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# A stratigraphic and sedimentologic study of the cretaceous and tertiary strata of east Kenya.

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# A STRATIGRAPHIC AND SEDIMENTOLOGIC STUDY OF THE CRETACEOUS AND TERTIARY STRATA OF EAST KENYA

by

Kivuti Nyagah

A Thesis
Submitted to the
Faculty of Graduate Studies and Research
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# ABSTRACT

Subsurface data from 940 wells drilled at onshore and offshore locations in East Kenya were integrated with outcrop observations in the Lamu and Mandera-Lugh basins in a stratigraphic-sedimentologic study of Cretaceous through Tertiary strata. A total of 37 cores from various sections of the study units and corresponding geophysical well logs were utilized in delineating main descriptive units and their lateral continuity. Correlations with equivalent strata in Ethiopia, Somalia and Tanzania were made to demonstrate lateral facies patterns and to reconstruct the regional depositional history.

The overall analysis reveals a systematic pattern of depositional units that have been grouped into megasequences, representing distinct provinces with regard to time stratigraphy, depositional environments, sedimentation, tectonics and hydrocarbon potential. Megasequence II includes strata of the Cretaceous and Paleocene ages, namely the Upper Member of the Mtomkuu Formation, Freretown Limestone, Walu Shale, Danissa Limestone, Upper and Lower Members of the Danissa Beds and the Marehan Sandstone. Meqasequence III includes strata of Eocene through Oligocene ages, deposited in fluvial, deltaic, and restricted-shelf settings, during intermittent episodes of uplift and subsidence. These include the Kipini Sandstone, Pate

Limestone, Linderina Limestone, Dodori Limestone and the Barren Beds. Meqasequnce IV includes strata Miocene to Pliocene in age, deposited in restricted-shelf and fluvial settings, during phases of more pronounced uplift, subsidence and faulting. These include the Baratumu Formation, Kipevu Beds, Fundi Isa Limestone Marafa Beds, Midadoni Beds, North Mombasa Crag, Lower Magarini Sands and the Merti Beds.

Strata with good reservoir potential in Meqasequence II consist of subtidal bioclastic limestones of the Danissa Limestone, tidal channel sandstones of the Marehan Sandstone, delta front sands and siliciclastic turbidite deposits comprising the Kipini Sandstone. Those of Meqasequence III: include reef and back-reef oolitic facies related to the deposition of the Pate Limestone, delta front sheet sands, point bar, distributary channel and turbidite deposits that constitute the Barren Beds. Subtidal bioclastic limestones of the Baratumu Formation and time-equivalent carbonate slump deposits in the offshore region make up the reservoir units of Meqasequence IV. Reservoir strata of these megasequences associated with salt-diapiric structures in the offshore area, form good prospects. Rocks with source rock potential are present in the Jurassic, Middle Cretaceous and Tertiary sequences. These prospects provide an alternative focus from past exploration strategies.

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My great indebtdness is due to Professor F. Simpson under whose supervision I had the most valuable opportunity to carry out thesis-related research on a topic based on my country. The sacrifices he made by travelling to Kenya in the summers of 1986 and 1987, in order to supervise the field studies are deeply acknowledged. His numerous suggestions for improvement were very valuable in preparation of the final text and accompanying illustrations. Few pages survived unscathed. My special thanks are also due to Miss M. Cooper for giving her time generously to assist in typing and for the keen interest she took in my work.

Finally I thank all my graduate student colleagues, Mr. S.W. Karanja and Mr. J. Bacopoulos in particular, for sharing in fruitful discussions and offering useful criticism.

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# INTRODUCTION

## STUDY AREA

The study area is located in eastern Kenya (Fig. 1), a region with an approximate area of 260,000 sq km. It is bordered by Ethiopia in the north, Somalia in the east and Tanzania in the south. It comprises the area east of the 39th meridian, including the adjacent continental shelf and slope of the Indian Ocean.

Three major sedimentary basins exist in the region: the Lamu basin, located in the south-east and continuing into the offshore western Somalia basin; the Anza basin situated between the equator and the 2° N parallel; and the Mandera-Lugh basin in the north-east, with its axis lying along the Kenya-Somalia border. These basins and related structures, were subjected to periodic tectonism that greatly influenced their sedimentation histories.

## STUDY OBJECTIVES

The study is confined to the Cretaceous and Tertiary strata preserved in the basins mentioned above, and comprises three major objectives:

1. to describe the stratigraphy and sedimentology of the main lithostratigraphic units of East Kenya and correlative strata in adjacent areas;

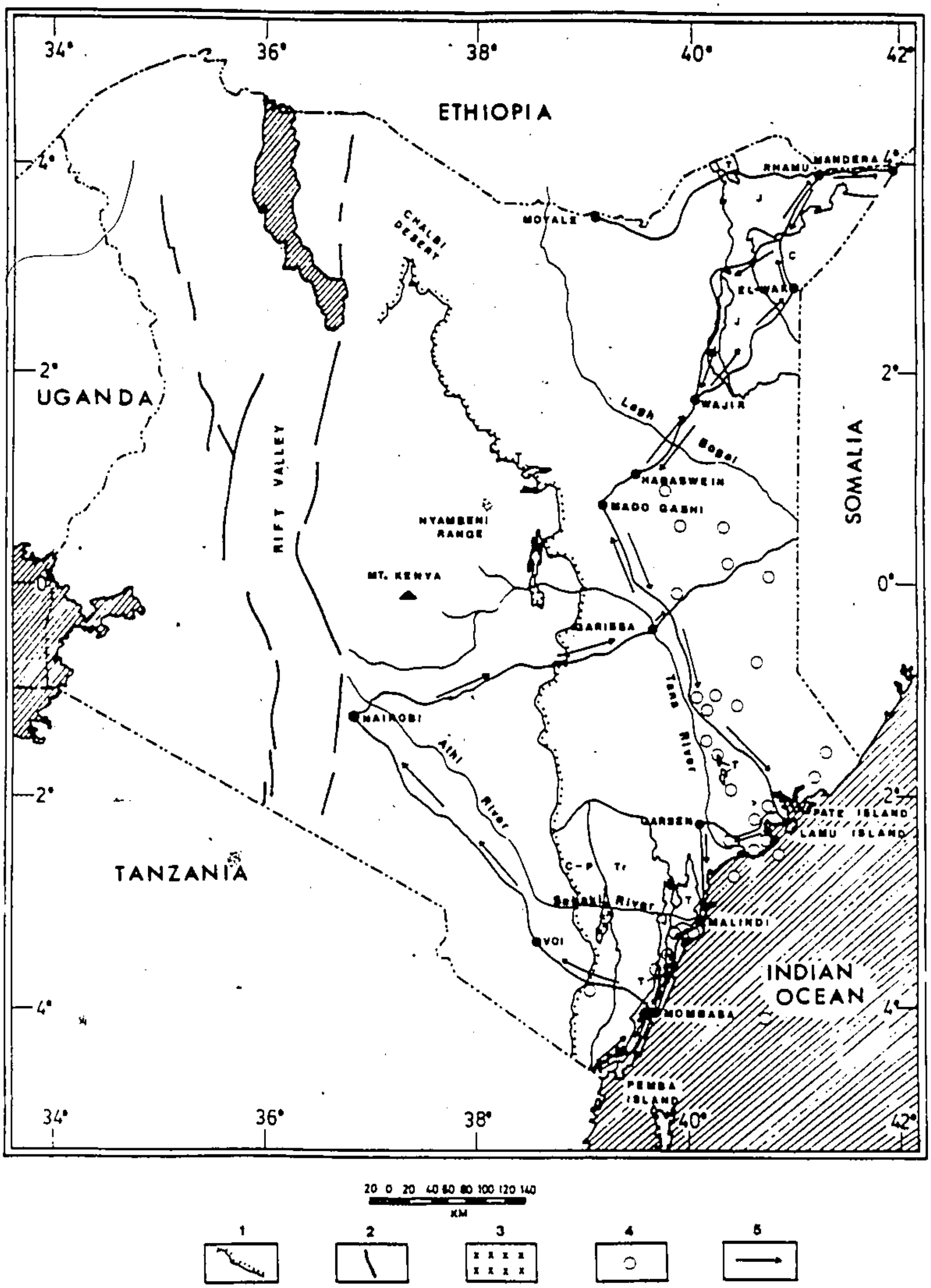


Fig. 1. Study location map showing the eastern sedimentary basin regions of Kenya and adjacent areas. 1 - western limit of sedimentary basin region; 2 - rift faults; 3 - basement horst block; 4 - stratigraphic-test wells; 5 - route of field study.

2. to establish an accurate chronostratigraphic framework and identify depositional sequence boundaries based on the concepts of sequence-stratigraphy developed by Haq et al.(1987);
3. to explain the origins of these units with reference to specific depositional systems; and
4. to assess the reservoir and source-rock potential and the hydrocarbon prospects of the area.

## PREVIOUS WORK

### Primary Mapping

The Geological Survey of Kenya systematically mapped the surface geology of east Kenya on a continuous basis since the early 1950s. Geological reports and the corresponding geological maps have been published for about 60 percent of the study area. The unmapped area, occurring between latitudes 1° 30'N and 2° 30'S, is covered by Quaternary sediments and lacks prominent rock exposures. More recent, but less extensive, surveys have been conducted by overseas oil companies in areas pertinent to their exploration interests.

Much of the ground where the field studies in the north-east were carried out during the summer of 1987, has been discussed in detail by Frey et al. (1975). The most important information provided by this work is the location of Mesozoic outcrops in the area.

The coastal area to the south-east dominated by Late

Paleozoic and Early Mesozoic strata, has received greater attention since Linton and MacLean's (1955) attempt to establish a complete stratigraphic column for the Phanerozoic rocks in the region. The most authoritative stratigraphic and sedimentologic study is that of Walters and Linton (1973), who estimated thicknesses of 4000 m for the Cretaceous strata and 4100 m for the Tertiary at the coast.

## Deep-Seated Tectonic Features

A significant amount of geophysical work has been conducted in the offshore and onshore areas, particularly in the region of Tertiary rifting west of the study area. The seismic surveys, conducted onshore since exploration efforts began in the 1960s, are inadequate and of poor quality. Offshore mapping by a variety of geophysical means, was considerably augmented by the investigations of the following research vessels: R.V. Vema, R.V. Argo, R.V. Atlantis, H.M.S. Owen, and the Glomar Challenger. Okoth (1981) correlated seismic reflection data, acquired by Total Exploration Company in the offshore region, with drilling results from the Total Simba No. 1 well. Rabinowitz (1971) compiled gravity data from the above voyages and discovered two offshore basement ridges, that reflect structural changes within the crust. The ridge seaward of Mombasa has an east-west trend, while the other strikes north-south and represents a probable submarine extension of Pemba Island. Another north-south trending ridge, the Davies Ridge (Bunce and

Molnar, 1977), has been interpreted as a fracture zone along which Madagascar drifted to its present position. Kent (1982) noted the similarity in general structural pattern in the offshore and onshore areas. McConnell (1977) attributed this to regional sub-crustal processes that served to dissipate mantle heat and pressure through the Precambrian basement.

Rabinowitz and Coffin (1982) documented the existence of diapiric structures, interpreted as salt domes, on the continental margin of north-east Kenya and Somalia. Similar structures, confirmed from drilling as non-piercing salt bulges (Kent, 1965), were encountered in the Mandawa graben of southern Tanzania. The relationship between these two discoveries and that of Turonian strata off the Somalia coast (Schlich _et al_. 1975) provided fundamental data for an objective assessment of paleopositions for Madagascar.

## Nature and Time Framework of Rift-Related Events

The development of extensional structural features, from a global perspective, occurred in several distinct phases. According to Milanovsky (1983), in Archean and Early Paleozoic time, extensional and compressional phenomena produced lineaments and orogenic belts, of which the Mozambiquean of Eastern and Southern Africa is an example. Horizontal extension, heralding the break-up of Gondwanaland, was generally a Late Paleozoic event. Rifting related to secondary ocean formation accompanied by blind branches of passive-margin type, characterized the

Mesozoic and Cenozoic Eras. Active rifts, arising from asthenospheric diapirism into an attenuated lithosphere under conditions of gravitational instability (Bermingham et al. 1983), were typical of the Cenozoic period. The East African rift system, running through Kenya and Ethiopia from northern Tanzania to join the Suez Rift at the Afar triple junction, represents such a feature. Illies (1969) noted that the rift system is engraved on the crest of a broad, elliptical dome in central Kenya. Baker and Wohlenberg (1971) related its development to intermittent phases of domal up-arching, crustal flexuring, faulting and isostatic subsidence, along deep north-south infrastructural lineaments. McConnell (1977), who used the term "taphrogenesis" to describe the vertical movements, recognized the deep-seated structural control of pre-existing lineaments in the Mozambiquean basement.

Girdler (1968) considered the most pronounced development of the rift and associated volcanism to have been Pliocene in age, when the translational and rotational movements of Arabia and North-East Africa opened the Red sea. Baker (1970) noted that the resultant of these relative movements was an element of sinistral shear and distension along the East African rift. Sowerbutts (1972) suggested two earlier periods of rifting. The first was Triassic-Jurassic in age, coinciding with the continental break-up of Africa from the India-Madagascar-Antarctica block (McElhinny, 1970) and related to the marine incursion that spread along the coasts of East

Africa and India (Tarling, 1971). The second took place in Cretaceous time and was associated with the oceanization process (Flores, 1984). Kent (1982) observed the linkage between the southern part of this rift system and the line of fault-controlled sedimentary troughs, running north-eastward from the Kenya coast. These are passive rifts, representing the failed arm of extensional zones along which the Gondwana landmass broke up.

## Nature and Time Framework of Plate Tectonic Events

Considerations of whether the continental margin of East Africa evolved as a passive margin or as a continental boundary unrelated to seafloor spreading, are closely related to alternative hypotheses on the pre-drift position of Madagascar. Three positions are commonly cited in the literature: at its present position (Tarling, 1971; Darracott, 1974), adjacent to Mozambique (Kent, 1974; Flores, 1984), and adjacent to Somalia, Kenya and Tanzania (Smith and Hallam, 1970; Heirtzler and Burroughs, 1971; Rabinowitz et al. 1983). The weight of geophysical and geological evidence appears to lean strongly toward the last-mentioned hypothesis. The presence of pre-Cretaceous salt diapirs and Turonian strata off the East African coast, however, precludes the possibility that Madagascar could have occupied this position during Cretaceous time.

Dietz and Holden (1970) postulated a Middle Triassic split of east Gondwanaland from west Gondwanaland, along the

Carlsberg rift system. A north-east-trending limb of this system created the incipient fracture, along which the separation of Madagascar and Africa took place. Kent (1982) links the development of the faulted troughs on the coastal margin to this break-up. Comparison of onshore stratigraphic information with the results of the Deep Sea Drilling Project confirm the existence of oceanic conditions along the East African coast in Middle Jurassic time. The marine connection was initiated from the north-east as an arm of the paleotethyan sea propagated southwards, parallel to north-east-oriented faulting in coastal Somalia, to form an epicontinental sea (Kent, 1974). In Late Cretaceous times, the Indian Ocean had attained complete development, following the fragmentation of the India-Madagascar-Antarctica block, and the northward movement of India along the Owen fracture (McElhinny, 1970). Significant dispersal of the Gondwanaland fragments, had occurred by Late Miocene time, when a spur of the Carlsberg rift extended into the Red Sea through the Gulf of Aden (Dietz and Holden, 1970). Associated with this system was a weaker branch, manifested inland as the East African rift system (Baker and Wohlenberg, 1971).

## Drilling History

A total of 49 offshore and onshore oil-exploration and stratigraphic-test wells have been drilled in the study region during the last 32 years. Of these, 36 are located in the Lamu basin and the rest in the Anza basin.

Table 1 presents names, locations and oldest strata penetrated at total depth for the wells, the records of which are in the custody of the Kenya Government. The B.P. Shell Mararani No. 1, B.P. Shell Pate No. 1, B.P. Shell Pandangua No. 1, B.P. Shell Meri No. 1, and B.P. Shell Lamu No. 1-4 wells, terminated in Tertiary strata, while the others reached Cretaceous or older strata. The Mehta Ria Kalui No. 1 well, was drilled entirely in Permo-Triassic strata. The B.P. Shell Walmerer No. 1, B.P. Shell Garissa No. 1, Texas Hagarso No. 1, B.P. Shell Walu No. 1 and No. 2 wells encountered the Tertiary-Cretaceous unconformity, while Union Kofia No. 1 and B.P. Shell Kipini No. 1 penetrated intra-Tertiary unconformities. The Deep Sea Drilling Project (DSDP) well No. 241, located 270 km east of the Kenya-Somalia border, penetrated Turonian strata at a depth of 1174 m. The intra-Tertiary and Tertiary-Cretaceous unconformities are documented from this well (Davies et al. 1975). The Fumbene, Gaji, Goshi and Chui shallow wells, drilled by Linton and McLean (1955), were restricted to the coastal Miocene and Oligocene sediments.

Other wells in the area include those drilled by various government ministries for either geological, hydrogeological or engineering purposes. Some 100 boreholes were drilled in the south-east and another 25 in the north-east by the Ministry of Transport and Communications for construction site investigation. Only 7 of those drilled in the south-east, in the general

TABLE 1: OFFSHORE AND ONSHORE OIL EXPLORATION AND STRATIGRAPHIC TEST WELLS DRILLED IN EASTERN KENYA

| WELL NAME AND YEAR | LAND LOCATION (LAT./LONG.) | GROUND ELEVATION OR WATER DEPTH (m) | K.B. ELEVATION (m) | TOTAL DEPTH (m) | AGE OF OLDEST MATERIAL PENETRATED |
|---|---|---|---|---|---|
| Total Simba #1 (1977) | 04°00'06.68" S<br>40°00'06.60" N | 921.0 | 933.0 | 3604 | Upper Cretaceous (Campanian) |
| Cities Service, Maridadi #1A (1981) | | 28.0 | | 687 | |
| Cities Service, Maridadi #1B (1981) | 02°53'08.79" S<br>40°24'07.85" N | 38.7 | 54.0 | 4197 | Tertiary (Upper Oligocene) |
| Union Oil Kofia #1 (1981) | 02°32'33.27" S<br>40°56'18.97" E | 92.1 | 15.5 | 3631 | Lower Cretaceous (Maastrichian) |
| DSDP #241 (1974) | 02°22.24'00" S<br>44°40.77'00" E | 4054.0 | | 1174 | Upper Cretaceous (Turonian) |
| B.P. Shell Mararani #1 (1961) | 01°34'57.00" S<br>41°14'10.00" E | | 33.8 | 1991 | Tertiary (Middle Eocene) |
| B.P. Shell Walu #2 (1962) | 01°38'02.00" S<br>40°14'10.00" E | 86.0 | 91.8 | 3729 | Upper Cretaceous (Aptian) |
| B.P. Shell Dodori #1 (1963) | 01°48'53.70" S<br>41°11'04.00" E | 26.2 | 32.0 | 4310 | Paleocene |
| B.P. Shell Walmerer #1 (1966) | 00°06'35.00" S<br>40°35'05.00" E | 147.6 | 153.7 | 3794 | Lower Cretaceous (Neocomian) |
| B.P. Shell Garissa #1 (1968) | 00°22'04.00" S<br>39°48'41.00" E | 225.0 | 231.0 | 1240 | Upper Jurassic (Oxfordian) |
| B.P. Shell Pate #1 (1971) | 02°03'53.98" S<br>41°04'52.00" E | 2.2 | 8.1 | 4188 | Paleocene |
| B.P. Shell Kipini #1 (1971) | 02°29'23.00" S<br>40°35'51.36" E | 16.8 | 23.3 | 3663 | Lower Cretaceous (Maastrichian) |

TABLE 1 (Cont'd)

| WELL NAME AND YEAR | LAND LOCATION (LAT./LONG.) | GROUND ELEVATION OR WATER DEPTH (m) | K.B. ELEVATION (m) | TOTAL DEPTH (m) | AGE OF OLDEST MATERIAL PENETRATED |
|---|---|---|---|---|---|
| Texas Hagarso #1 (1975) | 00°47'43.50" S<br>40°26'40.50" E | 85.3 | 92.7 | 3092 | Upper Cretaceous (Lower Albian) |
| Chevron Anza #1 (1976) | 00°55'35.00" N<br>39°41'67.00" E | 252.4 | 256.6 | 3662 | Lower Cretaceous |
| Chevron Bahati #1 (1976) | 00°26'09.00" N<br>39°47'03.00" E | 161.4 | 168.2 | 3420 | Lower Cretaceous |
| Petro-Canada Kencan #1 (1986) | 00°18'57.38" S<br>39°46'16.57" E | 231.0 | 238.8 | 3863 | Permian-Triassic (Karoo) |
| AMOCO Elgal #1 (1987) | 01°22'47.00" N<br>39°53'09.00" E | 222.0 |  | 1280 | Permian-Triassic (Karoo) |
| AMOCO Elgal #2 (1987) | 01°27'32.00" N<br>39°58'40.00" E | 227.4 |  | 1907 | Permian-Triassic (Middle Karoo) |
| B.P. Shell Pandagua #1 (1960) | 02°05'51" S<br>40°25'15" E |  | 20.4 | 1982 | Tertiary (Oligocene) |
| Mehta Oil Ria Kalui #1 (1961) | 03°45'00" S<br>29°14'00" E |  |  | 1538 | Permian-Triassic (Karoo) |
| B.P. Shell Walu #1 (1961) | 01°38'04" S<br>40°15'09" E |  | 88.7 | 1768 | Upper Cretaceous (Campanian) |
| B.P. Shell Meri #1 (1961) | 00°20'36" N<br>40°11'00" E |  | 179.3 | 1941 | Tertiary (Paleogene) |
| B.P. Shell Lamu #1 (1958) | 02°10'57" S<br>40°48'29" E |  | 12.8 | 749 | Lower Miocene (Burdigalian) |
| B.P. Shell Lamu #2 (1958) | 02°12'35" S<br>40°42'30" E |  | 8.2 | 742 | Lower Miocene (Burdigalian) |

TABLE 1 (Cont'd)

| WELL NAME AND YEAR | LAND LOCATION (LAT./LONG.) | GROUND ELEVATION OR WATER DEPTH (m) | K.B. ELEVATION (m) | TOTAL DEPTH (m) | AGE OF OLDEST MATERIAL PENETRATED |
|---|---|---|---|---|---|
| B.P. Shell Lamu #3 (1958) | 02°23'09" S<br>40°24'24" E | | 15.5 | 763 | Lower Miocene (Burdigalian) |
| B.P. Shell Lamu #4 (1959) | 02°20'52" S<br>40°35'20" E | | 14.9 | 696 | Lower Miocene (Burdigalian) |
| B.P. Shell Waligero #1 | | | | | |
| B.P. Shell Bura-Lamu #1 | | | | | |
| B.P. Shell Bura #1 | | | | | |
| B.P. Shell Bura #2 | | | | | |
| B.P. Shell Bura #3 | | | | | |
| B.P. Shell Bura #4 | | | | | |
| Shell D'Arcy Fumbene #1 (1954) | | | | 17 | Oligocene |
| Shell D'Arcy Fumbene #2 (1954) | | | | 4 | Oligocene |
| Shell D'Arcy Fumbene #3 (1954) | | | | 32 | Oligocene |
| Shell D'Arcy Mavwene #1 (1954) | | | | 32 | Oligocene |
| Shell D'Arcy Makwenga #1 (1954) | | | | 4 | |
| Shell D'Arcy Makwenga #2 (1954) | | | | 8.5 | |

TABLE 1 (Cont'd)

| WELL NAME AND YEAR | LAND LOCATION (LAT./LONG.) | GROUND ELEVATION OR WATER DEPTH (m) | K.B. ELEVATION (m) | TOTAL DEPTH (m) | AGE OF OLDEST MATERIAL PENETRATED |
|---|---|---|---|---|---|
| Shell D'Arcy Gaji #1 (1954) | | | | 32 | Oligocene |
| Shell D'Arcy Gaji #2 (1954) | | | | 32(?) | Oligocene |
| Shell D'Arcy Gaji #3 (1954) | | | | 32(?) | Oligocene |
| Shell D'Arcy Goshi #1 (1954) | | | | 32 | Oligocene |
| Shell D'Arcy Goshi #2 (1954) | | | | 16 | Oligocene |
| Shell D'Arcy Goshi #3 (1954) | | | | 1.5 | Oligocene |
| Shell D'Arcy Goshi #4 (1954) | | | | 32 | Oligocene |
| Shell D'Arcy Chui #1 (1954) | | | | 58 | Oligocene |
| Shell D'Arcy Chui #2 (1954) | | | | 58 | Oligocene |
| Shell D'Arcy Chui #3 (1954) | | | | 6 | |
| Shell D'Arcy Chui #4 (1954) | | | | 32 | Oligocene |
| Shell D'Arcy Chui #5 (1954) | | | | 32 | Oligocene |

vicinity of Baricho and Ramada, and 4 at the Katumba quarry in Garissa, reached probable Tertiary strata at depths of 10 m or more. Up to mid-1986 the Ministry of Water Development had drilled a total of 758 water-exploration boreholes, with a wide range in total depth. The deepest water-production wells were drilled by oil-exploration companies at Meri, Jara Jila, Hagarso and Garissa in the north-east for use in test drilling at deeper levels. The Geological Survey of Kenya has drilled only 14 wells within sedimentary strata of the north-eastern area.

## Hydrocarbon Prospects

None of the deep test wells drilled to date have recovered hydrocarbons in commercial quantity. The B.P. Shell Dodori No. 1 well tested volumes of gas in Eocene and Paleocene strata through the drill stem (Eames, 1964). The detection of oil shows in strata of similar age from the Sinclair No. 1 Oddo Alimo well in south-west Somalia lends plausibility to the inference of reservoir potential within the Paleocene (Barnes, 1976). A drill stem test was also conducted in Oligocene sandstones, through B.P. Shell Pandangua No. 1 (Stipewich, 1961). The results of these drill stem tests are summarized in Table 2. The shut-in-pressures in all cases were never recorded.

Texas Pacific and Chevron oil companies investigated prospects in Cretaceous strata since 1975. The Upper Cretaceous carbonates, penetrated in Texas Hagarso No. 1 yielded minor quantities of gas and insignificant shows of bitumen.

TABLE 2: DRILL STEM TEST RESULTS IN TERTIARY STRATA OF SOUTH-EAST KENYA

| WELL NAME | LOCATION LAT./LONG. | K.B. ELEVATION (m) | INTERVAL TESTED (m) | AGE OF STRATA | FLOW TIME | RECOVERY |
|---|---|---|---|---|---|---|
| B.P. Shell Pandagua #1 | 02°05'51" S<br>40°25'15" E | 50.9 | 1564.6-1614.0 | Oligocene sandstone | 29 mins. | 131 $ft^3$ water and gas 27 $ft^3$ mud and water |
| B.P. Shell Dodori #1 | 01°48'53.7" S<br>41°11'04.0" E | 32.0 | 2068.0-2072.0 | Middle Eocene sandstone | 3 hrs. | 403 $ft^3$ water and mud with some gas |
|  |  |  | 2291.0-2700.0 | Lower Eocene limestone | 2 hrs. | 70 $ft^3$ gas and 564 $ft^3$ mud |
|  |  |  | 3192.0-3233.0 | Lower Eocene limestone | 85 mins. | 633 $ft^3$ gas and 7.5 $ft^3$ mud |
|  |  |  | 3589.0-3630.0 | Paleocene sandstone | 3hrs. | 430 $ft^3$ gas and 70 $ft^3$ water |

From Patrut, (1977)

Drill stem tests in various intervals of Aptian strata, in B.P. Shell Walu No. 2, produced negative results (Eames, 1963). The Chevron Anza No. 1 and Chevron Bahati No. 1 wells encountered gilsonite layers in Tertiary deposits, suspected as being organic-rich, lacustrine shales (Hunt et al. 1954). A similar substance occurred in Neocomian shales of B.P. Shell Walmerer No. 1. The Total Simba No. 1 well, drilled offshore on a diapiric culmination, encountered Upper Cretaceous rocks with source quality and under-compacted shales at 3355 m.

The failure of past exploration efforts could in part be attributed to the poor definition of structures, due to seismic data of rather low quality, and to the lack of sufficient knowledge on prevalent hydrodynamic conditions.

## Late Tertiary and Quaternary Sedimentation

Kidd and Davies (1978) observed that the distribution of terrigenous detrital clays off the East African coast dominated Late Mesozoic and Tertiary sedimentation. These were related to the distal deposits of eastward-prograding rivers that experienced rejuvenated drainage at different times. In the intervening periods, carbonate deposition re-asserted itself with pronounced development of calcareous oozes offshore. Accumulation of these terrigenous and pelagic sediments accompanied progressive outbuilding of the continental margin. Kent (1974) noted the interruptions in sedimentation offshore, represented by major hiatuses in the Upper Cretaceous-Paleocene, Middle

Eocene-Oligocene, and Middle Miocene intervals. Most of these gaps were related to periods of clastic starvation in the ocean basin and the widespread erosional effects of strong oceanic currents (Kent, 1982). The periods of crustal stability, during which erosion surfaces developed on land, were punctuated by major Late Mesozoic and post-Mesozoic epeirogenic uplifts affecting the African continent (Bond, 1978). Saggerson and Baker (1965) distinguished three cycles of erosion in eastern Kenya, terminated respectively by the end-Cretaceous, Miocene and Pliocene phases of uplift. The Miocene deformation, which is connected with the rise of the central Kenya dome and related rift faulting, produced important effects: faulting and downwarping of the coastal belt and a Late Miocene marine invasion. The Pliocene deformation enhanced fluviatile deposition in the lower Tana Valley (Wright and Pix, 1967) and in the Turkana basin. The deposition occurred in north-south-trending fault troughs, formed contemporaneously with the meridional rift system and resemble the older Karoo troughs.

Deformation continued into Quaternary time with the building of Mt. Kenya and the Nyambeni range. These greatly increased the catchment area of the Tana River, causing it to dissect the Tertiary erosion surface and deposit large amounts of sediment along its course. At present, the river terminates in a delta where it discharges into the Indian Ocean. North-east current- and wave-generating monsoon winds, coinciding with the flood periods of the Tana, form large dunes parallel to the coastline.

The Plio-Pleistocene downflexure and eustatic change in sea level related to withdrawal of the European glaciers, permitted a shallow-marine incursion associated with the development of fringing reefs and lagoonal deposits. The effects of these movements are evident around the coast in modern coral reefs, raised beaches, and coastal bays. In the north-east, the prevailing lagoonal conditions gave rise to algal stromatolites and gypsum deposits exposed at El Wak and Wajir.

## SCOPE OF STUDY

Exploration for hydrocarbons in Kenya has regained momentum in the last three years. Various international oil companies have acquired exploration rights in four out of the ten designated blocks under a new and recently established legal framework. Interest by these firms has probably been aroused by the possibility of discovering a new petroleum province. A discovery in significant commercial quantities would, in the long term, stand the national economy in extremely good stead. The present drain on foreign exchange reserves is largely attributed to a high dependence on imported fuels.

Of much more recent and growing concern, is the high rate at which the population of Kenya is expanding. The total population is projected to reach 35 million by the turn of the century. Supporting such growth will impose very serious constraints on the economy. At present, many ongoing, government-funded projects are motivated by the projected needs of the expanded future population. The search for water, particularly in the remote and semi-arid parts of the north, constitutes the highest priority. An understanding of groundwater flow patterns, is fundamental to the success of such a venture. Groundwater flow drives hydrocarbons to areas of accumulation, a relationship that underlies the fact that the search objectives of exploration for oil and groundwater have common elements. The objectives of this study therefore appear to have much in common with the development strategies of the country at this level.

Past oil and gas exploration was restricted to structural features, most of which were poorly defined. Traps of a stratigraphic nature defined by lateral variation in lithology and wedges of permeability, have received very little attention. This is to a large extent related to the sparse distribution of wells and an inadequately mapped subsurface geology. Strata of the Kenya part of the Mandera-Lugh basin, for instance, have not been penetrated by any deep test well. In this study, subsurface lithological information in the area is augmented by shallow wells, drilled by various government institutions. This is an apprcach that also serves to demonstrate the potential for effective data flow, and utilization among the different government ministries routinely involved in geological and geological engineering investigations.

Detailed descriptions of available cores were augmented by observations of exposed strata in north-east and southern Kenya as the first stages in reconstruction of the depositional history of the Cretaceous-Tertiary succession. Correlation of descriptive units between wells, through geophysical well-log analysis, and recognition of dominant depositional trends, provided the format for identifying and determining the spatial distribution of strata with good reservoir quality. The strata associated with possible source rocks constitute locales of potential hydrocarbon accumulation, where future prospecting endeavours may be focussed.

Pursuit of the foregoing sub-objectives was constrained by various limitations. Most notable was the inability to obtain additional geophysical data for the region, especially seismic cross-sections in the possession of the National Oil Corporation of Kenya. Different suites of geophysical well logs exist for all but the B.P. Shell Walu No. 1, B.P. Shell Pandangua No. 1, B.P. Shell Meri No. 1 and B.P. Shell Mararani No. 1 wells. Cores are only available from B.P. Shell Dodori No. 1, B.P. Shell Walu No. 1, B.P. Shell Pate No. 1, B.P. Shell Kipini No. 1 and Cities Maridadi No. 1B wells. Several sections of the cored intervals were missing from these wells, whereas others were in poor condition.

Fieldwork in the Mandera-Lugh basin of north-east Kenya, presented a formidable task. The high July temperatures, scarcity of drinking water, dust storms, and the need for vigilance against attacks by marauding bandits, made outcrop study difficult, particularly when shortage of time was an added drawback imposed by financial limitations.

# REGIONAL GEOLOGY

## GENERAL REMARKS

The following chapter integrates existing information on regional stratigraphy and structure for eastern Kenya and adjacent areas.

## PHYSIOGRAPHY

A two-fold climatic and physiographic division is suggested for the study area: the northern two-thirds is climatically arid, whereas the southern coastal region has a hot and humid, tropical climate. The two regions are recognized as separate administrative provinces, the north-eastern and coast provinces separated by a boundary drawn more or less parallel to the south-east-flowing Tana River. The provinces exhibit major contrasts in physiography.

The north-east region is an area of low relief, consisting largely of extensive plains that are remnants of the Middle-Miocene and Late Tertiary peneplains. The Cretaceous Marehan Sandstone forms a series of discontinous strike ridges that rise above the plains as the Raiya, Borahara, Willeh, Bamba, Gari, Danissa and Ogar Wein Hills (Ayers, 1952). Wind erosion plays a considerable role in denudation, as characterized by the castellated and pitted surfaces of the sandstones. The meagre and sporadic rainfall gives rise to a general uniformity in the vegetation. Perennial grasses are absent and the low thorn bushes scattered throughout the area tend to be more prolific on the sandstone and limestone outcrops (Ominde, 1968). The northern limit is marked by the perennial Daua River, which rises in the Ethiopian Highlands and runs parallel to the strike of the strata. Another prominent stream, the Lugh Suri,contains water only in the rainy season and forms the boundary between the Wajir and Mandera administrative districts (Baker and Saggerson, 1958).

The coastal plain forms the eastern margin of the south-east region. The seaward edge of the plain consists of Pleistocene coral reefs, which give way to sand dunes standing at about 60 m in the Malindi area. West of the coastal plain, the land rises abruptly to form the Foot plateau at an elevation of 60 to 150 m (Ojany, 1966). A further increase in elevation by 150 m gives rise to the flat-topped Shimba Hills, which constitute a prominent topographic feature. The area is more densely inhabited than the north-east and better served with roads and tracks. Thick vegetation, however, renders certain parts inaccessible. The south-east and the north-east differ markedly from the western part of the country, which is dominated by the central Rift Valley system and associated high mountain ranges.

## STRATIGRAPHY

The stratigraphic succession of the Late Mesozic and Tertiary strata of eastern Kenya and correlative units in adjacent areas are shown in Table 3.

The Jurassic-Cretaceous boundary is unconformable along the entire East African coast. In the Lamu basin, the Lower Cretaceous is represented on the surface by a 60 m thick unit, the Upper Member of the Mtomkuu Formation, deposition of which commenced in the uppermost Jurassic (Karanja, 1982). It is dominantly shaly, and includes limestone and fine-grained sandstone intervals. This unit is succeeded by the Freretown Limestone, a 60 m thick succession of detrital and partly bioclastic limestones that extends into the Aptian (Nairn, 1978). In coastal Somalia, the Lower Cretaceous is represented by coarse siliciclastic deposits of the Brava Formation, and limestones in the Sinclair No. 1 Obbia well (Beltrandi and Pyre, 1973). During Late Cretaceous time, mud deposition prevailed over the entire East and South-East African coasts. The Upper Cretaceous rocks, for which a thickness of more than 2000 m is estimated (Kent, 1984), are not exposed in outcrop in south-east Kenya. An Albian-to-Cenomanian shale is, however, reported from the Kenya coast. Despite the regional similarities of Cretaceous lithofacies on the East African margin, differences in the stratigraphic position of local intraformational unconformities have been observed (Nairn, 1978).

In the Mandera-Lugh basin of north-east Kenya, the Cretaceous is represented by the Marehan Series, which unconformably overlies Jurassic strata (Joubert, 1957). Two units are distinguished on a lithological and paleontological

TABLE 3: STRATIGRAPHIC CORRELATION CHART FOR KENYA AND ADJACENT AREAS OF EAST AFRICA

| PERIOD | | AGE | | NW KENYA | ETHIOPIA | SOMALIA | N E KENYA | COASTAL SOMALIA | S E KENYA | COASTAL TANZANIA |
|---|---|---|---|---|---|---|---|---|---|---|
| TERTIARY | NEOGENE | PLIO | UPPER | Kubi Fora Fm | Volcanics | Merca Somal | Merti Beds | ▨ | Lower Magarini Sands | Mikindani Bds |
| | | | LOWER | Kubi Algi Fm | | | ▨ | ▨ | North Mombasa Crag | ▨ |
| | | MIOCENE | UPPER | Loyengalani Fm | | | ▨ | ▨ | Marafa & Midadoni Bds | ▨ |
| | | | MIDDLE | ▨ | | | ▨ | Somali Formation | ▨ | Pugu Series |
| | | | LOWER | Kajong Fm | | | ▨ | | Kipevu Baratumu & Fundi Isa Beds | |
| | | OLIG | UPPER | ▨ | | | ▨ | ▨ | ▨ | ▨ |
| | | | LOWER | ▨ | | | ▨ | ▨ | ▨ | ▨ |
| | PALEOGENE | EOCENE | UPPER | ▨ | Karkar Formation | | ▨ | Lach Dera Formation | ▨ | ▨ |
| | | | MIDDLE | ▨ | Taleh Formation | | ▨ | | ▨ | ▨ |
| | | | LOWER | ▨ | Auradu Formation | | ▨ | | ▨ | ▨ |
| | | PALEOC | UPPER | ▨ | | | ▨ | | ▨ | ▨ |
| | | | LOWER | ▨ | ▨ | ▨ | ▨ | | ▨ | ▨ |
| CRETACEOUS | LATE | SENONIAN | MAASTRICHTIAN | Serra Iltoma Formation | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | | | CAMPANIAN | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | | | SANTONIAN | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | | | CONIACIAN | | Gumburo Group | Jessoma Formation | Marehan Sandstone | ▨ | ▨ | ▨ |
| | | | TURONIAN | | | Belet Uen Formation | | ▨ | ▨ | ▨ |
| | | | CENOMANIAN | | | Ferfer Gypsum Fm | Danissa Beds | ▨ | ▨ | ▨ |
| | EARLY | | ALBIAN | ▨ | | Mustahil Formation | | Brava Formation | Unnamed Shale | Makonde Sst |
| | | | APTIAN | ▨ | Main Gypsum Formation | | ▨ | | Freretown Lmst | Trigonia Schwarzi Beds |
| | | NEOCOMIAN | BARREMIAN | ▨ | | | ▨ | | Upper Mtomkuu Formation | |
| | | | HAUTERIVIAN | ▨ | | | ▨ | | | Kipatimu Beds |
| | | | VALAGINIAN | ▨ | | | ▨ | | | |
| | | | BERRIASIAN | ▨ | | | ▨ | | | |

(sources: Saggerson and Miller, 1957; Barnes, 1976; Kamen-Kaye, 1978; Narin, 1978) basis: the Danissa Beds, consisting of a siltstone-mudstone sequence with thin limestone horizons; and the non-fossiliferous Marehan Sandstone (Saggerson and Miller, 1957). The total thickness of the Danissa Beds is 115 m and it yields fossils indicative of a Early Cretaceous age. The Marehan Sandstone forms prominent north-east-trending escarpments in the western part of the basin. The greatest thickness is in the north-east corner, where an outcrop forms a cliff 145 m high' on the Raiya Hills. Joubert (1957) compared these units with similar deposits in Somalia and Ethiopia, and suggested that the Marehan Series is confined to the interval between the Neocomian and Turonian. The Cretaceous strata of the Ogaden region of Somalia and Ethiopia is characterised by highly variable facies, comprising evaporites, reefoid carbonates and siliciclastics (Barnes, 1976).

