PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Adjacent Structures of Ethiopia: That Portion of the Red Sea Coast Including Dahlak Kebir Island and the Gulf of Zula

S. B. Frazier

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Adjacent structures of Ethiopia: that portion of the Red Sea coast including Dahlak Kebir Island and the Gulf of Zula

By S. B. FRAZIER†
Gulf Oil Company, Asmara, Ethiopia

As a result of petroleum exploration east and south of Massawa, Ethiopia, a review of local geologic features indicates the structural aspects of this distinct bend of alinements along the Red Sea coast. The Buri Peninsula holds a horst bounded on the west by a deep faulted corridor. To the east and northeast of the Buri high trend the Dahlak salt basin occurs, where deep faults seem to have initiated salt diapirs. Aeromagnetic information suggests a deepening of the magnetic basement toward the southwest where over 5000 m of sedimentary section is expected to occur opposite a shallow faulted belt near the coast. Conclusions: (1) a narrow passage extending south of the Gulf of Zula once connected the Red Sea with the Danakil depression, (2) a positive Precambrian trend on the Buri Peninsula continues the Danakil horst to the northwest until it plunges into the Bay of Massawa, and (3) results of deep exploratory drilling provide data for recognition of the extensive Dahlak salt basin.

Introduction

The recent search for petroleum along the Eritrean Red Sea coast reveals certain details about the structural geometry of this portion of Ethiopia. In this obvious region of trend junctions the pattern of faulting and the interpretation of structure may apply to other segments of the Red Sea province.

The index map, figure 1, defines an area near Massawa about 2° east–west and 1.5° north–south. The mapped area on the figures is bounded on the north by 16° 00′ N, on the east by 41° 00′ E, on the south by 14° 40′ N, and on the west by 38° 55′ E.

Figure 1 also shows the location of the few exploratory wells that have been drilled to more than 3000 m.

Structure

Area divided into geologic features

For a location map of the various geologic features figure 2 shows how this limited area can be divided into structural units oriented somewhat parallel to the edge of the Red Sea. Though this map also depicts the final conclusions of this discussion the comments and figures that follow supply the reasons for the interpretation of these features.

(*a*) *Basement terrain*

Figure 3 demonstrates the extent of the phyllites, slates, and granites of the Precambrian basement. Near Massawa, a bend of alinements forms the junction point of an older north–south trend with a younger northwest–southeast trend (Beltrandi and Cortesini 1964, Gulf Co.). The former one goes south into the Danakil depression and then north along the Sahel–Sahmar coast towards the Sudan. The latter, or the northwest–southeast alinement, eventually forces a narrowing of the southern Red Sea into the constriction of the Straits of Bab-al-Mandeb near Assab.

Below the basement rocks of the Eastern Slopes a faulted zone marks the boundary of lower

† Present address: c/o Gulf Oil Co., 2 Portman Street, London, W. 1.

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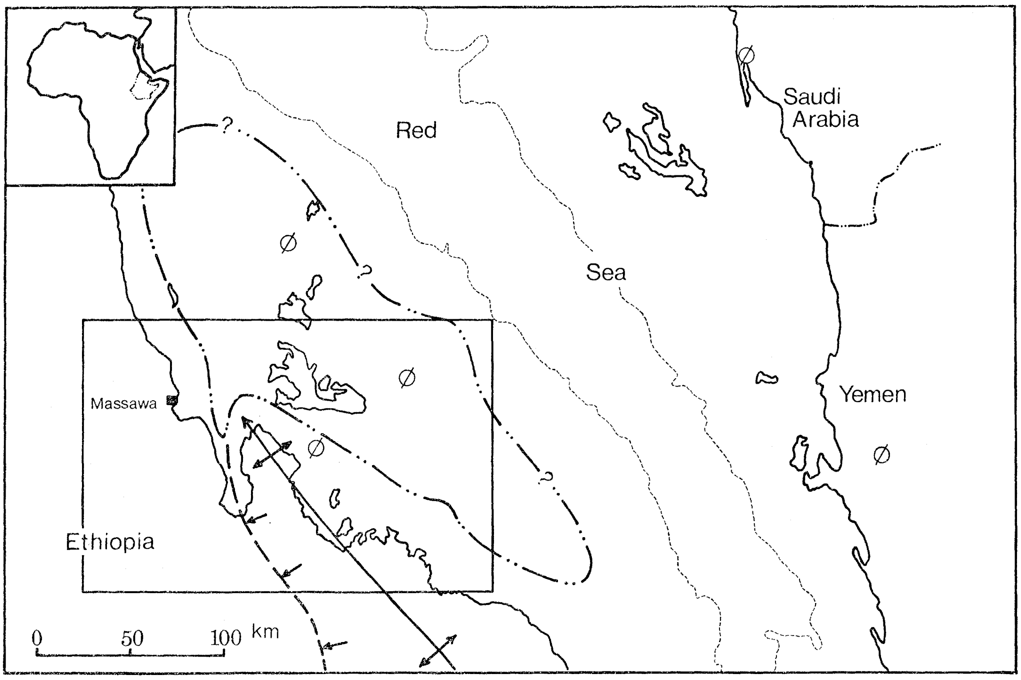

FIGURE 1. Index map–southern Red Sea. The fine dashed line in the central trench is the 200 m bathymetric contour line (from U.S.G.S. Geologic Map of the Arabian Peninsula). The line with a dash and two dots suggests a limit for the Dahlak salt basin. The anticline symbol represents the Buri-Danakil high. The thicker dashed line represents the Zula-Badda corridor. Well symbols show locations of the exploratory wildcats over 3000 m in depth.

