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Geology and the environment in Kenya

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Abstract—Kenya is in a unique environmental setting by virtue of its geographical location, range of altitudes and perhaps most importantly, the Great Rift System that traverses it. The country displays virtually every facet of environmental geological phenonmena - seismicity, volcanism, mass-movements, the impact of mining, mineral processing and geothermal energy resources development, soil and beach erosion, desertification, air, water and soil pollution, etc. A significant mass of data on these topics already exists, but it lies scattered in various journals and agency reports, some of which are not readily available to environmental researchers and country-planners. The aim of this paper, therefore, is to highlight some features of geology and the environment in Kenya and to set the scene for the subsequent papers in this issue, which examine more deeply various aspects of the subject. The uniqueness of the country's environmental setting is emphasised throughout, since it gives it a special appeal to geomorphologists, geophysicists, hydrologists and land-use planners. A comprehensive list of references is given at the end of this paper in order to aid the search process of those who seek additional information on areas covered in this review. © 1997 Elsevier Science Ltd. All rights reserved.

Résumé—Du point de vue environnemental, le Kenya occupe une place unique par sa situation géographique, ses variations d'altitude et, peut-être plus encore, par le système du Grand Rift qui le recoupe. Le pays présente pratiquement toutes les facettes de phénomènes géologiques en relation avec l'environnement: séismicité, volcanisme, mouvements en masse, impact tant des activités minières que du traitement de matières premières et du développement de ressources en énergie géothermique, érosion du sol et des plages, désertification, pollution de l'air, de l'eau et du sol, etc. Une importante quantité de données existe déjà sur ces sujets mais elle est dispersée dans diverses revues et rapports d'organismes, dont certains ne sont pas facilement accessibles aux chercheurs de l'environnement ainsi qu'aux responsables de la planification nationale. C'est pourquoi le but de cette note est d'insister sur certains aspects géologiques et environnementaux du Kenya en introduisant, par la même occasion, les notes subséquentes de ce volume traitant de façon plus approfondie divers aspects du sujet. La situation unique du pays dans le domaine environnemental est mise en évidence dans cet ouvrage puisqu'elle suscite l'intérêt particulier des géomorphologues, géophysiciens, hydrologues et autres planificateurs de l'utilisation des terres. A la fin de la note, une liste détaillée de références est fournie afin d'aider les recherches de ceux qui souhaitent une information complémentaire dans l'un des domaines couverts par cette synthèse. © 1997 Elsevier Science Ltd. All rights reserved.

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INTRODUCTION

Environmental geoscience research carried out in Kenya today focuses on the solutions to problems pertaining to surface- and groundwater pollution, geo-hazards and land-use. Despite a rapid growth in research, institution building, training and investment, an acceleration of environmental degradation in fields such as water pollution, soil erosion, desertification and mining is still witnesed. These phenomena and processes can often be related to the country's unique geography and

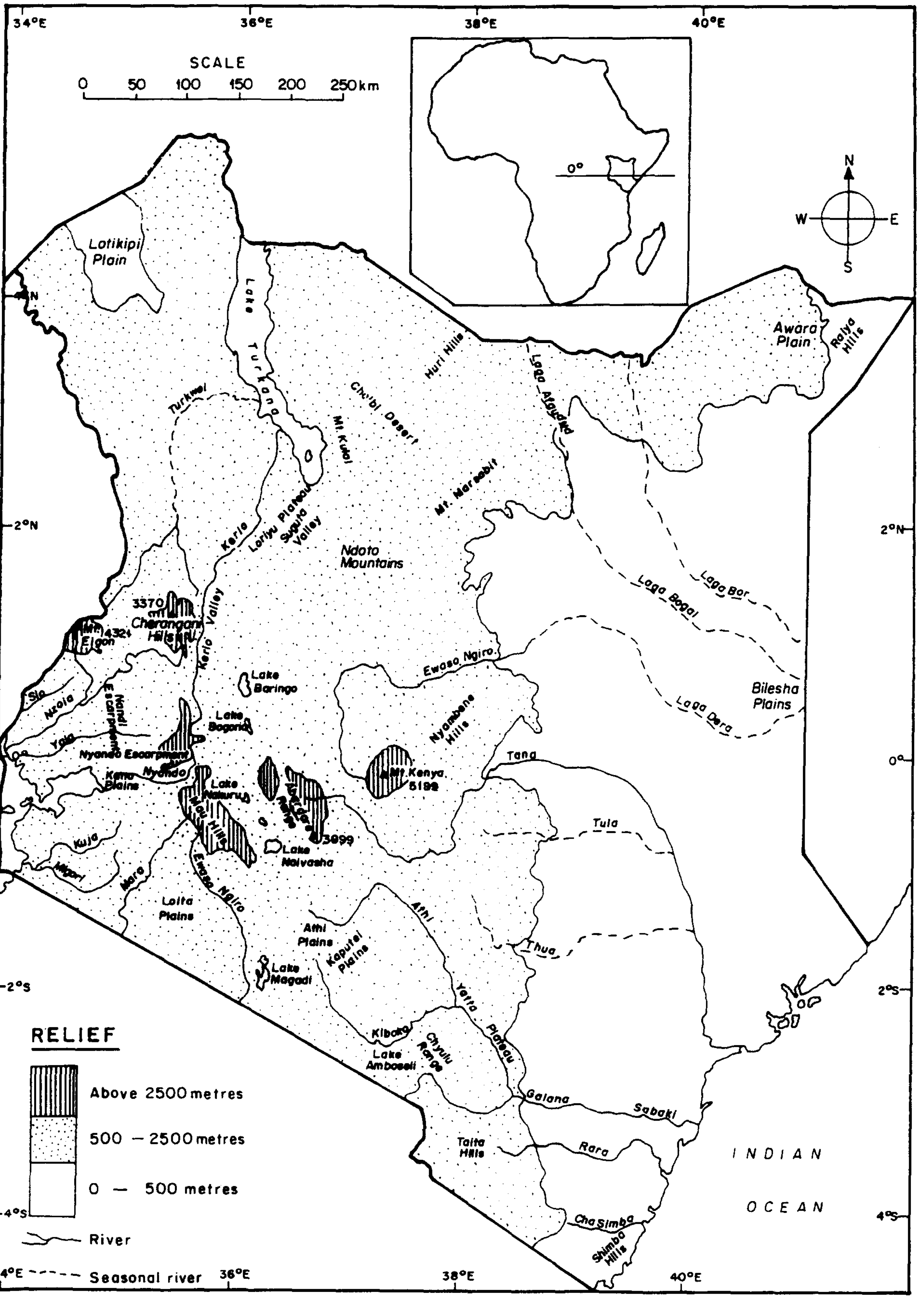

Figure 1. *Location, relief and drainage map of Kenya (modified from EAEP Limited, 1991).*

geology, which are in turn dominated by the great Rift Valley. This is a 50-70 km wide chasm extending south from Lake Turkana and deepens to 600-900 m below the surrounding land. The formation of this spectacular geological phenomenon, as well as other aspects of the geology of Kenya, is summarised under the section on 'Geology and Mineralisation'.

Kenya is a country of great diversity in the regional sense. The diversity of Kenya's landscape, for instance, is shaped by the relief, the formation of which, together with other pertinent aspects of the country's geography, are outlined in this paper. Almost exactly on the equator, the 5,200 m high glaciated peaks of Mount Kenya overtop the country, rising above sweeping plateaus of Tertiary lavas and towering over grassy plains alive with countless species of flora and fauna. Kenya's relief is of overiding importance for the climate of the country, particularly as regards the amount of precipitation and temperature. These climatic factors in turn condition the ecological endowment and the agrarian capacity, which greatly influence the density and distribution of the peasant and herding populations.

About 83% of the country falls within arid and semi-arid lands (ASAL). These ASALs have undergone long-term degradation that has reduced both their actual and potential productivity, thus increasing unemployment in such areas (Central Bank of Kenya, 1991). Desertification can be attributed in part to drought and in part to the highly variable precipitation, but its effect and extent have been greatly aggravated by unsustainable increases in human and livestock populations. Only 20% of the country's land is suitable for agriculture. The Kenyan approach to these problems through geo-scientific research and community participation are dicussed in this paper.

GEOGRAPHICAL SETTING

Location

The Republic of Kenya is located astride the equator on the eastern side of Africa (Fig. 1). It extends between latitudes 5°30'N and 4°30'S and longitudes 34°00'E and 42°00'E and is bordered by Sudan and Ethiopia to the north, Uganda to the west, Somalia to the east and Tanzania to the south. Kenya has a 500 km long coastline with the Indian ocean and a total area of about 583,000 km^2.

Physiography

Kenya has a varied relief which controls and constrains its drainage system (Fig. 1). The altitude varies from sea level at the coast to over 5,000 m at the top of Mt Kenya, which is located almost exactly on the equator. Like the other volcanoes of East Africa, its origin is linked with the formation of the Rift Valley. From the edge of the steep scarp slopes of the Rift Valley system one discerns a breath-taking scenery comprising savannas, salt lakes, picturesque extinct volcanoès and the well-tended landscapes of large farms providing maize, wheat, milk and meat for the growing urban population.

Relief

Four major relief zones are distinguishable within the country. These are the coastal and eastern plains, the central and western highlands, the Rift Valley Basin and the Lake Victoria Basin.

The coastal and eastern plains

These plains cover approximately one third of the total area of the country.They are roughly enclosed by the Indian Ocean and the Somali border to the east, the 39°E longitude to the west, the Tanzanian border to the south and the 3°N latitude to the north. Their elevation varies from 0 at the coastal belt up to 500 m at the hinterland coastal hill masses.

The Rift Valley Basin

The Rift Valley Basin has an elevation of about 500 m in its lowest and widest sections (the Lake Turkana area in the north and the Lake Magadi area in the south). However, the highest elevation reaches 500 m in its narrowest and middle zone around the equator, where it is enclosed by the Mau Hills to the west and the Aberdares Mountains to the east (Fig. 1). This basin runs approximately north-south along the 36°E longitude and separates both the eastern and western highlands. At its broadest northern part, around Lake Turkana, it is about 300 km wide, but between 50 and 60 km wide at its narrowest section around the Naivasha and Nakuru areas. The Laikipia and Mau Escarpments then mark the eastern and western boundaries, respectively, of this basin at its narrowest zone. Between the two escarpments, the Tungen Hills form a spectacular horst in the middle of this basin.

The eastern and western highlands

The eastern and western highland regions, separated by the Rift Valley Basin, have an altitude varying between 1500 and 5200 m above sea level. East of the Rift Valley Basin, the Ndoto Mountains mark the northern limit of these highlands, while the Aberdares Range (about 4000

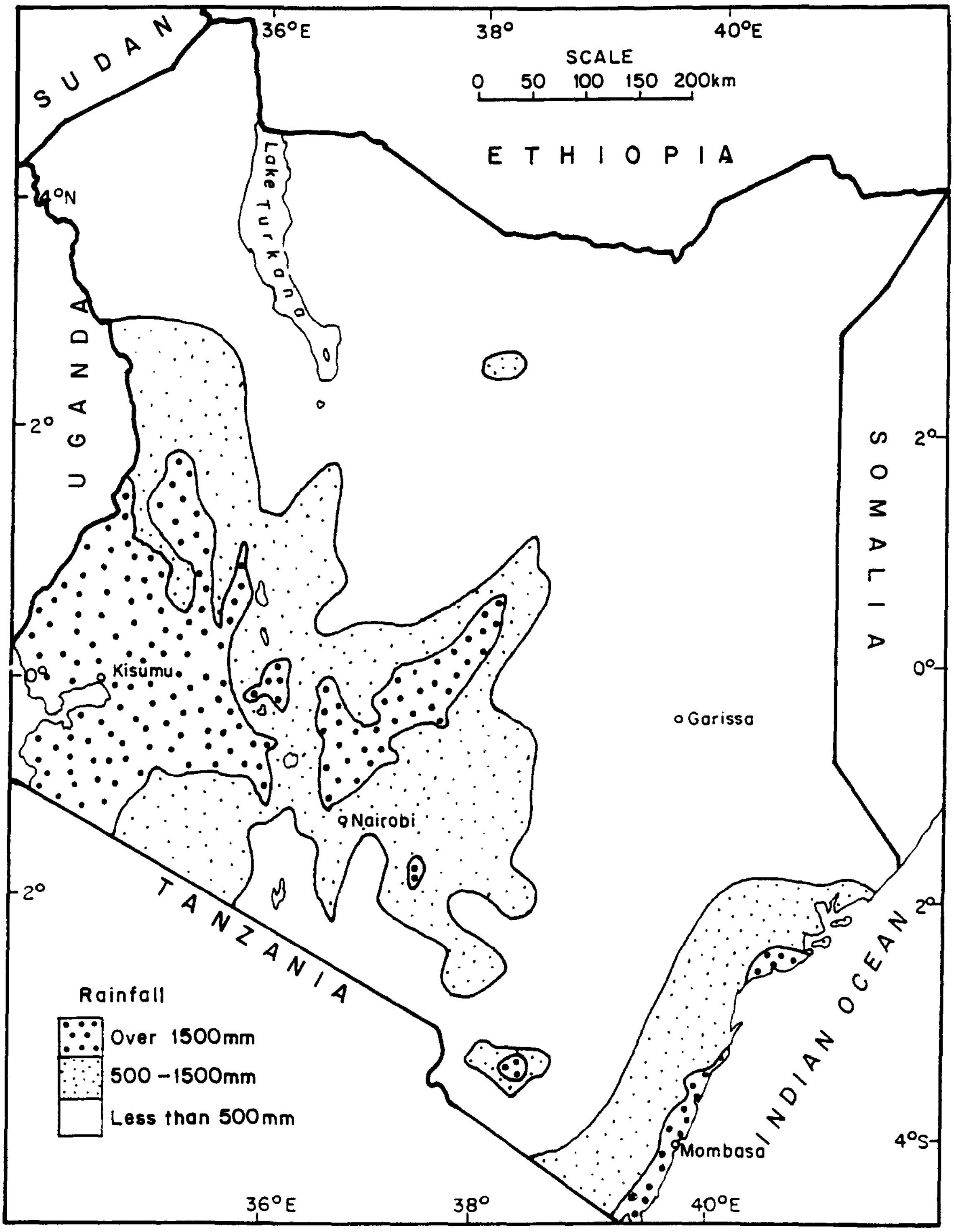

Figure 2. Generalised annual rainfall map of Kenya (modified from EAEP Limited, 1991)

m) and Mt Kenya (about 5200 m) mark the highest peaks in the high central area of these eastern highlands. The Nyambene Hills are an immediate northeastern extension of the Mt Kenya highland region. Further southwards these eastern highlands pass into the Athi and Kaputei Plains, which extend southeastwards to form the Chyulu Range. The Chyulu Range thereafter adjoins the Taita Hills.

