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BLOCK ROTATION AND CONTINENTAL EXTENSION IN AFAR: A COMPARISON TO OCEANIC MICROPLATE SYSTEMS

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Abstract. The reorganization of oceanic spreading centers separating major plates often appears to occur by a process in which discrete microplates form and evolve by rift propagation. To see whether such microplate behavior has implications for continental rifting, we investigate the application of a microplate model to the Afar region at the Nubia-Somalia-Arabia triple junction. Studies of marine magnetic anomalies, volcanic ages, bathymetry, and seismicity suggest that the westward propagating Gulf of Aden spreading center has propagated into eastern Afar within the past 2 m.y., causing rifting and extension within the continent. We derive constraints on the extension history from the geometry and timing of rift formation and from paleomagnetic data indicating that Pliocene to Pleistocene age rocks have undergone a clockwise rotation of ~11°. We suggest that the history of rifting, the rotation, and several other features of the regional geology can be described by combining features of an oceanic microplate model and the concept of rift localization previously proposed for Afar. In this scenario, motion occurring on several rifts within an extensional zone preceding the propagating spreading center is gradually transferred to a single rift. While motion is transferred, the overlap region between the growing and dying rifts acts as one or more microplates or blocks that rotate relative to the surrounding major plates. The rifting history and rotations in eastern Afar are thus related to the rift propagation and localization that occurs as the plate boundary evolves. Provided the constraints we use are appropriate, our model better describes the regional kinematics than alternative block models including one based on "bookshelf" faulting. If the tectonics of Afar are typical for continental breakup, they have interesting implications for the geometry of passive margins. In particular, asymmetric rifted margins can be produced if the final location of the rift axis is not at the center of the zone of initially disrupted lithosphere. Additionally, if the rate of rift propagation and the rate and location of rift localization are not uniform, then along-axis structural variations will result.

INTRODUCTION

The boundaries between major lithospheric plates often contain smaller regions that move relative to the surrounding plates while sustaining little or no internal deformation. These regions can thus be modeled as rigid blocks or microplates, whose motions are described by rotations about Euler poles in keeping with rigid plate tectonics. Such microplates, typically with areas >1000 km^2, occur along oceanic spreading centers. In oceanic lithosphere, microplate boundaries can be identified and the formation, growth, and motion of microplates can be studied using magnetic anomalies, seismicity, and bathymetry. Data of these types from along the East Pacific Rise near Easter Island and at the Pacific-Nazca-Antarctic triple junction are described well by microplate models [Engeln and Stein, 1984; Anderson-Fontana et al., 1986; Francheteau et al., 1987; Engeln et al., 1988; Naar and Hey, 1989; Searle et al., 1989]. Similarly,

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the Mesozoic and Cenozoic magnetic anomaly record in parts of the Pacific and Indian basins indicate fossil microplate systems [Tamaki and Larson, 1988; Mammerickx et al., 1988; Fullerton et al., 1989]. These microplates are commonly located between conjugate spreading centers and are associated with fan-shaped magnetic anomalies, which suggest that the microplates have rotated about nearby Euler poles.

The situation for continental plate boundaries is more complicated. In oceanic lithosphere, plate boundaries are typically fairly narrow and microplates are sparse. In contrast, continental plate boundaries are typically broader zones and rigid blocks are more common. By comparison with the oceanic case, the boundaries between blocks are less distinct and more difficult to identify. Nonetheless, the blocks can be identified from differential rotations and translations observed in paleomagnetic or geodetic data and block boundaries can be mapped structurally. Block rotations about nearby poles have been observed for a variety of continental boundary regions including extensional zones such as the Basin and Range and the Rio Grande Rift [Brown and Golombek, 1985; Ron et al., 1986; Hudson and Geissman, 1987; Li et al., 1990; Hagstrum and Gans, 1989], diffuse continental transform zones such as the Dead Sea transform zone or the San Andreas transform zone in southern California [Kamerling and Luyendyk, 1979; Luyendyk et al., 1980; Ron et al., 1984, Terres and Luyendyk, 1985; Luyendyk et al., 1985; Hornafius et al., 1986; Nur and Ron, 1987; Ron, 1987], and continental collision zones such as between India and Asia [Klootwijk and Conaghan, 1979; Achache et al., 1984].

In both continental and oceanic applications, microplates or blocks are used in describing the kinematic evolution of a region. "Microplates" or "blocks" are, of course, alternative names for regions which are assumed to act essentially rigidly. As for the plate tectonics of larger plates, this kinematic characterization is based on the idea that most relative motion occurs between essentially rigid regions. Similarly, since the models describe near-surface observations of relative motions, they are insensitive to whether "microplates" extend to the asthenosphere or represent detached crustal "blocks." Such models thus provide only indirect, though valuable, constraints on the dynamics of the plate boundary.

Our goal in this paper is to test the applicability of microplate models to the Afar region. Afar provides an excellent test case for such models, in that the rift geometry and history can be constrained by the morphology, geology, and regional tectonics while the rotation can be constrained by paleomagnetic data. Though the geologic and tectonic setting in eastern Afar differs from that along seafloor spreading centers, we suggest that the kinematics are similar.

We first review the oceanic microplate model and the relevant geological and geophysical data for Afar. We use these data to constrain two microplate models for Afar and discuss their similarity to oceanic microplate models. We then compare the predictions of our models for Afar to those of alternative models. Finally, we discuss the implications of our models for the geometry of passive margins.

OCEANIC MICROPLATE SYSTEMS

The basic microplate model we apply describes the kinematics of a region between major plates that grows as the spreading center geometry evolves by rift propagation. As discussed above, similar microplate models have been successfully applied to a number of oceanic regions. To illustrate a simple model of microplate formation by rift propagation, consider (Figure 1) a rift which begins to propagate from a ridge-transform-ridge configuration. If spreading is instantaneously transferred from the dying ridge to the propagating ridge, the ridges are connected by a migrating transform [Hey, 1977]. In contrast, if a finite time is required to transfer motion from the dying ridge to the propagating ridge, an overlap region forms between the two simultaneously active ridges, along which the spreading rates vary. The resulting kinematics depend on the behavior of the overlap region [Hey et al., 1980; Engeln and Stein, 1984; McKenzie, 1986; Engeln et al., 1988]. In a microplate model, the overlap region acts rigidly and thus moves relative to the surrounding major plates (Figure 1). As a result of the propagation, lithosphere is transferred from one major plate onto the microplate. Because the Euler pole describing the relative motion of the major plates is generally far away, and because of the rapid variation in the spreading rate that is apparent along the dual spreading centers, the Euler poles describing the motion of the microplate relative to the other plates are nearby [Engeln et al., 1988], and the microplate rotates. As propagation continues, the original transform fault becomes leaky and starts to spread slowly while the boundary connecting the propagating rift tip to the dying ridge migrates with the tip and, depending on its geometric configuration, may experience compression.

The results of this process are shown by the magnetic anomalies and structures produced and rotated during the microplate's evolution. These lineations, within the microplate and in lithosphere that has been transferred from the microplate to the second major plate, are oblique to the plate boundaries. Of particular interest in interpreting the kinematics of such systems are the magnetic anomalies and tectonic fabric from the two ridges, which fan in opposite directions as a result of the variation in spreading rate and length of spreading history along each ridge.

REGIONAL SETTING OF AFAR

Given the success of microplate models in describing the tectonics and evolution of changing plate geometries along mid-ocean ridges, our goal here is to test whether similar models can be usefully applied to continental rifting. We consider the Afar region at the triple junction between the

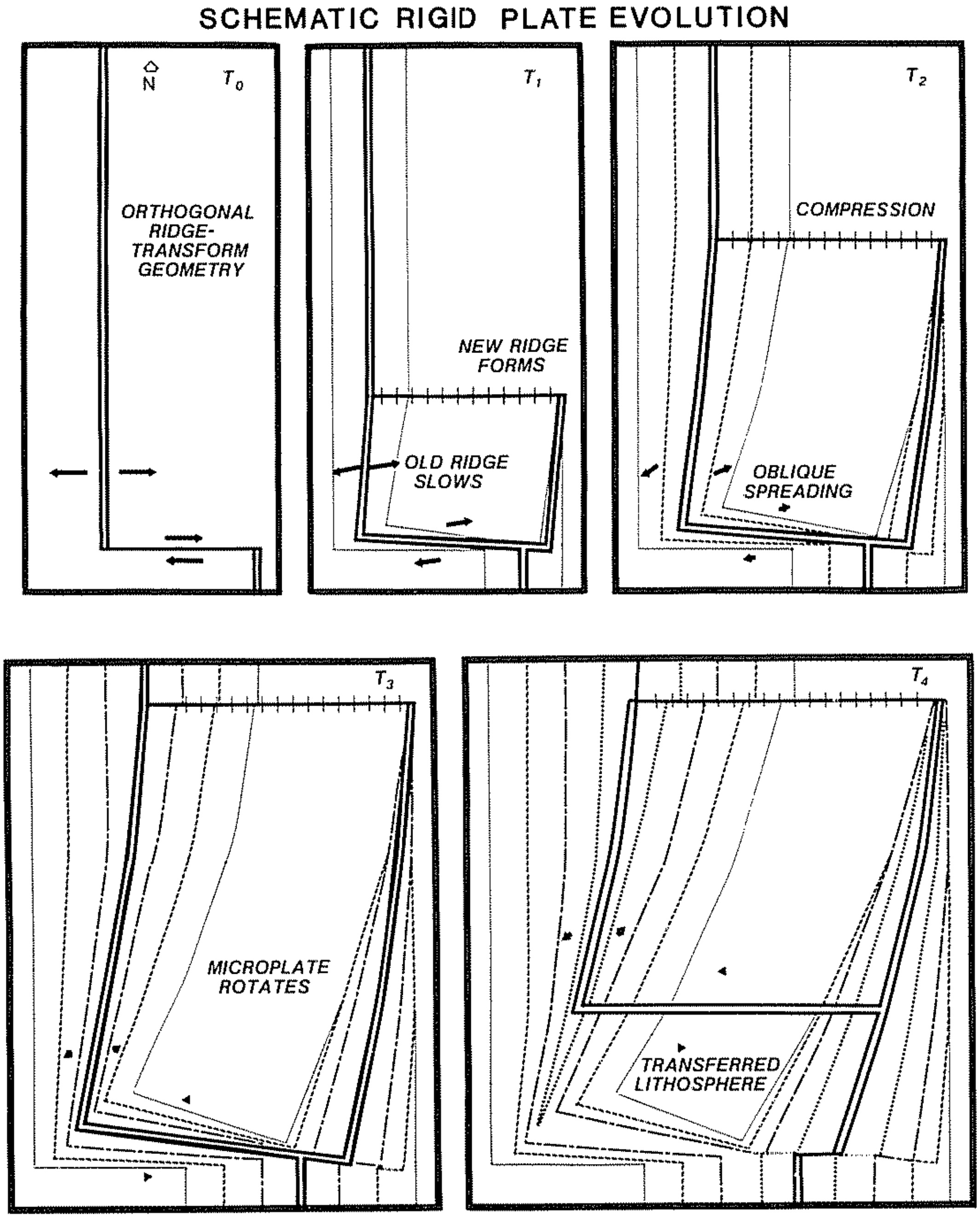


Fig. 1. Model for the evolution of a rigid microplate between two major plates by rift propagation. Successive isochrons illustrate the rift propagation, the rotation of the microplate, the reorientation of the two ridges, and the conversion of the initial transform into a slow spreading ridge [Engeln et al., 1988].

Nubia, Somalia, and Arabia plates (Figure 2). This plate geometry is possibly an outgrowth of the Eocene reorganization of global plate motions resulting from the collision of India with Eurasia [Tarling, 1970; Cochran, 1981; Hempton, 1987; Bohannon et al., 1989]. At present, Nubia and Somalia are separating slowly (~ 3 mm/yr) by continental rifting along the East African Rift [Gass, 1970; Ebinger et al., 1987; Mohr, 1987; Ebinger, 1989] and Arabia diverges more rapidly (~ 18 mm/yr) from Nubia and Somalia via seafloor spreading in the Red Sea [McKenzie et al., 1970;

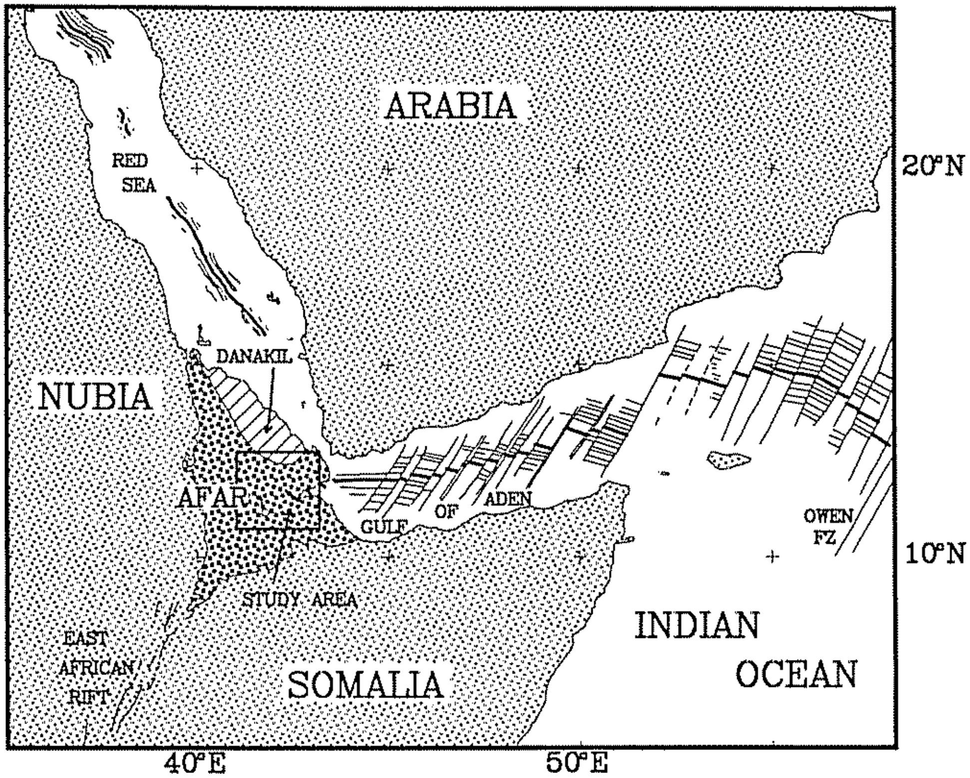


Fig. 2. Location of the Afar region at the Nubia-Somalia-Arabia triple junction.

