## Chapter 11

# The Continental Margins of Somalia

## Structural Evolution and Sequence Stratigraphy

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## ABSTRACT

Sea floor spreading between Africa and the Madagascar-India-Seychelles block began during the Jurassic Magnetic Quiet Zone and was preceded by earlier rifting of Gondwanaland and deposition of Karroo sediments. Basal clastic deposition was terminated in the Early Jurassic by a regional transgression, largely a result of continental separation, followed by a general depositional regression on shelves. A major transgression occurred over most of East Africa, from late Callovian to Oxfordian, which was related to the final breakup of this area and subsequent phase of regional subsidence.

Two distinct deformational episodes, documented by erosional unconformities and siliciclastic sedimentation, occurred during the pre-Aptian and late Maastrichtian. The older event was probably the distal intraplate effect of the separation of South America and Africa; whereas the Maastrichtian tilting of northern Somalia was possibly related to a rebound effect when the Oman subduction failed at about 70 Ma.

The Cretaceous-Tertiary history of the Indian Ocean continental margins is the result of a complex depositional regression that covered the underlying Early and Middle Jurassic rifted margin. To the north, Oligocene-Miocene sediments were deposited during the opening of the Gulf of Aden and accumulated in disconnected structural depressions formed by downfaulted rotating blocks bordering the rising Somali plateau.

## INTRODUCTION

The basic assumption of this paper is that the Mesozoic-Cenozoic sedimentary successions of East Africa (Somalia, coastal Kenya, and Tanzania) (Figure 1) were deposited in response to the plate tectonic evolution of the adjacent Indian Ocean and to the relative changes of sea level. The stratigraphy of Somalia is presented in terms of sequence

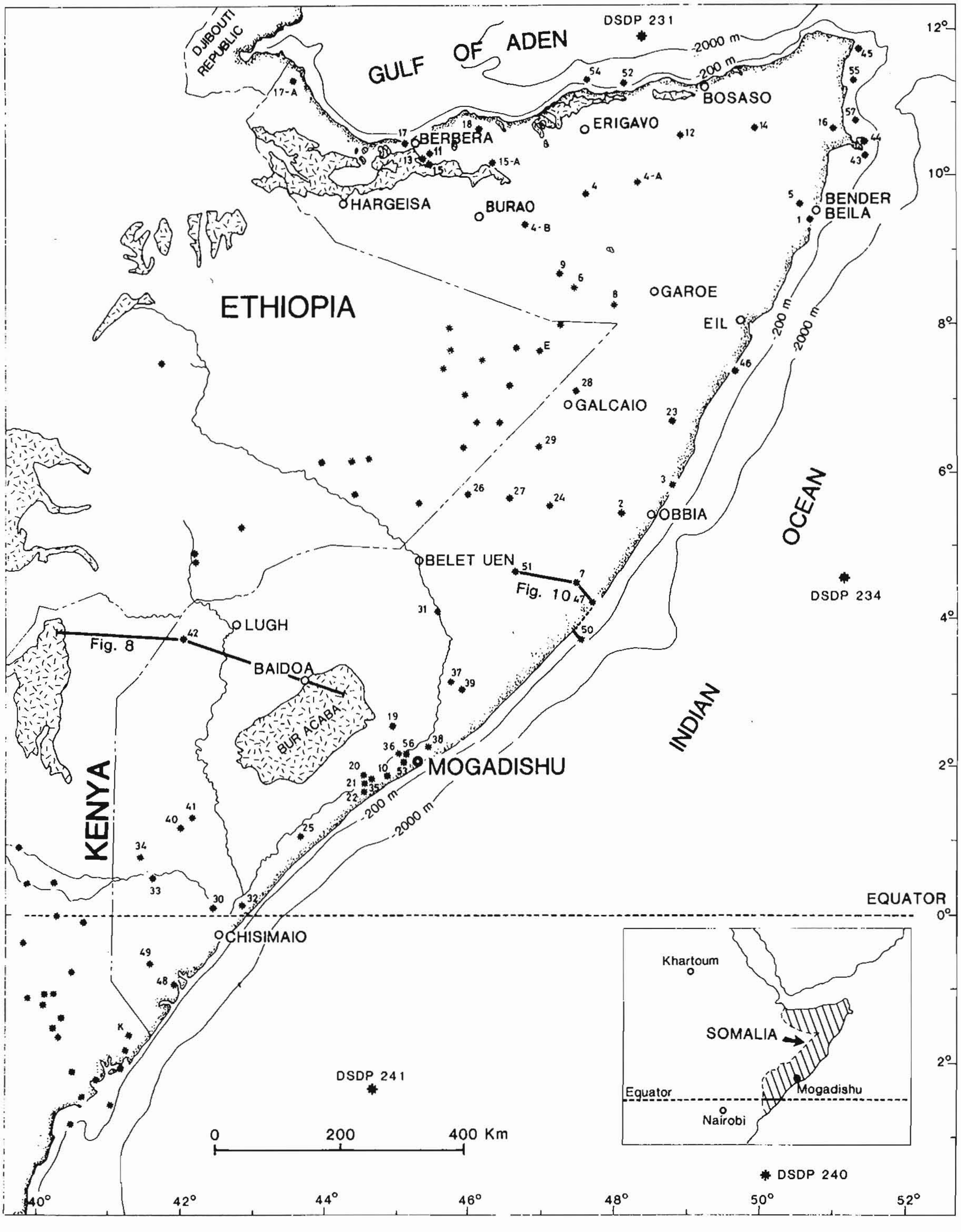

FIGURE 1. Map of Somalia and surrounding regions showing the principal basement outcrops (dash pattern), the position (asterisks) of oil wells drilled in the area, and DSDP holes. Legend of wells referred to in this report: (1) Sagaleh, (2) Gira, (3) Obbia, (4) Faro Hills, (4-A) Hedad, (4-B) Bur Dab, (5) Cotton, (6) Las Anod, (7) Marai Ascia, (8) Burhisso, (9) Yaguri, (10) Merca, (11) Dagah Shabell-1, (12) Buran, (13) Dagah Shabell-2, (14) Darin, (15) Dagah Shabell-3, (15-A) Las Dureh, (16) Hordio, (17) Berbera, (17-A) Zeila, (18) Bio Rader, (19) Duddumai, (20) Coriole-1, (21) Dobei-1, (22) Dobei-2, (23) El Hamurre, (24) En Dibirre, (25) Brava, (26) Dusa Mareb-1, (27) Dusa Mareb-2, (28) Galcaio-1-2, (29) Idole, (30) Oddo Alimo, (31) Bulo Burti, (32) Giamama, (33) Lach Dera, (34) Lach Bissigh, (35) Coriole-2, (36) Afgoi-1, (37) Gal Tardo, (38) Uarsciek, (39) Bio Addo, (40) Das Uen, (41) Gheferso, (42) Hol, (43) Hafun, (44) Hafun-T, (45) Guardafui, (46) Garad Mare, (47) El Cabobe, (48) Kudha, (49) Obbe, (50) Meregh, (51) El Bur, (52) Dab Qua, (53) Afgoi-2, (54) Bandar Harshau, (55) Ras Binnah, (56) Afgoi-3, (57) Gumbah, (E) Bokh, and (K) Mararani.

stratigraphy, but whether the Somalian sequence boundaries correlate to the global cycle chart proposed by Haq et al. (1987) is beyond the scope of this report.

This paper is a shorter version of a previous memoir (Bosellini, 1989b), in which analytical data and comparisons with the geology of adjacent countries (southern Arabian Peninsula, Ethiopia, Kenya, Madagascar, and India) were presented and discussed. It is partly based on a review of the confidential files of the Ministry of Mineral and Water Resources at Mogadishu. These files contain much of the data (well completion reports, geophysical reports, and geological reviews) submitted to the government of Somalia by oil/gas operators, including Sinclair, Amerada, Hammar, ARCO, Burma, AGIP, Conoco, ELF, Gulf, Texaco, Exxon, Shell, BP, Mobil, Citco, Amoco, and several private laboratories. The writer has visited and/or investigated the Jurassic and Cretaceous of central and southern Somalia, the Jurassic and Cretaceous of the Aden coast (from Berbera to Bosaso), and the Oligocene–Miocene of the Indian Ocean coastal area, from Eil to the peninsula of Hafun.

## PLATE TECTONIC EVOLUTION OF SOMALIA AND THE WESTERN INDIAN OCEAN

The following list records important events in the breakup of Gondwanaland and in the evolution of the western Indian Ocean that concern the East African margins and Somalia. The time scale used in this paper is that of Haq et al. (1987):

1. The beginning of separation of East Gondwana (Madagascar, India, Antarctica, and Australia) from West Gondwana (Africa and South America) resulted in north-south relative motion between Madagascar (attached to India, Antarctica, and Australia) and Africa, with the Davie fracture zone forming the western transform-fault margin. Sea floor spreading began during the Jurassic Magnetic Quiet Zone (about 151–159 Ma, Callovian–early Oxfordian) and ceased at anomaly M10 (about 120–121 Ma, early Hauterivian), leaving a small rectangular oceanic basin with restricted circulation (Rabinowitz et al., 1982, 1983; Coffin and Rabinowitz, 1983, 1987, 1988). The Jurassic Magnetic Quiet Zone oceanic crust flanking Somalia and Madagascar is the oldest crust yet dated in the Indian Ocean.

   In this tectonic scenario, northeastern Kenya-southeastern Somalia and northern Madagascar are conjugate passive rift margins, and southern Kenya-Tanzania-northeastern Mozambique and western Madagascar are conjugate passive transform margins. The entire 2200-km-long Davie fracture zone connects remnant spreading centers in the western Somali basin (Parson et al., 1981; Segoufin and Patriat, 1981; Rabinowitz et al., 1983) and was an active transform fault between 150 to 160 Ma and 120 Ma. As extensive normal faulting associated with the Davie fracture zone has been documented (Coffin and Rabinowitz, 1983; Mougenot et al., 1986), it has been hypothesized that the feature may have been reactivated as a rift in response to crustal stretching between the African craton and the Somali plate.

   A predrift fit for Somalia and environs is shown in Figure 2. The position of Madagascar with respect to Somalia is from Coffin (1985), since his is the only fit that has taken into account all of the following data: sea floor magnetic anomalies; recent information on crustal structure; new geophysical data that extend the position of the Davie fracture zone, a critical feature in tracking the azimuth of the southward movement of Madagascar; and the presence of a diapiric province in both the Somalia and Madagascar offshore areas. The position of India relative to Madagascar is adopted from Katz and Premoli (1979). The position of the Seychelles is based on a best approximate fit. The relationship of the north coast of Somalia to the Arabian plate is taken from Lowell and Genik (1972).

   The amount of continental stretching prior to separation of Africa and Madagascar-Seychelles-India is not known. An appreciable amount of rifting over a long time period, probably dating back to Karroo times, preceded the actual separation of the two continents.

   Separation of Somalia and Madagascar-Seychelles-India ceased at 120 Ma (Early Cretaceous), as shown by magnetic anomaly M10, the youngest anomaly mapped in the Somalia basin.

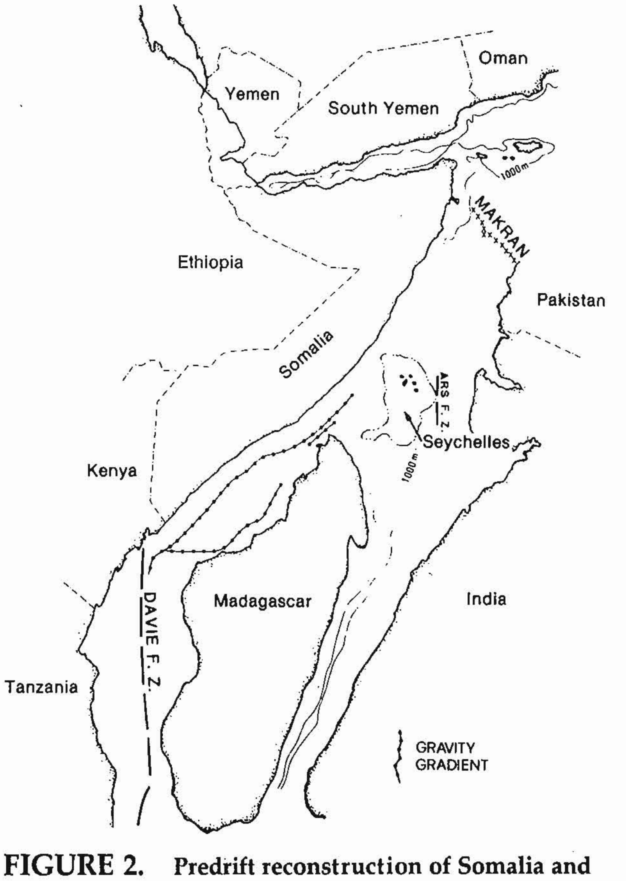

**FIGURE 2.** Predrift reconstruction of Somalia and adjacent areas.

2. Transcurrent motion between India and Madagascar began about 80 Ma (Norton and Sclater, 1979). In the Late Cretaceous and Paleocene, Indian Ocean spreading rates were very high. The rapid northward motion of India was parallel to the Chain Ridge-Owen fracture zone and to the northern sector of the Somali continental margin. The occurrence of Late Cretaceous ophiolites and ophiolite melange along the Oman continental margin (Moseley and Abbotts, 1979; Lippard et al., 1986) suggests that, during the India "voyage," a major sinistral transform fault was bounding southeastern Arabia and the northeastern sector of the present Horn of Africa. Movement on this fault coincided with upthrust of the ophiolite from the southeast onto the continental margin.
3. During the entire Mesozoic and early Cenozoic, Arabia, Nubia (Sudan-Ethiopia), and Somalia were assembled in a single continental block, sometimes partly covered by shallow seaways (Beydoun, 1970; Bruni and Fazzuoli, 1980). The separation of Arabia from Africa (Somali plate) started in the middle Miocene (14-10 Ma) (Cochran, 1981, 1987), after a late Oligocene-early Miocene (25-20 Ma) phase of crustal stretching. The sinistral shear movement along the Red Sea could have caused the Gulf of Aden to break along ancient east-northeast-trending crustal weaknesses (Behre, 1986). Continental separation, as documented in the Afar (Barberi et al., 1975), appears to have occurred after a protracted period of rifting, tilting of blocks, and crustal extension, as documented by dike injection.

