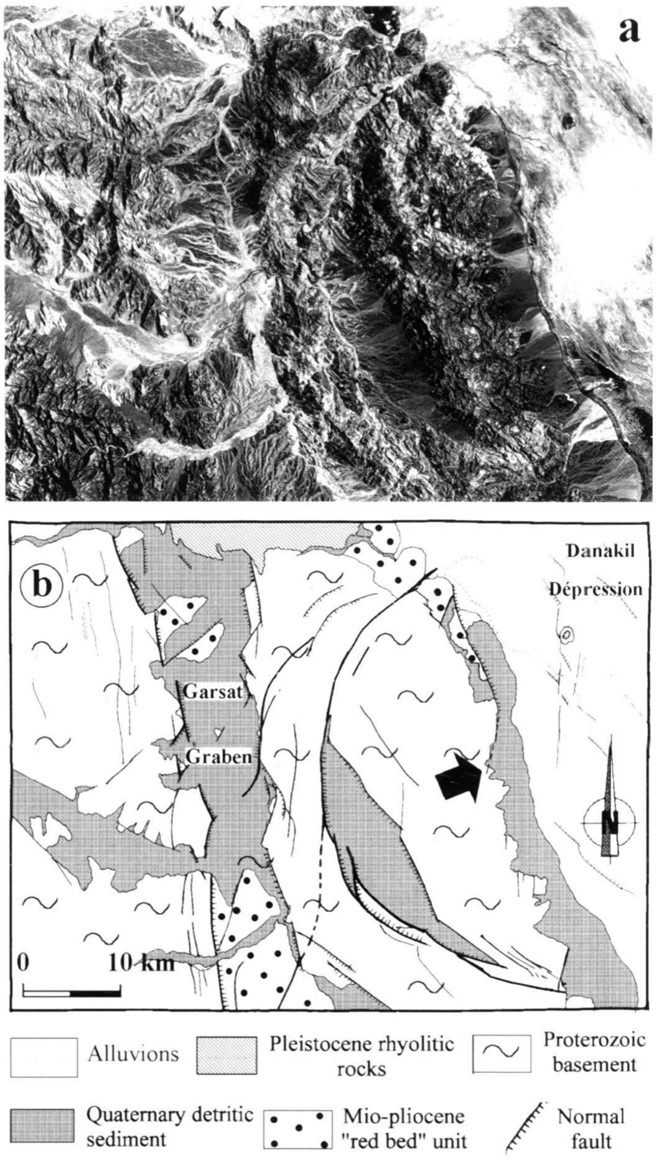

Fig. 13. Example of feature of gravity collapse tectonics in the northern part of west Afar margin. A) Combined 7, 4 and 2 Landsat-TM channels in RGB mode. B) Interpretative structural map.

(Fig. 12). The margin blocks first suffered left-lateral displacement relative to the Northwestern Ethiopian plateau, forming narrow releasing bend openings (Fig. 12A). After diffuse regional strain related to NW-SE extension in the Ethiopian Rift, motion was directed toward the Afar, parallel to transfer faults, and responsible for major basin formation (Fig. 12B). The transfer faults of the latest stage are not strictly parallel to each other, but motions remain more or less perpendicular to the different segments of the Ethiopian escarpment. This is consistent with crustal spreading over a ductile detachment in depth and related to important gravitational effect along the escarpment during the latest phase (Fig. 14a).

In the northern part of west Afar margin, a Landsat-TM image reveals a characteristic feature of gravity collaspe tectonics (Fig. 13). The fault bounded Garsat basin is partly filled with Pliocene-Quaternary sediments overlying reddish Mio-Pliocene rocks (Arkin et al. 1971; Kazmin 1976). To the east, inside the large block separating the Garsat graben from the Danakil depression, there is a smaller basin that is arcuate-shaped in plan view. Both ends of the basin are prolongated by arcuate-shaped normal faults which, together with the border of the small basin, form a spoon fault pattern. This geometry can be best explained admitting that motion of the large block toward the Afar is crustal spreading due to gravitational effect over a ductile detachment in depth.

A cross-section of the Afar margin in the Borkena region illustrates the structure at a crustal scale (Fig. 14a). The margin block is wide (60 km) and has a peculiar behavior. It is poorly faulted, except near its boundaries, and dips eastward, whereas the Ethiopian plateau dips west. To explain these observations, we interpret that an asymmetric continental pre-Afar rift formed in the Oligo-Miocene time (Fig. 14b) with in the west an E-dipping roll-over anticline affected by strike-slip faults and minor W-dipping faults, the major fault zone being in the east along the Danakil-Arabian side. Later, during the Afar Pliocene-Quaternary oceanisation, a large block collapsed from the Western Ethiopian plateau (Fig. 14c). Contin-

