Tectonic Significance of Regional Geology and Evaporite Lithofacies in Northeastern Ethiopia

R. W. Hutchinson and G. G. Engels

Phil. Trans. R. Soc. Lond. A 1970 **267**, 313-329
doi: 10.1098/rsta.1970.0038

Phil. Trans. Roy. Soc. Lond. A. **267**, 313–329 (1970) [313]
Printed in Great Britain

Tectonic significance of regional geology and evaporite lithofacies in northeastern Ethiopia

By R. W. HUTCHINSON
Department of Geology, University of Western Ontario, London, Canada

and G. G. ENGELS
Mobil Petroleum Ethiopia Inc., P.O. Box 899, Asmara, Eritrea, Ethiopia

Mesozoic and Precambrian rocks are exposed in the Danakil Alps of coastal Eritrea, but the Danakil Depression between the Alps and the Ethiopian plateau is covered by Tertiary–Quaternary rocks. The physiography, structural geology, regional stratigraphy and evaporite lithofacies distribution of this area all suggest that it is underlain by an asymmetrically subsided block of old sialic crust. The western edge of this block has subsided deeply along the Ethiopian rift and is covered, in the Danakil Depression, by an evaporite-basalt veneer, but its eastern edge has been uplifted as the Danakil Alps. These are bounded on the east by a rift escarpment facing the Red Sea. Although geologic data here is sparse compared to the Danakil region, certain features suggest that a similar asymmetrically subsided block of older sialic rocks, with an evaporite-basalt veneer, may also lie beneath much of the Red Sea.

This tectonic evolution apparently commenced in Miocene time with rifting near the centre of an earlier Mesozoic–Paleogene sedimentary basin. Uplift along this central rift caused tensional failure along a secondarily induced rift to the west, and east-side-down subsidence along this structure formed the asymmetrically subsided block. There were apparently two successive cycles of this tectonic activity. The earlier, of Miocene age, formed the easterly (Red Sea) block with a thicker veneer of older evaporite-basalt, and the later, of Plio-Pleistocene age formed the westerly (Danakil) block with a thinner veneer of younger evaporite-basalt. The separation of Arabia from Ethiopia across the southern Red Sea would thus be relatively minor, presumably represented by the width of the Red Sea's axial trough plus a few kilometres across each of the Danakil Alp and Ethiopian rifts.

Similar tectonic developments may accompany initial rifting and separation in the development of ocean basins by seafloor spreading, and might explain why oceans like the Atlantic, that have apparently developed in this manner, are fringed by shallow continental shelves with thick evaporite sequences and steep walled submarine canyons.

Introduction

Tectonic problems in the southern Red Sea region include the age of rift faulting, the duration and amount of separation of the rifted blocks, and the detailed mechanisms of fault block movement. Geophysical evidence bearing on these problems has led to contradictory suggestions concerning the tectonics of the region. Laughton (1965, p. 87) discussed this controversy, and using information from the Gulf of Aden, favoured major crustal separation of the rifted blocks (Laughton 1965, pp. 92–93). Data presented by Drake & Girdler (1964, p. 489, figure 14) and Girdler (1967, figure 6, p. 174) for the northern and southern Red Sea, however, suggested only minor separation but major subsidence of the crustal blocks.

Recent exploration for both petroleum and potash in northeastern Ethiopia provides geologic information that is significant to the tectonic problems and can be used to evaluate these alternative possibilities. It also permits a more complete and detailed interpretation of the tectonic evolution and geologic history of this area. The pertinent geologic information includes topographic and physiographic data, structural geologic relationships, geologic age determinations and, in particular, the stratigraphy of Mesozoic and Cenozoic rocks. Most of this information is derived from work in the regions westward from the Eritrean coast, south of latitude 15° N and is therefore highly informative about tectonic developments in the region between the Eritrean coast and the Ethiopian plateau, particularly the Danakil Depression and the Danakil Alps. Unfortunately it does not provide much evidence about tectonic events beneath the Red Sea itself, although a probable interpretation is presented.

The purpose of this paper is to present the pertinent geologic data, to consider it in relation to prior tectonic hypotheses, and to deduce from it revised concepts of the tectonic history and evolution of this interesting region.

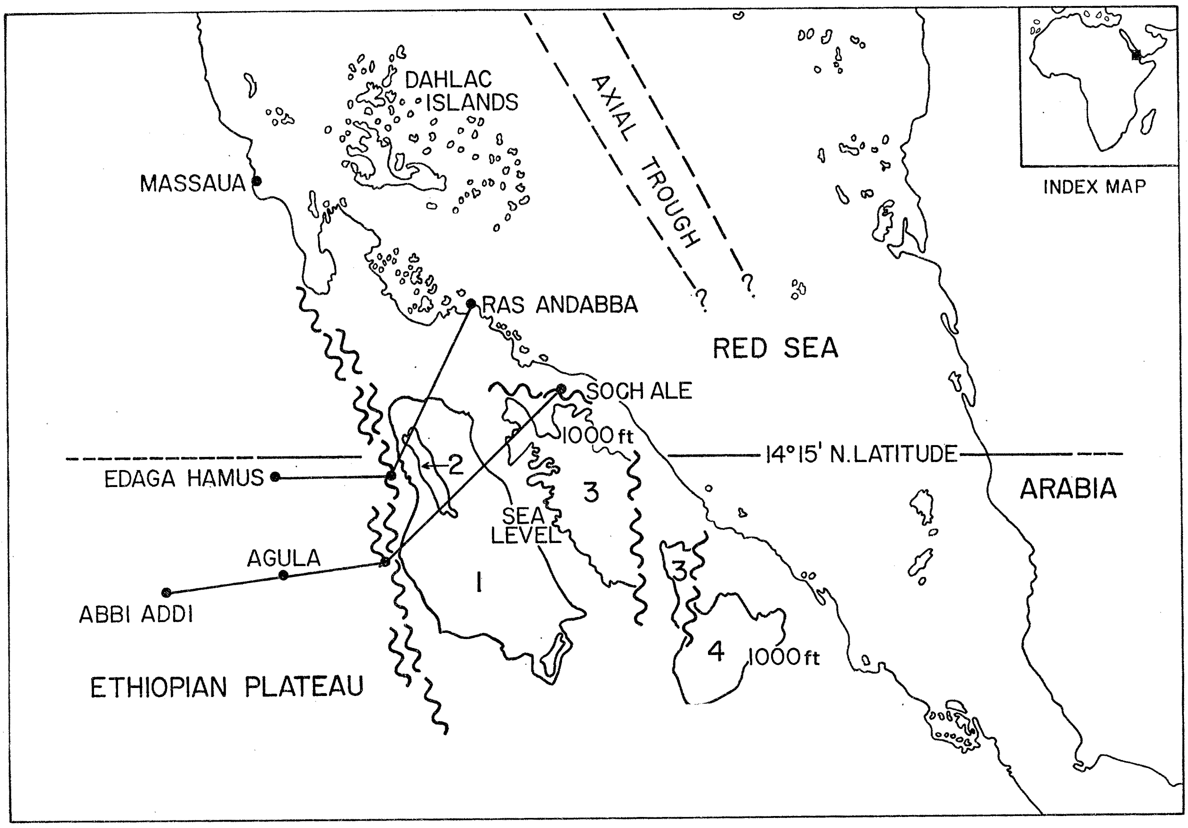

Figure 1. Generalized topographic and geologic map of the southern Red Sea. 1, Danakil Depression; 2, salt pan; 3, Danakil Alps (pre-Tertiary rock); 4, Danakil Alps (younger Basalt); ~ ~, fault zone; ●—●, line of section. Scale 1:4 000 000.