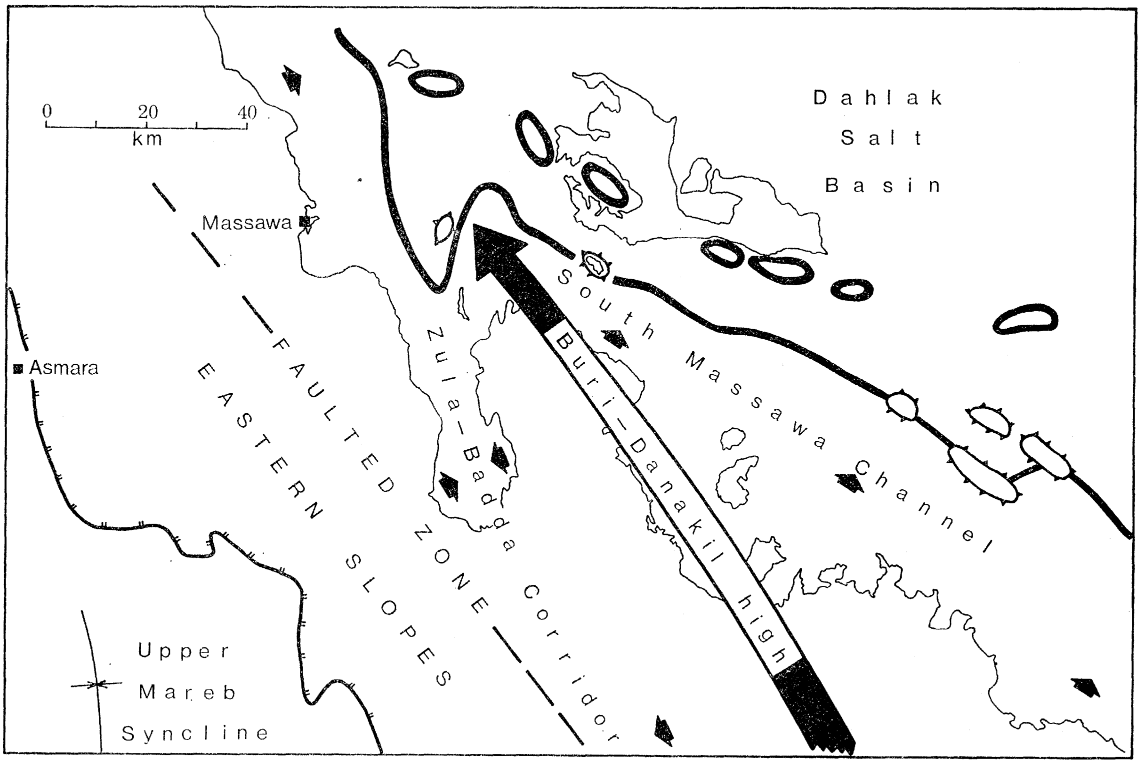

FIGURE 2. Location map of geologic features. Thick solid ovals indicate 'uncovered' salt diapirs. Ovals with hachure marks indicate 'covered' salt diapirs. The heavy solid line indicates the 'Halokinetic zone'. The line with short dashes is the eastern edge of the escarpment of the Eritrean Plateau. Heavy arrows point in the direction of regional dip.

country where abundant lava flows and intrusive volcanics are exposed. This lower country also holds a few but significant patches of Precambrian basement. And then just off this map to the southeast, an extensive area of basement and Jurassic rocks lay exposed in the Danakil Alps.

To the west of the Gulf of Zula, and south of Massawa, a separated horst of Precambrian rocks, Mount Ghedem, looks like a fold along a fault that runs through a valley just west of this topographic dome. South of Ghedem, two isolated remnants of basement rocks stick up near the village of Zula. *Note*: the potassium–argon dating of granitic and basaltic rocks was carried out by Weismann and Rupert (1968 Gulf Co.).

