SEDIMENTOLOGY AND DIAGENESIS OF NEOGENE SEDIMENTS IN THE CENTRAL KENYA RIFT VALLEY

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ABSTRACT.

Sedimentation in the central Kenya Rift between latitudes 0°30'N and 0°45'N is controlled primarily by tectonics and volcanism. Rift-floor subsidence led to the formation of many basins in which fluviatile, lacustrine and colluvial deposits have accumulated from the Miocene epoch to the present. Major lava flows in the region capped most of the Neogene rift sediments after sedimentation in the individual basins, but episodic tectonic uplift and subsidence within the main half-graben have exposed the sediments in some areas, notably west of Lake Baringo. Clastic sediments along the rift shoulder in these basins are derived from metamorphic basement rocks, volcanic rocks or a combination of both sources. This thesis describes the detailed sedimentology and diagenesis of selected Neogene siliciclastic sediments in the central Kenya Rift basins and assesses the potential hydrocarbon reservoir and source rocks in the region.

Petrographic and mineralogical analyses of siliciclastic rocks from throughout the region reveal that, in general, sands derived from basement rocks are better potential hydrocarbon reservoirs than those derived from volcanic sources. Sands of volcanic derivation are commonly susceptible to early diagenetic formation of authigenic clay minerals, zeolites, iron oxides and calcite cements, which reduce the porosity and permeability of the rocks before hydrocarbons can be come entrapped.

X-ray diffraction and electron microprobe analyses of authigenic analcimes in the Miocene Tambach Formation show that they formed by the reaction of clays with saline, alkaline pore fluids, whereas the analcimes in the Kapkiamo and Poi lacustrine sub-basins of the Ngorora Formation likely formed from zeolite precursors, that themselves

originated from reaction of volcanic glass with alkaline water. Authigenic analcimes in the sediments of the Ngorora Formation occur as pore-lining and pore-filling cements and predate authigenic smectites. The paleolakes of the Poi and Kapkiamo basins of the Ngorora Formation (Member C) were saline and alkaline (commonly, pH > 9.5) at certain stages and periodically underwent desiccation.

Early diagenesis is strongly controlled by groundwater levels and their fluctuations, while the effect of temperature likely becomes more significant with burial. The results of a diagenetic study of selected Miocene siliciclastic sediments in the central Kenya Rift show that the greatest hydrocarbon reservoir potential exists in fluviatile arkosic or quartzose sands that have not experienced much early diagenesis and retain much primary porosity.

CHAPTER 1

INTRODUCTION.

Most studies of the Kenya Rift to date have focused on the tectonic evolution of the rift system (e.g., Chapman *et al.*, 1978; King, 1978, Baker, 1986; Bosworth, 1987; Morley *et al.*, 1992) and the sedimentary processes within individual basins (e.g., Yuretich, 1979; Tiercelin *et al.*, 1980; Renaut & Owen, 1991). However, very little research has been made on the diagenesis of the sediments except for detailed studies in the late Quaternary deposits of the Magadi basin (Surdam & Eugster, 1976; Eugster, 1980) and less detailed analysis in the Bogoria (Renaut *et al.*, 1986) and Turkana (Cerling, 1979; Yuretich & Cerling, 1983) basins. This thesis tries to bridge that gap by describing some of the factors that control the sedimentology and diagenesis of selected Neogene siliciclastic sediments in the central Kenya Rift (the Tambach, Ngorora, Kimwarer and Kapthurin Formations). The formations selected for study were chosen specifically because they are of interest to petroleum exploration in the region, either as potential reservoir rocks, or in the case of the Ngorora Formation, as possible source rocks.

The Kenya Rift was initiated in the Late Oligocene to Early Miocene when major tectonic movements, extension and subsidence led to formation of the earliest sedimentary basins near present day Lake Turkana (Morley *et al.*, 1992). Throughout their history, sedimentation in the rift basins has been controlled primarily by tectonics and volcanism, under the influence of a spatially and temporally variable climate. The typical geometry of the rift system is one of alternating asymmetric half-grabens, separated and linked by transverse structures, commonly called "accommodation zones" (Gibbs, 1984; Rosendahl *et al.*, 1986; Rosendahl, 1987). In down-thrown sites adjacent to large border faults, half-graben basins were fed by local fluvial systems depositing coarse sandstones and conglomerates, commonly forming coalescent alluvial fans and fan-deltas. On the opposing (ramp) side of the half-graben, streams shed sediment lakeward, commonly forming prograding lateral delta systems (Frostick & Reid, 1987). In places streams flowed along the rift axis, forming axial deltas where entering lakes (e.g., Tiercelin *et al.*, 1992). Due to the periodic tectonic uplift or subsidence and extrusive volcanism, many basins in the study area were destroyed by erosion, but others were preserved in the geological record, sandwiched between volcanic units (Bishop *et al.*, 1971, 1978).

Although facies arrangements in rift basins are becoming reasonably well understood (e.g., Tiercelin *et al.*, 1982; Cohen, 1989; Johnson and Davis, 1989; Owen & Crossley, 1989; Scholz et al., 1990), the potential of sand bodies to host hydrocarbons is less clear. Diagenetic studies can help to elucidate the hydrocarbon potential of rift basins, both from the perspective of potential source rocks and reservoir rocks. In this thesis sandstones have been examined petrographically to assess their potential as hydrocarbon reservoirs. Many of the lacustrine sequences examined contain abundant authigenic zeolites. These can be used as indicators of the former alkalinity and salinity of the paleolakes. The preservation of organic matter (up to 4% TOC, National Oil Corporation of Kenya, unpublished report) in these sequences suggests that some of the paleolakes were meromictic, and that their shales and claystones could be potential source rocks. The diagenetic pathways of basement-derived clastics and volcanogenic sediments are explored in relation to the clastic reservoir characteristics of the sediments. Processes that control early diagenesis include the role of groundwater and its effect on porosity and permeability of the sediments. A comparison of the Kenya Rift basins is then made with other hydrocarbon-producing rift basins. Although these basins are older than the Kenya Rift basins, the high geothermal gradient in the Kenya Rift System is considered favourable for the early maturation of the lake-sourced hydrocarbons.

1.1 Objectives.

The two main objectives of this research are:

1) To study the sedimentology and diagenesis of selected Neogene sediments in the central Kenya Rift Valley (the Tambach, Kimwarer, Ngorora and Kapthurin Formations).

2) To make a preliminary assessment of hydrocarbon reservoir potential of these basins. In the Kenya Rift, sediments are shed both from metamorphic basement and volcanic rocks, and their diagenetic pathways are likely to differ considerably because of their different compositions. By examining their diagenesis, it may be possible to predict which facies are likely to retain or develop reservoir potential in the subsurface. In the study area, Miocene siliciclastic sediments that have experienced limited burial have been re-exposed by faulting. Elsewhere in the Kenya Rift, most exposed sediments are younger. The results of this study may be applied to sediments of other analogous basins within the eastern branch of the East African Rift System. This thesis thus lays some groundwork for more detailed future research in the diagenesis of the rift sediments.

1.2 Regional Geological Setting.

1.2.1 East African Rift

The East African Rift is part of a Tertiary-Quaternary extensional system that extends from the Afar triangle of Ethiopia in the north to southern Malawi. The rift system in East Africa is divided into the western and eastern branches (Baker *et al.*, 1972; Morley *et al.*, 1990). The western branch extends from Uganda to Malawi and since its inception has been dominated by subsidence and mainly siliciclastic sedimentation. It is characterized by deep lakes, thick sedimentary fills and few volcanic rocks. In contrast, the eastern branch has abundant volcanics and numerous shallow, closed lacustrine basins (Yuretich, 1982).

The tectonic evolution of the East African Rift system has been explained by early models of downwarping and volcanism (Baker & Wohlenberg, 1971) and more recently by half-graben systems (Ebinger *et al.*, 1984; Bosworth, 1985, 1987; Rosendahl *et al.*, 1986; Rosendahl, 1987; Morley *et al.*, 1992). Early models of deformation and volcanism were found to be simplistic and, as more geophysical and geological information became available, it became apparent that these models could not explain all the observed features. Geophysical surveys in the early 1980's from Lakes Tanganyika, Turkana and Malawi have shown that the rift basins are asymmetrical in form and composed of a series of alternating half-graben basins up to about 100 km long, separated by various transverse structures (Rosendahl *et al.*, 1986). These geophysical surveys led to development of the half-graben model, which recognises that continental rifts are strongly asymmetrical normal to their long axes (Bosworth, 1985). Most of the extension related to rifting was accommodated through displacement on low-angle normal faults. In extensional continental rifts, there is commonly a coordinated system of oblique deformational features, called transfer or accommodation zones that offset the regional extensional zones. The architecture of the East African Rift System, likewise, consists of offset half-grabens forming discrete rift zones linked together by transfer zones. The predominant type of transfer zone in the East African Rift is the overlapping synthetic transfer zone (Chapman *et al.*, 1978; King 1978). Transfer zones vary in scale depending on the size of the faults; the largest consist of cross faults with oblique or perpendicular orientation to the rift axis (Bosworth, 1985; Rosendahl *et al.*, 1986).