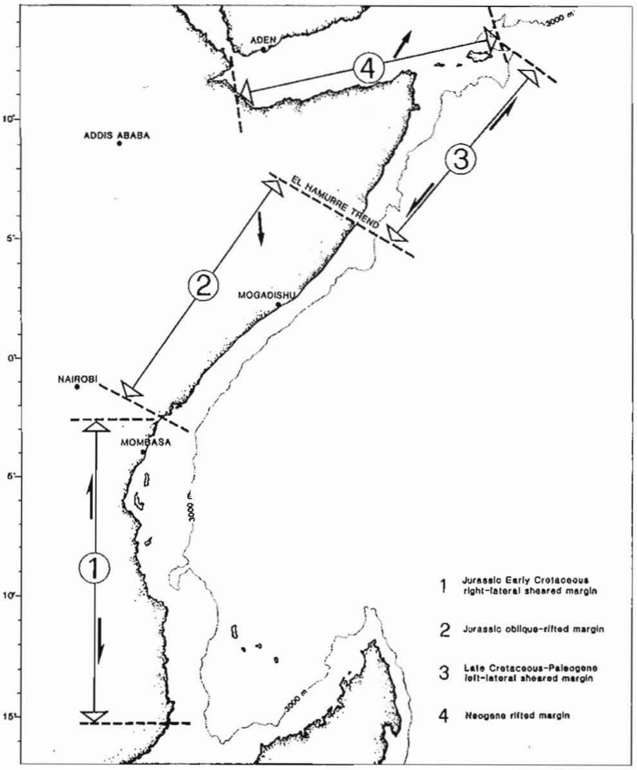

**FIGURE 3. The four different sectors of the East Africa continental margin (from Bosellini, 1986). Arrows indicate principal relative movements during continental separation.**

## The Continental Margins of East Africa

If we accept the general plate tectonic history outlined above, then the East African continental margin can be divided into four distinct sectors (Figure 3) that formed at different times under different geodynamic regimes (Bosellini, 1986).

1. The continental margin bordering northern Mozambique, Tanzania, and most of Kenya (between about lat. 15°S and lat. 2.5°S) formed by transform motion along the Davie fracture zone between Madagascar and Africa. It is a right-laterally sheared continental margin, formed over a span of about 30 million years and ranging in age from the Middle-Late Jurassic at the north and south ends to the Early-middle Cretaceous in the center.
2. The margin of northeast Kenya and Somalia, between about lat. 2.5 and lat. 6°N, formed during the Jurassic (around 150-160 Ma) by rifting and drifting of Madagascar from Africa. The relative motion of Madagascar was oblique (about 45°) to the direction of the Somali coast, which is not a pure rifting margin but has a right-lateral component.
3. The northernmost sector of the East African continental margin, from about lat. 4 to 5°N to the eastern corner of Socotra, is adjacent to the northern Somali basin, which appears as a distinctive subbasin in the western Indian Ocean both on bathymetry and Seasat-derived free air gravity maps. The northern Somali basin is bounded on the east by the Owen fracture zone and Chain Ridge, on the south by an east-west-trending structural high extending offshore from Somalia at about 3 to 4°N, on the west by the Somali continental margin, and on the north by the Socotra High and the young ocean crust created at the East Sheba Ridge. Basement has not been sampled from the basin, nor have marine magnetic anomalies been identified. Thus, its age is uncertain. But, according to J. R. Cochran (personal communication, 1987), magnetic anomalies (probably the M- sequence) do occur in the northern Somali basin. If this basin is indeed Mesozoic, then the northern sector of the East African continental margin is another right-laterally sheared segment formed during the detachment of India from Arabia and Africa.

Alternatively, this northern segment formed in the Late Cretaceous (80-90 Ma) when Greater India separated from Madagascar and began its northward drifting toward Asia. Former Jurassic and Cretaceous crust would have drifted northward with India, crushed into the collision zones of Asia, and finally either obducted onto the Arabian continental margin (Semail ophiolite) (Lippard et al., 1986) or expulsed along the lateral shear zones (Masirah ophiolite melange) (Moseley and Abbotts, 1979). If this is the case, the northern segment of the East African continental margin is an inactive, left-lateral transform margin (Bosellini, 1986) that continued northeastward into the Oman sheared margin during the Late Cretaceous to Paleocene.

4. A fourth Somali continental margin borders the Gulf of Aden, from the Afar Triangle to Socotra. This margin is a Neogene feature formed from the rifting and slightly oblique drifting of Africa and Arabia (LePichon and Francheteau, 1978; Courtillot, 1980; Cochran, 1981, 1987; Berhe, 1986; Abbate et al., 1988).

## EARLY FRACTURING OF GONDWANA AND THE KARROO RIFTS

As discussed above, sea floor spreading between Africa and the Madagascar-India-Seychelles block began in Callovian-early Oxfordian time (151-159 Ma). This movement was preceded by earlier rifting of Gondwanaland and deposition of the well-known Karroo sediments in a series of separate faulted basins with limited marine access. The failed arms of this complex system of rifts appear now as intracontinental deep troughs filled with Paleozoic and early Mesozoic sediments. Other rifted sites of Karroo deposition evolved at continental margins.

A major Paleozoic-Mesozoic branching rift system seems to have deeply dissected large parts of Gondwanaland, including East Africa, Madagascar, and India (Figure 4). This system of downfaulted basins was punctuated and segmented by some triple junctions located (1) near Dar-es-Salaam, (2) south of Chisimaio along the present coast of Somalia, (3) north of Cape d'Ambre (Madagascar) in what is now the Somali Basin, and (4) in India at the intersection of Narbada and Godavari rift valleys.

In this view of the Late Triassic-Early Jurassic paleogeography of the East African-Indo-Malgash landmass, three points deserve some attention regarding the geology of Somalia.

1. The Karroo rifts were best developed in the southern part of the study area, where they formed a deeply incised network of narrow intermontane depressions.

2. In the northern part of the Gondwana block discussed here (i.e., northern Somalia, Ethiopia, and Arabia), the fault-bounded Karroo depositional basins diminish and are replaced by a more subdued landscape of vast, arid, coalesced alluvial plains, locally interrupted by basement highs and inselbergs.

3. Some arms of the Karroo rift system did not open beyond the rifting stage during the Late Jurassic-Cretaceous breakup of Gondwanaland, thus becoming "failed arms" or intracontinental sedimentary basins. They include the Mandera-Lugh basin and the Hiraan trough of Somalia, the Tunduru break of Tanzania, the Morodava basin of Madagascar, and the Narbada and Godavari basins of India. Other branches of the rift system, however, were split apart during the Gondwana fragmentation and were partly incorporated into the present continental margins where they should be represented in the deepest parts of the local sedimentary succession. This is the case of the southern continental margin of Somalia, from about Hafun to the Kenyan border.

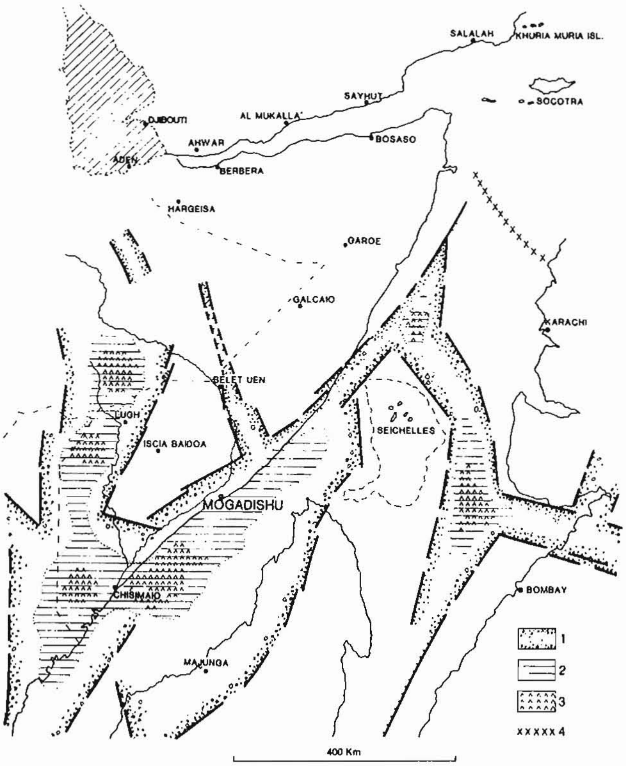

**FIGURE 4.** The Karroo rift system in East Africa, Madagascar, and India. Only the major rifts are shown; several other smaller ones were certainly present within Ethiopia and Arabia. (1) Intermontane clastics; (2) water bodies, mainly lacustrine; (3) evaporites; (4) present-day position of the Makran front.

## THE BASAL CLASTICS

The peneplained Precambrian-early Paleozoic basement of the Gondwana sector is generally overlain by terrigenous sediments of variable thickness. These sediments were deposited in a vast arid land, some 2000 by 3000 km in extent, characterized by subdued topography; however, basement blocks and isolated inselbergs protruded out of bajadas of sand plains crossed by ephemeral braided streams and some major meandering rivers.

The depositional environment of the basal clastics was mainly alluvial. The sedimentary features characteristic of this section include predominantly coarse-grained clastics at the base, shale units toward the top, an absence of marine fossils, scattered plant debris, and an areal extent of several thousands of square kilometers. Lacustrine or coastal plain-deltaic areas as well as inland sabkhas and eolian dune fields were locally present.

The age of the basal clastics is referred to as Triassic–Early Jurassic (Figure 5), but fossil control is very poor. The beginning of clastic accumulation was probably diachronous and strongly controlled by paleotopography. Thicknesses of more than 700 m are reported from Tanzania, Madagascar, eastern Kenya, southern coastal Somalia (Brava well), northern Ethiopia (Tigrai and Danakil), and western Yemen. Areas where the basal clastics are missing or extremely thin are quite common, however, and include western and southern Ethiopia, southern Yemen, northern Somalia, Bur Acaba high (Figure 1), and northeastern Kenya.

The term *Adigrat Sandstone* is the name now given in Ethiopia and Somalia to the basal siliciclastic unit. Equivalent terrigenous successions are referred to as the Kohlan Formation in the southern Arabian Peninsula, Lathi Formation in western India (Rajasthan), Mansa Guda Formation in northeastern Kenya, Isalo Group (Upper Karroo) in Madagascar, Mazeras Formation in coastal southern Kenya (Mombasa-Malindi area), and Ngerengere Beds in Tanzania (Figure 5).

The basal clastics are generally well exposed in northern Somalia along the escarpment of the Somali plateau or in some downfaulted blocks of the Gulf of Aden continental margin. They are represented by two different formations: the Adigrat Sandstone proper, which is fluviatile in origin, and the shallow marine Al Mado Formation of mixed siliciclastic-carbonate rocks, 500 to 600 m thick.

The best sedimentological description of the Adigrat Sandstone so far available is that of the Bihendula section (Figures 6, 7) near Berbera (Bruni and Fazzuoli, 1977). Here, the 130-m-thick Adigrat is a typical fluviatile succession, with braided stream deposits at the base, point-bar sequences in the middle, and coastal plain to lagoonal sediments in the upper 15 m. The basal contact is erosional and slightly unconformable on the underlying basalt flow. The unit gradually passes upward into late Bathonian to Callovian Bihen Limestone.

Original "depositional" thickness of the Adigrat Sandstone varies from a few meters to a maximum of 200 m (Dagah Shabel-1); on the plateau, thickness is less than 100 m, usually on the order of 30 to 40 m. The Adigrat, however, is missing in several localities as a result of Cretaceous uplifts. Basalt flows occur near the base of the Adigrat succession in several places of the Berbera basin. East of the Erigavo high (Figure 6), the basal lava flows do not occur and the succession gradually changes to a more distal facies. The Adigrat (5–50 m thick depending on the underlying basement relief) is clearly organized in fining-upward sequences, suggesting a more distal position with respect to the Berbera area. The overlying clastic succession, here called Al Mado Formation, is characterized by a series of cycles. Each cycle is 15 to 20 m thick and is represented from bottom to top by (1) laminated and hummocky cross-bedding sandstone, (2) thick-bedded, coarse sandstone channeling the underlying deposits and grading upward into (3) massive, burrowed, sandy dolostone.