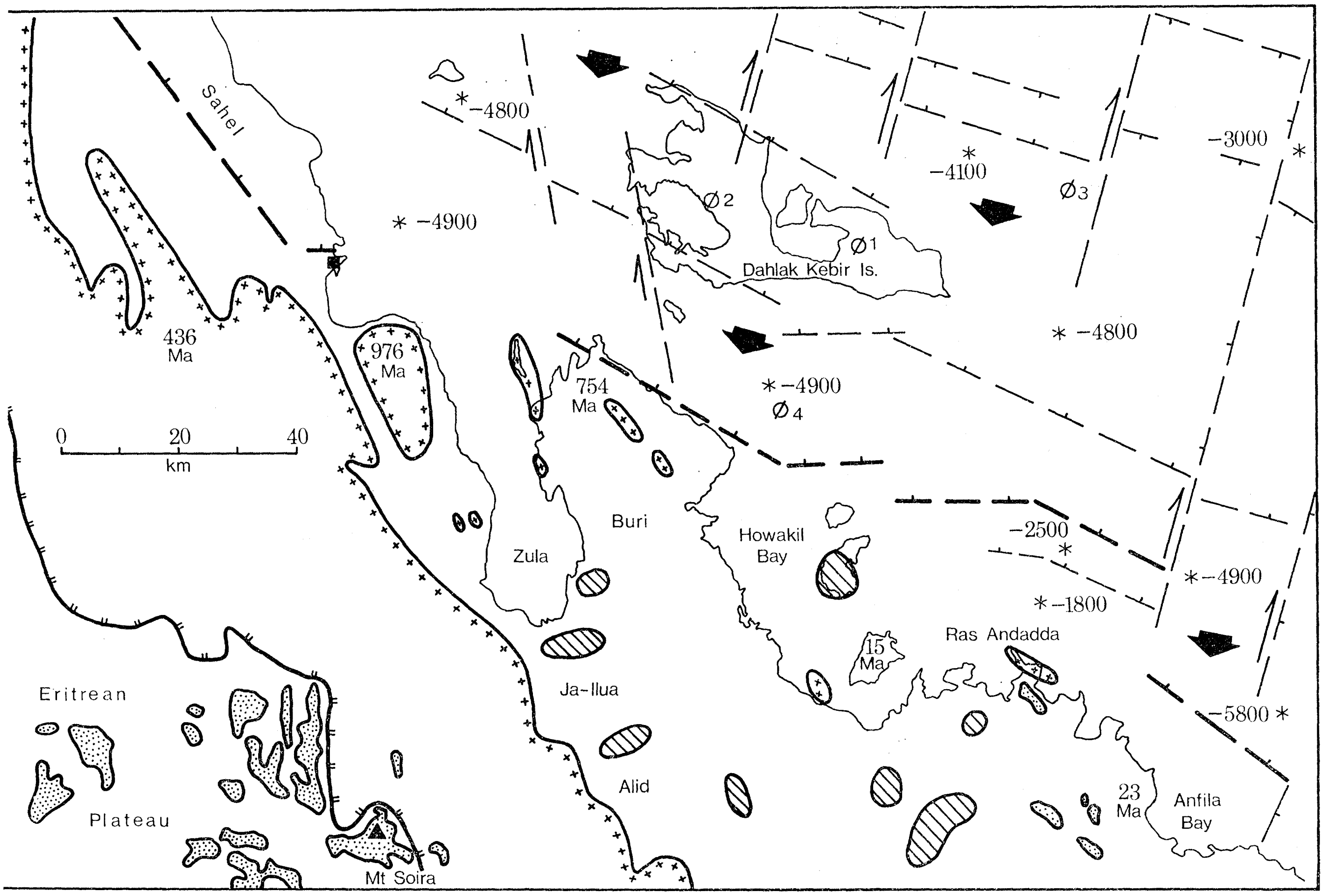

FIGURE 3. Basement and aeromagnetic interpretation. Basement rocks are enclosed within or behind the solid line with the crosses. Dotted areas represent Jurassic outcrops. Tertiary intrusions are the circular areas with cross-hatching. Numbers like 754 Ma indicate potassium–argon dating in millions of years. In the northeast half on the map the asterisks indicate depths in metres to magnetic basement. Large arrows indicate plunge of the magnetic basement. Fault symbols show normal or right lateral movement. Well symbols with numbers are named as follows: 1, Adal-2, total depth = 2475 m; 2, Suri-7, total depth = 2553 m; 3, Dhunishub-1, total depth = 3867 m; 4, Secca Fawn-1, total depth = 3363 m.

It was from a landing in the Gulf of Zula that the British-Indian Army started into Ethiopia in 1867 on Field Marshall Robert Napier's successful campaign against the Emperor Theodore. With their elephants they climbed up through a gap in the escarpment near Mount Soira to go south towards the fortress of Magdala. I mention this because W. T. Blandford went with the expedition and it was Blandford who first described and named the various units of Ethiopian geology. Blandford later became a Fellow of the Royal Society and his General became 1st Baron Napier of Magdala.

Position of Jurassic outcrops. Starting on the southwest corner of figure 3 Jurassic rocks occur on the rim of the Eritrean plateau at elevations over 3000 m on Mount Soira (Merla & Minucci 1938). To the west, extensive outcrops of Adigrat sandstone in the upper Mareb syncline define a trough expressed on the basement (Abul-Haggag 1961). On the other hand, and farther to the east, Jurassic rocks are found near sea level close to basement exposures on Ras Andadda.