1.2.2 Kenya Rift

The tectonic evolution and volcanic sequences of the Kenya Rift are well studied (McCall, 1967; Baker & Wohlenberg, 1971; Baker *et al.*, 1972; Chapman *et al.*, 1978; Williams, 1978, Morley *et al.*, 1992). Throughout its length from Lake Turkana in the north to the south (Fig.1.1), the Kenya Rift is dominated by extensive Miocene to Pleistocene volcanic sequences. The rift was initiated in the north and faulting occurred progressively later to the south (Baker & Wohlenberg, 1971). Early extensive volcanism took place west of Lake Turkana in the Lotikipi Plain and was followed by rifting in Late Oligocene-Early Miocene (Baker & Wohlenberg, 1971). Seismic surveys in the Kenya Rift show that the crust beneath the rift is only about 20 km thick in the north near Lake Turkana, while in the central rift it thickens to about 30 to 40 km (Baker *et al.*, 1972; Fairhead, 1986; Morley *et al.*, 1992). This thinning of the crust causes an isostatic rise

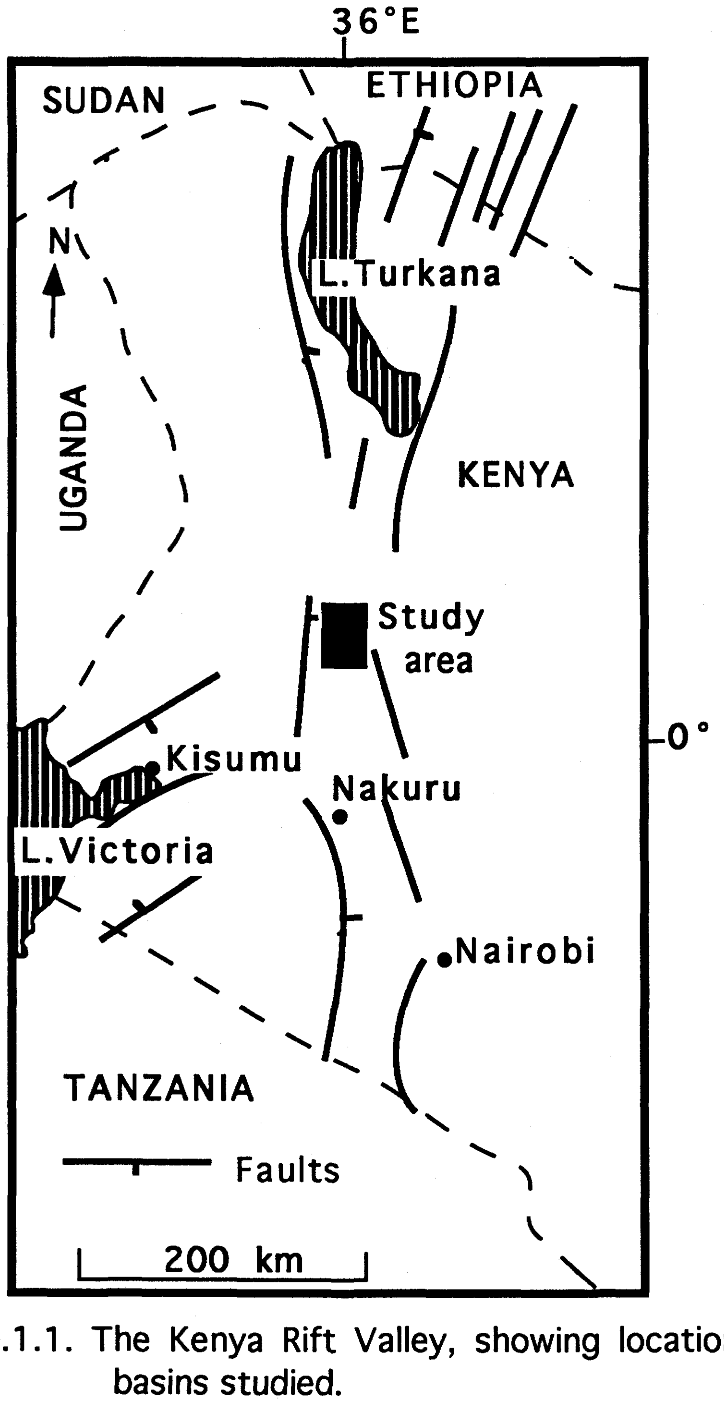


Fig.1.1. The Kenya Rift Valley, showing location of basins studied.

at the base of the lithosphere.

The Kenya Rift can be divided into a series of sub-basins, that have evolved with distinct tectonic and stratigraphic histories (Fig. 1.2). South-west of lake Turkana, the half-graben basins are bounded by mainly low-angle, east-dipping, curved to linear listric faults (Morley *et al.*, 1992). However, the boundary faults in the younger (Mio-Pliocene) rift of southern Kenya have steeper dips and are zig-zag in shape. The southern-most sub-basin in Kenya includes the Pleistocene Lake Magadi basin, which abuts the Nguruman Escarpment to the west. A detachment surface is inferred to dip beneath this sub-basin toward the east (Bosworth, 1987). North of this sub-basin the Aberdare detachment dips to the west with an accommodation zone between these detachments. North of the Aberdare Range in central Kenya there is another accommodation zone south of the Elgeyo Escarpment, which forms the Metkei-Marmanet accommodation zone (Fig. 1.2).

1.2.3 The Central Kenya Rift.

The central part of the Kenya Rift extends from the equator to about 1°N in a generally N-S to NNE-SSW direction (Fig. 1.3). West of Lake Baringo the rift is dominated by the Tugen Hills fault-block, which rises to a height of about 2500 m with an elevation of 960-1000 m above the rift floor. Between the Tugen Hills and the western margins of the rift is a large N-S trending (half-graben) depression, occupied by the Quaternary alluvial fill of the Kerio Valley (Fig. 1.3). The eastern side of the rift is represented by the Marmanet-Laikipia Escarpment. The important modern basins in the central Kenya Rift include the Pliocene-Quaternary Baringo graben, which abuts the Marmanet-Laikipia Escarpment to the east. The formation of the rift in central Kenya is believed to have taken place later than in northern Kenya (Turkana basin). Deposition of sediments in the basins of the central Kenya Rift occurred in a broad depression and probably filled to a depth of about 6-9 km (Morley et al., 1992). The rocks that were deposited in some of the basins in the central Kenya Rift can be seen on the present day rift shoulders, as for example in the Elgeyo Escarpment (Plate 1), where reactivation of the Elgeyo Fault led to some of the sediments being left in the footwall below the volcanics (Chapman *et al.*, 1978). Faulting in the central Kenya Rift since Miocene epoch has been accompanied by extensive basaltic and alkaline volcanism, and broad doming (Baker & Wohlenberg, 1971, Baker et al., 1972).

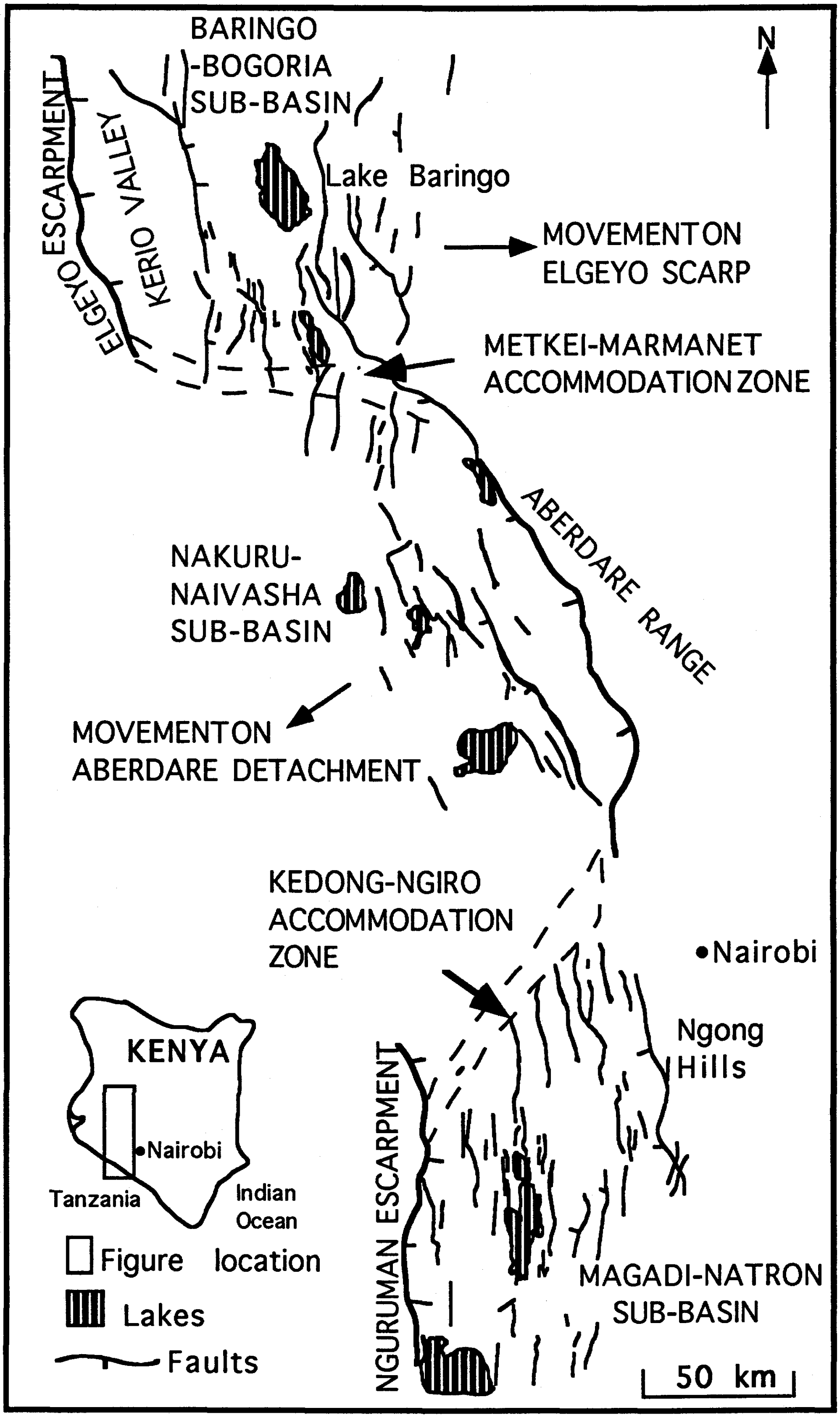


Fig. 1.2 Morphotectonic interpretation of the Central and South Kenya Rift System (Modified after Bosworth et al.,1986).