Lowell and Genik, 1972; Girdler and Styles, 1974, 1976; Le Pichon and Francheteau, 1978; Cochran, 1983; LaBrecque and Zitellini, 1985; Cochran and Martinez, 1988; Guennoc et al., 1988] and the Gulf of Aden [Laughton et al., 1970; Girdler and Styles, 1978; Cochran, 1981; Tamsett and Searle, 1988].

The area has been evolving, at least in part, by rift propagation. Using the ages of marine magnetic anomalies in the Gulf of Aden and basalts in Afar, Courtillot et al. [1980] show that in the past 10 m.y. the western Gulf of Aden has opened by means of a rift propagating westward at ~30 km/m.y. (Figure 3). Within the past 2 m.y., the spreading center has propagated onshore into eastern Afar. The Afar region thus provides a setting to study the differences between rift propagation in oceanic lithosphere and in lithosphere which may be transitional in properties between continental and oceanic lithosphere [Makris and Ginzburg, 1987].

LOCAL GEOLOGY

Afar occupies a triangular-shaped topographic basin containing unknown thicknesses of primarily Cenozoic detrital sedimentary units, evaporites, and volcanics [Barberi et al., 1972; CNR-CNRS, 1975; Christiansen et al., 1975; Varet and Gasse, 1978] (Figure 4). Our models concentrate on the eastern one third of Afar, including the Asal-Ghoubbet Rift and the roughly 100-km square to the southwest (Figure 5). Much of the region is covered by the Afar stratoid series (~1–4 Ma), an extensive, thick (up to 1500 m) basaltic unit. Rhyolitic flows and ignimbrites, generally postdating the Afar stratoid series, are commonly found near intersections of faults with different trends [Barberi et al., 1972; Barberi

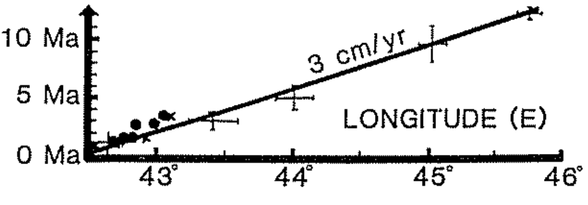


Fig. 3. Age of earliest recognizable marine magnetic anomalies (symbols with error bars) plotted against latitude along the axis of the Gulf of Tadjurah-Gulf of Aden spreading center. The dots without error bars and the crosses are ages of the first tholeiitic basalts emitted on the south and north sides of the Gulf of Tadjurah, respectively. Slope of the line fit to the data gives an approximate 3 cm/yr rate for the propagation of the Gulf of Aden spreading center inland [Courtillot et al., 1980].

and Varet, 1977]. In addition, Plio-Pleistocene basaltic fissure flows are commonly found along the major rifts. Dates from these flows were used by Courtillot et al. [1980] as evidence for rift propagation (Figure 3) because the dates are older in the Gulf of Tadjurah area (~3–4 Ma) than in the Lake Ghoubbet area (~1 Ma), indicating that opening progressed from east to west. The youngest volcanics, late Quaternary (< 1 Ma) basalt flows and spatter cones, occur within the Asal-Ghoubbet, Manda Inakir, and western Goba'Ad rifts, indicating that these are the zones where strain has most recently been concentrated. These young volcanics occur in axial volcanic ranges, which Barberi et al. [1975] interpret as the loci of present spreading owing to the ranges' similarities with oceanic spreading centers.

RIFT GEOMETRY AND HISTORY

A basic constraint on tectonic models comes from the geometry of the major rifts (Figure 5). The Gulf of Tadjurah, just east of Afar, began to open ~3–4 Ma and is now undergoing an early stage of seafloor spreading [Choukroune et al., 1986, 1988]. Past investigators have identified a series of active onshore rifts [Barberi et al, 1975; Christiansen et al., 1975; Schaefer, 1975; Varet and Gasse, 1978], the most prominent being the Asal-Ghoubbet Rift, the on-land continuation of the Gulf of Tadjurah, which extends northwest through Lake Asal and Lake Ghoubbet. This rift, the most seismically active of the on-land rifts, is morphologically similar to oceanic spreading centers [Harrison et al., 1975; Needham et al., 1976; Tamsett, 1986]. Northwest of the Asal-Ghoubbet Rift is Manda Inakir, a curvilinear axial volcanic range with an axial summit graben. To the southwest, the Gaggade, Hanle, and Goba'Ad-Tendaho rifts are subparallel to the Asal-Ghoubbet Rift. These rifts are truncated on the southeast by the Bada Weyn Rift, which curves at its southwest end to join with the Goba'Ad Rift. The observed vertical offsets between the horsts and graben formed by these rifts are ~200-1300 m and decrease progressively southwest of the Asal-Ghoubbet Rift (Figure 6). The Goba'Ad and Hanle rifts narrow to the southeast, whereas the Asal-Ghoubbet Rift narrows to the northwest. The width of the graben may provide a rough indication of the amount of extension over time, where wider graben suggest greater extension. That such a relationship may hold is supported by continental pull-apart basins, for example, the Dead Sea Rift, where the width of the basin increases with extension.

Following Varet and Gasse [1978], we infer the time of rifting from the age of the earliest sedimentary and igneous units exposed within the rifts and from the pattern of subsequent deformation of these units. The deposition history, summarized in Figure 7, shows that the Goba'Ad, Hanle, and Gaggade rifts were active depocenters several hundred thousand years earlier than was the Asal-Ghoubbet Rift; the Asal-Ghoubbet Rift apparently did not become a depocenter until some time in the Pleistocene. Since the middle Pleistocene the sediments within the Goba'Ad, Hanle, and Gaggade rifts have been little disturbed, except at the northwestern end of the Goba'Ad Rift, where the recently active Dama Ale volcano (Figure 5) is located. In contrast, faulting of sediments and igneous units have been pervasive and continuous since at least the upper Pleistocene within the Asal-Ghoubbet Rift.

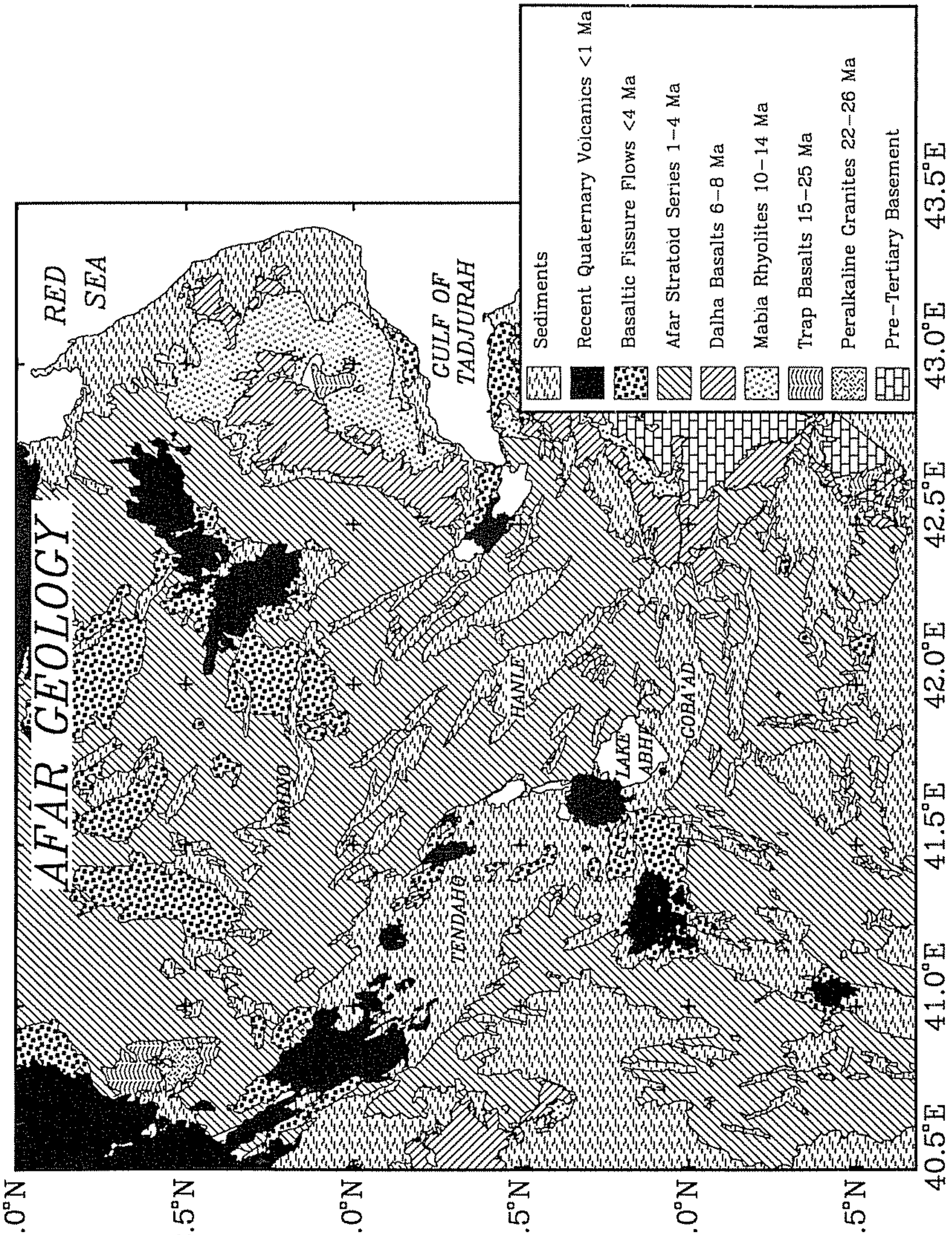
We can further infer the present-day distribution of discrete zones of extensional strain concentration from the distribution of seismicity (Figure 8) and Quaternary volcanism (Figure 4). The seismicity associated with the Gulf of Aden spreading center extends to the Gulf of Tadjurah and terminates at the northwestern end of the Asal-Ghoubbet Rift [Lepine et al., 1980; Ruegg et al., 1980; Courtillot and Vink, 1983; Choukroune et al., 1986]. The seismicity and volcanic activity at the Asal-Ghoubbet Rift indicate that it is the primary locus of recent extension in eastern Afar. Recent extension may also have occurred at the Manda Inakir volcanic range and near the Dama Ale volcano.

West of Lake Asal, the seismic activity decreases significantly and does not occur in well-defined zones, although there are several local concentrations. Courtillot et al. [1984] thus suggest that the Gulf of Aden spreading center has not propagated beyond the Lake Asal vicinity. Hence the separation of Arabia from Africa takes place on a discrete spreading center east of the Asal-Ghoubbet Rift, but is taken up by some more diffuse mode of deformation further west in Afar.

Focal mechanisms from the boundaries of oceanic microplate have been instrumental in constraining relative plate motions. Composite focal mechanisms from the Asal-Ghoubbet Rift and the Gulf of Tadjurah, though not well enough constrained to provide comparable information, support geological evidence for normal and strike-slip faulting [Ruegg et al., 1980]. In addition, focal mechanisms from a swarm of larger (m_b magnitudes 5–6) earthquakes in the Serdo area indicate strike-slip faulting [McKenzie et al., 1970; Fairhead and Girdler, 1971; Maasha and Molnar, 1972; Kebede et al., 1989].

