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NOTES ON THE AFAR TRIPLE JUNCTION

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The Red Sea, Gulf of Aden, and African rift systems meet at the Ethiopian Afar. The Afar depression is now widely agreed to be a neo-oceanic region, a part of the Red Sea–Gulf of Aden floor produced by drift of Arabia from Africa. Yet this simple hypothesis does not adequately account for some geological features of Afar and the bordering plateaus. Unexplained features include the following: the fact that most of Afar lies anomalously above sea level; the existence of the sialic horsts that separate Afar from the Red Sea and Gulf of Aden; the occurrence of sialic rocks in central Afar; the parallel development of spreading axes in the Red Sea and northern Afar (inconsistent with the transforming pattern of oceanic rifts); the pattern of intense surface faulting in Afar, which is peculiarly complex and displays large fault-belt virgations, bifurcations, and even intersections; the seismicity pattern, with most energy being released along the western margin of Afar; the gravity situation, which contrasts with that of the Red Sea. These facts, together with the strong extra-rift tectonics of the Ethiopian region, suggest that simple plate theory cannot be applied to this region. This is reinforced by the impossibility of fitting Arabia and Africa to the present spreading axes of the Red Sea and Gulf of Aden.

INTRODUCTION

The uniquely exposed occurrence of the Ethiopian Afar at a global tectonics triple junction is now well advertised [Tazieff, 1970]. However, the precise crustal, tectonic, and magmatic nature of Afar and the degree of relationship with the converging Red Sea, Gulf of Aden, and African rift systems remain disputed topics [see Laughton, 1966; Mohr, 1967; Roberts, 1969; Tazieff and Varet, 1969; Baker, 1970].

002-68

In this paper, some of the differing views on the tectonic significance of Afar will be discussed, and their effect on the interpretation of the region in terms of plate tectonics and sea-floor spreading. Some of the more important problems still awaiting resolution are also noted.

SITUATION OF AFAR

Figure 1 shows that while most of Afar lies above sea level, it is nevertheless a relatively depressed crustal region bounded by escarpments that mirror those of southwestern Arabia. The matching of these escarpments, together with the general matching of the opposing coastlines of the Red Sea and Gulf of Aden, has long attracted speculation on an original proximity of Arabia and Africa before continental drift [Wegener, 1912]. With the evidence that sea-floor spreading is operating in the Red Sea and Gulf of Aden [Vine, 1966; Phillips et al., 1969; Laughton et al., 1970], it has perhaps been inevitable that Afar is assumed to be neo-oceanic crust fortuitously exposed above sea level [Bullard, 1969; Tazieff and Varet, 1969; Tazieff, 1970]. Thus, no obstacle exists to southwest Arabia overlying the Afar region before drift.

The main boundaries of Afar can be defined morphologically. The meridional western margin with the Ethiopian plateau extends for 600 km, with vertical displacements exceeding 3000 m in places. This displacement has been effected by both downwarping and major faulting [Mohr, 1967]. The southern margin of Afar against the Somalian plateau is about 300 km long, with displacements reaching a maximum of some 1500 m. These two margins of Afar constitute direct continuations of the Red Sea and Gulf of Aden scarps, respectively, and are used in some predrift reconstructions of Arabia and Africa.

However, the Afar region also has morpho-tectonic boundaries to the northeast and east. These are formed, respectively, by the Danakil and Aisha horsts, which exclude the Red Sea and Gulf of Aden from direct entry into Afar (Figure 2). These two horsts, though lower in elevation than the main plateaus, expose plateau-type sialic rocks, and pose problems in any geometric reconstruction of Arabia-Africa. The Danakil horst is a block 500 by 70 km, with its long axis orientated NW-SE. The Aisha horst has the form of a crude equilateral triangle (with 200-km sides) and is contiguous with the Somalian plateau to the south. The Danakil and Aisha horsts are separated by the Gulf of Tajura, into which the midoceanic rift of the Gulf of Aden Sheba ridge penetrates [Roberts and Whitmarsh, 1969].

On a regional scale, the floor of Afar is monotonously flat and declines very gently from about 1000-m elevation in the south to -200 m in the northern apex. There is an ill-defined topographic step-up to the north of the Awash river in central Afar. In detail, the floor of Afar is exceedingly broken by belts of intense Quaternary faulting, accompanied by both basaltic and silicic volcanic piles.

NATURE OF THE RED SEA AND GULF OF ADEN

The coast-to-coast width of the Red Sea at latitude 16° N is 350 km. South of 16° N, this width decreases owing to the oblique situation of the Danakil horst, until at the southern end of the horst less than 30 km separates the African and Arabian coasts (see Figure 3). Before this narrowing is discussed, it is necessary to know the structure of the Red Sea in its normal development north of 16° N.

The work of Girdler [1958], Allan and Pisani [1966], and Knott et al. [1966] shows that the main trough of the Red Sea possesses broad shallow margins and also a deep axial (or central) trough. The central trough averages about 50-km width, and its floor may exceed 2000-m depth. Magnetic surveys over the central trough reveal lineations, which have been interpreted by Vine [1966] in terms of sea-floor spreading during the last 3 to 4 m. y. The central trough is also marked by high positive Bouguer gravity anomalies, which Girdler [1958] interprets as being due to basaltic injection between separating sialic plates. In later papers [e. g., Drake and Girdler, 1964], the same author gives cross sections that show continental sialic crust present under the whole width of the Red Sea, excepting only the Central trough. This view has recently been controverted by Tramontini and Davies [1969], who, from seismic refraction evidence that includes the data of Drake and Girdler [1964], interpret the entire width of the Red Sea as being underlain by basaltic and not continental crust. The work of Phillips et al. [1969] confirms that of Davies and Tramontini, and in terms of the drift of Arabia their results conform better with the nature of the Gulf of Aden.