Sedimentation in north-west Kenya began in the Late Cretaceous, following the inception of the Habaswein-Chalbi Desert depression. The initial deposits are coarse clastics that rest unconformably on the basement. The term "Turkana Grits" (Murray-Hughes, 1933) has been applied widely with reference to the entire range of deposits, occurring between the Basement System and the Miocene basaltic lavas. Savage and Williamson (1978) made a distinction between the Upper Cretaceous sediments, that form fining-upward fluvial cycles, and Lower Miocene fluvio-lacustrine sediments, unconformably overlain by the lavas. The Upper Cretaceous fluvial sediments are now referred to as the

Serra Iltoma Formation, the Lower Miocene fluvio-lacustrine sediments as the Kajong Formation and the lava deposits as the Loyengalani Formation respectively. The Pliocene strata occurring east of Lake Turkana, are divided into the coarse clastics of the Kubi Algi Formation and the much finer-grained Kubi Fora Formation (Bowen and Vondra, 1973). Both sequences were deposited in a delta-lacustrine environment, and contain interbeds of volcanic tuffs that constitute correlatable stratigraphic markers.

Lower Tertiary strata are not exposed in south-east Kenya but have been encountered at the subsurface in the B.P. Shell Dodori No. 1 well. The Paleocene shales and mudstones are estimated to be 730 m thick at Pate Island and change laterally into silts and sandstones in the B.P. Shell Dodori No. 1 well, where the measured thickness is 975 m. These rocks thicken and coarsen northwards into Somalia (Kamen-Kaye, 1978) and represent the basal subsurface equivalents of the Auradu fossiliferous limestone that outcrops in the Nogal Valley to the north (Barnes, 1976). These rocks extend into the Lower Eocene part of the section and grade upwards into the Karkar Limestones of Late Eocene age. To the south in Tanzania shales dominate the Paleocene through parts of the Lower Miocene subsurface sections with interruption by nummulitic limestones. The Paleocene in Kenya is separated by a disconformity from the Lower Eocene nummulitic limestones. The Middle and Upper Eocene strata comprise 2440 m of fine clastics and dense limestones that grade northward and eastward into argillaceous sandstones, siltstones and shales. Lower Eocene strata are also documented offshore at a distance between 850 km and 1100 km from the coast near Lamu (Scrutton _et al_. 1981). An early Miocene transgression deposited carbonates along the entire East African continental margin. In coastal Kenya, the Baratumu Formation, a fossiliferous limestone, is dated Aquitanian to Burdigalian (Eames and Kent, 1955). A foraminiferal limestone, called the Fundi Isa Limestone (Williams, 1962) and the Kipevu Beds (Walters and Linton, 1973), represent lateral equivalents of the Baratumu Formation in the north coast. In the subsurface the limestones are dolomitic and anhydritic and range in thickness from 400 to 900 m at different localities. Kent (1982) highlights the trapping effect of the Miocene deposits along the coast, depriving the ocean basin of terrigenous clastics. The Miocene carbonates occur as far south as Dar-es-Salaam in Tanzania and as the Somali Formation in north, coastal Somalia. The Marafa Beds are poorly consolidated, coarse-grained sandstones that lie unconformably on the Lower Miocene and begin at the base with a pebble conglomerate (Thompson, 1954). The rocks attain their greatest thickness of 120 m in the Malindi area. The largely unfossiliferous, unconsolidated, quartzose sandstones of the Dar-es-Salaam embayment are probably related to these beds. The deposits mark a change from shallow marine deposition to a terrestrial depositional regime.

In the north-eastern domain, Tertiary strata occur at the surface as claystones (Thompson and Dodson, 1960) and unconsolidated ferruginous gravels (Joubert, 1960). These consititute the Merti Beds, comprising lenticular beds of red and grey semi-consolidated gravels, sands, silts and clays, and are referable to Upper Pliocene post-uplift deposition. They are overlain by Pleistocene limestone and gypsum deposits in the El Wak and Wajir areas, and by Quaternary volcanics in the Garba Tula area, east of the Turkana basin.

## STRUCTURE

### Basin Configuration and Evolution

The term Lamu embayment, used in description of a graben-like sedimentary basin extending as far north as north-west of Wajir and eastward into Somalia from the Kenya coast, is a misnomer in the geological framework of the Cenozoic sedimentary basins of east Kenya. A progressive accumulation of geological and geophysical data has led to the separation of two major sedimentary depressions that evolved quite distinctly: the Lamu basin or Tana syncline (Patrut, 1977) which is downthrown against the basement outcrop to the west, by a north-south striking fault, and terminating in the north on the Garissa-Hagarso-Walmerer basement ridge; and the Anza basin, or Hataswein syncline (Patrut, 1977), situated between this basement ridge and the north-west-trending Lagh Bogal fault, extending eastwards into Somalia.

The Garissa-Hagarso-Walmerer ridge is a prominent structural feature emerging as Precambrian basement in the Bur Acaba uplift of Somalia (Reeves et al., 1986) and in the offshore area near latitude 2° S (Rabinowitz, 1971). Its development was most pronounced during end-Cretaceous epeirogenesis and was conjuctive with the inception of the Habaswein-Chalbi desert depression (Saggerson and Baker, 1965), which extends beyond the Turkana region to join the Abu Gabra rift of Sudan (Brown and Fairhead, 1983). The north-westward continuity of the Anza basin is severed by the Matasade horst, separating it from the Turkana depression.

The third and most north-easterly onshore basin is the Mandera-Lugh basin, representing a south-westerly extension of the Tamalo syncline of Somalia (Beltrandi and Pyre, 1973) and the Ogaden basin of Ethiopia. It borders the basement along the western margin while the eastern margin is defined by the fault-bound Hafura anticline (Joubert, 1960), running approximately parallel to the Kenya-Somalia border. This structure continues north eastward into Somalia as the Sengif anticline, where the folding is most intense.

The Lamu basin is a rift basin that began its development in Late Carboniferous time, at the onset of continental fragmentation. A sequence of up to 10,000 m (Kent, 1974) of fluvio-continental clastics, were deposited on a deformed crystalline basement until the Jurassic period. The separation of Madagascar along a strike-slip transverse fault, was accompanied by the establishment of open marine conditions allowing carbonate reefal deposits and evaporites to accumulate. Faulting along the Tana River hinge line in Jurassic time was also responsible for the separation of near-surface Carboniferous-to-Triassic strata in the west, from the Lower Jurassic to Tertiary sediments deposited in the east. The prolongation of sedimentation into the offshore area has been recognized on seismic profile (Francis et al. 1966). The eastern limit of the Lamu basin, is said to coincide with the continental-oceanic crust boundary marked by a basement ridge some 300 km from the coastline (Scrutton et al. 1981). A ridge extending from north of Pemba Island to about 4° S (Rabinowitz, 1971) bisects the sedimentary infill on the continental slope into two separate depositional troughs. The basin became a passive margin or intermediate stable coastal type (Klemme, 1980) from Early Mesozoic time as wedges of clastic sediments attained a thickness of about 8000 m (Kent, 1974) throughout the Late Cretaceous and Tertiary epeirogenic movements.

The Anza graben is a cratonic rift basin, the initiation of which is related to Cretaceous rifting associated with the opening of the Indian Ocean (Flores, 1984). It is defined by a gravity anomaly 130 km wide that runs over a strike length of 300 km (Reeves et al. 1986). Late Mesozoic deposits outcrop from beneath basaltic lava flows in its north-western extremity, while in the south-east they dip under Tertiary fluvial and lagoonal deposits. The deepest part of the basin is located in the north-east, where the strata are downthrown against the Lagh

Bogal fault. The basin contains an estimated sediment thickness of 3100 m.

The Mandera-Lugh basin is also of the cratonic rift type (Klemme, 1975), hinging on basement culminations to the south-east and south-west. The lowest sedimentary unit of the basin is the Mansa Guda Formation (Nairn, 1978), 650 m of sandstones and conglomerates with bituminous intervals, resting unconformably on the crystalline basement. It is correlated with the Triassic fluviatile sediments of the Lamu basin, an observation that infers a linkage at some period in the Early Mesozoic Era. The marine invasion associated with carbonate and evaporite deposition occurred in these extensive depositional trough in the Middle Jurassic, by which time 3000 to 4000 m of sediments had accumulated. Stratigraphic equivalents of the Toarcian neritic carbonates have been encountered as far north as Arabia (Kent, 1974). The end-Cretaceous phase of tectonism ushered a new phase of deposition accompanied by development of the Anza basin.

The offshore basin of Kenya constitutes a southern section of the Western Somalia basin, the growth of which is linked with the evolution of the south-western Indian Ocean. The Triassic rifting episode that split East Gondwanaland from West Gondwanaland (Dietz and Holden, 1970), probably caused a minor east-west separation of Madagascar from the East African coast. The seafloor-spreading phase commenced in the Jurassic and ended in the Late Cretaceous when the Somali basin became fully established as a true oceanic basin (Le Pichon and Heirtzler, 1968). Madagascar had moved south-eastwards over a distance estimated to be 1800 km (Reeves et al. 1986) by Early Cretaceous time. Geophysical and drilling data have confirmed the existence of Middle Jurassic and Lower Eocene strata (Schlich, 1974) underlying oceanic basement from the continent-ocean boundary to some 850 km offshore (Bunce et al. 1967). The more easterly sedimentary deposits underlie heavily faulted oceanic basement and terminate against the Dhow fracture which hindered substantial sediment progradation farther east. Kent (1982) commented on the remarkable congruity in tectonic regime between the onshore and offshore area. Vertical movements in the deep offshore were not as pronounced as those onshore. The variations in deposition were to a large extent the result of extrabasinal controls.

## Rift Features

Global studies of failed and passive continental rifts, have revealed general similarities in a variety of features, mainly related to closely comparable modes of origin. Most notable is the similarity between the rift basins on the continental margin of Kenya and further inland with those on the eastern coast of North America. Burke (1976) related their origin to the rupturing of continental lithospheric plates as a precursor to the development of major oceans. The associated normal faulting giving rise to grabens, developed at sites of upwardly convecting, cylindrical plumes of deep mantle material (Morgan, 1972) termed "hot spots" (Kinsman, 1975). Isolated individual hot spots produce three pronged or triple-rift junctions, and a failed rift progeny with a fault pattern that tends to parallel the structural grain of the basement. Bosworth et al. (1986) suggested that lateral propagation of the faults is accompanied by an inward curving, producing a neck in the rift beyond which new detachments appear. The resultant effect is lengthwise growth of the rift and the development of new sub-basins that constitute isolated depositional basins. These short offsets account for irregularities along the continental margin and localize major drainage channels, thereby causing delta progradation at the site of the developing ocean (Dewey and Burke, 1974).

Kent (1976) observed that not only is there this similarity in evolution, but also a global synchroneity in rheological yield pattern. In the Carboniferous to Permian, rift subsidence, producing a maze of horsts and grabens, was established on the East African seaboard and elsewhere, in areas such as the eastern Atlantic coast, the North Sea region and Greenland. A prominent basement horst, defining separate sub-basins in the Kilifi area of coastal Kenya (Cannon et al. 1981), may have developed during this time. Taphrogenic subsidence characterised Triassic and Early Cretaceous times in all these areas, and ceased in the Middle Cretaceous, when transgressions occurred across the fault structures. Important syn-rift phenomena accompanying taphrogenic subsidence involved the deposition of evaporite sequences and the intrusion of igneous complexes during Triassic through Early Cretaceous time. In East Africa, evaporite deposition began in the Middle Jurassic, in the offshore region of Kenya, the Mandera-Lugh basin and the Mandawa graben of Tanzania (Kent, 1965). Igneous rock outcrops of Cretaceous age are represented by major alkaline suites in the Jombo area, at the western margin of the Kenya coastal basin (Pulfrey, 1969). Intercratonic basinal subsidence and wide marine transgressions extending on to marginal areas of older Paleozoic rocks was generally a world-wide Middle to Late Cretaceous event, preceding the dominantly regressive Tertiary. The margins of north-east Kenya and north-west Somalia evolved passively during this time (Bosellini, 1986). Subsidence of the salt-bearing strata on the continental slope of Kenya, accompanied a seaward sliding of post-saliferous masses and their accumulation at the foot of the slope (Burollet, 1984). Tilting of fault blocks during this process produced growth faults, delimiting wedges of sediment that thickened on the downthrow side. Similar features are typical of the Texas Gulf Coast area and Niger delta. Bruce (1973) attributes the development of such faults to gravitational sliding and undercompaction of the underlying shales. The dissymmetric centres of such fault structures were commonly the loci of salt diapirism.

## Basement Lineaments

The Late Precambrian and Early Paleozoic phases of the Pan-African thermo-tectonic episode (Kennedy, 1965) in East Africa only affected the basement rocks. This is seen in the linearly folded, high-grade metamorphics of the Mozambiquean belt. The processes involved included crustal flexuring, collisions, subsidence and thrusting, modified by subsequent dextral and sinistral shearing, preceding the earliest period of rifting. Characterizing the craton are deep-seated dislocation zones or lineaments, extending vertically down into the crust and upper mantle, with directions ranging from north-south, north-west to south-east and north-east to south-west. Kroner (1977) attributed these developments to sub-crustal processes, just strong enough to create linear zones of weakness and intraplate graben systems, rather than cause complete continental rupture. These lineaments had a major influence on the development and localization of the Paleozoic-Mesozoic and later Tertiary rifts as well as the evolution of the continental margin (McConnell, 1977).

Using filtered satellite images, three sets of basement lineaments in northern Kenya, attributed to three main tectonic episodes, were analysed in areas marked by an absence of volcanic and sedimentary cover (Berke and Rothery, 1986). These include: the youngest Barsaloi phase, with a north-south structural domain; the Baragoi phase with a north-west to south-east fault pattern, and the oldest Samburu east-west structural phase. The north-south paleotectonic directions of the Tana hinge line and intracontinental rift along which Madagascar separated from the East African coast, were inherited from the Barsaloian structural trend. Reactivation of the basement through heat dissipation and tension exerted on the African plate along a north-west to south-east line, as the Atlantic and Indian Oceans opened, was accompanied by subsidence of the coastal basins and initiation of the Anza graben.

## Main Fault Systems

The trend of major faults in the study region is in conformity with the general pattern of the persistent, deep-basement lineaments and in places generated gently tilted horst blocks.

In the north-east, the Hegalu horst is bounded by two parallel faults striking north-east to south-west (Joubert, 1960), but tending to diverge in a northerly direction. Sediments of Cretaceous age are folded into an anticline between these two faults. West, and parallel to this structure, another major fault upthrows the sandstones of the Marehan Series by as much as 60 m. A cross-cutting relationship of north-east- and north-west-trending faults, defines the lateral limits of the Danissa, Garri, Willeh and Ogar Wein Hills. A prominent fault south of the Lugh Suri River, the Danissa fault (Saggerson and Miller, 1957), running north-eastwards from Wergadud to the east-west-trending Karantri hinge fault in the north, downthrows the Marehan Sandstone in the west and defines their south-eastern limit. Further west, the Cretaceous rocks are juxtaposed against Jurassic limestones by the north-west-striking Warido fault. Minor fractures inferred as lineaments from aerial photographs occur on the surface as zones of calcite and silica recrystallization.

Block faulting in the south-eastern part of the study area, is best demonstrated by the Sala and Kulalu faults (Sanders, 1959) of the mid-Galana area. The complementary grabens, flanking the horst on either side, are filled by strata of Karoo age. The Shimba Hills are also uplifted horsts developed during the episode of Jurassic faulting. Most faults in Mesozic rocks of the Kenya coastlands are normal and follow three main trends, north-south, north-east to south-east and east-west. The development and age of the coastal faults has been ascribed to several periods of tectonic activity (Caswell, 1956). The oldest phase of Middle Trassic time is linked with the break-up of Gondwanaland. In the Jurassic, two phases are observed: an earlier phase associated with the first major marine transgression, and a later phase connected with the galena-baryte mineralization of the Vitengeni area near Mombasa. The end-Cretaceous faulting was connected with the alkaline igneous intrusives at the boundary of the Basement and Karoo rocks. The mid-Pliocene faulting that followed the middle Miocene tectonic episode, displaced strata of the Marafa Beds (Thompson, 1954). The Baratumu Beds are also observed to be downthrown against the

Upper Cretaceous Mtomkuu Shales, by a Pliocene fault. A major Tertiary fault system, extending along the coastline south-westward from Somalia through the Bur Acaba uplift to Kenya and Tanzania, has downthrown the marine and continental sediments of Tertiary to Karoo age by 4000 m (Peterson, 1986). This faulting may be associated with the uppermost Oligocene - Lower Miocene, widespread marine transgression.

In the offshore area, the north-trending Davies fracture (Bunce and Molnar, 1977) is a curvilinear transform fault, to which the south-eastward movement of Madagascar from the East African coast is attributed.

# DEPOSITIONAL HISTORY

## GENERAL REMARKS

This chapter is an account of regional stratigraphy and is the first comprehensive study, involving integration of available subsurface data with observations of surface exposures. The subsurface lithological and paleontological information is from existing well records, compiled over the last 32 years of oil exploration in east Kenya. Broad interregional correlations, beyond the boundaries of the study area are discussed and provide a means of forecasting sedimentary trends, an aim otherwise severely limited by the sparse distribution of deep wells. Additional control was obtained from shallow boreholes drilled for various purposes other than hydrocarbon exploration. Past published information is scrutinized and evaluated in light of the new findings. The geological history of the area is reconstructed from the depositional and tectonic framework of the major stratigraphic units.

## DETAILED STRATIGRAPHY

### Cretaceous Strata

Mesozoic rocks of Early Cretaceous age are represented in outcrop by the Upper Member of the Mtomkuu Formation and Freretown Limestone, in the south-eastern part of the study area. In the north-east, the Lower to Upper Cretaceous Marehan Series occurs as outliers, unconformably overlying the Jurassic rocks.

These strata, except for the uppermost Cretaceous, are well represented in the onshore and offshore parts of the Lamu basin (Figs. 2 and 3).

## Lower Cretaceous Strata of South-East Kenya

The Mtomkuu Formation comprises a heterogeneous assemblage of shales and sandstones, exposed in the Kilifi, Gede and Sokoke areas. The fossil assemblage within the Mtomkuu Formation was described by Caswell (1953), who regarded the formation as representing the time span from Middle to Late Jurassic. The four-fold subdivision initially proposed by Caswell (1953), has since been revised and the formation is presently divided into three contrasting lithofacies of the Lower, Middle and Upper Members of the Mtomkuu Formation. The Kibiogoni Beds, comprising 30 m of dark grey shales and minor sandstones, hitherto considered as Late Jurassic in age, are now assigned to the Upper Member of the Mtomkuu Formation (Simiyu-Siambi, 1978). The Upper Mtomkuu Formation is exposed in the Mavweni-Mkongani area, near Kilifi Creek, where it is faulted against Lower Miocene sediments. The shales are interbedded with fine-grained, calcareous sandstones that show a small-scale cross-bedding and bands of thin calcilutite. The unit is 60 m thick and forms an intergral part of the Neocomian strata, encountered further northwards in the B.P. Shell Walmerer No. 1 well. This subsurface succession has a thickness of 1450 m and comprises an alternating sequence of fine - to coarse-grained

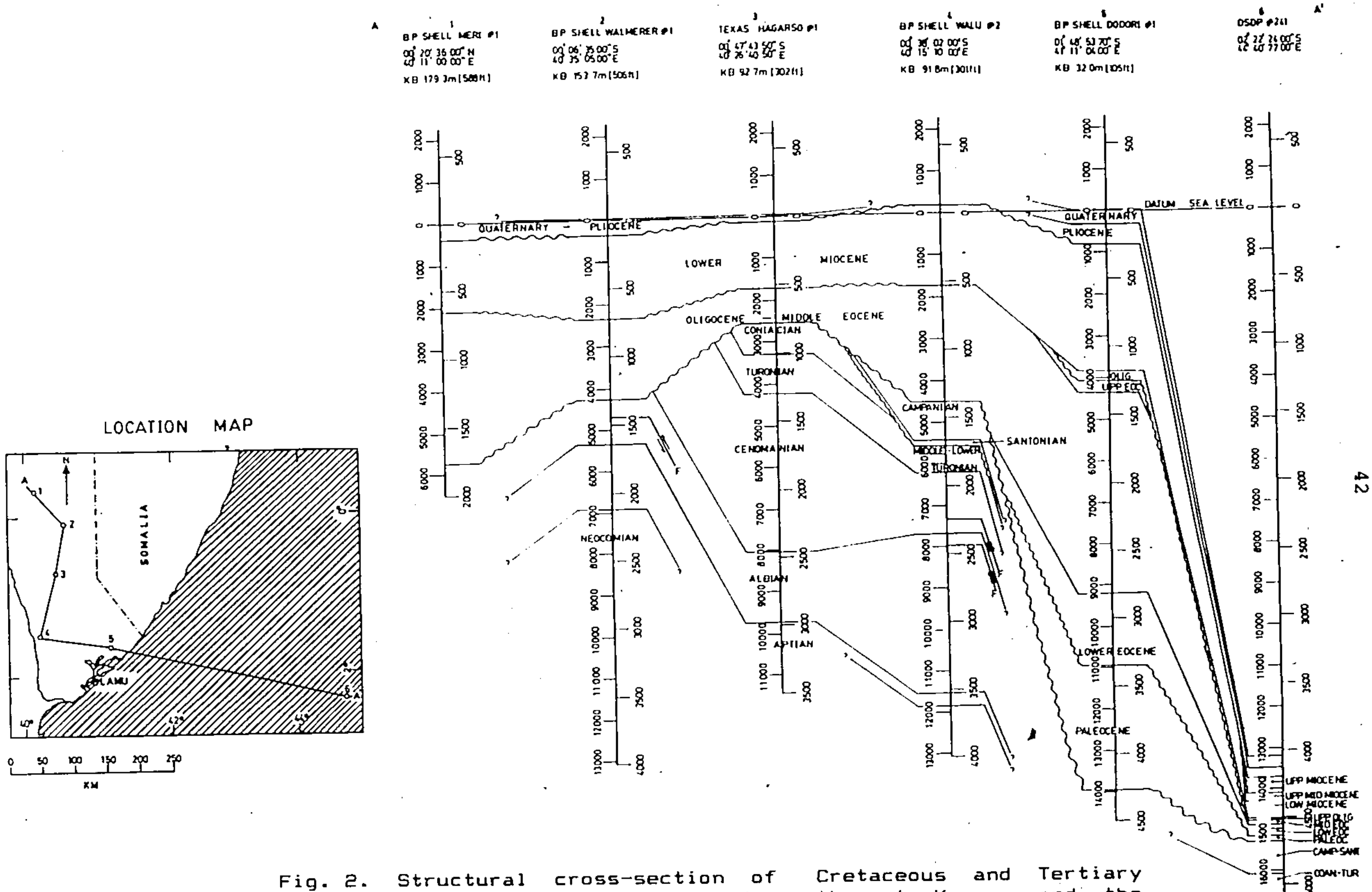


Fig. 2. Structural cross-section of Cretaceous and Tertiary strata in north-east and south-east Kenya and the

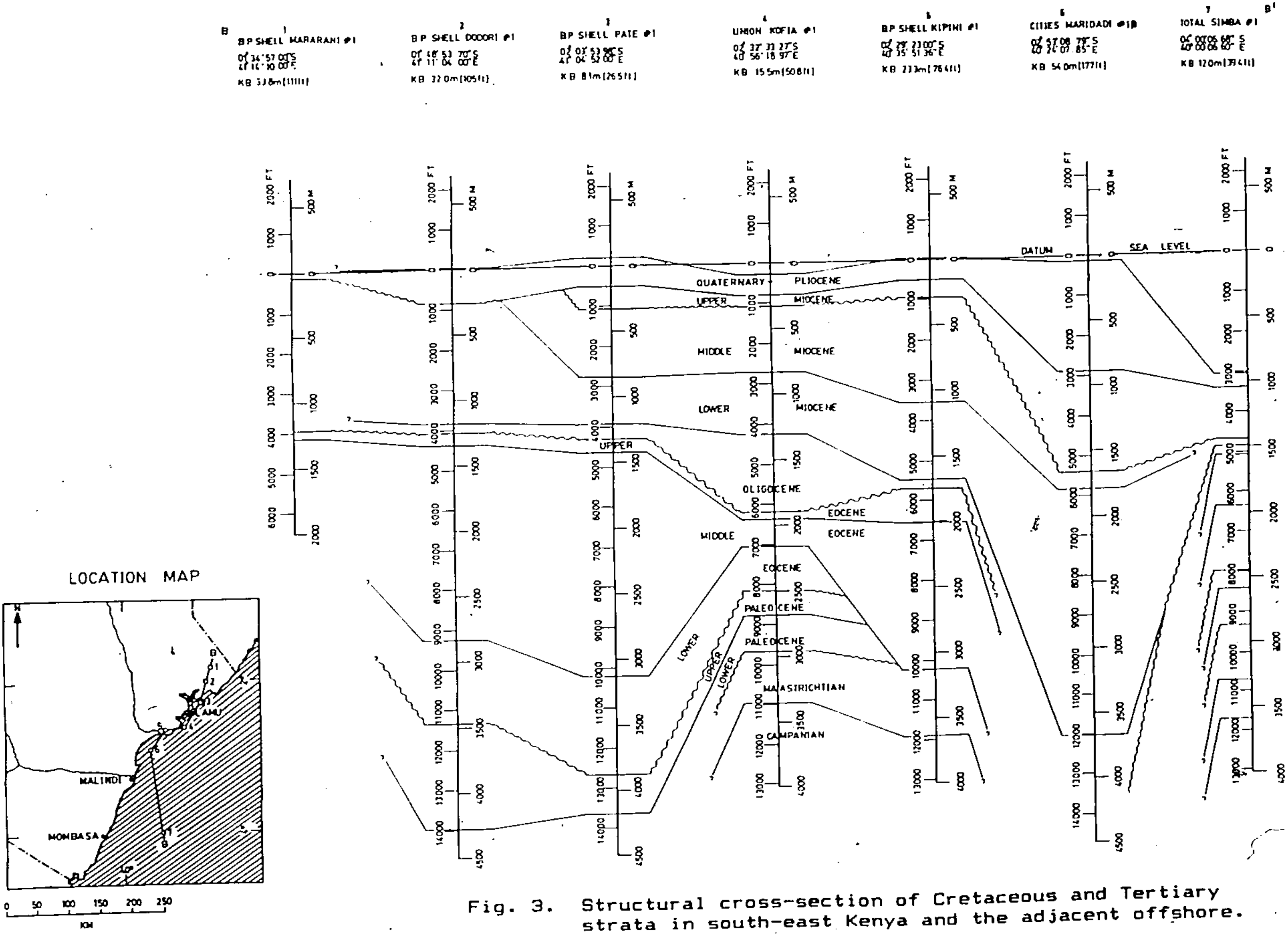


Fig. 3. Structural cross-section of Cretaceous and Tertiary strata in south-east Kenya and the adjacent offshore.

orthoquartzites, siltstones, shales and subordinate calcareous sandstones. A water borehole, the MOWD/C4358 well, drilled by the Ministry of Water Development at Mirarani south of Kilifi Creek, went through 200 m of quartzitic sandstone, and terminated at a basal conglomerate that probably marks the base of the Upper Member of the Mtomkuu Formation. The thickness of these Neocomian facies could therefore be at least 260 m at the coast.

## Upper Cretaceous Strata of South-East Kenya

The name Freretown Limestone was proposed by Caswell (1953) for exposures of thinly bedded silty and partly bioclastic limestones, occurring within a very small area of the exposed Upper Member of the Mtomkuu Formation. Linton and MacLean (1955) documented the occurrence of fractures and baryte veins in the limestones of an exposure in a small quarry at Freretown. The Freretown Limestone is considered to be Barremian to Aptian in age, on the basis of the presence of *Orbitolina bulgarica janenschi* and *Orbitulina kurdica* (Walters and Linton, 1973). The limestones are up to 60 m thick in the limited outcrop area.

Strata of the Freretown Limestone are in abrupt contact with 30 m of bluish grey shales that yielded *Hedbergella paradubia*, *Hedbergella trocoidea*, and *Ticinella roberti*, planktonic microfauna of Albian to Cenomamian age. The subsurface equivalents of the Freretown Limestone in the B.P. Shell Walu No. 2 well, are a contrasting lithofacies comprising 110 m of very fine-grained sandstones and siltstones, with worm burrows and highly fractured zones. These lithofacies remain essentially unchanged further north in the Texas Hagarso No. 1 well, where only 357 m of Aptian calcareous shales and siltstones were drilled, and in the B.P. Shell Walmerer No. 1 well, where the Aptian siltstones and sandstones are 550 m thick. The Albian shales encountered in outcrop compare very closely with those in the B.P. Shell Walu No. 2 well, and comprise 1174 m of pale grey to dark green, glauconitic, pyritic and ammonitic shales, exhibiting slumping, nodular and conglomeritic features. The interval has a plethora of open-marine planktonic fauna that includes *Ticinella roberti*, *Planomalina breggiensis*, *Prasglobotrucana washitensis* and the ammonite *Tetrahoplitoides sp.* The 30 m thick ammonitic shales at Freretown display similar characteristics and contain an identical fauna. A lithological change is observed in the Texas Hagarso No. 1 well with the occurrence of 280 m of siltstones interbedded with shale. A basal limestone with calcite and anhydrite veining makes up the remaining 180 m. Limestones become more dominant in the B.P. Shell Walmerer No. 1 well, where they form a 127 m thick unit, and interbedded limestones and silty calcareous shales make up the lower 190 m.

The Sinclair No. 1 Obbia well of central-coastal Somalia is devoid of Neocomian strata, but limestones prevail as the principal lithology of Aptian and later Cretaceous strata (Kamen-Kaye and Barnes, 1979). In South-west Somalia however, the Sinclair No. 1 Brava well includes 800 m of dark grey shales with sandstone interbeds, underlain by 60 m of basal quartzitic sandstones. These strata, named the Brava Formation (Beltrandi and Pyre, 1973), are Early Cretaceous in age and appear to be correlatable with the exposed Upper Member of the Mtomkuu Formation. Also equivalent to the Upper Mtomkuu Formation and Freretown Limestones, are the Kipatimu, Makonde and Trigornia Schwarzi Beds outcropping in southern Tanzania. These constitute a Neocomian-to-Aptian succession of sandstones and variegated shales, with the latter forming a limestone capping (Kent, 1974; Kamen-Kaye, 1978). The succeeding interval is a dark shale facies referable to the Albian transgression. The advent of a marine transgression is quite evident farther south-west of Dar-es-Salaam, where Albian shales rest unconformably on Jurassic rocks (Kent, 1982).

A complete Cenomanian successesion is present in the subsurface. Dark shales with prolific marine planktonic fauna persist in the B.P. Shell Walu No. 2 well and attain a thickness of 450 m. In the Texas Hagarso No. 1 well, similar shales are overlain by 850 m of calcilutites and calcisiltites.

The Turonian in the Texas Hagarso No. 1 well comprises 250 m of slightly carbonaceous shales associated with thin sandstones. The sandstones continue into an eroded 300 m of Coniacian strata below the end-Cretaceous unconformity. A non-depositional hiatus occurs in the B.P. Shell Walu No. 2 well, with the Upper Turonian and Coniacian absent. Less than 200 m of Lower and Middle

Turonian strata are overlain by 250 m of shale of Santonian age. The shales in both units contain sparse amounts of coaly terrestrial detritus. Also noteworthy is the absence of Cenomanian and Turonian strata in Tanzania (Kent and Perry, 1973).

Partly eroded silty shales and fine-grained sandstones of Campanian age are preserved in the B.P. Shell Walu No. 2 well and the sequence is similar to that of equivalent strata penetrated by the B.P. Shell Kipini No. 1 well. None of the wells in the Lamu basin have penetrated the entire thickness of the Campanian.

## Lower Cretaceous Strata of North-East Kenya

The Marehan Sandstone was the formational name first proposed by Weir (1929) for outcrops of sandstones, forming north-east-trending escarpments west of Mandera. Dixey (1938) viewed the sandstones as being the equivalents of the Jurassic limestones, representing the transition from a marine regime to a continental environment. He therefore concluded that they were Late Jurassic in age. Busk (1939) considered the outcrops as fault blocks, around which the marine Jurassic sediments had accumulated. A Late Jurassic to Cretaceous age was suggested by Ayers (1952). He grouped the sandstones with the Jurassic Mandera Series. The unconformable relationship between the Marehan Sandstone and underlying Jurassic sediments was recognized by Joubert (1957), who distinguished between these siliciclastic deposits and the dominantly marine Mandera Series.

The former were designated the Marehan Series and subdivided into the Danissa Beds and Marehan Sandstones.

At the type section (Table 4) in the Danissa Hills, the Danissa Beds form a cyclical sequence, comprising 115 m of alternating siltstones and mudstones, interrupted by pink sandstones at various horizons (Saggerson and Miller, 1957). The lowest part of the Danissa Beds is a grit, partly exposed at the base of the Ogar Wein and Danissa Hills. An outcrop section, measured by Joubert (1960) on the western flanks of the Raiya Hills exhibits the same kind of cyclicity and thickness for the Danissa Beds (Table 5). Slump bedding is documented from exposures on the Ogar Wein, Warido, Golberobe and Garri Hills, an area of pronounced north-east and north-west faulting. Saggerson and Miller (1957) collected the plant _Weischelia reticulata_ from siltstones, at the top of the Danissa Beds in Warido, which implied an Early Cretaceous age. They also identified silicified wood and fish remains from the beds exposed at Wergadud Hill.

The Marehan Sandstone overlies the Danissa Beds on most of the hills where the latter are exposed. Joubert (1957) differentiated the sequence from the underlying unit on the basis of a higher degree of iron oxide staining and its coarser and largely unfossiliferous nature. Baker and Saggerson (1958) related the variable staining to the distribution of detrital iron by circulating groundwater, preferentially flowing through the more permeable rocks. Joubert (1960) conceded the

TABLE 4: TYPE SECTION OF THE DANISSA BEDS ON A SCARP OF THE DANISSA HILLS

| UNIT | LITHOLOGY | THICKNESS (m) | HEIGHT ABOVE BASE (m) |
|---|---|---|---|
| | DANISSA BEDS | | |
| 11 | Sandstone, light pink, flaggy | 10.5 | 114.6 |
| 10 | Siltstone, variegated, laminated | 3.0 | 104.1 |
| 9 | Sandstone, light pink, flaggy ripple marked | 9.0 | 101.1 |
| 8 | Mudstone, grey-green, calcareous | 9.0 | 92.1 |
| 7 | Mudstone, orange-red | 0.3 | 83.1 |
| 6 | Limestone, nodular, marly | 0.3 | 82.8 |
| 5 | Mudstone, grey-green, calcareous with fucoids | 6.0 | 82.5 |
| 4 | Sandstone, pink | 9.0 | 76.5 |
| 3 | Siltstone, variegated | 3.0 | 67.5 |
| 2 | Siltstone and Mudstone, yellow to grey | 24.5 | 64.5 |
| 1 | Sandstone | 40.0 | 40.0 |

(from Saggerson and Miller, 1957)

TABLE 5: MEASURED SECTION OF THE MAREHAN SERIES ON THE WESTERN SLOPE OF RAIYA HILLS

| UNIT | LITHOLOGY | THICKNESS (m) | HEIGHT ABOVE BASE (m) |
|---|---|---|---|
| | MAREHAN SANDSTONE | | |
| 21 | Sandstone and Siltstone, interbedding, whitish pink, cross-bedding | 30.5 | 144.8 |
| | DANISSA BEDS | | |
| 20 | Siltstones, red and purple | 2.0 | 114.3 |
| 19 | Sandstone, clayey, cross-bedded | 1.5 | 112.3 |
| 18 | Siltstone, variegated with fossilized twigs | 3.5 | 110.8 |
| 17 | Sandstone, whitish, cross-bedded | 2.5 | 107.3 |
| 16 | Siltstone and Shale, variegated | 3.0 | 104.8 |
| 15 | Sandstone, whitish massive | 2.0 | 101.8 |
| 14 | Siltstones and silty Shales variegated, with clay galls | 6.0 | 99.8 |
| 13 | Sandstone, whitish silty | 1.0 | 93.8 |
| 12 | Sandstone, brown, calcareous silicified, lamellibranch casts | | |
| 11 | Shales, variegated, silty and sandy, finely laminated | 9.0 | 92.8 |
| 10 | Sandstone, silty, finely laminated and current bedded | 1.5 | 83.8 |
| 9 | Shales, greyish-brown, micaceous, current bedded | 2.0 | 82.3 |
| 8 | Clay, silty and ferruginous | | |

TABLE 5 (Cont'd)

| UNIT | LITHOLOGY | THICKNESS (m) | HEIGHT ABOVE BASE (m) |
|---|---|---|---|
| 7 | Sandstone, yellowish-white | 4.5 | 62.3 |
| 6 | Shales, yellow, red, silty | 9.0 | 57.8 |
| 5 | Sandstone, yellowish-white | 4.5 | 48.8 |
| 4 | Shales, Siltstones, silty Shales, Shales, yellow and green | 7.5 | 44.3 |
| 3 | Sandstones, silty grading downwards into Siltstones and Shales | 24.5 | 36.8 |
| 2 | Limestone, grey-brown | 0.3 | 112.3 |
| 1 | Shales and thin Sandstones | 12.0 | 12.0 |

(from Joubert, 1960)

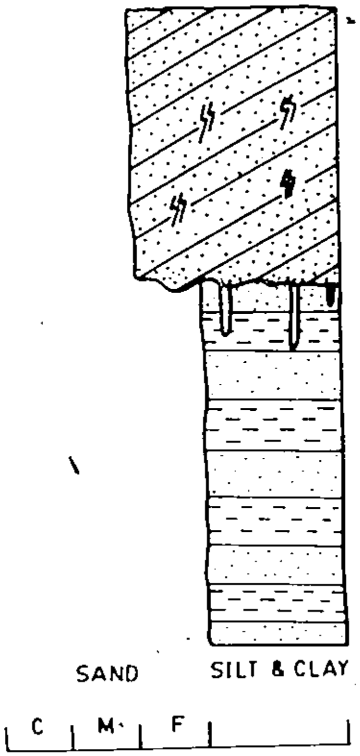
lithological similarity between the Marehan Sandstone and the Jesomma Sandstone of Ethiopia, regarded as Turonian and part Senonian (Barnes, 1976).

In the course of these studies, a number of exposures were examined in detail and definite vertical facies arrangements, previously unrecorded, were recognized. These attributes give insights into the depositional environment of the Marehan Series. The poor quality of the outcrops, as previous work disclosed, was a major limitation on the accurate measurement of exposure thicknesses and continuous sections.

In the southern limits of the Mandera basin, at Ankarass, near the Dimo Water Hole, two facies types of the Danissa Beds are found (Fig. 4). A lower unit consists of a yellowish orange, horizontally bedded siltstone with fine laminations of very pale orange clay, that weathers to kaolin (Plate 1 A). In thin section, the laminae appear to be defined by the presence of iron oxide within a clay matrix, surrounding subangular to sub-rounded poorly sorted quartz grains. The siltstones are homogeneous in composition, comprising well sorted and tightly packed quartz grains. Minor orthoquartzite and heavy-mineral grains are also observed under the microscope. Vertical tubular burrows with an average diameter of 1 cm, occur in the siltstone. The burrows are filled with silt and tend to occur beneath minor erosion surfaces. They probably represent traces of _Ophiomorpha_, escaping inundation attendant upon rapid sedimentation. The upper unit comprises a dark, yellowish orange quartz sandstone, with a low-angle cross-bedding indicating current movement to the south-east. Bulbous load casts and grooves are preserved on the undersurfaces of the sandstones, and display dominantly south-eastward orientations. The unit is cut by a series of clastic dykes (Plate 1 B) oriented in the same direction, toward the south-east. The mineralogical components within the fractures have been analysed by X-ray diffraction, and consist mainly of quartz, feldspar, micas, kaolinite, illite, siderite, calcite, and limonite.

Some isolated boulders found in the general vicinity of the Danissa Beds, below a small hill at Bur Hara, near El Katulo, contain clasts of shale lying flat to the plane of bedding, siltstone pebbles, moulds of brachiopods, and plant stem impressions. Flaggy sandstones occur at the top of the hill, and display bi-directional linear ripples and groove marks (Plate 2 A).

In the northern extremity of the study area, at Kobansu, some 53 km west of Mandera, five distinct facies types showing a bi-directional current pattern, are seen in beds of the Marehan Sandstone (Fig. 5). A lower, yellowish brown, fine- to medium-grained sandstone (Plate 3 A) has laminations defined by the concentrations of red ferric minerals in thin layers. Overlying this basal unit is a light to moderate brown, medium-grained sandstone (Plate 3 B), with large-scale trough cross-stratification. Individual cross-beds are up to 3.0 cm



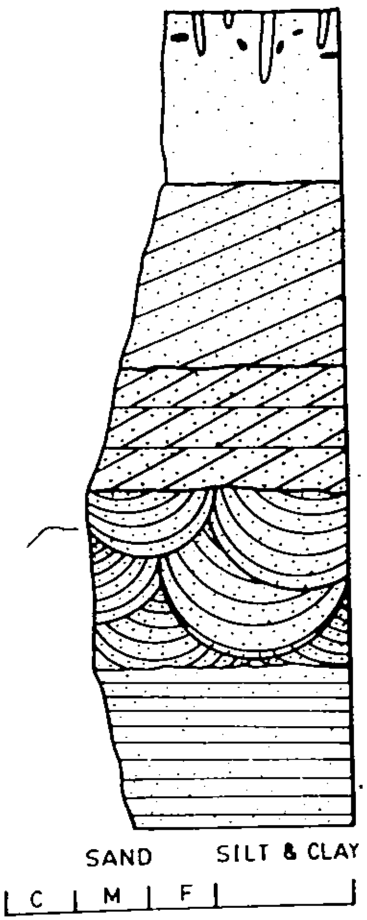
|  | SEDIMENTARY FACIES | PALEOCURRENT DIRECTION | DEPOSITIONAL ENVIRONMENT |
|---|---|---|---|
| DANISSA BEDS | Planar cross-bedded sandstone with load and groove casts, and clastic dykes [1.5m] | SE | Tidal creek ebb deposits (transition phase flow) |
|  | Horizontally bedded siltstone interlaminated with clay, and containing vertical tubular burrows [2.0m] |  | Intertidal flat deposits (<u>Skolithos ichnofacies</u>) |

Fig. 4. Sedimentary facies of the Danissa Beds (Cretaceous) at Ankarass, Dimo Water Hole, north-east Kenya.