PALEOMAGNETIC DATA

Paleomagnetic directions preserved by rocks emplaced along the Afro-Arabian rift system provide a record of its kinematic history. Past paleomagnetic studies indicate that crustal blocks bordering passive margins may move little relative to their adjacent. For instance, paleomagnetic directions from the uplifted flanks of parts of the East African Rift indicate no rotations or latitudinal translations relative to Africa [Raja et al., 1966; Patel and Gacii, 1972; Reilly et al., 1976]. Similarly, paleomagnetic directions from basalts on the Arabian side of the Gulf of Aden indicate no motion relative to Arabia but suggest ~7° counterclockwise rotation relative to Africa, presumably resulting from the separation of Arabia from Africa [Irving and Tarling, 1961; Tarling et al., 1967; Tarling, 1970].


AFAR GEOLOGY
RED SEA
GULF OF TADJURAH
HANLE
GOBA'AD
LAKE ABHE
TENDAHO
Sediments
Recent Quaternary Volcanics <1 Ma
Basaltic Fissure Flows <4 Ma
Afar Stratoid Series 1–4 Ma
Dalha Basalts 6–8 Ma
Mabla Rhyolites 10–14 Ma
Trap Basalts 15–25 Ma
Peralkaline Granites 22–26 Ma
Pre-Tertiary Basement
13.0°N
12.5°N
12.0°N
11.5°N
11.0°N
10.5°N
40.5°E
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43.0°E
43.5°E

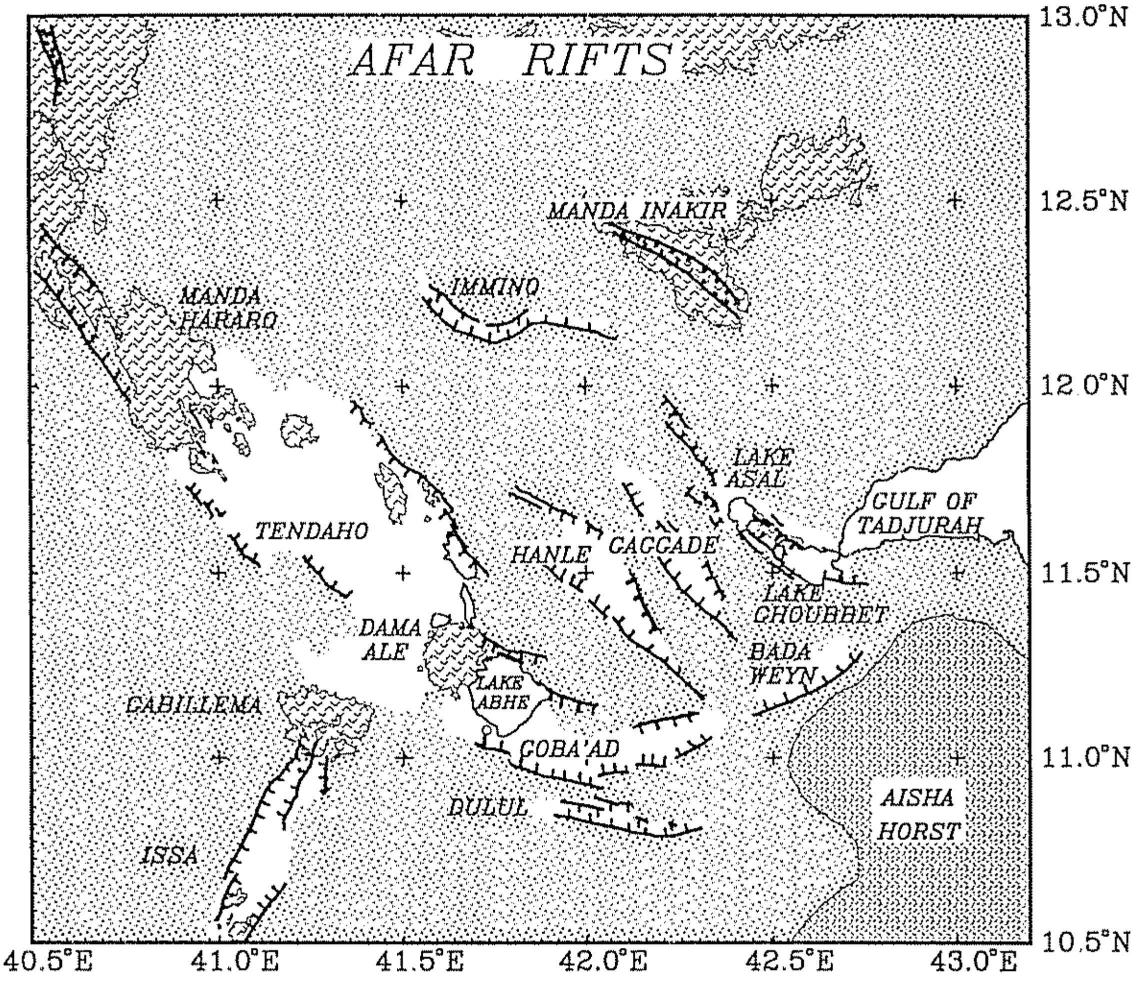

Fig. 5. Geometry of narrow rifts that act as high-strain zones in Afar, simplified from the CNR-CNRS [1975] geological map of Afar. Lakes and sedimentary units (white areas) and recent Quaternary volcanics (v-shaped pattern) occur along the high-strain zones.

This pattern may partially result from a sampling bias because many investigators avoid outcrops near or within rift valleys so as to obtain paleomagnetic poles for the African apparent polar wander path. Paleomagnetic results from the interior of other rift valleys, such as the Rio Grande Rift [Brown and Golombek, 1985], and within broad extensional zones, such as the Basin and Range [Ron et al., 1986; Calderone et al., 1990], show that some areas have been unaffected by vertical axis rotations whereas others have rotated in excess of 10–20°. Similarly, two areas along the Afro-Arabian rift have rotated with respect to their surroundings: The Danakil Block, on the northeastern edge of Afar, has rotated ~ 10° counterclockwise since the Miocene [Schult, 1974], and, as discussed below, eastern Afar has rotated.

Paleomagnetic data from eastern Afar [Harrison et al., 1977; Galibert et al., 1980; Courtillot et al., 1984] constrain the timing and extent of the rotations that occur as the Gulf of Aden spreading center propagates into the African continent. The paleomagnetic sampling localities are shown in Figure 9, and the paleomagnetic directions are summarized in Table 1 and Figure 10. The ages of the rocks sampled within the shaded wedge on Figure 9 vary from 1 to 3 Ma with a mean age of 1.8 ± 0.4 Ma [Courtillot et al., 1984]. The rocks sampled within the Asal-Ghoubbet Rift are from upper Pleistocene units and all paleomagnetic directions are normal polarity, which probably indicates that all the rocks are from the Brunhes epoch (less than 0.73 Ma). Courtillot et al. [1984] conclude from these data that a wedge-shaped area to the southwest of the Asal-Ghoubbet Rift (Figure 9) has rotated clockwise 14.5° ± 7.5° relative to Africa and the

Fig. 4. Geology of a portion of the Afar region, simplified from the CNR–CNRS [1975] geological map of Afar.

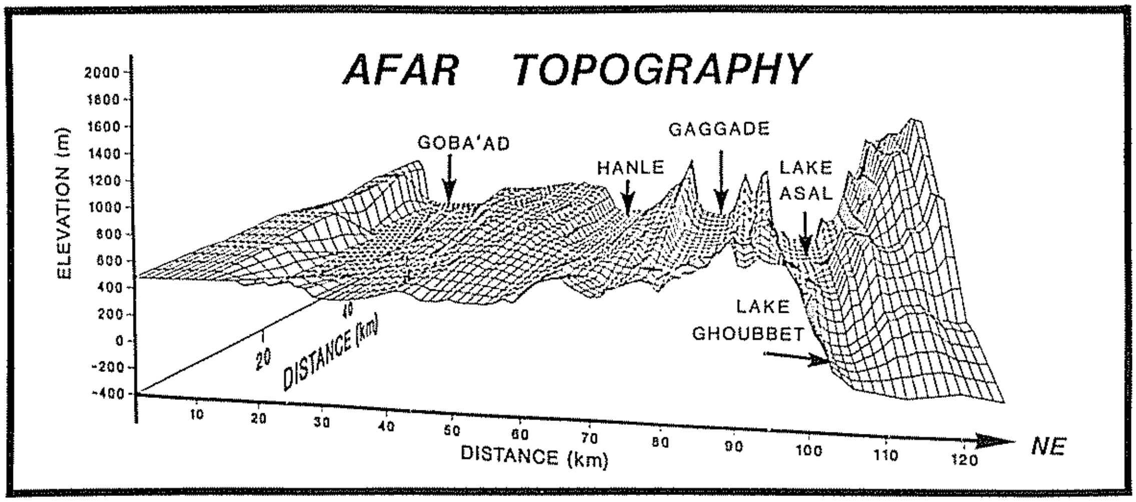

Fig. 6. Topography of the major rifts in eastern Afar, along profiles oriented N45°E (from Institut Geographique National [1953-1962] topographic maps).

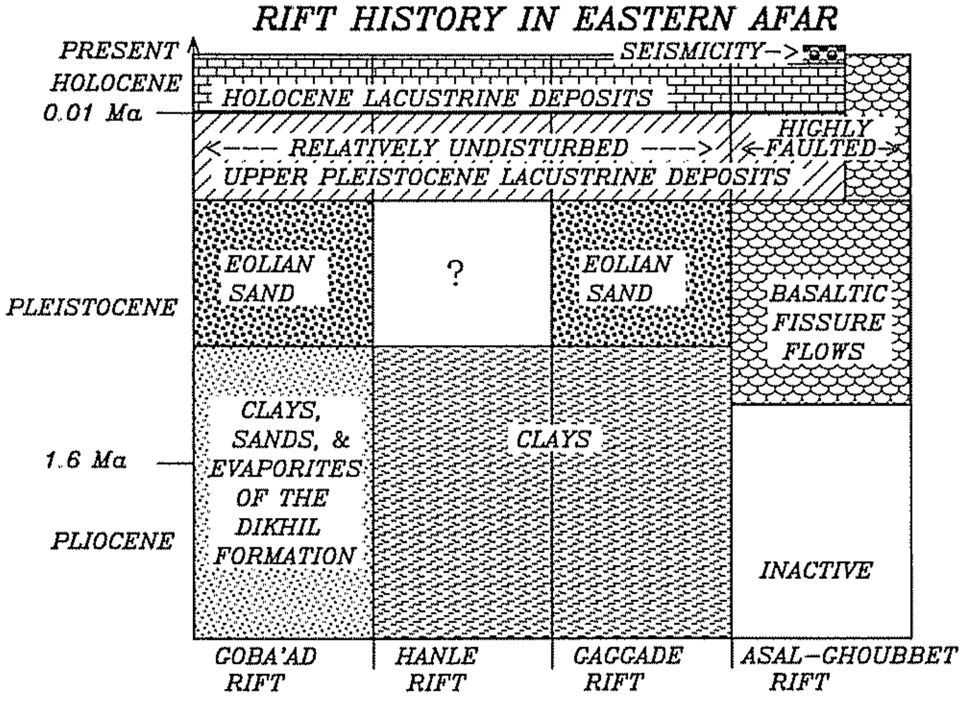

Fig. 7. Schematic geologic section for major eastern Afar rifts, simplified from Varet and Gasse [1978].

Asal-Ghoubbet Rift. The geographic extent of the rotated area, especially to the northwest, could not be ascertained due to sampling limitations.