The Gulf of Aden is entirely floored by oceanic crust [Laughton, 1966]. The mapped extent of the axial rift zone along the crest of the Sheba ridge, and its offsets along NE-SW transform faults, are fully confirmed by seismic epicenter distribution and by focal-plane solutions [Sykes and Landisman, 1964]. At its western end, the Gulf of Aden is 250 km wide, before an abrupt termination against the Aisha horst. The position of the rift in the western Gulf of Aden is strongly asymmetric, being displaced far north of the axis of the Gulf (Figure 3). The rift is prolonged into the Gulf of Tajura, but its continuation farther westward into Afar is in apparent contradiction to the NW-SE trend of intense surface faulting, though it follows a line of secondary volcanism features [Richard and Neumann van Padang, 1957].

The entirely oceanic nature of the Gulf of Aden floor is strong evidence for an original conjunction of Arabia and Africa, and a detailed knowledge of its structural elements, especially the transform faults, has enabled LePichon [1968] to employ a single pole of rotation for the opening of the northwestern Indian Ocean, the Gulf of Aden, and the Red Sea. While LePichon's assumptions on the number and boundaries of plates oversimplify his inductions, his thesis requires that Afar be included as a neo-oceanic region.

NATURE OF AFAR

Geophysical. Extensive gravity-survey work indicates that mean free-air and residual Bouguer anomalies are close to zero over Afar [Gouin, 1970a], which contrasts strongly with the Red Sea and Gulf of Aden

[Girdler, 1958]. Tazieff and Varet [1969, Figures 13 and 14] show the Salt Plain, the sub-sea-level region in the northern apex of Afar, as having a crustal structure identical with that of the Red Sea central trough, being a 50- to 60-km-wide zone of basaltic injection within sialic crust forming the remainder of Afar. Tazieff and Varet further consider that the Erta-ali and Alayta volcano-tectonic lines (Figure 4) are an en-echelon transposition of the Red Sea central trough south of latitude 15° N. (They specifically reject the possible presence of any transform faults.) But the gravity data fail to reveal the crustal-density contrast demanded by this hypothesis [Gouin, 1970a]. On the contrary, the regional absence of a strong positive gravity anomaly agrees with Wegener's [1929] observation that the elevation of most of Afar above sea-level points to the presence of sialic masses beneath the lava cover.

Regrettably, no seismic refraction data for the Afar region have been published, though work is in progress by West German UMC teams. Studies of surface-wave dispersion led Jones [1968] to suggest that the crustal structure of Afar is essentially continental.

Epicentral plots from teleseismic data show that the greater proportion of strain release in Afar is occurring along the western margin with the Ethiopian plateau [Gouin, 1970a]. No epicentral concentrations occur along the two volcano-tectonic lines mapped by Tazieff and his coworkers in northern Afar. A rather sparse number of epicenters in central Afar may be related to the northward extension of the Wonji fault belt from the main Ethiopian rift [Gouin, 1970a], though Fairhead and Girdler [1970] consider that recent epicenters (1965-1968) are aligned on a WSW projection of the Gulf of Tajura axis across Afar and intercept the Ethiopian plateau in the strongly seismic region of the Borkenna graben. However, the seismicity of this Afar marginal graben [Rogers, 1966; Mohr, 1967] is related to the meridional graben faulting subsequent to an initial alignment on WNW-ESE cross-rift faults [Gouin, 1970b].

By far the largest of recent Afar earthquakes occurred in the Sardo region of central Afar during spring 1969. This seismicity was centered on 12° N, 41°.25 E, and the highest magnitude was 6.2 for the April 5 shock. Gouin and Dakin [1970] observed the effects of oblique-slip movements along N40° W faults, the sense of shear being sinistral. Fracture lines running approximately E-W were also observed, a direction coinciding with an alignment of the major epicenters that released strain progressively eastward with time [Fairhead and Girdler, 1970]. Sinistral shear along NW-SE faults has occurred during the Quaternary in eastern Afar and the Danakil horst. Such shearing is not immediately reconcilable with the dilation of Afar as part of the Red Sea, though it does offer the possibility of an alternative cause for the formation of the en-echelon structures of northern Afar [Lensen, 1958].

An aeromagnetic survey of Afar [Girdler, 1970] suggests the presence of strong lineated anomalies of WSW-ENE trend in southern Afar, and rather weak NW-SE anomalies in northern Afar. This implies respective influence of the Gulf of Aden and Red Sea on the crustal structure of Afar, and Gibson [1970] presents a model that could explain the magnetic pattern in terms of asymmetric (unidirectional) crustal spreading. This interesting idea raises new problems: not only does the manner of dike injection into zones of asymmetric spreading need considering, but Gibson's model necessitates a northward migration of the Gulf of Aden spreading axis from original proximity with the Somalian plateau, across southern Afar. It is difficult to reconcile this thesis with the tectonics of Afar [Mohr, 1966]. The fault belts of southern and central Afar are so divergent from the trend of Girdler's magnetic anomalies as to suggest either that major uncoupling has occurred at the base of the crust or that the Afar magnetic anomalies do not reflect the results of spreading.

Stratigraphical. The geological succession in northern Afar, as established by Filjak et al. [1959] and Brinckmann and Kürsten [1970], can be summarized as follows:

Holocene	Afrera Series — conglomerates and sands, with lacustrine marls, clays, gypsum, and salt in the Salt Plain. Extensive lacustrine deposits in southern Afar.
	Basalt and silicic lavas and tuffs of the Aden series.
Pleistocene	Zariga Series — marine limestones, reefs, marls, sands, and conglomerates, with gypsum in Salt Plain.
	Extensive fissure basalts, and some alkali rhyolites and minor trachytes and related tuffs.
Tertiary	Danakil Series — marine sediments (upper part) lying upon lacustrine sediments (middle and lower parts), with intercalated basalt flows.
	Silicic lavas and syenitic intrusions in northern Afar and Danakil horst, and flood basalts of the Afar Series (3.4 to 25 m.y.) in central and eastern Afar.
	Upper Sandstone — regressive facies of sandstones, conglomerates, clays, and marls.
Mesozoic	Antalo Limestone — fossiliferous marine limestones and marls.
	Adigrat Sandstone — transgressive facies of sandstones, conglomerates, marls, and gypsum.
Pre-Cambrian and Lower Paleozoic	Phyllite Series — phyllites and a variety of low-grade schists, conglomerate, and quartzite, intruded by granites and granodiorites.
	The Phyllite Series is possibly unconformable on migmatic hornblende-biotite gneisses.