Plate 1 A. Laminated intertidal-flat siltstones and clays, lower unit of the Danissa Beds (Cretaceous) at Ankarass, Dimo Water Hole, north-east Kenya.

Plate 1 B. Planar, cross-bedded tidal-creek sandstone, showing south-east trending clastic dykes, upper unit of the Danissa Beds (Cretaceous) at Ankarass, near Dimo Water Hole, north-east Kenya.

Plate 2 A. Flaggy sandstone with linear ripples, load and groove casts, from the Danissa Beds (Cretaceous) at the small hill near Bur Hara, north-east Kenya.



| | SEDIMENTARY FACIES | PALEOCURRENT DIRECTION | DEPOSITIONAL ENVIRONMENT |
|---|---|---|---|
| MAREHAN SANDSTONE | Massive sandstone with burrows and root casts [0.2m] | | Intertidal flat deposits (*Skolithos ichnofacies*) |
| | Large scale planar cross-bedded sandstone [0.75m] | N E | Tidal channel flood deposits (transition phase flow) |
| | Cross-laminated sandstone [0.5m] | | |
| | Large scale trough cross-bedded sandstone [1.5m] | S E | Tidal channel ebb deposits (dune phase flow) |
| | Horizontally laminated sandstone [1.0m] | | Tidal channel accretionary deposits (plane bed phase flow) |

Fig. 5. Sedimentary facies of the Marehan Sandstone (Cretaceous) at Kobansu, near Mandera, north-east Kenya.

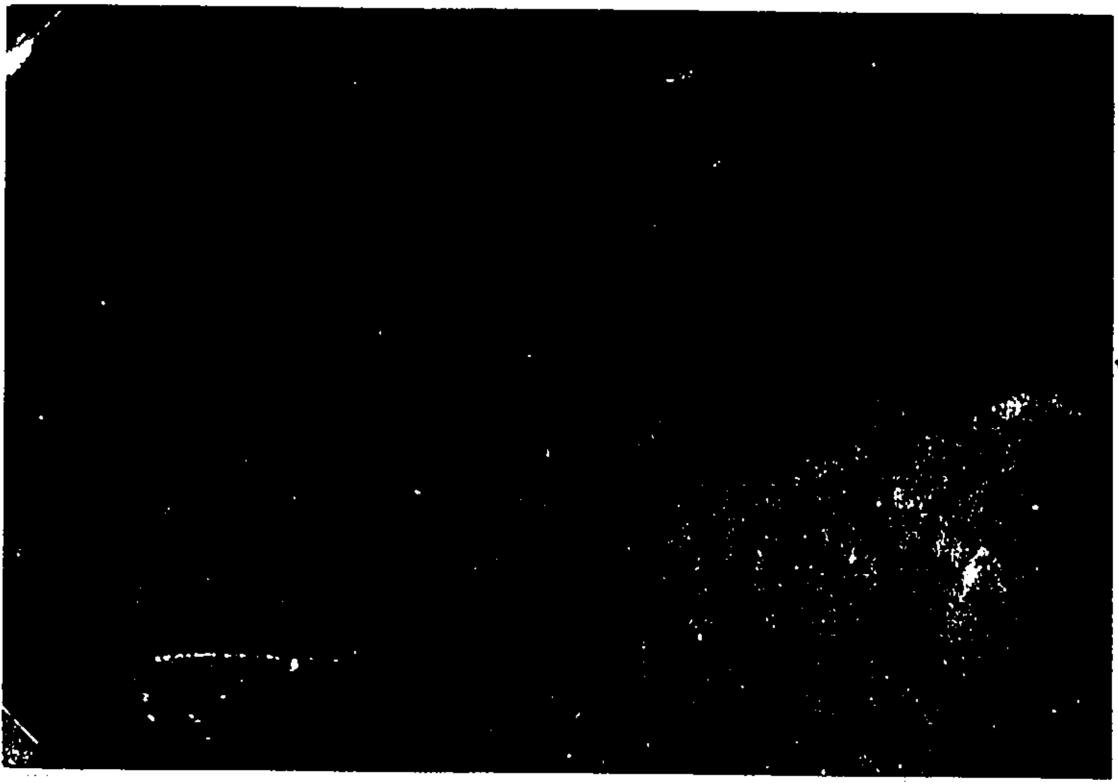


Plate 3 A. Laminations in tidal-channel sandstone, lowermost unit of the Marehan Sandstone (Upper Cretaceous) at Kobansu, near Mandera, north-east Kenya.

Plate 3 B. Large-scale, trough cross-bedding in tidal-channel sandstone, lower unit of the Marehan Sandstone (Upper Cretaceous) at Kobansu near Mandera, north-east Kenya.

thick and dip at 16 degrees in a north-easterly direction. Farther upwards, another unit, with a different scale of cross-stratification, occurs above what appears to be a reactivation surface. This middle sandstone unit is fine- to medium-grained and has low-angle cross-lamination (Plate 3 C), in which individual laminae average 2.5 cm in thickness and dip gently to the south-east. The sandstone overlying this unit is finer-grained and exhibits large-scale, planar cross-bedding (Plate 3 D). The cross-beds have an average thickness of 4.0 cm and dip south-eastward. The uppermost sandstone is a yellowish grey, fine-grained and structureless sandstone with tubular burrows and root casts (Plate 3 E). The root casts are formed of fine-grained, detrital hematite.

At another outcrop of the Marehan Sandstone, farther east of Kobansu at Gududiyu, some 29 km west of Mandera, three facies types are distinguishable (Fig. 6). The first unit is a reddish brown, fine- to medium-grained, horizontally bedded sandstone with branching burrow systems, high-energy undulatory ripples and plant debris (Plate 4 A). Two different populations of burrows are evident within the branching networks seen on sandstone soles (Plate 4 B). One type has a pustulated and sinuous form with diameters in the range of 0.7 to 3.5 cm and detrital hematite infilling. Smaller forms are filled with reddish brown sand, measuring 0.5 to 0.7 mm in diameter, and are superposed on the larger burrows. The succeeding unit is a light brown sandstone, exhibiting an upward decrease in grain size and

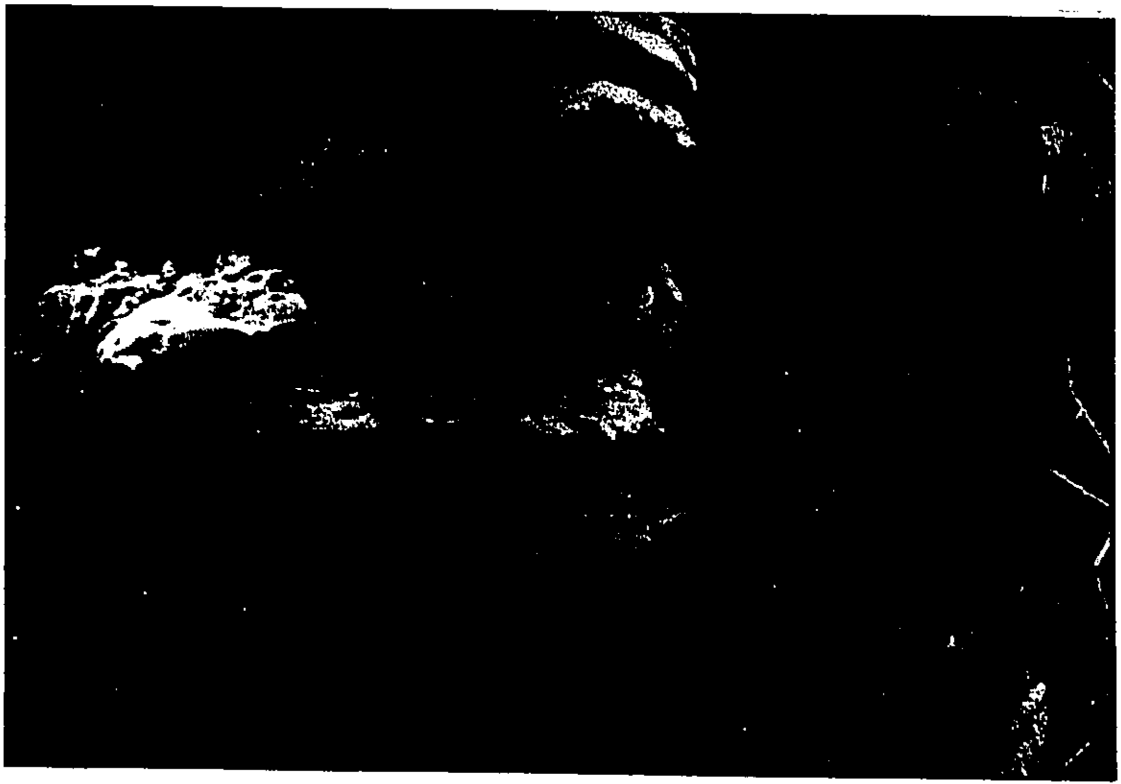
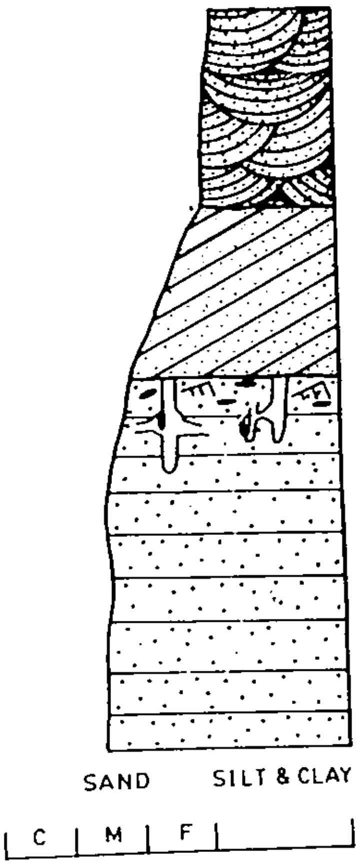


Plate 3 C. Cross-laminations in tidal-channel sandstone, showing reactivation surface, middle unit of the Marehan Sandstone (Cretaceous) at Kobansu, near Mandera, north-east Kenya.

Plate 3 D. Large-scale planar cross-bedding in sandstone, upper unit of the Marehan Sandstone (Cretaceous) at Kobansu, near Mandera, north-east Kenya.

Plate 3 E. Massive intertidal-flat sandstone showing root casts formed of detrital haematite, uppermost unit of the Marehan Sandstone (Cretaceous) at Kobansu, near Mandera, north-east Kenya.



|  | SEDIMENTARY FACIES | PALEOCURRENT DIRECTION |  | DEPOSITIONAL ENVIRONMENT |
|---|---|---|---|---|
| SANDSTONE | Large-scale trough cross-bedded sandstone [2.0m] | S E | strength↑ | Tidal channel ebb deposits (dune phase flow) |
|  | Planar cross-bedded sandstone [6.0m] | S E | flow | Tidal channel ebb deposits (transition phase flow) |
| MAREHAN | Evenly horizontally bedded sandstone with undulatory ripples, burrows and plant fragments [7.0m] | S E | decreasing | Tidal channel ebb accretionary deposits (plane-bed phase flow) |

Fig. 6. Sedimentary facies of the Marehan Sandstone (Cretaceous) at Gududiyu, near Mandera, north-east Kenya.

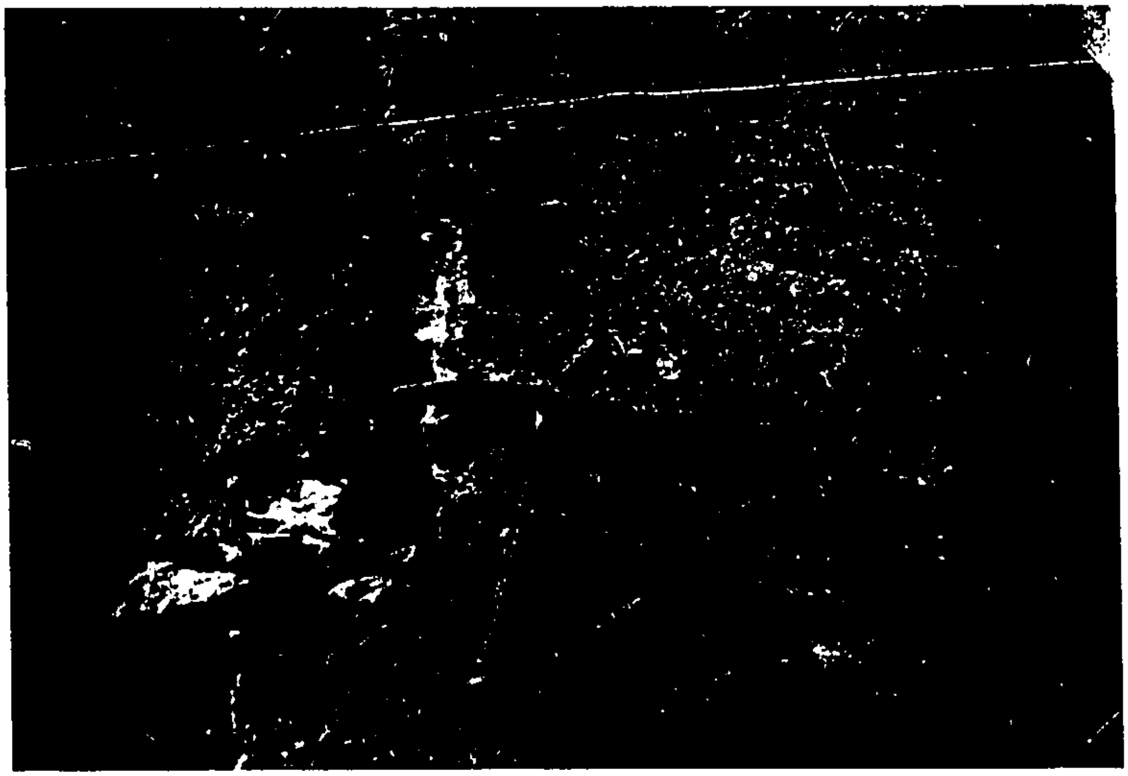


Plate 4 A. Even bedding in tidal-channel accretionary sandstone, showing high-energy undulatory ripples and plant debris, lower unit of the Marehan Sandstone at Gududiyu, near Mandera, north-east Kenya.

Plate 4 B. Burrow system in the lower unit of the Marehan Sandstones (Cretaceous) at Gududiyu, near Mandera, north-east Kenya.

high-angle, planar cross-bedding. The cross-strata are bounded above and below by parallel surfaces (Plate 4 C). Individual cross-beds are 4 to 5 m thick, curve towards the upper bounding surface, and dip north-eastwards. The top unit is a light brown and pale yellowish orange, very fine-grained sandstone, with north-east- dipping trough cross-bedding (Plate 4 D). A relationship between the dip of cross-strata, current ripple direction and preferred orientation of the plant debris is obvious, indicating a dominant southeastward paleocurrent trend.

The general lithology and texture of the Danissa Beds, invites comparison with the Aptian lithofacies found in the B.P. Shell Walu No. 2 and B.P. Shell Walmerer No. 1 wells. Of particular interest is the occurrence of a limestone band in the Danissa Beds (unit 6, Table 4 and unit 2, Table 5), and the limestone intervals at the base and top of the Albian of the Texas Hagarso No. 1 and B.P. Shell Walmerer No. 1 wells respectively. Eastwards, 35 m of limestone, referable to the Belet Uen Formation (Barnes, 1976) in southern Somalia, is Cenomanian in age and underlies 110 m of alternating shale and sandstone. It is quite apparent that the limestone becomes thinner and gradually younger northward and eastward, and may be related to the Albian transgression.

At its type locality, the Belet Uen Formation grades upwards into the Jesomma Sandstone, where the latter is predominantly carbonate and contains abundant molluscs and echinoids. However in the type section located a few kilometres east of Belet Uen

Plate 4 C. Large-scale planar cross-bedding in tidal-channel sandstone showing the parallel upper and lower bounding of sets, middle unit of the Marehan Sandstone (Cretaceous) at Gududiyu, near Mandera, north-east Kenya.

Plate 4 D. Large-scale trough cross-bedding in tidal-channel sandstone, showing inclined strata and lower bounding surface, upper unit of the Marehan Sandstone (Cretaceous) at Gududiyu, near Mandera, north-east Kenya.

and north of Mogadishu, the sandstone outcrops as 350 to 400 m of red-brown unfossiliferous, poorly consolidated quartzitic and cross-bedded facies, lithologically similar to the Marehan Sandstone. Its age is considered Upper Turonian and part Senonian. Fig. 7 shows a north-south structural cross-section through the Marehan Series and Danissa Beds and the Albian to Coniacian sections of the Texas Hagarso No. 1 and B.P. Shell Walu No. 2 wells of south-east Kenya. On the basis of this correlation and existing fossil evidence, the Danissa Beds are considered here to be Aptian to Cenomanian in age and the Marehan Sandstone Turonian to Coniacian. A substantial thickness of the Marehan Sandstone must have been eroded during the end-Cretaceous tectonic episode.

## Tertiary Stratigraphy

The Tertiary sequence is widely distributed in the Lamu basin and strata of different ages rest unconformably on the Late Cretaceous erosion surface. Tertiary rocks exposed in the south-east include the Baratumu Formation, Fundi Isa Limestone, and Kipevu Beds (Lower Miocene); the Marafa Beds and Midadoni Beds (Upper Miocene) and the North Mombasa Crag (Upper Miocene to Lower Pliocene). Near-surface Upper Pliocene strata are represented in the south-east by the Lower Maqarini Sands. The north-east is essentially without a complete Tertiary sequence, except for the Merti Beds that outcrop near Garba Tula, in the western part of the area.

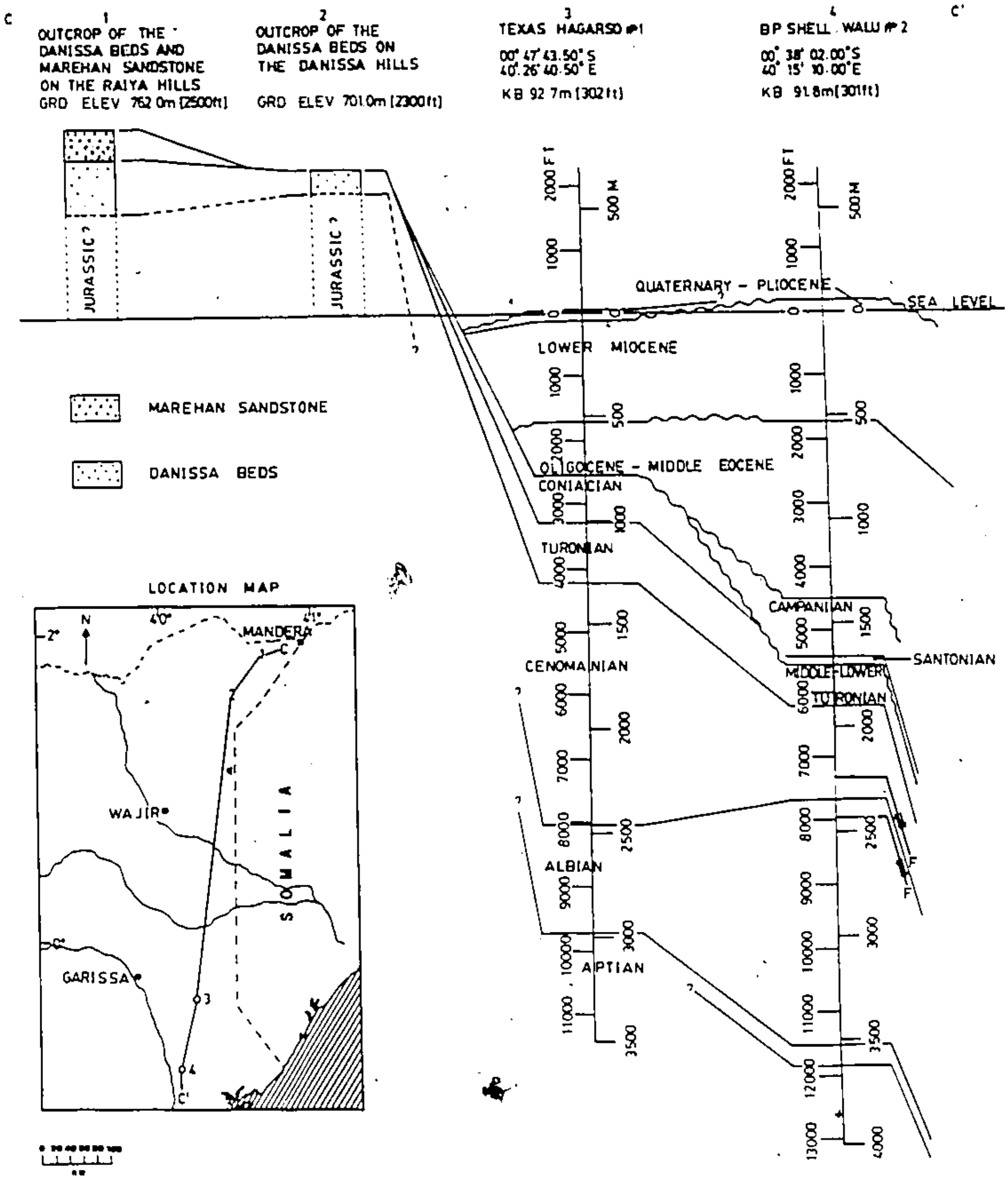


Fig. 7. Structural cross-section through the Marehan Series (Aptian to Coniacian), north-east Kenya.

## Paleogene Strata of South-East Kenya

Paleocene rocks in the south-eastern coastal region are known from the B.P. Shell Dodori No. 1 and B.P. Shell Pate No. 1 wells. Elsewhere and farther inland, Middle Eocene rocks rest unconformably on eroded Upper Cretaceous strata. This is consistent with the increase in magnitude of the hiatus associated with the Cretaceous-Tertiary unconformity toward the north. The B.P. Shell Dodori No. 1 well contains the most nearly complete succession of Paleocene strata, comprising light grey to yellowish grey micaceous sandstones, and carbonaceous siltstones and shales that are laminated near the base. The sandstones are mainly fine-grained, slightly calcareous and patchily bituminous. A sandstone bed occurring some 390 m from the base of the section, contains dark red ferruginous streaks representing a period of probable sub-aerial exposure and oxidization. Carbonaceous material is interspersed throughout, except in the uppermost section where it forms irregularly spaced bedding that projects upward into the overlying sandstone as flame structures. Previous determinations of the thickness assigned at least 1200 m of Paleocene strata to the B.P. Shell Dodori No. 1 well (Eames, 1964). It would appear that limestones of the Lower Eocene and some bituminous sandstones assigned to the Upper Cretaceous, were included in this measured sequence. This distinction based on lithology is made in the present account. The presence of Cibicidoides pseudoacutus at the base is attributed to reworking of Maastrichtian strata. Upper

Cretaceous strata are unlikely to be present, in view of the absence of the Maastrichtian section from the DSDP No. 241 well and the lack of the entire Upper Cretaceous succession in the Sinclair No. 1 Brava and Sinclair No. 1 Oddo Alimo wells of coastal Somalia, as well as the general trend of the end-Cretaceous erosion. The thickness determined here is 879 m but this does not necessarily include the entire Paleocene which may still occur at depth. The 295 m interval comprising fine-grained sandstones, argillaceous siltstones, carbonaceous shales and dark grey mudstones in the B.P. Shell Pate No. 1 well, previously included in the Lower Eocene part of the succession, are regarded here to constitute the Upper Paleocene sequence. The abrupt lithologic change from the Paleocene sandstone beds to the Eocene limestones is quite distinct in the gamma-ray logs. The Paleocene strata extend into Tanzania, where the mudstones and siltstones measure 217 m on Pemba Island (Kent and Perry, 1973). The continuation into south-western Somalia denotes a lateral north-eastward thickening and an increase in coarse- to fine-clastic ratio. The Lach Dera well penetrated over 2000 m of coarse-grained quartzose sandstones, interbedded with micaceous and carbonaceous shales and mudstones, belonging to the Lach Dera Formation (Beltrandi and Pyre, 1973). The sequence reaches a maximum thickness of 2134 m, near the Bur Acaba uplift in the Lach Bissigh well. In the Sinclair No. 1 Merca well, further north along the coast of Somalia, the sandstones show another decrease in grain size and the thickness increases to 960 m. The sandstones are tar-stained, similar to those in the B.P. Shell Dodori No. 1 well. In the extreme north, the lithology goes through a transition from a medium-depth facies in the Sinclair No. 1 Marai Ascia well, to deep-water, foraminifer-bearing shales of the Sagaleh Formation, and back to a shallow-water facies outcropping in the Nogal Valley as the Auradu Limestone. The foraminifer-bearing shale contains *Globorotalia Velascoensis*, *Globorotalia Crasea* and *Anomalina Granosa*. *Sakesaria*, *Lockhartia tipperi*, *Nummulites Somaliensis* and *Daviesina danieli* are present in the Auradu Limestone (Barnes, 1976). The rocks thus appear to be equivalent to both the Paleocene and Lower Eocene strata of east Kenya.

The Lower Eocene succession comprises a transgressive sequence of sediments that onlap on to the Paleocene terrigeneous clastics. They are present along a narrow tract on the south-eastern part of the coast, beneath 2864 m in the B.P. Shell Dodori No. 1 well and 3135 m in the B.P. Shell Pate No. 1 well. Towards the south-west, in the B.P. Shell Kipini No. 1 well and the deep boring on Pemba Island, Middle Eocene rocks rest on Cretaceous and Paleocene strata respectively. The deposits may be differentiated into two distinct shelf-carbonate facies best depicted in the B.P. Shell Dodori No. 1 well (Fig. 8). The lowest limestone of the sequence is a 380 m thick light grey algal stromatolite. This unit is however not discerned in the

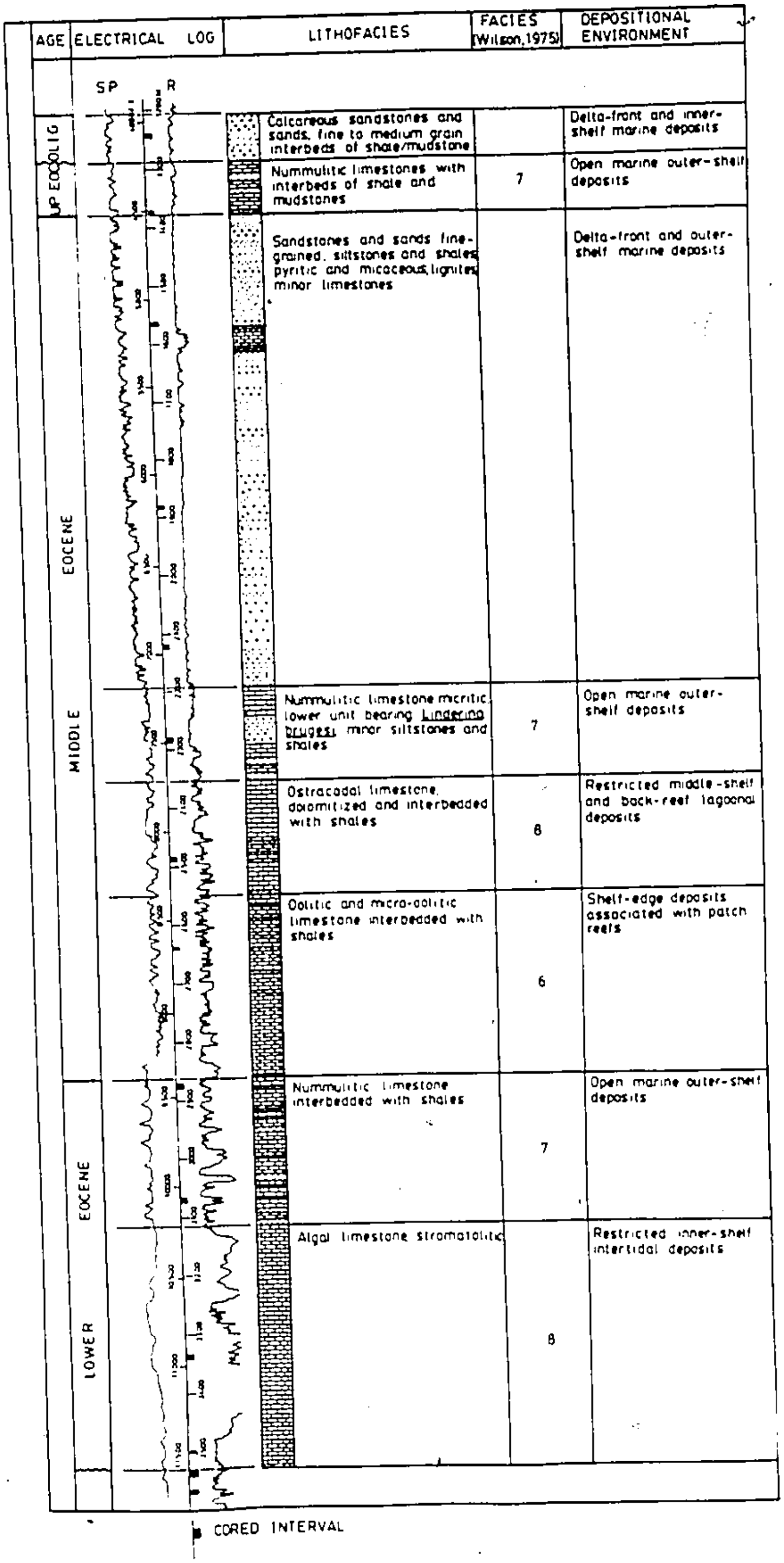


Fig. 8. Sedimentary facies of Lower Eocene-Oligocene strata in the B.P. Shell Dodori No. 1 well, south-east Kenya.

B.P. Shell Pate No. 1 well. The succeeding strata comprise alternating cycles of medium grey, nummulitic limestones and dark grey to greenish grey shales, that span the entire overlying interval of the Lower Eocene. This section measures 260 m in the B.P. Shell Dodori No. 1 and 757 m in the B.P. Shell Pate No. 1 well. The shales are vested with features that indicate a terrestrial derivation and deposition between periods of carbonate build-up. An Early Eocene age for this sequence is substantiated by the presence of Cavillierina vanbelleni, Nummulites globulus, Nummulites pernotus and Alveolina oblonga. These nummulitic limestones are common along much of the East African coast (Kent, 1982).

Carbonate deposition continued into early Middle Eocene time, a time of episodic tectonic movements and concomitant sea level fluctuations, along the south-eastern margin. The lowest unit of the sequence is a light grey, oolitic limstone with a generally uniform thickness of 300 m between the B.P. Shell Dodori No. 1 and B.P. Shell Pate No. 1 wells. Previous correlations have included the oolitic limestone in the B.P. Shell Dodori No. 1 well in the upper part of the Lower Eocene, resulting in a large discrepancy in the relative thicknesses of Lower Eocene strata between the two wells. The adjustment of the Lower Eocene-Middle Eocene boundary in the B.P. Shell Dodori No. 1 well to 2832 m below sea level is consistent with the biostratigraphy and lithology found in the B.P. Shell Pate No. 1 well. The oolitic limestone represents the final imprint of the transgression that began during the Early Eocene.

Overlying the oolitic limestone is a dolomitized limestone with shale interbeds and a fauna including ostracods and miliolids. The occurrence of this restricted facies coincides with a decrease in salinity evidenced by the presence of a low-salinity fauna in this part of the Middle Eocene succession. The oolitic and ostracodal limestones are not encountered in either the B.P. Shell Mararani No. 1 and B.P. Shell Kipini No. 1 wells, and it is conceivable that the two areas had started to emerge in early Middle Eocene time. Dolomite associated with anhydrite occurs at two intervals near the base of the sequence penetrated in each case. Another relatively brief rise in sea level was recorded in the deposition of a richly fossiliferous limestone unit, regarded as an excellent seismic marker (Patrut, 1977). The limestone contains the Middle Eocene species Linderina brugesi and thins landward from 63 m in the B.P. Shell Pate No. 1 well to about 27 m in the B.P. Shell Dodori No. 1 well. In the B.P. Shell Mararani No. 1 well it is extremely thin, whereas it is absent in the B.P. Shell Kipini No. 1 well. The progradation of an assortment of clastics over the Linderina-bearing limestone in the B.P. Shell Dodori No. 1 and B.P. Shell Pate No. 1 wells reflects renewed emergence in the west and north-west. The sediments are fining-upward, calcareous sandstones, sands, carbonaceous siltstones, greenish grey cross-laminated shales and lignites. These are in turn overlain by nummulitic limestones, olive-brown shales and mudstones, indicating another cycle of tectonic movements during the Late Eocene. The lower part of the sequence is made up of terrigenous clastics that decrease in coarse clastic content and thickness eastwards toward the B.P. Shell Mararani No. 1 well. Mudstones are more dominant in the B.P. Shell Mararani No. 1 well.

The upper limit of Eocene deposition is placed above the last occurrence of non-reworked forms of Nummulites hormoensis and Nummulites fabiani. The boundary is an unconformity separating the lower sequence of limestones and shales from the poorly indurated fine- to medium-grained calcareous sandstones, siltstones, shales and mudstones of Oligocene age. Chattian rocks of the Upper Oligocene are absent in the B.P. Shell Mararani No. 1 well.

### Paleogene Strata of the North-East

In the hinterland, a thick wedge of continentally derived clastics constitutes the terrestrial equivalent of the marine and marginal marine succession of the extreme south-east. These undifferentiated sediments have been termed the Barren Beds and rest on the eroded surface of the Upper Cretaceous rocks. In the B.P. Shell Walmerer No. 1 well the base of the Middle Eocene is located above the limestone horizon at the top of the Albian succession. A basal, ferrugenous conglomerate is recognized at this boundary in both the B.P. Shell Walmerer No. 1 and the B.P. Shell Garissa No. 1 wells. In the Texas Hagarso No. 1 well, the boundary is defined by an abrupt lithologic transition from

Coniacian shales to a coarse-grained sandstone referable to the overlying Barren Beds. A similar change, expressed by the spontaneous potential log response is observed in the B.P. Shell Walu No. 2 well. These sandstones occur as distinct packages of cyclical fining-upward fluvial assemblages (Fig. 9) typical of point-bar deposits. Cores from the B.P. Shell Walu No. 2 well (937.7 and 937.8 m, and 1452.7 and 1454 m) show the sandstones as chiefly consisting of poorly sorted and poorly indurated quartz sands that are calcite- cemented at various stratigraphic levels. This is attributed to intermittent marine flushing associated with the sea level fluctuations manifested at the coast. The whole series thins in the Texas Hagarso No. 1 well and expands into a broad fan south-westward, southward and south-eastward. An intertonguing relationship between the onshore and the coastal series is inferred. The amount of coarse clastics decreases in a largely south-eastward direction.

## Neogene Strata of South-East Kenya

Lower Miocene rocks are exposed at various sites east of the coastal Mesozoic outcrops. Thompson (1956) introduced the name Baratumu Beds for yellowish foraminiferal limestones from near Lake Baratumu in the Goshi area. Williams (1962) regarded the Fundi Isa Limestone as the lateral equivalents of the Baratumu Formation. These latter limestones are found restricted to small gullies on the Hadu-Marafa and Hadu-Fundi Isa roads. A

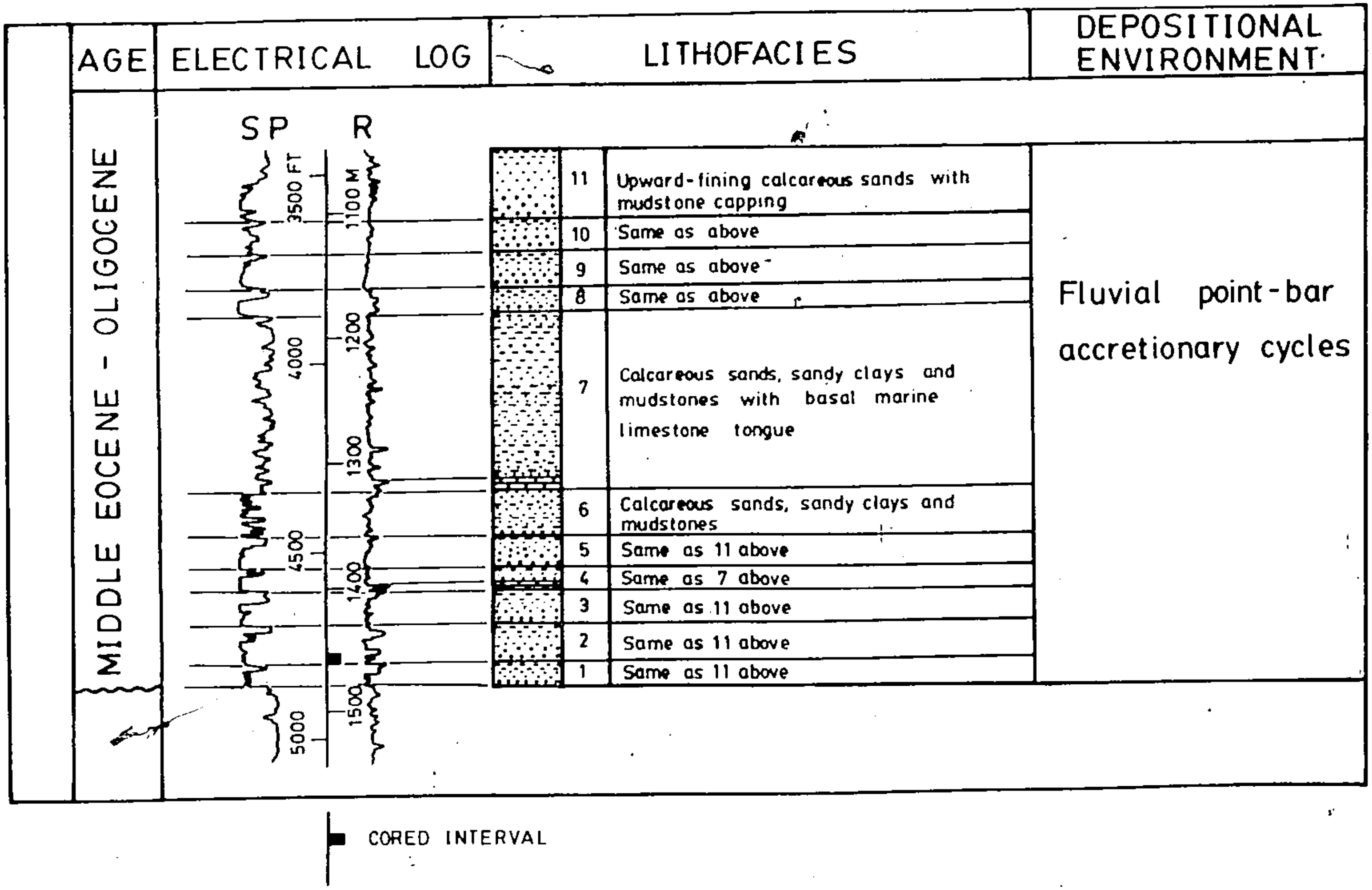


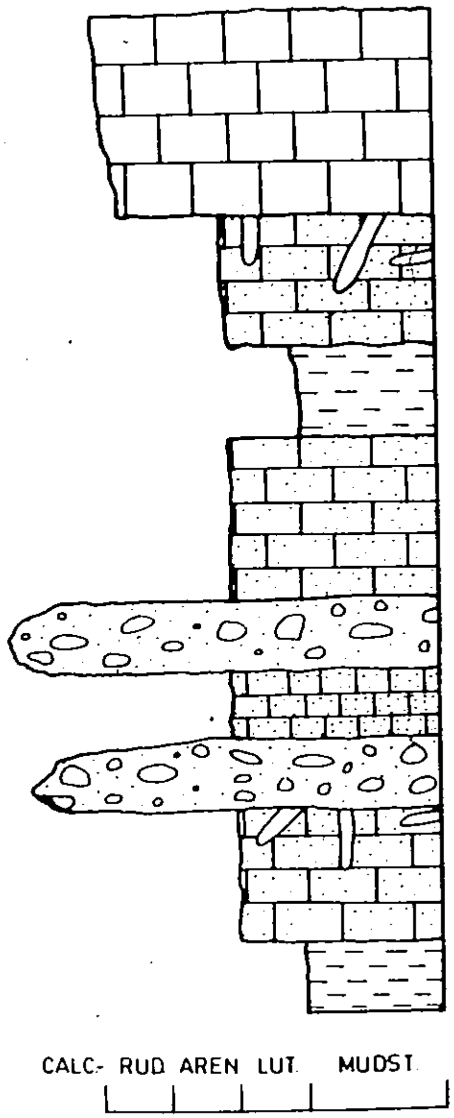
Fig. 9. Sedimentary facies of Middle Eocene-Oligocene strata in the B.P. Shell Walu No. 2 well, south-east Kenya.

comprehensive list and review of the fauna, collected from these rocks, is provided by the two authors in two separate reports on the Geology of the Malindi and Hadu-Fundi Isa areas. An Aquitanian to Burdigalian age was suggested by Eames and Kent (1955), who identified the foraminifer species, *Operculina venosa*, *Lepidocyclina gallienii*, *Lepidocyclina sumatrensis*, *Taberina malabrica* and *Miogyspinia sp.*

A typical exposure of the Baratumu Beds on the northern slopes of Gaji Hill was found to comprise, in ascending order: a light grey to dirty white marl, containing echinoid spines; calcareous nodules and lenticles of yellow sand with *Opercunlina sp.*, a yellowish foraminiferous marl containing *Miogyspina sp.*; a white nodular marly limestone with gastropods; a grey clay and a basal conglomerate, containing forminifer, gasteropods and pebbles derived from Archean, Karoo and Jurassic rocks. The aggregate thickness of the sequence was found to be 15 m, though Thompson (1956) postulated the possibility of at least 500 m being present in outcrop. Linton and MacLean (1955) considered this as somewhat of an overestimate. Interpretations of their depositional setting have been general and varied. Most authors are in agreement on a shallow-water, marine environment of deposition.