The rotation is illustrated by dividing the data into two groups such that differences in the mean directions can be attributed to their location and perhaps their age. The mean rotation for the sites within the shaded area of Figure 9, an area slightly different than that defined by Courtillot et al. [1984], is 12.6° ± 3.9° or 8.6° ± 3.6° (Table 1), depending on which reference pole is used for Africa. The differences between the rotations we compute and that computed by Courtillot et al. [1984] are not statistically significant, and

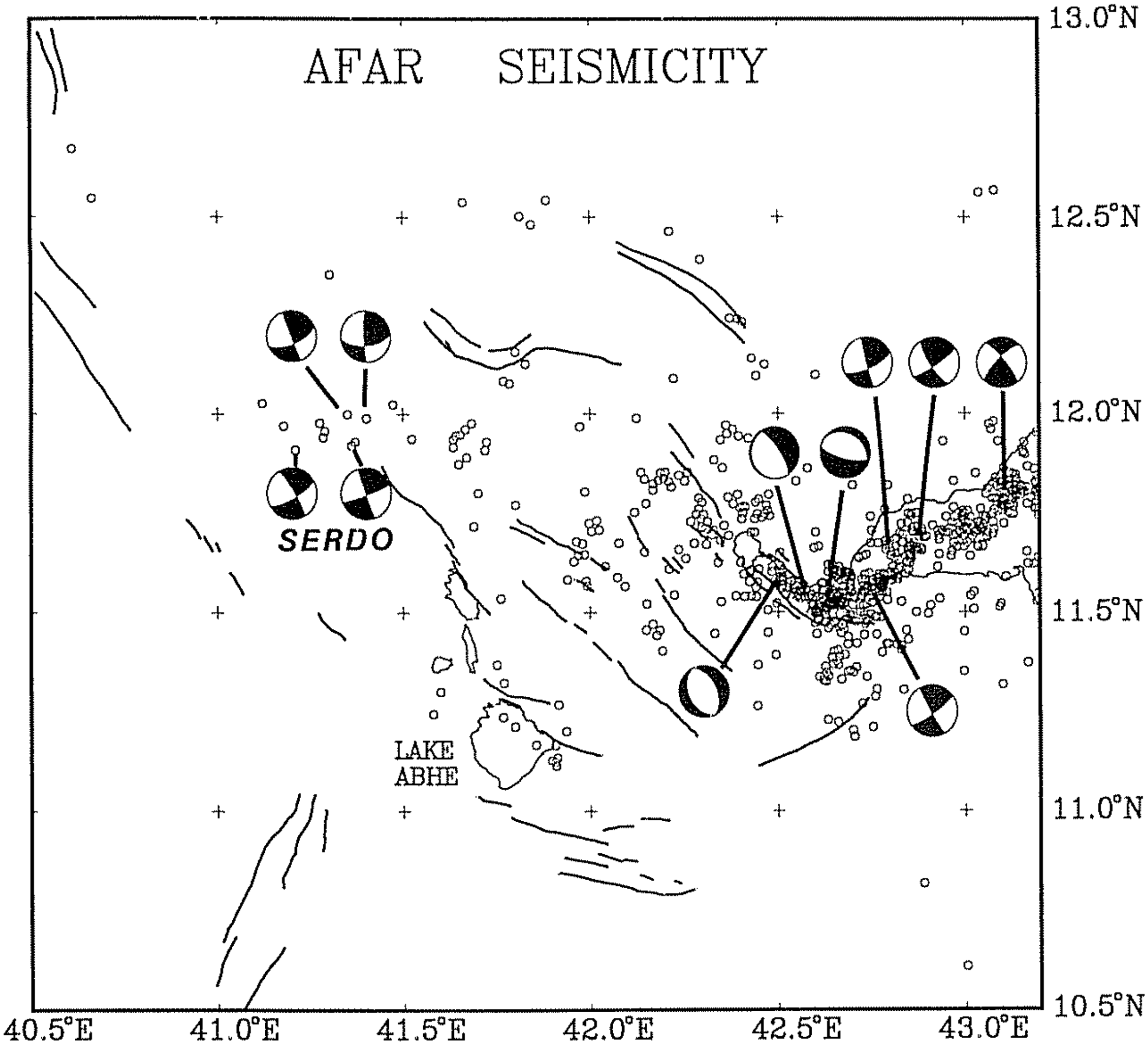

Fig. 8. Earthquake epicenters (hollow dots; digitized from Lepine et al. [1980], Ruegg et al. [1980], and Courtillot and Vink [1983], with additional epicenters from the National Earthquake Information Center database) and focal mechanisms (compressional quadrants are shaded black) for eastern Afar (see text).

merely reflect differences in the way the rotated region is defined and differences in the reference poles used. To incorporate these uncertainties, we take the mean of the values in Table 1 and use their range as a 95% confidence region, thus obtaining 11° ± 6° for the rotation. Biases caused by inadequate sampling of the geomagnetic secular variation should not affect the results, as both groups of data are sufficiently large and span several 100,000 years. (Had we divided the data into smaller subgroups to examine rotations of individual horsts, the significance of the findings would be questionable because it is doubtful that any of the smaller groups of data could average geomagnetic secular variation [e.g., Calderone et al., 1989].) Furthermore, small deviations of the paleomagnetic field from a geocentric axial dipole cannot account for the large amount of observed rotation. Thus the paleomagnetic data indicate that an area covering at least 5000 km^2 southwest of the Asal-Ghoubbet rift has rotated clockwise by ~11° ± 6° relative to Africa during the past 2 m.y.

STRUCTURAL DATA

We make additional inferences about the extension and rotation from structural data. Fortunately, the trends of

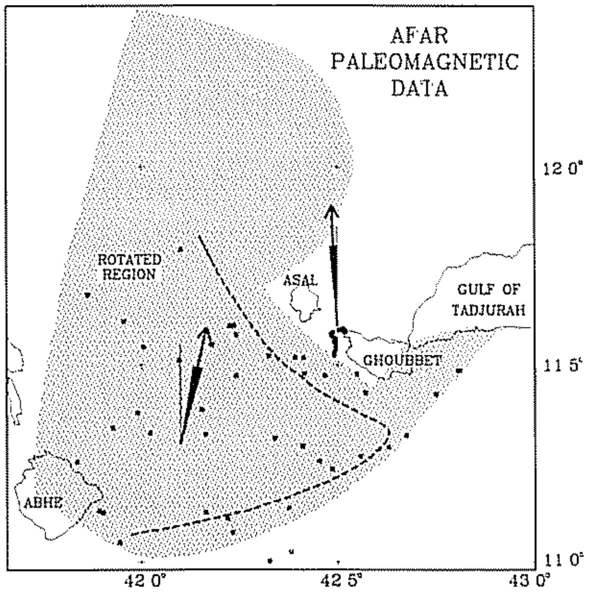

Fig. 9. Paleomagnetic sites (solid squares) in Afar [Courtillot et al., 1984]. We infer that the shaded region (the region used later in our microplate model) and the sites within it have rotated clockwise relative to Africa, based on the northeasterly paleomagnetic declinations obtained for this region. The mean declinations for two regions are given by the arrows and their uncertainties by the black wedges. Comparison of the mean declination from the shaded region to that obtained from rocks to the northeast in the Asal-Ghoubbet Rift or to the declination expected for a geocentric axial dipole field (the thin line) illustrates the size and sense of the rotation. The dashed line bounds the rotated area as it was originally defined by Courtillot et al. [1984].

structures including the horsts and graben, fissures, faults, and tilted fault blocks reflect the tectonics of the past ~ 4 m.y., since most older structures have been blanketed by the Afar stratoid series. These trends (Figure 11) are generally consistent with NNE-SSW extension, in accord with the direction of Somalia-Arabia plate motion. Southwest of Lake Abhe, ~NE-SW trends, which formed at the northern extent of the Ethiopian Rift, reflect Nubia–Somalia motion.

A distinct change in the fault trends occurs across the Goba'Ad Rift; to the south, most of the faults trend N70°–90°W, whereas to the north they trend N40°–75°W. This variation may reflect the clockwise rotation of the area to the north of Goba'Ad Rift as indicated by the paleomagnetic data. Alternatively, the fault trend variation may be attributed to a variety of effects including changes in stress orientation during faulting and preexisting structures that control the fault orientation [Barberi et al., 1974].

Another less common, but tectonically important, fault trend of N10°–50°E occurs at Arta, south of the Gulf of Tadjurah. This trend is approximately normal to that of the rifts. Barberi and Varet [1977] suggest that horizontal striations on fault planes in the Arta area indicate right-lateral strike-slip motion. Another set of faults trending at a high angle to the rifts is located just north of Lake Asal. Barberi and Varet [1977] interpret these en echelon faults as the surface expression of young transform faults, by analogy to the results of clay experiments.

An important feature of the lineations is that they are distributed over the area. This distribution indicates that extension has not been restricted to the major rifts. Nonetheless, it appears that the extension has occurred primarily on the rifts. For the normal faults, the horizontal displacement d can be inferred from the observed vertical offset h using $d = h/\tan\delta$ where δ is the fault dip. For Afar, Schaefer [1975] observed an average fault dip of ~73°, indicating that the horizontal displacements are about one third the size of vertical offsets. Thus the numerous faults with small vertical offsets do not give rise to significant extension, though significant deformation by strike-slip faulting cannot be ruled out. From over 1500 measurements of faults, dikes, and fissures, he determined that the areas of highest strain in eastern central Afar were the Goba'Ad and Manda Inakir rift zones. Delibrias et al. [1975] studied the Asal-Ghoubbet Rift using a similar technique, in addition to comparing average plagioclase compositions from the Asal-Ghoubbet Rift to those from other spreading centers, from which he inferred that the Asal-Ghoubbet Rift is extending at a rate of ~15 km/m.y., consistent with it being part of the Gulf of Aden spreading center. We conclude that extension is concentrated at the rifts that form major morphological depressions and that the areas between these depressions can be approximated as rigid blocks.

PRIOR INTERPRETATIONS

Prior investigators have interpreted the rifts within Afar as manifestations of the early stages of evolution of a continental plate boundary and the regions between the rifts as crustal blocks or microplates, which move relative to the major plates as the rifts evolve with time [Barberi et al., 1970; Barberi and Varet, 1977; Bannert, 1972; Le Pichon et al., 1973; Varet and Gasse, 1978]. Barberi and Varet [1977] further suggested that differential extension occurred along the boundary of several of the microplates, causing the microplates to rotate about local vertical axes. The relative motions of the microplates were, however, difficult to constrain owing to the lack of detailed kinematic data, which is partially alleviated by subsequent paleomagnetic studies. Barberi and Varet [1977] concluded from their analysis that plate tectonic models could account for most of the geophysical, geological, and petrological features of Afar but could not be rigorously applied because the microplates were not strictly rigid and because wide, rather than discrete, zones of deformation commonly occurred between microplates.

Other investigators have suggested that diffuse deformation, which occurred prior to propagation of the Gulf of Aden spreading center into Afar, led to the observed pat-

TABLE 1. Afar Paleomagnetic Data

Description	Site Mean Lat, Lon, °N, °E	Paleomag Inc, Dec deg, deg	N	k	α_{95}, deg	R±ΔR,[a] deg	F±ΔF,[a] deg	R±ΔR,[b] deg	F±ΔF,[b] deg
Asal-Ghoubbet Rift[c,d]	11.6, 42.5	24.2, 357.4	73	33.4	2.9	-2.6±3.5	-2.3±5.3	-6.6±3.2	-3.9±4.2
Eastern Afar block[d,e]	11.4, 42.1	22.4, 12.6	71	23.5	3.5	12.6±3.9	-0.3±5.1	8.6±3.6	-1.9±4.5
0 Ma geocentric axial dipole field direction	11.5, 42.3	22.1, 0.0			3.0[f]				
Pliocene–Quaternary expected direction[g]	11.5, 42.3	20.5, 4.0			2.4				
1980 I.G.R.F. direction[h]	11.5, 42.3	6.1, 0.7							

Lat, Lon give the site mean latitude and longitude; Inc, Dec give the paleomagnetic inclination and declination; N is the number of paleomagnetic sites used in computation of mean direction; k is the estimate of Fisher's [1953] precision parameter; α_{95} is the radius of the 95% confidence circle. R±ΔR is the vertical axis rotation and its 95% confidence limits [Beck, 1980], which have been corrected using factors from Demarest [1983]. Positive values indicate clockwise rotations. F±ΔF is the inclination flattening and its 95% confidence limits [Beck, 1980], corrected using factors from Demarest [1983]. Positive values indicate shallower than expected inclinations.

[a] Rotation and flattening values computed relative to 0 Ma geocentric axial dipole field direction.

[b] Rotation and flattening values computed relative to Pliocene–Quaternary expected direction.

[c] Data from Harrison et al. [1977].

[d] Data from Galibert et al. [1980].

[e] Data from Courtillot et al. [1984].

[f] Uncertainty assumed for expected direction in rotation and flattening computations.

[g] Data from Besse et al [1984].

[h] Computed from the 1980 International Geomagnetic Reference field coefficients.

terns of rifting [Courtillot et al., 1980; Courtillot, 1982; Vink, 1982]. In a model first proposed by Courtillot [1982], Afar acts as a locked zone deforming under regional extension in front of the westward propagating Gulf of Aden spreading center. Initially, the locked zone is characterized by dike intrusion, faulting, and thinning of the lithosphere. With time, the extension is concentrated into active zones of volcanism and, ultimately, localized into one stable spreading center, a process referred to as rift localization. As a result, motion is transferred from a broad zone of faults and fissures to a single dominant rift. In the following models, we use these observations and some of the concepts from prior models with the goal of better describing the tectonics of Afar and showing the similarity between Afar and oceanic microplate systems.

KINEMATIC MODELS FOR AFAR

The observations discussed previously impose a series of constraints on tectonic models for Afar. First, during the past 2–3 m.y., NE-SW extension appears to have been concentrated on several major rifts. During this time, the region bordered by the Goba'Ad, Bada Weyn, Manda Inakir, and Asal-Ghoubbet rifts rotated ~11° clockwise and sustained minor, but pervasive, deformation. Prior to the Pleistocene, the sedimentological data indicate that rifting occurred on the Goba'Ad, Hanle, and Gaggade rifts, but not on the Asal-Ghoubbet Rift. In contrast, the seismicity and volcanism imply that the extension is presently concentrated in the Asal-Ghoubbet Rift and, to a lesser extent, in the northwestern end of Goba'Ad. We interpret these observations as indicating that during the past 1–2 m.y., extension that was previously occurring on one or more rifts was transferred to the Asal-Ghoubbet rift. Extension may have begun first on the southeast end of the Asal-Ghoubbet rift, while extension on the southeast end of the other rifts began to slow. Provided that the width of the graben gives a rough indication of the net opening, then over the past 2 m.y. the Goba'Ad Rift was the dominant rift. By this criterion, the maximum extension on the Goba'Ad and Hanle rifts occurred to the northwest, whereas extension was greatest on the southeast end of the Asal-Ghoubbet Rift.