The pre-Tertiary rocks and especially the pre-Mesozoic rocks are the typical constituents of the sialic crust that forms the plateaus and at least portions of the Danakil and Aisha horsts. They have recently been confirmed as outcropping for 200 sq km in central Afar [Mohr, 1967; Brinckmann and Kürsten, 1970]. From the maps of Vinassa de Regny [1923], Filjak et al. [1959], and Brinckmann and Kürsten [1970], it is possible to show that, even assuming the pre-Tertiary rocks are bounded at the limits of their outcrop by vertical faults, the width of neo-oceanic 'Red Sea' crust is reduced from

350 km at 16° N (accepting the theory of Tramontini and Davies [1969]) to about 250 km at 14° N.

The studies of Holwerda and Hutchinson [1968] and Barberi et al. [1970] indicate the pre-Tertiary rocks to underlie a considerable proportion of the floor of northern Afar, thus according with the work of Jones [1968]. Tazieff and Varet [1969] consider that only the en-echelon volcanic lines of Erta-ali and Alayta lack underlying sialic crust in northern Afar, which would further reduce the maximum possible width of neo-oceanic 'Red Sea' crust at 14° N to 200 km. Yet Tazieff [1968, 1969, 1970] is emphatic that Afar is a neo-oceanic basin that structurally is merely part of the Red Sea: this argument seems to be inconsistent.

If the interpretation of Red Sea crustal structure made by Tramontini and Davies [1969] is correct, then Afar appears to have a singular stratigraphic character. Of course, if Girdler's original suggestion that the central trough represents the total dilation of the Red Sea proves valid, then the whole problem of the evolution of the Gulf of Aden and the significance of its NE-SW transform faults is reopened.

Structural. It is impossible to present in short compass a comprehensive picture of the violent structural deformation of Afar [Mohr, 1966, 1967]. Although warping and broad folding can be recognized in some localities, it is intense normal faulting that dominates the tectonics of the Afar floor. This floor faulting is largely of Pleistocene age, perhaps contemporaneous with an important uplift phase of the Arabo-Ethiopian swell.

The Afar floor faults are typically and notably concentrated in belts (Figure 5), which tend to maintain a single direction of upthrow (ratchet faulting), although horst-graben blocks are sometimes formed (the 'Clapham Junction faulting' of Gregory [1921]. There can be as many as 30 major faults within a belt 30 km wide, and as a typical hade is 70°, an appreciable amount of crustal extension and thinning is indicated: Baker (personal communication) estimates on this basis a total extension across central Afar of about 50 km.

The fault belts show a crude tendency to parallel the Red Sea structural trend in northern Afar, though major virgations and bifurcations occur south of Lake Julietti. In southern Afar the fault belts project NNE-ward from the opening out of the main Ethiopian rift to as far as Lake Abbe and are marked by Holocene graben and volcanism characteristic of the Ethiopian and Kenyan rifts. In eastern Afar, the fault belts trend between W-E and NW-SE, oblique to the Gulfs of Aden-Tajura trend (WSW-ENE), and in northeastern Afar annular faulting is superimposed on strong horst-graben development [Mohr, 1968].

It is difficult to reconcile the pattern of surface faulting in Afar with any crustal-spreading model so far proposed [e. g., Girdler, 1970; Gibson, 1970], unless there is significant uncoupling of crust from subcrustal processes, in which case the problem is merely removed a stage. But if the faulting has a connection with fundamental processes at depth, then it is hardly possible to envisage the large-scale virgations and annular faults as being directly related to typical midoceanic ridge-rift tectonism. Once again it is emphasized that the Afar region has some singular features that should preclude its facile inclusion in neo-oceanic hypotheses.

Turning brief attention to the structures of the Afar margins, Mohr [1967] has noted the interaction of warping and major Miocene-Pleistocene faulting in the depressing of Afar relative to the bordering plateaus. Tazieff [1968, 1969, 1970] denies the existence of marginal warping, perhaps because the role of warping is minimal in the region he has studied. Along the Afar-Ethiopian plateau margin, the degree of warping tends to increase southward, and warping continues into the main Ethiopian rift [Jepsen and Athearn, 1962; Abbate et al., 1968; Abbate and Sagri, 1969]. Warping has also been described from the Somalian plateau — Afar margin [e. g., Teilhard de Chardin, 1930].

The marginal downwarping of Afar is notably coincident with Tertiary floor basalt activity, an association Gibson [1966] considers to be a fundamental one. Marginal warping also occurs along the Gulf of Aden coast

[Azzaroli, 1958; Gass et al., 1965] and the Red Sea coast [Whiteman, 1968], though with only minor volumes of associated volcanics. Abundant dike swarms occur in the downwarped zones of Afar [Abbate et al., 1968], and their orientations have a complex pattern not immediately reconcilable with simple crustal spreading [Megrue and Mohr, 1970].

Rogers [1966] and Mohr [1967] have remarked on the occurrence of marginal graben within the downwarped zone bordering western Afar. These grabens owe their existence to antithetic faulting from a recent phase of crustal distension that is still continuing. The distension is generally E-W, which again is anomalous in the simple neo-oceanic model of Afar.