(*b*) *Zula-Badda corridor*

As you can see in figure 3 basement areas nearly flank the Gulf of Zula; but seismic faults indicate a deep trough with thick salt near the north entrance to the Gulf (Marshall 1968 Gulf Co.). In addition, deep water in the Gulf of Zula offers topographic evidence that the sea-way connexion with the Danakil depression went south towards Badda and Dalol through a narrow passage now occupied by extinct volcanoes. In more recent geologic time, the intrusive complex of Mount Alid and Mount Ja-Ilua rose up in a narrow part of this channel and created a dam that blocked the ingress of the sea. *Note*: The village of Badda is just off the south-central part of the map and is on trend with the Dalol salt dome of the Danakil depression.

Over to the east, near Anfila Bay, some field evidence discloses a very limited, and very recent, connexion of the Dalol area with the waters of the South Massawa Channel. The bulk of the indications, however, point to the Gulf of Zula as the former connecting link into the Danakil depression.

(*c*) *Buri-Danakil high*

East of Alid and Ja-Ilua other cones and fractures supplied enormous flows of basalt that cover a large portion of the country clear over to the edge of Howakil Bay. This great outpouring of lava conceals the underlying structure, but it is clear from the basement outcrops that a high trend continues northwest into the Bay of Massawa (Marchetti 1950 Gulf Co.).

For a topographic expression to this long plunging feature the hydrographic charts show deeper water in the Gulf of Zula, around the top of the Buri Peninsula, and down the South Massawa Channel. The gradual slope of the ocean floor into the side of the South Massawa Channel is obvious from the evenly spaced contour lines that carry along somewhat parallel to the coast from Anfila Bay clear to the northeast tip of the Buri Peninsula. Over near the reefs of the Dahlak area the contours stack up more steeply, but in all of this area a plotting of the 40 m bathymetric line can add revealing clues to the understanding of the topography.

(*d*) *Dahlak salt basin*

Out beyond the line of the halokinetic zone stretches a broad area, including the Dahlak Archipelago and part of the Dahlak Banks, that can be designated as the Dahlak salt basin (Rigo 1965 Gulf Co.); see figure 2. Interval thicknesses on figure 6 demonstrate that there is enough salt under this area of approximately 16 000 km^2 to give an estimate of 40 000 km^3 of salt.

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Aeromagnetic interpretation

In proceeding away from the land, the magnetic basement does not appear to get deeper toward the central trench of the Red Sea. Instead, figure 3 shows that the basement plunges to the southwest (map adapted from Affleck and Landau 1966 Gulf Co.). The shallowest depths offshore are out to the northeast on figure 3 where magnetic basement may be less than 3000 m. The deepest area lies to the southeast of Ras Andadda where interpreted depths could be 5000 to 6000 m, or more. *Note*: the central trench of the Red Sea is just off the upper right-hand corner of figure 3.

Locations of the deep wells are shown on figure 3, but none of these wells reached the basement. Gulf's Dhunishub-1, A.G.I.P's Adal-2, and A.G.I.P's Suri-7 stopped in salt while Gulf's Secca Fawn stopped in an evaporite section just below the salt (Scorcelletti 1969 Gulf Co.).

Near shore, a series of smaller tight anomalies could indicate volcanics. In this respect the drill bit in our Secca Fawn well penetrated several volcanic intervals in Red Beds above the salt, see figure 6.

But the picture is strikingly different further offshore. There, the magnetics indicate a basement composed of linear anomalies. In turn, these can be interpreted as fault blocks tilted to the south-west with the individual blocks being defined by vertical and by right-lateral faults.

The magnetic data in this part of Ethiopia shows a complex magnetic picture of west–northwest east–southeast trends closely related to rift tectonics. A letter from A. Pyre dated May 1968, makes the following observation: '...It is of interest that the Gulf aeromagnetic data—well outside of the central deep graben—are strikingly similar in appearance to the elongated magnetic anomalies which parallel the Mid-Atlantic ridge suggesting that the rifting was taking place well back in the Tertiary.'

Faults and salt diapirs

From these fault directions the magnetic interpretation supplies evidence that sedimentary structures are controlled by basement tectonics. For example, a string of salt diapirs has distinct surface and seismic expression on the downside of the fault that extends in a northwest–southeast direction off the south side of Dahlak Kebir Island (see figures 2 and 3).

For a similar interpretation of salt diapirs on the downside of deep faults see one of the cross-sections in the paper about the Paradox Basin of Utah and Colorado by Ohlen & McIntyre (1965).

From the magnetic interpretation it can be concluded that deep seated faults probably initiated the diapirs.

Fault patterns

Figure 4 represents an integration of the surface geology, the aeromagnetics, and the seismic information to reveal the fault pattern. It also presents an idea as to the supposed edge of the marine Miocene. Out on the Buri Peninsula a well exposed outcrop of Miocene sediments lies up against the basement near the north central end of the peninsula. Locally called the Desset Series, these rocks contain a sedimentary facies similar to the Miocene rocks that outcrop west of Massawa along the highway to Asmara.

In tracing the fault trend from the Buri Peninsula to the southeast a structural high sticks up in southwest Howakil Bay with its axis running through a tiny island of Precambrian rocks called 'Atcoma'. This island remains a key to the interpretation of the high trend along the west edge of the Bay.