The western highlands are marked by the Mau Hills (about 3100 m), which occur in the central part of the region and face the Aberdares Range. Further north they are marked by Mt Elgon (about 4300 m) on the Kenyan-Ugandan border, and the Cherangani Hills (about 3400 m). The Nandi, Nyando and Lolgorien Escarpments separate the western highlands from the Lake Victoria Basin in the northern, central and southern sides, respectively.

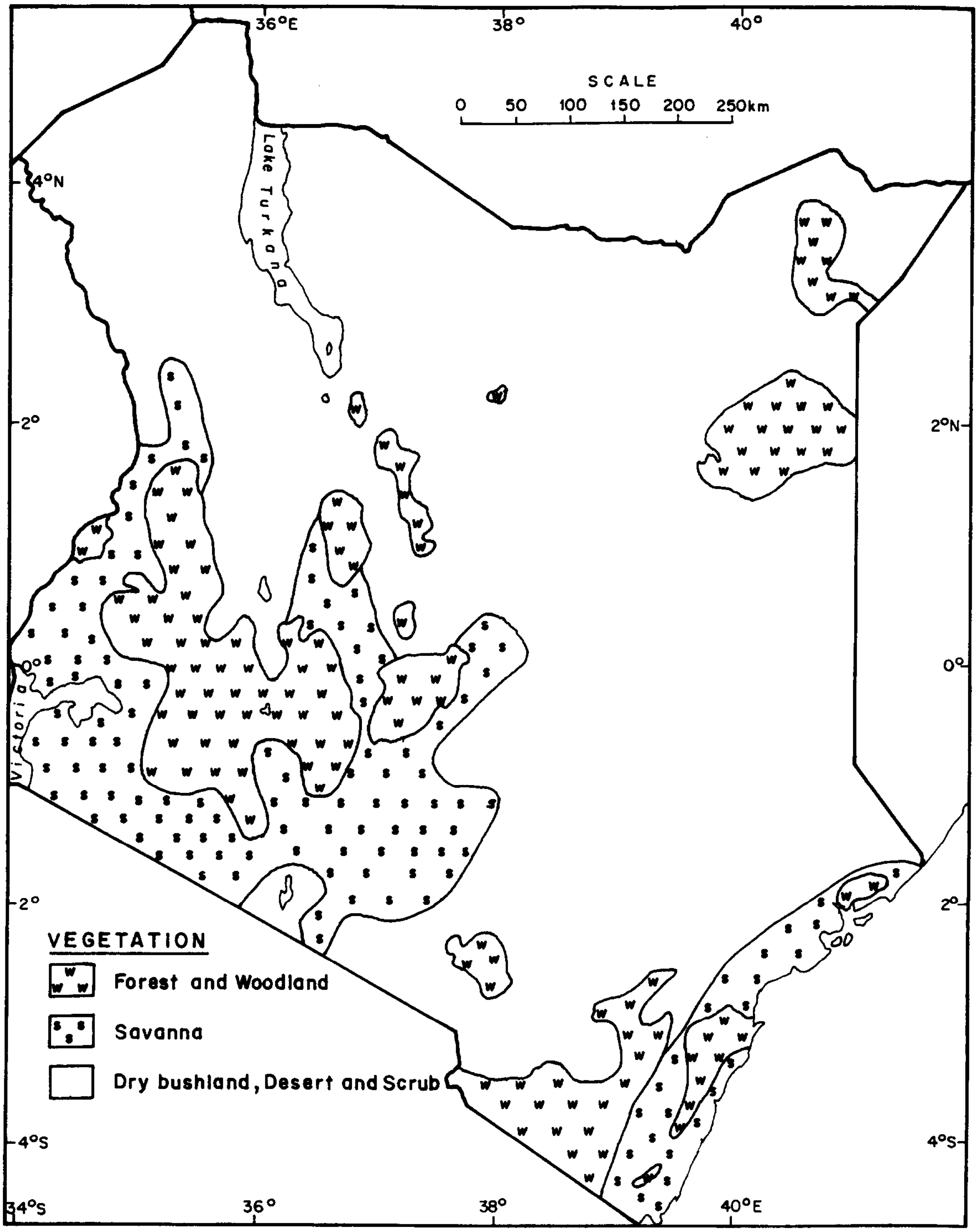

Figure 3. Generalised vegetation map of Kenya (modified from EAEP Limited, 1991).

The Lake Victoria Basin

This basin has a general elevation of about 500-1000 m above sea level. It is separated from the western highlands on its eastern side by the three escarpments mentioned in the preceeding section. Semi-circular in shape and enclosing Lake Victoria, this basin is approximately bounded on the eastern side by the 35°E longitude and by the latitudes 1°N and 1°S, respectively.

Drainage

Drainage is controlled by the four major relief zones described earlier. The longest rivers in Kenya are the Tana and the Athi, both over 700 m long. They rise from the eastern highlands and drain southeastwards, finally reaching the Indian Ocean. Most of the other rivers also originate in the precipitation-rich Kenya Highlands and run off radially; in so far as they do not dry out in the semi-arid areas or end up in swamps, they merge with the Tana and Athi (Fig. 1).

The water level of the rivers varies greatly. Whereas in the dry season they dry up or contract to a narrow channel, in the rainy season they swell enormously and carry large amounts of sediment.

The Rift Valley is basically a long north-south orientated inland drainage catchment with a number of lakes occurring along its entire floor. From the north to the south, they include Lakes Turkana, Baringo, Bogoria, Nakuru, Elmenteita, Naivasha and Magadi. The rest of the Rift Valley lakes in Kenya occur in its middle zone where they are found astride the equator. Both Lakes Turkana and Magadi are terminal basins within the larger Rift Valley catchment.

Two long rivers, the Turkwel and the Kerio, rise from the western highlands and drain northwards into Lake Magadi from the eastern and western sides of the southern Rift Valley scarps. The southern Ewaso Ngiro River drains along the Rift floor into Lake Natron at the Kenyan-Tanzanian border, adjacent to Lake Magadi.

The Rift Valley lakes vary in salinity. Lake Naivasha is a fresh water lake, and Lake Baringo is only weakly saline. The remainder of the lakes are alkaline to hyperalkaline in their chemistry. Lake Victoria, a large fresh water lake, occupies a basin into which the majority of the rivers and streams rising from the western highlands drain. These rivers include the Sio, the Nzoia, the Yala, the Kuja and the Mara.

Climate and vegetation

Lying in the middle of the equatorial belt, Kenya displays a variable climate and vegetation cover consistent with its range of altitudes. Four broad climatic zones are distinguishable within the country and include the lake basin around Lake Victoria to the west, the highlands (western and central highlands including Nairobi), the coastal and the semi-desert (including desert) climates (Fig. 2).

The lake basin climatic zone receives an average annual rainfall of 150 cm to >200 cm with the driest month receiving an average minimum of only 5 cm and the wettest month an average minimum of 20 cm. Temperatures are warm to hot, rarely falling below 20°C and reaching a maximum of about 30°C.

The coastal climatic zone receives an annual rainfall of 100-200 cm. During the hot months temperatures are about 30°C and in the warm months about 25°C. With the exception of January and February, which receive a rainfall of less than 1 cm each, the rest of the months receive an average rainfall of 5-10 cm, except for the wettest months (April and May) which receive over 20 cm of rainfall each.

The highlands receive an average annual rainfall of 50 cm to >200 cm. During the hot months the temperatures are 22-28°C and during the cool months 15-20°C. January, February and July to September are the driest months with an average rainfall of less than 3 cm each. The wettest months are April to May and October to November with an average rainfall of between 10 cm and 20 cm each month.

The semi-desert climate is hot to very hot throughout the year. Temperatures are over 25°C in the cool months and over 30°C during the hot months. The climate is largely dry and during the wet months of March to May and October to December, the rainfall is less than 5 cm each month.

The vegetation varies according to the climate and relief (Fig. 3). In the lake basin, the highlands and the coastal climatic zones, the vegetation varies from predominantly savanna type (grassland) to scattered woodlands and equatorial forest. In their upper reaches the montane forests are fringed by bamboo and heather growth, which gradually give way to grassland and moorland (highland forest and shrub). In the semi-desert climate, which accounts for over three quarters of the total area of the country, the vegetation is mainly desert and shrub. Moorland vegetation is found at the top of the Mt Kenya region. A few scattered areas with swamp vegetation also occur within the country. Their largest development is found slightly north of the equator about 150 km west of the Somali border in the Lorian swamp, where the River Engare Uaso Nyiro disappears through a network of tributaries.

Soils

Over three quarters of the country is covered by loam soils, which are particularly well-developed in the semi-arid and desert regions. These are well drained soils with an adequate amount of soil nutrients and therefore ideal for agriculture. Nevertheless, the lack of adequate rainfall or other forms of water continues to impede agricultural development in these areas. In the lake basin and central highlands regions, clays are the dominant soils. Young, very fertile, volcanic ash soils ideal for agriculture are found in the high mountain areas such as Mt Kenya, Mt Elgon and the Aberdares Range. These soils are known to have a high sorption capacity and are a contributory factor to landslide events in these areas (Davies and Nyambok, 1993). Along the coastal region, a narrow band of coastal sand borders the land adjacent to the Indian Ocean.

Table 1. Population of Kenya according to the 1989 Census

Province	Population
Nairobi	1,324,570
Central	3,116,703
Coast	1,829,191
Eastern	3,768,677
Northeastern	371,391
Nyanza	3,507,162
Rift Valley	4,981,613
Western	2,544,329
Total (Kenya)	21,443,636

Source: Central Bureau of Statistics, Government of Kenya (1994).

Population

The population of Kenya based on the last census (1989) is 21.4 million people, with a projected figure of about 30 million in the year 1996 (Central Bureau of Statistics, 1994). The highest population densities (>3 million people) are found in the Rift Valley, Eastern, North Eastern, Nyanza and Central Provinces, respectively (Table 1).

The capital city, Nairobi, has a population of about 1.5 million people (Central Bureau of Statistics, 1994), while Mombasa and Kisumu are the next major towns, respectively. Other major population centres include Nakuru, Eldoret, Meru, Thika, Nyeri, Kisii, Kericho, Bungoma, Busia, Malindi and Machakos (Fig. 4).

The population density is controlled mainly by agricultural productivity, which is in turn largely determined by rainfall. The high and medium density areas of the central highlands region and the Lake Victoria and coastal regions, receive medium to high rainfalls and have good arable lands. Major towns have high populations because they are either largely administrative and/or commercial and industrial centres. In contrast the low population density areas are either arid or semi-arid.

Land use

A wide variety of crops, depending on their ideal climatic and soil conditions, are grown in the different parts of the country (Fig. 5). However, only the major crops and agricultural activities are described in this section. Along the coastal strip cashew nuts, coconuts and sisal are the main cash crops grown.

In the central highlands coffee, tea, rice, fruit, sisal and pyrethrum are the main cash crops, while in the western Kenya region these are sugar cane, cotton, tea and rice. Some coffee and tobacco are also grown in this region. Maize and wheat are grown both as subsistence as well as cash crops. Cattle rearing, mainly for beef, is practised particularly in the semi-arid areas. Over 70 percent of the country is not arable and arable lands are only found in the central, western and coastal regions. Climatic conditions, vegetation and agriculture are largely controlled by the relief of the country which has already been discussed earlier.

Economics and industry

The economy of Kenya is largely dependent on tourism and agriculture. Since independence in 1963, the economy has undergone an overall structural transformation accompanied by significant changes in the contribution of various sectors to the gross domestic product. Agricultural production, which accounted for 44.2 and 38.4% of the gross domestic product in 1954 and 1963, respectively, declined to about 30% in 1990 (Central Bank of Kenya, 1991). This reflects the growing importance of the other sectors of the economy. Nevertheless, this sector remains the backbone of the economy, supporting the almost 80% of the population that live in rural areas.

The tourism industry has gained increased importance in the Kenyan economy since 1963. With the weak performance in coffee and tea over the last few years, this sector has become the country's leading foreign exchange earner. The phenomenal expansion in this sector reflects not only the diverse tourist attractions that Kenya has, but also the enormous investment that the country has undertaken in infrastructural facilities such as hotels of international standard and roads connecting the national parks and main urban centres.

The contribution of the manufacturing sector to the gross domestic product has also increased significantly since independence. Manufacturing production has been dominated by food, beverages and tobacco, chemical and petroleum products and metal products. The country has several tea processing factories within the tea growing zones in the western and central regions (the Kericho, Murang'a, Nyeri and Kiambu districts). Coffee factories are also common in the coffee growing zones, the majority of which are located in the central region. The tea and coffee industries utilise huge quatities of water and environmental pollution is frequently noted in the nearby rivers and streams into which factory effluents are discharged.