These cycles are interpreted as a series of prograding shorelines, where shelf sands in storm wave base are cut by current-generated channels with coarse sandstone. Lagoonal, calm water conditions produce the burrowed dolomite bank. The entire Al Mado Formation has a thickness of 500 to 600 m. As in the Berbera area, paleocurrents indicate a general southward transport.

## Structural and Paleogeographic Evolution during Adigrat Time

Both the lower and upper boundaries of the Adigrat succession are diachronous (Figure 5). The age of the lower

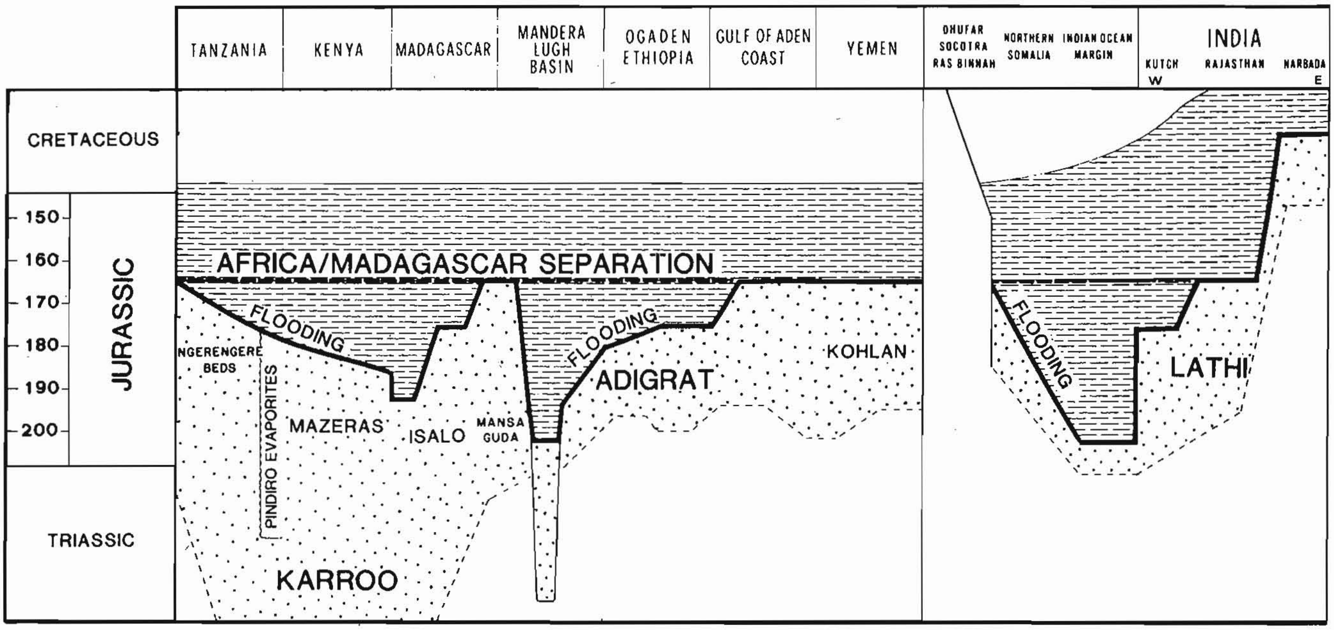

**FIGURE 5. Chronostratigraphic chart showing time of Jurassic flooding in various sectors of Gondwana adjacent to Somalia. The timing of Africa/Madagascar separation is also shown.**

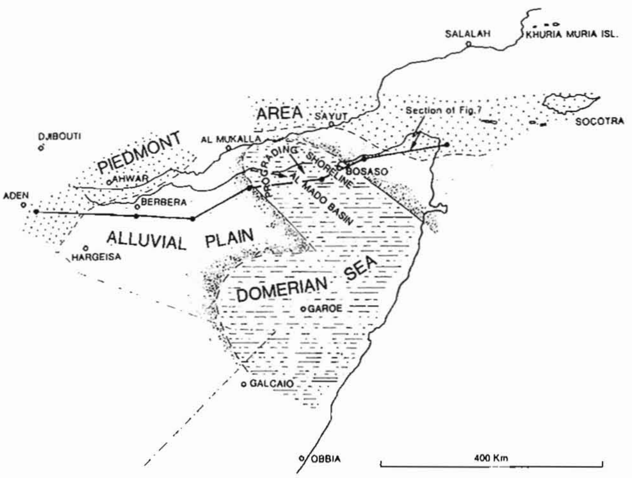

FIGURE 6. **Paleogeographic map of northern Somalia in Liassic (Domerian) time. The Al Mado sound, a shallow gulf surrounded by prograding shoreline systems, appears as the most prominent feature of this landscape.**

boundary (practically impossible to date) was controlled by the Gondwana relief and rifting. The age of the upper boundary, which is the age of the transgression, was controlled by Jurassic rifting and by the gradual onlapping of marine sediments onto the East African continent. The age span of the Adigrat is variable and extends from Triassic to Middle-Late Jurassic.

At the beginning of the Jurassic, most of Somalia and adjacent countries (Kenya, Ethiopia, southern Arabian Peninsula, India, and Madagascar) were subaerial. Facies and thickness patterns of the Adigrat and Kohlan sandstones suggest deposition by braided or low-sinuosity streams.

From the Ethiopian border southeastward, facies of the Adigrat changes gradually and fining-upward sequences are better developed. The area between Erigavo and Bosaso was a shallow sound (Figure 6) where several depositional regressions occurred. This marine area was also a structural low. Subsidence is demonstrated by comparing the thickness of the pre-Bathonian succession of the Al Mado range (600 m) with the coeval succession of the adjacent areas: 130 m at Bihendula, 170 m at Ras Antara, and much less in the Borama district and Yemen. The area of greater subsidence defines a proposed Early-Middle Jurassic Al Mado Basin (Figure 7). As shown in Figure 6, the basin had a northwest-southeast trend, was open southeastward, and was closed toward Yemen.

## RIFTING STAGE AND FLOODING OF THE EAST AFRICAN CRATON: THE HAMANLEI DEPOSITIONAL SEQUENCE

The Hamanlei depositional sequence is the Early-Middle Jurassic basal sediment package onlapping onto the East African craton and has a diachronous lower boundary. Its upper boundary will be discussed in the next section.

### The Shallow Water Facies: The Hamanlei Formation and Its Equivalents

The Hamanlei Formation (also called the Iscia Baidoa Formation) is a dominantly carbonate unit that abruptly overlies the Adigrat clastics and ranges in age from Pliensbachian to Callovian. In the Hol-1 well, it is 1031 m thick and overlies 1050 m of anhydrite and dolomite and 1500 m of black argillaceous mudstones (Figure 8).

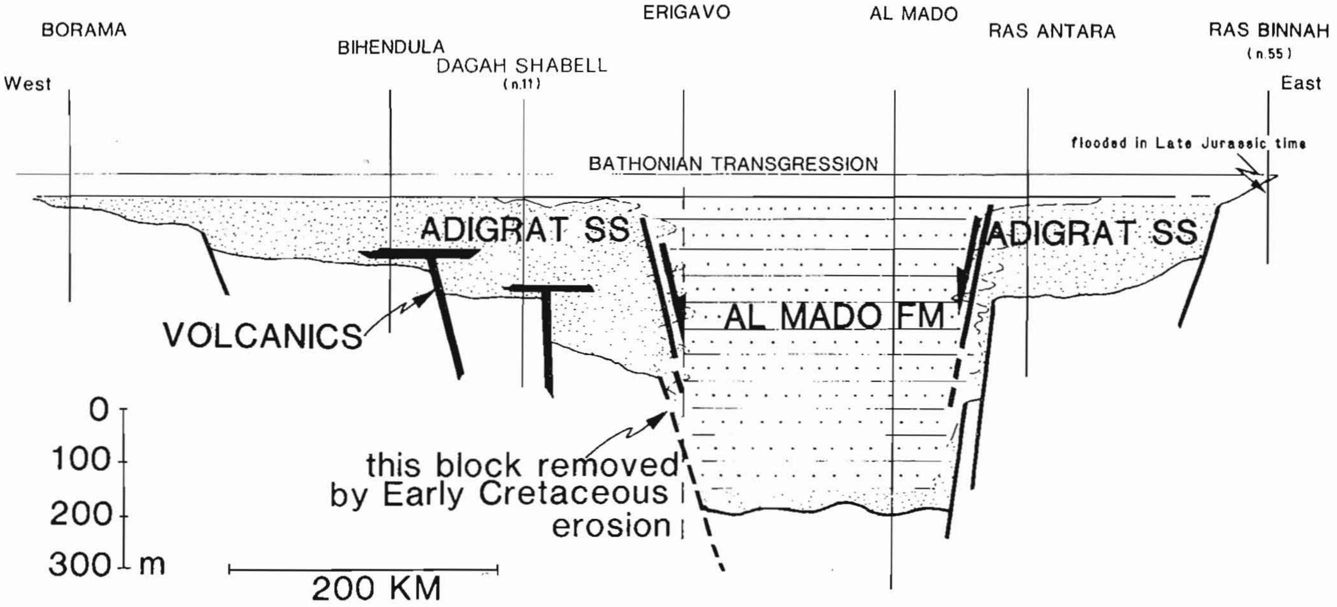

FIGURE 7. **Stratigraphic cross section of northern Somalia in Liassic time showing thickness and stratigraphic relationships of Adigrat and Al Mado formations. See Figure 6 for section location.**

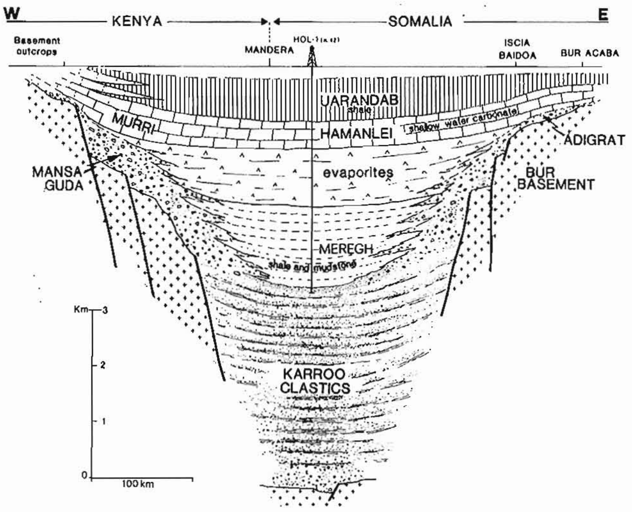

**FIGURE 8.** Cross section of the Mandera-Lugh basin, interpreted as an aborted Karroo rift. For section location see Figure 1.

Correlation of the Jurassic section penetrated by the Hol-1 well with surface exposure along the west flank of Bur Acaba remains uncertain. As the section dramatically thins eastward onto Bur Acaba (Figure 8), the basal black mudstone (Meregh Formation) and the overlying anhydrite-dolomite sequence encountered in the Hol-1 well are older, probably Hettangian to Pliensbachian.

The Hamanlei Formation is presented also along the Oddur arch (1200–1500 m thick) in the Ogaden and in the entire shallow water shelf of northern Somalia. To the north of the El Hamurre lineament, the base of the Hamanlei Formation is at least Pliensbachian (Domerian) as shown by the occurrence of *Vidalina martana, Lingulina tenera,* and *Orbitopsella praecursor* in several wells (e.g., Garad Mare-1, Cotton-1, Buran-1, Bokh-1).

The carbonate platform margin, which is the transition zone from shallow water (Hamanlei) to basinal (Meregh) facies, is very poorly constrained by well control between Bulo Burti-1 and Garad Mare-1. At Garad Mare-1 (AGIP Somalia, unpublished report, 1977), the Hamanlei Formation (1093 m thick) is mainly oolitic and pseudoolitic packstone-grainstone. The occurrence in this well of *Protopeneroplis striata* documents the Dogger age of the upper Hamanlei, whereas the presence of *Vidalina martana* in the lower 100 m confirms the Pliensbachian (Domerian) age of the transgression over the northern Somali shelf.

## The Basinal Facies: The Meregh Formation

In the Hol-1 well, a black, argillaceous lime mudstone with a gradational transition from the previously described anhydrite-carbonate succession directly overlies the Adigrat Sandstone (Figure 8). The mudstone's thickness is about 1500 m, with pelecypods, gastropods, echinoderms, and sponge spicules. These sediments were deposited in low-energy, relatively deep, and poorly circulated marine water. They are correlatable with a similar succession of thick, basinal dark mudstone, marlstone, and shale encountered in several wells of the Mudugh basin (Meregh-1, El Cabobe-1, Gal Tardo-1, Duddumai-1, Bio Addo-1, Marai Ascia-1, Gira-1, En Dibirre-1, Obbia-1, and El Hamurre-1).