Atcoma itself stands like a pyramid in shoal waters about 6 km west of Baka Island, but it remains unnamed on most of the charts and remains unvisited because of its small size. When driving by it on the coast road it looks like a volcanic cone, but a visit to the island very quickly discloses the crystalline nature of the rocks.

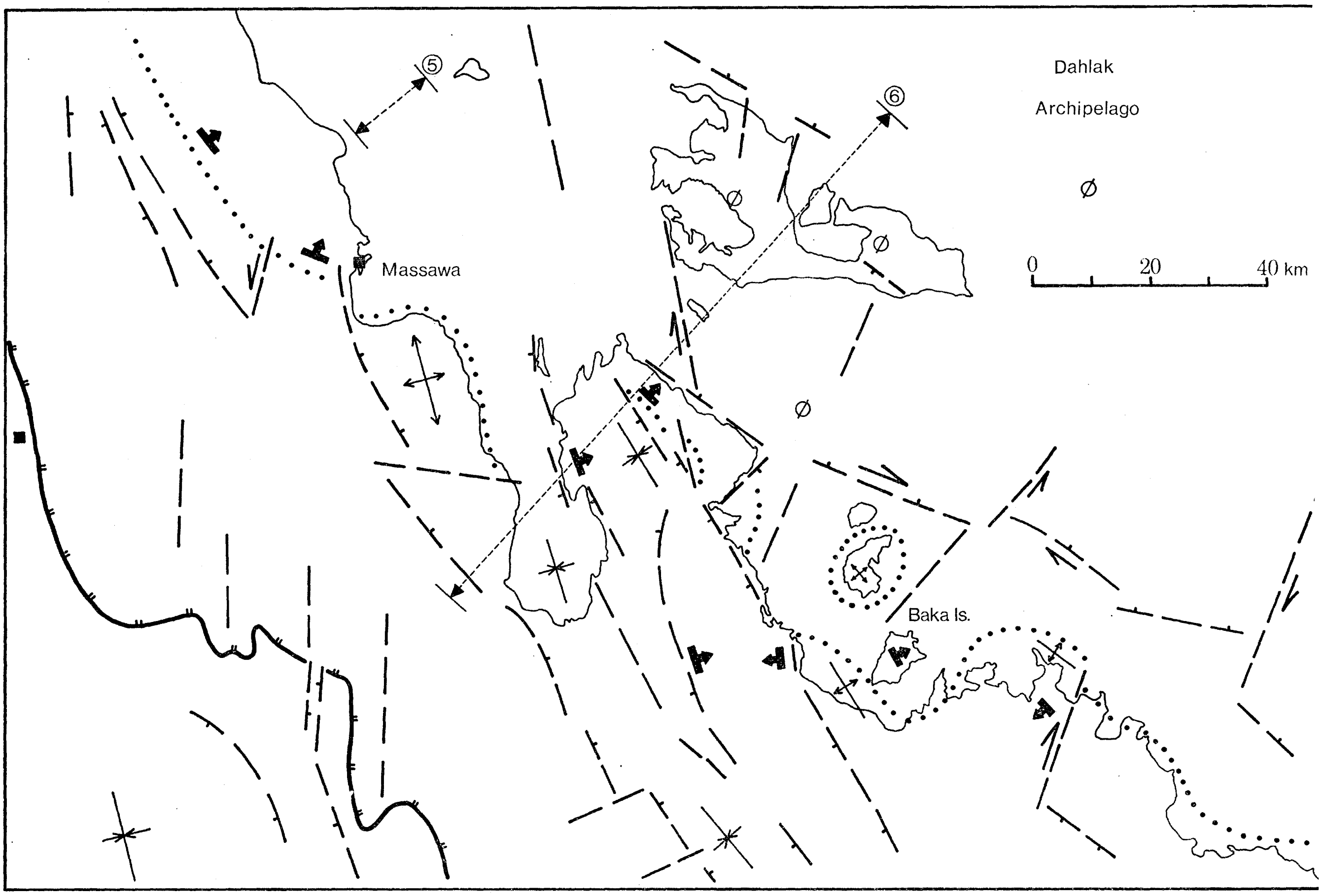

FIGURE 4. Fault pattern map. Heavy dashed lines are fault symbols, some with throw unknown. Anticline and syncline symbols are standard. Heavy arrows show regional dip. Dotted lines mark the approximate limit of the marine Miocene. Short dashed line with arrows at terminal points indicate location of cross Sections (figures 5 and 6). See legend of figure 3 for well names. Many small islands in the Dahlak Archipelago, Howakil Bay, and Anfila Bay are not indicated.

Across from Atcoma Island and under the basalt cover of Baka Island exists the most southerly outcrop of marine Miocene that we have been able to locate in the area. A cross-fault must exist near Baka because the basement comes up again some 35 km over to the east on Ras Andadda.

By means of all these faults, structural axes, and basement exposures the northwest extension of the Danakil horst can be plotted. Again, see figure 2.