To describe these observations, we use microplate or block models similar to the oceanic microplate model (Figure 1). The models are kinematic, in that they describe the evolution of Afar in terms of the relative motion between the major plates and one or more microplates or rigid blocks. Within our study area, we approximate the locations of the present plate boundaries within Afar generally following Schaefer [1975, his Figure 3] and Barberi and Varet [1977, their Figure 10]. Our models, however, are restricted to a portion of the region studied in these earlier papers. Because the paleomagnetic data provide the key constraint not available to the previous studies, our models deal pri-

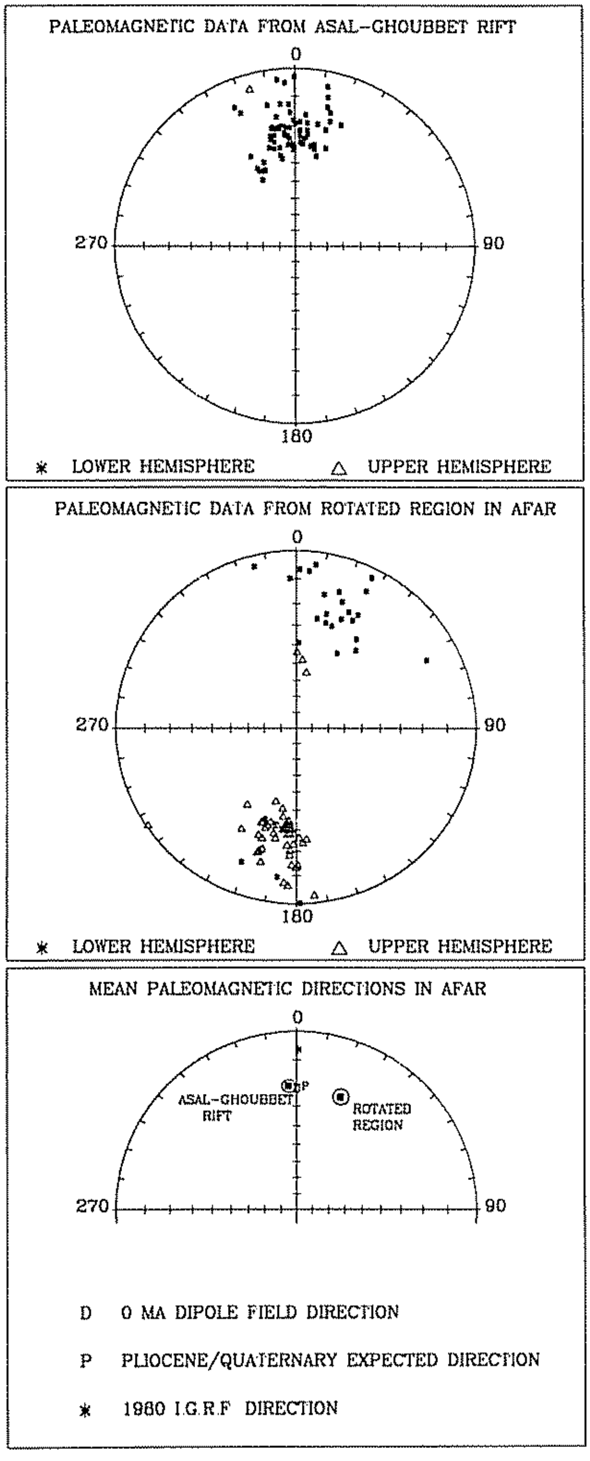

Fig. 10. Paleomagnetic directions from data from the Asal-Ghoubbet Rift region (top) and from the shaded (rotated) region in Figure 9 (center) [Harrison et al., 1977; Galibert et al., 1980; Courtillot et al., 1984]. Comparison of the mean directions to expected present and Pliocene/Quaternary directions is also shown (bottom).

marily with the area which these data show has been rotated. As a result, the northwest boundary is somewhat arbitrary. We believe, however, that the processes invoked by our models are active in the region to the northwest and would expect that clockwise rotations slightly smaller than those in eastern Afar have occurred in central Afar.

Additionally, we assume the area northwest of the Asal-Ghoubbet Rift moved as part of the Arabian plate during the past 2 m.y. Clearly this region has not always been part of Arabia, as it lies west of the Bab el Mandeb strait, which is now seismically inactive and probably represents an extinct segment of the Red Sea rift. Within the past few million years, however, extension between Arabia and Nubia has been displaced to the west, into northern Afar [Tazieff, 1970; Lowell and Genik, 1972; Barberi and Varet, 1977; Le Pichon and Francheteau, 1978]. This assumption is supported by the good fit we get when reconstructing the 100-m isobath in the Gulf of Tadjurah. The plate velocities used for the plates bounding eastern Afar are consistent with global plate motions [e.g., DeMets et al., 1990]. Thus, the motions described by our models produce no inconsistencies with relative motions observed at other plate boundaries.

In the following models, we neglect several complexities of the deformation process. In both models, we treat the region within each microplate or block as rigid. In the first model, we treat the boundary zones as their oceanic equivalents, so the rifts, which are zones of concentrated extension, are treated as spreading centers. Similarly, fault zones parallel to plate motion are treated as transforms. In the second model, we show the gaps and overlaps between blocks that occur as motion progresses. We are not suggesting that all boundaries are equivalent to spreading centers, transform faults, or subduction zones. Rather we assume that the overwhelming majority of motion occurs between blocks that are essentially undeformed. We provide a description of the relative motions of these largely coherent regions, and then show that these motions are similar to those produced by regions that do follow the basic tenets of plate tectonics. Some strain has clearly occurred within the regions we treat as rigid, but, as discussed earlier, it appears that this strain is much less than that which occurs at the boundaries of the regions. For the first order kinematics of Afar, these approximations are not bad, though clearly a more distributed mode of deformation must be considered to explain second order features. Finally, because only near-surface observations are used, the models are applicable whether the "microplates" extend to the asthenosphere or represent detached crustal blocks.

Model 1

In our simple model [Acton et al., 1986], the entire Afar region is represented by a single rigid microplate which grows by rift propagation. This model illustrates the basic features of the oceanic microplate model as applied to Afar. In its present configuration (Figure 12) the microplate is

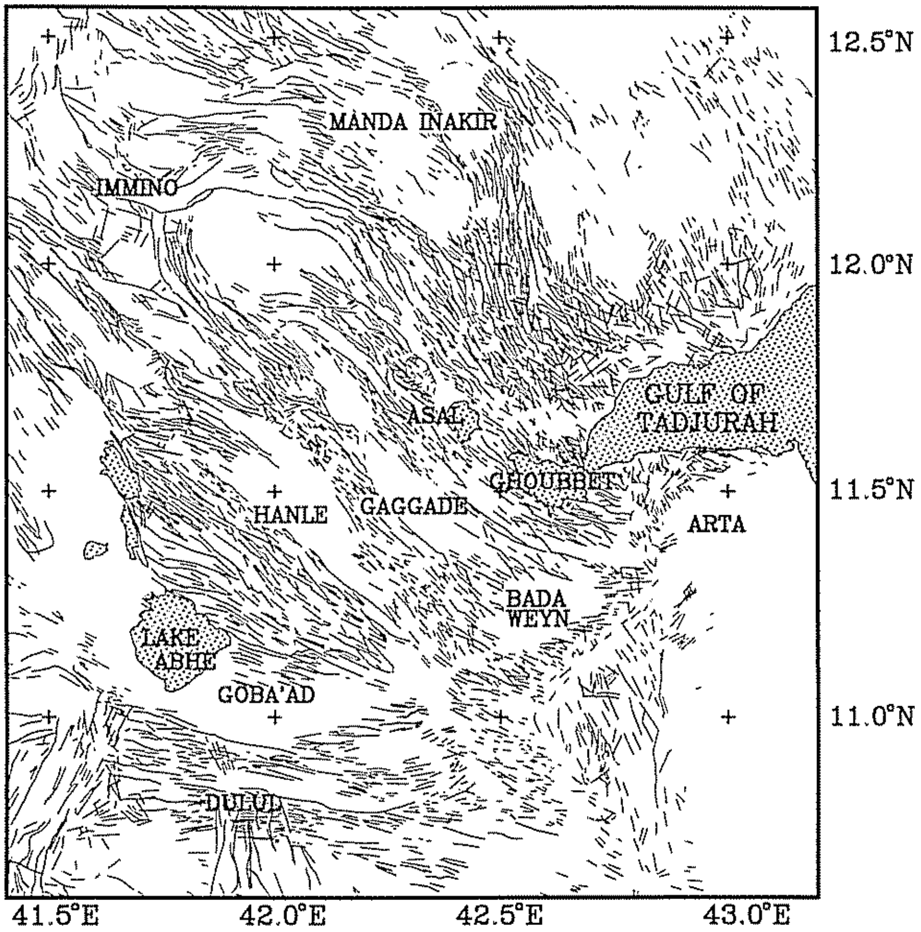

Fig. 11. Fault trends and tectonic lineations for eastern Afar region, simplified from CNR-CNRS [1975].

separated from Arabia by the Asal-Ghoubbet and Manda Inakir rifts, from Nubia by the Tendaho Rift, and from Somalia by the Goba'Ad and Bada Weyn rifts. The relative velocities between the three major plates, which are assumed to have remained constant during the period modeled, were provided by C. DeMets (pers. comm., 1986). In the figure, the evolution is shown in 0.8-m.y. time steps, with the Nubia plate fixed.

Model 1 begins at roughly 1.8 Ma. Prior to this time it is difficult to locate plate boundaries within Afar because the Afar stratoid series volcanics blanket older formations. The Nubia-Somalia-Arabia triple junction is placed just northwest of the present Lake Abhe.

By time T_2 (~1 Ma), new lithosphere has been accreted along the spreading centers. A new rift, an inland continuation of the incipient Gulf of Tadjurah, has formed between Arabia and Afar and has propagated northwest from 1.6 to 1.0 Ma, giving the initial opening on the Asal-Ghoubbet rift. Extension on the old rift segment to the southwest, which forms Lake Abhe and the Goba'Ad Rift, continues but at a slower rate. The Afar microplate, between the old and new rifts, grows and rotates with respect to the major plates. The opening on the new rift, or the motion of the microplate with respect to Arabia, is described by an Euler pole at the tip of the propagating rift throughout its evolution. As the microplate forms the southeast boundary changes from a transform to a slow spreading center or a leaky transform, giving rise to the Bada Weyn Rift. The northwest boundary becomes a zone of compression that migrates northwest with the propagating rift tip, and the microplate rotates clockwise.

With time, divergent plate motion previously concentrated on the older rift to the southwest is progressively transferred to the new rift to the northeast. By time T_3 (~0.2 Ma), the microplate has continued to grow and has rotated ~11° clockwise. The new rift has propagated further to the northwest, into what becomes the Manda Inakir axial volcanic range.

Subsequently, spreading on the southeast corner of the old rift becomes extremely slow. Rather than continue to spread slowly, this rift could fail and the southeast boundary of the microplate (the leaky transform) could migrate to the northwest. Such a phenomenon (Figure 1) is discussed by