2. Regional geology

(a) *Physiography*

Proceeding eastward along the 14° 15′ latitude parallel from central Ethiopia, the physiographic blocks that must be considered in relation to the tectonic problems are the main Ethiopian plateau, the Danakil Depression which is a northward extension of the Afar Depression, the Danakil Alps, the Eritrean coastal regions both onshore and offshore, and the axial trough of the Red Sea (figure 1).

General elevations above 2000 m, with local heights up to 4600 m, prevail in the west on the Ethiopian plateau (figure 2). This is bounded to the east by a steep, rugged, dissected escarpment some 50 km wide, across which elevations drop rapidly to a few hundred feet below sea level in the Danakil Depression. The deepest floor of this interior drainage basin, at an

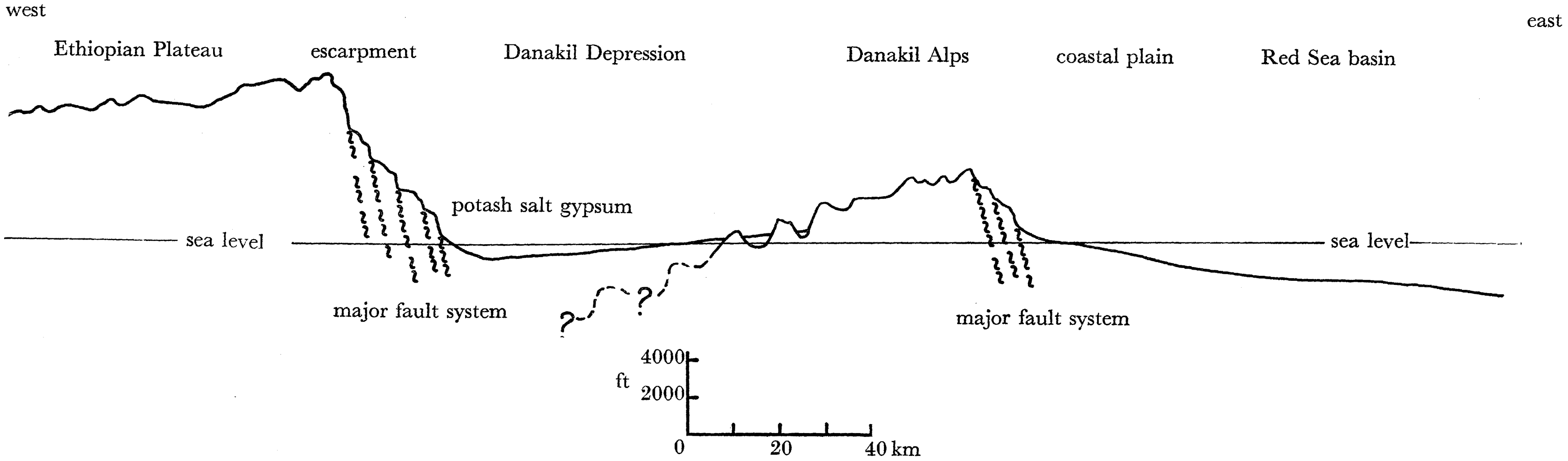

FIGURE 2. Topographic profile along 14° 15′ N, showing location of fault zones and evaporites.

elevation of −116 m, lies just east of the foot of this escarpment, and is occupied by a salt pan marking the surface exposure of extensive halitic evaporite beds (Holwerda & Hutchinson 1968, p. 128). Eastward from the salt pan, elevations rise very gradually for some 65 km, reaching average heights of about 370 m, with local elevations up to 730 m, in the Danakil Alps. These form the height of land between the Danakil Depression and the Red Sea. The western slopes of the Danakil Alps, although rugged and much dissected, are nowhere abrupt nor is there any apparent linear feature along which a break in slope occurs. Eastward from the Danakil Alps, elevations decrease gradually to the Red Sea coast, but in some places abrupt, low, eastfacing scarps are present. The eastern slopes are also rugged and dissected, especially in their higher parts, but a major break in slope, marking the eastern 'foot' of the Danakil Alps and separating their rugged, steeper, higher extremities from the gentle slopes of the coastal plain, occurs along a prominent north–south linear that is readily apparent on topographic maps. The Red Sea coast offshore has broad, shallow shelves dotted with coral reefs and islands (Laughton 1965, p. 79) and its axial trough may not extend south of latitude 15° N as a recognizable feature (Drake & Girdler 1964, figure 14).

(*b*) *Fault systems*

Geologic mapping reveals the presence of two prominent fault zones in these regions (figure 2). The greater of these, the Ethiopian rift system, crops out prominently along the main north-trending escarpment which marks the boundry between the Ethiopian plateau and the Danakil Depression. This broad fault zone consists of innumerable closely spaced, normal faults with northerly strikes and steep easterly dips as well as many west-dipping faults of lesser magnitude. Together these comprise an extremely complex fault system and, as a result, it is difficult to work out either the detailed structural relations between the various fault blocks and slices, or individual movement on any one fault. In general, however, proceeding eastward across the zone, bedding attitudes are tilted more steeply to the east, suggesting that successive slices have subsided and tilted downward and outward to the east away from the main plateau. The minor faults disrupt this regional pattern to produce local, west-tilted but smaller blocks. However, overall movement on this great fault zone is normal with east-side-down offset of unknown magnitude. Offset must be at least 1050 m based on drilling results in the salt pan about 5 km east of the foot of the escarpment, but is probably much greater. Less prominent, but apparently similar zones of faulting are present in places along the eastern and northern sides of the Danakil Alps (figures 1 and 2). These fault zones, hereafter termed the Danakil Alp rift, also consist of numbers of steep eastward dipping, normal faults with northerly trends along the east side of the Alps, and easterly trends with northerly dips along the north side. Some of the individual faults crop out along the low scarps that are present in this area. Mapping of bedding attitudes shows that successive fault slices here too are each tilted to the east or north as if they had collapsed and subsided outward and away from their neighbouring slices.

The geometry of both these fault systems is similar. Both have similar trends and dips, form the eastern boundary of physiographically high blocks, and result in east-facing scarps. Thus they are replicas, but not mirror images of one another. This is significant to an interpretation of tectonic relations, because no 'mirror image counterpart' of these fault systems has been recognized in the area in the form of west-dipping normal fault zones or west-facing scarps, either through geologic mapping or from air photo interpretation. In particular, no major west-dipping fault system or scarp such as that described by Laughton (1965, p. 92) is recognizable bounding the Danakil Alps on the west. However, minor faults, fissures and joints with no preferred trend are present in this area, and may show minor offset. Some of these are feeders for basalt flows that are abundant here. They appear to be minor disruptions that cut the Danakil Alp block into many smaller blocks tilted at varying angles relative to one another.

The west flank of the Danakil Alps is predominantly a gentle, west-sloping Quaternary outwash plain, broken occasionally by outliers of older rocks, including Precambrian rocks like those in the higher areas of the Alps to the east, that protrude through it. This is in contrast to the areas east of the two steep, east-facing, rift-controlled escarpments where no such outliers occur (figure 2).

(*c*) *The Danakil Depression*

The Danakil Depression, lying between the Danakil Alps and the great escarpment bounding the Ethiopian plateau, is entirely floored by very young strata including extensive marine evaporite beds, mainly halite (Holwerda & Hutchinson 1968). The deepest floor of the Depression is an elliptical salt pan about 40 km long, 10 km wide and elongated SSE–NNW. This salt pan is asymmetrically located near the Depression's western margin within 5 km of the foot of the rift escarpment, but is some 50 km from the eastern margin of the Depression. It is the outcrop of a very thick sequence of bedded halite. Within the bedded halite along the extreme western margin of the Depression are at least two intervals containing potash and other bittern salts. Both eastern and western edges of the salt pan are covered by Recent alluvium deposited above the salt by runoff streams draining into the Depression.