Bosellini (1989b) proposed to name this basinal facies the *Meregh Formation* after the Meregh-1 well where its thickness exceeds 2500 m. The Meregh Formation, which is confined to the Mudugh and Mandera-Lugh basins and to the Indian Ocean continental margin (Figure 9), is composed primarily of black, pyritic micrite and dolomite. Thick oolite intervals (Obbia-1, Marai Ascia-1, El Cabobe-1), many of which are porous, occur in the upper part of the succession. The stratigraphic setting suggests that they were gravity displaced, deposited by turbidity currents, and accumulated in the deeper parts of the basin. Derivation of some ooid sands from the Madagascar-Seychelles shelf in the area of Obbia-1 is probable. Mid-Jurassic oolitic shedding is a distinctive event of Tethyan paleoceanography (Bosellini, 1989a). Off-platform transport of carbonate sand was strongly enhanced from Nova Scotia, through the Mediterranean, to Oman, Somalia, and the Seychelle Islands during the Bajocian–Bathonian eustatic highstand.

The age of the first ingression of the sea in the basinal setting (Mandera-Lugh and Mudugh basins) is unknown. The shallow water succession of the adjacent shelf contains well-documented Pliensbachian (Domerian) foraminifers that suggest a Sinemurian or even an Hettangian age for the basal Meregh Formation.

## Paleogeographic and Structural Evolution during Hamanlei Time

The complex system of Gondwana rifts (Figure 4), the bases of which were probably near or even below sea level, was inundated by the sea at the beginning of Jurassic time. This transgression was the result of the rifting stage heralding the Gondwana breakup and the Mesozoic eustatic sea-level rise (Haq et al., 1987; Hallam, 1988). The sea flooded the land from the paleo-Tethyan margin to the northeast (Oman, Pakistan, and northern India) (Figure 9), following the lowest pathways, and initially formed a series of long and branching marine sounds. The Mudugh basin formed as a direct response to the incipient separation of Madagascar from Somalia. The Mudugh basin was bounded to the north by the El Hamurre lineament, which was a transform fault that allowed the release of the Madagascar block and set up the structural differentiation of the Somali continental margin in two different sectors (Figure 3) (Bosellini, 1986). The Mudugh basin proper and its southern continuation (the Mogadishu basin) consisted of several down-to-basin faults bounding elongated rotating blocks (Figure 10).

During the Pliensbachian, the Jurassic sea flooded the adjacent shelves and highs (Bur Acaba high, Las Anod arch, Ogaden). During the Toarcian, the entire Horn of Africa, except northwest Somalia and the adjacent Arabian block (Figures 6, 9), was probably submerged. In fact, no siliciclastics occur in the Toarcian Uanei Member (Iscia Baidoa Formation), even very close to the Bur basement outcrops,

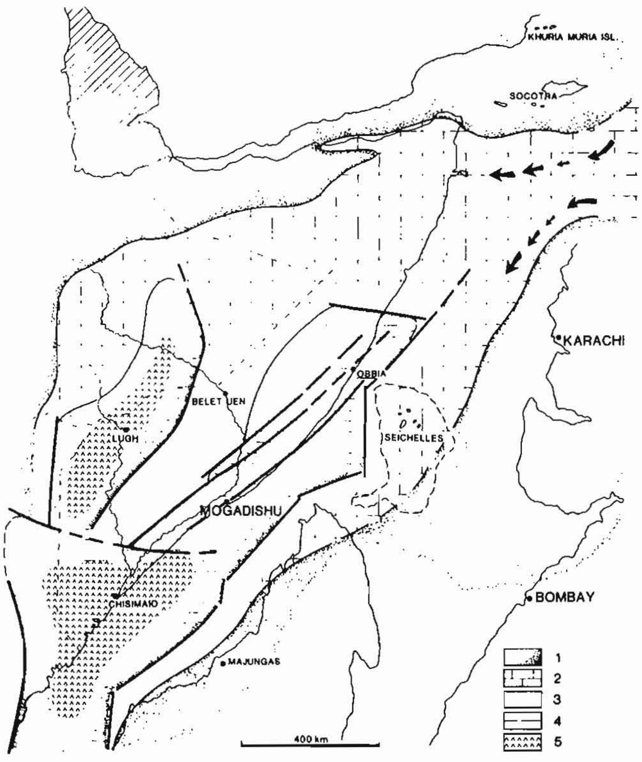

FIGURE 9. **Paleogeography of Somalia and adjacent Gondwana blocks during late Liassic time after the major transgression that flooded the former Karroo rifts. Arrows indicate the "Pakistan portal" (i.e., the connection with the Tethyan ocean). (1) Terrestrial sediments, mainly alluvial (Adigrat Sandstone); (2) shallow water carbonates and evaporites (Hamanlei Formation); (3) high-energy carbonate sediments at platform edges; (4) basinal sediments (Meregh Formation); (5) evaporites.**

and this implies that the Bur Acaba high had no relief at that time.

After the first flooding of the land, which lasted until Toarcian time in some parts of central and southern Somalia, a transgressive systems tract (Haq et al., 1987) was deposited. Afterwards shallow water and high-energy sedimentation produced a general depositional regression on shelf areas. This process, which produced the highstand systems tract of the sequence, is documented by the general thickening and coarsening-upward trend of the succession, as shown, for example, in the upper Iscia Baidoa Formation (Goloda Member) or in the upper part of the Bihen Limestone. The depositional regression was diachronous in the beginning, but the final highstand is generally Callovian. The top of the Hamanlei depositional sequence is a boundary that is coeval in all of Somalia.

## THE GONDWANA BREAKUP AND THE UARANDAB DEPOSITIONAL SEQUENCE

The separation of Africa and Madagascar was an important geodynamic event that marked the end of rifting and intense tectonic activity of the margin and the beginning of drifting and a more quiet and steady phase of regional subsidence.

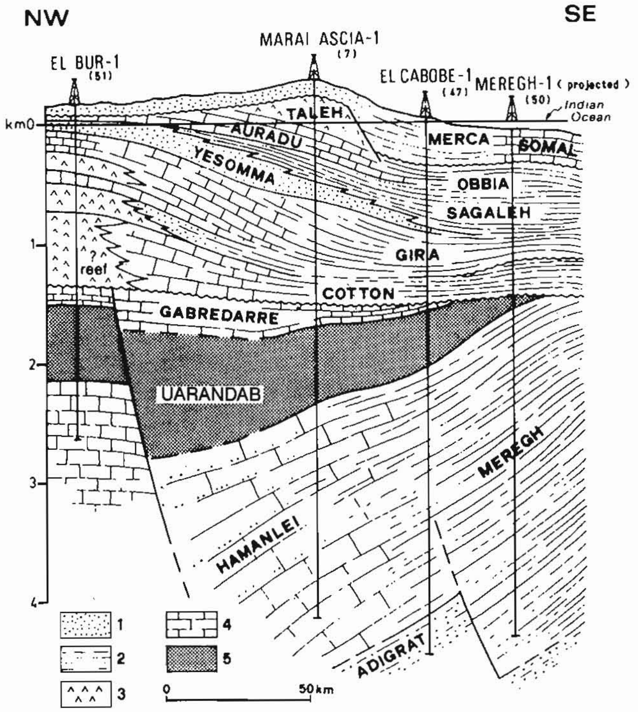

FIGURE 10. **Cross section of the Mudugh basin showing the faulted Jurassic section (rift phase) overlain by the Cretaceous-Tertiary prograding succession (drift phase). (1) Sandstone; (2) shale and mudstone (basinal); (3) boundstone (buildup, reef); (4) shallow water limestone; (5) Uarandab Formation: black fissile shale, marlstone, and mudstone (open shelf and basinal). For section location see Figure 1.**

A major transgression that appears to be related to the drifting phase occurred over most of East Africa, resulting in shale deposition over the Hamanlei depositional sequence. These shale units were deposited in deeper water and are variously called Uarandab Formation, Anole Formation, and Gahodleh Shale. They are overlain upward by a gradual return to shallow water carbonate sediments (Gabredarre Formation, Uegit Formation, Gawan Limestone). The Uarandab (Anole, Gahodleh) and Gabredarre (Uegit, Gawan) formations taken together are a sequence reflecting regional transgressive deepening followed by depositional regression. This interval is a single genetic unit designated as the Uarandab depositional sequence (Bosellini, 1989b).

### Uarandab Formation and Equivalent Units

The transgression and basin deepening occur over a large area of central and southern Somalia. West of Bur Acaba high, in the Mandera-Lugh basin, the contact between the thick-bedded oolitic calcarenites and coquinas of the uppermost Hamanlei (Goloda Member of Iscia Baidoa

Formation) and the overlying dark, shaly Uarandab succession, here called Anole Formation (Barbieri, 1968), is a sharp lithological break.

The Uarandab is mainly shaly or marly but contains thin beds of carbonate or siltstone, particularly in its upper part. The formation is about 180 m thick in the Hol-1 well, but it is reported to be about 400 m thick in the Bur Anole area (Barbieri, 1968). The age, according to its pelagic fauna (ammonites, belemnites, foraminifers), has been reported as late Callovian to late Oxfordian (Bruni and Fazzuoli in Ali Kassim et al., 1987). The Uarandab is widely distributed and is present in Ogaden along the northern extension of the Mandera-Lugh basin and across the Oddur arch where thicknesses average about 150 m.

Along the Indian Ocean continental margin, the Uarandab sequence consists of greenish-gray and black fissile shale and micrite. The maximum thickness occurs in the Brava-1 well (844 m) and in the center of the Mudugh basin (1050 m in En Dibirre-1). Thinner sections occur along the coast, suggesting possible uplifted margins of rotated blocks (Figure 10). To the north of the Mudugh basin, the interval has been partly eroded by post-Jurassic uplift at Galcaio-2, El Hamurre-1, and northeastern Ogaden.

In the western part of the Gulf of Aden (Berbera area), the Bihen Limestone, equivalent in age and facies to the Hamanlei depositional sequence of central and southern Somalia, is abruptly overlain by a 550-m-thick basinal succession of dark-gray or black shale (Gahodleh and Daghani shales) and mudstone (Wanderer Limestone), rich in ammonites, aptychi, belemnites, brachiopods, foraminifers, radiolarians, and nannoplankton. The shale grades upward into the Gawan Limestone, a 245-m-thick shallowing-upward unit (well-bedded mudstone and wackestone with thin shale intercalations).

The Gahodleh/Gawan succession is exactly equivalent to the Uarandab/Gabredarre sequence of central Somalia. The shaly part of the succession corresponds to the Uarandab Shale, while the overlying Gawan correlates with the shallowing-up carbonates of the Gabredarre/Uegit formations (Figure 11). The basinal succession of the Berbera area is restricted to a narrow belt, probably fault controlled (Figure 12).

## Gabredarre Formation and Equivalent Units

The Gabredarre, or Uegit, is mainly a well-bedded limestone sequence composed of bioclastic calcarenites, cross-stratified oolitic grainstones, and oncolitic micrites with thin shaly or marly intercalations. The age, according to Bruni and Fazzuoli (in Ali Kassim et al., 1987), is late Oxfordian-Kimmeridgian to? early Portlandian.

As reported above, the equivalent unit of the Berbera area, the 245-m-thick late Kimmeridgian-Portlandian Gawan Limestone, is represented by a progressively shallowing-upward succession. It consists of open-sea facies at the bottom and restricted lagoon facies, with some siliciclastic supply, at the top (Bruni and Fazzuoli, 1977).

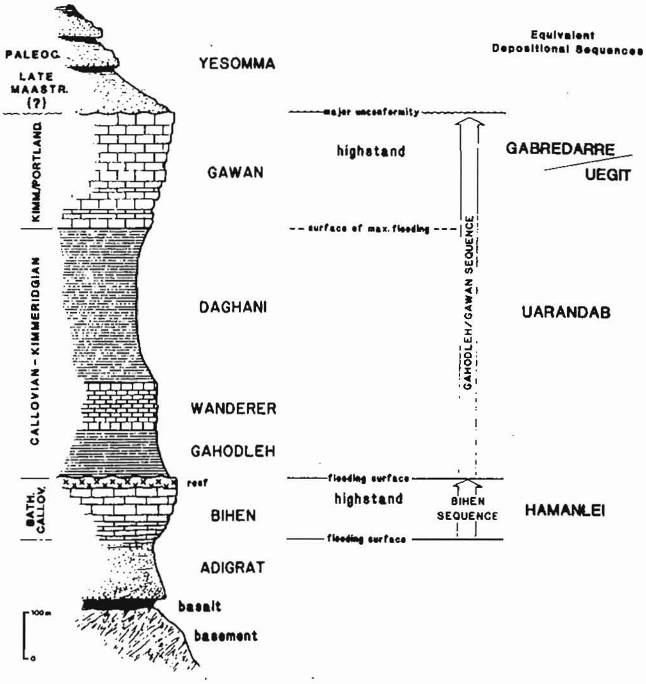

**FIGURE 11.** Stratigraphic column of the Bihendula section, southwest of Berbera, interpreted in terms of sequence stratigraphy and compared with the coeval successions of central and southern Somalia.