The Baratumu Beds acquired formational status through the work of Linton and MacLean (1955), who conducted a detailed survey and shallow drilling programme in the Gaji, Goshi, Mavwene, Makwenga and Fumbene areas of Kilifi and Malindi district. They distinguished eight lithologic divisions at one of the better exposures on the northern banks of a creek, at Bandara ya Wali Bay near Kilifi. In the present study, the outcrop was re-examined in greater detail, especially wiith reference to those features that define facies and elucidate their environment of deposition. The formation consists of the following repetitive beds (Fig. 10): a 0.3 m thick grey-green calcareous mudstone with specks of very pale green glauconite; a pale yellowish orange calcilutite with vertical, sub-vertical and horizontal burrows (Plate 5 A); two extraformational conglomerate beds (Plate 5 B), separated by a non-burrowed calcilutite; and a third calcilutite unit with highly comminuted fossil debris (Plate 5 C), terminating the first cycle. The second cycle begins with a calcareous mudstone, followed upward by a micritized calcilutite, which is in turn overlain by a greyish yellow, evenly bedded, fossiliferous limestone (Plate 5 D). Shell fragments have a higher concentration at lower levels in this unit, but show no preferred orientation. The nature of the sediments indicates that fossils do not constitute the binding agent, but are embedded in the calcareous matrix. The micritic matrix lacks lamination, partly owing to homogenization by burrowing. Geopetal structures are apparent in thin section, and may be related to an association between reefal debris and moderate wave-energy conditions. Individual strata within the unit have a thickness of 14 cm.

The trace-fossil record, hitherto unrecrognized occurs as



| | SEDIMENTARY FACIES | | DEPOSITIONAL ENVIRONMENT |
|---|---|---|---|
| BARATUMU FORMATION | Evenly horizontally bedded fossiliferous limestone [3·0m] | rhythmic shoaling sequence ↑ | Low energy subtidal (<u>Cruziana ichnofacies</u>) |
| | Calcilutite with burrows [0·4m] | | |
| | Calcareous mudstone [0·3m] | | Intertidal |
| | Calcilutite with highly comminuted fossil debris [7·5m] | | High energy subtidal |
| | Extraformational conglomerate with intervening band of calcilutite [1·0 & 1·5m] | | |
| | Calcilutite with burrows [0·5m] | | |
| | Calcareous mudstone [0·3m] | | Intertidal |

Fig. 10. Sedimentary facies of the Baratumu Formation, (Lower Miocene) at Kilifi Creek, south-east Kenya.

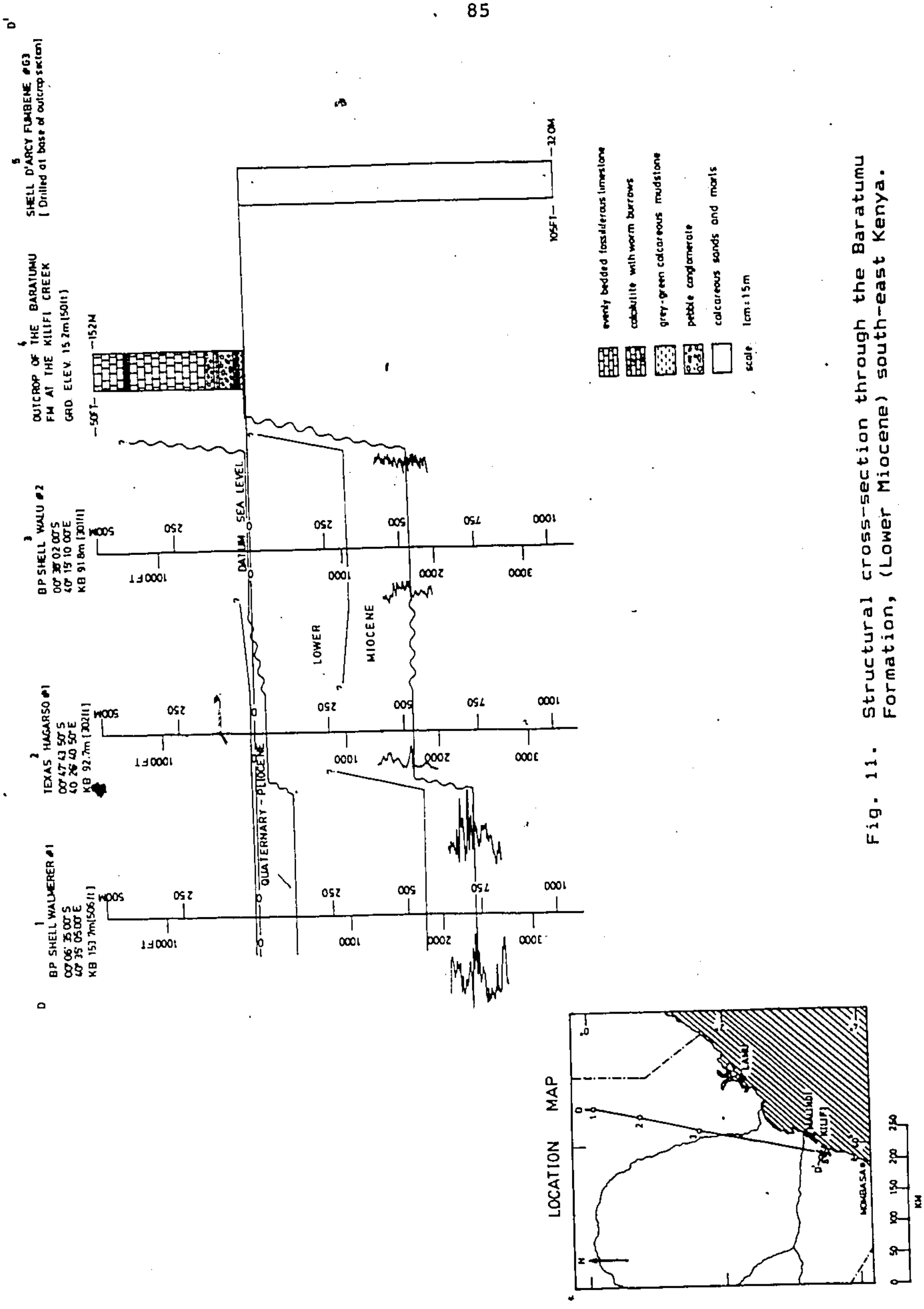


Fig. 11. Structural cross-section through the Baratumu Formation, (Lower Miocene) south-east Kenya.

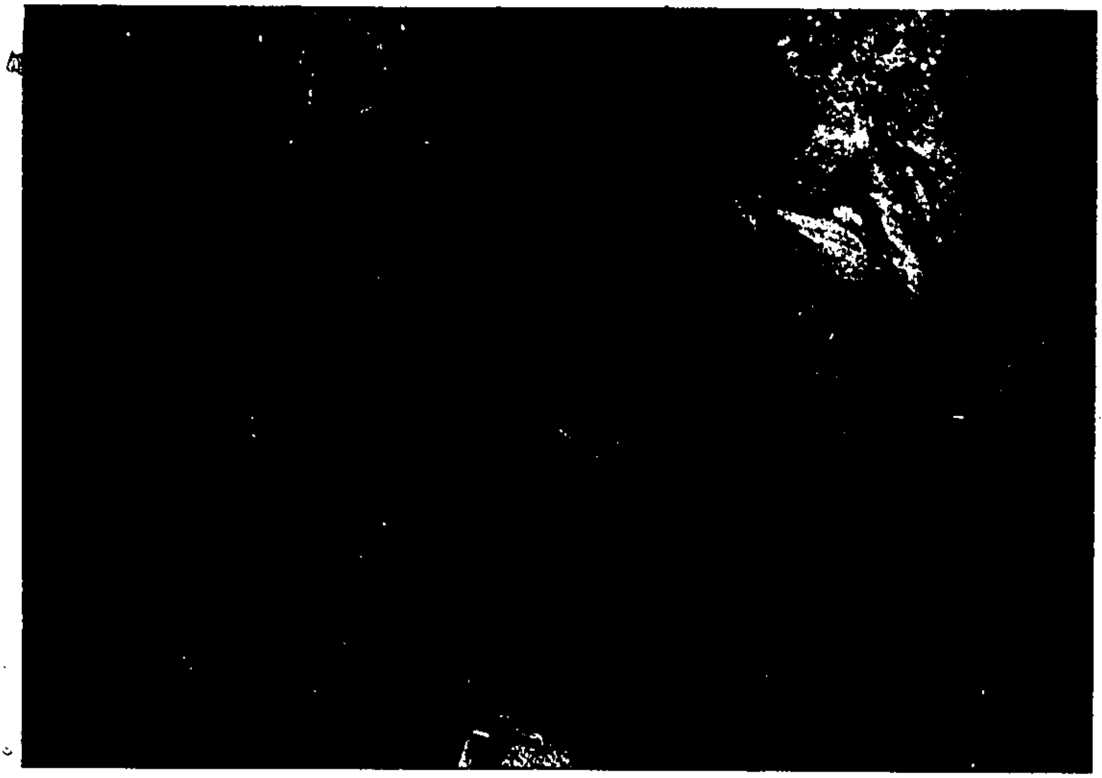


Plate 5 A. Calcilutite bed showing <u>Callianassa</u> burrow, lower unit of the Baratumu Formation (Lower Miocene) at Kilifi Creek, south-east Kenya.

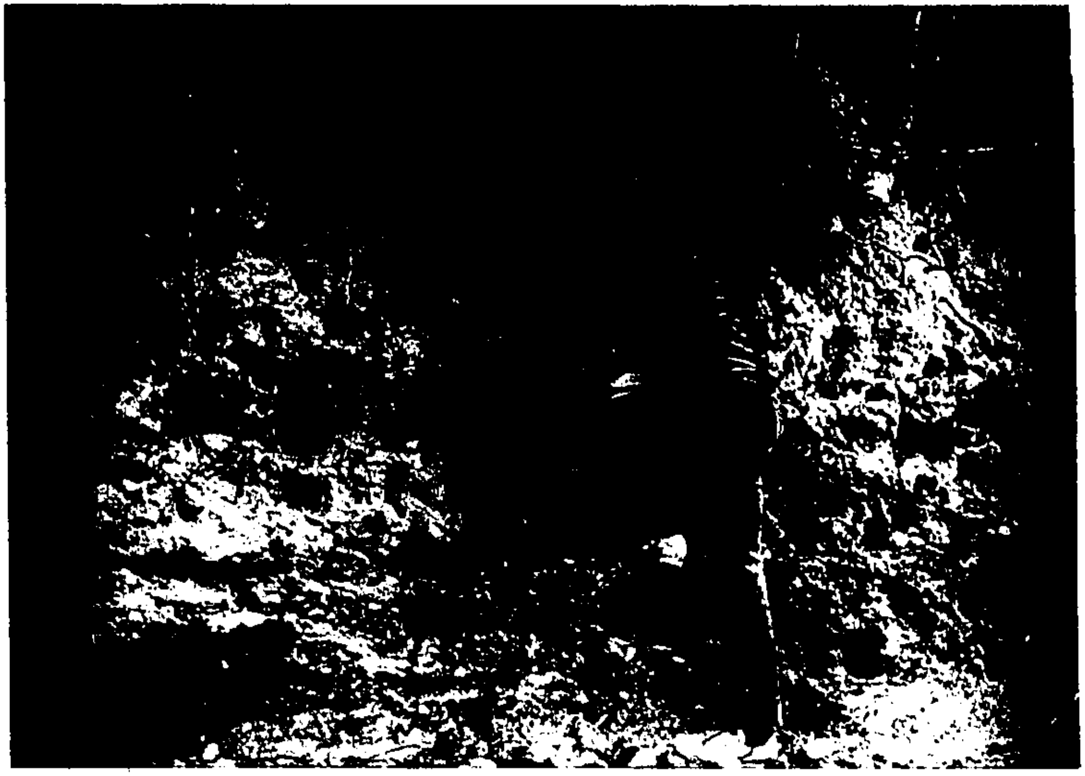


Plate 5 B. Syntectonic, extraformational conglomerate in the Baratumu Formation (Lower Miocene) at Kilifi Creek, south-east Kenya.

Plate 5 C. Calcilutite with highly comminuted fossil debris, Baratumu Formation (Lower Miocene) at Kilifi Creek, south-east Kenya.

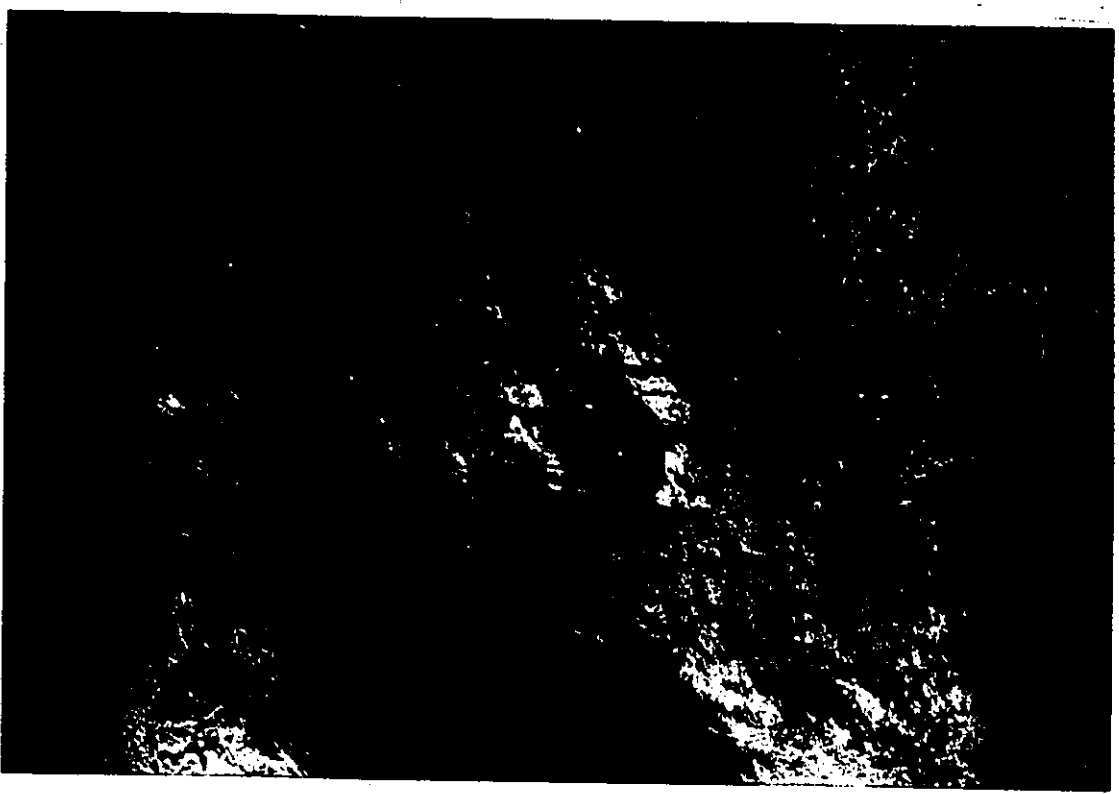


Plate 5 D. Evenly and horizontally bedded fossiliferous limestone, upper unit of the Baratumu Formation (Lower Miocene), south-east Kenya.

burrows that vary in diameter from 1.0-2.5 cm. The infilling material is calcareous and resembles that of the enclosing unit. In the lowermost calcilulite, waves have eroded the sediment from around the burrows rendering their three-dimensional form clearly visible. The pustulated surface probably originated from burrowing over original traces, a development best observed in thin section. The secondary tubes are much larger, and incorporate skeletal fragments. The primary and smaller tubes exibit characteristics that are diagnostic of the burrowing action of the crustacean Callianassa. A cylinder of muddy sediment forms the outer surface and enclose silt-sized particles of quartz.

The conglomerate beds are matrix-supported and polymictic. Clasts have sizes that range from a minimum of 2.0 cm to a maximum of 30 cm. The large clasts are highly angular and comprise sandstones, siltstones and shales, typical of the lithologies observed in the nearby occurrences of Mesozoic sediments. The concretionary boulders and fossil wood fragments within the conglomerate are characteristic of the Triassic Mazeras Formation. Prolate and oblate fragments have a preferred alignment parallel to the bedding plane. Many of these have been derived from within the formation itself. The upper conglomerate extends laterally for 200 m and is thus a localized occurrence.

Linton and MacLean (1955) regard these units as breccia-conglomerates related to movements along the faulted boundary between the Mesozoic and Miocene rocks. Their re-occurrence below the surface was not proven by the Fumbene G3 well, drilled at the base of this exposure, nor by the wells Goshi G1 and G2 and Gaji G1, located close to their respective outcrops, in the nearby area. These wells penetrated calcite-cemented quartz sands, clays and marls, containing abundant reworked fossil debris including microfauna. The conglomerate horizons at all three exposures have similar features and the presence of re-deposited _Operculinella_ _sp._, _Miogyspina_ _sp._, echinoids, bryozoans and oysters, provide evidence of an intraformational origin. A conglomerate 1 m thick akin to those exposed in outcrop occurs at 535 m below sea level in the B.P. Shell Walu No. 2 well. The basal unit of the Aquitanian-Burdigalian sequence, below the conglomerate in the well is a grey-green mudstone. A similar basal unit, characterized by a positive gamma ray peak, is recognized in the Texas Hagarso No. 1 and B.P. Shell Walmerer No. 1 wells at 529 m and 725 m below sea level respectively, and forms the basis for the correlation in Fig. 11. The conglomerate is not observed in the Texas Hagarso No. 1 well, whereas in the B.P. Shell Walmerer No. 1 well it occurs at 596 m below sea level. It is, however, completely intraformational in origin. The overlying strata in all the wells comprise a rhythmic sequence of limestones, calcilutites and mudstones, a facies comparable in lithology to that of the Baratumu Formation. The fossil content further corroborates the correlation and includes the low-salinity fauna _Elphidium_ _Craticulum_, _Streblus_ _sp._, _Spiroclypeus_ _ranjanae_, *Taberina malabrica*, *Flosculinella botangenis*, *Lepidocyclina sp.*, *Opercullinella sp.* and *Miogyspinoides dehaarti*. The Burdigalian section in the B.P. Shell Walu No. 2 well contains prominent thin beds of bryozoan reefs, and a dolomite horizon 15 m thick. A dolomite bed of similar thickness also occurs in the Burdigalian of the B.P. Shell Garissa No. 1 well. Several dolomite beds occur in the undifferentiated Lower Miocene interval of the B.P. Shell Kipini No. 1 well. It is likely that the lowest of these which has a thickness of 37 m is continuous with the unit encountered in the B.P. Shell Walu No. 2 and B.P. Shell Garissa No. 1 wells. In the other wells, dolomitization is only patchy and associated with anhydrite. Evaporite minerals filling moldic porosity or occurring as stringers in the Lower Miocene limestones are typical of the Texas Hagarso No. 1, B.P. Shell Mararani No. 1, B.P. Shell Dodori No. 1, and B.P. Shell Pate No. 1 wells. Some pyrobitumen occurs within small vugs in the Texas Hagarso No. 1 well (396 and 485 m). The secondary mineralization pattern thus appears to be an offshoot of the interaction between depositional environment and structure. The latter group of wells contain the thickest Lower Miocene deposits: 926 m in the B.P. Shell Dodori No. 1 well, 981 m in the B.P. Shell Mararani No. 1 well, and 440 m in the Texas Hagarso No. 1 well, compared to 582 m in the B.P. Shell Kipini No. 1 well, 828 m in the B.P. Shell Walu No. 2 well, 606 m in the B.P. Shell Walmerer No. 1 well, 529 m in the B.P. Shell Meri No. 1 well, and 412 m in the B.P. Shell Garissa No. 1 well. In the

B.P. Shell Pate No. 1 well the thickness is anomalously low, measuring only 352 m.

Mudstones are more common than carbonates along the northern margin of the basin by comparison with the deeper section in the south-east. Westward along the Somali coast, strata equivalent to the Somali Formation, are associated with greater amounts of evaporites, which are 457 m thick in the Sinclair No. 1 Merca well and cover the time range between the Upper Oligocene and Upper Miocene (Barnes, 1976). The formation increases in thickness from 900 m in the Sinclair No. 1 Oddo Alimo and Sinclair No. 1 Brava well, to some 1360 m in the Sinclair No. 1 Merca well. Noteworthy is the occurrence of Oligocene carbonates, resting unconformably on the Lower Cretaceous strata in the Sinclair No. 1 Brava well.

Tectonic and depositional affinities may also be drawn from southern Tanzania, where a conglomerate of Oligocene limestone clasts embedded in Middle Miocene deposits occurs at Lindi Bay (Kent, 1974). The Pugu Series near Dar-es-Salaam includes a Middle and Lower Miocene facies of mixed clastics and carbonates, that grade into marine quartz sands of Upper Oligocene age below the surface in the Agip Kisarawe No. 1 well. The Miocene rocks rest unconformably on Upper Mesozoic strata.

/The foregoing local and regional correlations furnish evidence that the calcareous quartz sands encountered in the Gaji, Goshi, Mavwene, Makwenga and Fumbene wells are uppermost Oligocene and not Lower Miocene in age, as considered by Linton and MacLean (1955). Also open to doubt is the Middle Miocene date suggested for the Kipevu Beds by Walters and Linton (1973), on the basis of a single occurrence of Austrotrillina howchini. The type section is exposed at Kipevu Creek, near the Port Reitz harbour in Mombasa, where they rest on upper Mesozoic sediments. The facies and their vertical arrangement are identical to those of the Baratumu Formation except for the conglomerate, which is entirely intraformational and incorporates ferruginous mudstone clasts. Its correlation with the Lower Miocene of the B.P. Shell Walmerer No. 1 well is quite striking. It would appear that on account of the lithologic similarities and Lower Miocene age for the subsurface calcareous sands, Walters and Linton (1973) equated the Kipevu and Baratumu strata and assigned a Middle Miocene age to the two outcrops. However, the foraminifer Austrotrillina howchini has been reported from rocks ranging in age from Oligocene to Middle Miocene (Ellis et al., 1969). Furthermore, surface occurrences of Middle Miocene sedimentary deposits are unknown in Kenya and where this age is suspected, an association with volcanics is imperative.

Middle Miocene rocks in the south-east, are only preserved in the B.P. Shell Kipini No. 1 and B.P. Shell Pate No. 1 wells, at depths of 1096 m and 856 m below sea level respectively. The sediments reflect continuity of the depositional realm, prevalent during the Lower Miocene. A core of bioclastic limestone, retrieved from the upper section of the Middle Miocene in the B.P. Shell Pate No. 1 well (337.2 to 338.1 m), incorporates complete and broken shelly remains, notably of pelecypods, gasteropods and corals that have undergone partial dolomitization and infilling by secondary sparry calcite. These limestones continue into the overlying interval, forming the lowermost unit of the Upper Miocene succession. Further upwards, the lithology changes abruptly to recessive calcareous sandstones and unconsolidated coarse sands, measuring 30 m in the B.P. Shell Kipini No. 1 well and 60 m in the B.P. Shell Pate No. 1 well. Bioclastic limestones and calcilutites, yielding *Globorotalia tumida pleisotumida*, *Pulleniatina primalis*, *Globigerinoides rubber* and *Globoquadrina altispira*, form the succeeding and final Upper Miocene interval, indicating a return to transgressive depositional conditions. The entire Upper Miocene interval sequence, measures 170 m in the B.P. Shell Pate No. 1 well and 130 m in the B.P. Shell Kipini No. 1 well. This contrasts with observations of the Middle Miocene strata, in that at Kipini the strata are 280 m thicker than in the B.P. Shell Pate No. 1 well.

The Pliocene sequence has been penetrated by all the deep test wells except for the B.P. Shell Walu No. 2 well, which was located on an outcrop of Lower Miocene rocks. In the south-eastern extremity, two different facies typify the succession. A lower marine facies constitutes a continuation of latest Miocene deposition of bioclastic limestones, calcilutites, and grey-green calcareous and foraminiferal mudstones. In the B.P. Shell Mararani No. 1 and B.P. Shell Dodori No. 1 wells, these lithologic assocations are found throughout the entire Pliocene, with relatively minor amounts of terrestrial detritus. The B.P. Shell Dodori No. 1 well contains the thickest carbonate succession, measuring some 160 m. In the B.P. Shell Pate No. 1 and B.P. Shell Kipini No. 1 wells, the thickness is reduced to just over 100 m, and a discrete siliciclastic unit overlies the marginal marine carbonates. It comprises interbedded, poorly consolidated, calcite-cemented quartz sandstones and a mixture of fine- to coarse-grained and pebbly iron-stained quartz sands, incorporating rock fragments and minerals of igneous origin. These facies are laterally very persistent and extend to the south and south-eastern parts of the north-eastern province, where they merge into the Upper Pliocene Merti Beds.

## Time Framework of Neogene Strata in South-East Kenya

The Neogene strata of the south-east are not readily related to a time framework, largely on account of the inherent limitations on faunal interpretations and, to some extent, because of erroneous identifications. A definite pattern recognized in the subsurface consists of distinct tectonically controlled and cyclical association of facies. Accordingly, the subsequent discussion focusses on assigning the equivalent surface occurrences to their proper stratigraphic positions.

Thompson (1956) proposed the name Marafa Beds for the fining-upward succession of poorly consolidated, varicoloured sands and sandstones, typically exposed in an erosional scarp at

Ulaya Nyira, north of Marafa Village. He recognized a conglomerate horizon at the base of an equivalent unit exposed at Chui Beacon, north-west of Malindi. Despite acknowledging the presence of fossils derived from the underlying Baratumu Formation within the conglomerate, he correlated the beds with lithologically comparable sediments, the Magarini Sands, exposed near Mombasa. These were described by Caswell (1953) as poorly consolidated, red-brown sands of Pleistocene age. Thompson (1956) thus defined the Marafa Beds as the lower representatives of the Magarini Sands, deposited under fluvio-lacustrine conditions, on account of the fossiliferous basal deposits. He assigned a Plio-Pleistocene age, and retained the term Magarini Sands for the uppermost eolian sediments. Williams (1962), on the other hand, gave the name Midadoni Beds to a sequence of poorly consolidated sediments, unconformably overlying the Fundi Isa Limestones, north-west of Fundi Isa. The identification of Opercullinella sp., Elphidium sp., Streblus sp. and Austrotrillina howchini from limestone clasts, within a syntectonic and polymictic conglomerate, was of major importance in his provisional dating of the beds as Pliocene. He considered the Magarini Sands as equivalent strata, and assigned the Marafa Beds to the Pleistocene.

Figure 12 is a north-east to south-west structural cross-section through the B.P. Shell Pate No. 1, and B.P. Shell Kipini No. 1 wells, the water borehole MOWD/C3641 located on the Wachu Hill at Hadu, the type section of the Marafa Beds, and

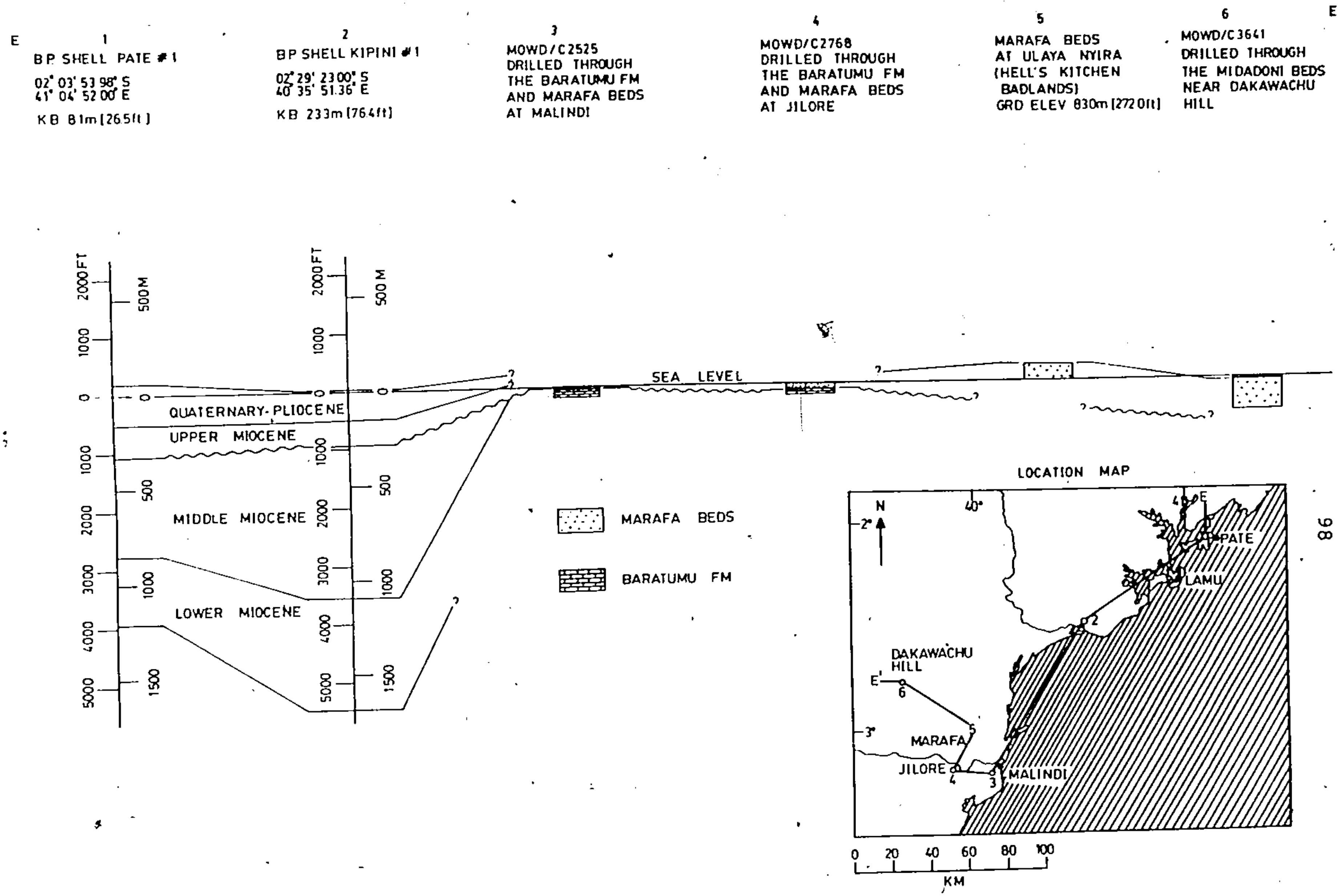


Fig. 12. Structural cross-section through the Marafa and Midadoni Beds, (Upper Miocene) south-east Kenya.

two selected boreholes drilled in the Jilore and Malindi areas. The Midadoni Beds and Marafa Beds are correlated with the poorly consolidated siliciclastic deposits, encountered at 200 m and 208 m below sea level, in the middle Upper Miocene sequence of the B.P. Shell Pate No. 1 and B.P. Shell Kipini No. 1 wells respectively. The boundary between the Upper Miocene siliclastic sediments and the carbonate deposits, is taken to be a basal conglomerate, which has been encountered in several water boreholes, in the Malindi area. The Midadoni Beds are probably as much as 170 m thick, while the Marafa Beds have an overall thickness of 120 m. In contrast, the sequence in the B.P. Shell Pate No. 1 and Kipini No. 1 wells is 60 m and 30 m, respectively, a difference that may be related to deposition of the near-surface occurrences in local depression or tectonic troughs. The faulted-boundary relationship between these deposits and younger subjacent strata, has been discussed by various authors (Linton and MacLean, 1955). At the type locality, the Marafa Beds are very pale orange to grayish orange-pink, medium- to coarse-grained sandstones and kaolinitic clays with inclined moderate red layers formed by iron minerals. The observed inclination of strata probably represents cross-bedding on a very large scale (Plate 6 A). Dip measurements obtained from a well indurated, calcite-cemented sandstone, north of Hadu indicate south-eastward dip of 24° (Plate 6 B). In thin section the sandstone is seen to contain well sorted and rounded, fine- to medium-grained quartz with coatings of red ferric oxide.

Plate 6 A. Outcrop of the Marafa Beds, showing cross-bedding on a very large scale, Hell's Kitchen badlands, north of Marafa Village, south-east Kenya.

Plate 6 B. Outcrop of the Marafa Beds (Upper Miocene) showing a dip of 24 degrees toward the south-east, near Hadu, south-east Kenya.

Thompson (1956) also comments on the possibility of a secondary origin for the kaolinite. The presence of fossil wood fragments, in association with limonitic pebbles in the beds, confirms that at least some material was derived from the Karoo Formation.

The overall impression is that the Midadoni and Marafa Beds are lateral equivalents that overlie likewise equivalent strata, the Lower Miocene Fundi Isa Limestone and Baratumu Formation, in their respective type areas. The basal conglomerate marks an unconformable junction and may be likened in definition to that at the base of the Lower Miocene sequence. A cyclic depositional pattern is present.

Walters and Linton (1973) included in the North Mombasa Crag, as referred to by earlier authors, a series of bioclastic limestones, calcilutites and foraminiferal calcareous mudstones, that outcrop at Shimanzi, near Mombasa, Mtwapa Creek, and Ras Junda, south-west of Mombasa. Its stratigraphic relationship with the Magarini Sands was established in a B.P. Shell borehole near Shimanzi, where 73 m of the unit are overlain by the lower fluviatile deposits of the Magarini Sands. Hence, a Late Miocene to Early Pliocene age was suggested, while deposition of the Magarini Sands was assigned to Late Pliocene time. The term North Mombasa Crag has found limited use in the coastal Tertiary stratigraphy, since subsequent authors (Simiyu-Siambi, 1980) referred it to the Pleistocene Reef Complex. The occurrence of an analogous sequence in parts of the Upper Miocene through Lower

Pliocene sections of the B.P. Shell Pate No. 1 and the B.P. Shell Kipini No. 1 wells, is in agreement with the dating suggested by Walters and Linton (1973). The subsurface equivalents measure 35 m in the B.P. Shell Pate No. 1 well and 54 m in the B.P. Shell Kipini No. 1 well. The south-westward thickening trend remains consistent, when the observation in the Shimanzi borehole is also taken into account. These strata yield a common foraminiferal assemblage that includes species of Operculina, Operculinella, Streblus, Elphidium and Amphistegina. The Upper Pliocene fluviatile deposits encountered in the B.P. Shell Pate No. 1, and the B.P. Shell Kipini No. 1 wells and extending to the north-east, are analogous to the Lower Magarini Sands. Kent (1982) described similar deposits in southern Tanzania, the Mikindani Sandstone that unconformably overlie the shallow-water Miocene marine limestones.

## Neogene Strata of North-East Kenya

The Merti Beds of Upper Pliocene age constitute the only Tertiary stratigraphic unit in the north-eastern part of the study area. Thompson and Dodson (1958) recognized the unconformable relationship between these strata and the underlying Jurassic limestones. They comment on their northward and fan-like broadening pattern, from Merille, west of Mandera, toward the Kenya-Ethiopia border. In depicting the vertical arrangement of successive strata, Thompson and Dodson (1958) distinguished two main units: a lower, fining-upward succession, beginning with an arenaceous bed near the basal unconformity and fining to a yellowish-brown claystone; coarse grits toward the top; and an uppermost interval of grits and quartz pebble conglomerates. The lateral continuity of the basal claystone, is traceable further south towards El Wak and Wajir and is exposed at Walmerer with a thickness of 3 to 6 m. In this area the claystones are overlain by the limestone and gypsum deposits of the El Wak and Wajir Beds. The limestones have been described in earlier literature, as "kunkar" deposits. Petrographic analysis of a sample obtained from an outcrop near the Wajir Agricultural Show Grounds revealed that the deposits are actually algal stromatolites. Baker and Saggerson (1958) linked the absence of the upper strata of grits and pebble conglomerates, in this area, to conditions approaching peneplanation, implying a source area depleted in coarse clastics. Ayers (1952) had related the genesis of the Merti Beds to south-eastward flowing rivers. Thompson and Dodson (1960) encountered the claystone again in a limited outcrop at Erib, east of Tarbaj, and introduced the name Erib Claystone. A thickness of 24 m was determined in a nearby water borehole. The coarse-grained interval is not represented in this area. The general features of the claystones are uniform wherever exposed. A fine lamination, defined by alternating layers of fine, sub-rounded to rounded quartz grains set in a limontic matrix, oxidized iron minerals and carbonaceous material, is atypical. A thin interval, variously described as a red-brown, orange-brown and tan mudstone or claystone, is reported in the Pliocene strata of the B.P. Shell Meri No. 1, B.P. Shell Walmerer No. 1, Texas Hagarso No. 1 and B.P. Shell Kipini No. 1 wells at 56, 8, 17, and 30 m below sea level, respectively. If these represent the same horizon, then the Erib Claystone may be a regionally extensive and correlatable marker, deposited on the end-Tertiary peneplain.

In the western part of the study area, the Merti Beds outcrop on the flanks of the Merti Plateau, near Garba Tula. Only the upper sequence is exposed under a layer of Pleistocene olivine basalts that sheltered the beds from erosion. The occurrence in this area has been mapped and described by Matheson (1971). He described a succession in a borehole at El Dera that comprises 51 m of basal coarse grit, incorporating volcanic debris, and 72 m of grits and clays overlain by surface sands. Swarzenski and Mundorff (1977) mapped the permeable zones of the Merti Beds, which extend from north-east of Habaswein to Liboi and into Somalia, along the line of the Uaso Nyiro and Lagh Dera rivers.

Strata of the Merti aquifer comprise an upward-fining succession of sands, gravels, grits and an assortment of quartz and granite pebbles. The Ministry of Transportation and Communications boreholes at Ramada reveal small-scale cross-bedding. These sediments have also been encountered in numerous water boreholes. The B.P. Shell Garissa No. 2, B.P. Shell Meri No. 2 wells, and Ministry of Water Development MOWD/C3636 well near Mado Gashi, went through 170 m, 216 m, and

188 m, respectively, of sediments that produced saline water from the Merti aquifer. Figure 13 shows a correlation of the Upper Pliocene, Lower Magarini Sands in the B.P. Shell Kipini No. 1 well through these wells to the Merti Plateau outcrop and the Upper Pliocene interval in the B.P. Shell Walmerer No. 1 well. The coarse-grained sediments forming the Merti aquifer, thicken north-westwards from 21.5 m in the B.P. Shell Garissa No. 2 well to 72 m at their type locality on the Merti Plateau. The trend parallels the flow of the Tana River. In the B.P. Shell Walmerer No. 1 well the sequence of Pliocene coarse clastics and mudstone deposits attain a thickness of less than 20 m. Equivalent strata in Somalia, measure 11 m in the Sinclair No. 1 Merca well. Coarse siliciclastic deposits interbedded with volcanic sediments are also typical of the Pliocene Kubi Algi and Kubi Fora Formations in the Turkana basin of north-west Kenya. The trend of these facies reflect the influence of the deformation in central Kenya on the Late Tertiary drainage pattern.