Finally, the disputed existence of cross-rift lineaments in Ethiopia [Mohr, 1967; Tazieff and Varet, 1969] is considered to be resolvable only on the basis of careful fieldwork and photogeological studies. The preliminary maps of Brinckmann and Kürsten [1970] confirm the existence of some but not all the cross faults indicated by Mohr [1966].

RELATIONSHIP OF AFAR TO THE RED SEA

The reiteration by many workers [e.g., Girdler, 1970; Gibson, 1970; Tazieff, 1970] that Afar, at least in its northern part, is merely a part of the Red Sea structure is tending to obscure some important and obdurate problems.

The Red Sea central trough begins to lose topographic expression south of about 15° N, though magnetic lineations have been mapped as continuing to latitude 14° N [Drake and Girdler, 1964]. In their study of the southern Red Sea volcanic islands, Gass et al. [1965] observed NW-SE fissures (gja) on the northerly islands of At Tayr and Zubayr, but NE-SW fissures on the southerly islands of Zuqur and Hanish (Figure 4). Therefore, despite the convergence of the Arabian and African coastlines at the south end of the Red Sea, the geophysical and volcanological evidence indicates that the Red Sea spreading axis continues at least as far south as 14° N. The Bab-el-Mandeb straits connecting the Red Sea with the Gulf of Aden lie on a further projection of this axis.

Tazieff and Varet [1969] emphasize that the presence of grabens and fissures (gja) along the active basaltic volcano-tectonic lines of northern Afar signifies active crustal tension. The same authors indicate an en-echelon transposition of the Red Sea spreading axis westward into northern Afar, ignoring the southward continuation of the magnetic lineations and volcanism in the Red Sea itself. No transform faults are said to be associated with this spreading-axis transposition [Tazieff and Varet, 1969, p. 435], yet the structures are propounded as neo-oceanic [Tazieff, 1970]. In this regard, it is noteworthy that the two NNW-SSE dilational zones of northern Afar are directly interconnected by strong NNE-SSW faulting [Mohr, 1966]. As emphasized previously, it is difficult to relate the pattern of faulting in Afar with any postulated sea-floor spreading process.

How then can we reconcile the known observations: (1) the parallel, side-by-side development of the Red Sea and northern Afar spreading axes (unless the Danakil horst lies on the line of a transform fault — see below); (2) the grossly asymmetric position of the Afar spreading axes between the African and Arabian plateaus; (3) the absence of transform faulting [Tazieff, 1968, 1969]; (4) the seismicity pattern of northern Afar [Gouin, 1970a], which reveals major energy release along the Ethiopian plateau—Afar margin and at the northern end of the Danakil horst, but not under the volcano-tectonic lines of northern Afar; (5) the known minimum amount of sialic crust in northern Afar (see previously).

First, let us consider the possibility that south of latitude 16° N, the spreading rate at the Red Sea axis decreases in proportion to the coastal narrowing. Such a phenomenon could help explain the Danakil horst in terms of rotation of a detached sialic block, especially if a converse southward increase in spreading rate occurs along the Afar axes. Unfortunately for this hypothesis, the Danakil horst would have had to rotate across the spreading axes, presuming that the Yemen and Ethiopian plateau escarpments mark the limits of sialic crust. Also, if the Red Sea spreading rate declines southward, then the Arabian plate must be deformed in the Yemen region, either by grid shear faulting parallel to the direction of spreading or by a major rotational shear of Yemen focused near Bab-el-Mandeb. There is no evidence for either type of shearing.

If the Red Sea spreading rate increases southward right through to the Gulf of Aden [Phillips et al., 1969], then uncoupling between lithosphere and mantle processes must have occurred. It would be significant to seek any magnetic lineations on the Red Sea floor that project southeastward under the Danakil horst and Yemen.

The apparent side-by-side development of the Red Sea and Afar spreading axes poses a problem for the theory of transform faults. It is unlikely that the Danakil horst overlies a connecting transform fault, because the necessary spreading directions (N45° W and S45° E) are inconsistent with the magnetic lineation orientations as given by Drake and Girdler [1964] and Girdler [1970]. If it is assumed that the Red Sea and Afar spreading rates, where in conjunction, total that of the Red Sea central trough north of 16° N, then no distortion of the continental-plate margins is required. But the two axes must have been pushing apart from each other since their inception, there being no trench feature associated with the Danakil horst. If the floor of Afar and the Red Sea shelves is neo-oceanic, then the two axes were once proximate with the Danakil horst margins, about 80 km apart. This hypothesis necessitates the existence of transform faults limiting the conjunction zone to north and south but still fails to explain the oblique position of the Danakil horst across the trend of the spreading axes.

There seem to be only two ways to escape the dilemma of Afar's structural relations with the Red Sea and at the same time to retain the validity of the hypothesis of sea-floor spreading in this region. The first necessitates that sialic crust underlies all except the Red Sea central trough and Afar volcano-tectonic lines. This would require a much later initiation of spreading in the Red Sea compared with the Gulf of Aden, despite their concurrent evolution in other respects [Laughton, 1966]. And the significance of the Danakil horst remains unexplained.

The second possibility is one of lithosphere-mantle uncoupling on a rather large scale. Uncoupling could explain the nonparallelism of the Red Sea axis and the Yemen plateau, assuming the whole width of the Red Sea is basaltic crust. The presumed rotation of the Danakil horst would require a degree of lithosphere uncoupling that increases to 100% at the spreading-line terminations. Uncoupling might also explain the highly asymmetric position of the western Gulf of Aden spreading axis [Laughton, 1966] and would do away with the necessity of invoking asymmetric sea-floor spreading [Gibson, 1970]. But although uncoupling has also been invoked for the development of other rift systems [Illies, 1969], there is as yet no direct evidence for it.