Eastward, beyond the alluvium, bedded gypsum crops out over an extensive area of the Depression's gently west-sloping eastern flank, and is locally both underlain and overlain by basalt flows that are apparently a result of fissure eruptions (Mohr 1961, p. 171). Further eastward are exposures in which the gypsum is intercalated with red clastic sedimentary rocks. Basalt flows again are numerous both above and below the red beds. Also overlying both the gypsum and the red beds is a thin reefal limestone of either uppermost Tertiary or Quaternary age.

Structural geology within the Depression, as deduced from surface geologic relations, geophysical data and drill hole information, is markedly asymmetric. Ground magnetic and gravimetric surveys of the salt pan, and of parts of its immediate margins (Holwerda & Hutchinson 1968, figures 17 and 18) indicate that the deepest part of this basin lies beneath a line through the major axis of the pan. This basinal trough thus trends parallel to the rift escarpment about 8 km east of its foot, but lies 50 km west of the Depression's eastern margin. The deepest hole drilled in the Danakil Depression was sited nearly on this trough, and penetrated 975 m of bedded halite containing two intervals of bittern salts.

Several unique topographic features, including volcanic vents, domal uplifts, thermal springs and brine pools occur along this axial line (Holwerda & Hutchinson 1968, pp. 129–131), and are apparently due to subsurface igneous activity. These features lie along the same trend as the active volcanic ranges of Erta'Ale and Alaita to the south. Basaltic lavas from these volcanos are considered to be of mafic subcrustal type, uncontaminated by any sialic crustal material (Barberi *et al.*, this volume, p. 293) although elsewhere in the Afar region silicic lavas are abundant and suggest interaction between subcrustal magma and sialic crustal rock.

The red clastic and gypsum strata east of the salt pan dip very gently westward toward the trough at a few to several metres per kilometre. Subsurface correlations indicate that the upper potash interval along the western edge of the basin dips eastward toward the trough at as much as 100 m per kilometre, more than ten times as great as dips prevalent in the east.

The lithofacies distribution in the Danakil Depression is significant, and also reflects the basin's asymmetry. Red beds with associated basalt flows occur high on the eastern flank. Further into the Depression these rocks are succeeded in turn by extensive gypsum beds also associated with basalt flows, by thick halite beds and finally, in the extreme west, by interbedded halite and bittern evaporites. Regardless of the correlation between these units, this pattern shows increasing salinity from east to west with extreme salinity in the trough of the Depression, where bittern salts were deposited, but with less saline evaporites being deposited over the shallower eastern flanks. Inflow of marine water into this basin is believed (Holwerda & Hutchinson 1968, p. 141) to have been from an easterly direction over a barrier provided by the emerging Danakil Alps, which would explain this distribution of evaporite lithofacies.

Textural and stratigraphic relationships suggested that sylvite-rich beds of the upper potash-bearing interval might be of Pleistocene age (Holwerda & Hutchinson 1968, p. 148). Four recent K/Ar age determinations on this sylvite all indicate ages between 76 and 88 ka ± 15 %. These determinations, using an MS 10 spectrometer, were on sylvite specimens containing between 22 and 38 % K from depths of 73 and 210 m in two drill holes within 3 km of the rift escarpment. Additional work on other potash minerals from this, and from the deeper potash interval is in progress. The present result, however, corroborates the suggested Pleistocene age for these beds and indicates that the uppermost Danakil evaporites are very young indeed. Additional corroboration of this result is provided by the recent discovery of a stone-age artefact in calcareous marine limestone beds along the foot of the escarpment west of the drilled area. These beds, which rim the salt pan, are believed to be somewhat older than the shallowest evaporite beds, and the artefact has been assigned to the Acheulian culture of mid-Pleistocene age (Faure & Roubet 1968).

(*d*) *Stratigraphy*

(i) *General remarks*

Stratigraphic information is based mainly on geologic mapping and observation along the Eritrean coast, on the central Ethiopian plateau, and also on subsurface correlations in exploration wells. A generalized column for the post-Paleozoic strata of these regions is shown in figure 3. The underlying basement includes a complex series of crystalline metamorphic and intrusive rocks that are of Precambrian to older Paleozoic age (Mohr 1961, p. 47) and have been described by Mohr (1961, pp. 19–50) and Holwerda & Hutchinson (1965, pp. 132–133). These, however, are not pertinent to the problems here considered.

(ii) *Mesozoic*

The regional distribution and stratigraphy of the Mesozoic formations are of particular interest. The Adigrat Sandstone is present both in the Danakil Alps and on the Ethiopian plateau. Together with other Mesozic and basement formations, it crops out extensively in the north-eastern portions of the Danakil Alps, there forming part of pre-Tertiary outliers whose lower flanks are covered by Tertiary and younger rocks.

Geologic work shows that the Adigrat thickens progressively from west to east across the entire region. In the southwest at Adaga Hamus on the main Ethiopian plateau (figure 1) the Adigrat measures 337 m in thickness. 64 km to the northeast several Adigrat exposures along the foot of the rift escarpment are 1000 m thick. Northeastward, the next Adigrat exposures are in the Danakil Alps where still greater thicknesses are present in several places, but where a maximum thickness of 1775 m has been measured at Ras Andabba, about 32 km northeast of Mersa Fatma (figure 1). The Ras Andabba section is not complete, however, because the top of the Adigrat is here covered by Quaternary alluvium. A plot of Adigrat thickness against southwest to northeast distance along a line joining these locations is shown in figure 4*a*, and indicates a nearly linear relation, especially allowing for some additional thickness of Adigrat obscured by alluvium at Ras Andabba. It is particularly significant that the Adigrat in the Danakil Alps is substantially thicker than at the foot of the rift escarpment, where it is, in turn, thicker than on the Ethiopian plateau. In this regard it is interesting that a similar situation is reported in the Kohlan Series of Arabia, which correlates with the Adigrat, and which also thickens toward the Red Sea on the Arabian side (Geukens 1966, pp. B7-B8).

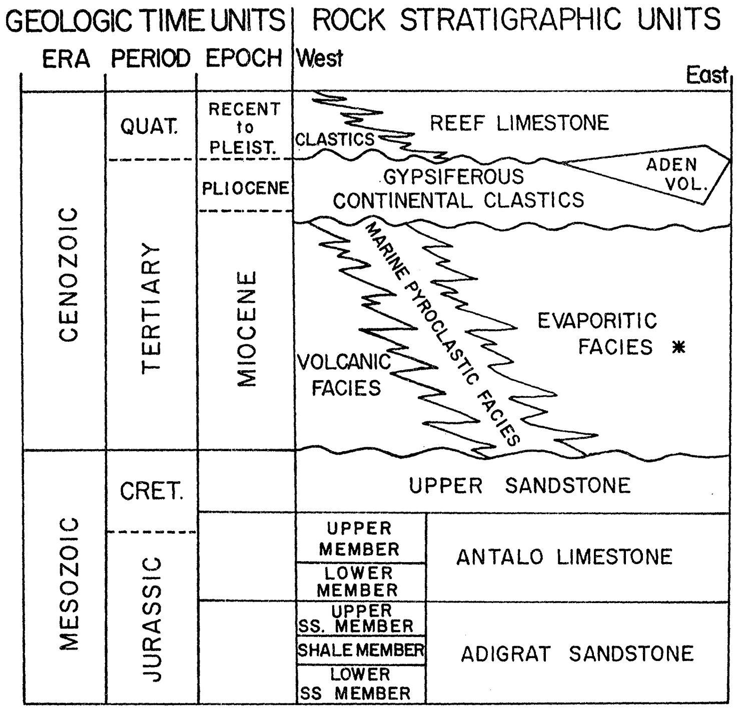

Figure 3. Rock stratigraphic units in northeastern Ethiopia.
* Partly synchronous with Danakil evaporites?