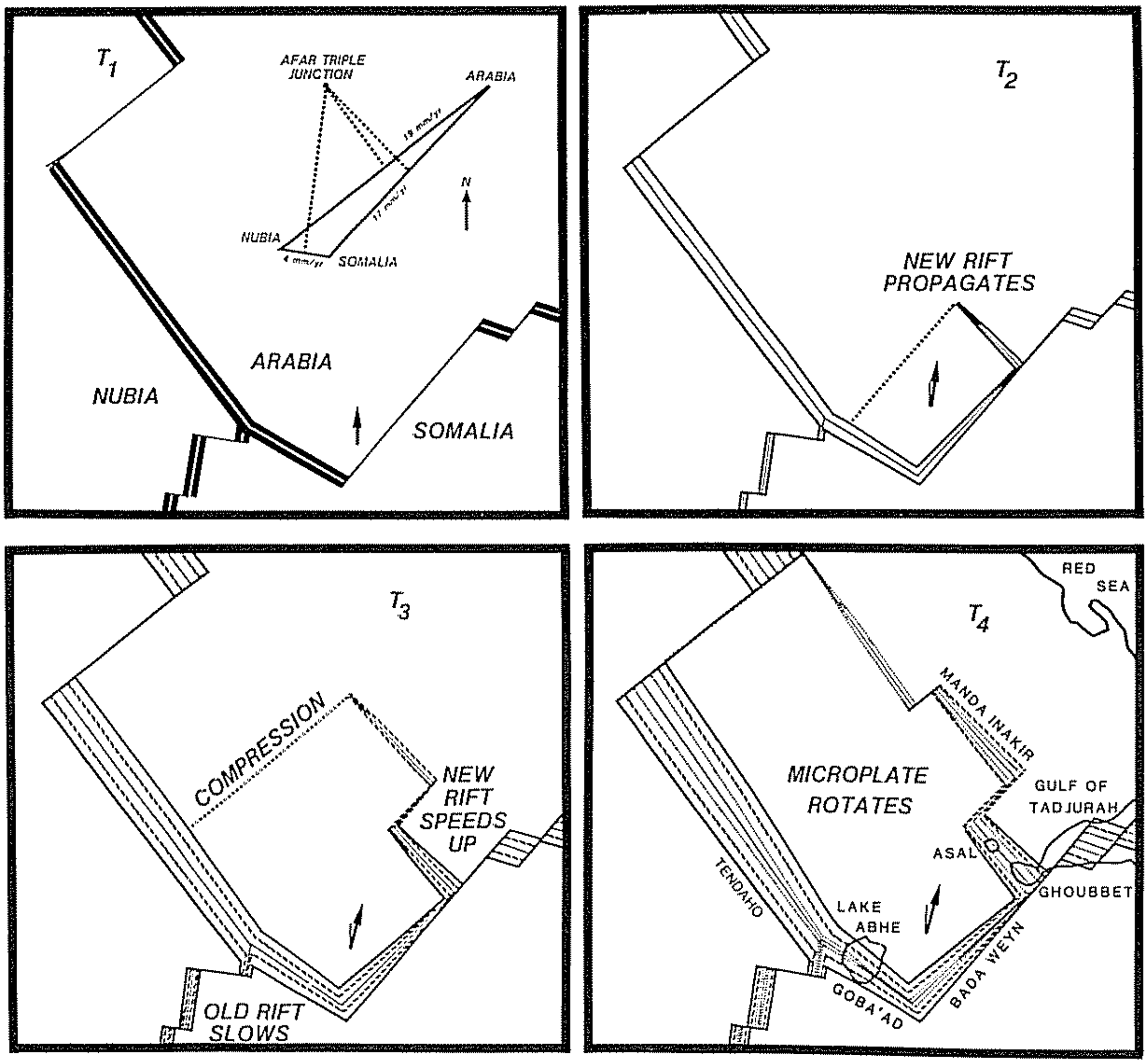

Fig. 12. Single microplate evolutionary model (model 1) for Afar. T_1 is the plate boundary configuration ~ 1.8 Ma with ridges shown as double lines and transforms as thin lines. The velocity triangle gives relative velocities used in the model. Time step corresponds to 0.8 m.y., such that T_4 represents a possible future evolution. Isochrons are illustrated by the dashed lines. The dotted line is a zone of compression that migrates to the NW as the rigid microplate grows and the new rift propagates. The rotation of the microplate between the propagating and failing ridges is represented by the angle between the north pointing line and the arrow.

Engeln et al. [1988]. This sequence of events would entail an interesting history for the lithosphere comprising the southeast end of the microplate, which would initially have been part of Arabia. When the propagating Asal-Ghoubbet Rift formed, this region became part of a microplate that rotated clockwise relative to Africa. Finally, when the old rift failed, this region was transferred to the Somalian plate. An alternative scenario (time T_4 in Figure 12) is for the microplate to persist into the future. This small microplate could eventually become part of Nubia and/or Somalia or could continue to grow as a separate plate.

Although model 1 oversimplifies the tectonics, it predicts the observed time of formation and location of the more prominent rifts. In addition, it predicts the ~11° of clockwise rotation shown by the paleomagnetic data. The main limitation of the model is that it treats an area that has sustained internal deformation, especially at the Hanle and Gaggade rifts, as a single rigid microplate.

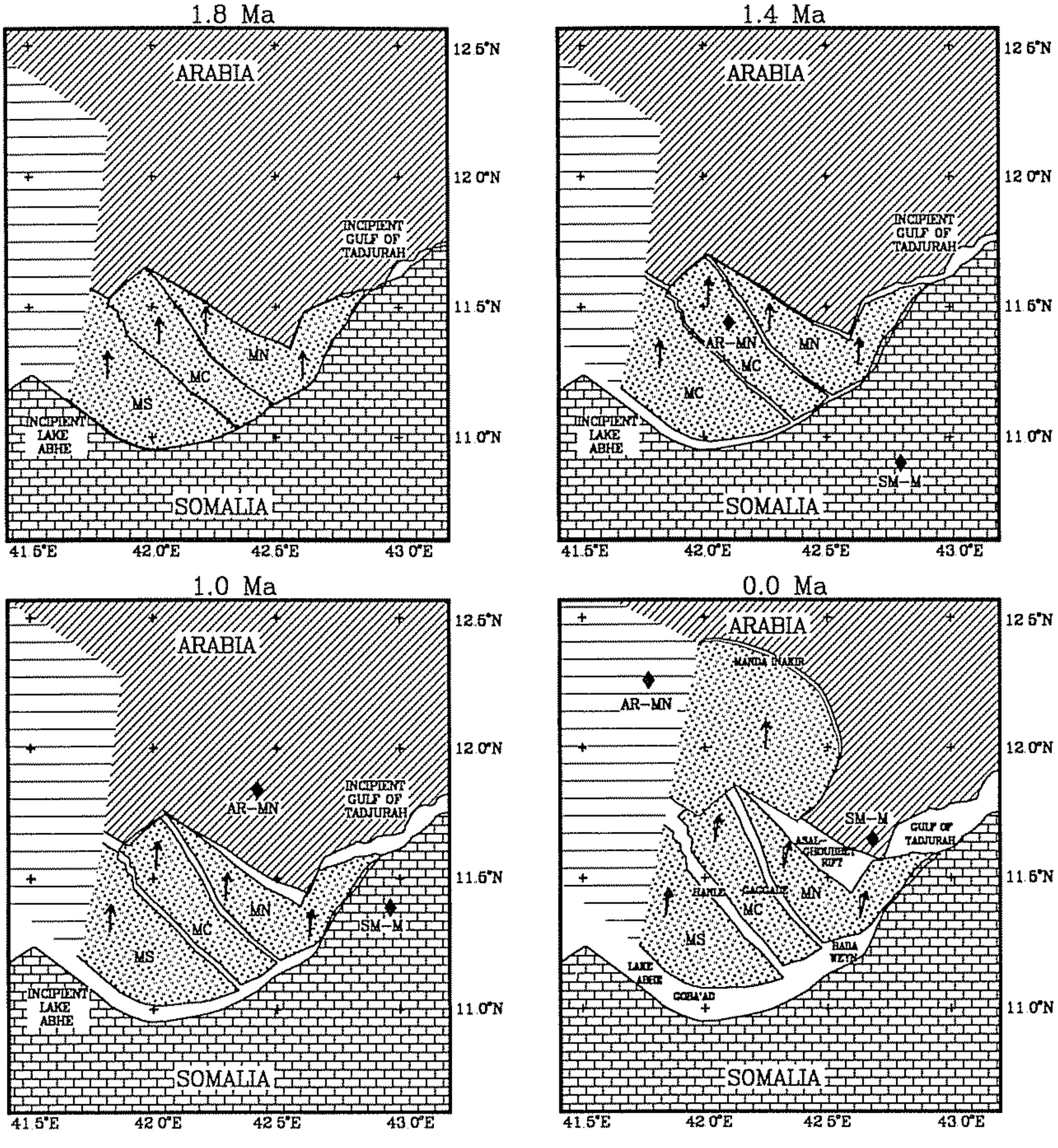

Fig. 13. Multiple microplate evolutionary model (model 2) for Afar. SM-M denotes Somalia-microplate Euler pole (diamond), and AR-MN denotes Arabia-northern microplate Euler pole (diamond). Microplate rotations are represented by the angles between the north pointing lines and arrows. The horizontally lined region was not modeled.

Model 2

The model can be improved by treating the interior of Afar as three microplates [Stein et al., 1989] (Figure 13). The additional microplates yield a more complex model which, not surprisingly, can fit the observations better. For simplicity, the three microplates have the same Euler pole relative to the Somalian plate, but their rates of rotation vary. As a result, motion with respect to Somalia is a minimum for the southern microplate, intermediate for the

TABLE 2. Rotation Parameters Used in Model 2

	Rotation Relative to Arabia			Rotation Relative to Somalia		
Plate	Lat °N	Lon °E	Rot Angle deg	Lat °N	Lon °E	Rot Angle deg
			Time Interval = 0.0–0.2 Ma			
Somalia	23.80	23.40	-0.08	0.00	0.00	0.00
Arabia	0.00	0.00	0.00	23.80	23.40	0.08
MN	12.51	41.50	-1.20	11.65	42.68	-1.12
MC	12.96	40.85	-0.78	11.65	42.68	-0.70
MS	13.41	40.21	-0.58	11.65	42.68	-0.50
			Time Interval = 0.2–1.4 Ma			
Somalia	23.80	23.40	-0.49	0.00	0.00	0.00
Arabia	0.00	0.00	0.00	23.80	23.40	0.49
MN	12.01	42.25	-11.54	11.39	42.96	-11.08
MC	12.18	42.01	-8.77	11.39	42.96	-8.31
MS	12.51	41.54	-5.99	11.39	42.96	-5.53
			Time Interval = 1.4–1.6 Ma			
Somalia	23.80	23.40	-0.08	0.00	0.00	0.00
Arabia	0.00	0.00	0.00	23.80	23.40	0.08
MN	11.44	42.10	-2.01	10.90	42.80	-1.94
MC	11.54	41.97	-1.69	10.90	42.80	-1.62
MS	11.69	41.77	-1.37	10.90	42.80	-1.30
			Time Interval = 1.6–1.8 Ma			
Somalia	23.80	23.40	-0.08	0.00	0.00	0.00
Arabia	0.00	0.00	0.00	23.80	23.40	0.08
MN	0.00	0.00	0.00	23.80	23.40	0.08
MC	23.80	23.40	-0.02	23.80	23.40	0.06
MS	23.80	23.40	-0.04	23.80	23.40	0.04

MN, MC, and MS refer to northern, central, and southern microplates of the model; Lat, Lon, and Rot Angle are the latitude, longitude, and rotation angle for the Euler pole.

central microplate, and maximum for the northern microplate. The northern microplate diverges from Somalia at a rate similar to that of the single microplate in model 1. The three microplates simulate a single microplate that is breaking up, so that extension, rather than being uniform, occurs at the boundaries between three relatively rigid blocks. Since most of the extension occurs on the major (Asal-Ghoubbet, Bada Weyn, and Goba'Ad) rifts, the area evolves essentially as a single microplate, even though minor internal deformation occurs on secondary (Gaggade and Hanle) rifts.

Model 1, though designed only to describe the area in which paleomagnetic data and data on the age of rifting are available, covers a somewhat larger region. The more detailed model 2 describes only the eastern portion of Afar and thus does not involve the Nubian plate. The Euler poles and rotations for this model are listed in Table 2. Arabia–Somalia motion is taken from the NUVEL-1 plate motion model [DeMets et al., 1990]. As in model 1, the Euler poles describing the motion of the microplates relative to Arabia are near the propagating Asal–Ghoubbet Rift tip.

The three microplates were defined as the regions between the major present rifts. The initial configuration, which is assumed to correspond to 1.8 Ma, was determined by rotating the blocks backwards in time to close the present rifts. This procedure ensures that the net extension through time yields the present graben widths, though it also slightly overestimates the net extension. The three microplates fit tightly between the Arabian and Somalian plates. Since the block boundaries could not be determined that precisely, they were chosen to avoid gaps and overlaps in the initial configuration. The Arabian and Somalian boundary east of 42.9°E is the 100-m bathymetric contour [CNR–CNRS, 1975]. Thus the small gap between Arabia and Somalia at 43°E longitude, after rotation to 1.8 Ma, results from the small misfit of this contour. We did not model the evolution of the area shown by the horizontal line pattern in Figure 13, where there is no paleomagnetic data and the timing of graben formation is not known well.

The plates begin to separate at 1.8 Ma. From 1.8 to 1.6 Ma the northernmost microplate moves as part of Arabia. The central microplate moves away from the southern microplate, which in turn separates from Somalia. The separation of the Arabia (AR), the northern microplate (MN, which is part of Arabia at 1.8 Ma), the central microplate (MC), and the southern microplate (MS) from Somalia (SM) is described by a single Euler pole with varying rotation rates. During this period, regional extension (modeled here as on discrete rifts) occurs, but rift propagation has not yet begun.

At 1.6 Ma, a rift, responsible for the opening of the western portion of the Gulf of Tadjurah and the creation of Lake Ghoubbet and Lake Asal, forms along the boundary between the northern microplate and Arabia. For simplicity, the rift is assumed to have propagated instantaneously to the position shown at 1.4 Ma. The AR–MN Euler pole is assumed to be near the rift tip. This geometry, and the assumption that the motion of all the microplates with respect to Somalia is about a single pole, produces rotations relative to Somalia. By 1.4 Ma the microplates have rotated by 1°–2° clockwise relative to Somalia, by 1.0 Ma they have rotated by 3°–6°, and by 0.5 Ma they have rotated by 5°–9°. These paleomagnetically detectable rotations are smallest for MS, intermediate for MC, and largest for MN.