## Relationship Between Onshore and Offshore Strata

The oldest Cretaceous deposits in the offshore area are Turonian in age and occur at the total depth of 1174 m in the DSDP No. 241 well. The interval comprises 300 m of interbedded, silty clay and claystones forming incomplete Bouma sequences of turbidite divisions (Schlich et al., 1972). Deposition of these were coeval with the onshore regressive episode, represented by the Marehan Sandstone in north-eastern Kenya and the Jesomma

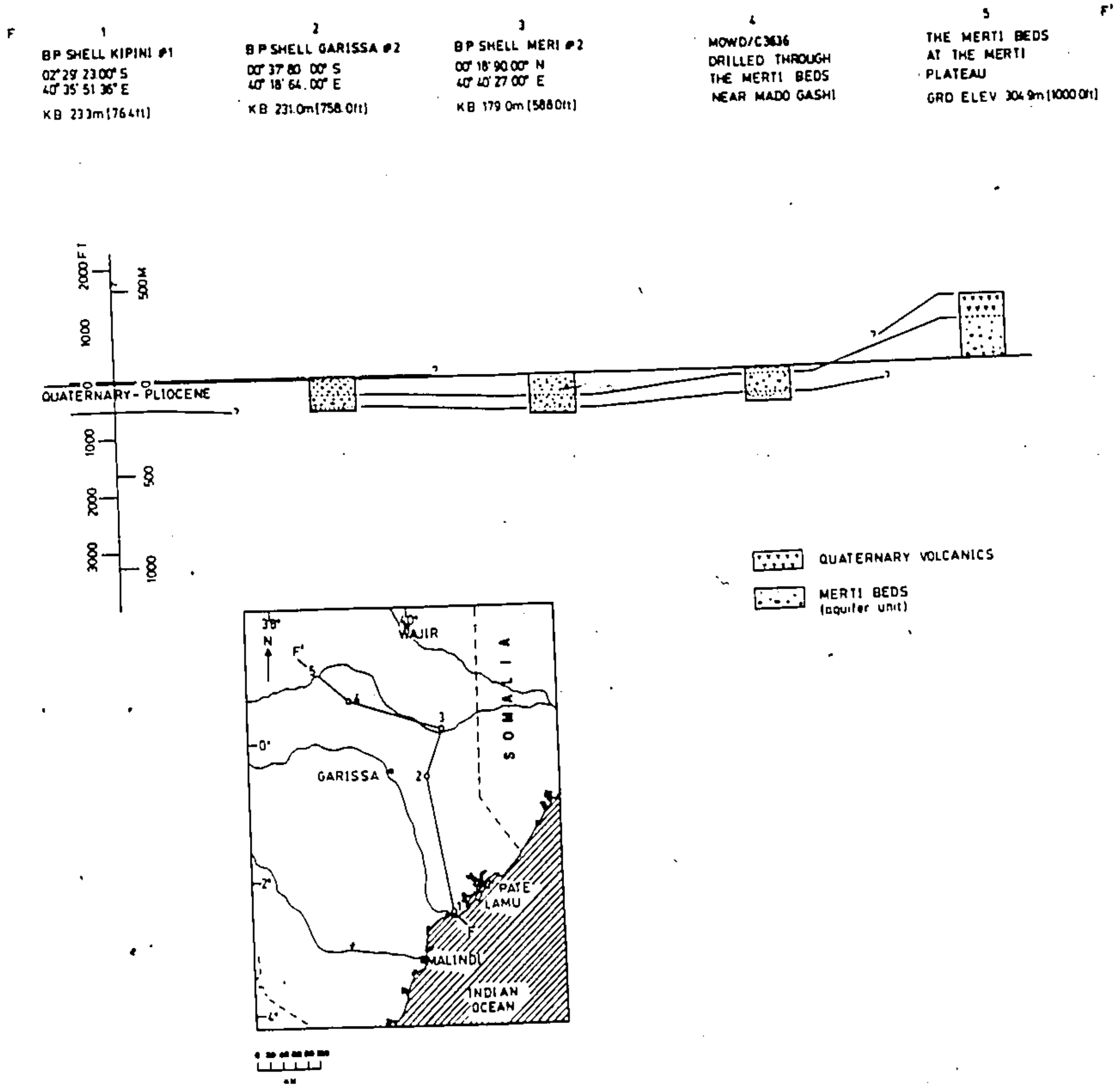


Fig. 13. Structural cross-section through the Merti Beds, (Upper Pliocene) south-east Kenya.

Sandstone of south-eastern Somalia. The succeeding Santonian-Campanian interval is continuous with these phase and is characterised by more complete nearly Bouma sequences, that include calcareous sandstones with an overall thickness approaching 250 m. A similar lithology occurs in the Campanian of the Union Kofia No. 1 well, but farther south-west, in the Total Simba No. 1, calcareous shales and clays are more dominant and the sandstones are finer in texture. The coarseness of the sandstones increases in the Maastrichtian section of both wells and incorporates minor limestones interbedded with calcareous shales, siltstones and clays. Maastrichtian strata are absent from the DSDP No. 241 well and the onshore wells on account of erosion associated with the Cretaceous-Tertiary unconformity.

The Paleocene offshore succession is identical in lithofacies and distribution to the underlying Upper Cretaceous and onshore Paleocene interval. The strata thin seaward from a maximum of 775 m, estimated in the B.P. Shell Dodori No. 1 well, to about 400 m. This thickness is constant between the Union Kofia No. 1 and the Total Simba No. 1 wells. In the DSDP No. 241, the interval is represented by only 40 m of silty clays and claystones, carried below the carbonate compensation depth by dilute-suspension turbidity currents.

Highly fossiliferous strata characterize the Lower Eocene offshore and onshore successions. The Total Simba No. 1 and the DSDP No. 241 wells preserve a record of open-marine planktonic species, in contrast to the restricted forms in the coastal wells. The sequence is comparatively thin offshore, measuring 500 m in the Total Simba No. 1 well and 340 m in the Union Kofia No. 1 well. The attenuation is most pronounced in the DSDP well which records 85 m of Lower Eocene strata. Greenish grey claystones and siltstones form the bottom unit of the Middle Eocene, in the Union Kofia No. 1 well and the DSDP No. 241 well, with evident reworking in the latter and lignite associated with fine-grained sandstones in the Total Simba No. 1 well. The unit forms the basal offshore extension of the regressive wedge of sediments inland, termed the Barren Beds. The Linderina Limestone, recognized in the B.P. Shell Mararani No. 1, B.P. Shell Dodori No. 1 and the B.P. Shell Pate No. 1 wells, occurs in the succeeding Middle Eocene interval of the Total Simba No. 1 well. In the Union Kofia No. 1 well it is not recognized. The fish teeth in the Middle Eocene succession of the DSDP No. 241 well probably relate to this transgression, since the Upper Eocene transgression was characterized by non-deposition. The intervening period corresponds with another brief episode of hemipelagic sedimentation. The entire Middle to Upper Eocene sequence thins significantly in an oceanward direction.

The Oligocene rocks in the deeper offshore are marked by an absence of strata in the Total Simba No. 1 well and only 7 m of altered sediments in the Upper Oligocene succession of the DSDP well. In the Union Kofia No. 1, the Lower Oligocene is characterized by an upward increase in the proportion of coarse clastics and a gradual change to calcareous quartz sands, with traces of garnet and limestones in the greater part of the Upper Oligocene interval. These occurrences are allied to the final depositional phase of the Barren Beds onshore and a decrease in the amount of sediment reaching the deeper offshore regions.

The Lower Miocene section exhibits a change in sedimentation both offshore and onshore, corresponding with a widespread marine transgression. The Cities Maridadi No. 1B and the Union Kofia No. 1 wells share an essentially identical facies, similar to that recognized in the Baratumu Formation. A cored interval between 2061.7 and 2069 m in the Cities Maridadi No. 1B well, shows limestones interbedded with greenish grey mudstones and some slump structures. Significant recrystallization and dolomitization is developed in the Union Kofia No. 1 well, establishing an offshore continuation of the onshore Garissa-Walu-Kipini trend. The Cities Maridadi No. 1B well contains a significant thickness of Lower Miocene strata which is 1400 m thicker than the Union Kofia No. 1 well. This situation is, however, reversed in the Middle Miocene, with the section measuring 500 m in the Union Kofia No. 1 well compared with 120 m in the Cities Maridadi No. 1B well. The observations in the Total Simba No. 1 well are markedly different, with calcareous sands, marls and clays forming 55 m of the Lower to Middle Miocene section. These deposits probably represent winnowed sediments eroded from the crest of the Kofia structure by oceanic currents. The equivalent interval in the DSDP No. 241

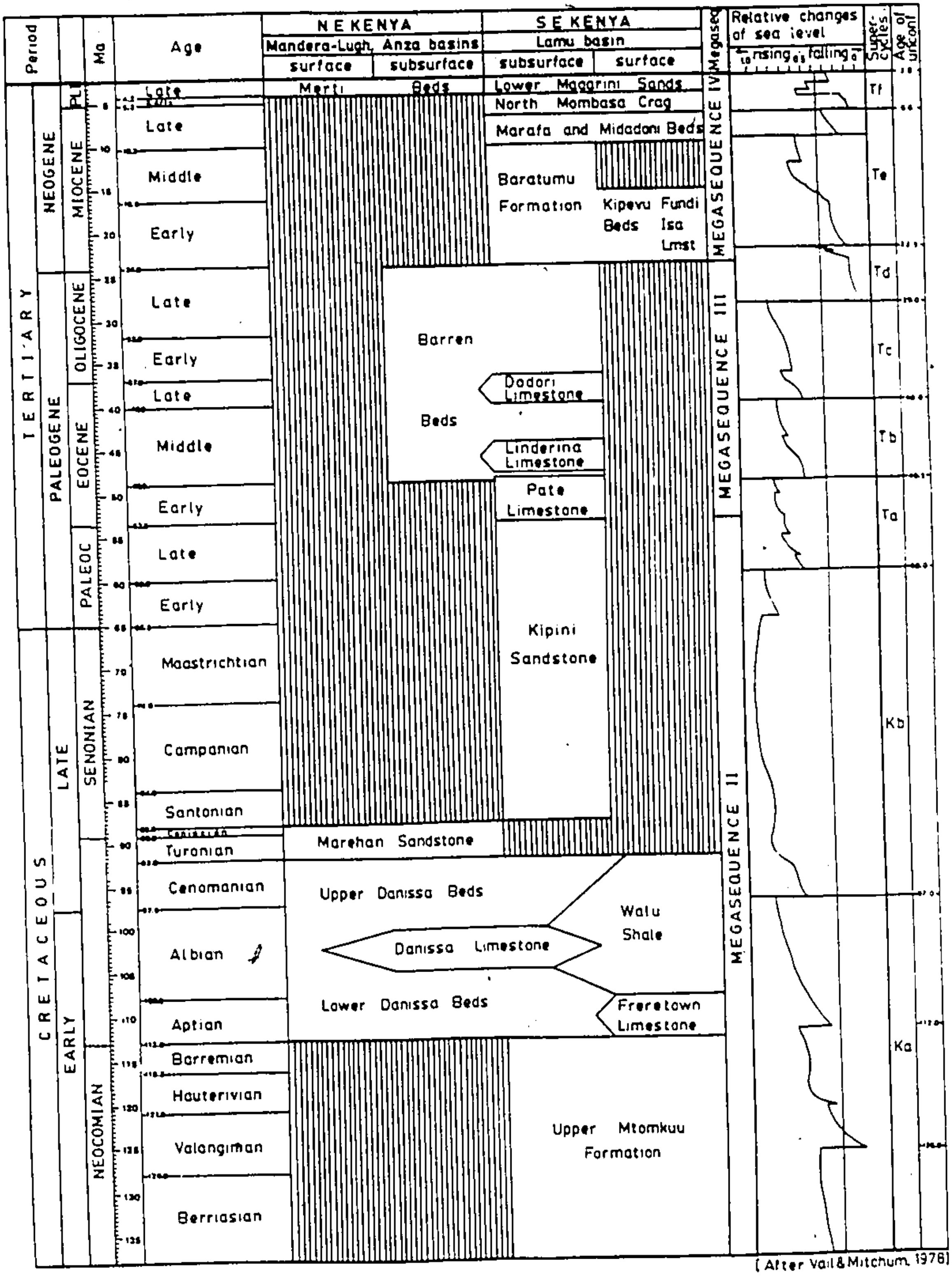
well is also relatively thin, comprising 192 m of sand bearing clay-rich nannoplankton ooze. The volcanic ash bed in the uppermost Middle Miocene may be related to volcanic eruptions inland, associated with termination of the Miocene transgression. The prominent development in the succeeding interval of regressive clastics, comprising coarse sandstones associated with coal and lignite fragments in the Union Kofia No. 1 well, bentonite and rock fragments in the Cities Maridadi No. 1B well and the Total Simba No. 1 well, and graded beds in the DSDP No. 241 well, supports the assignment of the Marafa and Midadoni Beds to this phase of Upper Miocene deposition. In the Cities Maridadi No. 1B well, the unit is similarly coarse-grained, poorly consolidated and attains a thickness of 180 m, which is consistent with a progressive seaward thinning from near-surface occurrences. The overlying strata extending from the Messinian to Zanclean age, comprise 1230 m of bioclastic limestones and fossiliferous greenish grey, calcareous mudstones, yielding a nearshore assemblage of the large foraminifer *Operculina sp.*, *Amphistegina sp.*, rare *Heterostegina sp.*, as well as *Ammonia sp.* and rare bryozoan. A lithological and paleoecological correlation is made with the North Mombasa Crag. The coccolith and silicoflagellate zonations in the DSDP No. 241 well (Burky, 1974) and the Cities Maridadi No. 1B well display good correlation and provide excellent stratigraphic control.

Coarse- to very coarse-grained unconsolidated sands and calcareous sandstones with intervals of bentonite clays, occur in the Total Simba No. 1, Cities Maridadi No. 1B and Union Kofia No. 1 wells, in the Upper Pliocene succession. The bentonite clays may be absent in the Union Kofia No. 1 well where the interval is rather thin, whereas volcanic glass is incorporated in the clays of the DSDP No. 241 well. The tectonic stresses operative inland, greatly influenced sedimentation offshore, as evidenced by the general congruity in stratigraphy and the remarkable similarity in gross structure, observed by Kent (1982).

## Classification of Cretaceous and Tertiary Stratigraphic Units

The complete Cretaceous through Tertiary stratigraphic succession is presented in Table 6. Three large groups of stratigraphic sequences are distinguished and constitute part of a four-fold classification, here introduced for the Late Paleozoic through Cenozoic strata of eastern Kenya. The classification is based upon the recognition of regional to local lithostratigraphic assemblages, delimited by major unconformities. Each major sequence comprises lithostratigraphic units, exposed near surface in the south-east and north-east of the study, with equivalents in the subsurface, or those restricted confined to either of these settings. They comprise sequences deposited under alternating periods of transgression and regression, thus incorporating unconformities of regional or local significance. These are regarded as sequences of the first order or megasequences. Lower in rank are sequences of the

## TABLE 6: STRATIGRAPHIC CORRELATION CHART FOR THE SEDIMENTARY BASINS OF EAST KENYA



[After Vail & Mitchum, 1976]

second order formed during a single event of transgression or regression and embody strata of essentially higher lithological homogeneity. They are either siliciclastic or carbonate facies, depicting modes of rhythmic or cyclic deposition limited in areal extent and time range. Where present, minor gaps in the rock record are represented by relatively brief non-depositional events, revealed by an absence of strata, breaks in the fossil record or an intraformational conglomerate.

This classification is the end product of systematic approaches in the analysis of sedimentary basins. A stratigraphic analysis checklist devised by Simpson (1986) provides such methodology and its application in this study enabled major depositional trends related to the periods of regression and transgression, and other subordinate facies patterns to be recognized. The overall pattern of cyclicity ties quite closely into the Vail curves of global relative changes of sea level, developed from data largely derived from seismic stratigraphy. Vail _et al_. (1977) determined the regional cycles in different continents and related them to major events of geotectonic and glacial processes. Facies and general patterns of distribution of many depositional sequences are affiliated to these cycles of global highstands and lowstands of sea level (Vail and Mitchum, 1978). These provide an important framework for identifying and dating sediments in any basin (Kerr, 1987), particularly in frontier areas. The periods of falling sea level created interregional unconformities bounding strata of each cycle. This observation was applied by Sloss (1963) in classifying sequences in the cratonic interior basins of North America. Sloss and Speed (1974) related the pattern to different modes of vertical cratonic behaviour which were in response to different plate tectonic motions, located on continental margins. Haq et al. (1987) have recently developed an alternative depositional model based on the integration of outcrop studies with well log and seismic reflection data. The new curves include minor sea level cycles rarely discernable in seismic profiles. The concept facilitates establishment of an accurate chronostratigraphic framework and identify depositional sequence boundaries. In this study only outcrop and subsurface lithological and paleontological data were available for utilization. Against this background, detailed descriptions of the megasequences are presented below. New designitions are proposed for lithostratigraphic units, hitherto unnamed, and incorporated within these major groups.

## Definition of Megasequence II

Megasequence II comprises the products of two marine regressions and an intervening transgression. It incorporates lithostratigraphic assemblages, ranging in age from Early Cretaceous to Late Paleocene. The base is the major unconformity, that separates Upper Jurassic marine shales from quartzitic sandstones of the lowest Cretaceous regression. The oldest formation of the megasequence is the Neocomian Upper

Member of the Mtomkuu Formation, exposed in outcrop in the south-east and present at the subsurface between 2394 m and 3794 m in the B.P. Shell Walmerer No. 1 well. Overlying this unit is the Freretown Limestone, representing a lateral facies change to fine-grained clastics of Aptian age, occurring between 3619 and 3729 m in the B.P. Shell Walu No. 2 well, below 3092 m in the Texas Hagarso No. 1 well, and between 1793 and 2349 m in the B.P. Shell Walmerer No. 1 well. These occur in outcrop in the extreme north-east as the Danissa Beds. A provisional differentiation is made here between the Lower Danissa Beds (Aptian to Albian) and the Upper Danissa Beds (Cenomanian). The two units are separated by a thin limestone band of probable Albian age, for which the name Danissa Limestone is proposed. The Danissa Limestone continues into the subsurface between 1471 and 1598 m in the B.P. Shell Walmerer No. 1 well and 2553 and 2735 m in the Texas Hagarso No. 1 well. Its equivalent in the B.P. Shell Walu No. 2 well, is the ammonitic shale, encountered from 2445 to 3619 m and overlying the Freretown Limestone at its type locality in the south-east. The Walu Shale is the name suggested here for the unit.

The Marehan Sandstone (Turonian to Coniacian) in the north-east and Kipini Sandstone (Santonian to Lower Paleocene) are the final and predominantly regressive lithostratigraphic units of Megasequence II. The Kipini Sandstone is newly introduced as a formational name for the latter sequence. It is restricted to the subsurface below the present shelf setting in the south-east.

## Definition of Megasequence III

Megasequence III embraces the products of three marine transgressions and intervening regressions. The sequences are restricted to the subsurface and the Paleogene phase of deposition. These units are preserved in their entirety in the B.P. Shell Dodori No. 1 well, which serves as the reference well for Megasequence III. The unconformity at the base is easily recognizable over a wide area. Towards the north-east its prominence is emplified by the relationship of Middle Eocene strata, resting unconformably on older rocks of Upper Cretaceous age. The lowest unit consists of cyclic carbonate facies, overstepping the Kipini Sandstone. The Pate Limestone is proposed as a unit name, and is present between 2360 and 3501 m in the B.P. Shell Dodori No. 1 well, and between 2748 and 3892 m in the B.P. Shell Pate No. 1 well, and spans the Early to early Middle Eocene interval. Though locally limited in extent, within the study area on account of erosion, its equivalent occurs in the coastal wells of Somalia and is exposed in the Nogal valley. The next sequence is regressive and consitutes the marginal extension of the Barren Beds, (Middle Eocene-Oligocene) present in all the wells located further north. The *Linderina* Limestone heralds the second transgression and is separated from the Upper Eocene Dodori Limestone, by a second seaward progradation of the Barren Beds. The Dodori Limestone represents the final transgression in the Megasequence.

The Linderina Limestone is present from 2294 to 2321 m in the B.P. Shell Dodori No. 1 well, 1643 to 1705 m in the B.P. Shell Pate No. 1 well, and 1570 to 1735 m in the Total Simba No. 1 well. The Dodori Limestone is present at the intervals 1288 to 1314, 1326 to 1364, and 1508 to 1570 m, respectively in the above wells. Both units form tongues, extending into the Barren Beds, with the latter terminating in the Oligocene as the final deposits of Megasequence III.

## Definition of Megasequence IV

Megasequence IV comprises sequences of the Neogene period, deposited in the course of two marine transgressions and two alternate periods of regression. Apart from the fewer, more abrupt and widespread sea-level oscillations, it mimicks the depositional pattern of Megasequence III. The lower bounding Oligocene unconformity is marked onshore by a basal conglomerate, and offshore by the virtual absence of Oligocene strata. In typical areas of exposure, in the south-east region, the degree of erosion of the underlying megasequence is most pronounced, such that the basal sequence of Megasequence IV rests on the strata of Megasequence II or Megasequence I. The lower sequence is typified by rhythmic repetitions of carbonate strata, seen in outcrop and the subsurface. They include the Fundi Isa Limestone, Baratumu Formation and Kipevu Beds, that were the products of a widespread Early to Middle Miocene transgression.

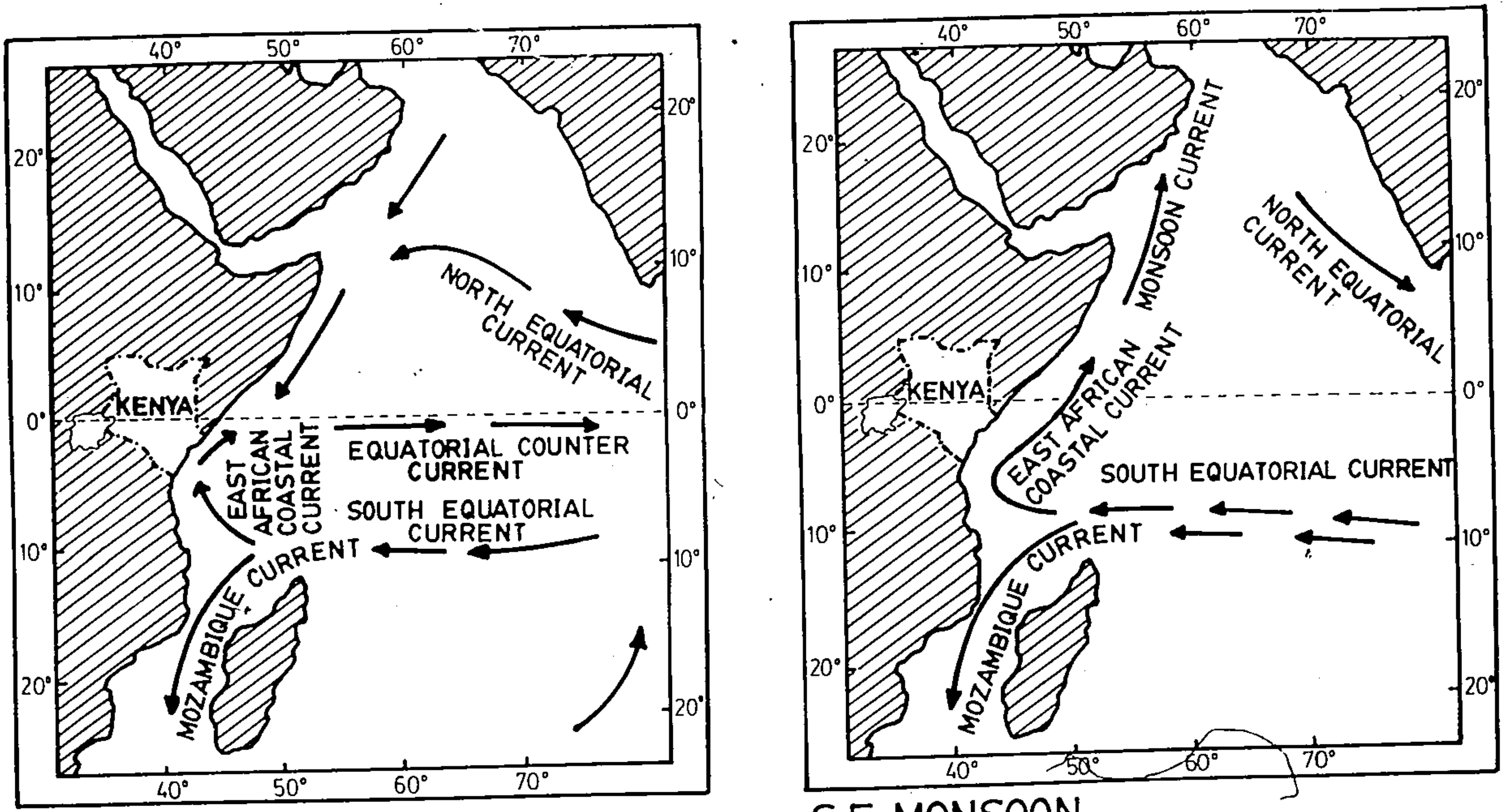
The Middle Miocene sequence only occurs in the basinal setting, penetrated by the B.P. Shell Pate No. 1 and B.P. Shell Kipini No. 1 wells. Their absence elsewhere is on account of erosion below the Middle Miocene unconformity, a long-recognized feature contained within this megasequence. The name Baratumu Formation is retained for the subsurface equivalents of the Lower and Middle Miocene successions. The subsequent regressive unit comprises the Midadoni and Marafa Beds, which are early Late Miocene in age. The latter term is retained for the subsurface representatives, present in the interval 200 to 257 m in the B.P. Shell Pate No. 1 well and 231 to 261 m in the B.P. Shell Kipini No. 1 well. This regression is reflected offshore in Upper Miocene turbidites penetrated by the DSDP No. 241 well. The attendant sequence constitutes a supplementary rhythmic carbonate facies, designated here the North Mombasa Crag for both near-surface and subsurface representatives. It is uppermost Miocene to Early Pliocene in age and occurs from 165 to 200 m in the B.P. Shell Pate No. 1 well and 177 to 231 m in the B.P. Shell Kipini No. 1 well. The reversion to Upper Pliocene regression, forming the Lower Magarini Sands of the south-east and the Erib Claystone and Merti Beds of the north-east, ends this megasequence.

## MAIN DEPOSITIONAL SYSTEMS

The spatial relationship of different facies and the diverse sedimentary processes operative on the present coastal area of

Kenya, provides fundamental insights into the dynamic and interactive conditions that existed throughout the depositional history of the eastern basins. Most notable are the accummulations of terrigenous material, brought in by the Sabaki and Tana Rivers. The south equatorial and East African coastal currents (Schroeder, 1974), related to the ubiquitous north-east and south-east monsoon winds (Fig. 14), prevail during alternate seasons to disperse these sediments into wide beaches, dune ridges and barrier islands. Mangroves are well developed in the adjacent swampy or lagoonal areas. Gypsum and halite precipitation is widespread in north-east- to south-west-trending depressions, sub-parallel to the coast. The delicate balance between constructive and destructive processes, has sustained reefal growth parallel to the coastal fringe, whereas patch reefs rise from the shelf bottom behind wide channels, separating the fringing reefs.

As previously noted the depositional pattern of the established megasequences terminated in a phase of abundant clastic progradation towards the continental shelf as a result of the emergent episodes inland. This material was redistributed onshore, creating restricted marine environments characterized by distinctive sedimentary facies. The depositional settings, within each megasequence, are recognizable as separate entities on the basis of particular lithostratigraphic units. The associated lithologic variation is largely the result of dynamic equilibrium in a setting of fluctuating environmental conditions.



N E MONSOON

S E MONSOON

Fig. 14. Prevailing currents of the Indian Ocean.(adapted from Schroeder, 1974)

## Depositional Settings of Megasequence II

During Cretaceous time, following the separation and south-eastward movement of Madagascar, the East African margin evolved as a trailing-edge coast, formed near the separation centre. According to Inman and Nordstrom (1971), coasts of this type have extensive coastal plains, well developed drainage basins and progradational shelves. The Upper Member of the Mtomkuu Formation represents the progradational deposits of an arcuate tidal delta (Fig. 15), formed on the inner shelf and associated with a marginal estuary. In the Aptian, a gradual landward encroachment of the estuary, south of the B.P. Shell Walu No. 2 well, culminated in the deposition of the Freretown Limestone along its margin. A complex of intertidal and shallow subtidal intracoastal facies, prevailed in the adjacent area, and in the north-east where the Lower Danissa Beds began to form (Fig. 16). By the end of the Albian, the estuary extended just north of the B.P. Shell Walu No. 2 well, resulting in deposition of the Danissa Limestone and the Walu shale, containing prolific marine fauna and slump bedding features (Fig. 17). The deposition of the Upper Danissa Beds continued in an intertidal-flat setting until the onset of Cenomanian time. The main elements of the environment are well recorded in existing outcrops, and constitute intertidal-flat deposits referable to the <u>Skolithos</u> ichnofacies, between which minor offshoots of tidal channels and tidal creeks of similar alignment projected. The creeks behaved much like meandering rivers, eroding the outer

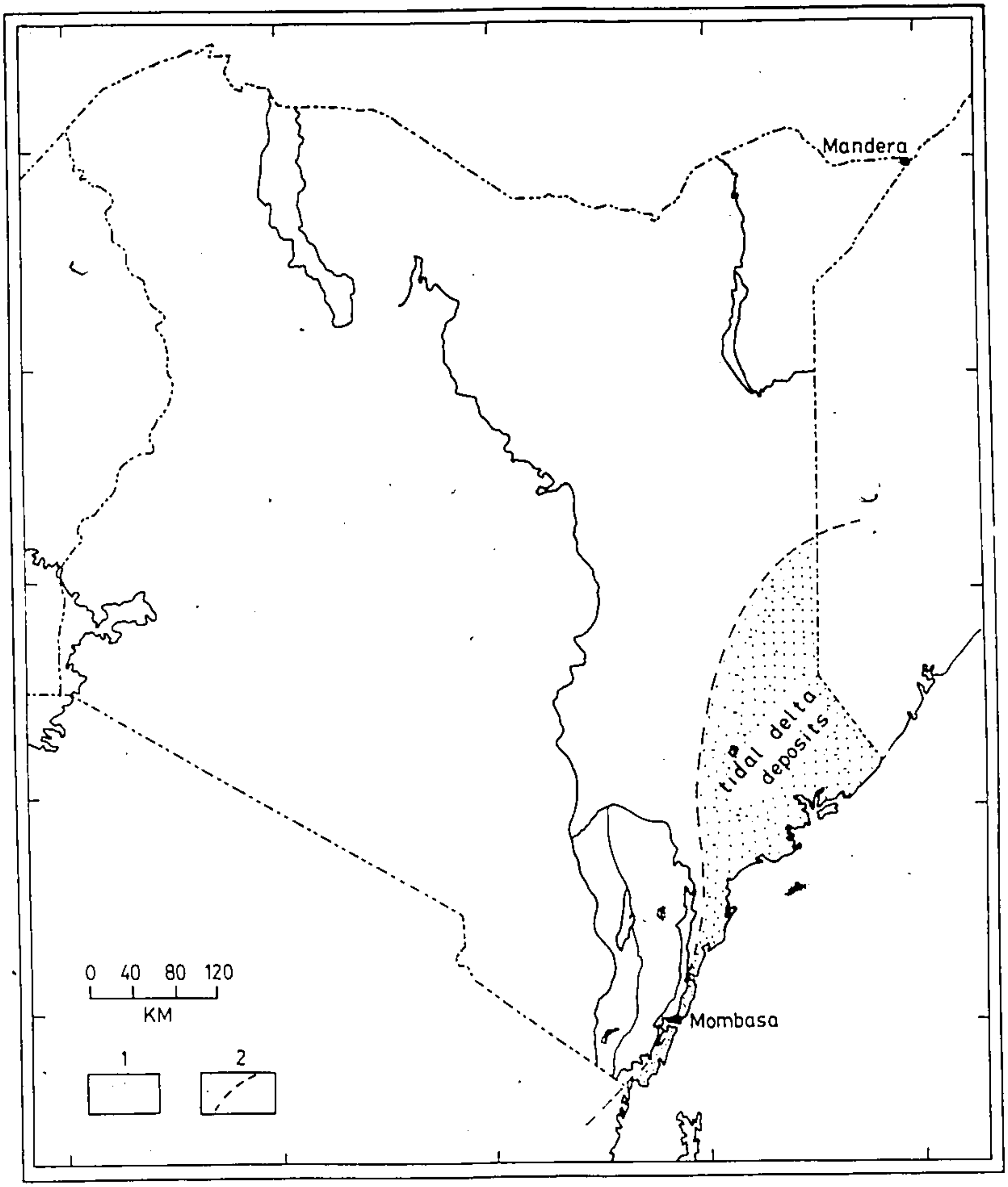


Fig. 15. Sedimentary facies and distribution of the Upper Member of the Mtomkuu Formation (Neocomian).
1 - orthoquartzites; 2 - sandstones and shales;
3 - approximate limit of lithofacies.

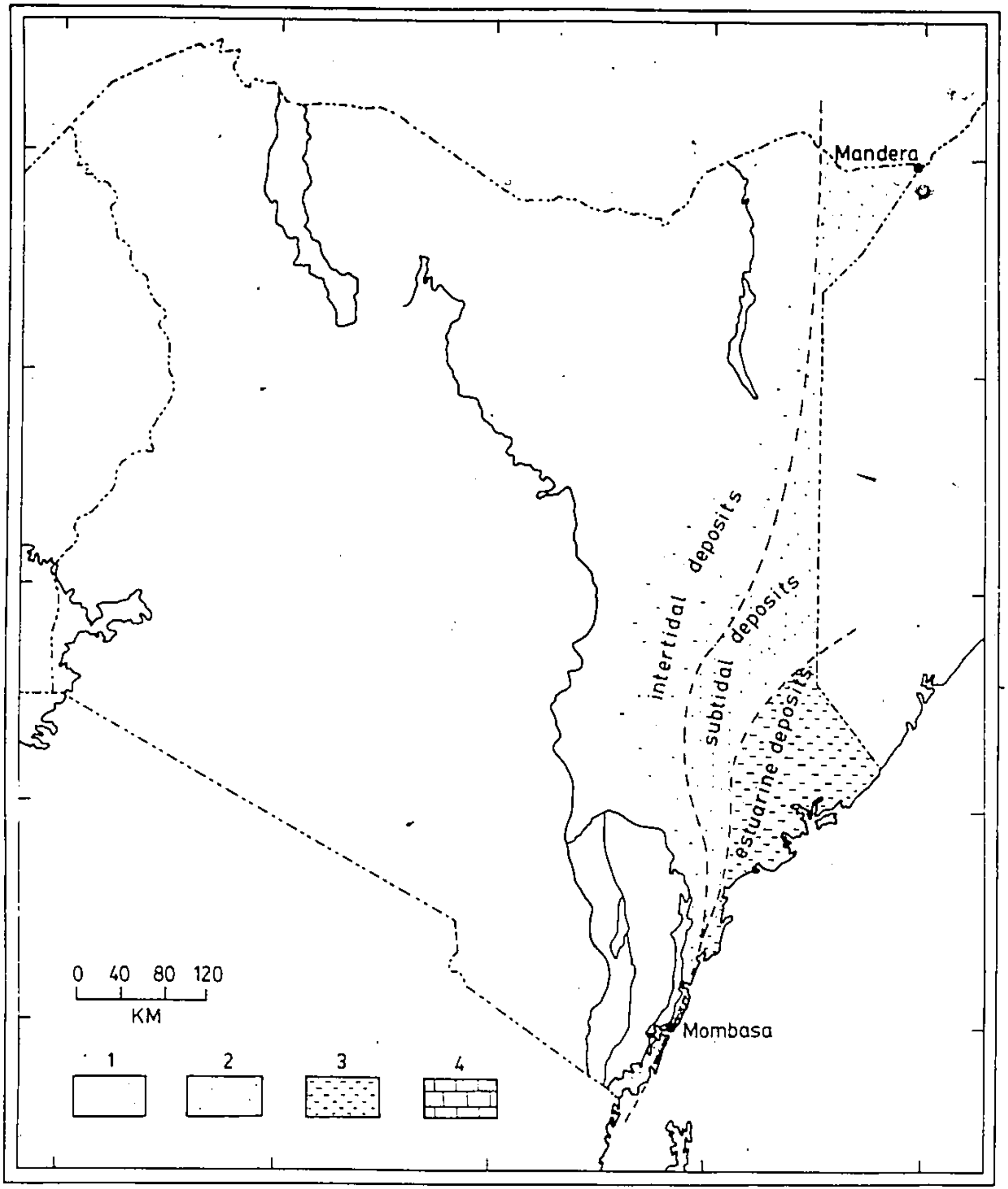


Fig. 16. Sedimentary facies and distribution of the Freretown Limestone and Lower Member of the Danissa Beds (Aptian)
1 - siltstones and shales; 2 - fine-grained sandstones and siltstones; 3 - shales; 4 - limestones.

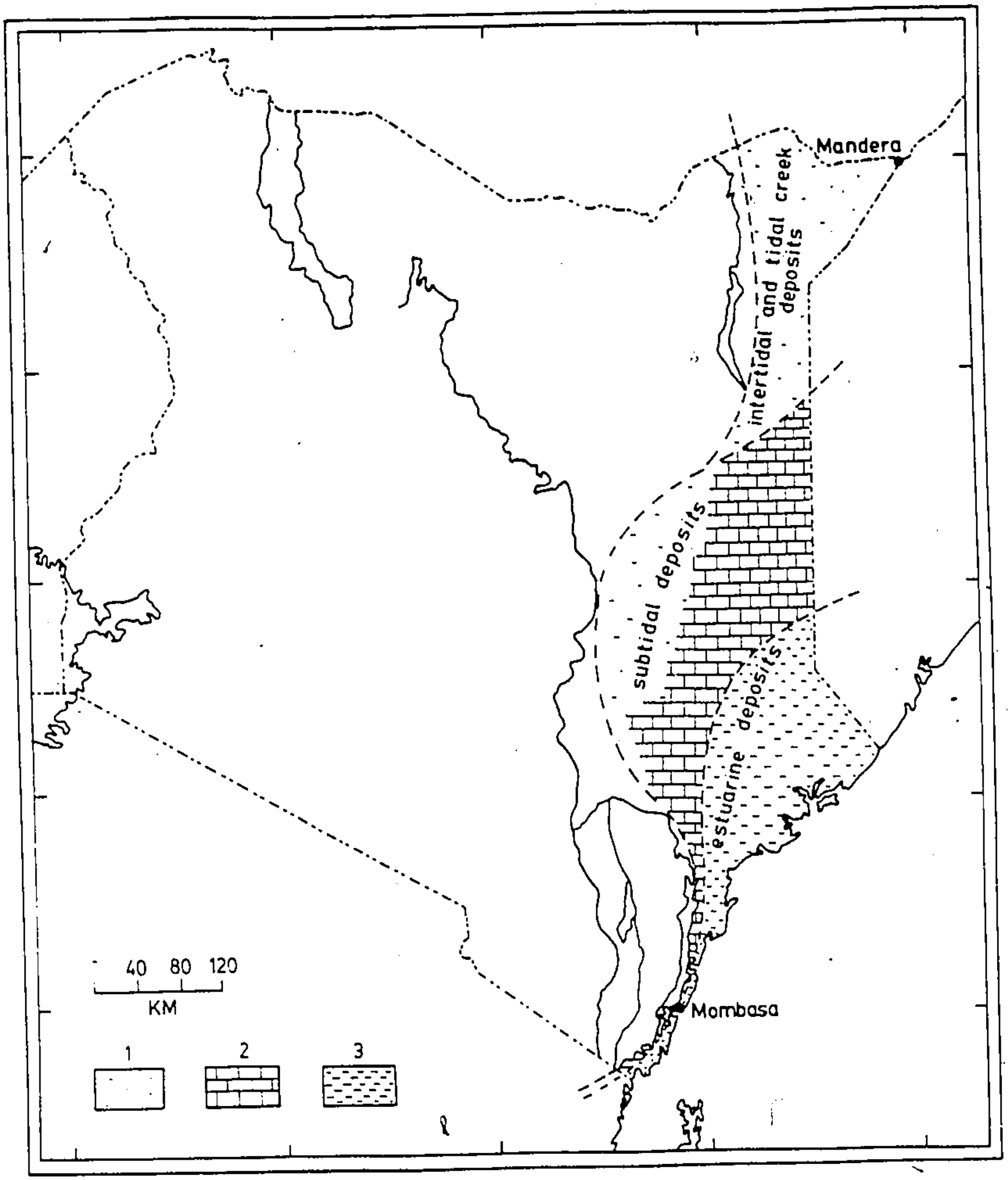


Fig. 17. Sedimentary facies and distribution of the Walu Shale, Danissa Limestone, and Upper Member of the Danissa Beds (Albian-Cenomanian).
1 - siltstones and shales; 2 - limestones; 3 - shales.

bank and depositing lateral accretionary point bar deposits (Allen, 1965). Such channels are sites of repeated phases of erosion and sedimentation, a phenomonon substantiated by the occurrence of vertical _Skolithos_ burrows in an underlying bed at the Ankarass outcrop. Goldring (1964) described similar traces truncated to a common erosion surface, from the Upper Devonian Baggy Beds of North Devon. The process (Fig. 18), begins with the development of a burrow (A). Degradation of the surface promotes deeper penetration (B), in order to maintain a constant depth below the surface. Colonization of the sediments, by more burrowing organisms, results in the construction of new tubes. Subsequent sedimentation, by lateral accretion, leads to the abandonment of some burrows (D and E). As sedimentation increases, all tubes are abandoned and erosion reduces them to a common base (F) below a capping sandstone unit. The sandstone bodies within such settings show little lateral continuity, on account of the complex dendritic pattern of the meandering creeks (Allen, 1965).

The Dutch Wadden Sea tidal flats have been studied in great detail (Van Straaten and Kuenen, 1957) and provide a suitable modern analogue for the Danissa environment.