Wood and paper factories are located in Thika, Nairobi and Webuye. The Pan Paper Mill is located in Webuye and discharges its effluent into the River Nzoia (Fig. 1). The level of toxic gas emission into the atmosphere, as well as organic and metal

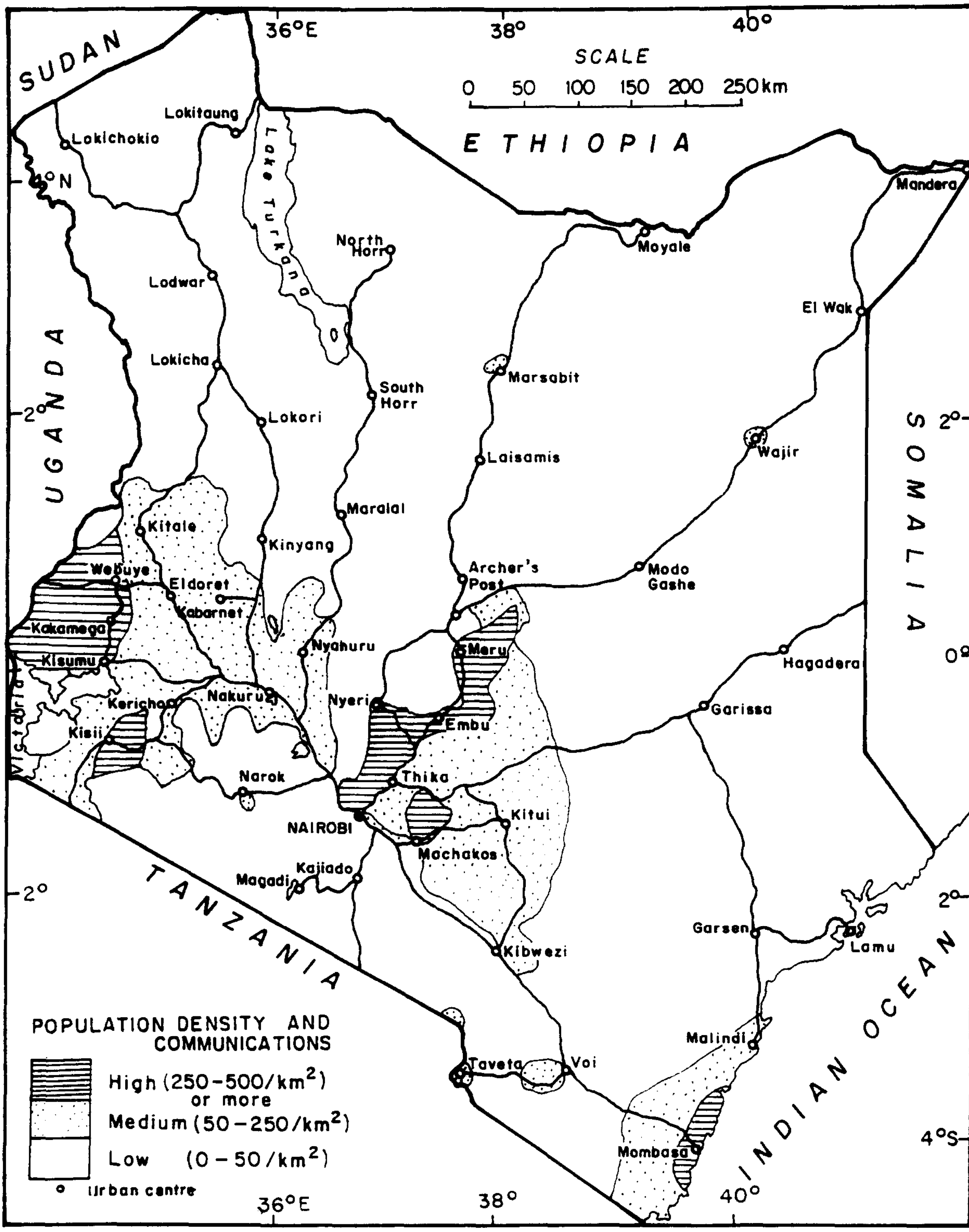

Figure 4. Communication and population distribution in Kenya (modified from EAEP Limited, 1991).

pollutants into the River Nzoia, has been a matter of concern for some time. Some hydrochemical parameters for this river are shown in Table 5 of Davies (1996a). Textile and chemical industries are located in several towns including Nairobi, Kisumu, Thika, Mombasa, Nakuru and Eldoret. As expected, chemical pollution of waterways by these industries takes place on a large scale and has been given serious consideration by government and other environmental institutions. Consequently, environ-mental impact assesment (EIA) is now a principal tool for meeting Kenya's environmental protection objectives. Hirji and Ortolano (1991) give an analysis of the leather industries of Kenya

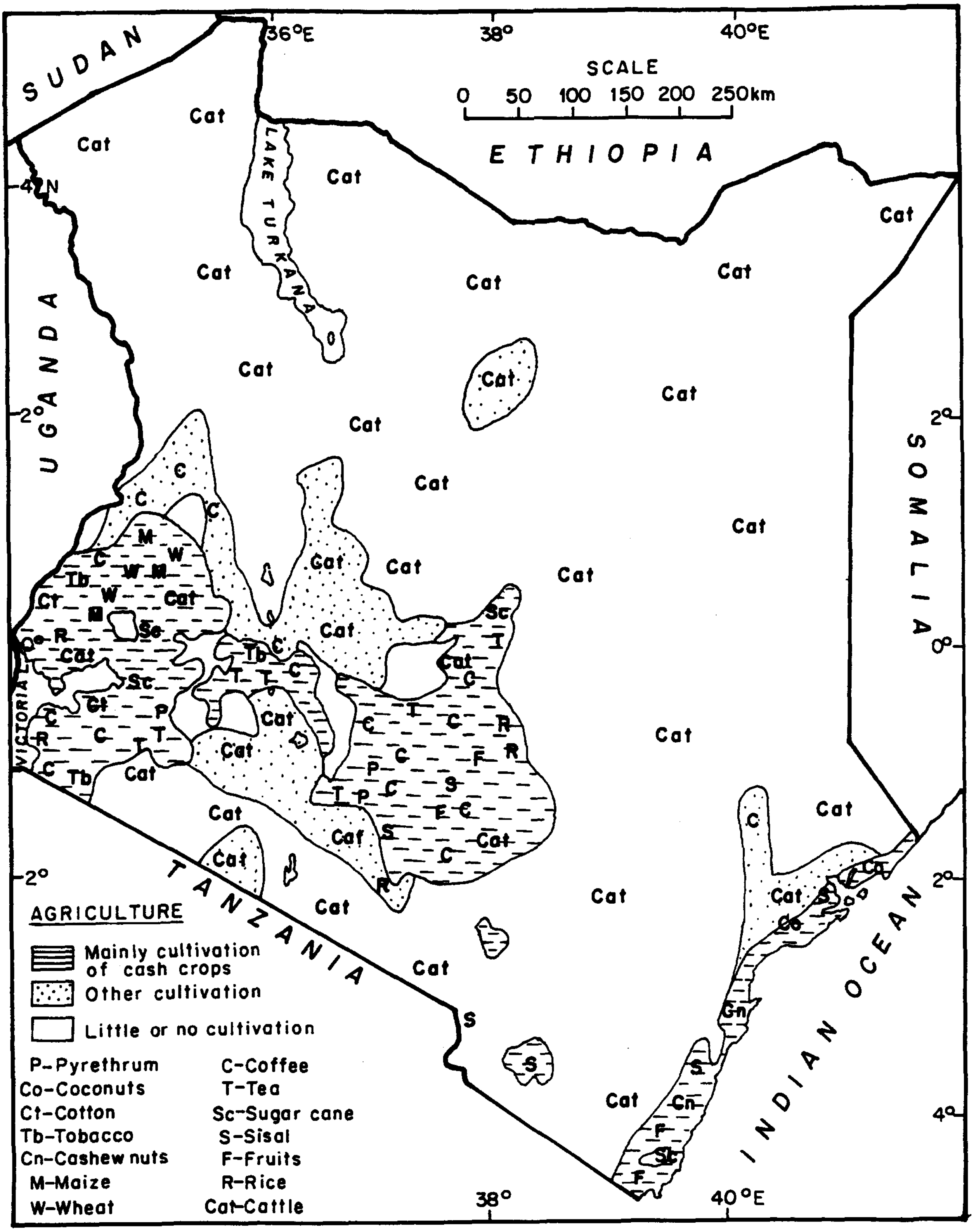

Figure 5. Generalised agricultural map of Kenya (modified from EAEP Limited, 1991).

planning process and provide useful insights into how EIA is implemented for new industrial facilities in Kenya.

At present, only one oil refinery operates in the country. This factory is located in the port city of Mombasa and refines crude oil (Central Bank of Kenya, 1991; EAEP Limited, 1991). Kenya has two portland cement factories located in Mombasa at Bamburi and in Nairobi at the Athi River. These factories utilise readily available geological materials.

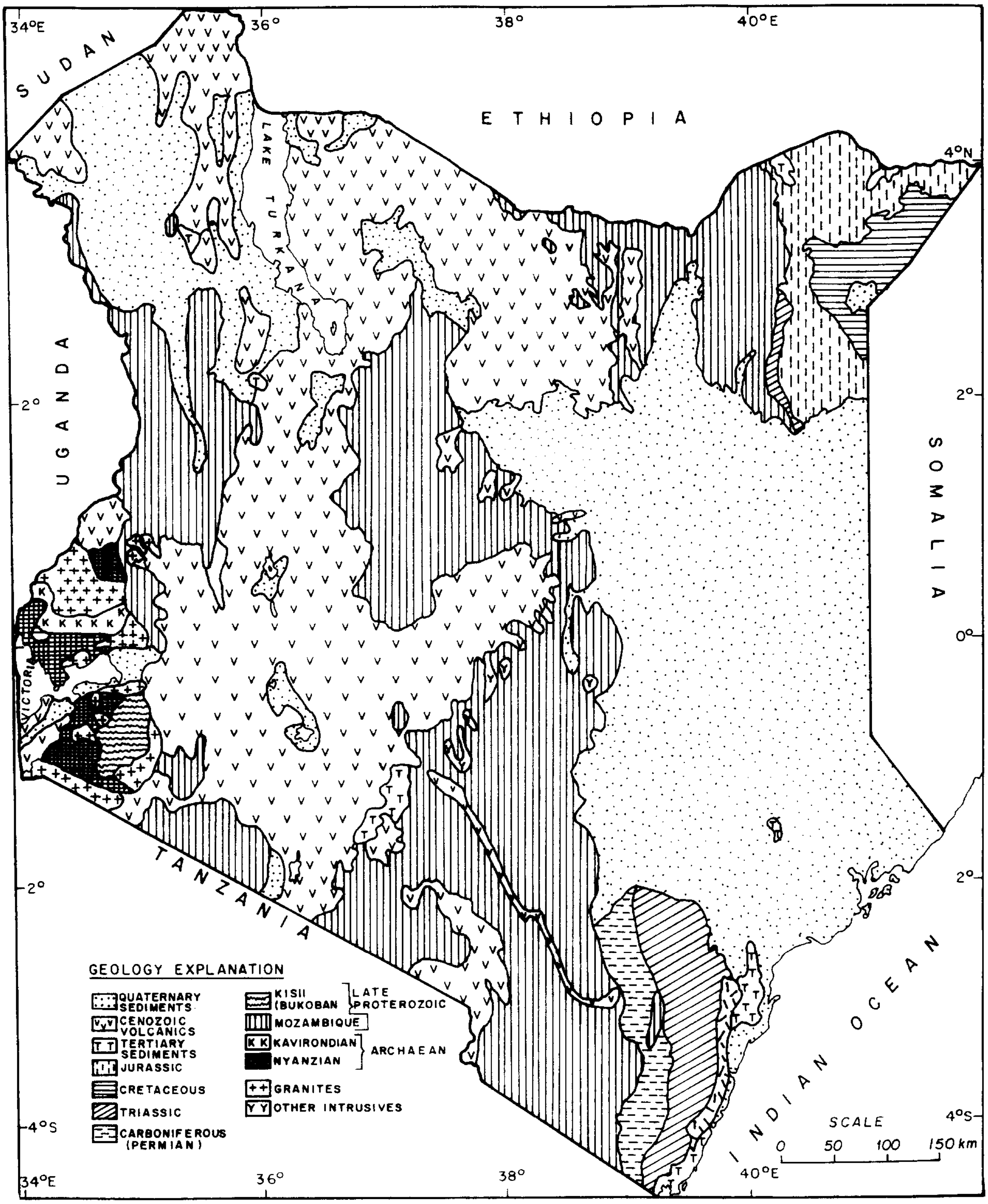

Figure 6. Simplified geological map of Kenya showing the major rock units (modified from EAEP Limited, 1991).

An important development in the industrial sector has been the growth of the informal manufacturing sub-sector, commonly known as 'Jua Kali' in response to the scarcity of formal wage employment. These are small manufacturing ventures that use very little capital in their production process and manufacture a wide range of products, including simple machines, utencils, steel window and door frames, boxes, charcoal stoves and furniture.

Kenya has a fairly open economy, with the proportion of external trade to total gross domestic product averaging about 46% during 1963-1990 (Central Bank of Kenya, 1991). The main export commodities include coffee, tea, sisal, pyrethrum, horticultural crops and some manufactured goods.

Table 2. A generalised sequence of the geology of Kenya

Era	Rock formations	Age	Major rock types
Cenozoic	Oloronga Beds High Magadi Beds	Quaternary sediments	clays, diatomites, shales, silts
	Magarini Beds		
	Fundi Isha Beds Faratumu Beds	Tertiary sediments	sands, marls, clays, conglomerates, limestones
	East African Rift System lavas and pyroclastic flows	Tertiary and Quaternary	basalts, phonolites, trachytes, nephelinites, tuffs, agglomerates
Mesozoic	Maheran Series	Upper Cretaceous	siltstones, sandstones, limestones, shales
	Mandera Beds Mazeras sandstones	Jurassic	coarse grits, feldspathic sandstone, sandy shales
	Mariakani sandstones Maji ya Chumvi Beds	Permo-Triassic	flaggy sandstones (fine-grained), micaceous shales, mudstone, shales, sandstones
Palaeozoic	Taru grits	Carbo-Permian (?)	grits, shales
	Lower Palaeozoic is not represented		
Precambrian	Mozambique Belt	Neoproterozoic (~0.75-0.45 Ga)	schists, gneisses, marble, amphibolites, migmatites, granitoid gneisses
	Kisii Series (the Bukoban)	Neoproterozoic (~1.0-0.8 Ga)	rhyolites, basalts, quartzites, conglomerates
	Mumias, Maragoli, Oyugis, Wanjare granites	Palaeoproterozoic (~1.8-2.4 Ga)	granites, granodiorites, leucogranites
	Kavirondian Group (formerly System)	Archaean (~2.5-2.8 Ga)	shales, mudstones, greywackes, phyllites, conglomerates
	Nyanzian Group (formerly System)	Archaean (~2.8-3.1 Ga)	basalts, andesites, dacites, agglomerates, andesitic tuffs, rhyolites

Modified from Cole (1950), Haughton (1963), Saggerson (1972) and Cannon *et al.* (1981).