1.3 PREVIOUS WORK.

1.3.1 Regional stratigraphy in the central Kenya Rift.

The stratigraphy of the central Kenya Rift has been studied in detail by Baker (1958), McCall (1967), Walsh (1969), Bishop et al., (1971), Lippard (1972), Pickford (1975, 1978a, 1978b) and Hill *et al.*, (1986). Most of the exposed sedimentary units occur within the complex, Tugen Hills tilted- block, the Baringo basin to the east, and along the Elgeyo Escarpment to the west. Correlation of the sedimentary units in the region shows that most of the sedimentary units are intercalated within a sequence of diverse volcanic rocks, including phonolites, trachytes and basalts (Fig. 1.4).

1.3.2 Tugen Hills

In the Tugen Hills area, the Kamego Formation is composed of arkosic quartzites and siltstones up to 80 m thick, that rest on the Precambrian basement rocks. The lack of vertebrate fossils in these sediments has precluded a precise age determination, but pollen grains of Tertiary age have been recovered (Chapman *et al.*, 1978). However, Wescott *et al.*, (1993) suggest a Late Oligocene to Early Miocene age. Unconformably overlying this formation is the Sidekh Phonolite Formation. North of the Tugen Hills, the Miocene Muruyur Beds occur within the Tiim Phonolite Formation, and are composed of lacustrine sediments up to 275 m thick. These sediments are very fossiliferous with a diverse mammal fauna (Pickford, 1978b). The Miocene Ngorora Formation, which is exposed in a number of fault-bounded blocks and outcrops along the Tugen Hills, overlies the Tiim Phonolite and is capped by the Ewalel Phonolite. These Mid-Miocene sediments

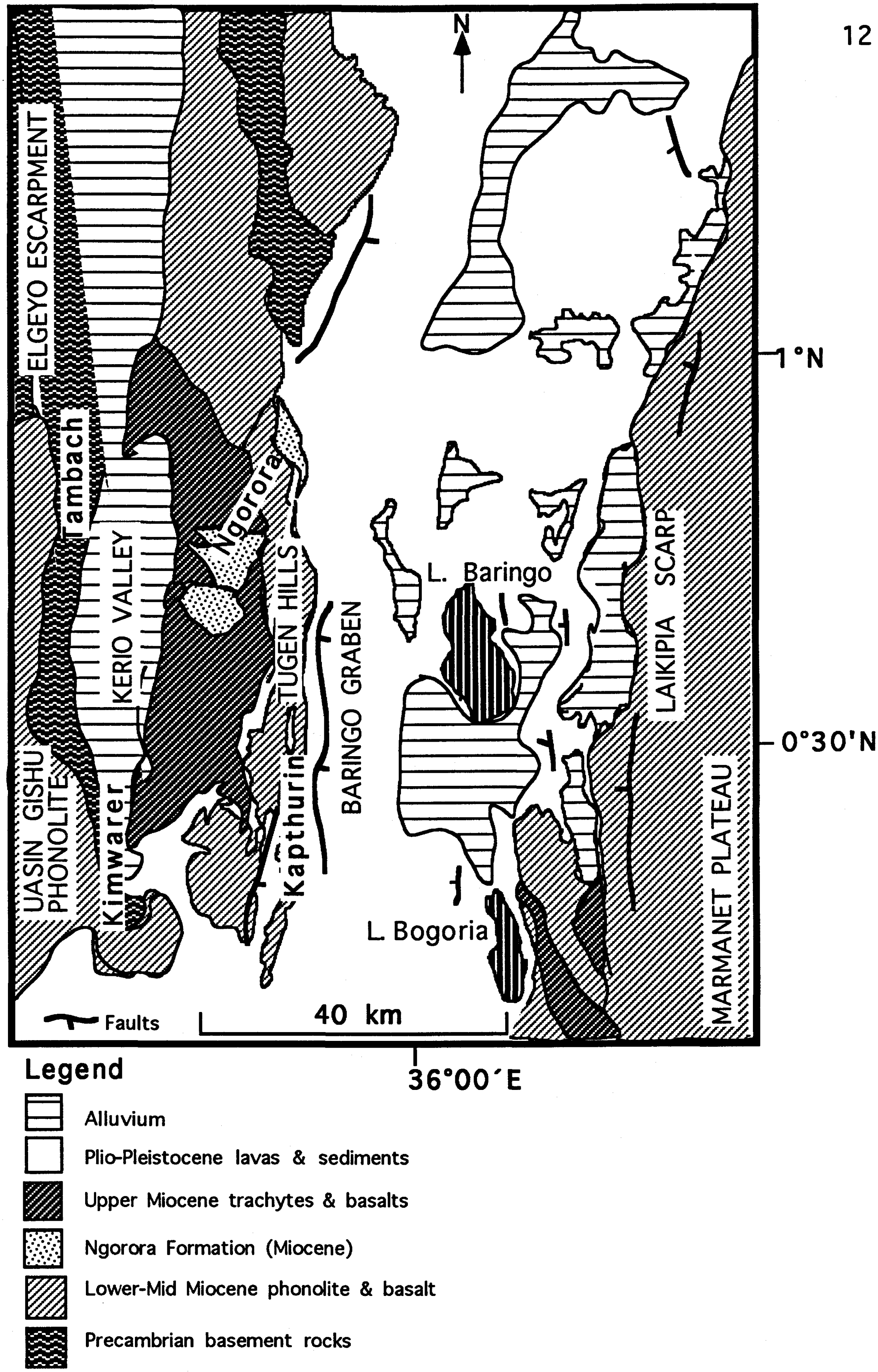


Fig.1.3 Simplified geological map of central Kenya Rift.

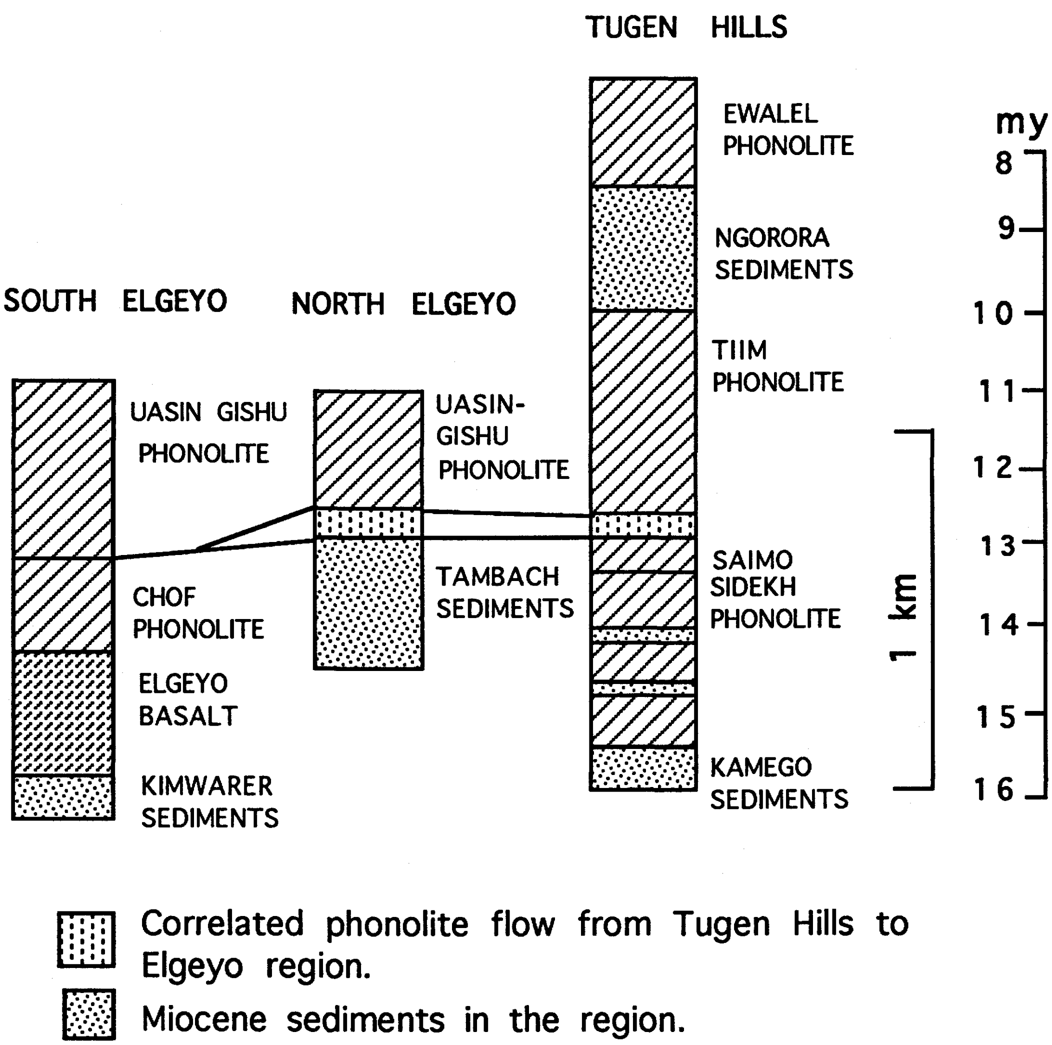
are dominated primarily by volcaniclastic sediments, ranging from agglomerates to tuffaceous sandstones (Bishop & Chapman, 1970). Details of the stratigraphy of the Ngorora Formation are given in Chapter 3. During the Pleistocene epoch in the Tugen Hills, the Mpesida Beds, consisting of silts, sandstones and feldspathic tuffs, were laid down contemporaneously with the Kabarnet Trachyte flows. After cessation of the Kabarnet Trachyte flows, subsidence in the area east of the Tugen Hills led to the deposition of sedimentary units known as the Lukeino Formation, composed of diatomaceous (mainly *Melosira granulata*) silty tuffs and shales, that accumulated under fresh to slightly saline, alkaline conditions (Pickford, 1978b, Owen, 1981). The Lukeino Formation was capped by lavas of the Kaparaina Basalt Formation.