A south-eastward shift of environments followed the retreat of the shoreline at the onset of the Turonian period (Fig. 19). Marehan Sandstone deposition began in subtidal channels that were the probable extensions of south-eastward flowing rivers, subjected to rapid rejuvenation. The currents within the tidal

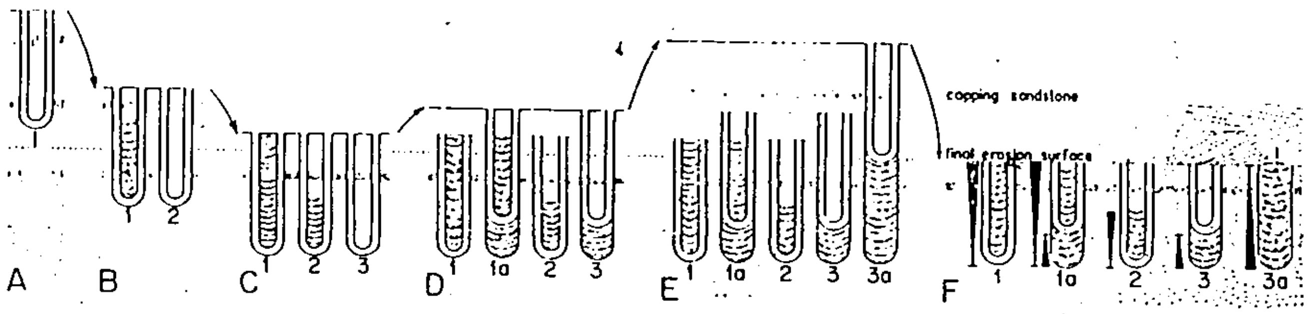


Fig. 18. Development of vertical burrow traces below an erosion surface: (A) development of burrow; (B) degradation of the surface; (C) colonization of surface by burrowing organisms; (E) abandonment of burrows; and (F) sedimentation and erosion of burrows to a common surface, below a capping sandstone unit. (adapted from Goldring, 1964).

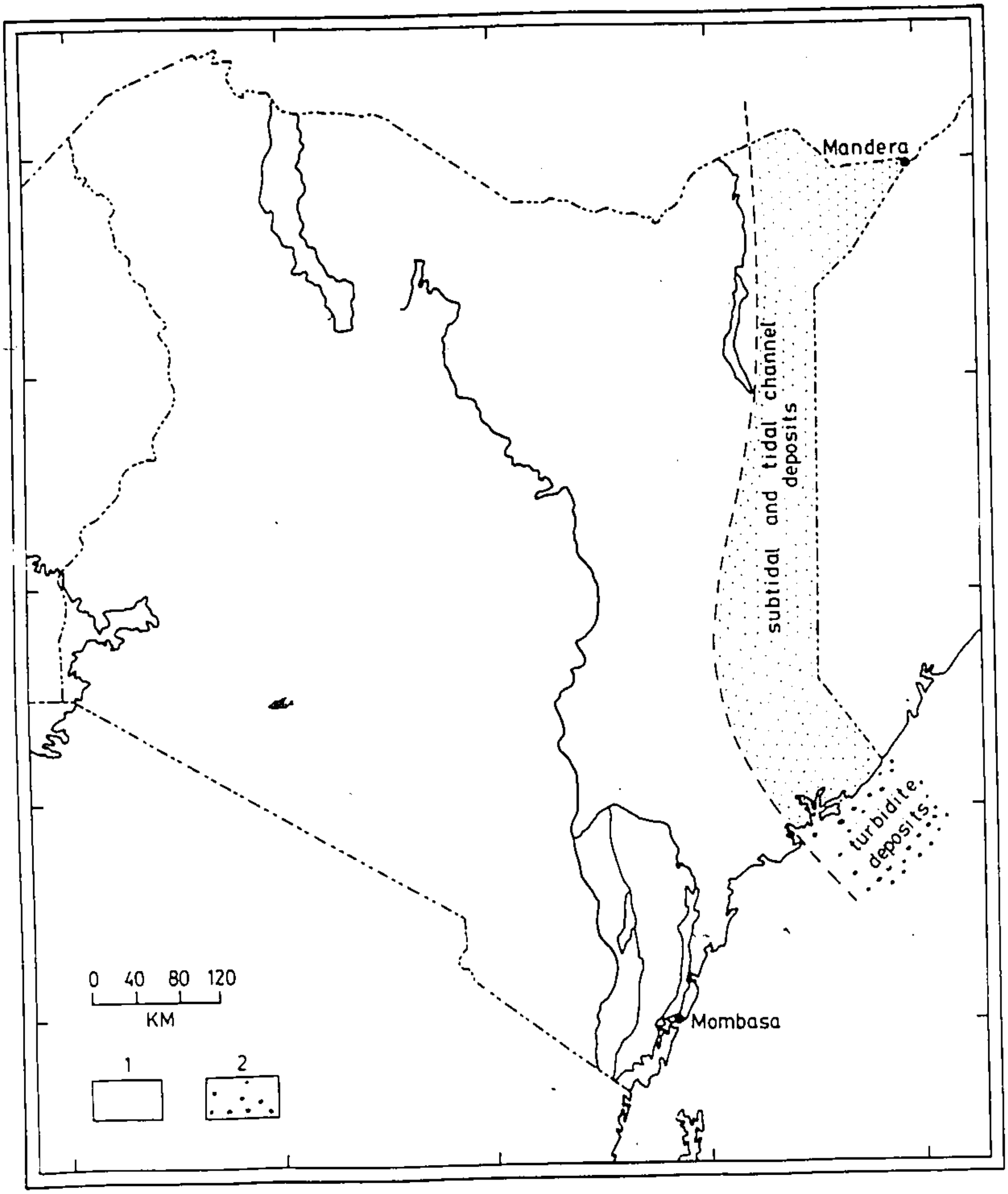


Fig. 19. Sedimentary facies and distribution of the Marehan Sandstone (Turonian-Coniacian).
1 - sandstones; 2 - graded sandstone beds.

channels experienced frequent reversals brought about by tide-generated forces, but in peak periods, were strong enough to attain upper-flow-regime conditions. The juxtaposition of units, produced from contrasting flow velocities, have been attributed to a tidally influenced environment (Bosence, 1973).

The sequential vertical arrangement of strata observed in the outcrop at Kobansu, strongly parallels the sequence described from the Lower Cretaceous Fall River Formation of Wyoming (Campbell and Oaks, 1973). Flood- and ebb-oriented cross-stratification characterize the sand bodies which are interpretrated as channel-fill deposits. Scours cut by tidal currents became depositional sinks of a very local nature, to which small streams grading seaward delivered sediments. The reversals in flow were recorded in the preservation of reactivation surfaces, found associated with the cross-strata. The feature is attributed to erosion of some previously deposited forset, by an ebb or flood current and re-deposition of this sand on the crest of the larger structure. The subsequent flow of the prevailing current, built reverse-dipping forsets that preserved the surface within the set of inclined bedforms (Clifton, 1982). The subtidal channels were capped by a thin veneer of intertidal deposits that built across the channel-fill sequences.

The combined effects of enhanced structural evolution and concurrent river drainage northward and eastward of the south-east retreating shoreline, ushered in a deltaic environment in which the Kipini Sandstone was deposited (Fig. 20). Implications of rapid depositional rates are evident in the development of turbiditic sedimentation, as recorded in the Total Simba No. 1 well and the DSDP No. 241 well, in the later Cretaceous part of the sequence. This phenomenon and other sediment gravity flows related to onshore-advancing deltas, have been documented off the River Rhine in Switzerland (Dott and Bird, 1979) and the Mississippi River (Coleman and Prior, 1982). The depositional model developed for Tertiary sedimentation in the southern Beaufort Sea by Willumsen and Cote (1982), finds application here in interpretation of the depositional environments of the Kipini Sandstone (Fig. 21).

## Depositional Settings of Megasequence III

A destructional process, following Cretaceous-Paleocene deltaic sedimentation, is suggested to account for the restricted environment, in which the first unit of the megasequence was deposited. Wave action and longshore currents, produced by tides such as those prevailing on the present coast, may have re-distributed sediments from the delta front in a shore-parallel fashion. This may have coincided with the time of oceanic divergence, when upwelling deeper waters carried nutrients to shelf settings, thus supporting biogenic production of pelagic sediments. Hence, the Pate Limestone largely developed as an upward-shoaling carbonate sequence, interrupted by minor influxes of terrigenous material. This produced localized cycles of

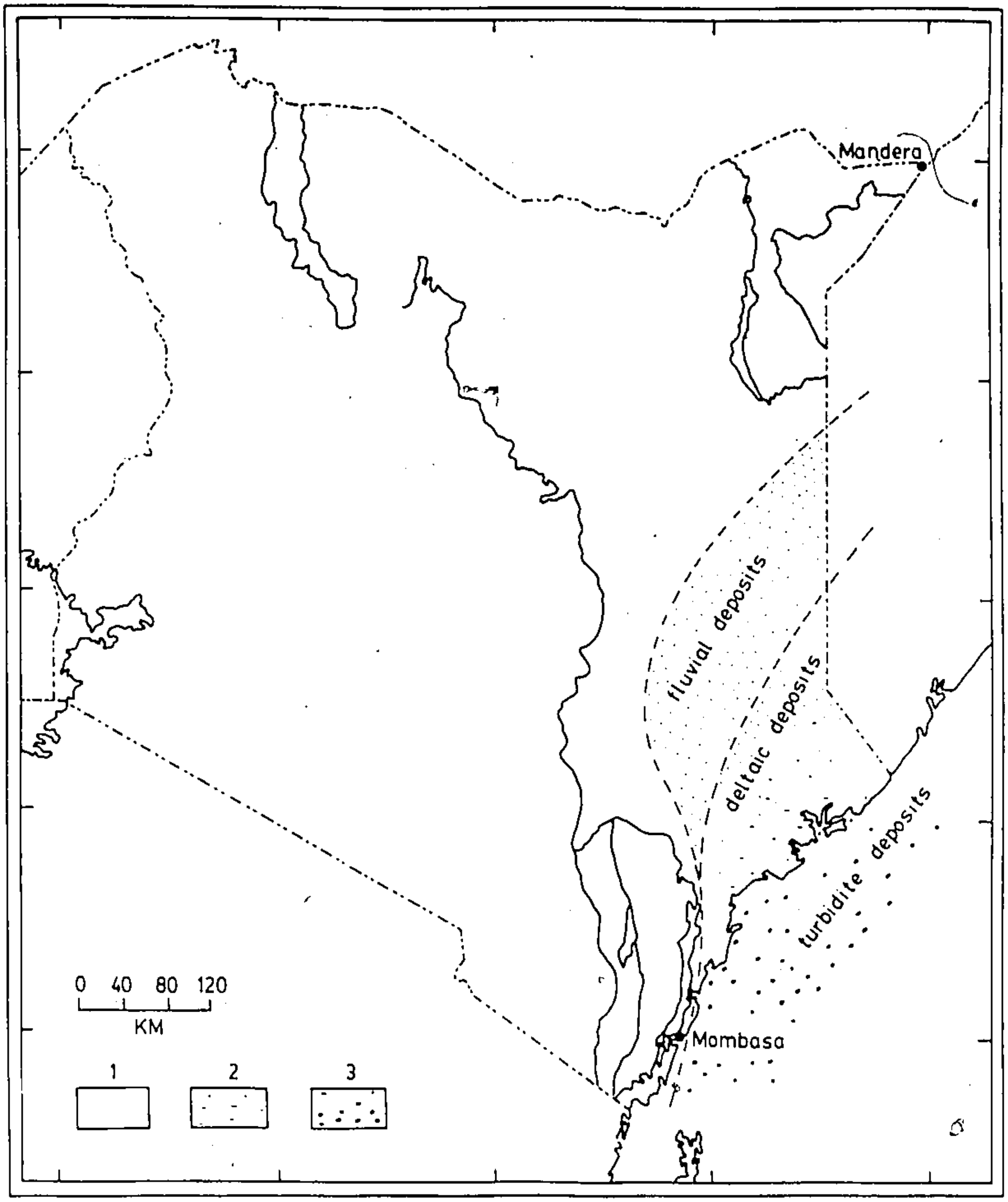


Fig. 20. Sedimentary facies and distribution of the Kipini Sandstone (Santonian - Upper Paleocene).
1 - unconsolidated sands and sandstones;
2 - sandstones, shales and mudstones;
3 - graded sandstone beds.

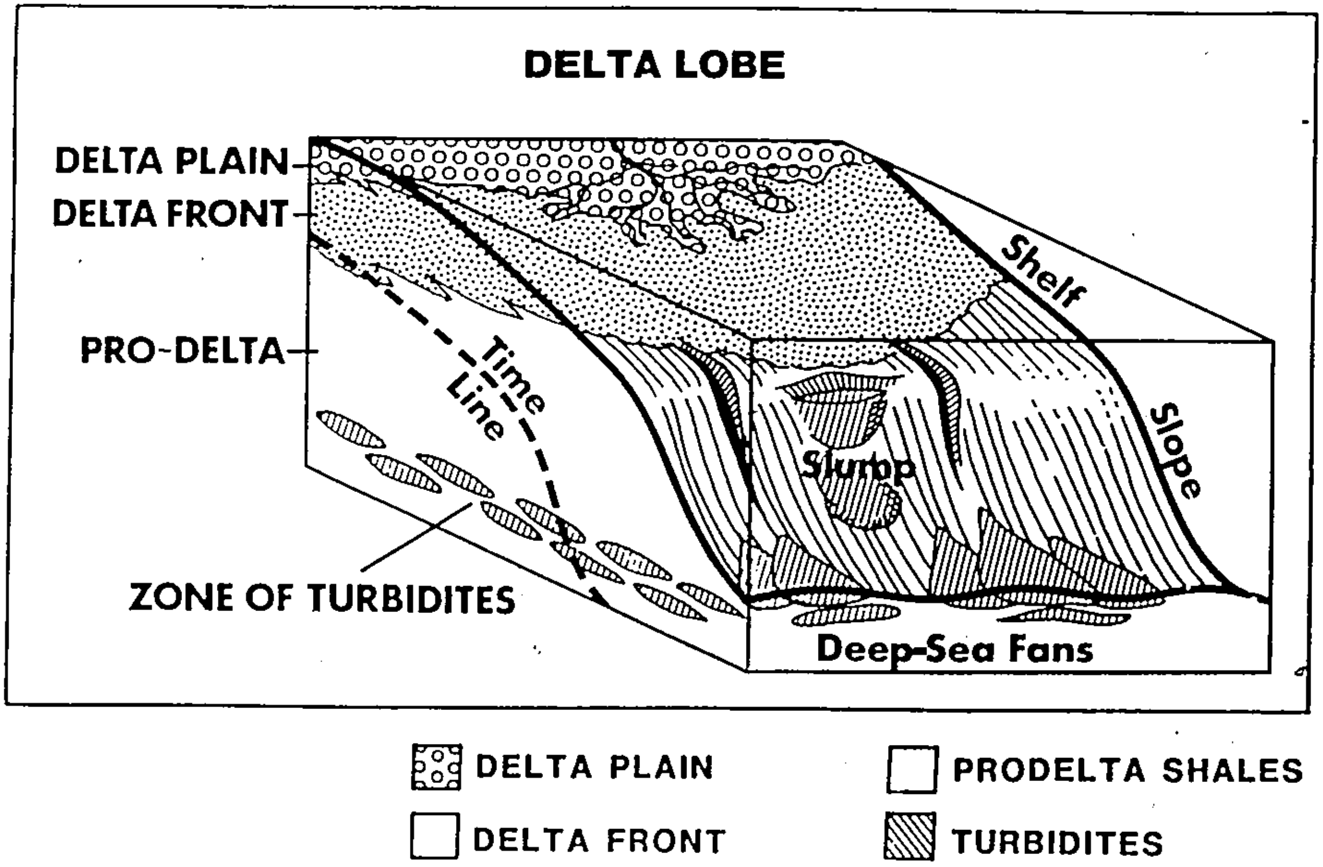


Fig. 21. Schematic diagram showing inferred depositional environments of the Kipini Sandstones. (adapted from Willumsen and Cote, 1982).

carbonate-clastic couplets. The lowermost stromatolitic unit is a typical intertidal deposit, formed on a restricted inner shelf. Likewise the oolitic and ostracodal limestone horizons, overlying the outer shelf carbonate-clastic cycles, characterize the restricted conditions within a shelf edge to middle-shelf and back-reef lagoonal setting. Purdy (1963), in a discussion of the oolitic shoals of the Bahamas Bank, observed that the facies are commonly confined to the part of the shelf lagoon margined by the outer shelf. He related their formation to sea water, supersaturated with calcium carbonate and subjected to great current agitation. Wilson (1975) described a sequence lithologically similar to the Pate Limestone, from the Yoredale Lower Carboniferous of the British Isles. The succession represents limestone and terrigenous clastic cyclothems, within a more complicated cycle. Patch reefs, consisting of various types of organisms, are known from this example and it is likely that similar build-ups rose sharply from the middle shelf lagoonal floor, in the realm of the B.P. Shell Pate No. 1 and the B.P. Shell Dodori No. 1 wells. As noted above, similar observations have been made on the modern Kenya coast. Conversely, the Linderina and Dodori Limestones are outer-shelf facies of open-marine circulation, that formed as well defined carbonate marker beds under non-terrigenous conditions. The intervening sand wedges are interpreted as delta-front facies (Barren Beds). Towards the north-east, these beds accumulated in a fluvial-dominated delta-plain setting, that included distributary channels, giving rise to large-scale cross-bed sets in the B.P. Shell Garissa No. 1 well, and composite, multistorey lateral-accretion deposits with a fining-upward trend in the B.P. Shell Walu No. 2 well. The fining-upward trend has been attributed to channel avulsion (Elliot, 1981).

The overall depositional pattern observed in the south-east, is documented from other areas including several coastal localities, such as the Lofer Cyclothem of the Alpine Triassic and the Eocene cyclic deposits of the Northern Texas Gulf Coast (Fischer, 1964). A simple sedimentologic explanation for the pattern infers conditions of intermittent shoreline flux due to steady subsidence of the shelf, and periodic ingress of terrigenous material on account of shifting deltaic distributaries. Wilson (1975) suggested the term "cyclic-reciprocal sedimentation" for this type of situation. Deepening of waters offshore, due to more continuous or rapid subsidence, commonly resulted in a starved-basin condition. This explanation may be advanced for the absence of the Upper Eocene in the DSDP No. 241 well.

## Depositional Settings of Megasequence IV

The sedimentary facies and general environmental setting of Megasequence IV reveal a repetition of the depositional and tectonic processes that were dominant in the development of the previous megasequence.

The Baratumu Formation, its lateral equivalents, and the

North Mombasa Crag, constitute an identical, upward-shoaling inner-shelf facies that were laid down during periods of sea-level fluctuations. Starved conditions prevailed again in deeper-water settings, as seen in the deposition of only pelagic and windblown sediments in the DSDP No. 241 well and in the absence of the entire Oligocene from the Total Simba No. 1 well. The effects of wind generated ocean currents were probably a supplementary factor in reworking and redistributing the Oligocene sediments onshore to nearshore settings. The nature of the component facies, their rhythmic arrangement, and their impoverished fauna in the Baratumu Formation, reflect restricted and oscillatory environmental conditions. The mudstones represent the lowest-energy unit deposited in an intertidal setting, whilst the conglomerate and overlying unit are indicative of higher-energy conditions, associated with an abrupt and tectonically controlled rise in sea level. Enos (1983) remarked that burrows are the most common structures of the restricted subtidal environment and their preservation is dependent upon slow rates of accumulation and relatively low population numbers. Shinn (1968) has described burrow forms, resembling those of the Baratumu Formation from the lime muds of Florida and the Bahamas. He accredits the traces to the crustaceans _Alpheus_ and _Callianassa_ that burrow into subtidal and intertidal deposits. Such a burrowing infauna persists in an oxygen-deficient environment, where a shelly epifauna is less likely to survive. During the intervening periods of cyclic subsidence and tilting of the hinterland, increased river gradients resulted in regressive progradation and deposition of the Lower Magarini Sands and the Merti Beds in fluvial settings. The rapid rate of sea-level fall caused terrigenous material and fine carbonate detritus to bypass the continental margin and accumulate offshore in a bathyal environment.

## SEDIMENTATION AND TECTONICS

The Cretaceous and Tertiary sedimentary cover occupies the greater part of eastern Kenya and is underlain by three types of basement in the extreme south-east: continental, transitional and oceanic (Kent, 1982). The continental crust under the inner shelf is marked by partly exposed and buried rift basins, and to the landward side by epeirogenic structural units, formed during Late Cretaceous movements. The general structure is an example of Atlantic-type continental margins, consisting of a seaward- thickening mass of stratified sediments, overlying a faulted and subsided basement platform. Figure 22 hypothetically illustrates the general scheme of evolution, and summarizes the salient tectono-sedimentary features defining the various phases of genesis.

The phase relevant to this study is the post-rift stage, characterised by passive development. Preceeding continental break-up, initiation of north-south, north-east to south-west and north-west to south-west lineaments created a structural fabric upon which the earliest rifts were superimposed, and

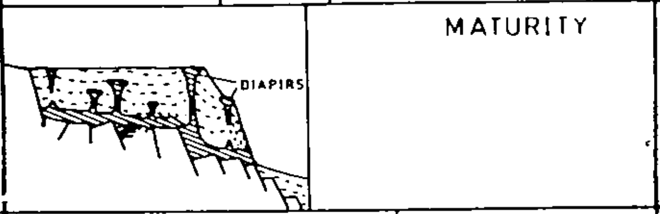
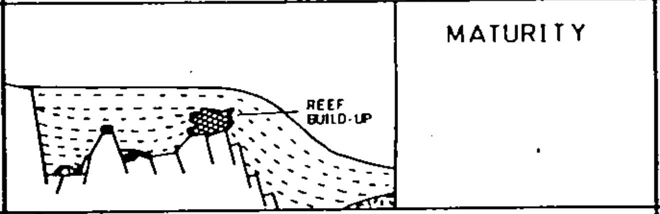
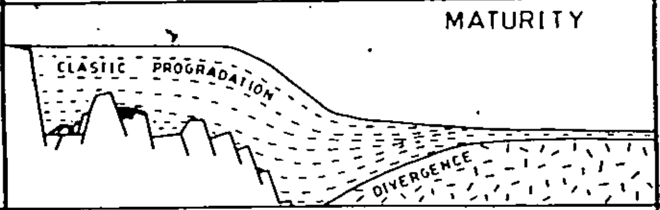
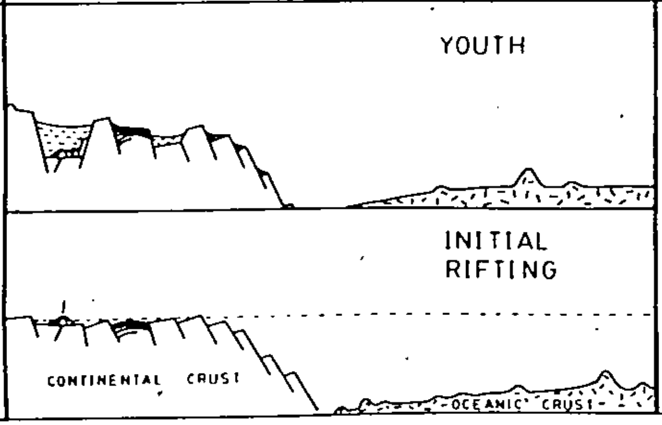
| TIME | SHELF | SLOPE | RISE | MAIN TECTONO-SEDIMENTOLOGIC FEATURES | |
|---|---|---|---|---|---|
| MIOCENE TO PLIOCENE |  | | | • Development of east African coastal fault trending NE-SW<br>• Hypersubsidence and syn-tectonic faulting<br>• Domal uplift in central Kenya, trough faulting<br>• Transgressive overstepping, dolomitization, fluvial sedimentation and salt diapirsm | MEGASEQUENCE IV |
| EOCENE TO OLIGOCENE |  | | | • Development of barriers and marine restriction<br>• Sediment-load-controlled margin subsidence along NE-SW hinge<br>• Cyclic-reciprocal sedimentation and growth of reefs | MEGASEQUENCE III |
| CRETACEOUS TO PALEOCENE |  | | | • Development of Owen fracture and drift of India<br>• Uplift of basement and Megasequence I rocks generating Anza basin and related structural elements<br>• Deltaic and turbiditic deposition, gravity tectonics | MEGASEQUENCE II |
| CARBONIFEROUS TO JURASSIC |  | | | • Rejuvenation of basement lineaments<br>• Rifting and separation of Madagascar<br>• Block faulting and graben formation<br>• Carbonate-evaporite deposition<br>• Intrusive volcanism | MEGASEQUENCE I |

Fig. 22. Hypothetical diagram illustrating general evolutionary scheme of the south-east Kenya, Atlantic-type continental margin. (adapted from Emery, 1980).

progradational sediments accumulated. After the movement of Madagascar along the Davies Fracture, in Early to Middle Jurassic time the paleo-Tethyan Sea invaded the Trans-Erythrean trough (Fig. 23), depositing carbonates and evaporites in the Ogaden, Mandera-Lugh and Lamu Basins. The overall events pertain to deposition of Megasequence I.

The compound effects of subsidence in marginal areas, and the waning of mantle convection, caused withdrawal of the Jurassic sea south-eastwards to ultimately form the Indian Ocean. This accompanied the Late Jurassic - Early Cretaceous phase of faulting. Uplift of Megasequence I and the Precambrian Basement in the west revitalized river drainage and induced deltaic sedimentation in Neocomian time. The contemporaneity in this phase of erosion and deposition of orthoquartzites along the East African coast is remarkable. Equivalent and distant movements occurred as far north as Somalia, as part of a rejuvenated rise of the Arabo-Somali massif (Kamen-Kaye *et al*. 1979). The succeeding transgression was a world-wide eustatic event, that may be related to the fragmentation of the India-Madagascar-Antarctica block, and movement of India along the Owen fracture. The rupture was an expansion of the mid-Atlantic ridge system into the Indian Ocean (Donovan and Jones, 1979). This phase of tectonic instability is linked with the pronounced fracturing of Aptian strata, allied hydrothermal activity and the slump features in the Albian Walu Shale. The second phase of epeirogenic uplift, concomitant

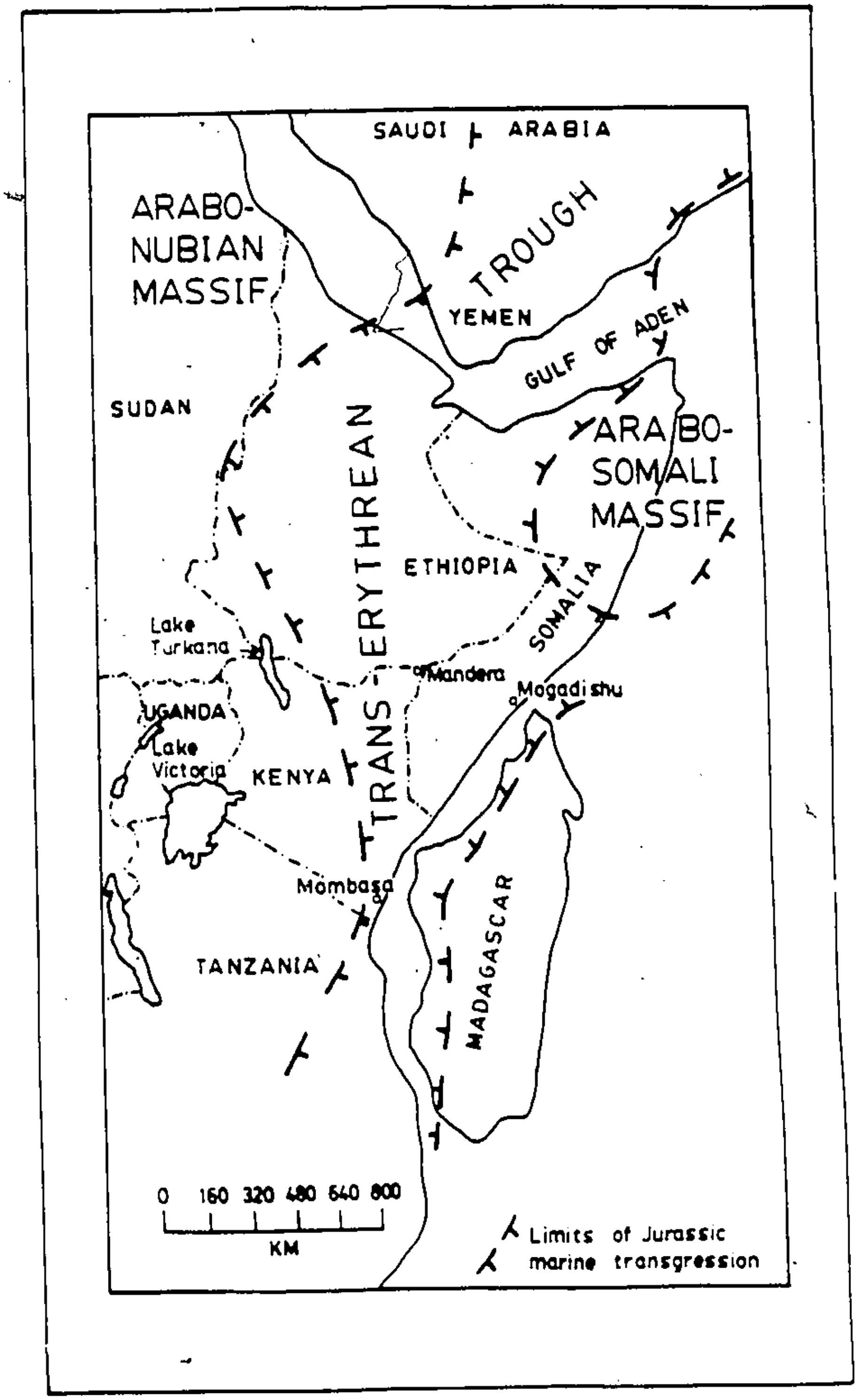


Fig. 23. Paleogeographic reconstruction of the Trans-Erythrean trough showing extent of the Jurassic-Tethyan transgression. (modified from Saggerson and Miller, 1957).

with the deposition of the Marehan Sandstone and distal turbidites offshore began during the Turonian. The phase was responsible for the genesis of the Mandera-Lugh Basin proper (Beltrandi and Pyre, 1973) and related structures, through renewed differential movements of north-east to south-west striking faults. The Ethiopian highlands probably reached advanced elevation levels in this period, and provided some of the source clastics that prograded towards the retreating estuary in the south-east. The estuary was probably of fault-block type (Biggs, 1976) and controlled by the regional geologic structure. Towards the end of the Turonian and the Coniacian, uplift of the basement to form the ridge extending from the offshore basin, parallel to the Davies fracture into the onshore area along the Walu-Kipini-Garissa trend commenced. This assumption is related to the absence of the Turonian and Coniacian intervals in the B.P. Shell Walu No. 2 well and farther south in Tanzania. The fault cutting Albian strata in the well in association with this uplift restricted the Turonian sediments to tidal channels east of the B.P.shell Walu No. 2 well. The tectonic upheaval acquired prominence in end-Cretaceous time when the Garissa, Walmerer, Hagarso and Bur Acaba structural units emerged substantially. Rifting affiliated to the formation of the Anza graben, between the Lagh Boghal and north-west Garissa faults, also took place at this time. The end of the Cretaceous Period is known to have coincided with a marked deterioration in faunal diversity world-wide (Ager, 1981). Hays and Pitman (1973) related this to increased ocean-floor spreading and enhanced thermal gradients.

Erosion of the Upper Cretaceous successions in Megasequence II was most severe along the trend of the above uplifts, which became the dominant sediment source areas for the lobate Paleocene delta, rapidly built out toward the newly formed Indian Ocean. The Dodori-Pate area contemporaneously evolved into a synclinal feature, continuous into both coastal Somalia and Tanzania, and received substantial quantities of the terrestrial detritus. The strandline migrated beyond the shelf edge to initiate deposition of proximal turbidites offshore. It is probably during the development of this regressive deltaic-offlap sequence that growth faults, clay diapirs and overthrusts, known from similar settings elsewhere, might have evolved. Dailly (1976) observed such features at the base of the Niger, Mississippi and Mackenzie deltas and related the disequilibrium, producing such structures to the superposition of rapidly deposited sand wedges on undercompacted shales. The Total Simba No. 1 well was terminated in similar shales.

Progradation of the deltaic wedges established a new configuration of the continental shelf. This might also have caused substantial flexural loading and subsidence, off the shelf area along a fixed landward north-easterly axis. These movements prevailed in episodes during deposition of Megasequence III deposition, resulting in oscillations of sea level. The western and north-eastern regions were again uplifted, followed by the erosion of Paleocene and Lower Eocene strata, and an influx of clastics eastwards and south-eastward. During high stands of sea-level, the clastics were arrested far from the shoreline and carbonate production dominated the shelf, with little or no deposition in the deeper subsiding offshore basin. It seems logical to suggest more regional influences to the sea level motions during Eocene time. These were simultaneous with mantle-wide convective motions, affecting the Afar region and the early stages of formation of the Red Sea graben (Girdler and Styles, 1974). The attendant volumetric changes in the capacity of the Indian Ocean (Pitman, 1978) may have had significant impact until the Late Eocene. The Early Oligocene regression coincided with extensive glaciation in Antarctica (Shackleton and Kennet, 1975) and a corresponding drop in sea level and water temperatures.

The importance of differential vertical faulting and structural reversals heightened during the phase of Megasequence IV sedimentation. The main elements conformed to the pattern of the basement grain and had a genetic affiliation to the developing central Rift Valley. Warping along the Kenya-Uganda border in Upper Oligocene, was accompanied by deformation east of the Tana River and in the Turkana area (Saggerson and Baker, 1965). The aftermath was the development of fold belts and fault trends that controlled the regularity of the coastline and degree of restriction of the marine waters. Dolomitization in the upper sections of the Lower Miocene carbonates along the Garissa-Walu-Kipini and Simba trend confirm that the areas were structurally elevated and subsequently submerged at the time of this transgression. A model relating shoaling-upward carbonate sedimentation and dolomitization, has been put forward by Wilson (1975). The requirement of a relatively positive area is considered vital in furnishing the hydraulic head for the volume of fresh phreatic water needed to interact with meteoric marine water. The Garissa-Walu-Kipini anticline may therefore have been connected with the offshore Tembo and Simba anticline (Davies fracture) in Oligocene time. Drowning of these local uplifts also permitted reefal growth, which was further enhanced by the orientation of the south equatorial currents trending normal to the major structural direction. The syntectonic conglomerate at the base of the Lower Miocene carbonates follows the trend of the Mombasa fault system, which downthrows the sequence against the older Megasequence I and II successions. Faulting also occurred along the coasts of Somalia (Peterson, 1986) and Tanzania (Kent, 1974). Slumping in the offshore the Cities Services Maridadi No. 1B well, was a consequence of this tectonic activity. The Pate and much younger Kofia sub-basins received large thickness of sediment and experienced a cyclic tectonic style that has been termed as hypersubsidence (Kamen-Kaye, 1967). The anomalous reduction in thickness, of Lower Miocene strata in the B.P. Shell Pate No. 1 well has been mentioned.

The domal uplift on which the meridional Rift Valley was formed, was initiated at the end of Middle Miocene time, terminating the latest Oligocene to Middle Miocene transgression.

The deformation was contemporaneous with north-south and north-west to south-east trough faulting in the Tana Valley, forming minor basins such as the Skot trough (Wright and Pix, 1967), floored by unconsolidated sediments and occurring on the western boundary of the sedimentary basin region. The uplift asserted a strong northward and south-eastward drainage, that transported coarse-grained erosional by-products oceanward and to the faulted depressions at rapid rates. The Marafa and Midadoni Beds were the result of such sedimentation. This regression was commensurate in time frame with the collision between the Indian sub-continent and Eurasia, uplifting the Himalaya mountains. An increase in the Indian Ocean basin capacity, due to the extensive continental crustal shortening (Pitman, 1978), gave rise to eustatic sea-level fall.

The northward prolongation of the Carlsberg Rift system, connecting the Red Sea with the Indian Ocean, may be linked with the Upper Miocene transgression responsible for the deposition of the North Mombasa Crag. It came to a conclusion in the Pliocene with the final and most outstanding deformational and volcanic activity, associated with the Rift Valley tectonic paroxysm. The rejuvenated fluvial regime culminated in the deposition of coarse clastics, including volcanic debris and windblown ash onshore and offshore. The conformity between the depositional trend of the Merti Beds, Lower Magarini Sands and the fluvial sediments of the Turkana basin with the Late Tertiary drainage pattern has been noted. The salt-diapiric movements recognized offshore may have reached a significant stage of development, following these last phases of shoreward clastic progradation.

# HYDROCARBON PROSPECTS

## GENERAL REMARKS

The rationale underlying the following hydrocarbon resource appraisal hinges on: the established time-stratigraphic framework; environmental interpretation of the different facies; and regional paleogeographic reconstruction. Emphasis is placed on stratigraphic prospects and combination traps related to unconformities. Inferences concerning basin hydrodynamics are tentative in the extreme. The suggested prospects are intended to provide directions for further detailed investigations as more subsurface data become available. Table 7 provides a summary of the different prospective facies, their general location with respect to the present exploration acreage (Fig. 24) and related stratigraphic units.

## PROSPECTS FOR STRATA OF MEGASEQUENCE II

The Danissa Limestone (Albian) in the north-eastern section of Block 4 between longitude 40° E and 41° E including the portion of Block 5 north of latitude 2° S, possesses excellent entrapment capabilities. The limestone grades down-dip into the Walu Shale, an estuarine deposit with source rock characteristics. An updip barrier is provided by truncation against the Cretaceous-Tertiary unconformity, on the southern flanks of the Walmerer structure. The combined effects of burrowing and permeability-enhancing diagenetic effects, may have

TABLE 7: PROSPECTIVE FACIES IN CRETACEOUS THROUGH TERTIARY STRATA OF THE EAST KENYA SEDIMENTARY BASINS

| | STRATIGRAPHIC UNIT | AGE | MAIN DEPOSITIONAL SETTING | PROSPECTIVE SEDIMENTARY FACIES | APPROXIMATE DEPTH (b.s.l.) | APPROXIMATE THICKNESS | LOCATION |
|---|---|---|---|---|---|---|---|
| MEGASEQUENCE IV | Baratumu Formation | Early to Middle Miocene | Inner shelf to Continental Slope | Subtidal bioclastic limestones | 300-1700m | 10-20m | South-east section of Block 5 adjacent offshore area including Block 6, i.e. the area east of longitude 40°E and between latitudes 1°S and 4°S. |
| | | | | Carbonate slump deposits | | over 30m | |
| | | | | Sandstone wedges related to salt diapirsm | | | |
| MEGASEQUENCE III | Barren Beds | Middle Eocene to Oligocene | Fluvial and Deltaic | Lenticular point bar sands and sandstones | 500-700m | 20-30m | Block 4, eastern half of Block 8 east of longitude 39°30'E, western half Block 5 west of longitude 40°45'E. |
| | | | | Distributary channel Shoestring sands | | 30-50m | |
| | | | | Delta front sheet sands, associated with growth faults turbidites and slump deposits | | 15-30m | South-east section of Block 5 and adjacent offshore region including Block 6, i.e. the area bound by longitude 39°E and 41°30'E and latitude 40°S to the equator. |
| | Pate Limestone | Early Eocene to early Middle Eocene | Middle shelf to shelf edge | Back-reef oolitic shoal facies | 3000m | 300m | |
| | | | | Patch reefs | | 10-15m | |

TABLE 7 (Cont'd)

| | STRATIGRAPHIC UNIT | AGE | MAIN DEPOSITIONAL SETTING | PROSPECTIVE SEDIMENTARY FACIES | APPROXIMATE DEPTH (b.s.l.) | APPROXIMATE THICKNESS | LOCATION |
|---|---|---|---|---|---|---|---|
| MEGASEQUENCE II | Kipini Sandstone | Santonian to Upper Paleocene | Deltaic | Delta front sheet sands, associated growth faults turbidites and slump deposits | over 3000m | 35-50m | South-east section of Block 5 and adjacent offshore area including Block 6, i.e. the area east of longitude 40°E and latitudes 1°S and 4°S. |
| | Marehan Sandstone | Turonian-Coniacian | Tidal flat | Tidal channel sandstones | 700-1200m | 10-15m | Central section to Block 5, between latitude 1°S and 1°30'S. |
| | Danissa Limestone | Albian | Tidal flat | Subtidal bioclastic limestones | 1300-1500m | 120m | North-east of Block 4, between longitude 40°E and 41°E including the northern section of Block 5 north of latitude 2°S. |

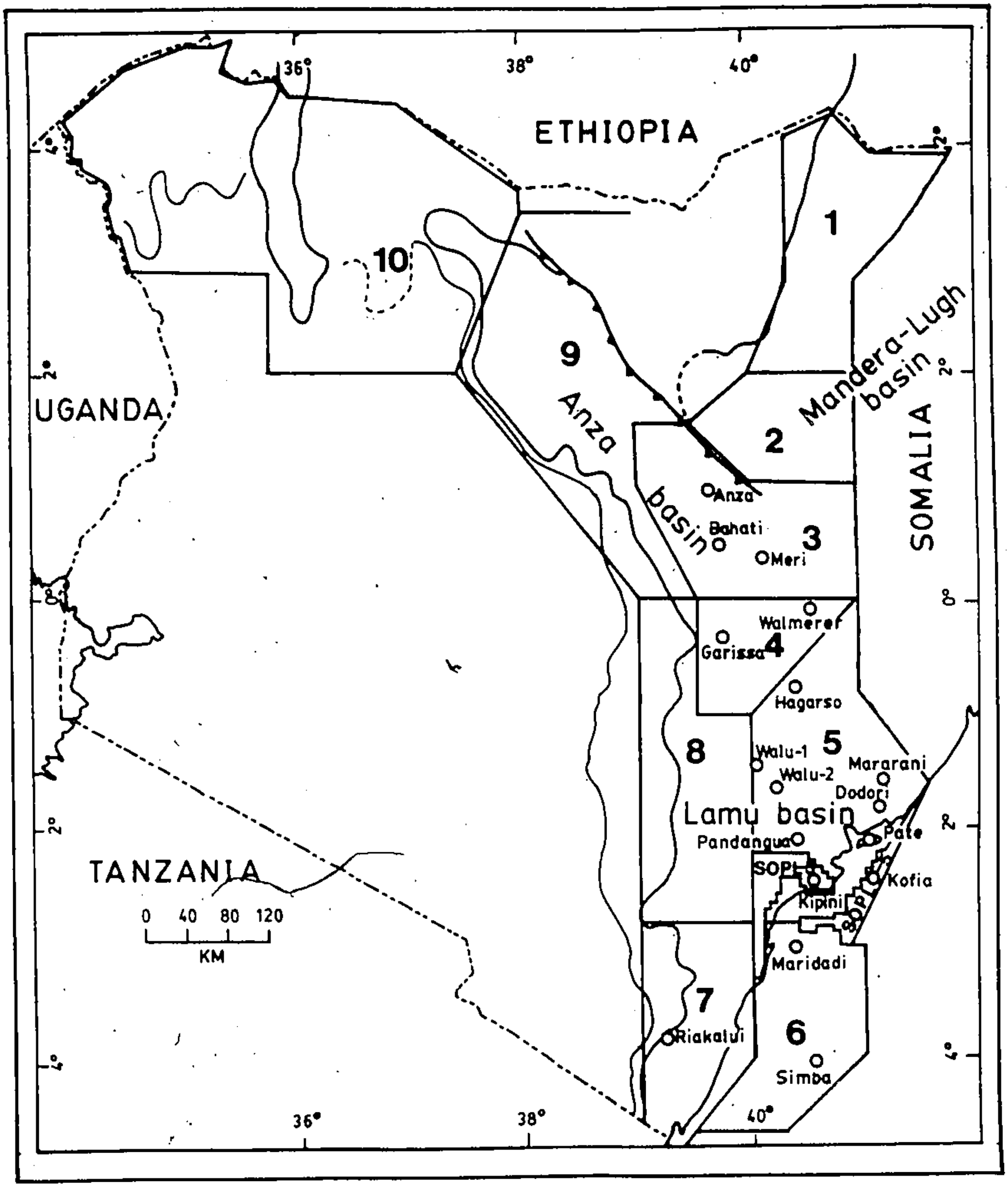


Fig. 24. Location map showing boundaries of present exploration blocks in the sedimentary basin regions of eastern Kenya.

produced the essential reservoir qualities. The presence of anhydrite and calcite filling, veins in limestones penetrated by the B.P. Shell Hagarso No. 1 well, limits the prospective section to the area between Walmerer and Hagarso. As much as 120 m of carbonate may be expected in the zone at a depths of 1300 to 1500 m below sea level.