The major imports consist of consumer, intermediate and capital goods. The destination of Kenya's major exports has been the European Community (EC) countries and other African countries.

GEOLOGICAL SETTING

Geology and mineralisation

The major rock types constituting the geology of Kenya include: the Archaean-Palaeoproterozoic granite-greenstone terrane found in western Kenya around Lake Victoria, the Neoproterozoic Kisii Group (formerly the Kisii Series), the Mozambique Belt and the Upper Palaeozoic to Mesozoic Karoo sediments of coastal and northeastern Kenya (Fig. 6).

Younger rocks are represented by Tertiary and Quaternary sediments in eastern Kenya and the coastal strip bordering the Indian Ocean. A generalised stratigraphy of these major rock types is given in Table 2.

Archaean-Palaeoproterozoic granite-greenstone terrane

The granite-greenstone terrane outcrops both to the south and to the north of Lake Victoria in western Kenya and is broadly similar in geology and tectonics to other granite-greenstone terranes in other parts of the world (Condie, 1989). The Kenyan greenstone belt is of Meso- to Neoarchaean age (3.10-2.55 Ga) (Cahen *et al.*, 1984), while the associated granites vary in age from Meso- or Neoarchaean to Palaeoproterozoic (2.55-1.8 Ga) (Bell and Dodson, 1981; Cahen *et al.*, 1984).

The greenstones are constituted of mainly two rock groups, the older Nyanzian Group (formerly Nyanzian System) which is unconformably overlain by the relatively younger Kavirondian Group (formerly Kavirondian System). This older group is dominated by metavolcanics varying from tholeitic basalts, with occasionally identifiable pillow structures, to calc-alkaline andesites, dacites, rhyolites and pyroclastic agglomerates, tuffs and ashes (Opiyo-Akech, 1988; Ichang'i and MacLean, 1991; Mathu and Nyambok, 1993). The younger group consists of basal polymict conglomerates, middle greywackes and sandstones, with shales and mudstones at the top (Huddlestone, 1954; Ngecu, 1993). Both the Nyanzian and Kavirondian greenstone belt rocks were affected by low-grade regional metamorphism (greeschist-facies) during the Archaean.

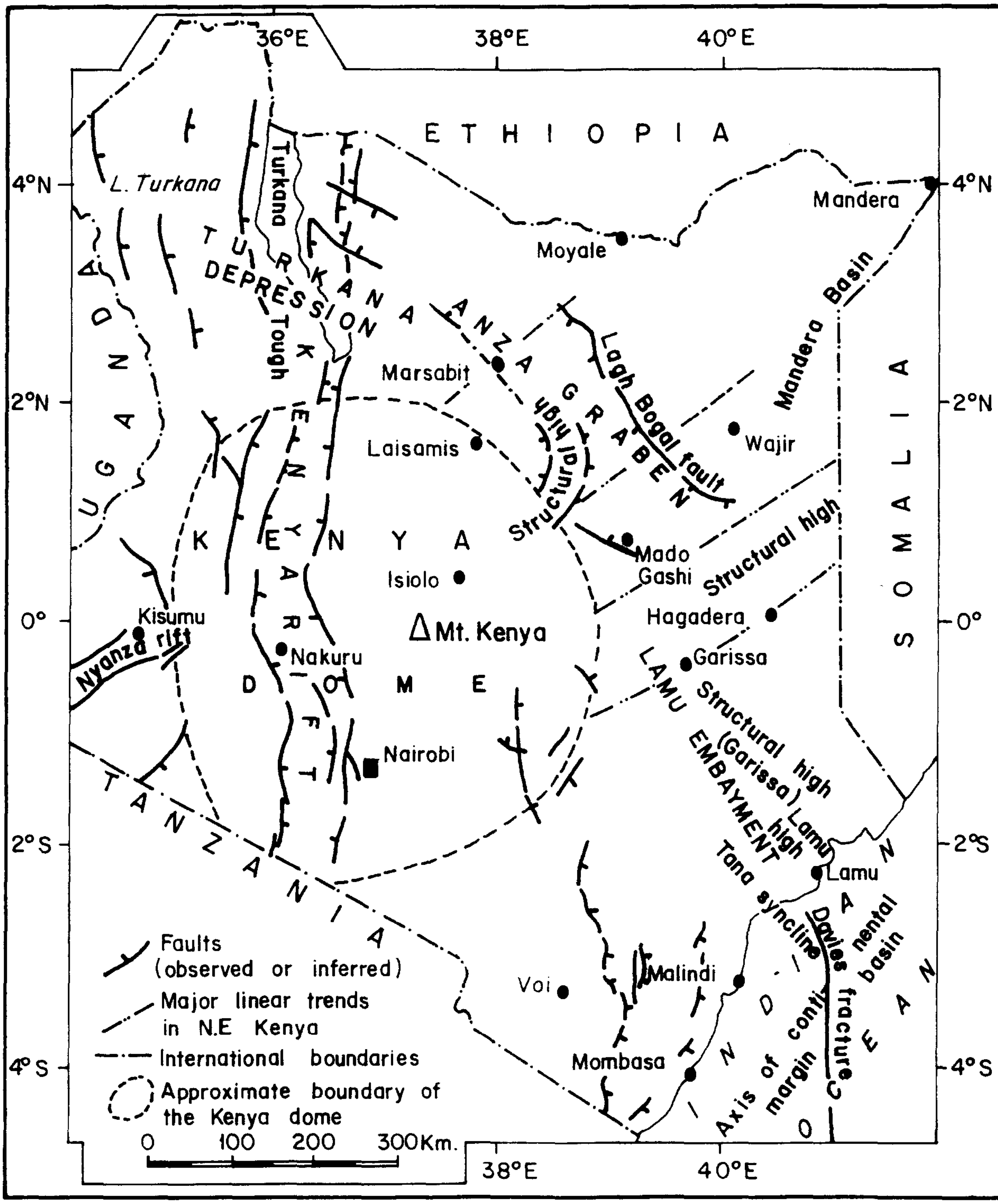

Figure 7. A simplified structural and tectonic map of Kenya (after National Oil Corporation of Kenya, 1986).

The batholitic granitoids of this terrane have a heterogeneous lithological nature and vary from granodiorites, adamellites and porphyritic granites to leucogranites. These granitoids have a multiple intrusive history spanning the Archaean and Palaeoproterozoic (Shiozaki, 1983; Mathu and Nyambok, 1993).

The structural geology of this terrane is characterised by a series of east-west orientated anticlinal and synclinal folds with steep dips (Hoshino *et al.*, 1993) and faults and shear zones are common (Fig. 7).

The granite-greenstone terrane is rich in base metal mineralisation and Au has been mined in the area since the 1930s (Ogola, 1987). Gold is often structurally controlled and is often found in shear zones. Native Cu has been mined in the Macalder mines south of Lake Victoria for some time and the potential for economic quantities of pyrite and chalcopyrite is high. Banded iron formations (BIFs) are also locally common in these greenstone belt rocks. Quarrying of the rock units, particularly the granitoids and greenstone metavolcanics for both dimensional and ornamental stone in the construction industry, is already underway within this terrane.

Kisii Group (the Bukoban)

The Kisii Group (formerly the Kisii Series) is alternatively called the Bukoban, particularly in Tanzania, where it is more extensively developed. In Kenya, the group is represented by a volcanosedimentary sequence that occurs in the Kisii area south of Lake Victoria (Fig. 6). It is found between the Neoproterozoic Mozambique Mobile Belt to the east and the Archaean-Palaeoproterozoic granite-greenstone terrane to the west. Dated to be about 1.30-1.00 Ga old (Cahen *et al.*, 1984), this group could represent the marginal marine shore sediments and volcanics of the original Mozambique geosynclinal basin. The dominant sedimentary lithological units are sandstones and quartzites, while the volcanic units include both basalts and rhyolites. Structures within the Kisii Group include a series of folds, weak foliation surfaces and arenaceous sedimentation features. It is within the sediments that a kaolinised feldspathic unit is mined for the 'so-called' Kisii soapstone, which is extensively used in making handcrafts which are world renowned for their beauty. Other mineral resources within the Kisii Group include Fe-ore, whose potential is yet to be fully investigated.

Mozambique Belt

The Mozambique Belt is a Neoproterozoic Mobile Belt, 1.00-0.5 Ga old (Cahen *et al.*, 1984; Stern, 1994), stretching from the south to the north across the eastern African countries. Stern (1994) proposed that it should be called the 'East African Orogenic Belt'. The varied and complex tectono-lithostratigraphy of this belt in Kenya has led to the identification of several of its groups (Sanders, 1954; Saggerson *et al.*, 1960; Sanders, 1965; Vearncombe, 1983; Berhe, 1990; Mathu, 1992; Mosley, 1993; Nyamai *et al.*, 1993; Nyambok *et al.*, 1993; Mathu *et al.*, 1994). The Mozambique Belt is characterised by medium- to high-grade metamorphic rocks, which include schists, gneisses, migmatites, granulites, granitoid gneisses and granites. Amphibolites, serpentinites, quartzites and marbles are common within this belt, while diorites, gabbros and ultramafic rocks are found more variably scattered.

Shackleton (1986) and Vearncombe (1983) have identified at least three ophiolitic rock assemblages within this belt in the West Pokot, Baragoi and Moyale areas in northwestern and northern Kenya.

The belt has a characteristic north to south structural trend, but local complex and variable structural trends are also present. Complex folding varying from outcrop to regional scale, is typical of this belt. Faults and shear zones of various dimensions, either obliquely transecting the belt or running parallel to its trend, are also present.

The Mozambique Belt in Kenya produces gemstones which include ruby, blue sapphire, beryl, amethyst, garnets and tourmaline. Fluorite and marbles are the major industrial minerals currently mined within this belt. Kenya's fluorite deposits at the Kerio Valley represent one of the world's largest fluorite deposits. It is also a principal foreign exchange earner for the country. The mineral has many uses, such as in steelmaking, cement manufacture, rocket fuels, aerosol sprays, dry cleaning fluids and in making highly durable paint.

Granites, gneisses, migmatites and quartzites are now extensively used in the construction industry, both as dimensional and decorative stones. Marble is also currently mined for use in the manufacture of cement and the production of lime.

Groundwater resources from this belt are potentially available or exploited in the aquifers between the underlying Mozambique Belt and its overlying Cenozoic volcanics and sediments. Groundwater is also available in the pervious regions where shear zones, faults and joint systems are frequent, such as in the Wundanyi area in the Taita Hills region.

Palaeozoic-Mesozoic sediments

All the Palaeozoic-Mesozoic sedimentary rocks in Kenya occur as north-south orientated strips in the coastal and northeastern regions of the country (Fig. 6). Recent oil exploration work is also reported to have encountered large deposits of these sedimentary rocks at depth in the Turkana Basin of the Rift System. These sediments include those of the Upper Palaeozoic to Lower Mesozoic, as well as those of middle and Upper Mesozoic age. Saggerson (1972) provides a more detailed description of these rocks in East Africa.

The Middle and Upper Mesozoic sediments are found in coastal and northeastern Kenya where they unconformably overlie the Karoo sediments (Saggerson, 1972) and include both Jurassic and Cretaceous sediments. The Jurassic beds in northeastern Kenya include a thick series (1600 m) of limestone and shale deposited in a neritic zone. The lowermost beds are known to be fossiliferous. Some of the beds contain gypsum, while others are calcareous shales. In coastal Kenya, Jurassic rocks include marine limestones, which are overlain by shaly beds.

The Cretaceous sediments of northeastern Kenya are represented by the Danissa Beds and the Marehan Sandstones, which include both marine and continental deposits. The Danissa Beds comprise siltstones, mudstones, thin limestones and sandstones (Saggerson, 1972) and are considered to represent deposits from a marine incursion in the area during the end of the Jurassic. The Maheran Sandstones contain subordinate siltstones and are interpreted to have been deposited under continental conditions during a period of marine regression.

Cenozoic volcanics and plutons

Throughout the Tertiary, most of Kenya and East Africa was above sea-level and marine transgressions occurred only along the coastal areas. The Tertiary in Kenya and East Africa is therefore notable largely for its igneous activity, which mainly included volcanism and associated minor plutonism. Both were associated with rift faulting. The volcanism has continued to occur up to the present. The Tertiary to Recent volcanics in Kenya lie along a north-south belt on the rift floor and beyond it to the east and west on the rift shoulders. They stretch from Lake Turkana in the north to Lake Magadi in the south and constitute some of the largest mountain ranges in East Africa.

The volcanic rocks include basalts, phonolites, nephelinites, trachytes and rhyolites, which show soda enrichment. Pyroclastics, such as tuffs, agglomerates and ashes, are also commonly associated with both the large central type volcanoes (Mts Kenya, Elgon and Kilimanjaro), as well as the numerous central volcanic cones that characterise the floor of the Rift System (such as Mts Longonot, Suswa, Menengai and the more minor Mt Margaret).