## Late Jurassic Structural and Paleogeographic Evolution

It is clear that the Callovian-Oxfordian transgression of the East African craton is related to the final breakup of this area and subsequent drifting and to the steady phase of regional subsidence. The abrupt lithologic change occurring at the top of the Hamanlei indicates sudden foundering during the late Callovian (150–155 Ma) of the entire oblique-rifted sector of the margin (from lat. 2.5°S to 6°N) (Figure 3) and the drowning of the shallow water carbonates of the upper Hamanlei depositional sequence (Iscia Baidoa Formation, Bihen Limestone). The "sag" or embayment thus formed (Figure 12) was bounded to the north by the southeast-trending El Hamurre escarpment (Bosellini, 1986). The tectonic foundering was confined not only to the sector of the continental margin facing the pulling-away Madagascar-Seychelles block but also extended a branch northward that formed the Berbera trough, a possible precursor of the Red Sea (Figure 12).

North of the El Hamurre trend, which was probably the site of reefs or at least of linear carbonate sandy shoals, the Jurassic is mainly shallow water or evaporitic facies or is missing, as, for example, in the entire area offshore from Hafun to Socotra Island (ELF Somalie, unpublished reports, 1970, 1972, 1973, 1975).

After this Callovian-Oxfordian flooding of large sectors of East Africa, the following highstand period, characterized by slower subsidence and tectonic quiescence, resulted in basin filling and progradation (deposi-

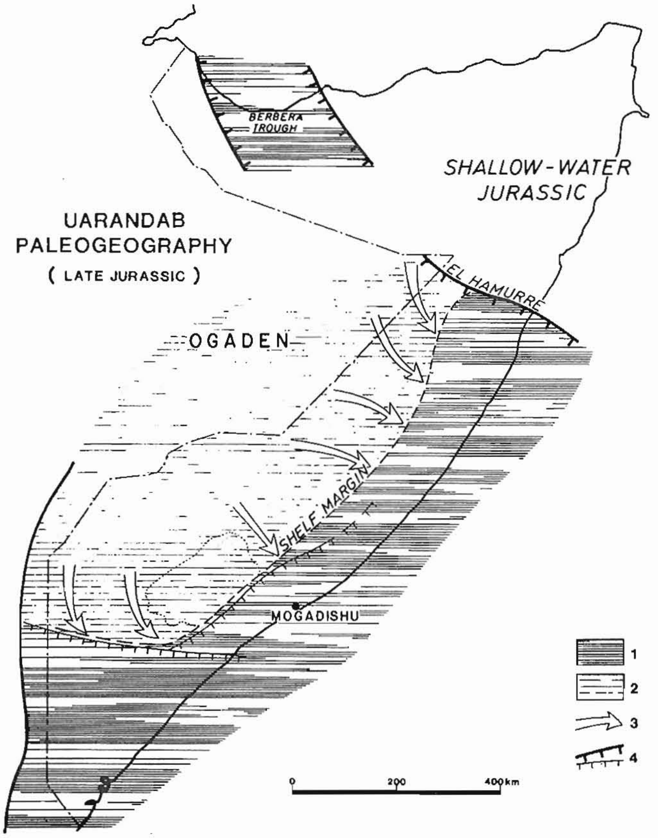

**FIGURE 12.** Paleogeography of Somalia during Late Jurassic time (Callovian–Oxfordian) after the separation of Madagascar and Africa. The segment of the continental margin that was formerly adjacent to Madagascar-Seychelles foundered suddenly, and the shallow water carbonates of the Hamanlei Formation were replaced by open-marine sediments (Uarandab/Anole marl and shale). The "sag" thus formed was bounded on the north by the El Hamurre tectonic trend and on the west by the margins of the former Juba-Lamu and Mandera-Lugh rift basins. The Berbera trough was also formed during this time. (1) Deep-water, basinal shale; (2) open-marine, shelf marlstone, and shale; (3) progradation of Kimmeridgian Gabredarre and Uegit shallow water carbonate systems; (4) structural margins: (a) active; (b) buried.

tional regression) all around the basinal areas. The Uegit and Gawan shallow water formations filled the Mandera-Lugh and Berbera areas, respectively, while the Gabredarre prograded eastward, as shown in Figure 12. In the Mudugh basin depocenter and eastward, the Gabredarre-equivalent deposits consist of deep-water sediments, not very different from the underlying Uarandab shale.

Concluding the description of these Jurassic sequences, it is worth mentioning the two different structural basins that originated in northern Somalia during the Jurassic: the Al Mado basin and Berbera trough. The two basins probably had the same northwest-southeast strike, but their onset had a different timing: Early Jurassic for the Al Mado basin; Late Jurassic for the Berbera trough. Unfortunately, Late Cretaceous uplift and erosion prevent the reconstruction of a satisfactory paleogeographic map, as the Jurassic is totally missing on the Somali plateau and on the Erigavo high. However, the total absence of siliciclastic sediments in the Jurassic of the Bihendula section rules out the possible occurrence of nearly exposed highs and strongly suggests a former connection of the Berbera trough with the Mudugh basin or even with the Mandera-Lugh basin (via Ogaden).

## THE NEOCOMIAN/BARREMIAN EVENT AND THE MAIN GYPSUM DEPOSITIONAL SEQUENCE

A major pre-Aptian deformation event is documented over northern Somalia where the Neocomian-Barremian interval is generally absent and the Aptian progressively transgresses from east to west over different Jurassic terrains. The unconformity is well documented both in outcrop sections (Erigavo, Al Mado, Ras Antara, Yemen, and Socotra) and in wells (Bokh, Las Anod-1, Buran-1, Darin-1, Cotton-1, Sagaleh-1, Garad Mare-1, and Hafun-1).

The Aptian transgression, however, did not flood the whole of northern Somalia. The Las Anod arch remained exposed and was transgressed by the sea during the Turonian when pelagic sediments were deposited in most parts of northern Somalia.

To the southeast, the same tectonic pulse resulted in a widespread supply of quartz sand from Kenya. A major fluviatile system (Ambar Sandstone) prograded northeast into a wide, restricted marine shelf. During the Early Cretaceous, central Somalia was a shallow gulf, largely surrounded by land. In this embayment, dolostones and sulfates (Main Gypsum) accumulated in sabkhas, lagoons, and shallow sounds. A narrow, high-energy belt of reefs and associated sandy shoals separated the evaporite embayment from the adjacent marginal basin (Mudugh basin) of the continental margin.

### Structural and Paleogeographic Evolution during Early Cretaceous

The Early Cretaceous was a time of relative lowstand (Figure 13), with continuous regression after the general flooding of the Uarandab time. The shallow marine facies shifted southeast across the relatively deep marine deposits of the Jurassic. Tectonics was the prime mechanism controlling the Early Cretaceous paleogeography. The only body of water left on the craton was accumulating the evaporites of the Main Gypsum, while in the narrow Mudugh basin, considerable mass wasting was taking place triggered by the lowstand position of the Neocomian sea. Neocomian deposits appear to have been confined within a major east–west structural depression that shallowed westward (Ogaden) and deepened toward the proto-Indian Ocean.

The facies and thickness patterns of Figure 13 suggest that the Main Gypsum facies originally extended farther

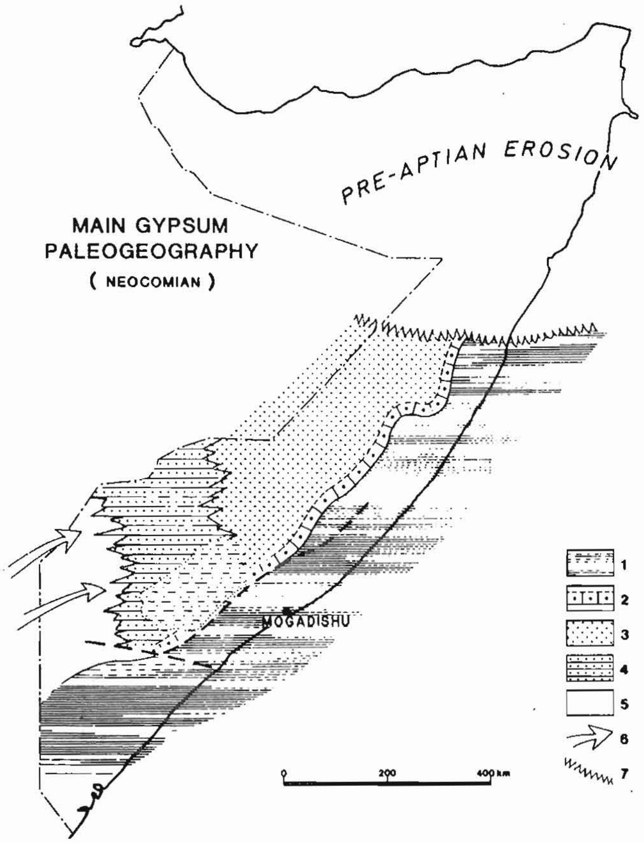

FIGURE 13. **Paleogeography of Somalia during the Neocomian. (1) Basinal mudstone and shale; (2) shelf margin carbonates (El Bur trend); (3) Main Gypsum: dolostone and sulfates; (4) Garbaharre Formation: carbonates, evaporites, shale, and sandstone; occurrence over the Bur area is inferred; (5) Ambar Sandstone: fluviatile system; (6) paleocurrent direction; (7) erosional boundary.**

north in Ogaden and adjacent Somalia but was later truncated. This erosion was promoted by regional tilting or uplift that caused the progressive beveling of the Upper Jurassic.

The Main Gypsum depositional sequence is unconformity bounded over most of Somalia. The lower unconformity is documented in wells of the basinal area (Gheferso-1, Das Uen-1, Obbe-1, Meregh-1, and Marai Ascia-1), where it separates an underlying rifted section of Jurassic strata from the overlying, laterally continuous Early Cretaceous sediments (Figure 10). In this sense, the lower unconformity could well be a classic breakup unconformity. Its timing, however, is different from that expected. The actual breakup occurred in Callovian-Oxfordian times (Hamanlei/Uarandab boundary), some 15 to 20 Ma earlier.

If we consider the eustatic curve of Haq et al. (1987) where two extremely pronounced lowstands occur in the Valanginian, respectively, at 128 and 126 Ma, the pre-Aptian unconformity may be related to these eustatic fluctuations. Even if the Neocomian lowstands enhanced subaerial exposure and erosion, the event was mainly tectonic in origin, probably a distal effect of regional geodynamic processes. A major tectonic event shifted plate motions around the world at the end of the Neocomian (anomaly M11 time) (Klitgord and Schouten, 1986) and the South American-African plate began to break up at about this time (Rabinowitz and Labrecque, 1979).

## THE APTIAN TRANSGRESSION AND THE GIRA SUPERSEQUENCE (APTIAN-SENONIAN)

The long interval represented by the middle-Upper Cretaceous (Aptian-Senonian) deposits of Somalia is defined as the Gira supersequence. This stratigraphic interval can probably be subdivided into at least three sequences, in turn made up of several parasequences. For example, Turonian pelagic sediments that occur over most of northern Somalia could represent the condensed basal transgressive system tract of an upper Turonian-Senonian sequence. The late Cenomanian-Turonian Belet Uen Formation of Hiraan and the underlying Fer Fer Gypsum and Mustahil Formation could well be two other sequences. Information is lacking, however, to calibrate, chronologically and sedimentologically, the various sections across Somalia.

### The Cretaceous of Hiraan (Central Somalia)

In central Somalia (Hiraan region) along the wide Scebeli Valley, continuous outcrops of Cretaceous limestones occur from the town of Bulo Burti to as far as Ogaden. The succession consists of three units known from bottom to top as Mustahil, Fer Fer, and Belet Uen formations.

The Mustahil Formation is a very fossiliferous marlstone-limestone unit with rudist and coral buildups. Thicknesses vary from 130 to about 300 m, and the age is late Aptian-Albian. A 50-m-thick member of marl and shale, rich in Aptian ammonites, occurs at the base directly overlying the Main Gypsum (Barbieri et al., 1979). This flooding surface corresponds to the Aptian transgression observed all over central and northern Somalia. Shallowing-upward cycles (Figure 14) that start with marls and marly limestones rich in *Orbitolina* and terminate with thick rudist and coral beds characterize the remaining Mustahil Formation.

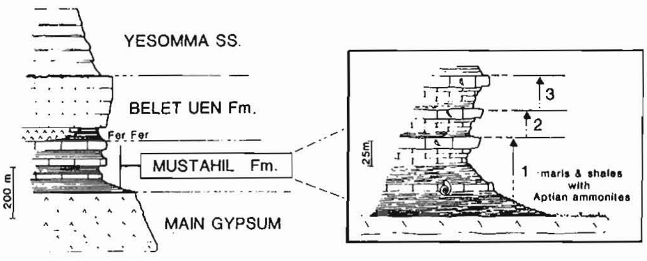

FIGURE 14. **The Cretaceous succession of central Somalia (Hiraan region) and the shallowing-up cycles of the Mustahil Formation. Note the Aptian flooding surface at the top of the Main Gypsum.**

The Fer Fer Formation, which follows upward, is a lens-shaped evaporite unit with a maximum thickness of 100 m, whereas the Belet Uen Formation is a subtidal, burrowed, and thick-bedded white micritic limestone.