The Antalo Formation shows similar distribution and thickness variations as the Adigrat. At Abbi Addi (figure 1) high on the plateau the measured thickness of Antalo is 170 m and here it is certain that an appreciable thickness has been erosionally removed. Antalo thicknesses of 1075 m have been measured in several places along the rift escarpment, but its maximum known thickness of 1420 m is in the Danakil Alps at Soch Ale just southeast of Thio, and also at Hacor Mountain 48 km farther northwest. A plot of Antalo thickness against southwest to northeast distance along the line joining these locations is shown in figure 4 *b*. In this case the relation is not linear, although incompleteness of section at Abbi Addi may account for much of the departure from linearity. Nevertheless, it is again significant that the Antalo is appreciably thicker in the Danakil Alps than along the rift escarpment and on the plateau.

Lithologically, the Mesozoic section differs as greatly as it does in thickness variations, and this too is significant. On the plateau the Adigrat sandstone is a poorly sorted, coarse grained, cross-bedded sandstone with conglomerate lenses. Near the centre of the sandstone sequence is a distinct shale or mudstone member (figure 3). In the Alps the Adigrat exhibits different characteristics. Here it is finer grained with only a basal conglomerate zone, calcareous, locally fossiliferous, essentially non-cross-bedded and contains no shale or mudstone member. The Antalo limestone consists of two distinct members on the plateau. These are a predominantly shaley unit which contains thin clacareous beds and a massive, dense, black, pyritic limestone. Neither of these is evident in the Alps where the Antalo is a thin-bedded, fossiliferous and light coloured limestone. Moreover, in the Alps the Antalo contains an uppermost bed of massive gypsum which is absent on the Plateau.

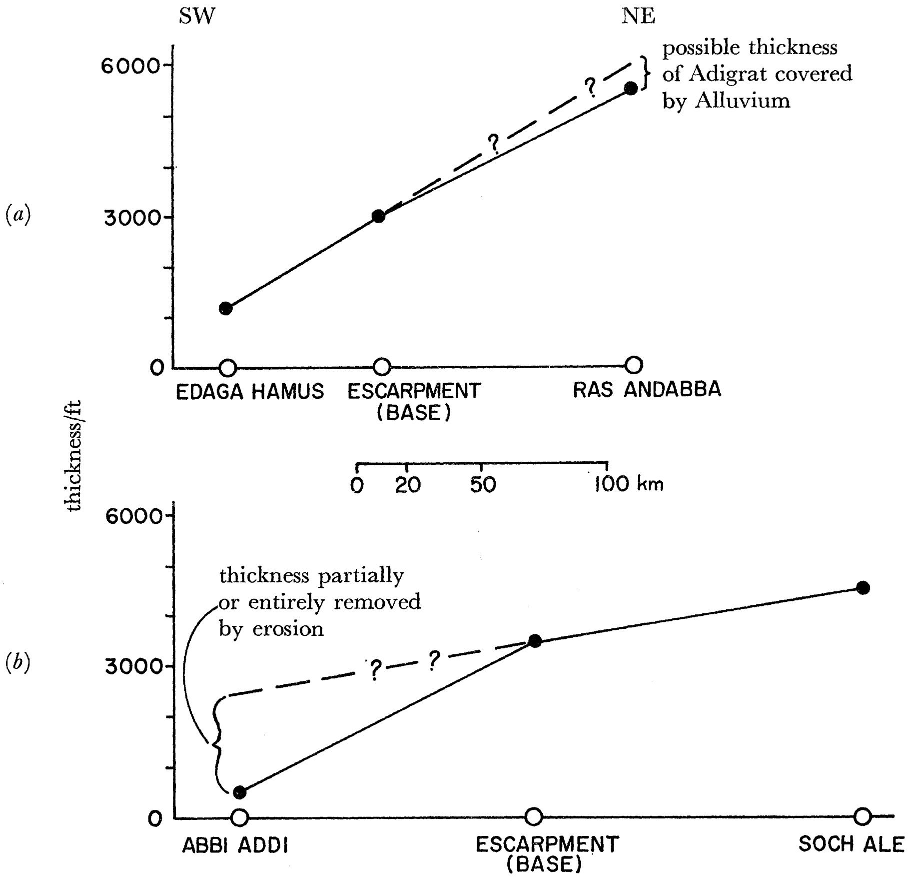

FIGURE 4. (*a*) Plot of Adigrat thickness against SW–NE distance between Adaga Hamus and Ras Andabba; (*b*) plot of Antalo thickness against SW–NE distance between Abbi Addi and Soch Ale.

Above the Antalo Formation is an unnamed Upper Mesozoic sandstone which is not widespread, hence is not further considered here. It is lithologically similar to, and probably correlative with, a formation variously named Upper Sandstone, Eritrean Sandstone and Nubian Sandstone elsewhere in northeastern Africa (Blandford 1869; de Regny 1931).

There is suggestive faunal evidence from several wells drilled in the southern Red Sea and from the Arabian peninsula (Geukens 1966, p. B 15) that the Mesozoic basin in which these formations were deposited may have received marine sediments during later Mesozoic and early Tertiary time as a final stage of its history.

(iii) *Cenozoic*

Unconformably overlying the Mesozoic formations is a thick section of volcanic rocks (figure 3), including spilitic and locally pillowed basalts with clastic and pyroclastic interbeds. These rocks occur along the northern and eastern flanks of the Danakil Alps and are up to 3050 m thick near Massaua. They are predominantly basaltic in the southern end of the Red Sea, becoming increasingly tuffaceous northward away from the Alps. Thus they pass laterally into a pyroclastic facies that is probably both a lithofacies and time equivalent of the extrusive rocks. This pyroclastic facies contains mafic, apparently first-cycle volcanic debris, and is undoubtedly related to the extensive volcanism that was taking place along the eastern and northern flanks of the Danakil Alps, and elsewhere in the southern end of the Red Sea. In the subsurface, eastward toward the centre of the Red Sea, the pyroclastics change gradually into tuffaceous marine sediments. From subsurface relations alone, these rocks are believed to be intercalated with a very thick evaporite facies (figure 3), which is believed to be their lateral lithofacies and time equivalent. Offshore wells in Eritrea have penetrated more than 3650 m of bedded halite but its maximum thickness is unknown. Gypsum and anhydrite beds are rare, suggesting that these strata were deposited from relatively saline brines that had already been depleted of the less soluble calcium sulphates. The salt contains thin clay and shale interbeds and also bittern salt intervals, and it is possible that near-desiccation was periodically achieved. The volcanic, marine pyroclastic and evaporite facies are all of probable Lower-Middle Miocene age based on faunal evidence and on K/Ar age dating. The fauna has Mediterranean affinities.

Unconformably above these rocks are beds of poorly sorted, oxidized clastics with thin gypsum zones believed on sparse faunal evidence to be Upper Miocene-Pliocene in age. In exposures they contain numerous local unconformities, and are therefore believed to be a transgressive littoral, relatively non-marine sedimentary rock. Because of their content of calcium sulphates, these rocks appear to have been deposited from fresher marine waters than the underlying halite.

Seismic and well data suggest that all the above rocks are overlain unconformably by Quaternary rocks. These include two types which are probably lateral lithofacies equivalents of one another (figure 3). In the west is a coarse clastic unit, often calcareous but containing no interbedded evaporites. Eastward from the coast, and probably a lateral equivalent of the clastics, is a reef limestone that is commonly a coquina but contains interbedded sand, gravel and clay horizons which are coarser and more abundant westward. Its Pleistocene to Recent fauna has Indo-Pacific affinities, in contrast to that of the older rocks.