Associated with the rifting and volcanism were relatively minor alkaline plutons, which resulted in the intrusion of carbonatite-bearing complexes (Le Bas, 1978). In Kenya, these intrusions include the Rangwe-Homa intrusive complex in the Lake Victoria region. Other carbonatite occurrences include the Mrima and Jumbo carbonatitic plutons in the coastal regions close to the Tanzanian border and a small carbonatite intrusion in the Muhoroni area on the way to Kisumu from Kericho. These carbonatite intrusives are potential sources of rare earth elements and apatite and a possible source of P. Saggerson (1972) reported over four hundred tons of Nb (in pyrochlore) from these carbonatites.

The volcanic rocks, especially the basalts, phonolites and trachytes, have been frequently quarried for road gravel and railway line ballast material. Tuffs have been the most widely used as dimensional stones in the central region of Kenya. The tectonics and volcanism associated with the Rift System resulted in the formation of various types of lake basins, fault scarps and mountain ranges of great tourist attraction. Geothermal steam, currently exploited in the Naivasha area for electricity, was formed as a result of the Cenozoic igneous activity in Kenya. Tole (1996) reviews geothermal energy development in the Naivasha area, as well as other occurrences in the country. The potential for exploitation of the mineral resources, such as the carbonatite complexes, is far from being fully developed. Water resources and agriculture also offer considerable promise in many of the areas underlain by the Cenozoic volcanics.

Several regional reports and publications have thoroughly documented the volcanics and associated plutons in Kenya. The principal works include those by Dixey (1946); McCall (1967); Williams (1970, 1978); Baker and Wohlenberg (1971); Crossley (1976, 1979); King (1978); Le Bas (1978); Williams *et al.* (1983); Baker *et al.* (1988); Clarke *et al.* (1990) and Randel and Johnson (1991).

Cenozoic sediments

During the Tertiary, most of Kenya was above sea-level. The little marine transgression that occurred was confined to the coastal region. The Tertiary is therefore dominated by continental deposits overlying a peneplain (Saggerson, 1972). Cenozoic sediments have been penetrated to a depth of more than 4 km in some parts of Kenya.

Although the Lower Tertiary does not crop out in Kenya, considerable thicknesses of Tertiary strata have been proved in boreholes north of the Tana River in the coastal region (Saggerson, 1972).

Miocene marine littoral deposits in coastal Kenya near Malindi are overlain by Pliocene sands, sandstones, clays and conglomerates. A considerable thickness of Middle and later Tertiary sediments also occur in the lower Tana River Basin.

Quaternary sediments, largely terrestrial in origin, are widespread in Kenya, especially in the eastern side of the country and in the Rift System. These sediments contain artefacts and mammalian fossil remains that have facilitated their dating. They are formed of thick lacustrine and fluvial deposits, including evaporites, the diatomite deposits currently being exploited at Kariandusi near Lake Elmentaita and the trona deposits of Lake Magadi. Gypsum deposits found in several localities in Kenya, together with the lignite occurrences in the Kitui area, are all of Quaternary age and were formed in former lagoon or lacustrine areas. It is considered that a number of Quaternary movements resulted in the formation of fossil and modern coral reefs in the coastal region of Kenya and also wave-cut platforms.

Pleistocene to Recent glaciation in Kenya and East Africa is recorded in glacial remnants at the top of Mts Kenya, Kilimanjaro and the Ruwenzori Range, as well as by glacial moraines and solifluction deposits noted in some of the country and the rest of East Africa.

Soils and alluvial deposits are the principal recent sediments found in Kenya. They occur as thick terrestrial deposits, mainly sands, clays, silts, limestones, some hot spring deposits and gypsum.

The Cenozoic deposits are widely exploited throughout the country. Sand and gravel are quarried in eastern and coastal Kenya. Gypsum is exploited in Nairobi and in the coastal region by the cement industries. The diatomite and trona deposits already referred to have been exploited for centuries. Coral reef and other limestones are commonly used in the coast as dimensional stones

Tectonic framework

Several tectonic movements characterising the geological history of Kenya, from the Archaean to Recent, have been a major factor in creating a remarkable environmental setting in the country. These movements are associated with the formation of mountain chains, lakes and other scenic landscape features, as well as mineralisation. The extent of structural and tectonic control on mineralisation has been highlighted earlier.

The Archaean-Palaeoproterozoic granite-greenstone terrane, which is Au-bearing, constitutes the Nyanza Shield and the Kenyan part of the larger Tanzania Craton. The oldest rocks in the Nyanza Shield are the Nyanzian Group greenstone metavolcanics and these have been dated as Mesoarchaean (Cahen *et al.*, 1984). These metavolcanics are interpreted to have experienced a folding movement prior to the Kavirondian Group sedimentation.

The Kavirondian Group metasediments formed after the Nyanzian Group experienced several phases of folding, shearing and fault movements, most of which are attributable to the syn- to post-tectonic granitoid plutonism (Mathu and Nyambok, 1993). The metasediments comprise shoreline alluvial fan sequences and deep sea marine turbidite deposits associated with the formation of Archaean island arcs (Ichang'i and MacLean, 1991; Mathu and Nyambok, 1993; Ngecu, 1993).

The granitoid plutons of the Archaean-Palaeoproterozoic granite-greenstone terrane are interpreted to have been intruded during different episodes (Shiozaki, 1983; Mathu and Nyambok, 1993), in a manner related to other Archaean granitoid plutonisms found in the Australian Shield, the Canadian Shield (Card, 1990) and the Baltic Shield (Hornemann *et al.*, 1988). These granitoid diapiric plutons were largely responsible for the fold movements of the greenstone rocks in the granite-greenstone terrane. After the intrusion of the granitoids, the Nyanza Shield became a stable block.

Later orogenic movements in the Meso- to Neoproterozoic, during the formation of the Mozambique Belt, thrusted rocks of the Mozambique Belt over a stable block of the Nyanza Shield. The Nandi Fault Escarpment and the Siria Fault Escarpment are of Tertiary or Quaternary age. These formed along pre-existing Precambrian shear zones, which mark the Precambrian tectonic plate boundary between the Nyanza Shield and the Mozambique Belt rocks (Daly *et al.*, 1989; Nyambok *et al.*, 1993). The Cenozoic tectonic reactivation of the Nandi plate boundary and the formation of the Nandi Escarpment diverted the formerly easterly drainage in western Kenya to a westerly drainage, draining into and forming the present day Lake Victoria.

The Kisii Group is slightly older than the Mozambique Orogenic Belt rocks, although some geologists (e.g. Stern, *pers. comm.*) believe that the Kisii Group represents marginal volcanics of the Mozambique Belt. The Kisii Group lies almost flat with only gentle folding across the upturned edges of the older rocks. No major deformational movements are thought to have affected the Kisii Group.

The Neoproterozoic-Early Palaeozoic Mozambique Belt, which covers large areas of Kenya, is considered to be an ancient suture involving Wilson Cycle models in its evolution. It is interpreted as the collision site of two early continent-continent plates involving East and West Gondwanaland (Shackleton, 1986; Muhongo, 1994; Stern, 1994). Complex deformations, for example involving polyphase folding, faulting, thrusting and thrust stacking and shear movements, have all occurred within this belt as a result of the two plate collisional event.

Ophiolite sequences have been postulated to occur in the West Pokot, Maralal-Baragoi and Moyale-Shakiso areas of this belt by Vearncombe (1983) and Shackleton (1986). It is now considered that at least six phases of deformation affected the Mozambique Belt rocks (Key *et al.*, 1989; Mosley, 1993), resulting in the varied positions of its lithological units (Nyamai *et al.*, 1993).

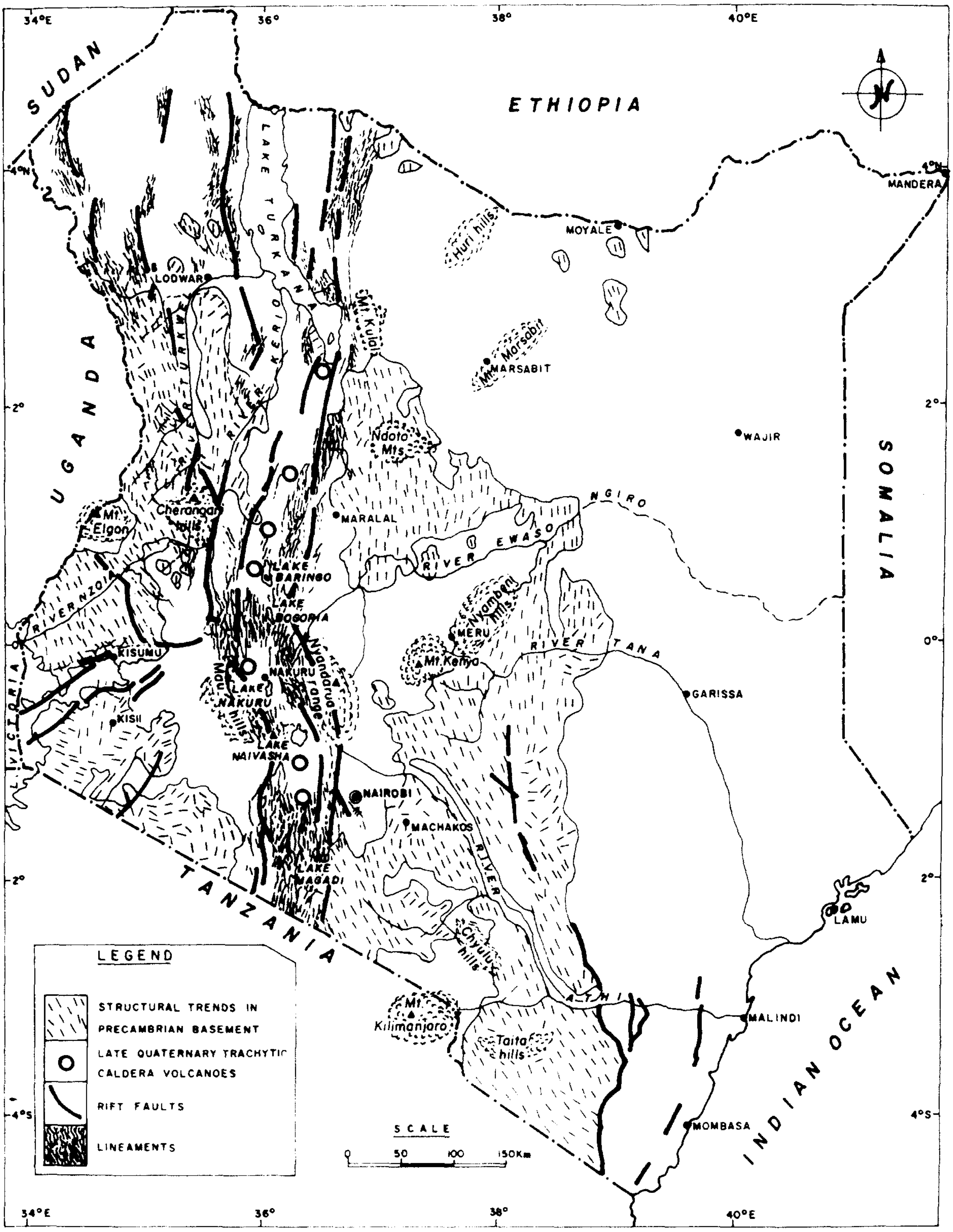

Figure 8. Lineaments and structural trends in Kenya (after Gaciri, 1992).

The Rift System in Kenya

The formation of the north-south main Rift System (the Gregory Rift) in the mid-Tertiary (Saggerson, 1972) took place subsequent to the emplacement of the Kenya Dome (Fig. 7). The formation of the Rift Valley was associated with volcanic and tectonic activities during Tertiary and Quaternary times. Contemporaneous coastal downwarping was also recorded along with this late Tertiary and Quaternary downwarping and faulting.

The Rift System is bounded by normal faults; its model of formation involves crustal extension, brittle crustal failure and sinking of the middle block to form the Rift System graben. Later, vertical movements of different magnitudes involving the sinking of crustal blocks within the Rift floor also occurred in the Rift System from Miocene times to Recent; these have resulted in the local tilting of numerous small blocks, which give rise to the present linear topographic expression (Fig. 8). Generally, the north-south trend of the Gregory Rift and the east-west trend of the Nyanza Rift (formerly the Kavirondo Rift) are all controlled by the structural trends of the underlying older Precambrian rocks (Daly *et al.*, 1989).

In the Quaternary, the country experienced numerous positive and negative eustatic changes in sea-level, rift faulting, erosion and infilling of several independent basins. These processes have resulted in the formation of the various Quaternary deposits (gypsum, trona, diatomite), which have previously been referred to in this paper.

ENVIRONMENTAL ISSUES

The recent upsurge in research effort in environmental geology in Kenya has been in response both to the global call for environmental protection and the need for averting future geo-hazards of the kinds we have witnessed in the country over the last few years: widespread flooding of lowlands as rivers from the western highlands such as Ahero, Sondu, Nzoia and Yala seasonally overtop their banks, landslides in the central Kenya highlands and droughts in the arid and semi-arid regions of the north. On the other hand, the country's contrasting landscapes of highlands, open plains and divides, and a most impressive biological diversity of flora and fauna, make it a natural environmental field laboratory that attracts hundreds of scientists every year.

The key issue in environmental planning in Kenya is the preservation of the environment which holds some of the country's last vestiges of wilderness. The application of environmental geology to this development is vital as geological processes are the controlling factors in soil formation, topography, the distribution of vegetation, land-use suitability, groundwater location, hydroelectric development and the localisation and exploitation of minerals and fuels.

The following sections give brief summaries of the current state of knowledge of some environmental issues not specifically covered by individual articles in this volume. A selection of the recent literature on these topics is referenced to aid the search process of those requiring more information on these subjects.

Soil erosion and conservation

In Kenya, soil erosion is proceeding at an alarming rate by uncontrolled water drainage, improper cultivation and cutting of forests for fuelwood and charcoal-making, population pressure and generally poor land management practices. These problems are accentuated by a semi-arid climate over much of the country's interior. Soil is also being polluted by the use of pesticides.