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Seismic cross-section

To help define the geologic features it remains necessary to cut a slice or two across the area to reveal the subsurface configuration. Figure 5 depicts an interpretation of a reflexion seismic profile whose location can be seen on figure 4. It was surveyed in a southwest–northeast position in the channel north of Massawa. On this profile salt can be interpreted as it extends westwards under thick sediments away from the edge of the halokinetic zone. The weight of sediments rapidly filling in the basin from the mountain slopes has squeezed the salt into pillows or deep domes before the salt goes sweeping up into a diapir as you proceed to the east.

Near the top of the chart is an exaggerated depiction of the sea bottom topography. It seems to reflect the seismic reversal even though the deep dome is cut off by an unconformity.

Geologic cross-section

For a longer slice across the country, the cross-section on figure 6 demonstrates an interpretation of the subsurface through the different elements. Here, to the southwest, salt could be preserved under the Gulf of Zula; then, high blocks are found holding up the Buri Peninsula; and finally, thick salt extends out under the Dahlak Archipelago (Rigo 1965 Gulf Co.).

Around the tip of the Buri Peninsula and down along the edge of the South Massawa Channel a narrow belt of thicker Tertiary sediments lies between basement outcrops and diapiric salt. Our most recent exploratory well, the Secca Fawn, drilled through younger sediments with volcanics, and then went through 877 m of salt before it reached a change of formation near total depth.

Of interest, perhaps, is the fact that the Secca Fawn well was drilled on the Fawn Shoal—an area of the Red Sea mapped by Commander W. J. L. Wharton and the officers of the H.M.S. *Fawn* during a survey cruise in 1877. Commander Wharton later became an F.R.S. Even earlier, Commander R. Moresby, I.N., made soundings on the outer reef in 1830–34 (Massawa Channel chart 1878).

Despite many attempts to interpret a strong rift fault along the northeast edge of the Buri it is possible to tie the surface dips into the seismic sections without a major fault (Scorcelletti 1969 Gulf Co.). A similar situation has been noted in the Jizan area of Saudi Arabia (Gillmann 1968).

Further to the northeast and along the South Massawa Channel, the edge of the main salt basin can be recognized by a zone where salt is believed to rise to a level very near the ocean floor. Since we fail to get reflexions on seismic profiles across this boundry, we call it the 'mush zone', or the 'salt wall', whenever we hit it (Hooper 1967 Gulf Co.). Shumma Island represents what might be called a 'covered' diapir—an island sits on top of it; while Mus Nefit represents an 'uncovered' diapir—in the form of a deep bay where salt water has dissolved the rock salt to depths of 160 to 200 m (80–100 fathoms).

Near the surface to the northeast, coral limestones on top of red beds and evaporites form a thin cover over the area. Marine seismic profiles shot out among the islands of the Archipelago display unusual shallow geometry, and it is clear that the salt does not remain undisturbed (Baade 1967 Gulf Co.). The surface on top of the salt reminds one of hot porridge with bumps, and swells, and with an occasional bubble, or diapir, that reaches the surface.