Of particular interest are reports that certain wells drilled in the Red Sea basin in recent years have encountered sialic crustal rocks beneath a younger sedimentary veneer. Much of the data from these wells is confidential, company-file information, but if the reports are correct this finding is of extreme importance to the tectonic problems of the area, for it suggests the presence of continental crust beneath the Red Sea. It is further reported that radioactive age dating of these rocks suggests that they were weakly metamorphosed in early Tertiary time, thus must be of somewhat older original age.

Unfortunately the Cenozoic formations of the coastal area cannot now be correlated with those in the Danakil Depression. It is possible that the upper part of the thick Miocene halite in the Red Sea basin may be a correlative of the deepest Danakil salt. The shallow potash interval in the Danakil evaporites, however, is Pleistocene and its overlying halite is still younger. The uppermost part of the Danakil evaporites thus is much younger than the uppermost Red Sea salt. Evaporitic deposition in the Danakil Depression, therefore, continued until recently, long after cessation of similar sedimentation in the Red Sea basin, although it may have begun before the latter ceased. This denotes the Quaternary, and possibly the later Tertiary, as a period of major subsidence in the Danakil Basin. It is also possible that the extensive gypsiferous strata along the eastern margin of the Danakil Depression are correlative with the gypsiferous clastic beds of Mio-Pliocene age that unconformably overly the Lower-Middle Miocene rocks in the Danakil Alps. This correlation, however, is based only on lithology, hence is suspect and open to revision.

3. Interpretation of geologic relations

(a) *General remarks*

If the southern Red Sea and the related Afar Depression are consequences of rift faulting and separation of Arabia from Ethiopia, it is necessary to explain the Danakil Alps, a prominent basement uplift within the area of separation where only young simatic oceanic rocks should occur. The simplest explanation is that of Laughton (1965, p. 93, figure 9) who regarded the Alps as an isolated, simple, horst block that was rotated and left behind during the separation. Presumably, such a block in cross-section would resemble figure 5*a*. In contrast with Laughton's suggestion is that of Drake & Girdler (1964, p. 489, figure 14) and Girdler (1967, p. 174, figure 6). This is based on geophysical data from the northern and southern Red Sea, and involves down-faulted and tilted blocks of older, continental rocks beneath much of the Red Sea, excepting only its central, axial trough, which alone represents crustal separation (figure 5*b*). The geologic data described above suggest that Laughton's explanation is incorrect and strongly indicate that tectonic relations of the type implied by Drake & Girdler obtain in the Danakil region. They also suggest certain additions and refinements to this tectonic picture, and permit an interpretation of the tectonic evolution of the area.

(b) *The Danakil Basin*

The geologic relations are unusually consistent with one another and are strongly indicative of the tectonic developments which were their common parental cause. The Danakil Depression is floored by very young rocks, mainly evaporites and basalts, a condition that is in overall accord with the regional concepts of rift faulting and subsidence. The Danakil basin, lying between older pre-Tertiary rocks on the Ethiopian plateau and similar rocks uplifted in the Danakil Alps, was undoubtedly formed by this subsidence. The age of initial subsidence is undetermined but the shallowest evaporites in the basin's deepest trough are Pleistocene. Several geologic features indicate that Danakil Basin subsidence in the west, with accompanying Danakil Alp uplift in the east, cannot be the result of 'graben-horst' tectonics. Major, east-dipping, rift fault systems occur along east-facing escarpments that bound both the Ethiopian plateau and the Danakil Alps on the east. No major west-dipping fault system or west-facing scarp is known, however, on the west side of the Danakil Alps, which should be present if the latter represent an uplifted horst block, or if the west side of the Alp block has broken away and separated from the east side of the Ethiopian plateau. Furthermore, stratigraphic relations in the basin, including both regional dips of strata and lithofacies distribution, emphatically indicate that the Danakil depositional basin was asymmetric with shallow, gently west-sloping eastern flanks, deeper and steeper east-tilted western margins, and a deepest trough located far toward its western edge. These relations are not in accord with simple 'graben-horst' tectonics, in which case the resulting basin should not show such marked asymmetry of structure, stratigraphy and lithofacies distribution.

Also to be considered is the stratigraphy of the Mesozoic formations, including both their marked thickening from west to east across the region between the plateau in central Ethiopia and the Danakil Alps, and their changing lithofacies. If the Danakil Alp block is a rotated horst isolated during separation, then thickness in the Danakil Alps should approximate that at the edge of the plateau, and this is not the case. Moreover, any separation between the Alps

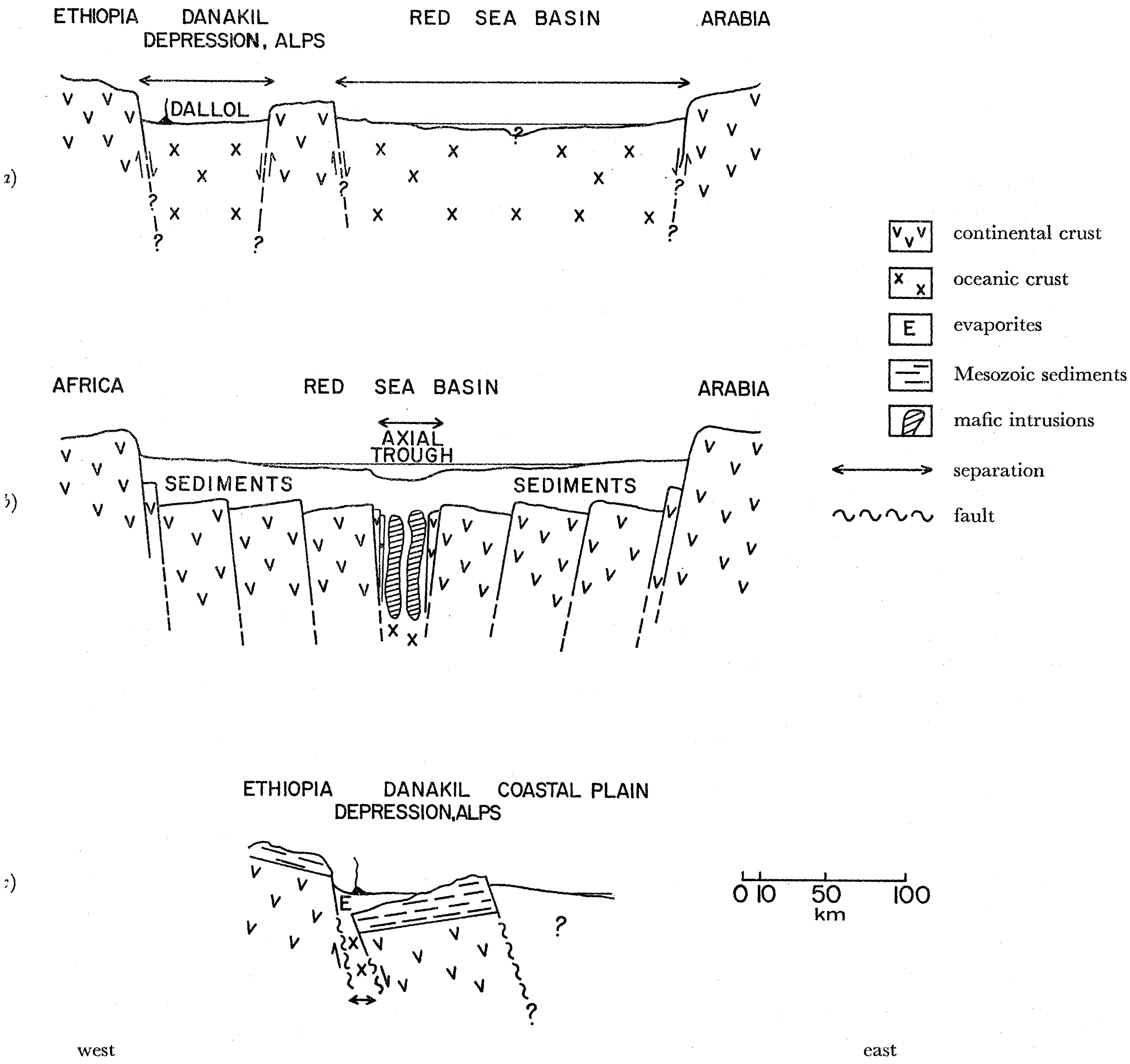

FIGURE 5. Tectonic models of (*a*) southern Red Sea (from Laughton 1966), (*b*) northern Red Sea (from Drake & Girdler 1964) and (*c*) the Danakil Depression (from Holwerda & Hutchinson 1968).