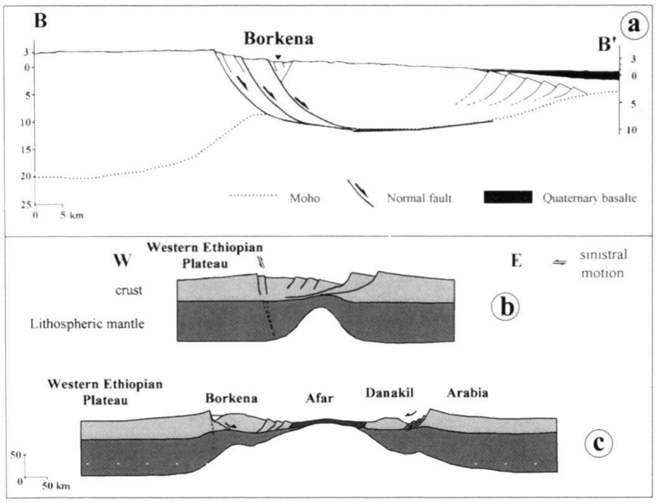

Fig. 14. Interpreted cross-sections. a) Cross-section at crust scale, located BB' in Fig. 1b. b) Initial stage opening model at lithospheric scale. c) Oceanisation of Afar, at lithospheric scale. Gravity induced motion of marginal blocks. Note vertical exaggeration.

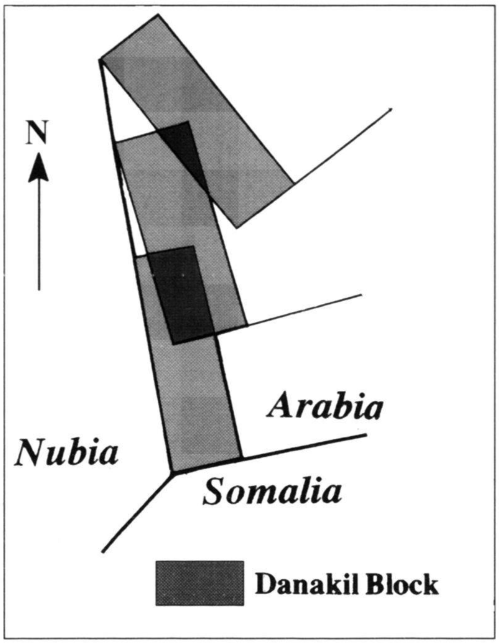

Fig. 15. Simplified model of the Danakil block undergoing rotation and left-lateral motion along the western Afar margin

uous rifting in the Afar thinned the lithosphere (Makris & Ginzburg 1987) and subsidence favoured E-directed gravity sliding of the downfaulted plateau margin along E-dipping detachment faults (Fig. 14a). This movement formed the Borkena basin. Lithospheric thinning under the Borkena basin may explain renewal of uplift and tilting to the west of the plateau margin. We imply that the Danakil block may have collapsed symmetrically along the eastern margin (Fig. 14c).

Our model has some similarities with models discussed by Lister et al. (1991) but in the western Afar margin the initiation of the opening is a left-lateral, NE-trending strike-slip motion. More importantly, the 'internal rift basin' of Lister et al. (1991) is supposed to subside permanently during the rift evolution whilst the Borkena basin was filled only at a late stage of the extensional process. Late age of the Borkena basin, postdating uplift of the Western Ethiopian plateau, is consistent with local gravity induced detachment.

In the East African rift system in general and also in the Ethiopian rift, Cenozoic extension reactivated Panafrican structures (Chorowicz 1988; Ebinger 1989). We consequently propose that both location of the pre-Afar rift and contemporaneous etching of the pre-basins along strike-slip faults were related to a zone of weakness in the crust which may be a suture zone (Collet & Chorowicz, submitted).

Conclusions

We interpret that left-lateral slip motion along the western Afar margin was responsible for initiating the Borkena protobasin in the releasing zone of en echelon NNE-striking oblique-slip faults. Because other basins formed to the north (Fig. 1b), left-lateral strike-slip movement must have affected the whole margin.

We infer that eruption of the Wati volcano occurred across a tail-crack at termination of a NNE-striking sinistral oblique-slip fault. The earlier ($\varphi 1$) strike-slip phase consequently occurred in early to mid-Miocene time when eruption of the Wati volcano started (Justin-Visentin et al. 1974). The NNE-directed sinistral strike-slip displacement along the margin operated on a regional scale (Abbate et al. 1995) and is compatible with N40°E divergence between Africa and Arabia in the early- and mid-Miocene, deduced from cinematic analysis by Jestin & Huchon (1992). Therefore, we invoke sinistral strike-slip as the initial motion of the Danakil block relative to Africa (Fig. 15).

The NW-SE trending extension event ($\varphi 2$) was a diffuse regional strain which fits with NW- to NNW-extension of the Ethiopian rift. We place this $\varphi 2$ event between late Miocene and Pliocene time.

In the Pliocene-Quaternary time, the enlargement of the Borkena basin is due to E-directed motion ($\varphi 3$-phase) deduced from the geometry of E-striking transfer faults and from sense of motion along Pliocene-Quaternary faults. This E-directed motion occurred only along the western Afar margin. In the central Afar, during this period, the direction of extension was NE to NNE (Tapponnier et al. 1990; Jestin & Huchon 1992). From the geometry of the structures in cross-section and maps we propose that gravity induced detachment of large blocks occurred along the escarpment zone. Large blocks of this size and shape are frequently found in passive margins (e.g., East Atlantic margins) or paleo-margins (e.g., the Briançonnais block in the Western Alps). Therefore, the western Afar escarpment zone can be regarded as the type-example of the individualisation of such blocks at continental break-up.

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