AFAR AND PLATE TECTONICS

Gass and Gibson [1969] have attempted to analyze the Afro-Arabian rift system in terms of plate rotations about the pole (26° N, 21° E) established from the Gulf of Aden transform faults [LePichon, 1968]. This pole fits well for the opening of the northwest Indian Ocean, and of course the Gulf of Aden, but is less satisfactory for the Red Sea and Jordan rift. On this thesis, the Ethiopian rift is essentially a shear zone separating the Nubian and Somalian blocks, though as this rift is not an arc focused on the rotation pole, some dilation from a northeastward movement of Somalia is also likely [Baker, 1969].

Afar can be considered as the junction of a three-rift, three-plate, three-pole system [Roberts, 1969; McKenzie, 1970]. Large problems enter, however, when the analysis is logically extended to the African rift system as a whole. This is not the place for such an analysis, but it can be noted that the Ethiopian rift is floored with Precambrian gneisses south of Lake Chamo (latitude 5.5 to 6°N). This and other evidence preclude a whole-width crustal dilation of the main Ethiopian rift.

Estimates of dilation rates for the Rhine and Kenya rifts are of the order of 0.1 cm/yr [Illies, 1967; Baker, personal communication], which is also probable for the Baikal rift [Lamakin, 1968]. The newly established precise geodetic traverse across the main Ethiopian rift will, it is hoped, give more certain values within the next few years. But unless there is uncoupling of the crust from underlying oceanic-rate processes, the much slower opening rates of continental rifts indicate they are being formed by causes different from those of oceanic rifts. It is of course to be expected that the initial breakup of a continental plate, with its thick crust, will modify the processes observed on the midoceanic ridges, yet there are differences that appear to be outside the scope of mere modification.

Longitudinal transcurrent faulting has been described from the Jordan rift [Quennell, 1959], the Rhine graben [Bederke, 1966], the Baikal rift [Lamakin, 1968], and possible equivalents in the Ethiopian rift [Mohr, 1967]. In the Ethiopian region, there are numerous active or recently active volcano-tectonic lines that lie outside the rift itself: For example, the Omo valley faulting, the Lake Tana rift, the Sudan boundary faulting along the western limit of the Ethiopian plateau, and various lines on the Somalian plateau. In almost all cases, these extra-rift fault zones run SSW-NNE, parallel to the main rift. Along one of them, the 1966 Jebel Dumbeir earthquakes of central Sudan produced sinistral ground shear [Qureshi and Sadig, 1967], which is suspected to be typical of major SSW-NNE faults in the Ethiopian region. Therefore, even if continental rifts can be equated with oceanic rifts as marking lines of crustal spreading, there are additional factors of longitudinal shearing, slower dilation, and the continuing deformation within the bordering plates to be considered.

In Afar itself, the existence of two sialic horsts and the outcrop of sialic rocks on the floor of the depression add difficulties to the detailed analysis of this region in terms of plate boundaries and processes [Mohr, 1970]. It is immediately evident (Figures 2 and 3) that Arabia cannot be fitted against Africa without overriding several spreading axes, even on the assumption that Afar is neo-oceanic. Until further information is available on the crustal nature of Afar and the Red Sea shelves, on the significance of the sialic horsts, on the movements producing the main Ethiopian rift, and on the significance of plateau seismicity and tectonics, it would perhaps be prudent to refrain from claiming Afar as an exposed region of typical neo-oceanic crust.

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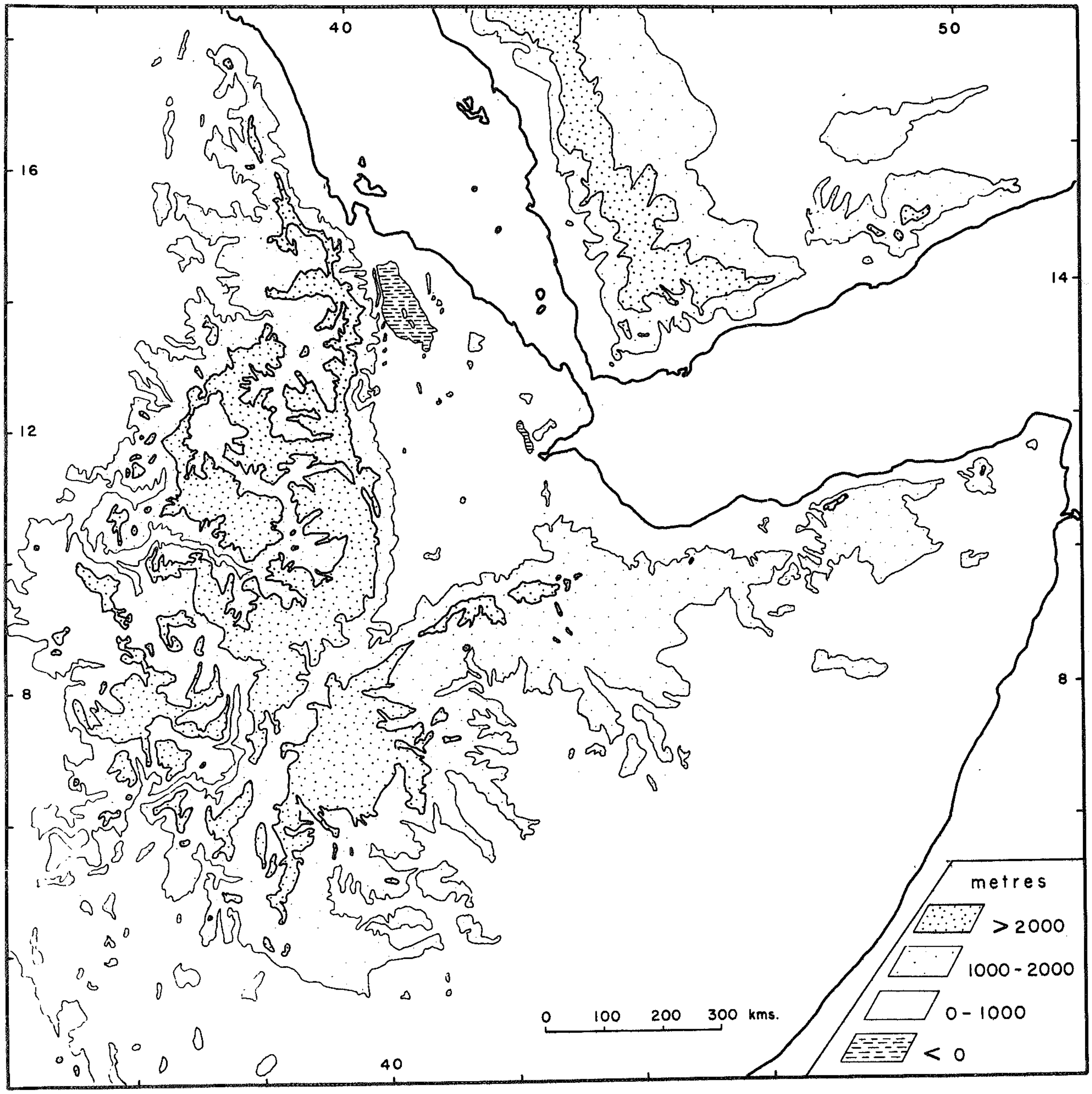