Soil erosion is very much in evidence on slopes over 15%, near river banks (despite laws preventing the cultivation of both of these land units), and in the marginal land where cropping practices, usually involving maize, have been taken up by recent migrants. Most of this erosion is water-induced, but in the semi-arid, pastoral zone it is effected by wind after the soil has been exposed by overgrazing. The scars of soil erosion are widespread and the results can be seen in the declining per capita yields of subsistence food crops returned since 1970. The soil which has been stripped by water is now threatening one of the country's major development initiatives, the Tana River Irrigation Scheme where accumulations of silt are reducing the expected life of the dams to a fraction of that planned in the original cost-benefit analysis. An estimated three million tons of silt per annum is collecting behind the Gitaru dam, whilst the heavy silt load has been responsible for the closure of hydropower facilities as a result of damage to the turbine blades. Some rivers, such as the Perkera, have ceased to be perrenial and are being turned into swampy terrain.

In the light of the above scenerio, the conservation of soil and water is among the top ten priorities of those concerned with agricultural production and rural development in Kenya (Thomas et al., 1986). Faced with a rapidly growing population and rising expectations there is an urgent need to increase output from the land on a sustainable basis. However, the net effect of increased agricultural production is a more intensified use of the soil which in turn, can lead to degradation. In attempts to come to grips with mounting soil losses, officials are introducing better crop management techniques, coupled with simple terracing in erosion-prone areas.

The increasing interest in the subject of soil and water erosion was amply illustrated back in 1986 at the Third National Workshop on Soil and Water Conservation in Kenya (Thomas *et al.*, 1986). A total of 44 papers were presented and tens of soil scientists from Kenya and abroad participated. The workshop coincided with a complete restructuring of the agricultural research services, which provides for a major research component on soil and water management.

Conservation in the past has relied too much on trial and error, sometimes at the expense of the farmers. This is largely because quantitative documentation of the extent, causes and impact of soil erosion is almost nonexistent (Kilewe, 1989). The available knowledge allows erosion and conservation workers in Kenya to make some qualitative assessments of the extent and forms of soil erosion, appropriate estimates of various causative parameters, crude evaluations of the various effects and selected prescriptions of appropriate control measures.

Fortunately, the development of a scientific approach through investigation, research, testing and evaluation is beginning to keep up with the demand for implementation. The University of Nairobi now offers M. Sc. programmes in soil and water engineering and land and water management to help meet the need for specialised manpower for planning, teaching, research and extension. The task given to Kenya's scientists and research institutions is threefold: the highly erodible or susceptible soils must be protected to prevent accelerated erosion; the potentially productive soils must be properly conserved to sustain their fertility; and the eroded soils must be rehabilitated while averting their further degradation.

In meeting this challenge, special research effort should be given to determine:

i) how the loss of soil productivity changes as erosion progresses;

ii) how soil productivity varies over time under a given land-use;

iii) the process whereby soil productivity declines;

iv) the rehabilitation requirements of eroded land; and

v) the role of agroforestry practices and systems in erosion control and the maintenance of soil fertility (Kilewe, 1989).

Coastal erosion

Tourism has now become Kenya's fastest growing sector and the largest single foreign exchange earner. The beaches of the Indian Ocean coast constitute the most important tourist attraction, next to the various wildlife parks (Abuodha, 1991). Sadly, it is becoming increasingly evident that tourism may severely affect the coastal resources upon which it is dependent. A number of instances of coastal water pollution (e.g. Delft Hydraulics,1970, 1991; WMO/UNEP, 1990; Alusa and Ogallo, 1991), degradation of the reef ecology (Odada *et al.*, 1987; Nyambok, 1988) and destruction of beach amenities (Odada, 1992) have already been documented for Kenya. The following summary is an excerpt from Odada's (1992) project proposal document on beach restoration, protection and development of the tourist beaches of the Mombasa-Malindi resort of coastal Kenya.

The aim of the project was to re-evaluate and strengthen the scientific basis for tourist-related coastal developments in order to rationalise the use of the available resources. An outline is given for the formation of a master plan for coastal zone development in the area. Collaborators in this research are the University of Nairobi, the Kenya Marine and Fisheries Research Institute (KEMFRI) and the Coastal Section of Delft Hydraulics.

Coastal erosion is an increasing problem along the Kenyan coasts. In many places, the rate of coastal retreat and the resulting environmental degradation and economic loss are tremendous. Off the coast the unique ecology of the fringing reefs is threatened by the increasing pollution of coastal waters by sewage outfalls, direct disposal of swimming pool waters, dredging for navigation passages, limestone mining on the reef platform and damage due to the anchoring of boats.

It is considered that such a clearly focused research on management of the coastal zone would provide the basis for creating an acceptable and sustainable balance between economic welfare and environmental well-being.

Floods

Floods have been a major focus of concern for hydrologists and country planners in Kenya for decades. The worst occurrences have been recorded in the Ahero region of the Kano plains in western Kenya. These hazards have been characterised by few deaths but a significant damage level. Rivers rising from the western highlands, such as Ahero, Miriu, Sondu, Nzoia and Yala, seasonally overtop their banks causing widespread damage to crops, livestock and dwellings on the flood plains. A similar, almost annual situation occurs in coastal Kenya where the Tana and Sabaki (Athi) Rivers break their banks and flood the flat coastal lands.

The principal flood seasons in Kenya coincide approximately with the peak rainy season periods of April-June and October-November. Records of measured discharge, however, are scarce and only in the last twenty years or so has a wide coverage of observation stations been possible, making flood prediction hitherto difficult. Alternative methods have included the mapping and measuring of flood-related features of the landscape, including flood

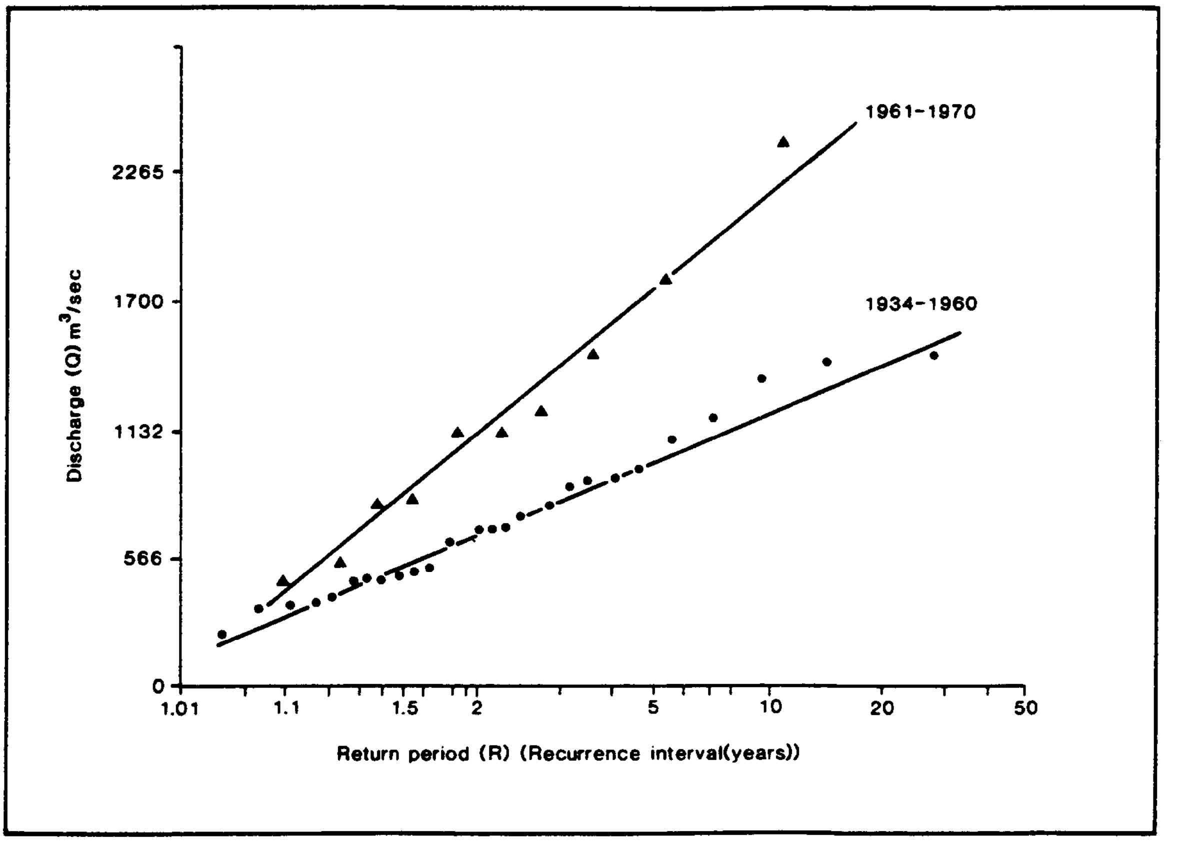

Figure 9. *Flood-frequency curves for two different time periods, Tana River at Garissa, Kenya (from Dunne and Leopold, 1978).*

plains, river terraces, residual flood deposits and old flood channels. Such geomorphological mapping has to extend from upsteam of the urban area, through the town or city, to some distance downstream. In addition, man-made structures that might alter the natural incidence of flooding also have to be taken into account. Urbanisation eliminates the natural basin and channel features and replaces them with man-made features such as pavements and roads, houses, parking lots and artificial drainage channels (Krhoda, 1992). Urban development also usually starts with the removal of vegetation from an area (Obudho, 1975).

Dunne and Leopold (1978) report that many parts of East Africa have experienced a notable change in rainfall since 1960. If a discharge versus return period (recurrence interval) graph is drawn for some of the Kenya rivers, such as the Tana River at Garissa (Fig. 9), two quite different graphs are obtained, one for the pre-1960 period and the other for the post-1960 period. This clearly demonstrates the importance of checking the climatological data as well as the river discharge data before statistical judgements are made.

Today, over 200 gauging stations are being operated by the Ministry of Arid Lands, Water and Land Development and other non-governmental agencies and these have formed the basis for planning flood control measures and the use of floodwaters.

Reliable estimates on the amount of damage due to flooding in Kenya are not available. However, there is evidently a slow decline in death rate and per capita damages as a result of recent government initiatives and expenditure on flood protection and control. In 1990, the Kenyan Government, under the auspices of the Ministry of Housing and supported by other public institutions, held a symposium at Eldoret on 'Natural Disasters and Disaster Management', in which the subject of flooding was a key issue on the agenda. It was clear from the proceedings of this meeting that the rising frequency of flood hazards in the country calls for a re-assessment of riparian policies, especially with regard to flood-resistant design to avoid or minimise exposure to floods. Among the general strategies cited for reducing flood losses were:

i) modifying the flood in order to keep flood water away from developments and populated areas by decreasing run off, increasing channel capacity, or by containing, diverting or storing flood water;

ii) reducing the danger of, and susceptibility to, damage from flooding by keeping people and developments out of the flood hazard area or by making them more resistant; and

iii) reducing the financial and social impact of flooding through measures such as insurance and post-flood assistance.

Particular adjustments to floods should include land-use regulations, forecast and warning systems and emergency relief and rehabilitation.

The International Decade of the East African Lakes

The International Decade of the East African Lakes (IDEAL) is a ten-year international programme of research on the large lakes of the East African Rift Valley. The programme was formulated in Bern, Switzerland, in 1990 and is currently in progress (Johnson and Odada, 1996). The primary goals of the project are:

i) to obtain long, high resolution records of climatic change in tropical East Africa; and

ii) to provide a comprehensive training programme for African students and scientists that will result in collaborative efforts between African and northern hemisphere limnologists and palaeoclimatologists, and provide the scientific infrastructure within East Africa to carry on the proper monitoring and guardianship of the East African lakes after the termination of IDEAL.

Several valid and exciting aspects of research on the large East African lakes are recognised, but the main focus of the IDEAL project is on the study of the lakes as archives of environmental and climatic dynamics. With an increased understanding of how large lakes at low latitudes respond to climatic forcing, it might be possible to decipher the long records of climatic variability stored in the sediments of these complex natural systems. These records will make a major contribution to the study of global climatic change.

The Rift Valley lakes are among the oldest on Earth and are vital resources for East Africa. They provide the potential of obtaining very long, continuous, records of continental environmental change in the tropics paralleling those from ocean and ice cores. Sedimentation rates in the lakes typically range between 0.2 and 5 mm y^{-1}, so their palaeoclimatic records are resolvable to decades, if not years. The total sediment thickness beneath some of the rift lakes is 2-4 km. Thus the age of these basins may be in the order of 20 million years (Johnson and Odada, 1996).

Each of these lakes has its own unique ecosystem and responds differently to climatic variability. They are all extremely sensitive to climatic change, as well as in their chemical and biological responses to variation in the hydrological budget. Thus the sedimentological change associated with relatively slight changes in regional climate should be significant.

Finally, the rift lakes are situated precisely where man evolved in Africa and their sediments archive the regional climate record against which to view this important evolutionary history.

The impact of mining

The mining industry in Kenya is not large, but its effect on the environment is significant. The requirement for mining operators to address and minimise the potential environmental impacts of Au and base metal exploitation, as well as non-metals, is becoming increasingly recognised.

The suite of minerals is quite varied, with current production being dominated by non-metallic minerals such as fluorite, soda ash, diatomite, vermiculite, gypsum, limestone, a variety of gemstones and ornamental and constructional stones. Metals include Au, Ag, Cu, Zn and Fe ore, but these are produced in small quantities. In general, it appears that the precious metals like Au, Ag and Cu are confined to the Precambrian rocks in western and northwestern Kenya. The potential for petroleum deposits lies in the sedimentary formations of the coast and offshore, as well as in northeastern Kenya.

Among instances of environmental degradation due to mining are the effects of fluorite mining on the waterways of the Kerio Valley area of western Kenya (Gaciri and Davies, 1993; Davies, 1994), the effect of dust produced during the processing of diatomite at Kariandusi, near Gilgil in Central Kenya and asbestos (Davies, 1996b), the pollution of waterways and the atmosphere by Hg, which is used for amalgamating Au in the alluvial Au workings in the Greenstone Belt of western Kenya, and the effect of escaped volatiles and spent liquor in the processing of trona at Lake Magadi.