1.3.3 Baringo basin

The Baringo basin lies to the east of the Tugen Hills in the westerly part of the central Kenya Rift. The two most important formations in this basin are the Pliocene Chemeron Formation and the Pleistocene Kapthurin Formation. The Chemeron Formation overlies the Kaparaina Basalt Formation; its sediments are predominantly stratified tuffs and silts that are locally diatomaceous (Hill *et al.*, 1976). Overlying the Chemeron Formation, the sediments of the Pleistocene Kapthurin Formation range from coarsely bedded, boulder conglomerates to well-bedded tuffs and silts that were deposited in fluvial and lacustrine environments.

1.3.4 Basins along the Elgeyo Escarpment

The western part of the central rift system is defined by the Elgeyo Escarpment. The main sedimentary units in the area are the Miocene Tambach and Kimwarer Formations. These sediments are exposed along the present footwall of the Elgeyo Escarpment. Lippard (1972) briefly studied the sedimentology of these basins, while focusing on the regional geology. The Kimwarer sediments were deposited unconformably on the metamorphic basement rocks (mainly gneisses and amphibolites) at the southern end of the Elgeyo Escarpment. Lithofacies in this formation range from fluviatile to lacustrine. The Tambach Formation lies to the north of Kimwarer Formation, and comprises fluviatile sediments at the base of the formation and a lacustrine depositional sequence at the top. A detailed stratigraphic study of the Kimwarer and Tambach Formations is presented in Chapter 3.



Correlated phonolite flow from Tugen Hills to Elgeyo region.

Miocene sediments in the region.

Fig.1.4 Correlation diagram of Miocene sequence in the Tugen Hills, North and South Elgeyo areas. The thickness and time scales are approximate (modified from Chapman et al., 1978).

1.4 METHODS.

This study included both fieldwork and laboratory analysis of rock samples. Fieldwork was undertaken over a 4-week period in November 1991. In the field, outcrops were examined and selected sections logged. Lithological features, including visible mineralogy and colour, were noted, as were textural features including grain size, shape and sorting. To help interpret the depositional processes and sedimentary structures, vertical and lateral variations in textures and structures within the sandstone bodies were recorded in the field. Representative grab samples of the sandstones, siltstones, mudstones and shales were collected for laboratory analyses.

In the laboratory, thin sections were examined by conventional petrographic methods; some samples were impregnated with blue-stained epoxy prior to sectioning to highlight porosity. In thin sections textural relationships, cements and mineralogy were described. To analyze for clay mineralogy and other fine-grained minerals, X-ray diffraction (XRD) was used. Samples were prepared by grinding to 150 mesh and slurry mounted on glass, then analyzed from 3° to 45° 2 theta, using a Rigaku Rotaflex X-ray diffractometer with Cu K-alpha radiation, with power set at 40Kv and 80 mA.

Scanning electron microscopy (SEM) was used to examine authigenic minerals, porosity characteristics and cements. To confirm composition and mineralogy, qualitative spot analyses were made using an attached EDS system. For quantitative analyses of zeolites an electron microprobe was used. For analyses, rock samples were broken into optimal size of about 5 by 10 by 10 mm and, to prevent skin oil causing outgassing in the SEM vacuum system, samples were handled with tongs. Samples were selectively coated with carbon or gold to obtain clear images (method of Welton, 1984). All microprobe analyses were made using a Jeol JXA-8600 Superprobe set at 15 kv.

CHAPTER 2

Modern Sedimentary Environments of the Central Kenya Rift

2.1 Basin geometry

The modern sedimentary depositional environments in the central Kenya Rift are mainly colluvial, fluvial and lacustrine. Eolian environments are poorly represented, but dune fields exist in the Suguta Valley, south of Lake Turkana. The arrangement of these environments and depositional facies is controlled by the basin architecture. Most basins, including the modern Baringo-Bogoria half-graben of the central Kenya Rift, exhibit an asymmetric fill, that thickens towards the controlling boundary fault (Frostick & Reid, 1987; Rosendahl, 1987). During the early phase of the rifting the majority of the coarse sediments is laid down on the ramp of the basin by fluvial systems, with small alluvial fans on the footwall scarp (Blair, 1987; Frostick & Reid, 1990). However, spasmodic fault activity may lead to propagation of waves of coarse detritus into the basin (Fig. 2.1). In the Baringo-Bogoria half-graben the rift is broad with complex fault patterns and a strong NW-SE tectonic trend. The basins in this region are compartmentalised by the tilted fault blocks of the Tugen Hills to the north-west, and to the east and south-east, by the Laikipia and Siracho-Emsos Escarpments, respectively (Tiercelin *et al.*, 1980; Frostick & Reid, 1990). The sedimentary basins in the central Kenya Rift span from Neogene to recent times and have been characterised by intense recurrent volcanic activity throughout their history.

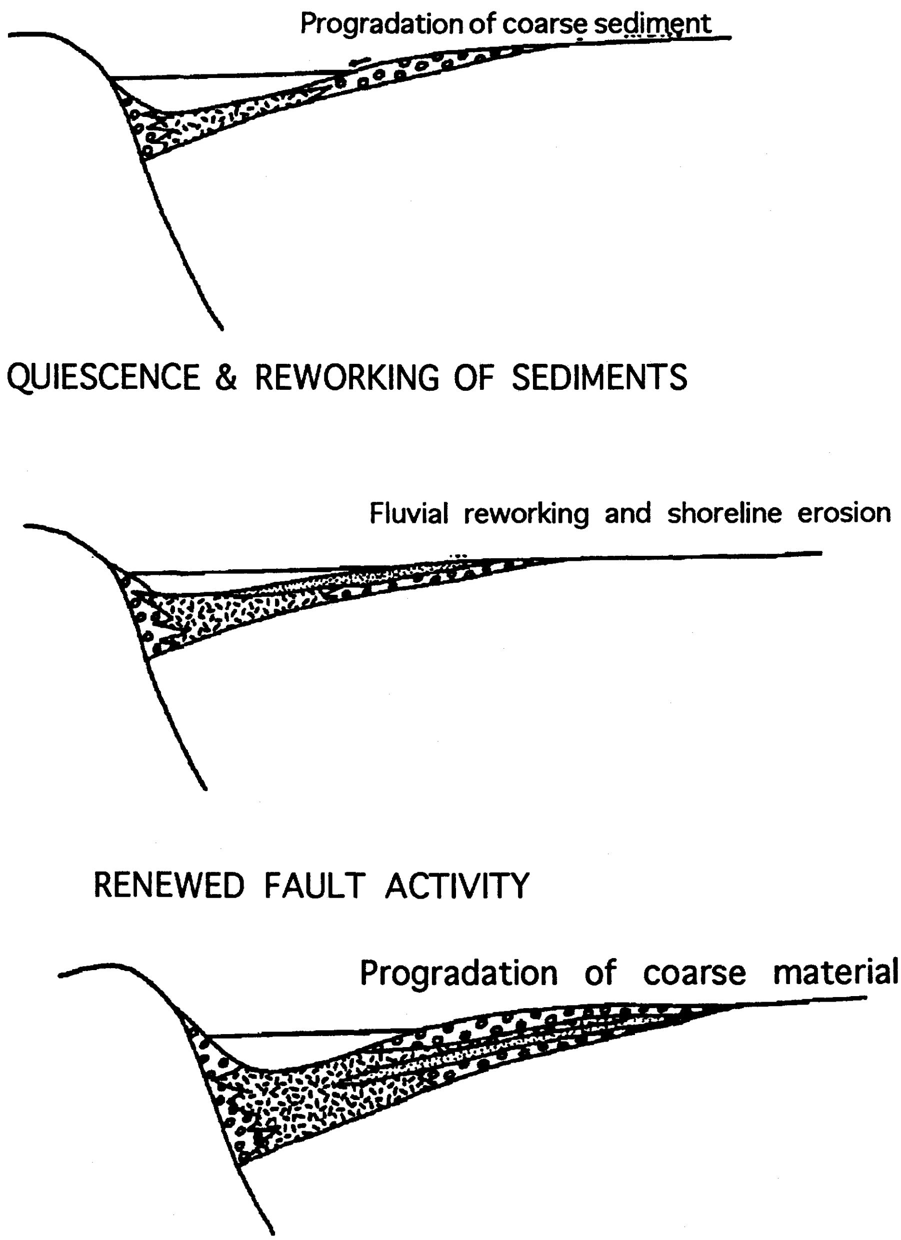


Fig.2.1 Schematic diagram showing the way in which sediment accumulates in a half-graben in response to spasmodic fault activity (after Frostick & Reid, 1987).