Fig. 1. Outline physiography of the Horn of Africa and southwest Arabia.

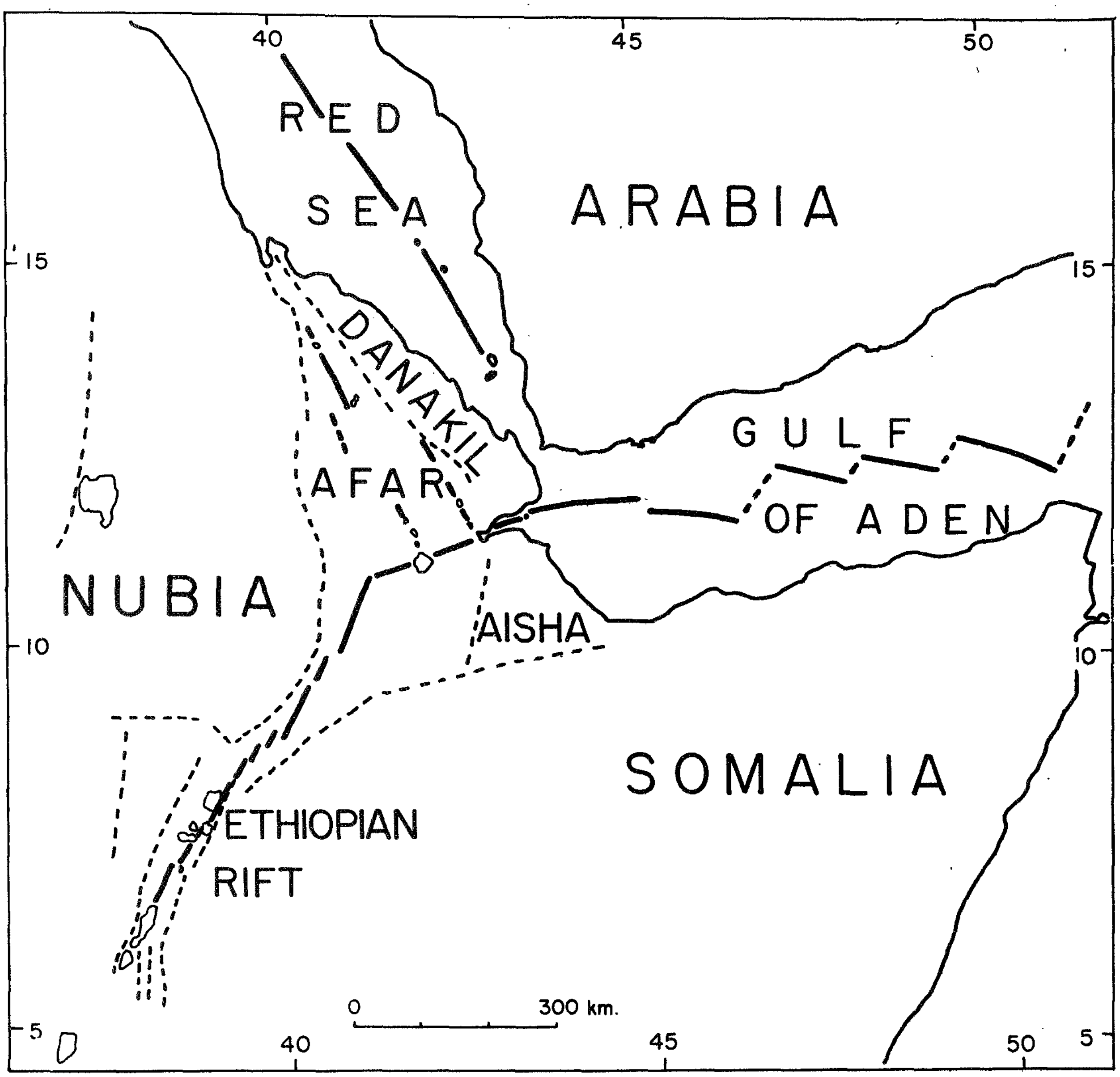

Fig. 2. Schematic representation of main crustal units and crustal spreading lines in Afar and neighboring regions.