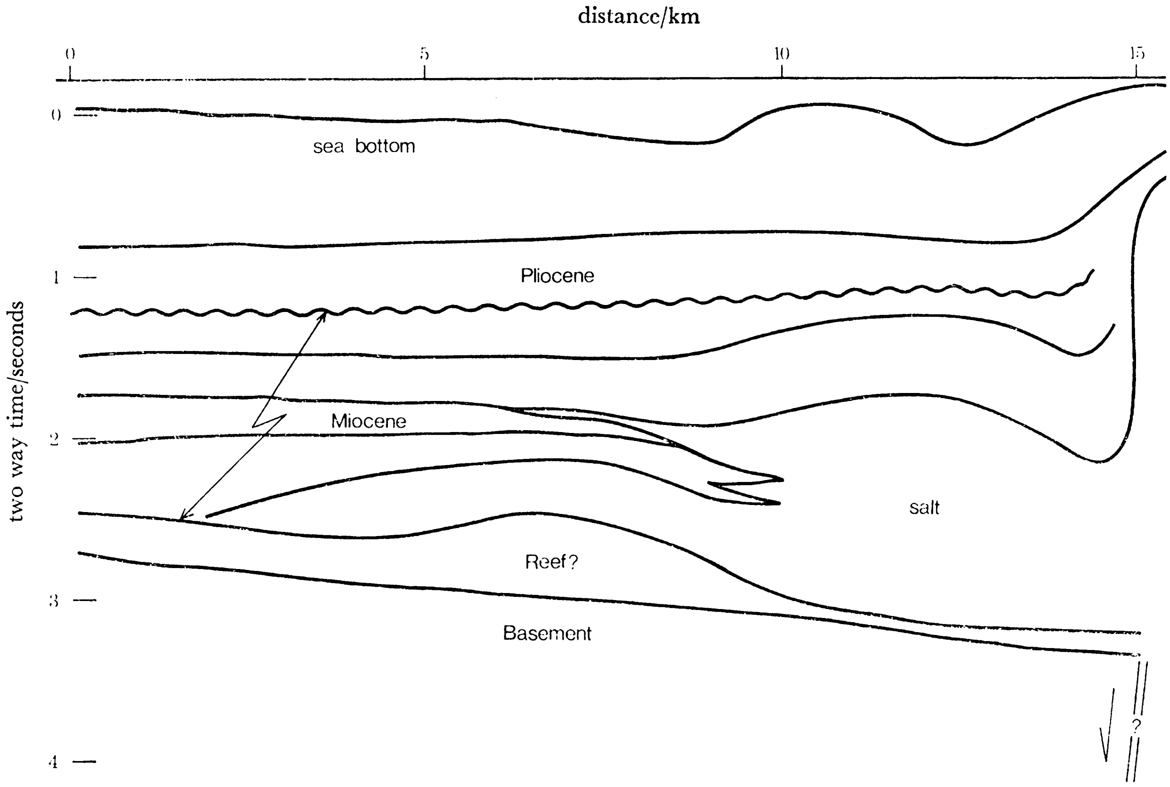

Figure 5. Seismic cross section, SW–NE. Horizon lines indicate geological interpretation of seismic reflexions, but the top line shows an exaggerated depiction of the sea bottom topography.

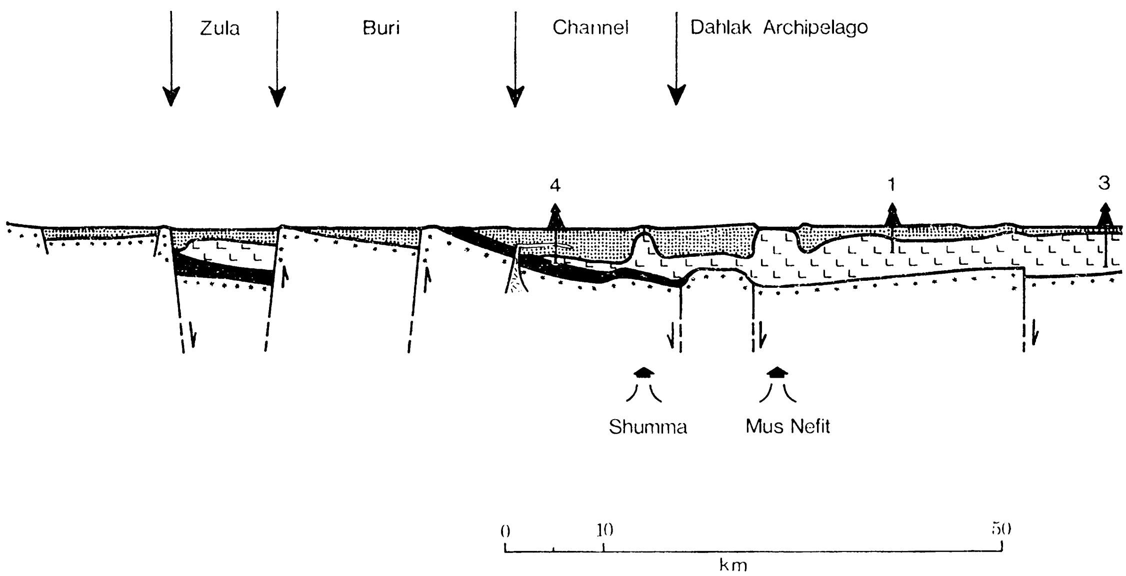

Figure 6. Geologic cross-section, SW–NE. Dotted areas indicate undifferentiated Pliocene and Miocene rocks. Area with 'L' symbols indicates Miocene salt. Solid areas indicate marine Miocene (?) below the salt Asterisks indicate basement. Vertical and horizontal scales are the same. Well numbers are the same as found on the legend for figure 3.

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By using the magnetic interpretation salt mounds can be plotted over basement highs; but the strongest diapirs appear to rise on the down side of deep faults.

(*a*) *Drilled lithology*

A.G.I.P.: Adal-2	
Reefoidal limestone	surf–183 m
Calcareous mud, anhydrite, shale	183–274 m
Shale with anhydrite and some salt	274–728 m
Salt with some anhydrite and shale	728–2475 m (TD)
A.G.I.P.: Suri-7	
Reefoidal limestone	surf–57 m
Calcareous mud, anhydrite, shale	57–96 m
Shale with some anhydrite	96–2553 m (TD)
Gulf: Dhunishub-1	
Reefoidal limestone	surf–169 m
Limestone, shale, some anhydrite	169–251 m
Shale, anhydrite, limestone, salt	251–350 m
Salt with some shale	350–3867 m (TD)
Gulf: Secca Fawn-1	
Reefoidal limestone	surf–411 m
Clay, marl, red sand and gravel	411–1163 m
Sandstone, dolomite, anhydrite, volcanics	1163–2477 m
Salt, anhydrite and shale	2477–3354 m
Shale, marl, dolomite, anhydrite	3354–3363 m (TD)

(*b*) *Salt flowage in deep wells*

Subsurface evidence of salt flowage in the area can be seen in the results of our Dhunishub well. In that deep test the sidetracked hole—due to a fishing job—did not find the shale intercalations and gas shows that were present in the original well. In addition, the hole was affected by annulus restrictions; for example, in the few hours from the time of cessation of drilling to the time when the caliper log was run, the walls moved in and reduced the size of the hole from 32 to 23 cm. During Dahlak Island drilling by A.G.I.P., in 1939–41, casing collapses are reported in their wells (Rigo 1965 Gulf Co.). All of these observations contribute evidence of salt movement in an area where rock salt is found to be over 3000 m in thickness.