2.1.1 Sedimentation along the boundary fault

In the central Kenya Rift the major boundary fault is the Elgeyo Escarpment with a throw of about 2 km. This fault, which marks the western margin of the rift, is characterised by piedmont sedimentation zones, which include colluvial rock deposits triggered by gravity, and fluvial sediments deposited by perennial streams flowing down the escarpment (e.g., the Torok and Kessup rivers, Fig. 3.1). These colluvial deposits include phonolite and basalt boulders, which move downslope mainly during rainy seasons when the slopes are less stable. The finer detritus, mainly sand and gravel, is carried by seasonal streams to form coalescent alluvial fans along the Kerio Valley.

2.1.2 Alluvial fan and fan-delta environments

In the Baringo-Bogoria half-graben basins of the central Kenya Rift, alluvial fan environments are common (Tiercelin *et al.*, 1980). They occur near where perennial and ephemeral streams discharge into Lakes Baringo and Bogoria. The alluvial fans normally radiate downslope. Distally many prograde lakeward to form fan deltas. The facies of these fans are mainly matrix-supported paraconglomerates produced by debris flows in the proximal areas, and orthoconglomerates and bedded sands produced by stream floods on lower parts of fans and at the fan deltas (Tiercelin *et al.*, 1980; Renaut & Tiercelin, in press).

2.1.3 Fluvial environments

Fluvial systems in the central Kenya Rift are both perennial and ephemeral. The ephemeral streams mainly flow during the rainy seasons. In the Baringo-Bogoria half-graben streams flow into the basins both from lateral littoral platforms (ramp), such as the Ndau river, and from the axial littoral platforms, like for example the Molo river which drain into Lake Baringo (Fig. 3.9). In contrast to the alluvial fan and fan delta depositional environments, where coarse sediments are dominant, fluvial environments are predominantly bimodal, with gravels as channels deposit and silts and fine sands, as overbank deposits. The Molo river, which crosses the Loboi Plain carry silts rich in K-feldspar and montmorillonite (Fig. 2.2) which are deposited in Lake Baringo, giving the water of the lake a characteristic brown colour.

2.1.4 Lacustrine environments

Lake Baringo

Lake Baringo is a shallow (4 m deep) freshwater lake covering an area of about 150 km^2. The lake is situated in a half-graben basin, about 22 km north of Lake Bogoria in the central Kenya Rift and has almost oval morphology, following the NW-SE regional tectonic trend. Sedimentation in the lake is defined by its morphology, hydrodynamics and the prevailing chemical conditions. Most sedimentation is detrital, with sand, silt and clay deposited by perennial and ephemeral streams. There is some minor organic sedimentation mainly comprising vegetable debris. The lake has a polymictic regime; the energy from waves and current activity is sufficient to ensure complete circulation of water. Although

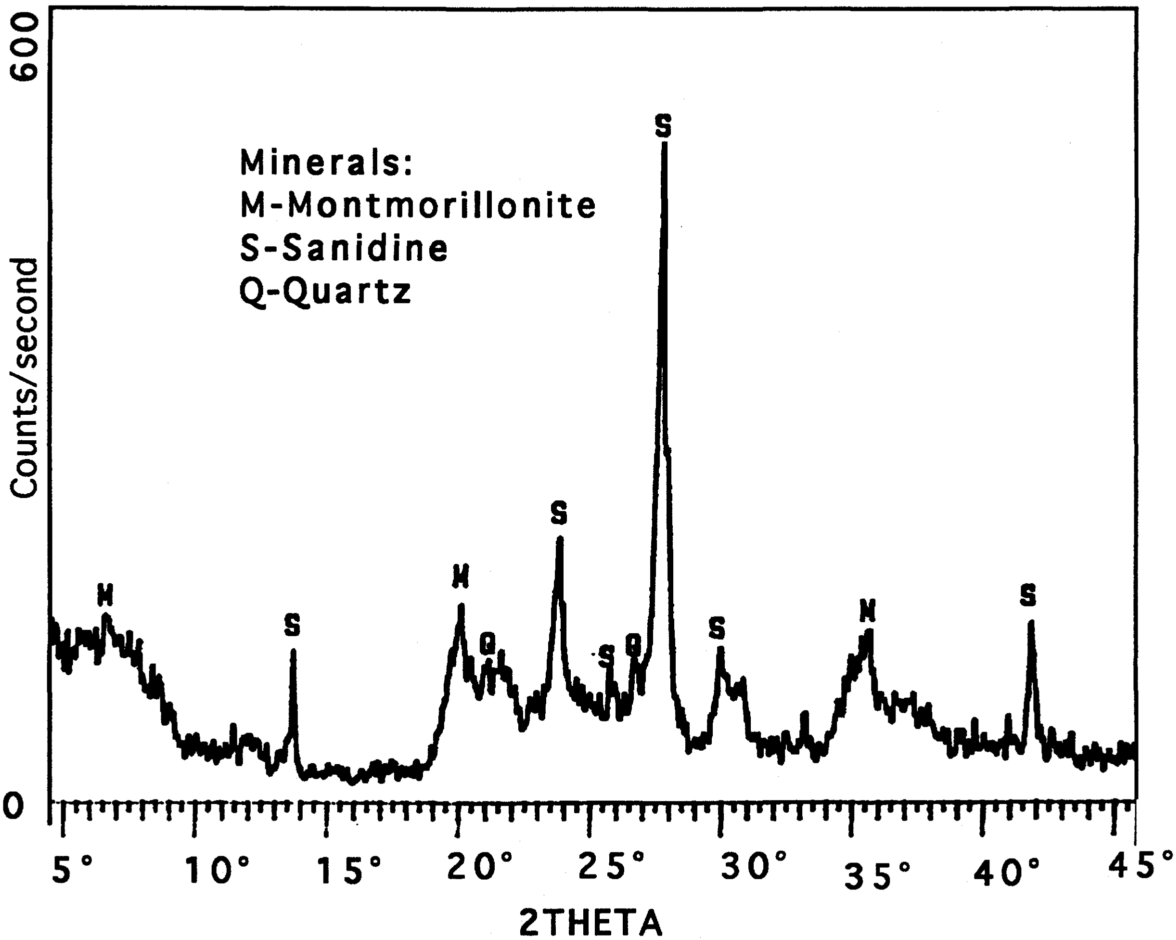


Fig.2.2 X-ray diffraction of Loboi silts, air dried and scanned at 40kV, 80mA and 3°/min.

the lake has no visible outlet, it may have underground seepage, which keeps the waters relatively fresh (Tiercelin et al., 1980).

Lake Bogoria

Lake Bogoria is a closed, shallow (11 m deep), saline, alkaline lake with a meromictic regime in the half-graben basin of the central Kenya Rift. The lake is fed by ephemeral streams, seasonal runoff and hot springs. The waters in the lake are Na-CO_3-Cl in ionic composition (Table 5.1). This ionic composition reflects the bedrock in the catchment area, which is mainly alkaline phonolites and trachytes.

Sedimentation in the lake is mainly siliciclastic in the littoral zones, with organic material in the deep centre of the lake (Tiercelin *et al.*, 1980; Renaut & Owen, 1991). The littoral facies are principally sand, gravel, silts, muds and clays deposited by currents and waves, which form small deltas and lobes. In the central zone of the lake the sediments are mostly black muds and clays with up to 2.9% TOC (Total organic carbon) mostly of algal origin. In some Holocene muds, the TOC exceeds 6% (Renaut & Tiercelin, in press). The muds in the deep part of the basin show a cyclic pattern of sedimentation between organic muds and organic muds with evaporites, mainly trona with small amounts of halite and gaylussite (Tiercelin *et al.*, 1980). The organic-rich muds without evaporites are associated with periods of high organic productivity during higher lake levels, while the sediments rich in evaporites are linked to periods when the lake level was low.

The western and southern shores of Lake Bogoria basin are punctuated by a group of hot springs, which have deposited mounds and terraces of travertine (Casanova, 1986; Renaut *et al.*, 1986). The formation of travertine is attributed to removal of carbon dioxide from saturated solutions. The springs discharging along the western shores emanate from a shallow steam-heated thermal aquifer with temperatures of about 100^{0}C, while the springs to the south of the basin have their discharge from a deeper and hotter geothermal reservoir (Cioni *et al.*, 1992).

CHAPTER 3 SEDIMENTOLOGY.

3.1 THE TAMBACH FORMATION

INTRODUCTION.

The Miocene Tambach Formation lies in the central part of the Kenya Rift between latitudes 0°33′N and 0°49′N, (Fig. 3.1). Previous studies of these Mid-Miocene sediments focused mainly on the stratigraphy of the formation as part of regional studies (Shackleton, 1951; Lippard, 1972; Chapman *et al.*, 1978). This study incorporates the stratigraphy, sedimentary facies and mineralogy of the rocks, in an attempt to interpret the depositional environments and the stratigraphic relationships of the facies exposed.

The Tambach Formation is composed of more than 100 m of sediments, deposited in an elongate basin, probably an half-graben, oriented almost north-south for about 30 km east of the present Elgeyo Escarpment. The basin was initiated in the Middle Miocene by downwarping (Chapman *et al.*, 1978). The trough was subsequently filled by fluviatile and lacustrine sediments. Sedimentation was terminated when the basin was inundated by the Uasin Gishu flood phonolite lavas (Fig.3.2a). The filling of the basin was controlled by its elongate geometry and temporal changes in the relative rates of subsidence and sedimentation. Tectonic uplift along the developing Elgeyo Escarpment created a watershed from which sediments were eroded to be deposited in the trough. Other sediments were probably shed from the ramp margin of the half-graben to the east, but the evidence is now buried below later sediments and lavas of the present rift floor.