Environmental hazards are often most pronounced in the regions where high rates of chemical weathering and bio-geochemical activity induce relatively rapid mobilisation of potentially toxic elements from mine-waste (e.g. Davies, 1994). Such problems are exacerbated by inadequate environmental legislation or by the logistical difficulties of monitoring and enforcement.

Research on the impact of the minerals industry and geothermal energy development in Kenya was intensified only recently in line with the current environmental awareness. Davies (1993) summarises the possible effects that mineral development in Kenya has on the population. Tole (1996) also reviews geothermal energy development in the country, pointing out some of its major impacts. Other relevant works on the subject have already been referred to above.

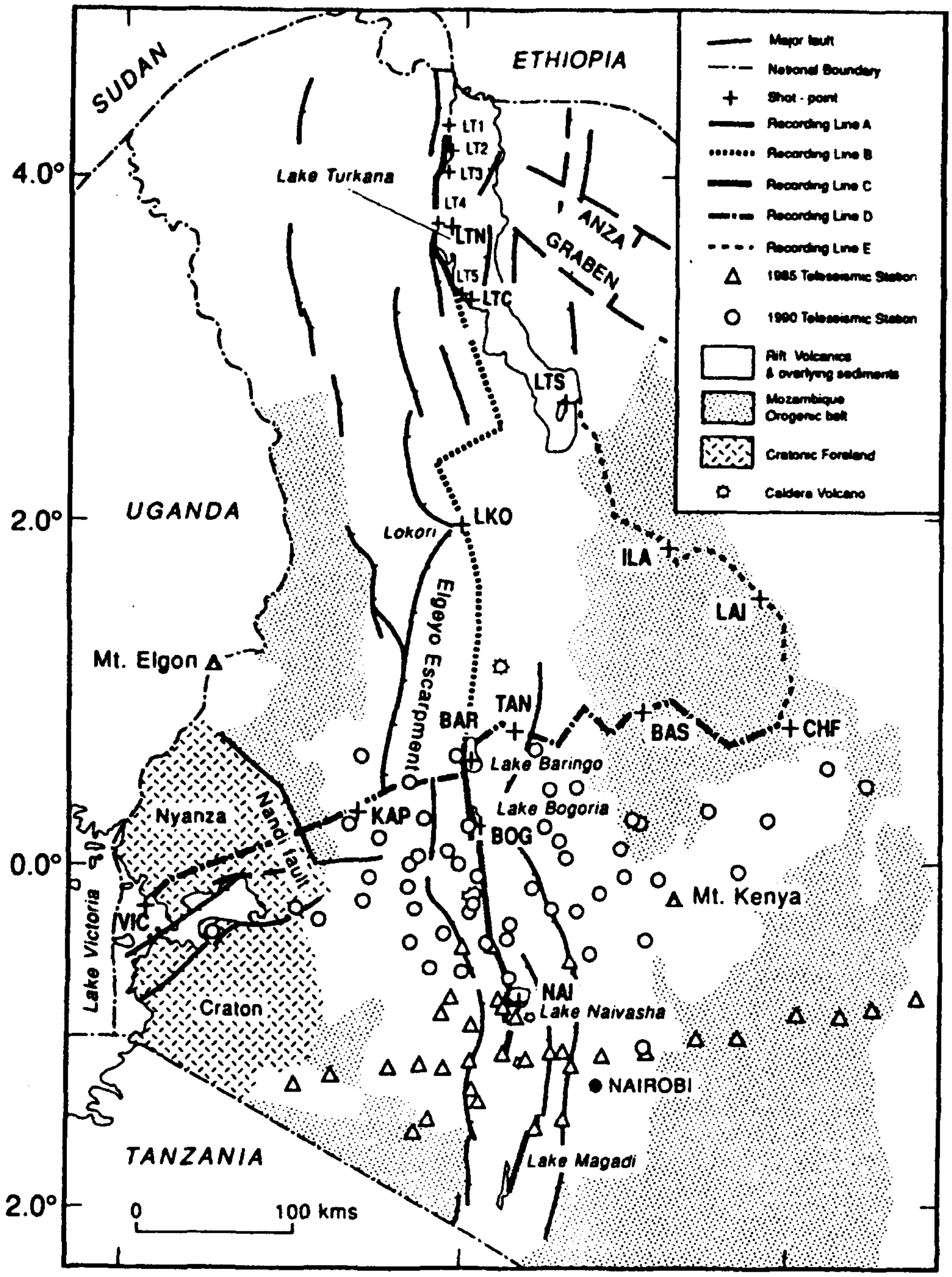

Figure 10. *Index map of the 1989-1990 KRISP study. The locations of both the teleseismic stations and therefraction/reflection profiles are shown. The 1985 preliminary experiment axial line extended from Lake Baringo to Lake Magadi, as did Line C in 1990 (from Keller* et al.*, 1992).*

The Kenya Rift international seismic project

Kenya experiences an earthquake almost every day, but only a small number of these quakes are noticeable and even fewer are significant in terms of the effect they have on people or the damage they cause. However, the extensional structures of the Kenya Rift, which runs north-south through central Kenya, have fascinated geologists and geophysicists since they were first described over a hundred years ago by J. W. Gregory, after whom the rift is often named. Since then, the East African Rift System , extending from Ethiopia in the north to the Zambezi in the south, has been recognised as the classical example of an active continental rift zone. In particular, the Kenya Rift, which has experienced widespread volcanic activity, has become the focus of numerous geological investigations during the past 40 years.

Almost all the seismological research done presently in Kenya is within the framework of the great Kenya Rift International Seismic Project (KRISP), which is trying to open up a window into the upper mantle using seismic refraction and microseismics in the northern sector of the Rift Valley. Monitoring of seismic activity is made by installing mobile and semi-permanent stations.

Rifting is a key process in the evolution of the continents and the Kenya Rift represents a model of comparison for other rifts. Although the surface structure of the Kenya Rift is fairly well known, its relationship to deeper features is not. The purpose of the KRISP is to provide essential seismic data for determining the deep structure of this feature and to use this information to better understand rift processes on a global basis. A preliminary experiment was conducted in 1985 and a major experiment in 1989-1990. In the main passive-recording effort (1989-1990), an array of 54 seismographs (Fig. 10) was deployed to record teleseismic, regional and local events for a period of 5 months. Results of the two sets of experiments provide a picture of the Kenya Rift that is significantly different from what was previously inferred; the crustal thickness is now known to vary greatly along the rift and the occurrence of abrupt, generally symmetrical variations in lithospheric structure established across the rift (Keller *et al.*, 1992).

The cross-rift crustal structure emerging from the data indicates abrupt thinning near the centre of the Rift Valley, with the crust of the Rift Valley slightly thicker to the west than to the east. Since the crustal variations along the rift ($\sim$15 km of thinning) were not expected, they are more striking and the dramatic thinning of the crust near Lake Turkana suggests considerable extension in the area. The combined interpretation of the reflected and refracted mantle phases and the teleseismic results indicate the presence of two thin ($<$10 km), high velocity layers in the upper mantle, which is otherwise characterised by low velocities. A full report of the most up-to-date results of the KRISP experiments is given in Prodehl *et al.* (1994). This work is an attempt to obtain a comprehensive picture of the deep structure of the Kenya Rift based on the synthesis of all available geophysical data and to view this in the context of other geoscientific data and models of the Kenya Rift. It includes the latest interpretations of data from geology, petrology, local seismicity, geothermics, gravity, aeromagnetics and commercial seismic reflection and presents a model of the dynamics of selected basins and the evolution of the rift in time.

Water resource management and water use

Human use of the land depends on the availability of water, and the lack of water is a limiting factor in many areas of Kenya. This constraint is confronted all the time and water resource management is now recognised as an integral part of the government's planning policy.

Kenya's water resources are divided into five catchment areas: the Lake Victoria Basin, the Rift Valley Basin, the Athi River Basin, the Tana River Basin and the Ewaso Ngino Basin. The total annual mean surface run-off is 14.8×10^9 m^3 (WHO/UNEP, 1991). River flows tend to be highly variable, with low or no flow at certain times of the year alternating with high flow periods with high erosion. Large areas of the country are arid or semi-arid.

The major water uses in Kenya are for agriculture, human consumption, livestock, industry, power development and natural resource development. The total water use in Kenya (1985-1987) is about 600×10^6 m^3 a^{-1}, which is projected to rise to 25×10^9 m^3 a^{-1} by the year 2000. The estimated sectoral use for 1985-1987 was 69% agricultural, 18% domestic and 13% industrial (WHO/UNEP, 1991), making agriculture the dominant consumer of water. Water is supplied to 15% of the rural and 85% of the urban population and sanitation is available to 19% of the rural and 89% of the urban population. The sources of water are surface water, groundwater and saline water.

Sources of water

Rainfall is the climatic factor which has the greatest influence on water resources in Kenya. The country receives an average of 360,801 million cubic metres of rainwater annually based on the estimated national mean annual precipitation of 621 mm. However, about two-thirds of the surface area of the country receives a long-term average of only 510 mm of precipitation annually; most of this water is lost through evapo-transpiration, part of it infiltrates into the ground to form groundwater and most of the remainder is drained by rivers and streams into the lakes and the Indian Ocean. Loss through evapo-transpiration is greatest ($>$2500 mm per annum) in areas over 300 m (Ojany, 1974).

Available estimates put the total surface water resources in Kenya at about 5% of the mean annual precipitation. Permanent streams are rare in the northeastern areas of the country (Fig. 1); most carry water only during the wet seasons. The highly seasonal nature of the majority of the streams, coupled with their low density, means that the local population, dependent on surface water for their daily requirements, has at times to travel considerable distances in search of water. The minimum flow of the two main rivers in the country (the Tana and Athi) is 15.04 and 0.99 cusecs, respectively (Ojany, 1974). A fair proportion of rainfall therefore infiltrates into the ground so that groundwater sources, though also limited and unevenly distributed throughout the country, constitute perhaps the most important form of the country's water resources. In most high rainfall areas there are many freshwater aquifers with high yields, while in most of the drier areas aquifers have low yields.

Groundwater recovery is at present through boreholes, which were started in Kenya back in 1927 (Ojany, 1974). Currently, there exists a Borehole Subsidiary Scheme by which the government encourages farmers (both crop and animal farmers) to provide their own boreholes. At the end of 1977 there were about 4000 boreholes in the whole country. Now there are over 10,000 and an indeterminate number of shallow wells spread all over the country (WHO/UNEP, 1991). Groundwater abstraction is estimated to be 17 to $36 \times 10^6 m^3 a^{-1}$.

Exact statistics are still unavailable, but it is thought that between 10 and 20% of the rural population have access to piped water. The bulk of the population therefore depends on getting their water from natural sources. The situation in the urban centres is, however, a lot better. It is estimated that most people in the municipalities and other urban centres have access to a safe water supply.

The sectors most badly affected by water shortage are those living in the dry areas (especially the northeast) and, partly due to their normadic life, have little chance of reaching a water source. Groundwater supplies are often located at considerable depths (below 100-200 m), and are often of poor quality with too high a fluoride content for potability, or too saline or otherwise polluted (Gaciri and Davies, 1993).

The existing information on groundwater quality and quantity in Kenya is scanty and scattered, but considerable efforts are being made by the government with international and bilateral assistance in this field. All water quality monitoring has now been decentralised to six regions under the authority of the Ministry of Water Development, although a general lack of resources and man-power makes the implementation of the water monitoring programmes difficult. Davies (1996a) has attempted a synthesis of the current state of knowledge of the quality of water bodies in the western part of the country.

The future

The main objective of the Ministry of Water Development is to supply enough potable water to the people within reasonable distance as soon as is practicable. In urban areas, the Ministry, in conjunction with the National Water Conservation and Pipeline Corporation, has come up with a long-term plan that will cater for the needs of Kenya's towns for 15 or more years (Central Bank of Kenya, 1991). Under this programme there are some high priority projects which are currently being implemented or are about to start. These include:

i) Mzima Pipeline 11 at the coast, which is estimated to cost Ksh. 30 million;

ii) Greater Nakuru East, whose provision is Ksh. 100 million;

iii) Sabaki/Baricho intake, also at the coast, at a cost of Ksh. 51 million; and

iv) Kilimanjaro/Machakos, at an estimated cost of Ksh. 20 million.

These projects have been planned to meet the needs of rapid population growth and also the influx of people from rural to urban areas seeking to improve their quality of living.

Water conservation in the ASALs aims at starting high up in catchment areas and constructing different water-holding structures as the water proceeds downstream. These will be appropriate for either crop production, human or livestock consumption, or for recharging groundwater aquifers.

Environmental impact assessment

Kenya has an overall land mass of 58,264,600 ha, made up of 56,925,000 ha of dry land and 1,339,600 ha of water surfaces (Central Bank of Kenya, 1991). Land is a basic resource and the key to so much of Kenya's history. Water issues are also at the forefront of the country's developmental goals. Water of the required quality is in limited supply (*op. cit.*) and in limited areas within the country, and its judicious use without despoiling the purity, freshness and source and the strict avoidance of waste are essential elements of water management planning. On account of the value of these resources to the country's development, the assessment of the impact on land and water from construction activities related to various projects now constitutes a crucial dimension of the government's environmental policy.