The southward subsurface prolongation of tidal-channel deposits in the Marehan Sandstone offers prospects in the central sector of Block 5, south of the Texas Hagarso No. 1 well and north of latitude 1° 30'. On the basis of outcrop observations, the sandstones have a high degree of textural maturity, and form units of 10 to 15 m with good porosity. The sandstones abutt against the Cretaceous-Tertiary unconformity on the Hagarso structure at depths between 700 to 1200 m and are collateral with the Walu Shale.

Multiple stratigraphic and stratigraphic-structural traps, associated with the Santonian to Upper Paleocene deltaic deposits, are considered likely for areas bounded by longitude 40° and 42° E and latitude 1° S and 4° S. The area includes the south-eastern section of Block 5, the adjoining offshore region and the entire area enclosed by Block 6. The setting characterized by the conjunction of reservoir beds, seals, source materials and rapid deposition provides a maximum interplay between these factors. The offshore area has a number of trapping possibilities that combine stratigraphic and structural entrapment configurations. These include: deltaic facies draped over deep seated basement horsts, deltaic sand bodies rolled over growth faults or abutting against the faults, and updip pinchouts of turbiditic sands, sealed by pro-delta clays or associated with shale diapirs.

## PROSPECTS FOR STRATA OF MEGASEQUENCE III

The Eocene to Oligocene fluvio-deltaic and shelf deposits, underlying the area between longitudes 39° E to 41° 30' E, and north from 4° S to the equator, provide good prospects. The present shelf setting, coinciding with the south-east section of Block 5, the adjacent offshore including Block 6, is underlain by the transgressive-regressive cycle wedges, corresponding to the intertonguing of delta front sands of the Barren Beds and carbonate strata. The carbonate strata constitute the Pate, Linderina and Dodori Limestones. The entire sequence has geologically similar prospects with the same source-reservoir trap controls. The Pate Limestone is a promising target at a depth of 3000 m below sea level. It comprises high-energy oolitic and micro-oolitic limestone lenses, overlain by an ostracodal limestone. Initial porosity and permeability in the ostracodal limestone has been lost through micritization and dolomitization. The oolitic strata have produced gas in solution, through the drill stem, which may have originated in the lower-energy offshore deposits or in the underlying algal stromatolites. Shelf-edge patch reefs, considered to occur in association with this facies, are possible offshore targets.

The delta-front sands provide other alternatives but are likely to incorporate heterogeneities in greater amounts. The end members of the regressive sequence, transported by a variety of gravitational processes along submarine channels, form better-quality reservoirs offshore. Traps formed by syn-sedimentary faulting are also likely. Multistoried and upward-coarsening sandstone deposits of distributary and fluvial channels, occur north-west of the shelf, in the areas bordering the present Tana river system. Both hydrodynamic and unconformity-related trapping conditions may exist on the southern flanks of the Walu, Hagarso and Walmerer structures. The Lower Miocene calcareous mudstone, traced in the outcrop of the Baratumu Formation and into the subsurface as far as the B.P. Shell Walmerer No. 1 well, could constitute a regional cap rock. The sandstones occur at an approximate depth of 700 m below sea level.

## PROSPECTS FOR STRATA OF MEGASEQUENCE IV

The potential reservoir strata falling within the depositional spectrum of Megasequence IV constitute a carbonate facies. These include bioclastic limestones of the Baratumu Formation, occurring at depths ranging from 300 to 1700 m along the trend of the offshore Cities Maridadi No. 1B well to the B.P. Shell Dodori No. 1 well. The facies grade from the offshore starved-basin argillaceous deposits, to the upslope cycles of alternating bioclastic limestones, calcilutites and calcareous mudstones. They occur below the Middle Miocene unconformity, a situation likely to have imposed a diagenetic overlay, enhancing reservoir quality in the carbonates. The strata truncate the Middle Miocene unconformity, near the B.P. Dodori No. 1 well, thus providing a prime drilling target. Bitumen showings, are observed in cores from the Lower Miocene rocks in the B.P. Shell Dodori No. 1 well (899.4 to 901.2 m and 1122 to 1123.2 m). The bioclastic debris, transported by mass movement downslope to sites adjacent to the Cities Maridadi No. 1B well, provide alternative reservoirs below the shelf margin. Salt intrusions piercing reservoir units of Megasequence II, Megasequence III, and Megasequence IV in the offshore region would provide excellent settings for traps, related to sandstone pinchouts, local unconformities, and faulting.

## REGIONAL HYDRODYNAMICS, GEOTHERMAL REGIMES AND ACCUMULATION PARAMETERS

Hitchon (1984) established a relationship between regional hydrodynamic flow patterns, geothermal gradients and hydrocarbon occurrence for the western Canada sedimentary basin, a model that may be equally applied to the south-east Kenya coastal basin. The main premise of the model suggests that: 1) regions of high elevation correspond with areas of high water-table elevation; 2) regional recharge of cold meteoric waters and hence low, geothermal gradients; and 3) the regions of low relief, corresponding with areas of sediment compaction, control the discharge of warm interstitial waters and have high geothermal gradients. Meteoric water movement takes place from higher structural elevation to lower areas, whereas formation waters move towards the structural highs (Magara, 1977). Hydrocarbons generated in the areas of high geothermal regime are squeezed out of the rock interstices as particles entrained in the formation waters (Levorsen, 1954) and transported up-dip to accumulate at the sites where the two flow systems meet. An up-dip change in lithology in the stratigraphic section is prerequisite. The down-dip system reinforces the trap capacity to impede further upward movement. The regional flow pattern is of general significance and based on the assumption that reservoir strata possess homogeneous permeability. In such assessments, the variation of topographic relief through geologic time has to be considered.

The occurrence of most of the world's hydrocarbon reserves in Cretaceous strata has been attributed to the geologic events in Late Mesozoic time (Arthur and Schlanger, 1979). Many parts of newly formed ocean floors and various sites along new continental margins, lay within or below oxygen-deficient waters. These enhanced the preservation of organic matter in shelf, slope and basinal facies. An explanation that may be advanced for the presence of organic-rich shales, in Jurassic and Lower Cretaceous strata of the East African coastal basins. Source rocks of Aptian through Turonian age have been identified from deep sea cores drilled along the western coast of Africa. These were related to the break-up of South America from the West African coast and the development of euxinic basin conditions (Lehner and De Ruiter, 1976). The period following the Middle Cretaceous transgression was marked by a faunal crisis, that was the result of a contrast in ocean circulation and increased geothermal gradients (Hays and Pitman, 1973). This concept may have implications for maturation of the Jurassic and Lower Cretaceous source rocks of the East African coast. Hydrocarbon generation could only have taken place if the termperature history of the source sediments was sufficiently intense and if the nature and amount of organic source material was appropriate. Pusey (1973) proposed the liquid window concept, whereby with increased temperature a progression from biogenic gas to oil to thermal gas occurs. The oil phase occurs between 65° C and 150° C at depths ranging from 750 and 5000 m. In Tertiary sequences, where higher gradients are considered essential the range of the oil window is estimated as 115 to 150° C.

The Late Cretaceous orogenic upheaval of basement and Megasequence I strata, was influential in the subsequent migration and possible accumulation of these hydrocarbons. The uplift gave rise to the Garissa, Walmerer, Hagarso and Bur Acaba structures on the northern margins of the Lamu basin. A south-east flowing recharge regime, corresponding to these relief elements and an updip migration of hydrocarbons from the centre of the Lamu basin, is suggested. Bitumen stainings observed in Paleocene strata of coastal Kenya and Somalia, are possible indications of associated hydrocarbon flushing toward the recharge foci. Accumulations could have taken place in any of the reservoir units of Megasequence II strata, discussed in the previous section. The regional discharge regime probably existed until Late Tertiary time converting into a somewhat radial pattern, which diverged from the central Kenya domal uplift.

The Tertiary episodes of subsidence, cyclic-reciprocal-sedimentation, faulting, and halokinesis were important from the standpoint of hydrocarbon formation and migration. Royden _et_ _al_. (1980) observed that starved ocean basin conditions following basin subsidence are critical in limiting compaction and conductivity and hence the development of favourable, shallow, thermal regimes. The pattern of alternating periods of subsidence and sedimentation brought about source and reservoir sediments into spatial and temporal coincidence. The associated uplifts and unconformity surfaces that were formed during the Tertiary depositional period of the Kenya coastal basin, facilitated generation, migration, and ultimate entrapment of hydrocarbons.

Thermal maturation of shales at very shallow depths, has been associated with abnormally high geothermal gradients created by underlying piercement salt domes (Rashid _et_ _al_., 1977). This relationship has been established in the Scotian basin, and attributed to hot fluids migrating up the sides and across the tops of the diapirs. The intrusive effects provided expulsion pressures, resulting in the discharge of hydrocarbons into off-flank reservoirs (Keen, 1983). Geothermal gradients determined in the offshore area in the Total Simba No. 1 well indicate a favourable regime existed for gas generation from Upper Cretaceous and Lower Eocene shales (Okoth, 1982).

## REGIONAL HYDROCARBON OCCURRENCES

Numerous showings of oil and gas in Cretaceous through Tertiary strata, have been observed in various stratigraphic units of the east African coastal basins (Table 8). The presence of gas shows in Albian shales of the B.P. Shell Walu No. 2 well, coincide with similar indications from the Agip Kizimbani No. 1 well of coastal Tanzania, and the Cretaceous anoxic events.

Siciclastic reservoirs yielding hydrocarbons are known from the Cretaceous strata penetrated by the T.P.D.C. Songo Songo No. 3, T.P.D.C. Songo Songo No. 4, and Agip Mnazi Bay No. 1 wells of southern, coastal Tanzania.

Showings of gas are recorded from equivalent strata in Somalia (Kamen Kaye and Barnes, 1979) and Kenya. Indications of oil in Cretaceous strata are observed in the B.P. Shell Walmerer No. 1 well as stainings in rocks that have experienced silicification and the invasion of hydrothermal fluids into fractures.

Paleocene through Eocene carbonate and siliciclastic strata

TABLE 8: HYDROCARBON OCCURRENCES IN CRETACEOUS THROUGH TERTIARY STRATA OF KENYA AND ADJACENT REGIONS OF EAST AFRICA

| REGIONS | WELL NAME | WELL LOCATION (LAT./LONG.) | AGE OF STRATA WITH HYDROCARBON OCCURRENCE | LITHOFACIES | DEPTH OF HYDROCARBON OCCURRENCE (w.r.t. K.B,) | TYPE OF HYDROCARBONS |
|---|---|---|---|---|---|---|
| SOMALIA | Stanvac #1 Daga Shabel | 10°10'34" N<br>45°17'08" E | Miocene | Sandstone | | oil seep |
| | Sinclair #1 Merca | 01°52'26" N<br>44°55'12" E | Eocene | Sandstone | | gas shows |
| | Sinclair #1 Afgoi | 02°06'52" N<br>45°04'10" E | Eocene | Sandstone | | gas shows |
| | Sinclair #1 Gira | 05°29'59" N<br>48°04'41" E | Paleocene - Lower Eocene | Nummulitic Limestone | | bitumen stains |
| | Agip #1 Cotton | 09°32'43" N<br>50°30'54" E | Paleocene - Lower Eocene | Nummulitic Limestone | | bitumen stains |
| | Agip #1 Sagaleh | 09°24'45" N<br>50°40'20" E | Paleocene - Lower Eocene | Nummulitic Limestone | | bitumen stains |
| | Sinclair #1 Oddo Alimo | 00°04'16" N<br>42°25'08" E | Paleocene - Eocene | Sandstone | | oil stains |
| | Agip #1 Coriole | 09°32'43" N<br>50°30'54" E | Upper Cretaceous | Sandstone | | gas shows |
| KENYA | Texas Hagarso #1 | 00°47'43.50" S<br>40°26'40.50" E | Lower Miocene | Limestone | 396 - 485m | pyrobitumen |
| | B.P. Shell Dodori #1 | 01°48'53.70" S<br>41°11'04.00" E | Lower Miocene | Limestone and Dolomite | 768 - 1079m<br>899 - 1123m | bitumen |
| | Total Simba #1 | 04°00'06.68" S<br>40°00'06.60" E | Lower Miocene | Limestone | 2100m | gas shows |

TABLE 8 (Cont'd)

| REGIONS | WELL NAME | WELL LOCATION (LAT./LONG.) | AGE OF STRATA WITH HYDROCARBON OCCURRENCE | LITHOFACIES | DEPTH OF HYDROCARBON OCCURRENCE (w.r.t. K.B.) | TYPE OF HYDROCARBONS |
|---|---|---|---|---|---|---|
| KENYA (Cont'd) | B.P. Shell Dodori #1 | 01°48'53.70" S<br>41°11'04.00" E | Lower Eocene | Oolitic Limestone | 2397 - 2713m | gas shows and bitumen stains |
| | B.P. Shell Dodori #1 | 01°48'53.70" S<br>41°11'04.00" E | Lower Eocene | Algal Stromalite | 3201 - 3478m | gas shows |
| | B.P. Shell Mararani #1 | 01°34'57.00" S<br>41°14'10.00" E | Middle Eocene | Sandstone | 1777m | bitumen |
| | B.P. Shell Kipini #1 | 02°29'23.00" S<br>40°35'51.36" E | Middle Eocene | Sandstone | 2173 - 2338m | gas shows |
| | B.P. Shell Pate #1 | 02°03'53.98" S<br>41°04'52.00" E | Paleocene | Sands | 3918 - 4185m | gas shows |
| | B.P. Shell Dodori #1 | 01°48'53.70" S<br>41°11'04.00" E | Paleocene | Sandstone | 3587 - 3628m | gas shows and bitumen stains |
| | Union Kofia #1 | 02°32'33.27" S<br>40°56'18.97" E | Campanian | Sandstone | 3558 - 3570m | gas shows |
| | B.P. Shell Kipini #1 | 02°29'23.00" S<br>40°35'51.36" E | Maastrichtian | Sandstone | 3295 m | gas and oil shows |
| | Texas Hagarso #1 | 00°47'43.50" S<br>00°26'40.50" E | Coniacian | Sandstone | 1016 m | gas and bitumen |
| | Texas Hagarso #1 | 00°47'43.50" S<br>40°26'40.50" E | Albian | Limestone | 2460 - 2660m | gas shows |
| | B.P. Shell Walu #2 | 00°38'02.00" S<br>40°15'10.00" E | Albian | Shale | 2445m | oil stain and amber |

TABLE 8 (Cont'd)

| REGIONS | WELL NAME | WELL LOCATION (LAT./LONG.) | AGE OF STRATA WITH HYDROCARBON OCCURRENCE | LITHOFACIES | DEPTH OF HYDROCARBON OCCURRENCE (w.r.t. K.B.) | TYPE OF HYDROCARBONS |
|---|---|---|---|---|---|---|
| KENYA (Cont'd) | B.P. Shell Walmerer | 00°06'35.00" S<br>40°35'05.00" E | Aptian | Silts and Shales | 2184m | oil stain |
| | B.P. Shell Walmerer | 00°06'35.00" S<br>40°35'05.00" E | Neocomian | Shales | 3353 - 3657m | oil stains |
| TANZANIA | T.P.D.C. Songo Songe #2 | 09°31' S (approx)<br>39°30' E (approx) | Eocene | Shale, Marl and Calcarenites | --- | gas shows |
| | B.P. Shell Mandawa #7 | 09°24'58.4" S<br>39°25'03.7" E | Paleocene - Middle Eocene | Shale and Marls | | gas shows |
| | T.P.D.C. Songo Songo #3 | 905778 Northing*<br>554385 Easting | Upper Cretaceous | Sandstone | | gas production |
| | Agip Mnazi Bay #1 | 10°19'45.2" S<br>40°23'27.5" E | Upper Cretaceous | Sandstone | | gas production |
| | B.P. Shell Pemba #5 | 05°16'10.7" S<br>39°41'52.7" E | Upper Cretaceous | Shale | | gas shows |
| | Agip Ras Machuis #1 | 06°00'59.9" S<br>38°51'19.2" E | Upper Cretaceous | Shale | | gas shows |
| | T.P.D.C. Songo Songo #4 | 905880 Northing*<br>554075 Easting | Lower Cretaceous | Sandstones | | gas production |
| | Agip Kizimbani #1 | 09°02'25" S<br>39°22'30" E | Albian | Shale | | gas shows |

* East African Grid
(from Barnes, 1976; Patrut, 1977; Kamen-Kaye, 1978; Kamen-Kaye and Barnes, 1979)

incorporate gas and bitumen indications in the three East African countries. The Miocene strata are petroliferous in coastal Kenya and northern Somalia, where an oil seep was observed near Daga Shabel (Barnes, 1976).

# CONCLUDING REMARKS

Three sedimentary basins, namely: Lamu, Anza, and Mandera-Lugh basins, as well as the deep offshore, occupy the region of Eastern Kenya. The Lamu basin contains the most nearly complete succession of Cretaceous through Tertiary strata measuring as much as 8000 m in thickness. Erosion has stripped virtually all deposits of the Paleogene and Neogene from the Mandera-Lugh and Anza basins.

The oldest Cretaceous deposits occur in the Lamu basin and include deltaic facies of the Neocomian Upper Member of the Mtomkuu Formation. These Lower Cretaceous deposits are overlain by a conformable sequence of deposits that include the Freretown Limestone and Lower Danissa Beds (Aptian), the Walu Shale, Danissa Limestone and Upper Danissa Beds (Albian to Cenomanian), the deposition of which terminated the Middle Cretaceous transgression.

Tectonic movements associated with the separation of Madagascar from the East African coast and ultimate genesis of the Indian Ocean, were followed by regressive deposition of the Marehan Sandstone during Turonian through Coniacian time. The Marehan Sandstone was deposited across the Mandera-Lugh basin and in parts of the Lamu basin, under a tidally influenced environment. Turbidites associated with this phase of deposition occur in the offshore basin. The linkage between the Mandera-Lugh and Lamu basins was severed at the end of the Cretaceous Period when faulting and uplift of the basement formed a ridge extending parallel to the Davies fracture in the offshore region to the onshore area. This event produced the Kipini-Walu-Garissa-Walmerer anticline and the Anza basin.

The Kipini Sandstone is a deltaic facies of the Lamu basin, that was deposited during Santonian through Paleocene time, following the above uplift. In the offshore region deposits of this regressive depositional phase are associated with turbidite deposits, growth faults and clay diapirs. The Pate Limestone rests directly on the Kipini Sandstone and is a restricted-shelf facies, deposited during the Early Eocene transgression. The overlying Middle Eocene to Oligocene Barren Beds consist of fluvial sands in the northern parts of the Lamu basin and are deltaic towards the southeast. The Linderina Limestone of Middle Eocene time and Dodori Limestone of Upper Eocene, are open marine transgressive deposits that intertongue with the above deltaic facies and continue into the offshore basin. Restricted-shelf facies again represent the initial deposits of the Neogene, and occur as carbonate strata termed the Baratumu Formation, Kipevu Beds, and Fundi Isa Limestone, in the Lower and Middle Miocene intervals of the Lamu basin. The succeeding Upper Miocene and Pliocene sequences comprises fluvial sands of the Marafa and Midadoni Beds, carbonates of the North Mombasa Crag (latest Miocene - Early Pliocene) and the Lower Magarini Sands (Late Pliocene). The Merti Beds are coarse-grained siliciclastic deposits of the Anza Basin associated with the rejuvenation and modification of river drainage during the domal uplift of central Kenya in Pliocene times.

The Cretaceous and Tertiary strata occur in a well recognizable pattern of succession and form three major groups of stratigraphic assemblages. Megasequence II includes the lithostratigraphic units of Cretaceous through Paleocene time, bounded by the end-Jurasic and Cretaceous-Tertiary regional unconformities. Megasequence III includes the lithostratigraphic units of the Eocene through Oligocene times bounded by the Paleocene-Eocene and Oligocene-Miocene regional unconformities. Megasequence IV includes the lithostratigraphic units of the Miocene through Pliocene age bounded by the Oligocene-Miocene and end-Pliocene regional unconformities.

Reservoir units of Megasequence II include carbonate strata of the Danissa Limestone, siliciclastic facies of the Marehan Sandstone and Kipini Sandstone, that could have been charged by the Walu Shale or Jurassic source rocks. Reservoir units of Megasequence III include fluvial and deltaic facies of the Barren Beds and the oolitic interval of the Pate Limestone. These could have been fed by source strata formed during the Tertiary Period in the offshore region. Reservoir strata in Megasequence IV include bioclastic limestones of the Baratumu

Formation, which might also have been fed by source rocks belonging to the Tertiary sequence. Prospective offshore strata include siliciclastic deposits forming turbidites, wedges cut by salt diapirs or associated with growth faults.

# REFERENCES

Ager, D.V. 1981. Major marine cycles in the Mesozoic. Journal of the Geological Society of London, v. 138, p. 159-166.

Allen, J.R.L. 1965. Late Quaternary Niger delta, and adjacent areas: Sedimentary environments and lithofacies. American Association of Petroleum Geologists Bulletin, v. 49, p. 547-600.

Arthur, M.A. and Schlanger, S.O. 1979. Cretaceous anoxic events as causal factors in development of reef reservoired giant oil fields. American Association of Petroleum Geologists Bulletin, v. 63, p. 870-885.

Ayers, F.M. 1952. Geology of the Wajir-Mandera district. Geological Survey of Kenya, Report No. 22.

Baker, B.H. 1970. The structural pattern of the Afro-Arabian rift system in relation to plate tectonics. Philosophical Transacations Royal Society of London, Series A, v. 267, p. 383-391.

Baker, B.H. and Saggerson, E.P. 1958. Geology of the El Wak-Aus Mandula area. Geological Survey of Kenya, Report No. 44.

Baker, B.H. and Wohlenberg, J. 1971. Structure and evolution of the Kenya Rift Valley. Nature, v. 229, p. 538-542.

Barnes, S.U. 1976. Geology and oil prospects of Somalia, East Africa. American Association of Petroleum Geologists Bulletin, v. 60, p. 389-413.

Beltrandi, M.D. and Pyre, A. 1973. Geological evolution of southwest Somalia. In: Blant, G. (Ed.), Sedimentary Basins of the African coasts, Part 2, South and East coast, Paris, Association of African Geological Surveys, p. 113-131.

Berke, S.M. and Rothery, D.A. 1986. Interactive processing of satellite images for structural and lithological mapping in northeast Africa. Geological Magazine, v. 123, p.393-403.

Bermingham, P.M., Fairhead, J.D., and Stuart, G.W. 1983. Gravity study of the central African rift system: a model of continental disruption. 2: The Ngaoundere and Abu Gabra Rifts, Tectonophysics, v. 94, p. 187-203.

Biggs, R.B. 1978. Coastal bays. In: Davis, R.A. (Ed.), Coastal Sedimentary Environments. Springer-Verlag, New York, p.69-99.

Bond, G. 1978. Evidence of late Tertiary uplift of Africa relative to North America, South America, Australia and Europe. Journal of Geology, v. 86, p. 47-65.

Bosellini, A. 1986. East Africa continental margins. Geology, v. 14, p. 76-78.

Bosence, D.W.J. 1973. Facies relationships in a tidally influenced environment - A study from the London Eocene Basin. Geologie en Mijinbouw, v. 19, p. 329-354.

Bosworth, W., Lambiase, J., and Keisler, R. 1986. A new look at Gregory's rift: the structural style of continental rifting. EOS, v. 67, p. 577-583.

Bowen, B.E., and Vondra, C.F. 1973. Stratigraphical relationships of the Plio-Pleistocene deposits, east Rudolf, Kenya. Nature, v. 242, p. 391-393.

Brown, S.E. and Fairhead, J.D. 1983. Gravity study of the central African rift system: a model of continental disruption. 1: The Ngaoundere and Abu Gabra rifts. Tectonophysics, v. 94, p. 187-203.

Bruce, C.H. 1973. Pressured shale and related sediment deformation mechanism for the development of regional contemporaneous faults. American Association of Petroleum Geologists Bulletin, v. 57, p. 878-886.

Bunce, E.T., Langseth, M.G., Chase, R.L., and Ewing, M. 1967. Structure of the western Somali basin. Journal of Geophysical Research, v. 72, p. 2547-2555.

Bunce, E.T. and Molnar, P. 1977. Seismic reflection profiling and basement topography in the Somali basin: possible fracture zones between Madagascar and Africa. Journal Geophysical Research, v. 82, p. 5305-5311.

Burke, K. 1976. Development of grabens associated with the initial rupture of the Atlantic ocean. Tectonophysics, v. 36, p. 93-112.

Burkey, D. 1974. Cretaceous and Paleogene Coccolith stratigraphy. In: Inital Reports of the Deep Sea Drilling Project, v. 25, Washington D.C., U.S. Government Printing Office, p. 669-673.

Burollet, P.F. 1984. Intracratonic and pericratonic basins in Africa. Sedimentary Geology, v. 40, p. 1-11.

Busk, H.G. 1939. Notes on the geology of the northeastern extremity of the Northern Frontier Province, Kenya Colony. Geological Magazine, v. 76, p. 215-221.

Campbell, C.V., and Oaks, R.Q. 1973. Estuarine sandstone filling tidal scours, Lower Cretaceous Fall River Formation, Wyoming. Journal of Sedimentary Petrology, v. 43, p. 765-778.

Cannon, R.T., Siambi, W.M.N., and Karanja, F.M. 1981. The Proto-Indian Ocean and probable Paleozoic/Mesozoic triradial rift system in East Africa. Earth and Planetary Science Letters, v. 52, p. 419-426.

Caswell, P.V. 1953. Geology of the Mombasa-Kwale area. Geological Survey of Kenya, Report no. 24, 54 p.

Caswell, P.V. 1956. Geology of the Kilifi-Mazeras area Geological Survey of Kenya, Report No. 34, 54 p.

Clifton, H.E. 1982. Estuarine deposits. In: Scholle, P.A. and Spearing, D. (Eds.), Sandstone Depositional Environments. American Association of Petroleum Geologists, Memoir 31, p. 179-189.

Coleman, J.M., and Prior, D.B. 1982. Deltaic environments. In: Scholle, P.A., and Spearing, D. (Eds.), Sandstone Depositional Environments. American Association of Petroleum Geologists, Memoir 31, p. 139-178.

Dailly, G.C. 1976. A possible mechanism relating progradation, growth faulting, clay diapirsm and overthrusting in a regressive sequence of sediments. Bulletin of Canadian Petroleum Geology, v. 24, p. 92-116.

Darracott, B.W. 1974. On the crustal structure and evolution of southeastern Africa and the adjacent Indian Ocean. Earth and Planetary Science Letters, v. 24, p. 282-290.

Davies, R.A., Weser, O.E., Luyendyk, B.P., and Kidd, R.B. 1975. Unconformities in the sediments of the Indian Ocean. Nature, v. 253, p. 15-19.

Dewey, J.F. and Burke K., 1974. Hot spots and continental break-up: Implications for collisional orogeny. Geology, v. 2, p. 57-60.

Dietz, R.S. and Holden, J.C. 1970. Reconstruction of Pangea: Breakup and dispersion of continents, Permian to present. Journal of Geophysical Research, v. 75, p. 4939-4957.

Dixey, F. 1948. Geology of Northern Kenya, Geological Survey of Kenya, Report no. 14, 42 p.

Donovan, D.T. and Jones, E.J.W. 1979. Causes of world wide changes in sea level. Journal Geological Society of London, v. 136, p. 187-192.

Dott Jr., R.H. and Bird, K.J. 1979. Sand transport through channels across an Eocene shelf and slope in southwestern Oregon, U.S.A. Society of Economic Paleontologists and Mineralogists, Special Publication, no. 27, p, 327-342.

Eames, F.E. and Kent, P.E. 1955. Miocene beds of the East African coast. Geological Magazine, v. 92, p. 338-344.

Eames, T.D. 1963. Geological completion report, Walu no. 2. BP-Shell Petroleum Development Company Limited, Report EADT/5.

Eames, T.D. 1964. Geological completion report, Dodori no. 1. BP-Shell Petroleum Development Company of Kenya Limited, Report EADT/6.

Elliott, T. 1981. Facies, sequences and sand-bodies of the principal clastic depositional environments. In: Parker, A. and Sellwood, B.W. (Eds.), Sediment Diagenesis. NATO Advanced Science Institute, Series C: Mathematical and Physical Sciences, v. 114, p. 1-56.

Ellis, B.F., Messina, A.R., Charmatz, R., and Ronaig, L.E. 1969. Mesozoic-Tertiary benthonic foraminifera. In: Catalogue of Index Smaller Foraminifera, Special Publication of American Museum of Natural History, New York, v. 3.

Emery, K.O. 1980. Continental margins - Classification and petroleum prospects. Bulletin of the Association of Petroleum Geologists, v. 64, p. 297-315.

Enos, P. 1983. Shelf environments. In: Scholle, P.A., Bebout, Don G., and Moore, C.H. (Eds.), Carbonate Depositional Environments. American Asociation of Petroleum Geologists, Memoir 33, p. 268-295.

Fischer, W.L. 1964. The Lofer cyclothem of the Alpine Triasssic. Kansas Geological Survey Bulletin, v. 169, p. 107-149.

Flores, G. 1984. The S.E. Africa triple junction and the drift of Madagascar. Journal of Petroleum Geology, v. 7, no. 4, p. 403-418.

Francis, T.J.G., Davies, D., and Hill, M.N. 1966. Crustal structure between Kenya and the Seychelles. Philosophical Transactions Royal Society of London, Series A., v. 259, p. 240-261.

Frey, J.D., Kopsen, E., and Keag, K. 1975. Geological field party El Wak-Mandera, Permit no. 6 Burma Oil Kenya Ltd., v. 1, p. 1-35.

Girdler, R.W. 1968. Drifting and rifting of Africa. Nature, v. 217, p. 1102-1106.

Girdler, R.W. and Styles, D. 1974. Two stage Red Sea floor spreading. Nature, v. 247, p. 7-11.

Goldring, R. 1964. Trace fossils and the sedimentary surface in shallow water marine environments. In: van Straaten, L.M.J.U. (Ed.), Deltaic and Shallow Marine Deposits. Developments in Sedimentology, v. 1, p. 136-143.

Haq, B.U., Hardenbal, J., and Vail, P.R. 1987. Chronology of fluctuating sea levels since the Triassic. Science, v. 235, p. 1156-1167.

Hays, J.D., and Pitman, W.C. 1973. Lithospheric plate motion, sea level changes and climatic and ecological consequences. Nature, v. 246, p. 18-22.

Heirtzler, J.R. and Burroughs, R.H. 1971. Madagascar's paleoposition: New data from the Mozambique channel. Science, v. 174, p. 488-490.

Hitchon, B. 1984. Geothermal gradients, hydrodynamics and hydrocarbon occurrences, Alberta, Canada. American Association of Petroleum Geologists Bulletin, v. 68, p. 713-743.

Hunt, J.M., Stewart, F., and Dickey, P.A. 1954. Origin of hydrocarbons of Uinta basin, Utah. American Association of Petroleum Geologists Bulletin, v. 38, p. 1671-1698.

Illies, J.H. 1969. An intercontinental belt of world rift system. Tectonophysics, v. 8, p. 5-29.

Inman, D.L. and Nordstrom, C.E. 1971. On the tectonic and morphologic classification of coasts. Journal of Geology, v. 79, p. 1-21.

Joubert, P. 1957. Geology of the Mandera-Damassa area. Geological Society of Kenya, Report no. 48, p. 65.

Joubert, P. 1960. Geology of the Mandera-Damassa area. Geological Survey of Kenya, Report no. 48, p. 65.

Kamen-Kaye, M. 1967. Basin subsidence and hypersubsidence American Association of Petroleum Geologists Bulletin, v. 51 p. 1833-1842.

Kamen-Kaye, M. 1978. Permian to Tertiary facies and paleogeography: Somalia, Kenya, Tanzania, Mozambique, Madagascar, South Africa. Journal of Petroleum Geology, v. 1, p. 79-101.

Kamen-Kaye, M. and Barnes, S.U. 1978. Exploration outlook for Somalia, coastal Kenya and Tanzania - 1. Oil and Gas Journal, v. 76, p. 80-84.

Kamen-Kaye, M. and Barnes, S.U. 1979. Exploration geology of northeastern Africa - Seychelles basin. Journal of Petroleum Geology, v. 2, no. 1, p. 23-45.

Karanja, F.M. 1982. Report on the Geology of the Kilifi, Gede and Sokoke area. Geological Survey of Kenya, p. 32.

Keen, C.E. 1983. Salt diapirs and thermal maturity - Scotian basin. Bulletin of Canadian Petroleum Geology, v. 31, p. 101-108.

Kennedy, W.Q. 1965. The influence of basement structure on the evolution of the coastal Mesozoic and Tertiary basins of Africa. In: Salt Basins Around Africa, Proceedings Joint Meeting of Institute of Petroleum and Geological Society, London, 3 March 1965, p.7-16

Kent, P.E. 1965. An evaporite basin in southern Tanzania. In: Salt Basins Around Africa, Proceedings Joint Meeting of Petroleum and Geological Society, London, 3 March 1965, p. 41-65.

Kent, P.E. 1972. Mesozoic history of the east coast of Africa. Nature, v. 238, p. 147-148.

Kent, P.E. 1974. Continental margin of east Africa - a region of vertical movements. In: Burk, C.A. and Drake, C.L. (Eds.), The Geology of Continental Margins, New York, Springer-Verlag, p. 313-320.

Kent, P.E. 1974. Leg 25 results in relation to east African coastal stratigraphy. In: Initial Reports of the Deep Sea Drilling Project, v. 25, Washington D.C., U.S. Government Printing Office, p. 679-684.

Kent, P.E. 1976. Major synchronous events in continental shelves. Tectonophysics, v. 36, p. 87-91.

Kent, P.E. 1982. The Somali ocean basin and the continental margin of east Africa. In: Nairn, A.E,M. and Stehli, F.G. (Eds.), The Ocean Basins and Margins, v.6, The Indian Ocean, New York, Plenum Press, p. 185-204.

Kent, P.E. and Perry, J.T. 1973. The development of the Indian Ocean margin in Tanzania. In: Blant, G. (Ed.), Sedimentary Basins of the African Coasts, Part 2, South and East Coast, Paris, Association of African Geological Surveys, p. 113-131.

Kerr, R.A. 1987. Refining and defining the Vail sea level curve. Science, v. 235, p. 1141-1142.

Kidd, R.B. and Davies, T.A. 1978. Indian Ocean sediment distribution since the late Jurassic. Marine Geology, v. 26, p. 49-70.

Kinsman, D.J.J. 1975. Rift valley basins and sedimentary history of trailing continental margins. In: Fischer, A.G., and Judson, S. (Eds.), Petroleum and Global Tectonics, Princeton University Press, New Jersey, p. 83-126.

Klemme, H.D. 1980. Petroleum basins, classification and characteristics. Journal of Petroleum Geology, v. 3, p. 187-207.

Kroner, A. 1977. Precambrian mobile belts of southern and eastern Africa: Ancient sutures and sites of ensialic mobility? A case for coastal evolution toward plate tectonics. Tectonophysics, v. 40, p. 101-135.

Lehner, P. and De Ruiter, P.A.D. 1976. Africa's Atlantic margin typified by string of basins. Oil and Gas Journal, v. 74, no. 5, p. 252-266.

Le Pichon, X. and Heirtzler, J.R. 1968. Magnetic anomalies in the Indian ocean and sea-floor spreading. Journal of Geophysical Research, v. 73, p. 2101-2117.

Levorsen, A.E. 1954. Geology of Petroleum. San Francisco, W.H. Freeman and Company, 724 p.

Linton, R.E. and MacLean, R.G. 1955. The sediments of coastal Kenya. Kenya Coastal Survey Part 1, Shell D'Arcy Exploration Party, 24 p.

Magara, K. 1977. A theory relating isopachs to paleocompaction water movement in a sedimentary basin. Bulletin of Canadian Petroleum Geology, v. 25, p. 195-207.

McConnel, R.B. 1977. East African rift system dynamics in view of Mesozoic polar wandering. Journal Geological Society of London, v. 134, p. 33-39.

McElhinny, M.W. 1970. Formation of the Indian Ocean. Nature, v. 228, p. 977-979.

Milanovsky, E.E. 1983. Major stages of rifting in the earth's history. Tectonophysics, v. 94, p. 599-607.

Morgan, W.J. 1972. Deep mantle convection plumes and plate tectonics. American Association of Petroleum Geologists Bulletin, v. 56, p. 203-213.

Murray-Hughes, R. 1933. Notes on the geological succession tectonics and economic geology of the western half of Kenya colony. Geological Survey of Kenya, Report no. 3, 8 p.

Nairn, A.E.M. 1978. Northern and eastern Africa. In: Monllade, M. and Nairn A.E.M. (Eds.), The Phanerozoic Geology of the world II: The Mesozoic, A. Amsterdam, Elsevier, p. 329-370.

Ojany, F.F. 1966. The physique of Kenya: A contribution in landscape analysis. Annals of the Association of American Geographers, v. 50, no. 2, p. 183-196.

Okoth, W.S. 1981. Evaluation of hydrocarbon potential of the Kenya margin on the basis of structure and stratigraphy. Unpublished M.Sc. thesis, Dalhousie University, 115 p.

Patrut, 1977. Hydrocarbon potential of the Eastern Kenya Sedimentary. Bucharest Rumania, Unpublished Report. 51 p.

Peterson, J.A. 1986. Geology and petroleum resources of central and east-central Africa. Modern Geology, v. 10, p. 329-364.

Pitman, W.C. 1978. The relationship between eustacy and stratigraphic sequences of passive margins. Bulletin of the Geological Society of America, v. 84, p. 2851-2872.

Pulfrey, W.P. 1969. The geology and mineral resources of Kenya. Geological Society of Kenya, Bulletin no. 2, Government Printers, Nairobi.

Purdy, E.G. 1961. Bahamian oolite shales. American Association of Petroleum Geologists Bulletin, v. 45, p. 53-62.

Pusey, W.C. 1973. How to evaluate potential gas and oil source rocks. World Oil, v. 176, no. 5, p. 71-75.

Rabinowitz, P.D., Coffin, M.F., and Falvey, D. 1983. The separation of Madagascar and Africa. Science, v. 220, p. 67-69.

Rabinowitz, P.D. and Coffin, M.F. 1982. Salt diapirs bordering the continental margin of northern Kenya and southern Somalia. Science, v. 215, p. 663-665.

Rabinowitz, P.D. 1971. Gravity anomalies across the east African continental margin. Journal of Geophysical Research v. 76, p. 7107-7117.

Rashid, M.A. and McAlary, J.R. 1977. Early maturation of organic matter and genesis of hydrocarbons as a result of shallow piercement domes. Journal of Geochemical Exploration, v. 8, p. 549-560.