(*c*) *Bottom-hole temperature data*

The chart on figure 7 shows the recorded and estimated temperatures from our two deep wildcats:

Dhunishub: maximum temperature at 3867 m was 171 °C (recorded),
Secca Fawn: maximum temperature at 3363 m was 193 °C (estimated)

In both wells exceptionally high bottom-hole temperatures are found. These high temperatures, along with high pressures, must have supplied the sustaining energy to build the line of salt diapirs after the deep faults had kicked them into movement.

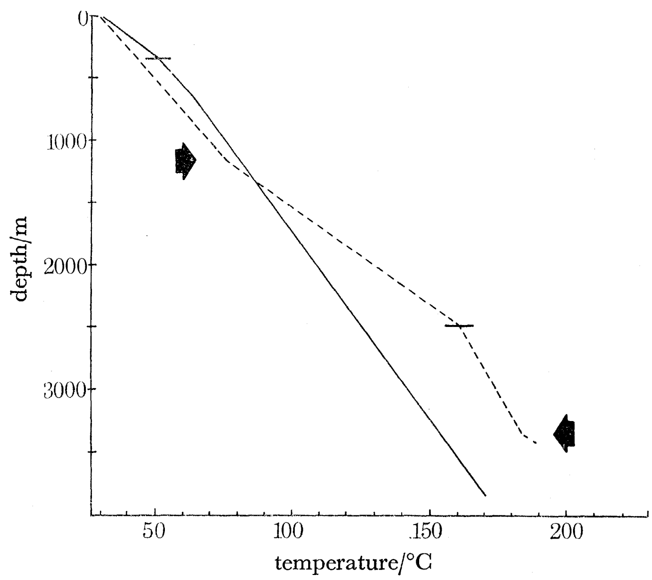

Figure 7. Temperature chart. The solid line indicates the temperature curve for Dhunishub-1. The dashed line indicates the temperature curve for Secca Fawn-1. The deepest recorded temperature was 166 °C at 2665 m, some 43 h after circulation stopped. The temperature at total depth was estimated from the flow line temperature of 92 °C at the surface (Scorcelletti 1969 Gulf Co.). Short horizontal line on each curve indicate the top of massive salt. Large arrow indicates a significant formation change, other than salt. Temperature gradients, using 30 °C as a mean annual surface temperature were: Dhunishub-1, 3.6 °C/100 m (recorded); Secca Fawn-1, 4.9 °C/100 m (estimated).

Review of geologic features

With these cross-sections and other data as a background, reference is made again to figure 2, the geologic features. Here, the southwestern border of the salt basin is shown, and behind it a line of 'uncovered' salt diapirs appear.

Bay of Mus Nefit

Of these diapirs, Mus Nefit Bay on Dahlak Kebir Island is the most obvious one along this trend (Rigo 1966 Gulf Co.). Gubbet (meaning: Bay of) Mus Nefit has the configuration of an oval-shaped hole, some 15 km long and 7 km wide. From fathometer profiles it looks like an elongated dishpan with very steep sides and a flat bottom having nearly uniform depths of 160 m (85 fathoms). It remains a closed basin having a shallow sill in the short, narrow canal that joins it with the deeper waters of Massawa Bay. From surface geology observations, Mus Nefit can be interpreted as a collapse structure due to salt solution on top of a salt diapir (Hooper 1967 Gulf Co.).

From experimental studies of the mechanics of salt domes the morphology around this lake-like gulf fits the fracture pattern related to collapse structures (Currie 1952 Gulf Co.).

Incidentally, this particular bay was described by Darwin (1851) in his comments about the Red Sea: '...The form of the banks and islands is most singular in the part just referred to, namely, from lat. 15° to 17°, where the sea deepens quite gradually: the Dhalac group, in the western coast, is surrounded by an intricate archipelago of islets and shoals; the main island is very irregularly shaped, and it includes a bay 7 miles long, by four across, in which no bottom was found with 252 ft: there is only one entrance into this bay, half a mile wide, and with an island in front of it...Dhalac has been rent by fissures, the opposite sides of which have been unequally elevated, (in one instance to the amount of 50 ft,)...it is almost certain that their form cannot be attributed to the growth of coral...'

Although Darwin did not know about the thick salt he recognized an unusual situation. Later information about the Dahlak Archipelago; the surface geology, the topography, the geophysical surveys, and the subsurface results all offer clear evidence of salt deformation.

Conclusions

(1) A narrow passage extending south of the Gulf of Zula, the Zula–Badda corridor, once connected the Red Sea with the Danakil depression.

(2) A positive Precambrian trend on the Buri Peninsula, the Buri-Danakil high, continues the Danakil horst to the northwest until it plunges into the Bay of Massawa.

(3) Results of deep exploratory drilling provide data for recognition of the extensive Dahlak Salt Basin.

This explanation of adjacent structures near the bend of alinements pivoted on Massawa should assist in the interpretation of other sectors of the Red Sea.

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