The National Environment Secretariat (NES) was set up in 1974 in the context of Kenya's preparation for the United Nation's Conference on the Human Environment. The emergence and development of NES is detailed in Hirji and Ortolano

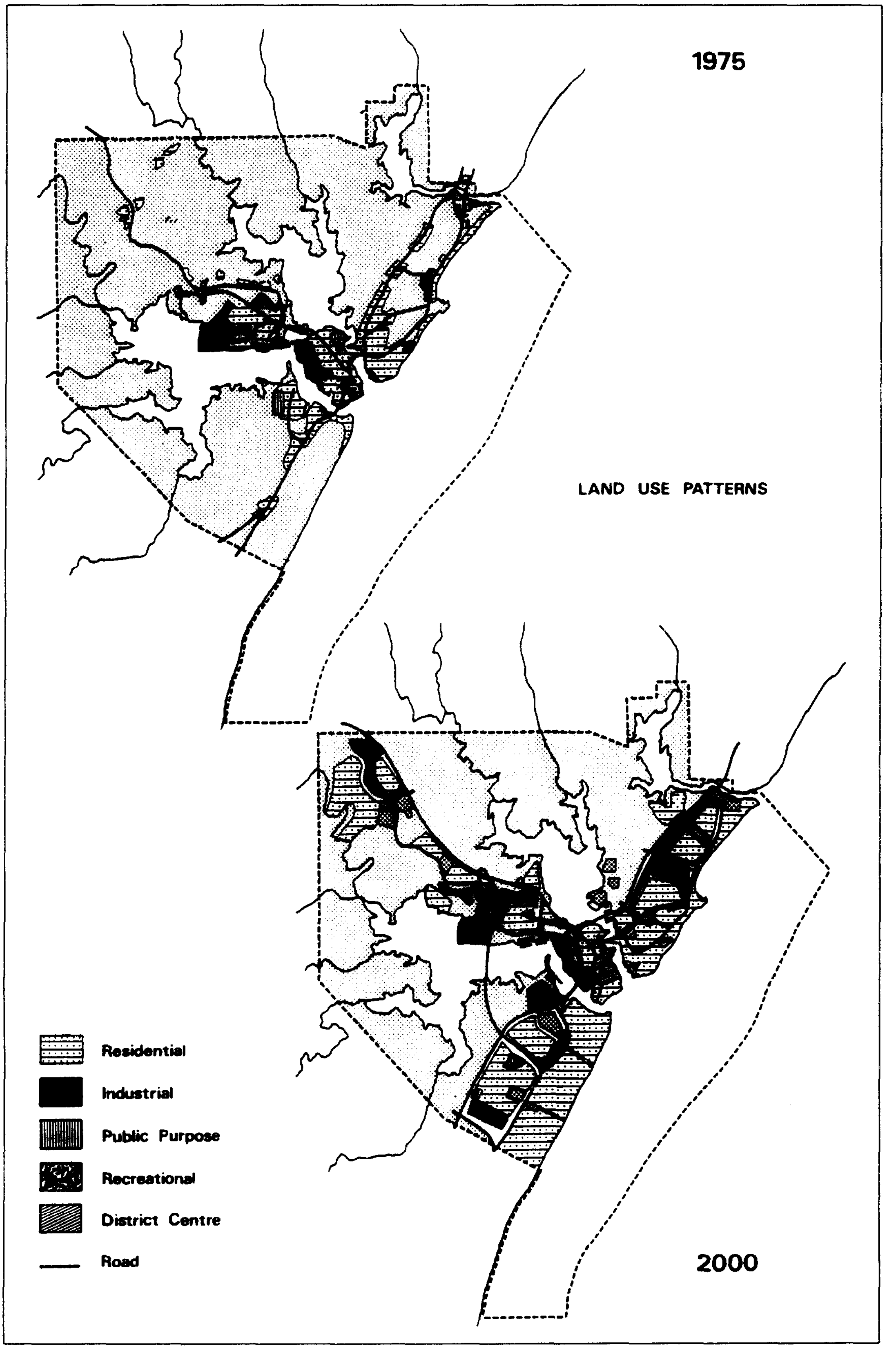

Figure 11. *The proposed urban development of Mombasa, Kenya (after Doornkamp, 1985).*

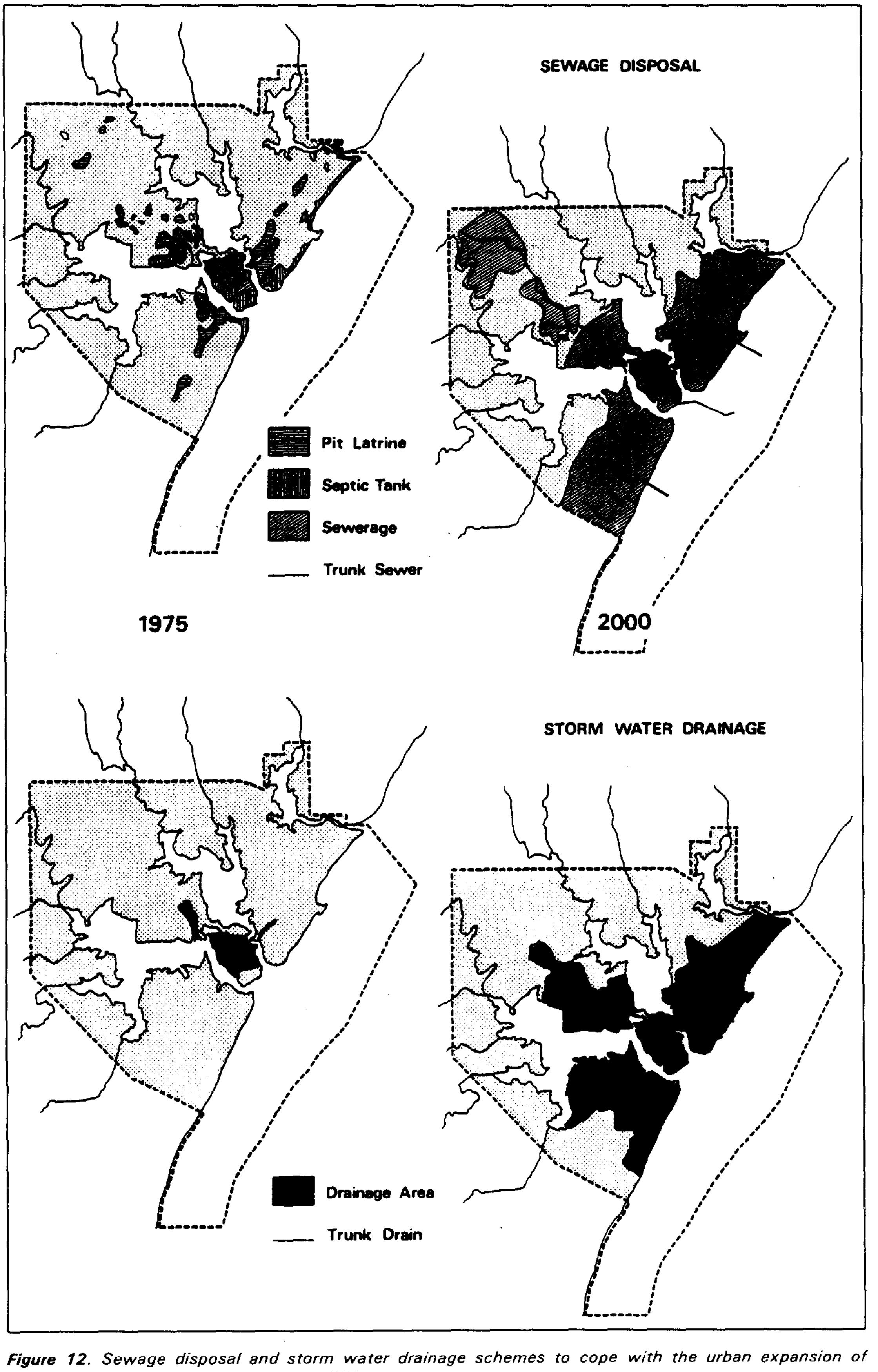

Figure 12. *Sewage disposal and storm water drainage schemes to cope with the urban expansion of Mombasa, Kenya (after Doornkamp, 1985).*

(1991). During the late 1970's, NES began promoting a national environmental impact assessment (EIA) requirement that was intended to apply to all major projects, both public and private.

In 1976, an environmental impact study was undertaken for the Upper Tana Reservoir (Doornkamp, 1985). The Tana is Kenya's largest river and the building of a dam at Masinga, below the Tana's junction with the Thika, will create a reservoir over 1000 ha in extent (i.e. about the size of Lake Naivasha). It was anticipated that this might lead to environmental problems and so the assessment was carried out. For example, people would have to be resettled, the lake would provide a potential for fishing and tourism, or provide the site for an incursion of harmful weeds, important forests might be destroyed and the changes in river flow could affect the people living downstream, while land use on the margins of the lake could have a bad affect on the lake itself. All these factors were studied using aerial photographic techniques and ground surveys and the recommendation was made that there were no good environmental reasons for aborting the project.

NES's concept was to use EIA as an instrument for meeting its two main goals: promoting environmental awareness and environmental protection. However, its efforts to promote an EIA requirement for all major public and private projects have been unsuccessful. Success at imposing EIA requirements for private sector projects began to be realised only after the formation in 1981 of the Inter-Ministerial Committee on the Environment (IMCE), which entered into a collaborative association with NES. A notable illustration of the gains from this more collaborative context for environmental policy making is the EIA requirement that the IMCE imposed on private industrial projects. The control of industrial pollution had been identified as a priority area in the 1979 National Environment Management Policy and NES has promoted industrial waste management ahead of other IMCE agenda items.

At coastal sites, waste is frequently disposed of directly into the sea, which can be harmful, especially when too little is known about tidal currents. The projected expansion of Mombasa (for instance), from 370,000 people in 1975 to 1 million by 2000 means a massive expansion in its sewage and water disposal facilities (Figs 11 and 12). Care has been taken to protect marine life and prevent pollution of the beaches, which have an important place in Kenya's tourist industry, by making a full investigation first. In 1974, the Ministry of Water Development commissioned a study that included an analysis of the ecology of the inshore waters and coral reefs, tidal currents, sea-bed configuration, water depth and the composition of the sea water (Doornkamp, 1985). This definition provided the framework for the location of sewage outfalls such that the damage done to the environment will be an absolute minimum.

The key to NES's success in implementing EIA requirements for private projects was its ability to use the legislatively based authorities and sanctions of other IMCE members to force industrial project proponents to conduct EIA's. A good illustration of how NES's co-option of IMCE members allowed it to influence a major private undertaking is that of the Leather Industries of Kenya, one of the first projects to come under the EIA requirements of the IMCE. A full account of the environmental impact statement on this project is given in Hirji and Ortolano (1991). Other documented accounts of EIA conducted as a means of monitoring the behaviour and amounts of water and air pollutants from mining, industrial and waste disposal activities include those of Sakari (1990), Davies (1993, 1994), Masibo (1993) and Owuor (1993).

Although NES's reliance on the IMCE for co-ordinating the EIA process has its advantages, it also has some drawbacks (Hirji and Ortolano, 1991). The principal shortcoming is that NES's effectiveness depends heavily on the willingness of other agencies to continue working within the IMCE framework to help NES institutionalise EIA for industrial projects. An unwillingness on the part of other agencies to co-operate with NES could cause significant delays and lead to inefficiencies, or even a complete breakdown, in the EIA process.

Another shortcoming of the Kenyan EIA process is the limited scope of the pollution control laws on which it depends. The most well-defined pollution control law is the Water Act, which is used to monitor, control and regulate water pollution. Similar statutes to regulate air quality and hazardous materials are not yet in place. Thus, there is no counterpart to the Water Act to provide a legal mandate for an evaluation of air pollution or other industrial pollution problems early in the life cycle of a project. Although the Factories Act has provisions against harmful toxic emissions, it is concerned primarily with the safety of the worker. The NES has occasionally attempted to control air quality, but its authority is restricted and thus it cannot act effectively or systematically.

The lack of clear, well-defined guidelines for obtaining approvals for new industrial facilities also hampers the EIA process. Although guidelines for each stage of the planning cycle exist, comprehensive, up-to-date requirements for establishing new industrial facilities are neither fully defined nor carefully explained. In addition there is much duplication in the information required by different agencies. For example, project proponents must complete four different applications in setting up a new facility: the application for a new industry, industrial land, a water permit and the request for an environmental impact report. Each requires similar information on water quality.

The final shortcoming of the EIA process is its restricted coverage. The EIA process, co-ordinated by NES through the IMCE, has been adopted only to control pollution in private sector industrial projects. Although many public sector agencies are part of the IMCE, none of them have brought their projects to NES's attention for an environmental review.

Kenya has shown for many years now that it is ready for the environmental challenge. The United Nations Environment Programme (UNEP) has its headquarters in Nairobi, the only UN agency to be located in a developing country. Kenya already has specially trained District Officers responsible for the sound management of the environment in each district (Central Bank of Kenya, 1991). There is a fully-fledged Ministry of Environment and Natural Resources. The IMCE has now expanded and established subcommittees which deal with issues such as research promotion, toxic chemicals, biodiversity, pollution control and monitoring, planning and economic incentives, education and legal matters.

The Committee appointed to formulate a National Environmental Action Plan (NEAP) is now fully in action. The NEAP will take account of such questions as desertification and drought, management of natural resources, conservation of the tremendous biodiversity in flora and fauna and control of pesticide use (Central Bank of Kenya, 1991). The plan will contain within it the details and timing of its implementation, together with practical answers to its financing. It will show the strategic planning and utilisation of resources that will be required to achieve the right environment for long-term sustainable development. This, almost by definition, means incorporating environmental concerns into development plans.

SUMMARY AND CONCLUSIONS

Kenya's remarkable environmental setting is shaped largely by its unique geography (location and range of altitudes) and geology (continental rifting); the country displays virtually every facet of environmental geological phenomena.

Despite a strong sense of awareness about environmental issues by government and other agencies, and a consequent rapid growth in research, institution building, training and investment, there is still evidence of environmental degradation in fields such as soil and beach erosion, desertification, mining and water management.

The future of environmental protection and conservation in Kenya is none-the-less promising, as the machinery for environmental monitoring is being firmly put in place. The setting up of a Ministry of Environment and Natural Resources and the National Environmental Secretariat, the requirement of an environmental impact assessment for all major projects, the promulgation of the Water Act and finally, the implementation of the National Environmental Action Plan, all attest to the intensity of the environmental campaign in Kenya.

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