and the plateau in Cenozoic time should have sharply interrupted any systematic variations in the thickness of earlier formations. Yet the thickening of the Jurassic Adigrat sandstone is nearly linear with distance between Adaga Hamus on the plateau and Ras Andabba in the Danakil Alps (figure 4*a*). All this indicates that there has been no appreciable separation between the Danakil Alp block and the Ethiopian plateau since deposition of the Adigrat. The evidence in the case of the Antalo formation is less certain. Thickening again is pronounced from the plateau in the west to the Danakil Alps in the east, and again, thickness in the Alps is appreciably greater than in the rift escarpment (figure 4*b*). Thickening of this formation, however, is not linear with distance, hence could have been disrupted by separation. On the other hand, the thickness data for the Antalo is suspect, because of erosion. Erosional removal is an equally good explanation of the apparent disruption as separation of the blocks, and considering relations in the underlying Adigrat it must be accepted in this case as the more likely. Finally, the appreciable difference in lithologic character of both the Adigrat and Antalo formations between the edge of the plateau and the Danakil Alps suggests that these two sections were not originally deposited in close juxtaposition, as must have been the case if appreciable separation has since occurred.

Any one of these geological facts alone would not provide sufficiently concrete evidence on which to base conclusions, but taken in concert and considering their unanimity of implication, they conclusively indicate that the Danakil Alps and the Danakil Depression are not a simple case of ‘horst’ and ‘graben’ tectonics, and that little separation has taken place between the Ethiopian plateau and the Danakil Alps, particularly in the northern portions of the Danakil region.

Another simple tectonic model has been suggested (Holwerda & Hutchinson 1968, figure 23) that appears to satisfactorily explain these geological relations, and is reproduced with minor revisions in figure 5*c*. This is similar to that proposed by Drake & Girdler (1964) based on geophysical data. It seems probable that major east-side-down subsidence in the west along the rift escarpment bounding the Ethiopian plateau was accompanied, and in part compensated by uplift of the opposite edge of this tectonic block in the Danakil Alps to the east. Thus the entire block between the escarpment and the Alps has apparently undergone asymmetric subsidence, but little separation. The western extremities have been covered by evaporites and basalts, whereas the Danakil Alps are the exposed, uplifted eastern edge of the tilted block of older continental rocks. In this case, no normal fault system or west-facing scarp would occur along the western flank of the Danakil Alps. The basin formed in the west by these tectonics would be asymmetric, like the Danakil Depression, thus explaining the observed structural, stratigraphic and lithofacies relations. The extreme western edge of this subsided block probably corresponds closely with the axial line along which volcanic activity presently occurs, and marks the locus of asymmetric ‘graben’ subsidence beneath the salt. Minor separation is possible here, and is perhaps suggested by the presence of subcrustal-type basalts along this axis in active volcanic ranges to the south (Barberi *et al.* this volume, p. 293).

Satellite outliers of metamorphic rocks on the gently sloping western flanks of the Danakil Alps represent old topographic highs in the pre-Mesozoic surface that emerged during Tertiary uplift along with the Alps. This model implies that older continental rocks, similar to those in the Danakil Alps and on the Ethiopian plateau, underlie most of the Danakil Depression, although the thickness of covering younger rocks is unknown. Geophysical data collected farther to the north by Drake & Girdler (1964, p. 489, figure 14) suggested similar relations and the mutual corroboration of both geological and geophysical data lends additional support to this hypothesis.

(*c*) *Relations to Afar*

The regional dip of Mesozoic formations in the Danakil Alps is southwesterly, suggesting that the asymmetrically tilted Danakil Alp block had maximum uplift in the northeast near Soch Ale (figure 1), and that the deepest part of the basin lies to the southwest. This might explain the southward widening of the Danakil Depression into the broader Afar Depression, the extensive basalt in the Afar region, and the active volcanism that characterizes this area. It is also possible that actual northeast–southwest separation, like that proposed by Laughton (1965) for the Gulf of Aden, has occurred here, or perhaps a combination of these tectonic developments.

(*d*) *The Red Sea*

It is more conjectural but perhaps more interesting to attempt to apply these ideas to the Red Sea itself in the area east of the Danakil Alps. Here concrete evidence is sparse because available geologic data is taken from a few wells that have been drilled in coastal areas to the north. In general, these wells all penetrated major thicknesses of Miocene salt, below varied thicknesses of younger strata. The halite is quite pure, up to 3650 m or more thick, and lacks the less saline gypsum-anhydrite members that are so prominent in the Danakil evaporites. Correlation between the Miocene and Danakil evaporites is uncertain. It is possible that the deep Danakil salt may be equivalent to the upper part of the Miocene salt, or alternatively the Danakil salt may be entirely younger than the latter. The uppermost Danakil salt, however, is Pleistocene whereas the Red Sea salt is entirely Miocene.

If, as reported, certain wells have encountered sialic crustal rocks below the Miocene salt, then pre-Tertiary rocks may exist beneath much of the Red Sea itself. Support for this possibility is derived by extrapolating and comparing the tectonic relationships in the Danakil Basin to the Red Sea Basin. Both the Ethiopian plateau and the Danakil Alps are bounded on the east by major rift systems and east-facing scarps. The Danakil basin east of the Ethiopian rift is underlain by an asymmetrically subsided block; thus, by analogy, it is likely that the Red Sea basin east of the Danakil Alp rift is underlain by a similar block. In this case, continental rocks would also be present under much of the Red Sea as well as its coastal region, lying beneath a thick cover of younger rocks, including basalt, clastics and evaporites. The western edge of this block would have subsided deeply, but its eastern edge may be tilted upward. It is probable that the thickness of rocks covering the tilted Red Sea block is greater than that of the rocks covering the tilted Danakil block, because the Danakil Alps lack a veneer of younger sediments, whereas seismic data indicate a few thousand metres of sediments above the uptilted edge of the Red Sea block.

If this hypothesis is correct there remains the question of how far the continental rocks extend eastward beneath their younger veneer, or alternatively how much separation has occurred between the Ethiopian and Arabian plateaus. It is possible that actual separation has been minor, and is represented only by the distance across the Red Sea's axial trough, plus a few kilometres of additional separation across each of the Danakil Alp and Ethiopian rifts. This separation may be of post-Pliocene age (Phillips & Ross, this volume, p. 143). If so it is one of the latest tectonic developments of the region, as also suggested by Laughton (1965, p. 90) and may be continuing by seafloor spreading. The hypothesis is in accord with some geophysical observations (Gouin, this volume, p. 339; Drake & Girdler 1964, p. 488; Malone 1958, p. 104) although not with current interpretations of seismic velocity measurements.