## Mudugh Basin

Shallow water carbonates occur throughout the intervals penetrated at Galcaio-2, El Bur-1, Bulo Burti-1, and Garad Mare-1, although at this latter well the upper 12 m of the interval show mid-Maastrichtian drowning and deeper water deposition. At Dusa Mareb-1 and Dusa Mareb-2, sandstones interbedded with dark, carbonaceous, lignitic clay with carbonized plant fragments (the so-called "transition beds") occupy the upper part of the interval and suggest proximity to a deltaic environment during the Coniacian and Senonian. A similar but more marine succession has been penetrated at En Dibirre-1 and Idole-1.

Deeper marine conditions prevailed at El Hamurre-1, Gira-1, Marai Ascia-1, El Cabobe-1, Meregh-1, Gal Tardo-1, and Duddumi-1. At Bio Addo-1 and Uarshiek-1, a terrigenous deep-water section could indicate the occurrence of a local turbidite fan.

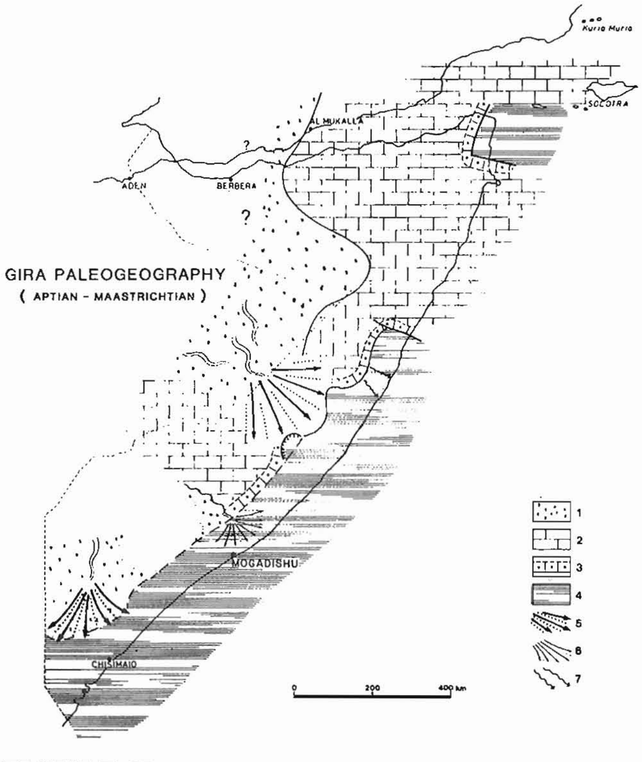

**FIGURE 15. Middle Cretaceous paleogeography of Somalia. (1) Pediment and fluvial sandstone; (2) shallow water carbonate succession, normally organized in shallowing-up cycles; (3) marginal, high-energy carbonates (sandy shoals, reefs); (4) deep-water mudstone and shale (Gira Formation); (5) deltaic and transitional facies; (6) deep-water turbidite fan; (7) paths of gravity-displaced skeletal grainstone.**

## Northern Somalia

The Aptian-Senonian succession is present over northern Somalia from the Indian Ocean coast to approximately lat. 47°E. Westward of a line that runs obliquely from northeast to southwest, the sequence is absent, and the Yesomma Sandstone lies directly on various Jurassic strata and basement. As the Aptian sea transgressed a morphologically varied substructure, the base of the sequence is time transgressive. The base is Barremian at Ras Antara; Aptian at Erigavo, Al Mado, Socotra, Yemen, Darin, Hafun, Cotton, and Garad Mare; Albian at Buran; and Turonian on the Las Anod arch.

Both a shallow water and a deep-water facies are represented in the Aptian-Senonian succession of northern Somalia. The shallow water facies typically consists of several marly shallowing-upward cycles similar to those described for the Cretaceous of central Somalia (Mustahil Formation). The deep-water facies occurs only in the extreme corner of the Horn of Africa and is represented by a thick monotonous succession of dark pelagic shale (755 m at Ras Binnah-1; 1750 m at Gardafui-1, with turbidites in the Albian/Aptian interval).

## Middle-Late Cretaceous Structural and Paleogeographic Evolution

After the Neocomian event, the sea started to transgress eastern Africa in late Aptian time. Except for the Las Anod arch, the Early Cretaceous positive structures (Erigavo high, Hafun high) were flooded, and a shallow water carbonate shelf was established over most of present-day northern Somalia and eastern Yemen (Figure 15). After the Aptian flooding, the following highstand period (Albian-Late Cretaceous), probably punctuated by subsidiary sea level oscillations, was characterized mainly by aggradational processes. No major progradation or modification of the shelf margin is observed in the Mudugh basin.

Basinal, deep-water conditions were present also in the extreme corners of the Horn of Africa. A thick pelagic succession of shale with some minor calciturbidites occurs at Guardafui-1 and Ras Binnah-1. The detrital carbonates had their source in the exposed area of Candala, where a major unconformity represents the Aptian-Albian interval.

In conclusion, the Aptian-Senonian interval was a period of relative tectonic quiescence. A vast shelf, gently dipping seaward, registered the various Cretaceous sea-level fluctuations, as shown by the shallowing-upward cycles so common in the sequence.

In central-southern Somalia (Mogadishu and Juba-Lamu basins), the middle-Upper Cretaceous succession indicates relatively deep-water, basinal conditions. The beginning of substantial terrigenous supply, probably related to the fully exposed Bur Acaba and Mandera-Lugh areas, is registered only at the very end of the Cretaceous.

# THE TERMINAL CRETACEOUS CRUSTAL UPWARPING AND THE YESOMMA DEPOSITIONAL SEQUENCE (LATE MAASTRICHTIAN-PALEOCENE)

The Yesomma depositional sequence appears to be well defined and unconformity bounded all over northern Somalia, Yemen, Ethiopia, and in the proximal areas of the Mudugh and Mogadishu basins. It gradually changes its lithology from west to east (Figure 16) and four general facies belts can be recognized: (1) a fluviatile facies, the Yesomma Sandstone proper; (2) a marginal, shallow marine belt of shale, sandstone, and carbonate; (3) a zone of shallow water carbonate; and (4) a block-faulted basinal area where deep-water claystone and shale (Sagaleh Formation) accumulated in the downfaulted blocks. Unconformities or condensed sections, however, developed on the structural highs. To the south, this facies belt is replaced by a deltaic-marine sandy succession (Mogadishu and Juba basins).

The best exposed section of the fluviatile facies is at Bihendula, located south of Berbera (Bruni and Fazzuoli, 1977). Thickness is 1708 m according to Macfadyen (1933). The contact with the underlying upper Jurassic Gawan Limestone is clearly unconformable and suggests the occurrence of a major unconformity. The top of the Gawan is strongly weathered (earthy and yellow), whereas the immediately overlying Yesomma Sandstone is very coarse and contains big clasts of the underlying yellow limestone. Moreover, the lower 50 m of the Yesomma show a deep red, rusty color that suggests the possible occurrence of a former terra rossa-like soil. The Yesomma Sandstone is typically arranged in fining-upward sequences topped by red-brown massive mudstone and shale. Cross-bedding is frequently tabular (sand waves), and paleocurrents indicate an east and southeast transport direction.

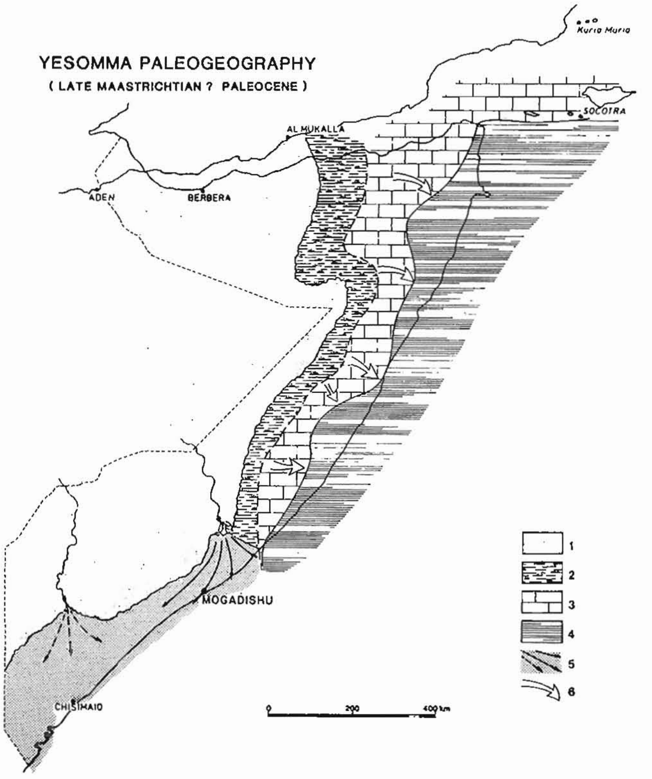

**FIGURE 16.** **Paleogeography of Somalia during "Yesomma time" (late Maastrichtian?-Paleocene). (1) Pediment and fluvial sandstone (Yesomma Sandstone); (2) marginal belt of shale, sandstone, and carbonate; local lignite deposits; (3) shallow water carbonate; (4) deep-water claystone and shale (Sagaleh Formation); (5) paleodeltaic areas; (6) trends of carbonate progradation.**

The type section of Yesomma Sandstone near Bulo Burti is 350 to 400 m thick and is composed of red, purple, and yellow cross-bedded sandstone with minor conglomerate and siltstone/shale beds. These lithologies are commonly arranged in fining-upward sequences interpreted as point bars. Bioturbation and root casts occur in the overbank siltstones. Compositionally, the Yesomma is a mature quartzarenite with rounded quartz grains and variable sorting and grain size. Cement is hematitic or siliceous colloform. Near the village of Yesomma, paleocurrents interpreted from cross strata show transport toward the east and southeast.

The Yesomma overlies progressively older formations (Main Gypsum, Gabredarre, Hamanlei) toward the north (Azzaroli and Fois, 1964; Merla et al., 1973, 1979; Barnes, 1976; Barbieri et al., 1979), as a result of its position above a broad regional truncation. On the northern edge of the Somali plateau (Hargeisa, Burao), where the sandstone rests directly on the basement, its thickness varies from 200 to 400 m. In the Guban, the downfaulted coastal area, it is 500 to 1700 m thick.

## Structural and Paleogeographic Evolution during Yesomma Time

The age range of the Yesomma is a critical point in reconstructing the sedimentary and structural evolution of north-central Somalia. A major crustal upwarping affected the entire region prior to the Yesomma sedimentation, and the unit is time transgressive.

The Maastrichtian tectonic event that preceded the onset of the Yesomma occurred from Ethiopia and Yemen to the Indian Ocean continental margin, where it produced shallow intrusions and basaltic lava flows. It was clearly more pronounced in the western part of the country, where the fluviatile Yesomma rests unconformably on various terrains of the Jurassic and even on the basement. Along the Indian Ocean coast, the mid-Cretaceous carbonate platform drowned suddenly and was replaced by pelagic sediments (Hordio-1, Cotton-1, Sagaleh-1, and Garad Mare-1).

The available data suggest an episode of uplift and block faulting. Horsts and grabens mainly had an east-west trend, grossly parallel to the present Gulf of Aden margin. The peculiar structural grain of the northern tract of the Somali continental margin, characterized by a series of highs and lows oriented normal to the coast (Hafun horst, Darror graben, Ras Binnah plateau, Gardafui depression, Socotra high), is mainly the result of this Late Cretaceous event, which has been related to the northward drift of the adjacent Indian plate (Bosellini, 1986). It is also tempting to associate this broad uplift episode of eastern Africa with the Late Cretaceous tectonic events that affected the Oman continental margin. When, at about 70 Ma (Maastrichtian) the Oman subduction failed because of the inability of the Arabian continental crust to be involved in the Semail subduction zone (Lippard et al., 1986), there was possibly a rebound effect on the continental crust of Yemen and northern Somalia. Uplift and erosion of the nappes were complete by the Maastrichtian, when a transgressive series of clastic sediments and shallow water limestones were deposited across the mountain area.

## THE EOCENE TRANSGRESSION AND THE AURADU DEPOSITIONAL SUPERSEQUENCE

A late Paleocene or early Eocene marine transgression terminated the terrestrial conditions that previously existed over much of eastern Africa and southern Arabia. The first Eocene calcareous deposits, called Auradu Limestone, are rich in corals, mollusks, and foraminifers and overlie middle Cretaceous carbonates at Socotra (Beydoun and Bichan, 1970), littoral sandstones and carbonates in northeast Somalia, and alluvial sandstones and the crystalline basement in central and western parts of northern Somalia. There was probably land west of about long. 43°30'E (Figure 17). The base of the Auradu is time transgressive, being older to the east and progressively younger westward. In middle Eocene times, the sea started to withdraw, and finally, in the early Oligocene, all of Somalia was practically subaerially exposed.