The sediments are exposed in two main regions. The Tambach locality is used to refer to the sediments exposed in road cuts south of Tambach township, where fluviatile facies predominate; other sediments are exposed near Kessup, about 3 km north of Tambach, where lacustrine facies are dominant (Fig. 3.1). Where exposed, the Tambach sediments lie discordantly on basement rocks, but down-faulted sediments of the formation probably underlie the sedimentary and volcanic fill of the Kerio Valley.

The depositional sequence began with alluvial fan deposits, exposed at the base of the sequence, passing upward through perennial and ephemeral sandy stream deposits, to shallow lacustrine sediments at the top of the sequence, which is generally confined to the north-central part of the basin. The fluvial facies exposed to the south of the basin are mainly composed of paraconglomerates, conglomerates and sandstones, while the lacustrine facies are mainly claystones and shales. Most exposed fluvial sediments were derived from erosion of the uplifted basement rocks to the west of the basin.

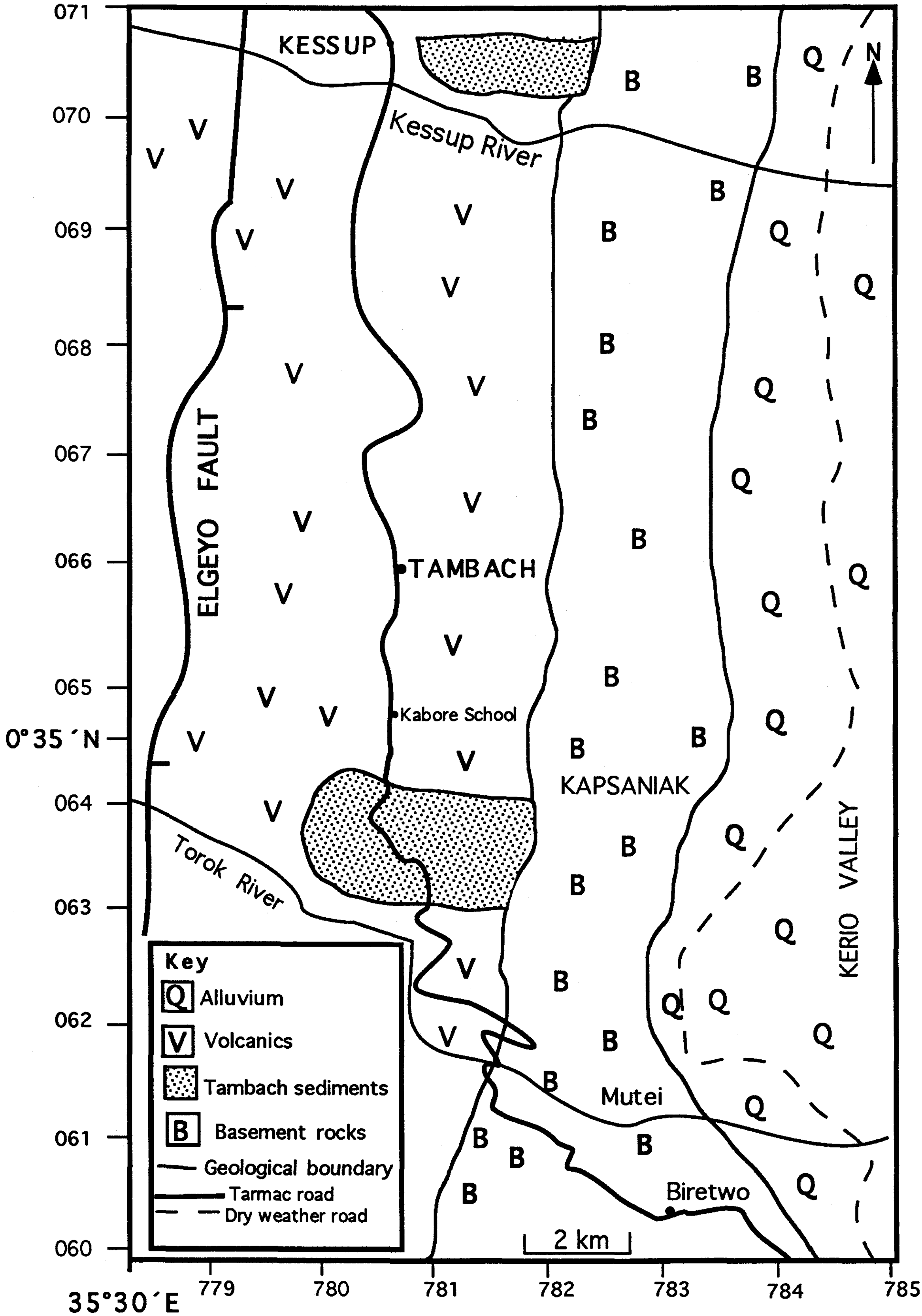


Fig.3.1. Geological map of Tambach area showing location of sediments.

3.1.1 Stratigraphy of the Tambach Formation

Lippard (1972) divided the Tambach Formation into two sedimentary, and three volcanic members:

1) Coarse fluviatile, largely basement-derived, conglomerates, pebbly sandstones, siltstones, mudstones and claystones at the bottom of the sequence;

2) Fine lacustrine sediments, mainly fissile grey and green shales and siltstones, rich in fish remains at the top of the sequence;

3) Glassy phonolite lava;

4) Trachytic tuffs and lavas; and

5) Basanitoid plugs and sills that intruded mainly the lower sequence.

Deposition of sediments in the Tambach basin began during the early post-rift phase in the Middle Miocene. Faulting along the Elgeyo Escarpment, a major border fault, created a physiographic high to the west of the Tambach basin, and most fluviatile sedimentation was probably activated from this direction, although a large catchment area probably lay on the ramp margin to the east (Plate 1).

The roadside exposures located south of Tambach township illustrate both the fluviatile and lacustrine facies well and are designated here as the type locality of the Tambach Formation. The sediments forming the type section are best exposed in a 2 km section of road cut (Fig. 3.1) and discontinuously in gullies and cliffs below the road, where access is more difficult. This section of the formation, as logged, is shown in Fig. 3.2a.

The Tambach Formation is a fining-upward sequence from the coarse-grained

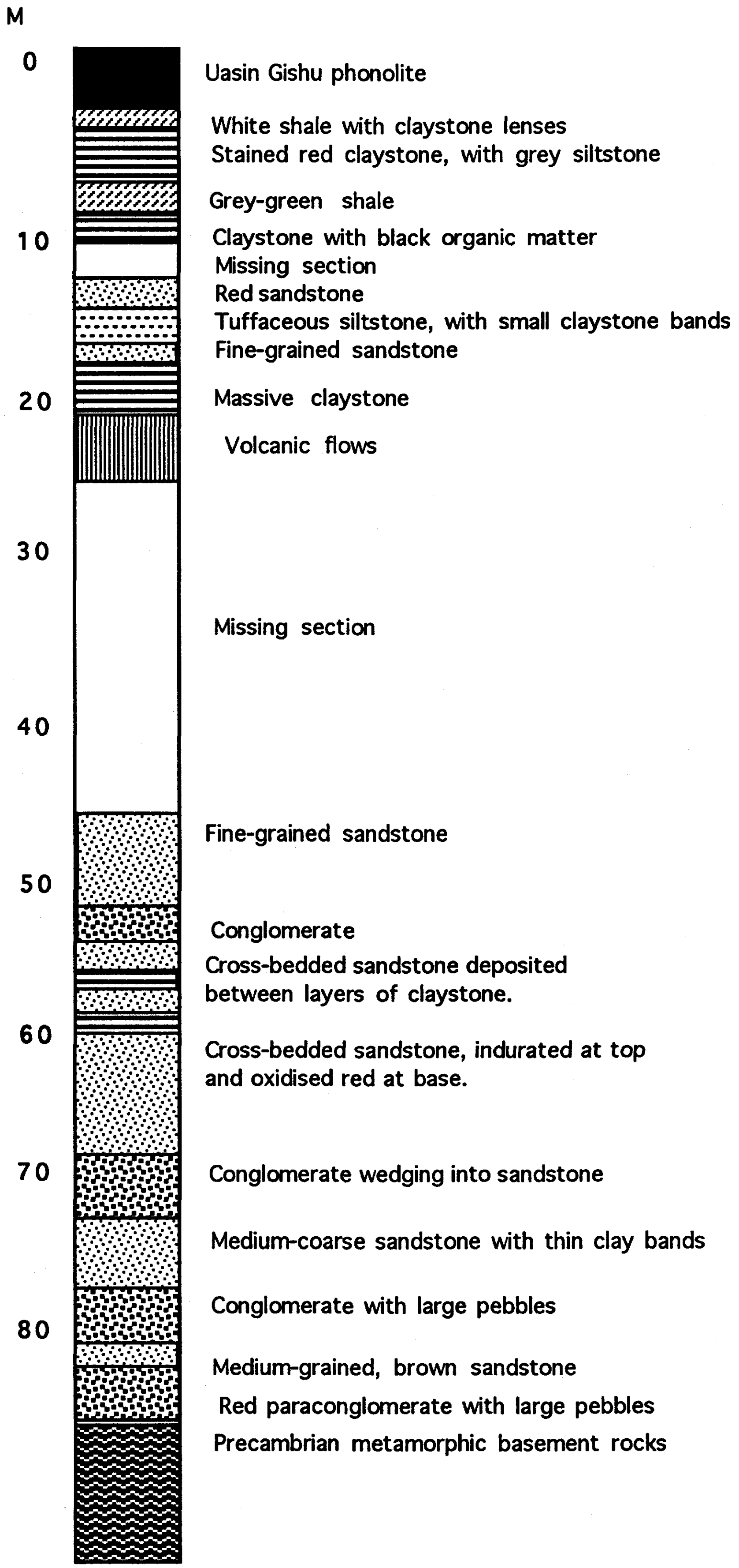


Fig.3.2a Stratigraphic section of Tambach Formation at the type section south of Tambach township.

paraconglomerates at the base, through coarse to fine grained sandstones, siltstone, claystones and shales at the top of the sequence (Fig. 3.2a). The exposed thickness of the formation varies according to the pre-Tambach terrain, but at its type section it is about 80-100 m thick. In many parts of the formation the sediments have been obscured by slope debris. Thin red ash beds (2 cm thick) found within the claystone facies indicate volcanic activity in the region during deposition. These ash beds were used locally as markers for correlation.