Reeves, C.V., Karanja, F.M., and MacLeod, I.N. 1986. Geophysical evidence for a Jurassic triple-junction in Kenya. Earth and Planetary Science Letters, v. 81, p. 299-311.

Royden, L., Sclater, J.G., and von Herzen, R.P. 1980. Continental margin subsidence and heat flow - Important parameters in formation of hydrocarbons. American Association of Petroleum Geologists, Bulletin, v. 64, p. 173-187.

Saggerson, E.P. and Miller, J.M. 1957. Geology of the Takabba-Wergadud area, Mandera district. Geological Survey of Kenya, Report no. 40, p. 42.

Saggerson, E.P. and Baker, B.H. 1965. Post-Jurassic erosion-surfaces in eastern Kenya and their deformation in relation to rift structure. Journal Geological Society of London, v. 121, p. 51-72.

Sanders, L.D. 1959. Geology of the mid-Galana area. Geological survery of Kenya, Report no. 45, 50 p.

Savage, R.J.G. and Williamson, P.G. 1978. The early history of the Turkana depression. In: Bishop, W.W. (Ed.), Geological Background to Fossil Man: Recent Research in the Gregory Rift Valley, East Africa. Edinburgh, Scottish Academic Press, p. 375-394.

Schlich, R., Simpson, E.S.W., and Vallier, R.L. 1974. Regional aspects of deep sea drilling in the western Indian ocean, Leg 25, DSDP. In: Initial Reports of the Deep Sea Drilling Project, vol. 25, Washington D.C., U.S. Government Printing Office, p. 743-759.

Schlich, R. 1974. Sea-floor spreading history and deep-sea drilling results in the Madagascar and Mascarene basins, western Indian ocean, leg 25, DSDP. In: Initial Reports of the Deep Sea Drilling Project, vol. 25, Washington D.C., U.S. Government Printing Office, p. 663-678.

Schroeder, J.H. 1974. Course notes on sedimentology of coast and shelf environments, Regional Training course organized by UNESCO, Regional Office of Science and Technology for Africa, Nairobi, 55 p.

Scrutton, R.A., Heptonstall, W.B., and Peacock, J.H. 1981. Constraints on the motion of Madagascar with respect to Africa. Marine Geology, v. 43, p. 1-20.

Shackleton, N.J. and Kennett, J.P. 1975. Late Cenozic oxygen and carbon isotopic changes of DSDP site 284. Implications for glacial history of the northern hemisphere and Antarctica. In: Initial Reports of the Deep Sea Drilling Project, v. 29, Washington D.C., U.S. Government Printing Office, p. 801-808.

Shinn, E.A. 1968. Burrowing in recent line sediments of Florida and the Bahamas. Journal of Paleontology, v. 2, no. 4, p. 879-894.

Simiyu-Siambi, W.M.N. 1978. Geology of the Mazeras-Mariakani area. Geological Survey of Kenya, 37 p.

Simiyu-Siambi, W.M.N. 1980. Geology of the Jilore-Malindi area. Geological Survey of Kenya, 30 p.

Simpson, F. 1986. Short Course on Stratigraphic Analysis of Subsurface Data. Department of Geology, University of St. Andrews, Unpublished, 7 p.

Sloss, L.L. R.C. 1963. Sequences in the cratonic interior of North America. Bulletin of the Geological Society of America, v. 74, p. 93-114.

Sloss, L.L. and Speed, R.C. 1974. Cratonic and continental-margin tectonics. In: Dickinson, W.R. (Ed.), Sedimentation and Tectonics. Society of Economic Paleontologists and Mineralogists, special publication, no. 22, p. 98-119

Smith, A. and Hallam, A. 1970. The fit of the southern continents. Nature, v. 225, p. 139-144.

Sowerbutts, W.T.C. 1972. Rifting in eastern Africa and the fragmentation of Gondwanaland. Nature, v. 225, p. 435-436.

Stipewich, J.C. 1961. Geological completion report, Pandangua no. 1. British Petroleum development Company of Kenya Limited, Report JCS/6.

Tarling, D. 1971. Gondwanaland, Paleomagnetism and continental drift. Nature, v. 229, p. 17-21.

Thompson, A.O. 1954. Geology of the Malindi area. Geological Survey of Kenya, Report no. 36.

Thompson, A.O. and Dodson, R.G. 1960. Geology of the Bur-Mayo-Tarbaj area. Geological Survey of Kenya, Report no. 47, 49 p.

Vail, P.R., Mitchum, Jr., R.M., and Thompson, S. 1977. Seismic stratigraphy and global changes of sea level. In: Payton, C.E. (Ed.), Seismic Stratigraphy-Applications to Hydrocarbon Exploration. American Association of Petroleum Geologists, Memoir 26, p. 83-97.

Vail, P.R. and Mitchum Jr., R.M. 1978. Global cycles of relative changes of sea level from seismic stratigraphy. In: Watkins, J.S., Montadert, L. and Dickerson, P.W. (Eds.), The Geological and Geophysical Investigations of Continental Margins. American Associaton of Petroleum Geologists, Memoir 29, p. 469-472.

Walters, L. and Linton, E.R. 1973. The Sedimentary basins of coastal Kenya. In: Blant, G. (Ed.), Sedimentary Basins of the African Coasts Part 2. South and East Coast, Paris, Association of African Geological Surveys, p. 133-158.

Weir, J., Currie, E., and Latham, M. 1929. Jurassic fossils from Jubaland, East Africa, collected by Glenlay V.G., and the Jurassic geology of Somaliland. Monograph Geological Department, Hunterian Museum, Glasgow, no. 3, p. 2.

Williams, L.A.J. 1962. Geology of the Hadu-Fundi Isa area, north of Malindi. Geological Survey of Kenya, Report no. 52, p. 62.

Willumsen, P.S. and Cote, R.P. 1982. Tertiary sedimentation in the southern Beaufort Sea, Canada. In: Watkins, J.S. and Drake, C.L. (Eds.), Studies in Continental Margin Geology, Bulletin of American Associaton of Petroleum Geologists, Memoir 34, p. 283-293.

Wilson, J.L. 1975. Carbonate facies in geologic history. Springer-Verlag, New York, 471 p.

Wright, J.B. and Pix, P. 1967. Evidence for trough faulting in eastern central Kenya. Institute of Geological Sciences, Overseas Geology and Mineral Resources, v. 10, p. 30-41.

# APPENDIX 1

## ELEVATIONS OF MAIN CRETACEOUS-TERTIARY CORRELATION SURFACES WITH RESPECT TO KELLY BUSHING IN SOUTH-EAST KENYA AND OFFSHORE

ELEVATIONS OF MAIN CRETACEOUS THROUGH TERTIARY CORRELATION SURFACES IN NORTH-EAST KENYA AND OFFSHORE (SECTION A-A$^{1}$)

| | | STRATIGRAPHY | | B.P. SHELL MERI #1 KB 179.3m (588ft) | B.P. SHELL WALMERER #1 KB 153.7m (504ft) | TEXAS HAGARSO #1 KB 92.7m (304ft) | B.P. SHELL WALU #2 KB 91.8m (301ft) | B.P. SHELL DODORI #1 KB 32.0m (105ft) | DSDP #241 W.D=4054m (13297ft) |
|---|---|---|---|---|---|---|---|---|---|
| | | QUARTERNARY | | | | | | | |
| TERTIARY | NEOGENE | PLIOCENE | UPPER<br>LOWER | 222m (728ft) | 148m (485ft) | | | 128m (420ft) | 74m (243ft) |
| | | MIOCENE | UPPER<br>MIDDLE<br>LOWER | 305m (1000ft) | 273m (895ft) | 132m (433ft) | 417m (1368ft) | 287m (941ft) | 151m (495ft)<br>265m (869ft)<br>403m (1321ft) |
| | PALEOGENE | OLIGOCENE | UPPER<br>LOWER | 834m (2735ft) | 879m (2883ft) | 622m (2040ft) | 628m (2060ft) | 1213m (3979ft) | 457m (1499ft) |
| | | EOCENE | UPPER<br>MIDDLE<br>LOWER | 1941m (6366ft) | | | | 1288m (4225ft)<br>1378m (4520ft)<br>2460m (8069ft) | 464m (1522ft)<br>501m (1643ft) |
| | | PALEOCENE | UPPER<br>LOWER | | | | | 3501m (11585ft) | 587m (1925ft) |
| CRETACEOUS | UPPER | MAASTRICHTIAN | | | | | | | |
| | | CAMPANIAN | | | | | 1480m (4854ft) | | 626m (2053ft) |
| | | SANTONIAN | | | | | | | |
| | | CONIACIAN | | | | 845m (2772ft) | | | 873m (2863ft) |
| | | TURONIAN | | | | 1143m (3749ft) | 1801m (5907ft) | | 1174m (3850ft) |
| | | CENOMANIAN | | | | 1390m (4559ft) | 1995m (6544ft) | | |
| | LOWER | ALBIAN | | | 1471m (4825ft) | 2553m (8374ft) | 2445m (8020ft) | | |
| | | APTIAN | | | 1793m (5881ft) | 2735m (8971ft) | 3619m (11870ft) | | |
| | | NEOCOMIAN | | | 2349m (7704ft) | | | | |

ELEVATIONS OF MAIN UPPER CRETACEOUS THROUGH TERTIARY CORRELATION SURFACES IN SOUTH-EAST KENYA AND OFFSHORE (SECTION B-B$^1$)

| | | STRATIGRAPHY | | B.P. SHELL<br>MARARANI #1<br>KB 33.8m<br>(111ft) | B.P. SHELL<br>DODORI #1<br>KB 32.0m<br>(105ft) | B.P. SHELL<br>PATE #1<br>KB 8.1m<br>(26.5ft) | UNION<br>KOFIA #1<br>KB 15.5m<br>(50.8ft) | B.P. SHELL<br>KIPINI #1<br>KB 23.3m<br>(76.4ft) | CITIES<br>MARIDADI #1B<br>KB 54.0m<br>(177ft) | TOTAL<br>SIMBA #1<br>KB 12.0m<br>(39.4ft) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | QUARTERNARY | | | | | | | | |
| TERTIARY | NEOGENE | PLIOCENE | UPPER | 76m (249ft) | 128m (420ft) | | 157m (515ft) | | 125m (410ft) | 921m (3021ft) |
| | | | LOWER | | | | | | | |
| | | MIOCENE | UPPER | | | 165m (541ft) | 258m (846ft) | 177m (581ft) | 950m (3116ft) | 1060m (3477ft) |
| | | | MIDDLE | 184m (604ft) | | 335m (1099ft) | 349m (1145ft) | 310m (1017ft) | 1730m (5674ft) | 1455m (4772ft) |
| | | | LOWER | | 287m (941ft) | 864m (2834ft) | 852m (2795ft) | 1119m (3670ft) | 1850m (6068ft) | |
| | PALEOGENE | OLIGOCENE | UPPER | | 1213m (3979ft) | 1216m (3988ft) | 1332m (4369ft) | 1701m (5579ft) | | |
| | | | LOWER | 1165m (3821ft) | | | 1662m (5451ft) | | | |
| | | EOCENE | UPPER | 1252m (4107ft) | 1288m (4225ft) | 1326m (4349ft) | 1907m (6255ft) | 1772m (5812ft) | | 1508m (4946ft) |
| | | | MIDDLE | 1314m (4310ft) | 1378m (4520ft) | 1433m (4700ft) | 1976m (6481ft) | 2087m (6845ft) | | 1570m (5150ft) |
| | | | LOWER | 1991m (6530ft) | 2460m (8069ft) | 3135m (10282ft) | 2174m (7131ft) | | | 1962m (6435ft) |
| | | PALEOCENE | UPPER | | 3501m (11585ft) | 3892m (12766ft) | 2513m (8243ft) | | | 2457m (8059ft) |
| | | | LOWER | | 4310m (14137ft) | | | | | 2605m (8544ft) |
| CRETACEOUS | UPPER | MAASTRICHTIAN | | | | | 2976m (9761ft) | 3155m (10348ft) | | 2882m (9453ft) |
| | | CAMPANIAN | | | | | 3373m (11063ft) | 3663m (12015ft) | | |

# APPENDIX 2

# LITHOLOGIC DESCRIPTIONS OF SELECTED CORED SECTIONS THROUGH CRETACEOUS-TERTIARY STRATA OF SOUTH-EAST KENYA AND ADJACENT OFFSHORE

## CORE DESCRIPTIONS

B.P./SHELL WALU No. 2
01° 38' 02.00" S
40° 15' 10.00" E KB 91.8 m (301 ft)

| Depth below KB in meters (feet) | |
|---|---|
| | MIDDLE EOCENE-OLIGOCENE UNDIFFERENTIATED |
| 937.7 - 937.8<br>(3075.6 - 3076) | Sandstone with sandy clay intercalations: Sandstone greyish pink (5R8/2), friable fine to medium-grained, sub-rounded smokey quartz grains, muscovite flakes. Sandy clay moderate reddish brown (10R4/6) and moderate red (5R4/6). |
| 1452.7 - 1454<br>(4765 - 4769) | Sandstone: Greyish pink (5R8/2) and very light grey (N8) fine to medium-grained, induration poor to medium, quartz grains rounded to sub-rounded and well sorted, few rock grains, altered felspars, slightly calcareous cement variably leached. |
| | LATE CRETACEOUS (CAMPANIAN) |
| 1870.4 - 1874.1<br>(6135 - 6147) | Mudstone: Dark greenish grey (5G4/1) calcareous, silty, finely laminated and fissile, pyritic and coaly in places. Core badly shattered. |

B.P. SHELL DODORI No. 1
01° 48'53.70" S
41° 11'04.00" E KB 32.0 m (105 ft)

## PLIOCENE

| | |
|---|---|
| 230.2 - 234.7<br>(735 - 770) | Bioclastic limestone. Very light grey (N8) includes abundant lamellibranch, bryozoan coral and fish skeletal debris, well rounded grains of quartz, chert, felspar and dark rock fragments. |

## EARLY MIOCENE (AQUITANIAN)

| | |
|---|---|
| 899.4 - 901.2<br>(2950 - 2956) | Limestone. Yellowish grey (5Y8/1) microcrystalline to sparitic; mottled, bitumenous in places, carbonaceous material define a lamination, vugs with recrystallized calcite and anhydrite veins in basal part. |
| 1122 - 1123.2<br>(3680 - 3684) | Limestone and calcareous shale: Limestone very light grey (N8) micro-crystalline to sparitic, carbonaceous flecks incorporated in micritic matrix. Pelecypod skeletal material aligned parallel and sub-parallel to bedding at base, rings with recrystallized calcite and rimmed with bitumen, shale greenish grey (5GY6/1) slightly chalky and occupying micro-stylolitic partings. |

## OLIGOCENE

| | |
|---|---|
| 1240.5 - 1244.8<br>(4068.8 - 4082.9) | Sandstone and sandy siltstone: Sandstone dark yellowish brown (10YR4/2) friable, fine to medium-grained angular quartz grains with iron staining, randomly scattered coalified plant fragments, finely pyritic Siltstone dark yellowish brown (10YR4/2) with dark carbonaceous material imparting a lamination. *Nummulites hormoensis* and *Nummulite fabiani* reworked from Upper Eocene. |

## LATE EOCENE

| | |
|---|---|
| 1372 - 1373<br>(4500 - 4504) | Shale and mudstone: Shale light olive brown (5Y5/6) carbonaceous, cross-laminated. Mudstone pale olive (10Y6/2) finely pyritic along planes of fissility. |

## MIDDLE EOCENE

| | |
|---|---|
| 1879.6 - 1881.3<br>(6165 - 6170.7) | Sandstone, shale and siltstone: Sandstone yellowish grey (5Y8/1) fine-grained, induration poor, calcareous, micaceous, cross-laminated; shale greenish black (5GY2/1) highly fissile siltstone with white silty and black (N1) carbonaceous laminae, micaceous, pyritic, glauconitic and cross-laminated. |
| 2119 - 2125<br>(6950 - 6970) | Sandstone. Light olive grey (5Y6/1) fine grained; quartzose glauconitic, micaceous forming fissile laminae and burrow lining, moderately indurated and calcareous towards base. |
| 2280.5 - 2286.5<br>(7480 - 7500) | Siltstone. Yellowish grey (5Y8/1) fine grained, well indurated calcareous; carbonaceous and micaceous occurring as horizontal laminae, mottled, nummulite shell impressions prevalent. |
| 2484.7 - 2487.5<br>(8150 - 8159) | Limestone. White (N9) micritic; calcite crystals scattered within matrix, irregular stromatolitic layering incorporating skeletal debris in basal part. |
| 2637 - 2640.8<br>(8652 - 8662) | Limestone. As in 2484.7 - 2487.5m with small geodes rimmed by calcite crystals. |

## EARLY EOCENE

| | |
|---|---|
| 2876.8 - 2879.6<br>(9436 - 9445) | Limestone. Medium light grey (N7), micritic with discontinuous shale partings in basal section. Nummulites and alveolinoids present. |
| 3066.7 - 3070.4<br>(10059-10070.9) | Limestone and shale. Limestone medium grey (N5) micritic, nummulitic shale greenish black (5GY2/1) carbonaceous, finely pyritic, pelecypod and ammonite moulds. |
| 3169.2 - 3174.4<br>(10395 - 10412) | Limestone and shale. Limestone medium grey (N5) on account of increased argillaceous content otherwise as in 2484.7 - 2487.5 m; Shale greenish black (5GY2/1) bending around nodular algal bodies. |
| 3333.8 - 3334.7<br>(10935 - 10938) | Limestone. Light grey (N7) to very light grey (N8) micritic, finely pyritic and recrystallized. |
| 3496.9 - 3500.3<br>(11470 - 11481) | Siltstone. Dark grey (N3) carbonaceous, micaceous along plane of lamination, coalified plant fragments. |

## PALEOCENE

| | |
|---|---|
| 3529 - 3535<br>(11575 - 11595) | Limestone and sandstone. Limestone medium grey (N5) micritic, skeletal debris, patches of quartzose sandstone with calcareous cement. Very thin solution lines parallel bedding plane filled with very dark red ferrugenous material. Sandstone very light grey (N8) fine-grained, calcareous, pyritic irregular and discontinuous carbonaceous partings and coalified plant fragments aligned parallel and sub-parallel to bedding. |
| 3535 - 3541<br>(11595 - 11615) | Sandstone. Very light grey (N8) fine-grained grading downwards to yellowish grey (58Y/1) and medium-grained in basal portion. Calcareous micaceous, thin irregularly spaced carbonaceous intervals parallel to bedding form a flame structure. |

| | |
|---|---|
| 3564 - 3569<br>(11690 - 11707) | Sandstone and shale. Sandstone as in upper part of 3535 - 3541m; shale greyish black (N2) carbonaceous, very slightly calcareous, some shell debris and plant fragments. |
| 3594.5 - 3600<br>(11790 - 11809) | Sandstone and shale. As in 3564 - 3569m. |
| 3779.3 - 3785.4<br>(12396 - 12416) | Sandstone and shale. As in 3564 - 3569m. |
| 3921.3 - 3925<br>(12862 - 12874) | Sandstone and siltstone. Sandstone yellowish grey (5BY/1) fine-grained, dark red ferruginous streaks; siltstone greyish black (N2) very fine-grained, carbonaceous micaceous along evenly spaced laminae, moderately fissile. |
| 4116.7 - 4121.6<br>(13502.8 - 13518.8) | Sandstone, siltstone and shale. Sandstone and siltstone as in 3921.3 - 3925 m; shale, greyish black (N2) silty, poorly fissile, at base of core. *Cibicidoides pseudoacutus* reworked from Maastrichtian. |

B.P. SHELL PATE No. 1
02° 03'53.98" S
41° 04'52.00" E KB 8.1 m (26.5 ft)

### MIDDLE MIOCENE

| | |
|---|---|
| 337.2 - 338.1<br>(1106 - 1109) | Limestone. Yellowish grey (5Y8/1) sparry skeletal material includes complete pelecypods, gasteropods and broken coral branches, partly dolomitized, dolomite crystals occupy small open cavities. *Miogyspina* *sp*. |

### MIDDLE EOCENE

| | |
|---|---|
| 2594.2 - 2594.4<br>(8509 - 9509.6) | Sandstone and mudstone. Sandstone medium light grey (N6) fine grained, carbonaceous; Mudstone medium grey (N5) silty, calcerous, with abundant nummulites. |
| 2601.5 - 2601.8<br>(8532.9 - 8534) | Limestone. Light grey (N7) sparritic slightly argillaceous, well indurated alveolinoids and nummulites in higher proportion than matrix. |

### LOWER EOCENE

| | |
|---|---|
| 3367 - 3367.4<br>(11044 - 11045) | Mudstone. Dark greenish grey (5G4/1) calcareous very thinly laminated, abundant nummulites. |
| 3945.4 - 3948.5<br>(12941 - 12951) | Mudstone. Medium dark grey (N4) calcerous, micaceous, thinly laminated. |

B.P. SHELL KIPINI No. 1
02° 29'23.00" S
40° 35'51.36" E KB 23.3 m (76.4 ft)

## MIDDLE EOCENE

| | |
|---|---|
| 2703 - 2710.4<br>(8866 - 8880) | Limestone and mudstone intercalations. Medium dark grey (N4) pelecypod debris in argillaceous matrix; mudstone very thinly cross-laminated, micaceous, with carbonaceous plant fragments. |

## UPPER CRETACEOUS (MAASTRICHTIAN)

| | |
|---|---|
| 3458.8 - 3459<br>(11345 - 11346) | Shale. Dark grey, silty, micaceous, moderately fissile, carbonaceous plant fragments. |
| 3658.2 - 3660<br>(11999 - 12006) | Main lithology as in 3458.8 - 3459m; stringer of crystalline limestone horizontal to bedding plane in middle part of core. |

CITIES MARIDADI No. 1B
02° 53'08.79" S
40° 24'07.85" E KB 54.0 m (177 ft)

EARLY LATE MIOCENE (EARLY BURDIGALIAN)

| | |
|---|---|
| 2061.7 - 2062<br>(6672 - 6763.4) | Limestone. Light greenish grey (5GY8/1) micritic, slightly chalky, some skeletal debris and slump structures, vuggy with calcite crystals forming spherulitic growth. |
| 2963 - 2064<br>(6766.6 - 6767) | Limestone and mudstone: Limestone as in 2061.7 - 2062 m; Mudstone dark greenish grey (5G4/1), horizontal lamination mildly disrupted in basal portion. |
| 2068 - 2069<br>(6783 - 6786.3) | Limestone. As in 2061.7 - 2062 m. |

# APPENDIX 3

## ROAD LOG FOR SELECTED OUTCROPS OF PALEOZOIC THROUGH CENOZOIC STRATA IN THE SEDIMENTARY BASIN REGION OF EAST KENYA

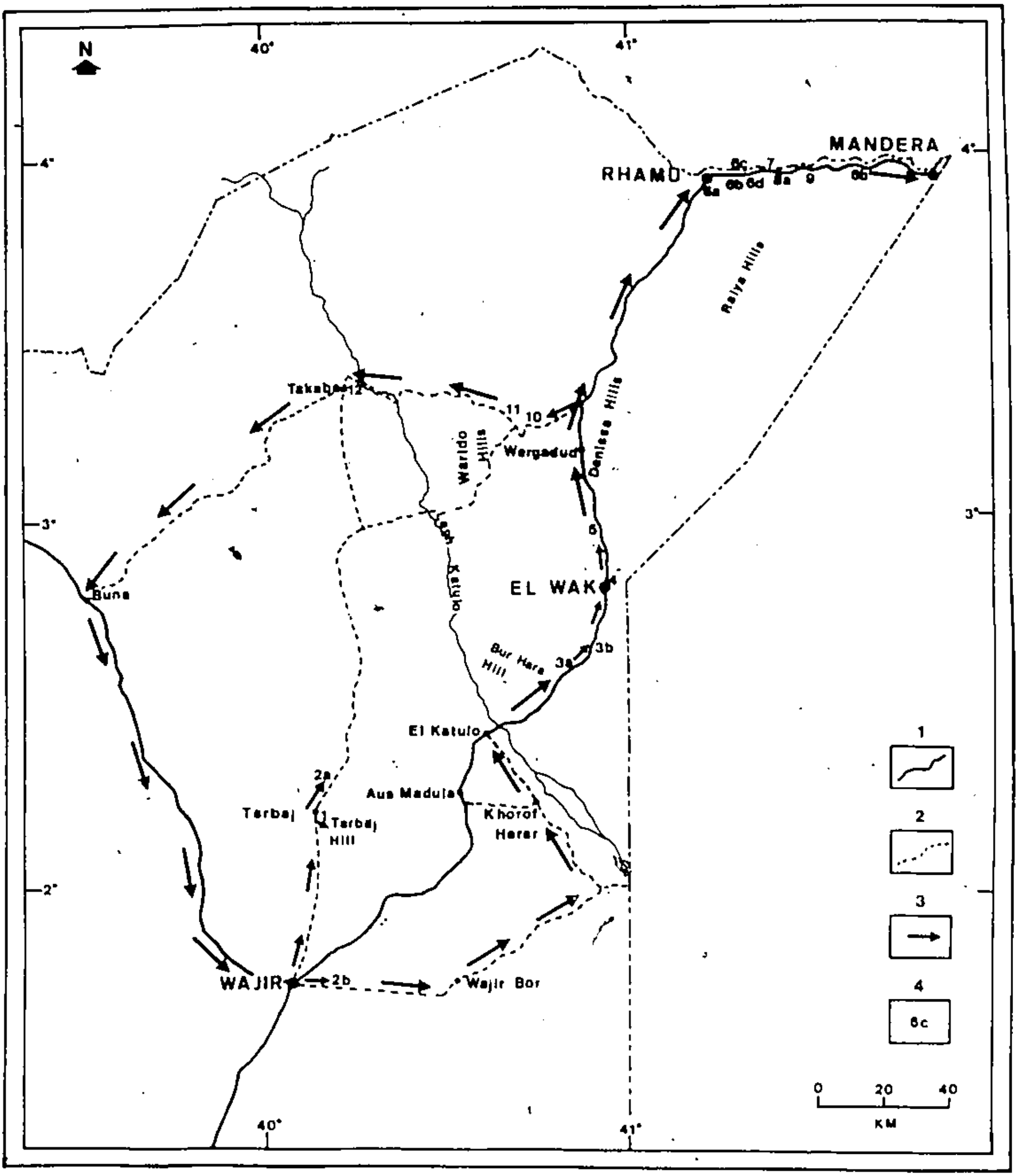


Fig. 25. Location map of the north-east sedimentary basin region of Kenya showing route followed during the field study and stops at selected rock outcrops. 1 - major roads; 2 - minor roads or tracks; 3 - route followed during field study; 3 - stops at rock outcrop.

| STOP | INTERVAL MILEAGE | TOTAL MILEAGE | STRATIGRAPHIC UNIT | OUTCROP DESCRIPTION |
|---|---|---|---|---|
| | 0 | 0 | Distances start from Mombasa New Palm Tree Hotel | |
| | 36 | 36 | Mariakani trading centre | |
| 17 | 22 | 58 | Lower Member of the Maji Ya Chumvi Formation (Triassic) | The formation comprises a fining-upward sequence represented at the base by shales and siltstones with rainprints and ripple marks. These are overlain by fine-grained sandstone units with ill-defined cross-bedding. |
| | 41 | 63 | Samburu trading centre | |
| | 15 | 78 | Taru trading centre | |
| | 2 | 80 | Road leading to the Kenya oil pipeline turn left | |
| 18 | 1 | 81 | Upper Member of Taru Formation (Triassic) | The coarse-grained sandstones display syn-sedimentary deformational features which include flame structures and prolapsed bedding. |

## NORTH - EAST KENYA

| STOP | INTERVAL MILEAGE | TOTAL MILEAGE | STRATIGRAPHIC UNIT | OUTCROP DESCRIPTION |
|---|---|---|---|---|
| | 0 | 0 | Distances start from Wajir town at the D.C's office | |
| 1 | 53 | 53 | Mansa Guda Fm. (Triassic) | An upward-fining sequence consisting of conglomerates, coarse- and medium grained sandstones that form three major cyclic units. Each cycle also displays an upward-finning trend. The strata are cross-bedded and indicate a paleocurrent flow toward the ESE. |
| | 60 | 7 | Tarbaj trading centre | |
| 2a | 70 | 10 | Didmitu Beds (L.Jurassic) | This formation comprises lime-mud bioclastic wackestones and evaporites occuring as crystals within pores. |

| STOP | INTERVAL MILEAGE | TOTAL MILEAGE | STRATIGRAPHIC UNIT | OUTCROP DESCRIPTION |
|---|---|---|---|---|
| | 0 | 0 | Distances start at Wajir High school, travel **east** on the Wajir Bor - Harar Khorof road | |
| 2b | 12 | 12 | Didimtu Beds (L.Jurassic) | Oolitic unit of the Didimitu Beds. |
| | 45 | 57 | Same as stop 2b | |
| | 4 | 61 | Wajir Bor trading centre | |
| | 11 | 72 | Same as stop 2b upto Khorof Harar | |
| | 52 | 124 | Khorof Harar trading centre | |
| | 33 | 157 | El Katulo trading centre, turn right on Wajir - El Wak road | |
| | 6 | 164 | Lagh Katulo river (dry) | |
| 3a | 30 | 187 | Danissa Beds (M.Cretaceous) | Outcrop of fine-grained flaggy sandstones with bi-directional ripple marks and conglomerates containing siltstone pebbles, moulds of brachiopods and clasts of shale lying flat to the bedding. |
| 3b | 8 | 195 | Danissa Beds (M.Cretaceous) | Two lithofacies are exposed; a lower unit of siltstone interlaminated with clay and incorporating vertical tubular burrows, and an upper planar cross-bedded sandstone with clastic |

| | | | | |
|---|---|---|---|---|
| | | | | dykes groove and load casts oriented SE. |
| 4 | 27 | 222 | El Wak Beds (Pleistocene) | Surface exposures of limestones (probably algal) |

| STOP | INTERVAL MILEAGE | TOTAL MILEAGE | STRATIGRAPHIC UNIT | OUTCROP DESCRIPTION |
|---|---|---|---|---|
| | 0 | 0 | Distances start from the police fort El Wak | |
| 5 | 15 | 15 | Murri Limestone (M.Jurassic) | The oolitic facies of this sequence is exposed at this locality the base of which contains cherty nodules with numerous ooids elongated parallel to bedding. |
| | 27 | 42 | Wergadud trading centre | |
| | 1 | 43 | Junction Wergadud - Takabba - Rhamu road, continue northwards to Rhamu. Exposures of the Danissa Beds on the western flanks of the Danissa hills visible on the right hand side of this road. | |
| 6a | 139 | 142 | Seir Limestone (Kimmeridgian) | The unit consists of bioclastic limestones interbedded with sandstones. The sandstones contain a network of burows filled with shell debris. |
| | 2 | 144 | Rhamu trading centre | |

| STOP | INTERVAL MILEAGE | TOTAL MILEAGE | STRATIGRAPHIC UNIT | OUTCROP DESCRIPTION |
|---|---|---|---|---|
| | 0 | 0 | Distances start from Rhamu trading centre | |
| 6b | 9 | 9 | Seir Limestone (Kimmeridgian) | At this locality the limestones exibit current structures that include ripple and groove marks. |
| 6c | 1 | 10 | Seir Limestone (Kimmeridgian) | Same as stop 6b |
| 6d | 2 | 11 | Seir Limestone (Kimmeridgian) | Sandstone units of the Seir Limestone are exposed at this this stop. These are massive and are seperated by thin layers of evaporites. |
| 7 | 22 | 17 | Rhamu Shales (Oxfordian) | Shales interbedded with minor limestones |
| 8a | 5 | 22 | Marehan Sandstone (U.Cretaceous) | Five distinct units are seen at this outcrop; a lower sandstone with laminations, a large-scale trough cross-bedded sandstone, a cross-laminated sandstone. showing a reversal in the paleocurrent direction and a large-scale cross-bedded sandstone capped by a massive with worm burrows and root casts. |
| 9 | 11 | 33 | Hereri Shales (Kimmeridgian) | The shales are gypsiferous and interbedded with |

| | | | | |
|---|---|---|---|---|
| | | | | argillaceous limestones. This incorporate ovoid and elongate concretions parallel to the the bedding. |
| 8b | 13 | 46 | Marehan Sandstone (U.Cretaceous) | Three facies occur; a horizontally bedded sandstone with ripple marks and worm burrows, a planar cross-bedded sandstone unit and a large scale cross-bedded sandstone forming the highest unit. |
| | 29 | 75 | Mandera town | |

| STOP | INTERVAL MILEAGE | TOTAL MILEAGE | STRATIGRAPHIC UNIT | OUTCROP DESCRIPTION |
|---|---|---|---|---|
| | 0 | 0 | Distances start from Mandera town D.C's office | |
| | 75 | 75 | Rhamu trading centre | |
| | 101 | 176 | Junction El Wak - Wergadud - Takabba roads turn right | |
| 10 | 115 | 216 | Danissa Beds (M.Cretaceous) | A number of structures occur in this unit which include concretions, linguoids ripples groove markings, horizontal and vertical burrows. The vertical burrows disrupt primary layering. |
| 11 | 8 | 224 | Murri Limestone (M.Jurassic) | Same as stop 5 |
| 12 | 35 | 259 | Takabba trading centre | Prominent outcrops of granitic intrusives. |

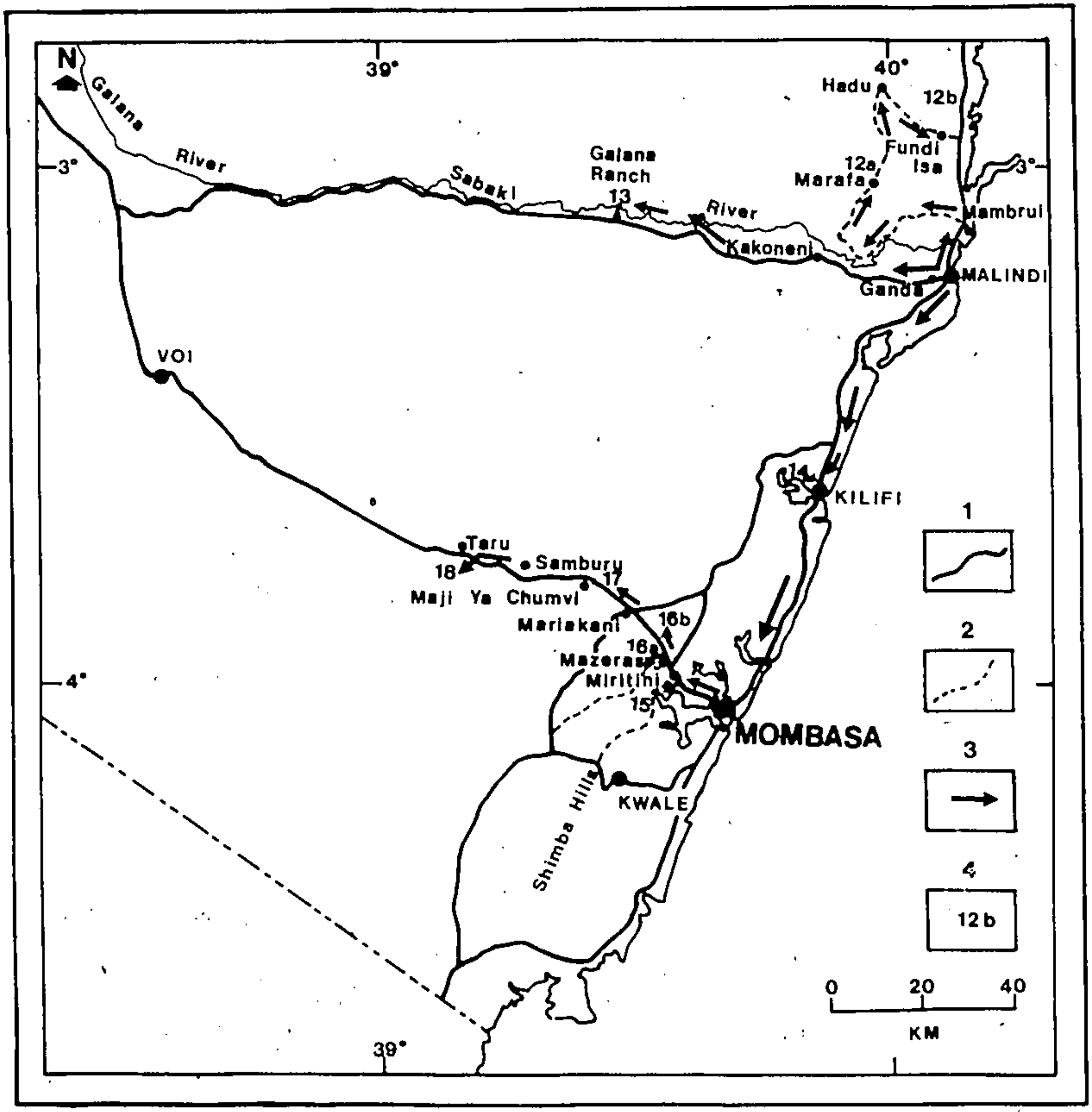


Fig. 26. Location map of the south-east sedimentary basin region of Kenya showing route followed during the field study and stops at selected rock outcrops. 1 - major roads; 2 - minor roads or tracks; 3 - route followed during field study; 3 - stops at rock outcrop.

## SOUTH - EAST KENYA

| STOP | INTERVAL MILEAGE | TOTAL MILEAGE | STRATIGRAPHIC UNIT | OUTCROP DESCRIPTION |
|---|---|---|---|---|
| | 0 | 0 | Distances start from Malindi post office | |
| | 8 | 8 | Sabaki bridge | |
| | 12 | 20 | Junction Malindi - Garsen - Mambrui road turn left | |
| | 30 | 42 | Kabiboni trading centre | |
| | 13 | 43 | Marafa trading centre turn right on Hadu road | |
| 12a | 1 | 44 | Marafa Beds (U.Miocene) | Coarse-grained sandstones exhibiting very large-scale cross-bedding. Ferric minerals disseminated in in the rock have been concentrated in layers or eroded to form limonite pebbles and botryoidal aggregates. |
| | 33 | 77 | Ramada trading centre | |
| | 4 | 81 | Fundi Isa Limestone (L.Miocene) | |
| | 3 | 84 | Fundi Isa trading centre turn left on the track 1 km north of Fundi Isa | |
| 12b | 6 | 90 | Marafa Beds (U.Miocene) | Same as stop 12a, the unit is better indurated and dips 24 degrees toward the SE. |

| STOP | INTERVAL MILEAGE | TOTAL MILEAGE | STRATIGRAPHIC UNIT | OUTCROP DESCRIPTION |
|---|---|---|---|---|
| | 0 | 0 | Distances start from Malindi post office take the Ganda - Kakoneni - Galana road | |
| | 10 | 10 | Ganda trading centre | |
| | 24 | 34 | Kakoneni trading centre | |
| | 73 | 107 | Galana Ranch road turn right | |
| 13 | 2 | 109 | Upper Member of Taru Formation (Triassic) | The unit is exposed at the Galana river crossing where it exhibits flaser bedding and large scale-cross stratification. |

| STOP | INTERVAL MILEAGE | TOTAL MILEAGE | STRATIGRAPHIC UNIT | OUTCROP DESCRIPTION |
|---|---|---|---|---|
|  | 0 | 0 | Distances start from Malindi Ozi's Hotel |  |
|  | 18 | 18 | Gede trading centre |  |
|  | 48 | 66 | Road leading to the African Safari Club Seahorse Hotel turn right |  |
| 14 | 22 | 67 | Baratumu Formation (L.Miocene) | A rhythmic upward-shoaling sequence of carbonate strata. Each cycle begins with a mudstone overlain by calcilutite beds. The lower cycle incorporates two extraformational conglomerates, and the upper cycle terminates in a bioclastic limestone. |

| STOP | INTERVAL MILEAGE | TOTAL MILEAGE | STRATIGRAPHIC UNIT | OUTCROP DESCRIPTION |
|---|---|---|---|---|
| | 0 | 0 | Distances start from Mombasa New Palm Tree Hotel | |
| | 23 | 23 | Miritini trading centre turn left on road leading to Shimba hills and Kwale | |
| 15 | 8 | 31 | Kambe Limestone (M.Jurassic) | The limestones are bioclastic with an oolitic matrix. Siltstones with large scale-cross-bedding overlie the carbonate sequence. |
| | 8 | 39 | Return to junction of Kwale - Mombasa - Nairobi road turn left at Miritini and go towards Mazeras | |
| | 2 | 41 | Mazeras trading centre turn left on road leading to Bombolulu Girls' school | |
| 16a | 6 | 47 | Lower Member of the Mariakani Formation (Triassic) | Two facies are seen, a massive sandstone outcrops downstream while trough and tabular crossbedded strata occur upstream. |
| | 6 | 53 | Return to junction ofBombolulu - Mombasa - Nairobi road turn left at Mazeras go toward Mariakani | |
| | 6 | 59 | Road leading to Kaydee quarry turn | |

| | | | | |
|---|---|---|---|---|
| | | | right | |
| 16b | 1 | 60 | Lower Member of of the Mariakani (Triassic) | Four facies are exposed on the face of the quarry; a large scale-planar cross-bedded sandstone, a dark shale with load deformational structures, a mottled sandstone and a tabular sandstone at the top of the sequence. |

# VITAE AUCTORIS

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| | | |
|---|---|---|
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| | |
|---|---|
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