(*e*) *Tectonic history and geologic evolution*

It is pertinent to now consider the evolution of tectonic events that produced the geologic relations discussed above. The Mesozoic stratigraphy of the region indicates the existence of a Mesozoic sedimentary basin whose western fringes, marked by thin sedimentation, were located on the Ethiopian Plateau. The Mesozoic sediments thicken eastward and the centre of this basin apparently lay somewhere east of the Danakil Alps, beneath what is now the Red Sea. The earliest regional subsidence in this basin began in Jurassic time, continued through the Mesozoic and perhaps, judging from faunal evidence, into the early Tertiary. At that time the deepest part of this basin apparently failed by rift faulting and fracture, presumably due to tension and crustal stretching (figure 6*a*). This was accompanied by uplift, explaining an apparent hiatus in Eocene-Oligocene time (figure 6*b*) indicated by regional geologic relationships (Beydoun 1966, p. 32; Greenwood & Bleackley 1966, p. 52; Mohr 1962, p. 107; Said 1962, p. 193). By early Miocene time, uplift along the central axial rift caused tensional failure (figure 6*b*) followed by subsidence (figure 6*c*) far to the west along the Danakil Alp rift which became the block's western side. This created a Miocene basin (figure 6*c*) which was filled by waters from the north. These brought a Mediterranean fauna and were relatively saline for they had previously deposited the early precipitating calcium sulphates during their movement southward into the deepening evaporite basin. Consequently, halite predominates in Miocene evaporites at the southern end of the Red Sea. The newly induced failure in the west was there accompanied by mafic volcanism that laid down the Miocene volcanic and marine pyroclastic facies as landward equivalents of the evaporites in the basin (figure 6*c*). Relative uplift along the west side of the Danakil Alp rift then caused a second, later but similar cycle of developments, still further to the west. The uplift, with attendant volcanism, in what became the Danakil Alps, caused failure (figure 6*c*) and subsidence (figure 6*d*) along what is now the boundary rift escarpment of the Ethiopian Plateau. This block also subsided asymmetrically, forming the Danakil Depression, and uplifting the Danakil Alps in the east (figure 6*d*). Tilting of this block involved maximum uplift in the northeast and maximum subsidence in the southwest.

Both of these asymmetrically subsided blocks are covered along their westerly or southerly margins by thick basalt sections, the Red Sea block by the Miocene volcanic facies near the Danakil Alp rift (figure 6*d*) and the Danakil block by the Afar basalts. Withdrawal of major volumes of basaltic lava from below, accompanied by its extrusion above onto the subsiding edges of these blocks may have been the tectonic agent that caused the subsidence, and that holds the blocks in isostatic adjustment (Gouin, this volume, p. 339; Girdler 1967, p. 175) in their asymmetric positions.

This southerly component of subsidence is believed related to, or may have caused opening of, the southern Red Sea through to the Gulf of Aden and the Indian Ocean, which apparently occurred in Pliocene time as suggested by Dubertret (this volume, p. 9) and as evidenced by the Indo-Pacific fauna in the younger strata. Influx of these fresher waters from the south into the older Red Sea basin, and from it into the newer Danakil basin, explains the presence of the calcium sulphates in the younger evaporites. Continued crustal stretching at this time may have opened the central axial trough of the Red Sea, which may still be expanding, and has apparently been occupied by ultramafic subcrustal rock (Girdler 1964, p. 135; 1967, p. 175). It may also have caused slight separation across the Danakil Alp and Ethiopian rifts as suggested by the presence of young olivine basalts (Aden basalts) along these structures in many places.

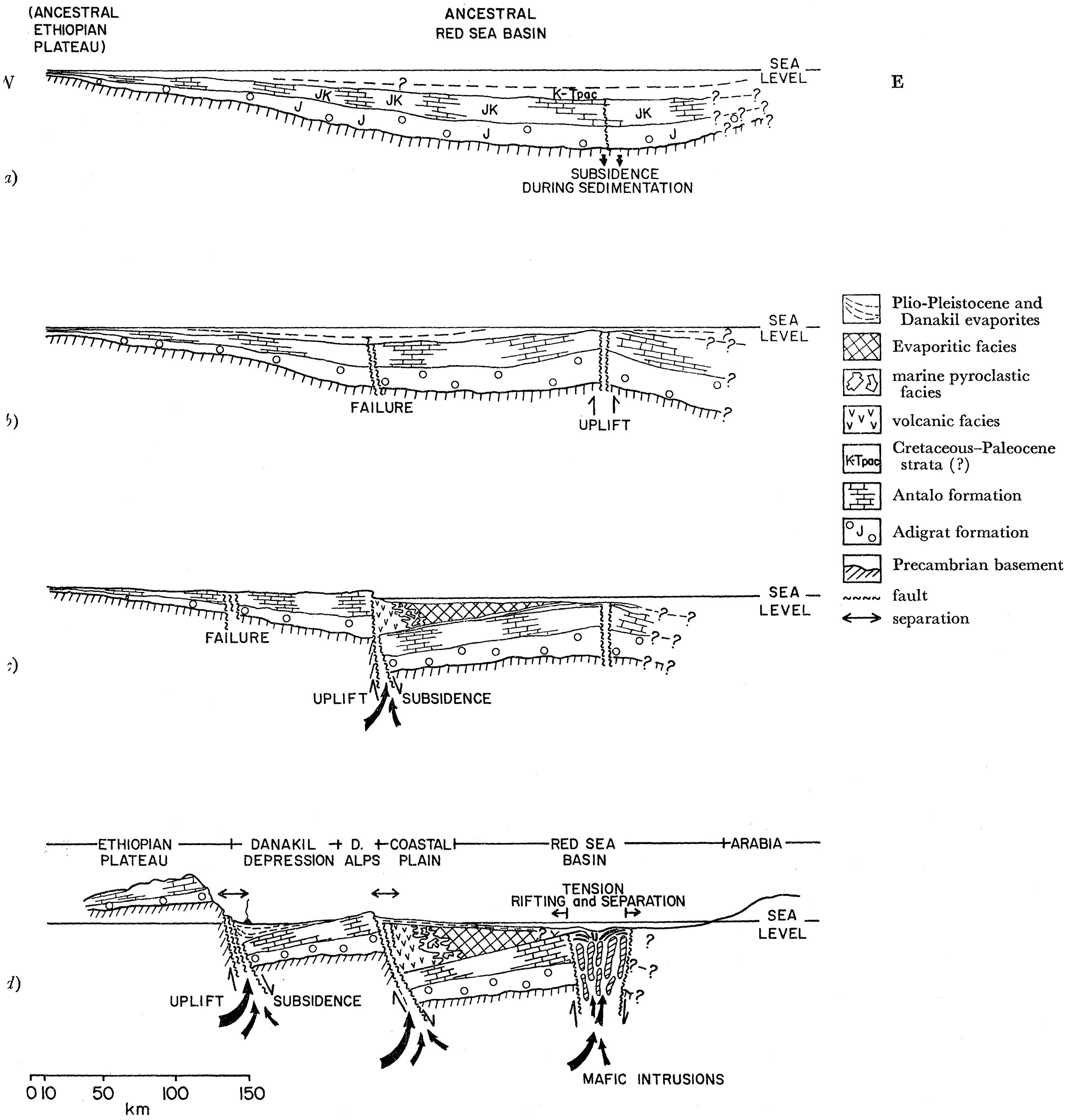

Figure 6. Diagrammatic cross-sections at latitude 14° 15′ N illustrating tectonic history and geologic evolution of the southern Red Sea. (*a*) Jurassic–Paleocene; (*b*) Eocene–Oligocene; (*c*) early Miocene; (*d*) late Miocene–Quaternary.

The final, resulting tectonic arrangement of these blocks across both Danakil and Red Sea basins as it is believed to exist is shown in figure 7.