At 0.2 Ma, the MN-AR boundary continues to evolve as a new rift forms to the northwest of the Asal–Ghoubbet Rift. The new rift, which corresponds to the Manda Inakir Rift, is connected to the Asal–Ghoubbet Rift by a transformlike zone corresponding to the highly faulted region north of Lake Asal (Figure 9). The region south of Manda Inakir becomes part of the northern microplate.

Comparison of the 0.0 Ma model 2 plate geometry to the present day geology (Figure 14) illustrates that the predicted zones of extension (gaps) correspond to the sediment filled rifts and the zones of recent volcanism. The predicted rift widths reflect the assumption that most of the extension occurred on the major (Asal-Ghoubbet, Bada Weyn, and Goba'Ad) rifts. The sense of motion on the boundaries of the microplates agrees with observed normal and left-lateral strike-slip faulting and with the extensional focal mechanisms in the Asal–Ghoubbet rift. The model also predicts right-lateral motion between Somalia and MN along its eastern boundary, in agreement with the faulting observed at Arta [Lepine et al., 1976]. The predicted history of rifting accords with that observed (Figure 7). Finally, the predicted ~11° of clockwise rotation agrees with that paleomagnetically determined.

ANALOGY TO DISTRIBUTED DEFORMATION MODELS

Our preferred model, model 2, describes the kinematics of Afar using three microplates that lie between the major plates. In the model, the area evolves essentially as a single microplate bordered by the major (Asal-Ghoubbet and Goba'Ad) rifts, though minor deformation within the region occurs on secondary (Gaggade and Hanle) rifts. It is interesting to compare our model to other models for the motion of rigid blocks between major plates. We will see that the other models are generally similar, but have some different features.

Tapponnier et al. [1990] proposed that the deformation within the major rifts occurred by "bookshelf" faulting [Freund, 1974; Garfunkel, 1974; Garfunkel and Ron, 1985], such that this region is broken into roughly eight northwest-southeast trending blocks that slide past each other as the rotation occurs. This model differs from ours largely in treating NW-SE structures within the region as pure strike-slip faults, whereas we treat them as largely extensional. Their model predicts left-lateral motion on the faults, consistent with their observations of left-lateral faulting just north of the Hanle graben and at Serdo. Their model does not, however, predict the dominant normal faulting within the region. Instead, the region sustains a small amount of shortening in the Arabia-Somalia extension direction (their Figure 5). Our model, in contrast, predicts that motion on the NW-SE structures treated as secondary rifts is dominantly extensional, with some left-lateral strike-slip.

Another class of block models for distributed deformation considers the motion of blocks floating in a deforming fluid [McKenzie and Jackson, 1983, 1986; Garfunkel and Ron, 1985; Lamb, 1987; Garfunkel, 1988]. These models are motivated by a desire to relate the observed crustal motions, which occur as blocks translate and rotate while incurring essentially no internal deformation, to presumed motions of a continuously deforming lower lithosphere. Such a variation in deformation mode with depth is suggested by seismological observations [Chen and Molnar, 1983; Wiens and Stein, 1983] and rheological models based on laboratory studies [Goetze and Evans, 1979; Kirby, 1980; Brace and Kohlstedt, 1980] indicating that only the upper lithosphere is strong enough to sustain significant stresses.

In such models, the blocks are not required to remain in contact. McKenzie and Jackson [1986] use a model in which the blocks in the deforming zone are pinned to the two major plates bounding the zone. Figure 15 shows such a geometry for eastern Afar, in which the x-axis trends N50°E and corresponds roughly to the southeast boundary of the blocks in our model 2, from the Arta region through the Bada Weyn graben to Goba'Ad graben. The faults which bound the blocks originally trend N60°W, making an angle $\theta = 70°$ with the x-axis prior to rotation. As the Arabian plate moves away from Africa, the deforming region is extended and sheared in a right-lateral sense, and the blocks rotate. Faulting between the blocks consist of both normal

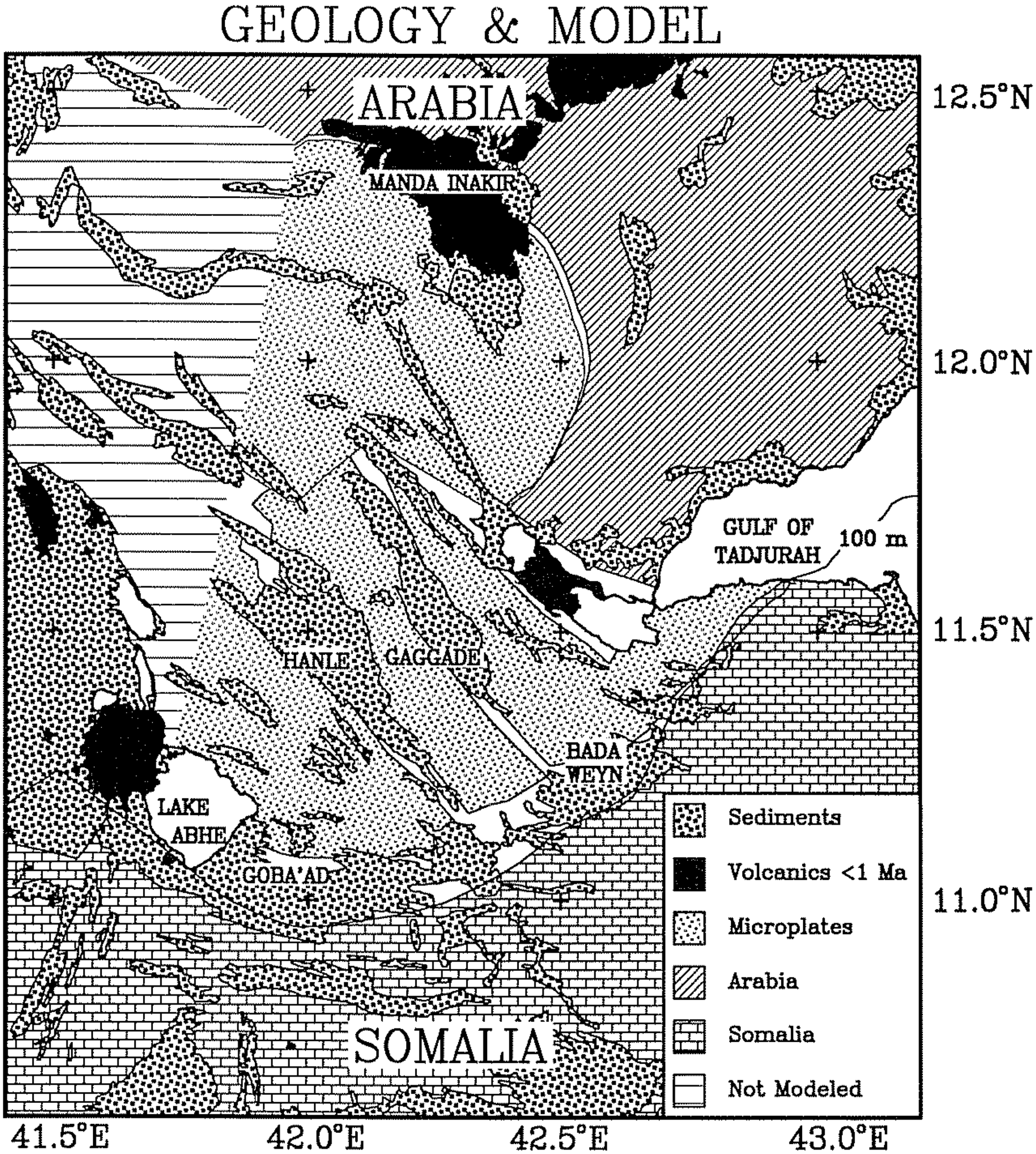

Fig. 14. Comparison of present rift geometry predicted by the multiple microplate model (Figure 13, lower right) with distribution of recent basalts and rift filling sediments (Figure 5).

and left-lateral strike-slip motion. The final geometry of the blocks and zones bounding them, assuming a rotation of 11°, is similar to that of our model 2. One difference occurs along the southeast boundary, running from the southeast Goba'Ad graben to the Bada Weyn graben, where we have inferred extension. Both the pinned-model and the model proposed by Tapponnier et al. [1990] predict little extension in this region. McKenzie and Jackson [1986] discuss another version of the distributed deformation model in which the blocks, rather than being pinned, are free floating.

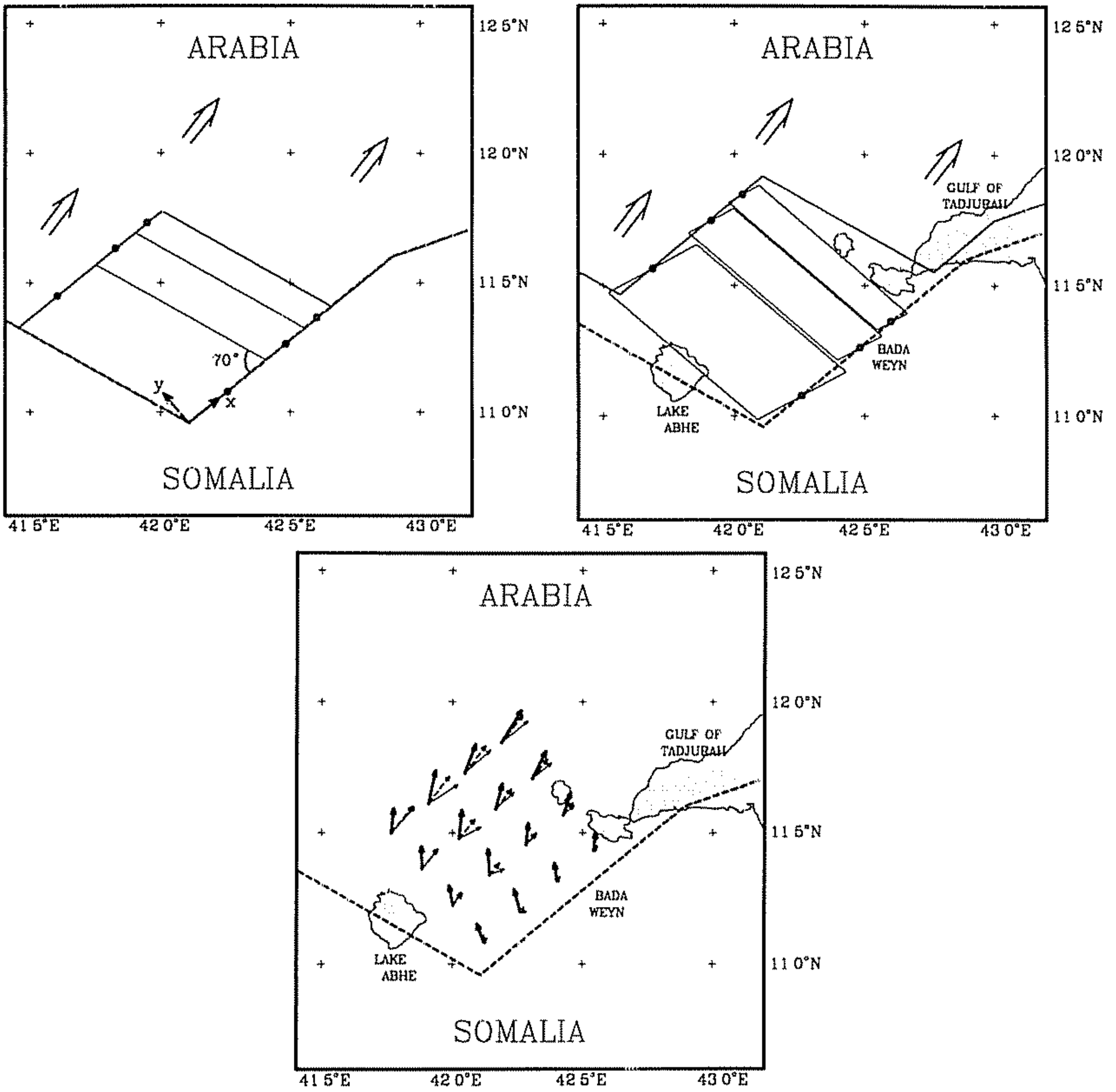

Fig. 15. (Top left) Initial geometry used for the pinned rigid block model, showing blocks (thin lines), pin positions (dots), and coordinate axes. The boundaries of the deforming zone with Arabia and Somalia are shown. Arrows show motion of Arabia relative to a fixed Somalia. (Top right) Geometry for the pinned rigid block model after 12° rotation about pins. As for the microplate model (Figure 13), extension occurs along the main rifts and both extension and left-lateral strike-slip occur between blocks. In contrast, opening does not occur along the Bada Weyn Rift (southeast boundary). (Bottom) Velocities with respect to Somalia of points within Afar for the microplate model 2 (thick arrows) and for the blocks (thin arrows) and fluid substratum (dashed arrows) for the pinned model

In the free-floating version, the blocks would not be required to remain near the major plates, and features such as the southeastern Goba'Ad and Bada Weyn rifts might form.