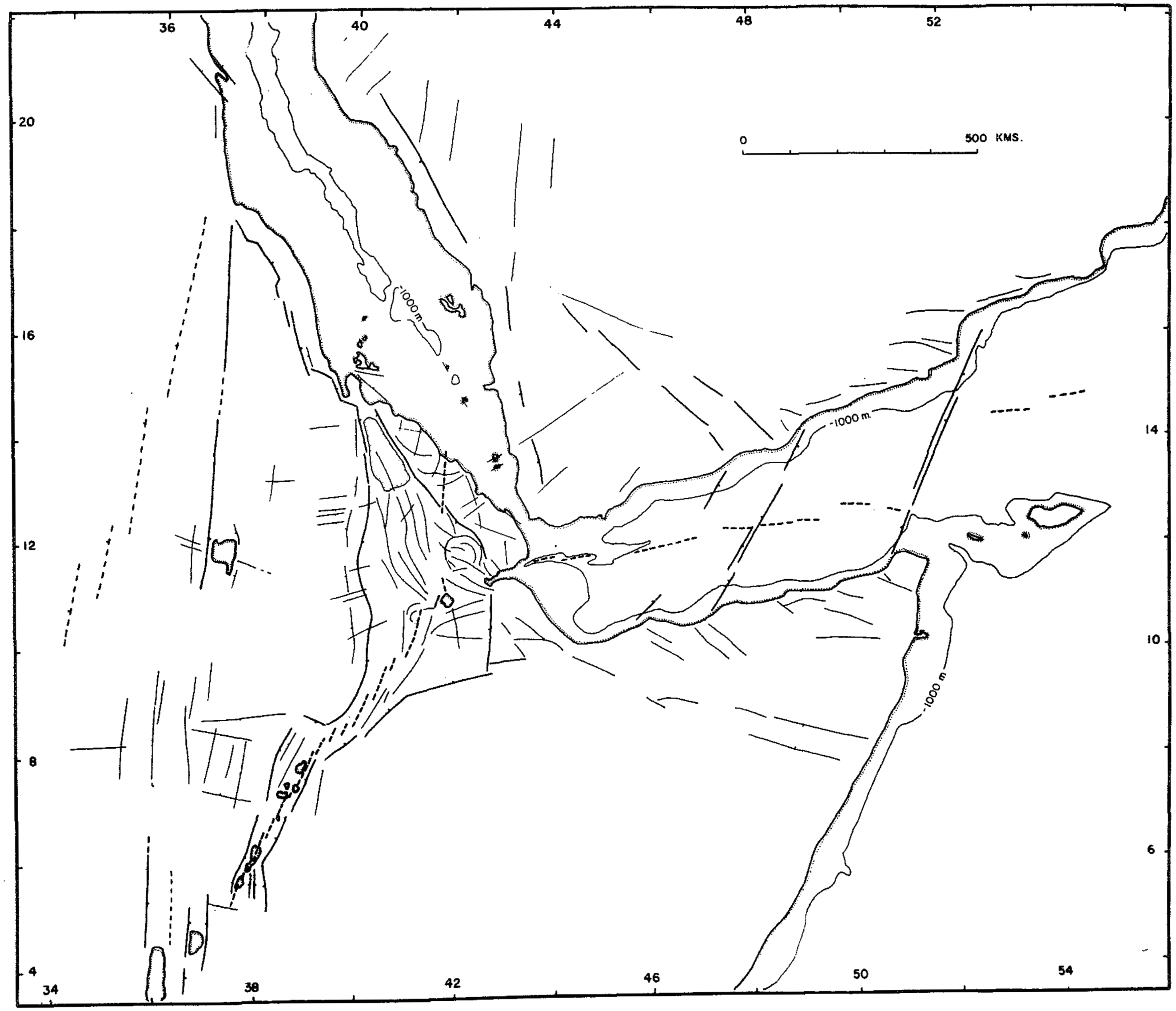

Fig. 3. Tectonic map of Horn of Africa and southwest Arabia showing major fault zones. The 1000-m depth contour for the ocean is also shown.