(*f*) *Possible significance of tectonic evolution*

As a final speculation one wonders, in the light of this tectonic evolution, whether a similar mechanism may have had a role in the formation of shallow continental shelves along the margins of oceans like the Atlantic that appear to have formed by rifting and seafloor spreading.

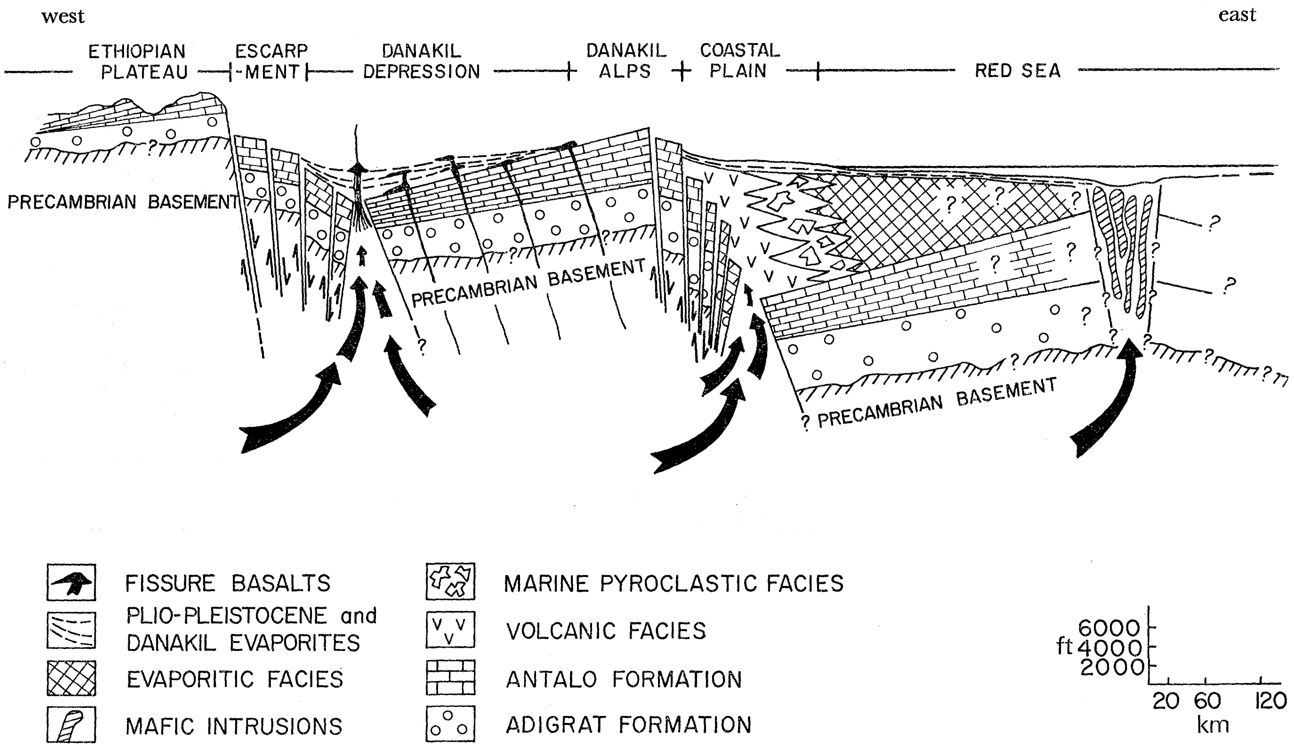

Figure 7. Diagrammatic cross section at latitude 14° 15′ N illustrating tectonic relations of the Danakil and Red Sea basins.

Asymmetric subsidence of continental blocks marginal to newly opened rifts during the initial stages of ocean basin development could form restricted basins for the accumulation of thick evaporite sections, and rapid subsidence of these blocks would result in stream rejuvenation with deep dissection before final ‘drowning’ below sea level. Such developments might provide an explanation for thick offshore evaporite sequences that rim the Atlantic basin in many places (Belmonte, Hirtz & Wenger 1965), for submarine canyons and other topographic and geologic peculiarities of the shallow continental shelves.

Financial support for this study has been supplied by The National Research Council of Canada under an operating research grant to one of the writers, and the Royal Society provided funds that made possible its oral presentation at a Discussion Meeting in London, England on 28 March, 1969.

Thanks are due to Dr J. G. Holwerda and the Ralph M. Parsons Co. for permission to use certain company information concerning evaporite deposits in the Danakil region. Potassium–argon age determinations were carried out by Dr A. Hayatsu, post-doctorate researcher in the

Department of Geophysics at the University of Western Ontario, and Dr G. G. Suffel of the Geology Department offered helpful suggestions by reviewing the manuscript. Mr Peter Giles, graduate research assistant in the Geology Department, assisted with bibliographic work and in preparation of illustrated drawings, which were prepared by Mrs R. Ringsman, draughtswoman in the same department. Numerous colleagues of both authors have supported the work through their interested comments and helpful advice concerning the geology of the region.

All this assistance is gratefully acknowledged, but the writers accept responsibility for the interpretations of the geologic data that are presented.

REFERENCES (Hutchinson & Engels)

Belmonte, Y., Hirtz, P. & Wenger, R. 1965 The salt basins of the Gabon and the Congo (Brazzaville): a tentative Paleogeographic interpretation. In *Salt Basins around Africa*, pp. 55–74. London: Inst. Pet. New York and Amsterdam: Elsevier.

Beydoun, Z. R. 1966 Geology of the Arabian Peninsula, Eastern Aden Protectorate and Part of Dhufar. *U.S.G.S. Prof. Pap.* 560-H.

Blanford, W. T. 1869 On the geology of a portion of Abyssinia. *Q. Jl Geol. Soc. Lond.* **25**,

Drake, C. L. & Girdler, R. W. 1964 A geophysical study of the Red Sea. *Geophys. J. R. astr. Soc.* **8**, 473–495.

Faure, H. & Roubet, C. 1968 Decouverte d'un biface acheuleen dans les calcaires marins du golfe pleistocene de l'Afar (Mer Rouge, Ethiopie). *C. r. hebd. Séanc. Acad. Sci., Paris* **267**, 18–21.

Geukens, F. 1966 Geology of the Arabian Peninsula, Yemen. *U.S.G.S. Prof. Pap.* 560 B.

Girdler, R. W. 1965 The formation of new oceanic crust, Symposium on Continental Drift. *Phil. Trans. Roy. Soc. Lond.* **258**, 123–136.

Girdler, R. W. 1967 Earth satellites, terrestrial heat-flow, mantle convection and the location of extensional and compressional features on the Earth's surface. *Proc. Geol. Ass., Lond.* **78**, 165–178.

Greenwood, J. E. G. W. & Bleackley, D. 1966 Geology of the Arabian Peninsula, Aden Protectorate. *U.S.G.S. Prof. Pap.* 560 C.

Holwerda, J. G. & Hutchinson, R. W. 1968 Potash-bearing evaporites in the Danakil area, Ethiopia. *Econ. Geol.* **63**, 124–150.

Laughton, A. S. 1965 The Gulf of Aden, in relation to the Red Sea and the Afar depression of Ethiopia. In The World Rift System. *Geol. Sur. Pap. Can.* **66–14**, 78–97.

Malone, A. B. 1958 Discussion in *Q. Jl geol. Soc. Lond.* **114**, 104.

Mohr, P. A. 1969 *The geology of Ethiopia*. Asmara, Eritrea, Ethiopia: Il Poligrafico.

Said, R. 1962 *The geology of Egypt*. New York: Elsevier.

Regny, Vinassa de, P. 1931 La geologia delle Alpi Dancale. *Boll. Soc. geol. Ital.* **50**.