It is interesting to compare the velocities for the rigid blocks predicted by our model to the predictions of the McKenzie and Jackson [1986] model for the rigid blocks and the underlying deforming continuum. The Euler poles in Table 2 are used to compute the velocities for our model 2 relative to Somalia, shown by the thick solid arrows in Figure 15 (bottom). For the McKenzie and Jackson model, with a deforming zone of width a, the instantaneous components of the plate velocities normal and parallel to the zone are $-2Ta$ and Wa. For the geometry in Figure 15 and for a velocity of Arabia relative to Somalia of 17.2 mm/yr directed N37°E [DeMets et al., 1990], $Wa = 16.8$ mm/yr and $-2Ta = 3.9$ mm/yr. The fault trend θ and rotation rate $d\theta/dt$ are given by

$$\tan\theta = -W/2T \qquad d\theta/dt = W \tag{1}$$

for the pinned block model and by

$$\tan\theta = -W/4T \qquad d\theta/dt = W/2 \tag{2}$$

for the free-floating block model. For the velocities derived here and assuming $a = 80$ km, we obtain $\theta = 77°$ and $d\theta/dt = 12°$/m.y. for the pinned model and $\theta = 65°$ and $d\theta/dt = 6°$/m.y. for the free-floating model. Thus the present and prerotation fault trends are comparable to the predictions of either model. Assuming that most of the rotation occurred over about 1.5 m.y., the observed rotation rate is 8°/m.y., also comparable to either model. The computed rotation rate, however, depends on the value of a, which is poorly constrained. Similarly, the observed rotation rate is poorly constrained because all we know is that the rotation occurred subsequent to the formation of the rocks at ~1.8 Ma. The block velocities for the pinned model, computed assuming rotation about the pins at 12°/m.y., are shown by thin solid arrows. Since this model precludes much opening at the Bada Weyn Rift, the predicted velocities trend east of those predicted by our model.

The velocity of a point in the underlying continuous medium can be obtained from the velocity gradient tensor **L**, formed from the derivatives of the velocity components u, v, and w in the x, y, and z directions

$$\mathbf{L} = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z} \end{bmatrix} = \begin{bmatrix} 0 & W & 0 \\ 0 & -2T & 0 \\ 0 & 0 & 2T \end{bmatrix} \tag{3}$$

[McKenzie and Jackson, 1983]. The velocity gradient tensor on the right side of the equation is derived assuming that the velocity gradients are constant within the deforming zone. For the assumed geometry, the predicted velocities appropriate for both the pinned and free-floating block models are shown by the dashed arrows in Figure 15 (bottom). These typically lie between the rigid block velocities predicted by our model and the pinned model. All vary rapidly in the y direction and less so in the x direction. As for the rigid blocks, the predicted fluid motion does not show extension near the southeastern Goba'Ad and Bada Weyn rifts.

Comparison of models suggests that the block motions are better described by our microplate model than by the bookshelf model or the pinned block model used here, provided that extension has occurred along the secondary rifts and along the Goba'Ad and Bada Weyn rifts. Additional geological and geophysical studies are needed in these regions to quantify the amount of extension and thus provide better model constraints. Our model 2 is most similar to the free-floating block model in that both predict extension and left-lateral strike-slip faulting between blocks and neither model requires that the blocks remain in contact with the surrounding major plates. More direct model comparisons may be possible in the complicated regions bounding the major plates, such as those occurring near the Bada Weyn Rift, if complexities in relating fluid motions of the lower crust or mantle to deformation of the brittle upper crust are incorporated into the continuum models.

Analysis of the fluid motions in the lower lithosphere predicted by the various models is difficult, since the fluid motions are not directly observable at the surface. As a result, whether any of the models accurately describe the deformation of the lower lithosphere is unclear. The velocity field presumably depends on the three-dimensional geometry of the plate boundaries, on the size, shape, and orientation of the blocks, and on the interaction of the blocks with the medium, with other blocks, and with the major plates. Numerical models that consider these complexities and incorporate realistic rheologies may provide additional insight into the complex tectonics of Afar.

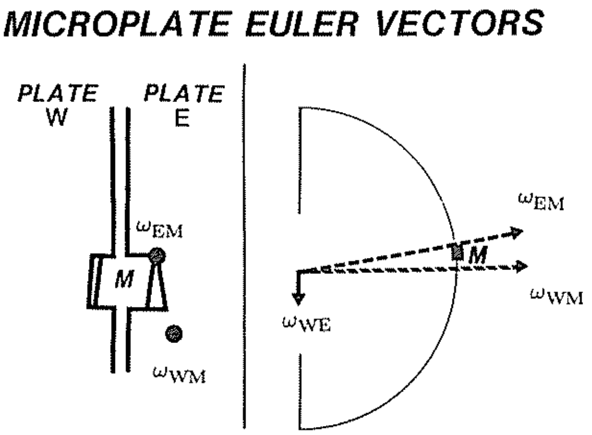

Fig. 16. Geometric constraints on the Euler vectors for a three-plate system: a microplate (M) between western (W) and eastern (E) major plates. If ω_{WE}, the Euler vector for the western plate relative to the eastern one, is far away, and ω_{EM}, the Euler vector for the eastern plate relative to the microplate, is near the rift tip, the magnitude of the latter must be much greater for the spreading rate on the southernmost portion of the propagating rift to be comparable to that between the major plates. As a result, ω_{WM}, the sum of the other two Euler vectors, is similar in both direction and magnitude to ω_{EM}. Since both poles are nearby, relative velocities vary rapidly along the microplate's boundaries [Engeln et al., 1988].

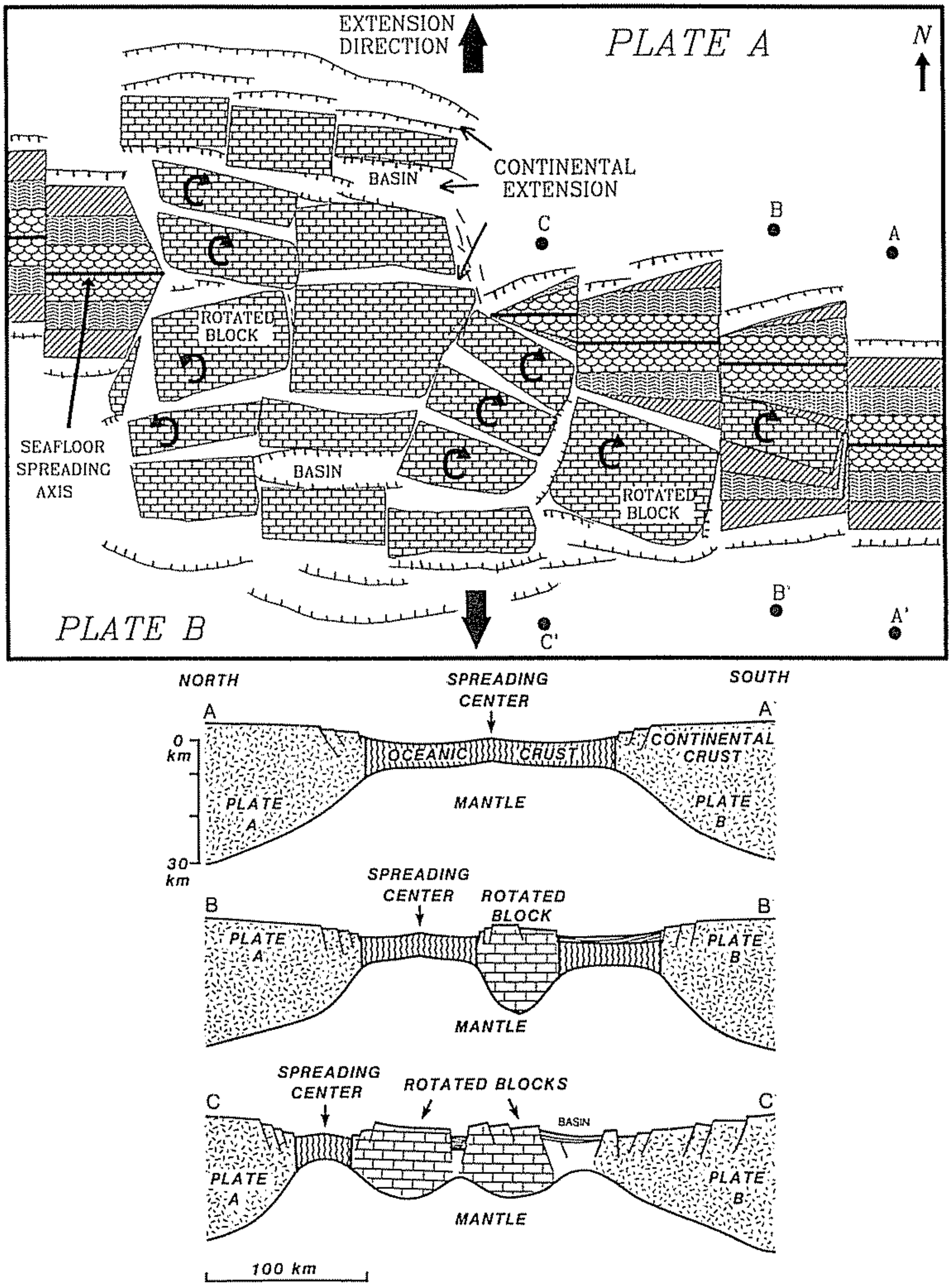

Fig. 17. Implications of microplate evolution models for continental margin geometry. (Top) Schematic map view of extensional region between continental plates, in which rift propagation rate and geometry, the final location of the spreading axis, and the size and shape of microplates vary along strike. (Bottom) Schematic cross sections through the region shown above, illustrating various possible geometries.

DISCUSSION

We have seen that the history of rifting, the rotation, and several other features of the regional geology of Afar can be described using block models. The simple model, essentially an oceanic microplate model, describes the geometric relation and timing of motion on the Goba'Ad, Bada Weyn, Manda Inakir, and Asal–Ghoubbet rifts and the paleomagnetically observed rotation. Its limitation is that it does not describe the internal deformation, especially at the Hanle and Gaggade rifts, of the Afar region.

The second model, which treats the extension within Afar, incorporates features of the concept of rift localization [Courtillot, 1982], in which extension within a broad locked zone is eventually concentrated on a single spreading center. In the early stages (> 1.6 Ma) of this model, Afar acts as a zone deforming under extension, and seafloor spreading does not yet occur. Our model treats the extension as occurring on several discrete rifts. Subsequently, the Asal-Ghoubbet Rift begins to form as the Gulf of Aden spreading center propagates westward into Afar, while extension still occurs on several other rifts. We treat this phase by analogy to the oceanic microplate situation, in that a finite "rise time" is required to transfer all of the spreading to the new rift, so several ridges are simultaneously active [Engeln and Stein, 1984]. In this conceptualization, the process differs from the simple oceanic microplate case only in that several microplates are present. In the Courtillot [1982] formulation, rift localization could be viewed as proceeding but not yet completed. Our model has the feature that this localization occurs in a specific fashion, in which extension concentrated on a set of rifts is transferred to a single rift that eventually evolves into a seafloor spreading center. The pattern of this sequence of events predicts the observed rift history and the rotations. In the Lake Asal area, localization may have reach completion and the early stages of seafloor spreading may be occurring. Further to the northwest, it appears that the localization process is still continuing.

The localization process, which gives rise to observable block rotations, may reflect two constraints, one kinematic and one mechanical. Over a length comparable to the block or microplate dimensions, the spreading rate changes from essentially zero to the full spreading rate between the major plates. To achieve this rapid variation, the Euler pole for the propagating rift and hence those for the other microplate boundaries are near the microplate (Figure 16). In the oceanic case, the dimension of the microplates varies significantly [Acton et al., 1988], perhaps because microplates can evolve from ridge-transform configurations with varying offsets. In a continental case, the block dimension may reflect the thickness of the mechanically strong upper portion of the lithosphere.

If the tectonics of Afar are typical of that at continental rifts, they have interesting implications for the geometry of rifted continental margins [Courtillot, 1982; Vink, 1982; Bosworth, 1985; Dunbar and Sawyer, 1989a]. For example, if the final location of the rift axis does not always occur at the center of the zone of disrupted lithosphere, then passive margins may often be asymmetric in structure and may have abrupt as well as gradual along strike variations (Figure 17). Similarly, an asymmetric location of the rift axis could lead to asymmetry between opposing margins, as observed for the Red Sea, even if subsequent seafloor spreading was symmetric. Additionally, along-axis structural variations will result if the rates of rift propagation and localization are not uniform (Figure 17). Variations in the rate of rift propagation and in the location and rate of localization may be reflected in the variations in total tectonic subsidence across the passive margins of the central and north Atlantic and Labrador basins [Dunbar and Sawyer, 1989a]. Such variations may also reflect variations in the mechanical properties of the lithosphere due to compositional and topographic variations, thermal anomalies, and preexisting structural fabric [e.g., Wilson, 1968; Morgan, 1972, 1981; Vink et al., 1984; Steckler and ten Brink, 1986; Dunbar and Sawyer, 1989a, b; White and McKenzie, 1989].

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