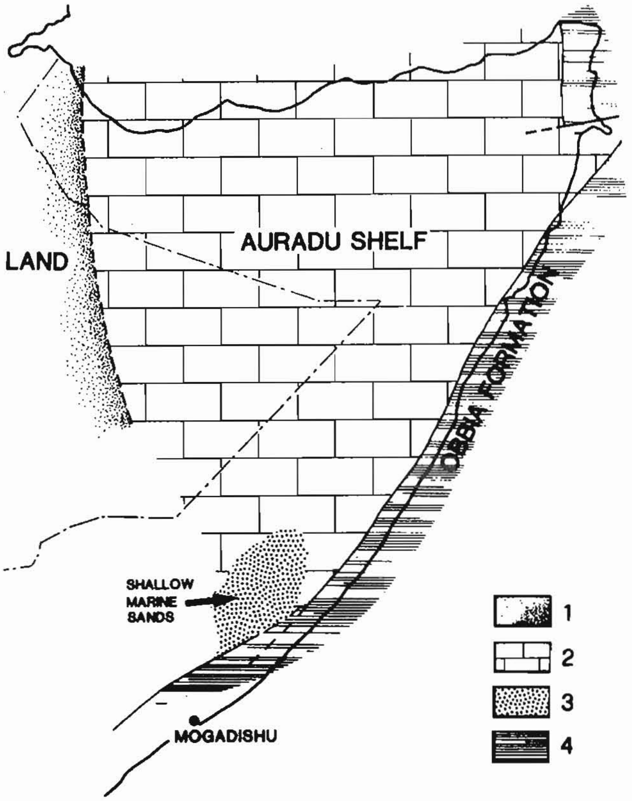

**FIGURE 17.** **Early Eocene paleogeography of northern Somalia showing the carbonate shelf established after the Auradu transgression. (1) Fluvial and littoral sandstone; (2) shallow water carbonate (Auradu Limestone); (3) shallow marine sandstone; (4) *Globorotalia* and *Globigerina* clay and shale (Obbia Formation).**

### Auradu Limestone

The Auradu Limestone, a thick shallow water limestone unit (mainly mudstone/wackestone), is massive or thick bedded in the lower part, with frequent iron-stained cherty concretions. Thickness of the entire Auradu succession is on the order of 400 to 450 m, but westward to Hargeisa, it thins toward the edge of the basin.

The Auradu is generally assigned to the early Eocene (Macfadyen, 1933; SOEC, 1954; Altichieri et al., 1981). According to ELF Somalie, (unpublished report, 1975), the basal Auradu is middle Eocene at Darin and Candala. This dating seems to be a regional stratigraphic feature.

### Taleh Formation

The massive limestones of the Auradu series are overlain by the Taleh Formation, a nearly pure deposit of anhydrite, averaging 300 to 350 m thick. It consists of dense, massive to banded or laminated anhydrite, often smelling of oil when freshly fractured. The anhydrite is often altered on the surface to gypsum and irregularly interbedded throughout with marls, shales, and thin limestone bands.

The paucity of terrigenous sediments in the succession suggests that the evaporite basin, an extremely large and shallow bay (Figure 18), was surrounded by a very arid land without any substantial fluvial transport.

From Garad to Ras Antara, a marginal dolomitic belt of reefs and high-energy deposits separated the shallow bay from the open and relatively deep sea (Guardafui-1, Ras Binnah-1, Hafun-1, and Garad Mare-1). Farther south the evaporite basin merged transitionally into a vast carbonate shelf without a clear reefal edge (Figure 18).

### Karkar Formation

The Karkar Formation, the youngest unit of the Eocene depositional supersequence, consists of marly, nodular, fossiliferous limestones, with *Nummulites, Alveolina, Assilina, Lucina, Sismondia, Natica, Ostrea, Pinna,* and other mollusks, corals, etc. Light-brown, limey paper shales and intercalations of gypsum and anhydrite occur especially in the lower part. In places, the upper part shows evidence of cyclic sedimentation, repeating a sequence of strongly bioturbated marls at the base becoming more calcareous and rich in small nummulites upward and culminating with 2 to 5 m of coarse bioturbated calcarenites bearing big gastropods, echinoids, and nummulitids.

The reduced depositional area of the Karkar (Figure 19) suggests that much of the region was being uplifted

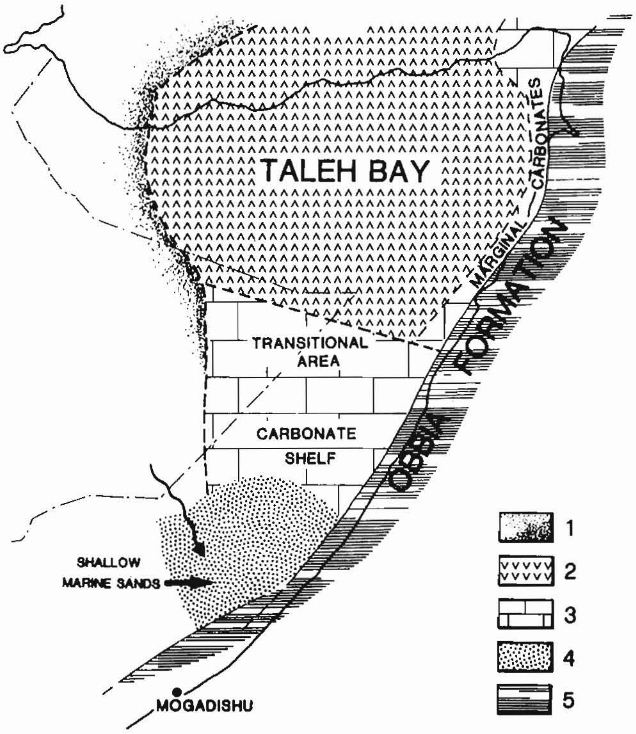

**FIGURE 18.** Middle Eocene paleogeography of northern Somalia showing the shallow and evaporitic Taleh bay. (1) Fluvial and littoral sandstones; (2) evaporite, marl, shale, and limestone (Taleh Formation); (3) shallow water carbonate (shelf and dolomitic marginal belt); (4) shallow marine sandstone; (5) *Globorotalia* and *Globigerina* clay and shale (Obbia Formation).

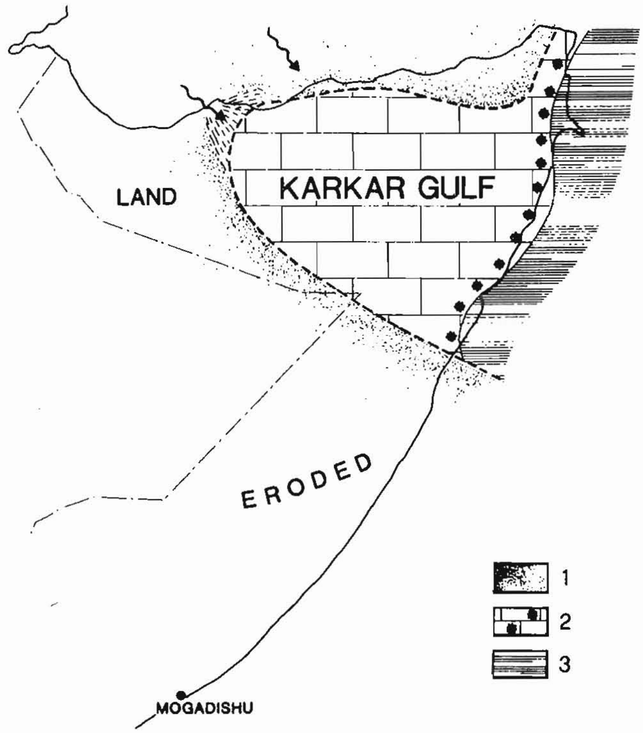

**FIGURE 19.** Late Eocene paleogeography of northern Somalia showing the reduced marine depositional area with respect to early-middle Eocene times. (1) Alluvial and deltaic succession (arrows indicate provenance and transport direction); (2) shallow water carbonate (Karkar Formation) and marginal high-energy belt of reefs and buildups; (3) *Globorotalia* and *Globigerina* clay and shale (Obbia Formation).

about this time. Near the basin center (Darin-1), the Karkar is about 360 m thick but thins to the south and west. This thinning, accompanied by interfingering with sandy lower beds, and the lack of outcrops farther west indicate the western shoreline of the "Karkar sea" at about long. 46°E (Figure 19). In the Daban basin near Berbera, the Taleh evaporites are overlain by a thick deltaic succession (Abbate et al., 1987, 1988). In the offshore wells of the Gulf of Aden, the Karkar is either missing (Bandar Harshau-1) or replaced by a terrestrial succession (Dab Qua-1). Eastward, the Karkar Formation reaches the Indian Ocean from Cape Guardafui to as far south as Illig and Garad Mare-1. Guardafui-1 shows the transition from platform to basinal conditions.

## Obbia Formation

The Obbia Formation is used to denote deep-water Eocene facies. It consists mostly of clay and shale, rich in *Globorotalia* and *Globigerina* and occurs in many coastal wells (Guardafui-1, Ras Binnah-1, Hordio-1, Hafun Terrestre, and Garad Mare-1).

## Structural and Paleogeographic Evolution during the Eocene

The Auradu transgression is undoubtedly a regional event that affected the entire Horn of Africa, southern Arabia, and Socotra. The transgression may be related to the general Ypresian highstand that followed the pronounced sea-level fall of the late Paleocene at 58.5 Ma. The thickness of Auradu, however, resulted also from tectonic subsidence in the area. Similarly, the Taleh evaporites could be the result of the subsequent abrupt eustatic drop observed at 49.5 Ma (latest Ypresian) (Haq et al., 1987).

During early-middle Eocene time, a further progradation of the shelf edge in the Mudugh basin occurred and almost reached the present-day coastline. Basinal successions have been encountered offshore or along the coast (Obbia-1, El Cabobe-1, and Meregh-1). At the end of the Eocene, central Somalia became largely subaerially exposed.

In the Juba-Lamu embayment, the Eocene succession is the result of a general depositional regression produced by the gradual infilling of the basin by the prograding Juba delta. The relative sea-level fluctuations, dramatically registered in central and northern Somalia, do not appear to have substantially affected this area. Possibly, the high rate of deltaic sedimentation counterbalanced and masked the relative sea-level variations.

As the middle Eocene Taleh evaporite is the last unit to occur on both sides of the Gulf (Abbate et al., 1988), the Karkar Formation signals the onset of the structural evolution of the Gulf of Aden. The return of the sea (Karkar Gulf of Figure 19) in an area adjacent to the Aden bulge signifies a downwarp movement of the crust situated immediately south of the uplifted block.

In summary, the Auradu supersequence is a composite succession that records both structural and eustatic movements. Clearly registered in northern Somalia, their evidence and control on sedimentation become more subdued southward and are overwhelmed by high sedimentation rates of the Juba delta.

## THE OLIGOCENE-MIOCENE TERRAINS OF SOMALIA

Oligocene and Miocene terrains of Somalia are mostly restricted to a narrow and discontinuous coastal belt that extends from Berbera to Cape Guardafui in the north and then south along the Indian Ocean coast to the Juba-Lamu basin. Oligocene-Miocene strata outcropping along the Gulf of Aden occur in disconnected structural basins and are largely represented by deltaic and lacustrine sediments (see Abbate et al., 1988, for a recent review).

The mainly carbonate Oligocene-Miocene succession (Hafun Series) outcropping along the Indian Ocean coast north of El Hamurre-1 is the product of a depositional regression. It constitutes a 150-m-thick depositional sequence, called the *Eil sequence* by Bosellini et al. (1987), that prograded seaward for several kilometers.

The study by Bosellini et al. (1987) has demonstrated that the Eil sequence is late Oligocene-early Miocene and that early-middle Oligocene sediments are apparently missing. Bosellini et al. (1987) believed that the unconformity might be related to the dramatic sea-level drop that occurred 30 Ma ago (Haq et al., 1987). The seaward progradation of the Eil sequence took place after the late Oligocene flooding of the old land surface and during the late Oligocene-early Miocene highstand.

Along coastal Somalia, south of El Hamurre, the Somal and Merca formations have been used to designate the Oligocene-Miocene marine section. The Somal consists of shallow water carbonates, and the Merca is a regressive, shallow marine and continental sequence of sandstone, claystone, and sandy limestone.

There is also a deep-water equivalent to these shallower facies. At Garad Mare-1, there is a continuous 1327-m-thick succession of outer shelf to bathyal pelagic fossiliferous claystone, spanning the time from Paleocene to early Miocene and designated by AGIP Somalia as the Garad Formation.