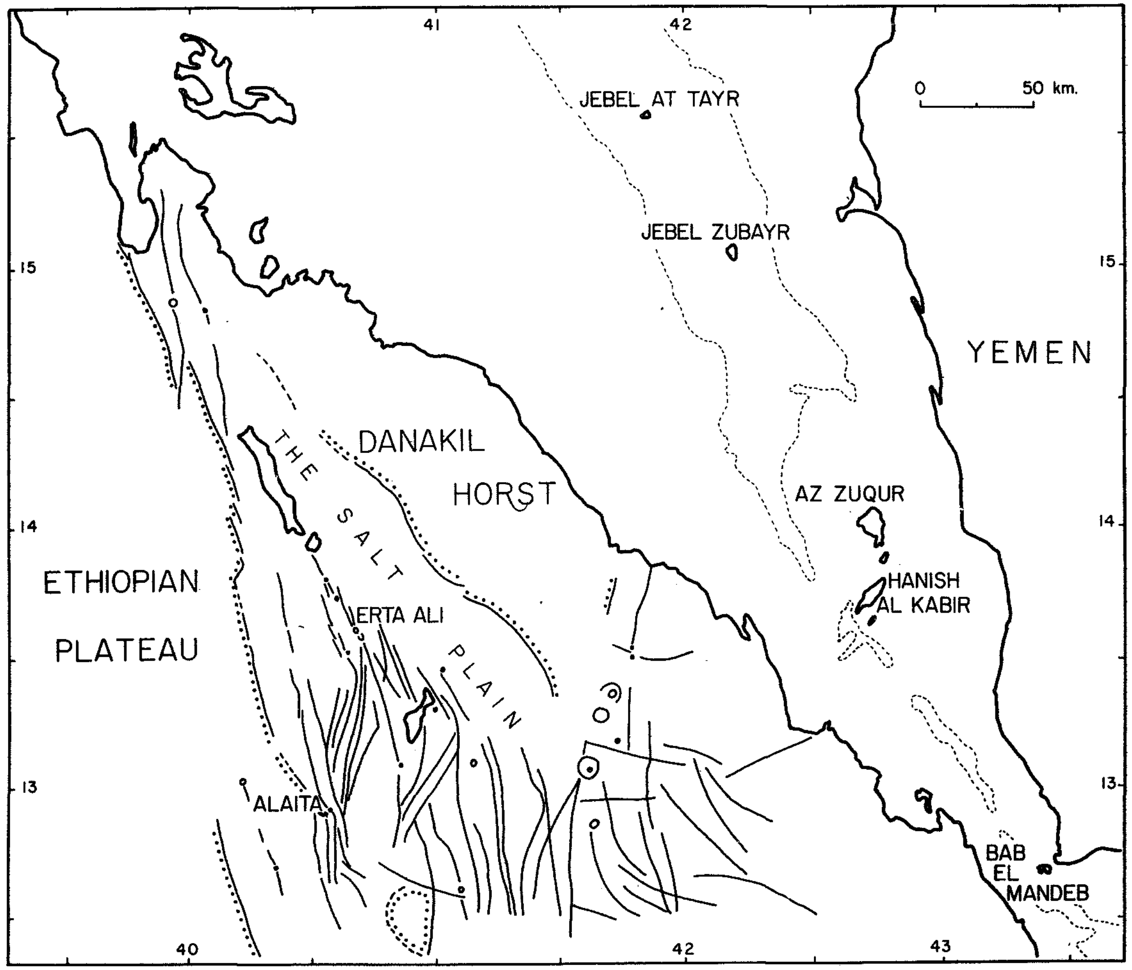

Fig. 4. Map of northern Afar and southern Red Sea area. Major fault belts of Afar are shown schematically (after Mohr [1966]), together with significant volcanic craters and calderas. The lines backed by dots mark the exposed limit of sialic continental rocks. The two large lakes in the Salt Plain are Alel Bad (Lake Assale) and Egoji Bad (Lake Julietti), in the north and south, respectively. In the Red Sea the 200-m depth line is indicated.

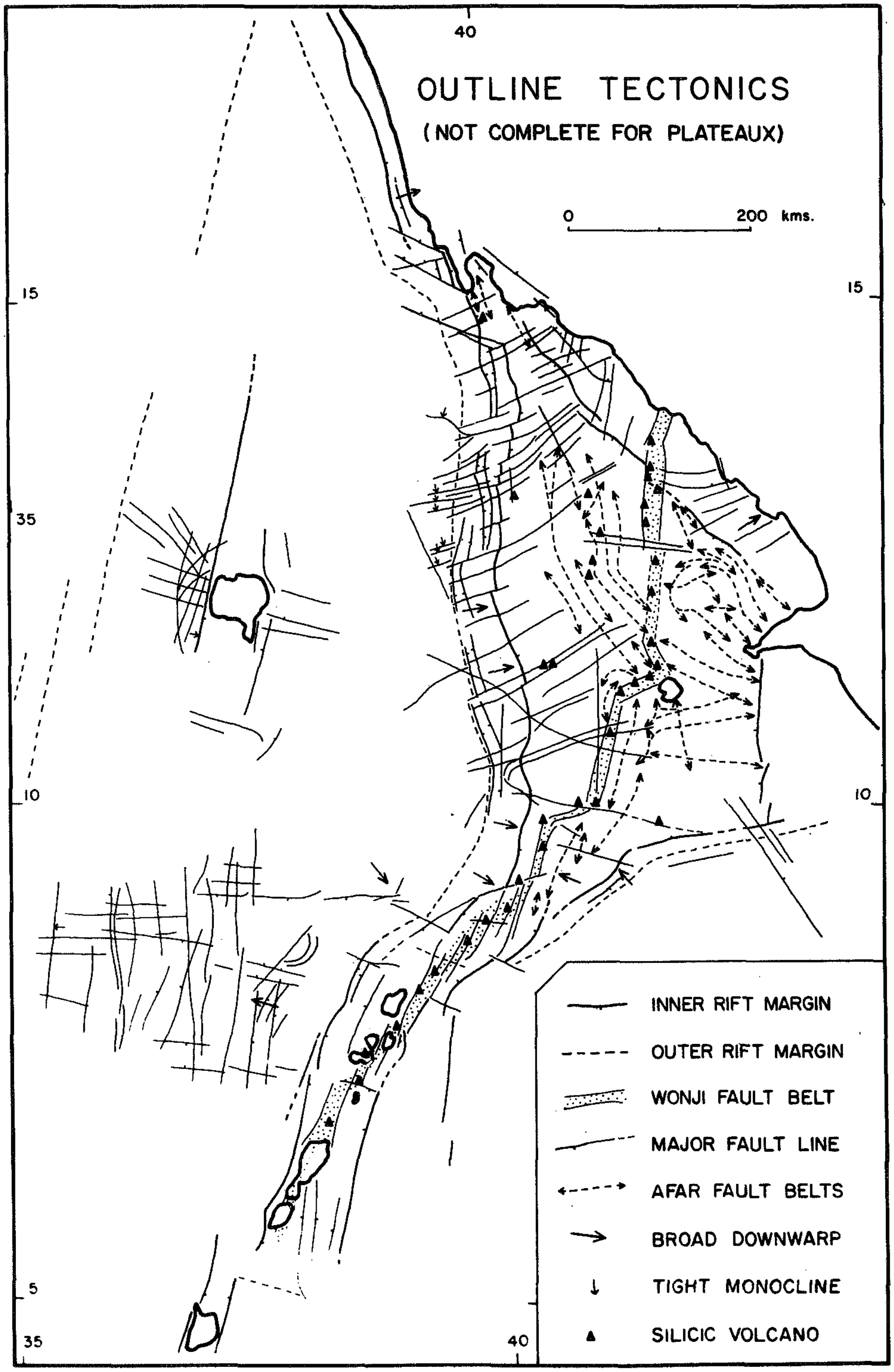

Fig. 5. Outline tectonic map showing the relationship of the main Ethiopian rift with Afar.