Tambach locality

The Tambach locality, as defined in this study, consists of the portion of the Tambach Formation that is exposed near Tambach township, in which both the fluviatile and lacustrine facies of the formation are exposed. The unit is exposed extensively south of Tambach. At the base of the sequence, the sediments are composed of massive paraconglomerate facies (7.5 m thick) lying discordantly on a breccia (paleoregolith) that rests on the basement rocks. The conglomerates are overlain by thin lenses of reddish brown, cross-bedded sandstone bodies with a total thickness of 1 m.

Above the sandstone facies, the deposits change to a conglomeratic facies with large clasts, intercalated with coarse indurated red sandstones (3.6 m thick). This coarse clastic sequence is overlain by green bands of claystones with rootlets with total thickness of 1 m. The strata above this sequence are characterised by well sorted sandstones and conglomerates, about 10 m thick. The section above these fluviatile facies (20 m thick) is obscured by landslips and recent debris flows. A small volcanic intrusion within the formation has caused local baking of the overlying claystone facies with an aureole extending for up to 5 m. The claystones are weakly laminated and punctuated by lenticular bedded siltstones and sandstones with sharp contacts. Near the top of the sequence there is another section of about 2 m, obscured by rock debris, which is probably composed of sandstones and claystones. The top part of the section (8 m thick) is largely composed of claystones and shales with small intercalated siltstones and sandstone units (Plate 3). The upper part of the section is covered by slope rubble and deeply weathered red soils.

Kessup locality

The Kessup locality refers to the sediments found near Kessup, north of Tambach township. The sediments are exposed about 1 km east of Kessup and the facies in this section are principally laminated grey-green shales and siltstones. Fig. 3.2b shows the exposed upper part of the section. They fine upward from indurated siltstones at the base to highly fissile green shales at the top of the sequence. The shales are rich in ostracods and plant debris, with few basement-derived clasts, which are also common in the sediments found at Tambach locality.

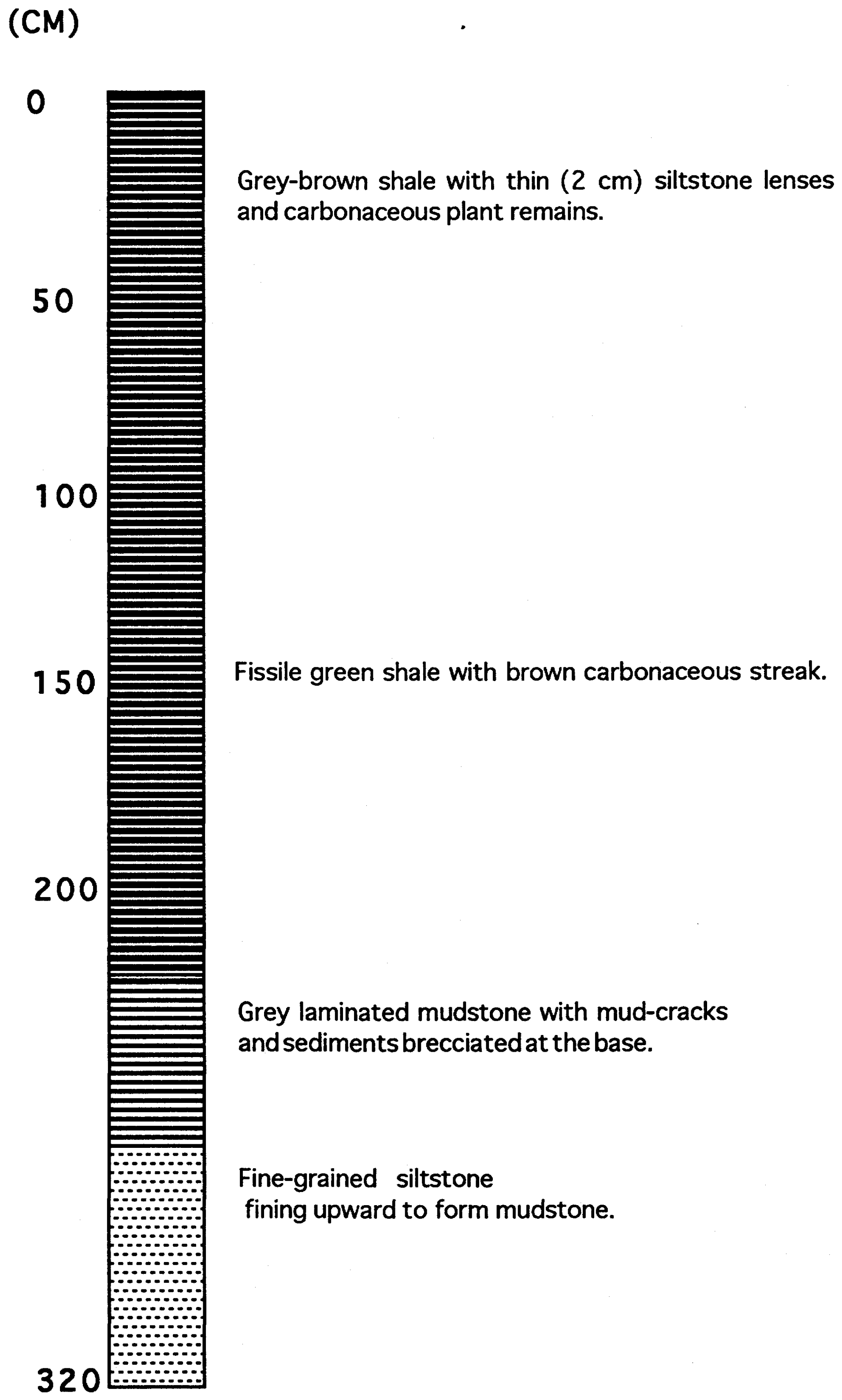


Fig. 3.2b Stratigraphic section of mainly lacustrine facies, Tambach Formation at Kessup locality.

3.1.2 Facies and Environments of Deposition of the Tambach Formation

Six lithofacies, have been recognised in the type section of the Tambach sequence of the formation. These are:

Red paraconglomerate facies;

Coarse orthoconglomerate facies;

Red indurated sandstones facies;

Cross-stratified sandstone facies;

Sandstone/claystone facies; and

Laminated white shales.

The **red paraconglomerate** facies occurs near the base of the sequence, resting on a breccia whose age is unclear. They are exposed about 4 km south of Tambach, with a total exposed thickness of at least 7 m. The rock is composed of poorly sorted angular clasts (1-5 cm) of basement derivation, supported within a sandy matrix. These deposits are immature and have quartz and feldspars in the matrix. The basal contact of this facies with the underlying breccia and basement rocks is mainly sharp, while their upper boundaries are commonly gradational with the overlying conglomerates. The upper units of the facies become progressively better sorted and in places grade into orthoconglomerates.

The poor sorting, coarse clasts and matrix support indicate deposition by mass flow processes. The paraconglomerates were probably deposited by debris flows on steep alluvial fans below the Elgeyo Escarpment (cf. Tiercelin et al., 1980). The angularity and size of the clasts suggest close proximity to the source area. The sediments were likely deposited in a strongly oxidising environment, as suggested by their red coloration.

In the **coarse orthoconglomerate facies** (at least 4 m thick), which occurs above the paraconglomerates, the rocks are clast supported, and locally show well-defined imbrication, small-scale planar cross-stratification, channelled or scoured erosional bases, and tops that are gradational with the overlying sandstone units. The matrix of this facies is composed of coarse arkosic sandstone.

Petrographic analyses of these rocks (Chapter 4) show that the rock matrix is composed of coarse polycrystalline quartz and feldspar grains (mainly microcline), which are angular to subangular and commonly show preferred grain orientation. The coarse grained nature of the clasts, erosional bases and interfingering of the conglomerate facies with the sandstones, indicate deposition in fluvial, probably braided, channels with variable flow velocity. The mineralogy suggests that most of the sediments were locally derived from the basement rocks.

The **red sandstone facies**, at Tambach locality, has a total thickness of 4.5 m and is characterised by poorly sorted sandstones with small-scale planar cross-bedding. These sandstones interfinger with the underlying conglomeratic facies and are composed of medium to coarse, angular to subangular grains that are cemented by iron oxides. Compositionally, the facies is an arkosic arenite. Studies in thin section show that most of the coarse grains are supported by a finer matrix of feldspars and quartz. Texturally, and compositionally the rocks are immature, containing some angular rock fragments.

The sandstones are interpreted to have formed in sandy ephemeral braided streams on the lower flanks of the alluvial fans, as shown by their poor sorting and immaturity.

The **cross-stratified sandstone facies** is composed of fine to medium-grained sands that interfinger with floodplain claystone and siltstone facies. The sandstones have planar and trough cross-bedding and a clay matrix; individual units have typical thicknesses of about 30 cm. However, some thin sandstone lenses (4-10 cm thick) in the facies are channelled into claystones, with erosive contacts (Plate 2).