### Paleogeographic and Structural Evolution during the Oligocene-Miocene

The Oligocene-Miocene map of the Indian Ocean margin (Figure 20) clearly shows the occurrence of two different paleogeographic settings. North of El Hamurre, the Oligocene-Miocene (Eil sequence) is a relatively narrow (25-50 km) and thin (100-150 m) prograding carbonate platform (Bosellini et al., 1987) that passes into deeper-water environments along the present-day coastline. Garad Mare-1, Hafun-T and 1, Hordio-1, Ras Binnah-1, and Guardafui-1 wells penetrated pelagic and relatively deep mudstone and shale. Inland, however, the platform abuts against a Karkar scarp, and in some structural depressions (Darror graben), it is substituted by lagoonal and transitional deposits (Scusciuban Formation).

To the south of El Hamurre was a vast alluvial plain. It was probably crossed by ephemeral streams that discharged sediment into a deep-sea fan of the Obbia area where the plain passed abruptly into slope and basinal settings. Westward, it merged into a prevalently pediment area. No evidence of a scarp contact has been reported or can be inferred by geological maps.

Farther south around El Cabobe-1, the alluvial plain was flanked by a carbonate platform located on a nose.

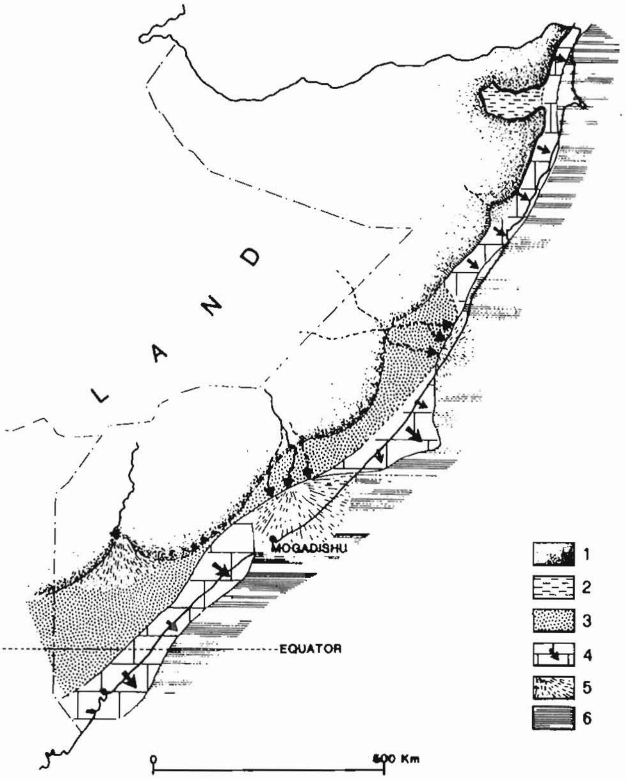

**FIGURE 20.** **Paleogeographic map of the Indian Ocean continental margin of Somalia during Oligocene-Miocene. (1) Terrestrial sediment (pediment, alluvial, caliche, etc.); (2) lagoonal sediment (Scusciuban Formation); (3) deltaic and shelf clastics; (4) carbonate platforms (arrows indicate progradation); (5) deep-sea fan; (6) deep-water mudstone and shale.**

Possibly, the present-day submarine contours in that area reflect the occurrence of the El Cabobe platform. Farther south, the alluvial plain narrowed into the paleo-Scebeli delta and related deep-sea fan (Duddumai-1 and Bio Addo-1) and into the vast and shallow Juba Gulf.

By the end of early Oligocene, most of Somalia was exposed to subaerial conditions, possibly as a consequence of tectonic uplift and deformation. This event is marked by an unconformity documented below the Merca-Somal sequence in many places, by the widespread basaltic flows of the Mudugh region, and by the infilling of structural lows (Darror graben) by Miocene sediments.

## CONCLUSIONS

The sedimentary succession of Somalia has been subdivided into seven major depositional sequences that appear to mark the most important turning points in the plate tectonic history of the region and related sea-level fluctuations (Figure 21). They include the following:

1. *Hamanlei Depositional Sequence*—This is the Early-Middle Jurassic basal sediment package onlapping the East African craton. It is partly the result of the rifting stage heralding the Gondwana breakup and partly due to the Mesozoic sea-level rise. The Hamanlei sequence is composed of several formations, including the Hamanlei proper, the Iscia Baidoa, the Bihen, and the basinal Meregh. The lower boundary is time transgressive and, after the first flooding episode recorded by the ammonite-rich Uanei Member of the Iscia Baidoa Formation, contains shallow water sedimentation. The transgression is followed by a general depositional regression on shelf areas.

2. *Uarandab Depositional Sequence*—A major transgression that was related to the final breakup of Africa and Madagascar and the subsequent regional subsidence occurred over most of East Africa in late Callovian-Oxfordian time. The abrupt lithologic change occurring at the top of the Hamanlei depositional sequence indicates sudden foundering during the late Callovian (150-155 Ma) of the entire oblique-rifted sector of the continental margin (Figures 3, 12). After the Callovian-Oxfordian flooding of large sectors of East Africa, the following highstand period, characterized by slower subsidence and tectonic quiescence, resulted in basin filling and progradation (depositional regression) all around the basinal areas. The open-marine and relatively deep Uarandab, Anole, and Gahodleh/Daghani shales and the overlying shallow water Gabredarre, Uegit, and Gawan limestones belong to the same depositional sequence and are partly coeval.

3. *Main Gypsum Depositional Sequence*—The Early Cretaceous was a time of relative lowstand, and a major pre-Aptian deformation is documented over northern Somalia where the Neocomian-Barremian interval is generally absent and the Aptian is transgressed progressively from east to west over various Jurassic terrains. To the southeast, the tectonic pulse was registered by a widespread supply of quartz sand (Ambar Sandstone), while in central Somalia, a shallow gulf, largely surrounded by land, was accumulating dolostone and sulfate (Main Gypsum). From general geology, stratigraphic relationships, and timing of major geodynamic events, the Neocomian event was possibly the distal intraplate effect of a regional geodynamic process (i.e., the separation of South America and Africa and the development of the West and Central Africa rift system) (Burke and Dewey, 1974; Rabinowitz and Labrecque, 1979; Pindell and Dewey, 1982; Klitgord and Schouten, 1986; Fairhead, 1986).

4. *Gira Supersequence*—After the Neocomian-Barremian event, the sea started to transgress East Africa in late Aptian time, and a shallow water carbonate shelf became established over most of central and northern Somalia. The sequence includes several formations, such as Mustahil, Fer Fer, Belet Uen, Gira, and the Cretaceous succession of the Al Mado escarpment. After the Aptian flooding, the gently seaward-dipping shelf registered the various Cretaceous sea-level fluctuations, as shown by the shallowing-up cycles that are so common in the sequence.

5. *Yesomma Depositional Sequence*—Generally well defined and unconformably bounded, this predominantly Paleocene depositional sequence is comprised of rock units, such as fluviatile Yesomma Sandstone; a marginal shallow marine belt of shale, sandstone, and carbonate; a zone of shallow water carbonates; and the basinal Sagaleh shale and claystone. It overlies progressively older formations toward the north above a broad regional truncation. The Yesomma sequence is clearly related to a major crustal upwarping affecting central and northern Somalia to the north of the El Hamurre lineament. Because the uplift of Ogaden and northern Somalia was contemporaneous with the sinking of the Hafun-Guardafui coastal area, a causal link may exist between the two phenomena. A tilting of the entire northern Somali block is suggested, possibly related to the rebound effect when the Oman subduction process failed at about 70 Ma (Maastrichtian). The El Hamurre structural lineament probably played the role of release boundary (transform fault?). To the south in the Mudugh, Mogadishu, and Juba basins, the structural stability is documented by the general depositional regression occurring along the entire edge of the shelf.

6. *Auradu Supersequence*—This is a composite succession (Auradu Limestone, Taleh Formation, Karkar Formation, Obbia Formation, etc.) that records both structural and eustatic movements. These events, clearly registered in northern Somalia, become more subdued southward and are overwhelmed by the high sedimentation rate of the Juba delta. A late Paleocene or early Eocene marine transgression terminated the terrestrial conditions that previously existed over much of eastern Africa and southern Arabia. The Auradu Limestone represents the transgressive and probably also the highstand system tracts of the early Eocene part of this supersequence. In middle Eocene time, the sea started to withdraw, as documented by the lowstand deposits

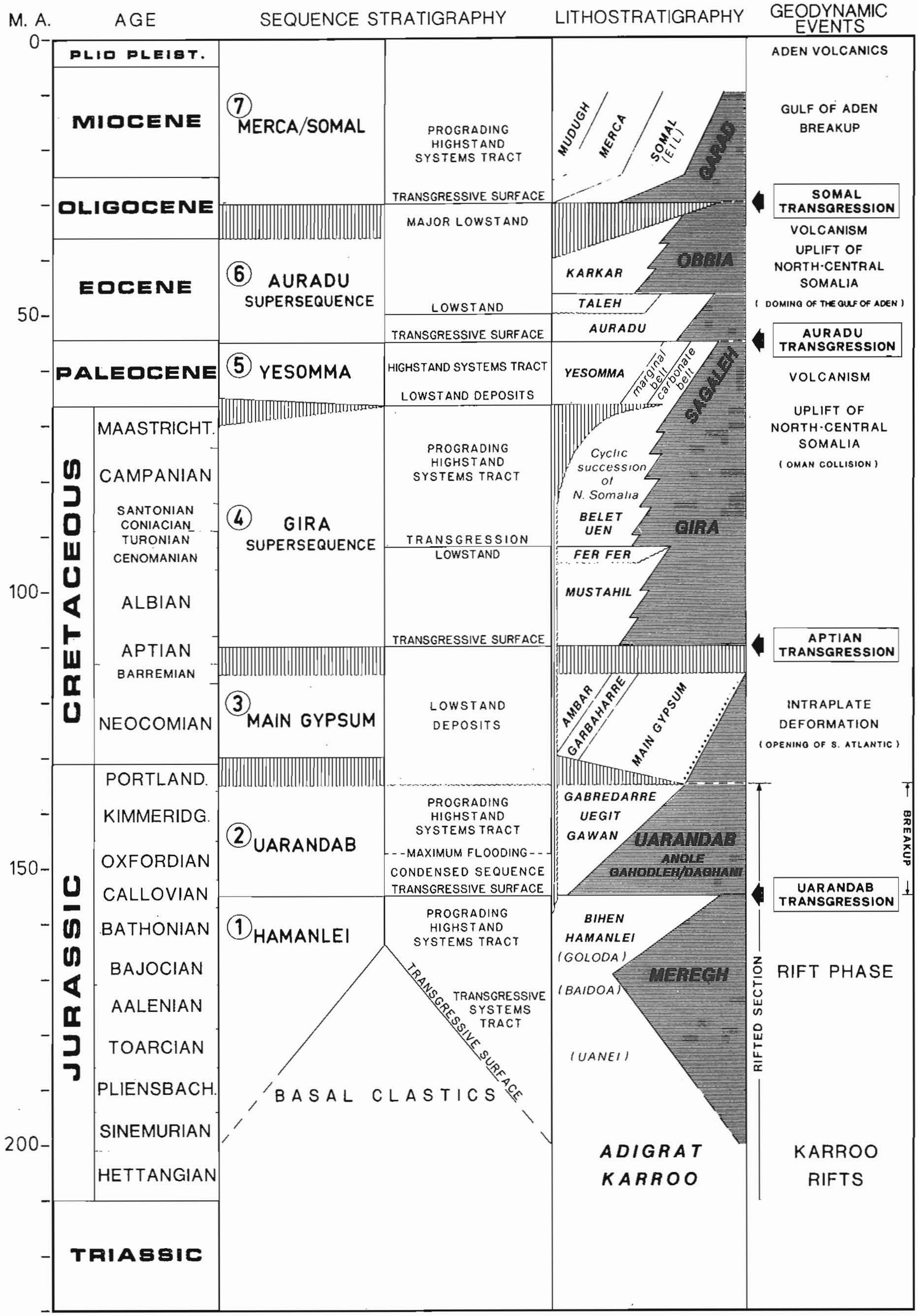

**FIGURE 21.** Chronostratigraphic chart of Somalia relating sequence stratigraphy, lithostratigraphy, and the major geodynamic events affecting East Africa.

of the Taleh evaporite. As this formation is the last unit to occur across the Gulf of Aden, the following Karkar Formation signals the onset of the structural evolution of the Gulf itself.

7. *Merca/Somal Depositional Sequence and the Oligocene-Miocene Terrains of Northern Somalia*—By the end of early Oligocene, most of Somalia was exposed to subaerial conditions, possibly as a consequence of a major tectonic uplift and deformation, as documented by the angular unconformity below the Merca/Somal sequence and by the widespread basaltic flows of the Mudugh region. Along the Indian Ocean continental margin, the late Oligocene-Miocene were dominated first by a general marine transgression (Somal Formation, base of Eil sequence), followed by a Miocene depositional regression during the highstand phase of the cycle (Merca Formation, upper part of the Eil sequence). The Gulf of Aden coast of Somalia represents a typical passive margin, where geological history can be described in three phases: a prerift phase, a rift phase, and a drift phase (Abbate et al., 1988). By the end of the Oligocene, the main rifting stage was over, and the drift phase started during middle-late Miocene time.

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