Petrographic and X-ray diffraction analyses of the samples show that the grains vary from angular to subangular arkosic arenites rich in quartz, albite and sanidine. The rock is compositionally immature. These deposits were probably deposited by shallow, possibly perennial, streams flowing into a lake from the west of the basin, as shown by the cross-stratification of the sandstones, dip direction of the foresets and the interfingering of the sandstones with the floodplain claystones.

The sandstone/claystone facies occurs near the top of the sequence of the section. This facies consists of thin, planar cross-bedded red-brown sandstones (4 cm thick), with some thicker units (50-70 cm), channelled to depths of 5-8 cm into the claystones. The claystones in this facies are grey and generally massive, with small mud-cracks and some *in situ* plant remains, and vary in thickness from 20-30 cm.

The depositional environment is interpreted as one where shallow ephemeral sandy channels cross muddy, lake marginal plains that were periodically exposed. This is shown by the intercalations of the channelled sandstone bodies with claystone facies. The planar cross-bedding indicate fluvial sedimentation, while the claystones with plant remains are probably deposits either of overbank floods or deposits of a transgressive lake.

The **white shales** (at least 1.5 m thick) form the top sequence of the Tambach section of the formation. The sediments have broken fossil fish bones and some carbonaceous plant remains. These laminated shales are intercalated with the massive underlying mud-cracked, green claystones.

X-ray diffraction analyses of the samples have shown that the clay mineralogy of the claystones and shale facies is principally montmorillonite, illite-montmorillonite, illite, analcime and sanidine. The depositional environment of these sediments is interpreted to be a shallow, quiet, lacustrine regime as indicated by the lamination of the shale and fish fossils. However, the paleolake became saline and highly alkaline at certain stages as shown by the presence of authigenic analcime (Chapter 4).

3.1.3 Depositional History of the Tambach Formation.

Deposition of sediments in the Tambach Formation occurred in the Middle Miocene, in a downwarped broad depression, during a time of tectonic quiescence (Chapman et al, 1978; Morley et al., 1992). The earliest sediments were mainly paraconglomerates, conglomerates and sandstones that were deposited in alluvial fans along the base of the evolving Elgeyo Escarpment. The sedimentary facies in the basin show an overall, well-developed fining-upward sequence, from coarse conglomerate and sandstone facies at the base to fine siltstone, claystone and shale sequence at the top. These facies are interpreted to represent deposition from high energy, alluvial fan deposits, perennial and ephemeral stream deposits, and lacustrine deposits, respectively. This sedimentary sequence represents a gradually filling of the basin and suggests a reduction of stream gradients in the catchment through time. The fact that coarse deposits are not exposed high in the sequence suggests that either major subsidence of the basin took place, followed by filling, or that gradual subsidence occurred coeval with a high sedimentation rate, such that the sediments filled the basin faster than the rate at which the floor subsided. The paleogeography of the Tambach basin in its early stages cannot be reconstructed reliably from present evidence. Thus, it is possible that through flowing axial drainage or a contemporary lake may have existed elsewhere in the half-graben to the east or north, but the evidence lies buried below later deposits. Fig. 3.3 shows a general reconstructed facies model of the Tambach basin. The lacustrine facies are likely to have accumulated in a shallow closed lake basin which became saline and alkaline in its later stages (i.e. pH > 9.5) and was probably shallow. Based on the fact that the lake underwent periodic regression, becoming highly saline and alkaline and possibly desiccating, the estimated maximum depth of the paleolake was about 15-20 m. Volcanic eruptions must have taken place in the region during the deposition of lacustrine sediments, as exemplified by distinct red ash beds (2 cm thick), which are continous through most of the type section at Tambach. The sediments were eventually capped by the extensive Uasin Gishu phonolite flow.

During the Pleistocene, tectonic movements reactivated the Elgeyo fault and led to alluvial sedimentation in the downwarped part of the Kerio Valley and uplift along the Elgeyo Escarpment. This is probably responsible for the higher elevation of the phonolite flow along the scarp than in the adjacent western plateau (Lippard, 1972).

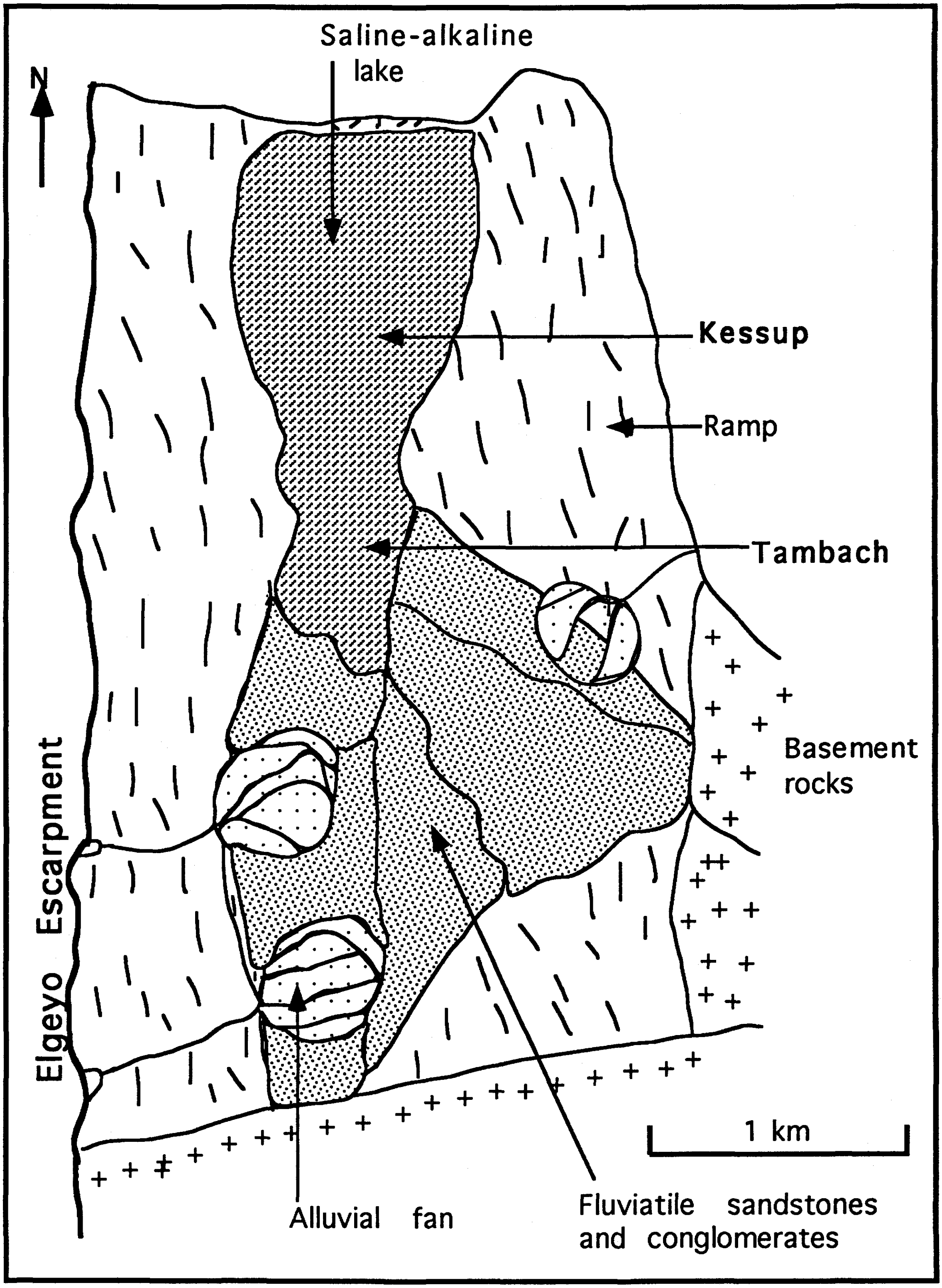


Fig.3.3 A generalised reconstructed model of the facies in the Tambach Formation.

3.2 STRATIGRAPHY OF KIMWARER FORMATION.

The poorly exposed Kimwarer Formation is found in the Kerio Valley at the southern end of the Elgeyo Escarpment (Fig. 3.4). The sediments in this formation are the oldest in the region, probably of Early Tertiary period (Chapman *et al.*, 1978). They consist of fluvial and lacustrine sediments which, like those of Tambach Formation, are lying on the basement system; unlike the Tambach Formation, they are localised in a depression in the Kimwarer area. Lippard (1972) sub-divided the formation into upper and lower members. The lower member consists of sandstones, conglomerates, siltstones and shales. The upper member consists of basaltic tuffs and is overlain by basic agglomerates of the Elgeyo Formation (Fig. 3.5). The sediments forming the lower member are derived from the basement system and are mainly arkosic arenites with thickness of about 45 m south of Kimwarer (Lippard, 1972). The sedimentary sequence in this member changes from coarse, highly indurated sandstones and conglomerates with mud-cracks at the base, to fine grained laminated siltstones and fissile shales at the top. These sediments were deposited by ephemeral streams. however, during later stages of deposition, a small lake developed, resulting in deposition of the laminated siltstones and shales. The upper member of the formation is rich in friable, poorly consolidated volcaniclastic material with pebbles of quartz and quartzite.

The sandstones and conglomerates are cross-bedded. From the study of thin sections the sandstones are clean with few rock fragments and little clay matrix, which suggests that they were eroded and fluvially deposited from basement rocks prior to volcanic eruptions in the area. Overlying the Kimwarer Formation, the Elgeyo Formation

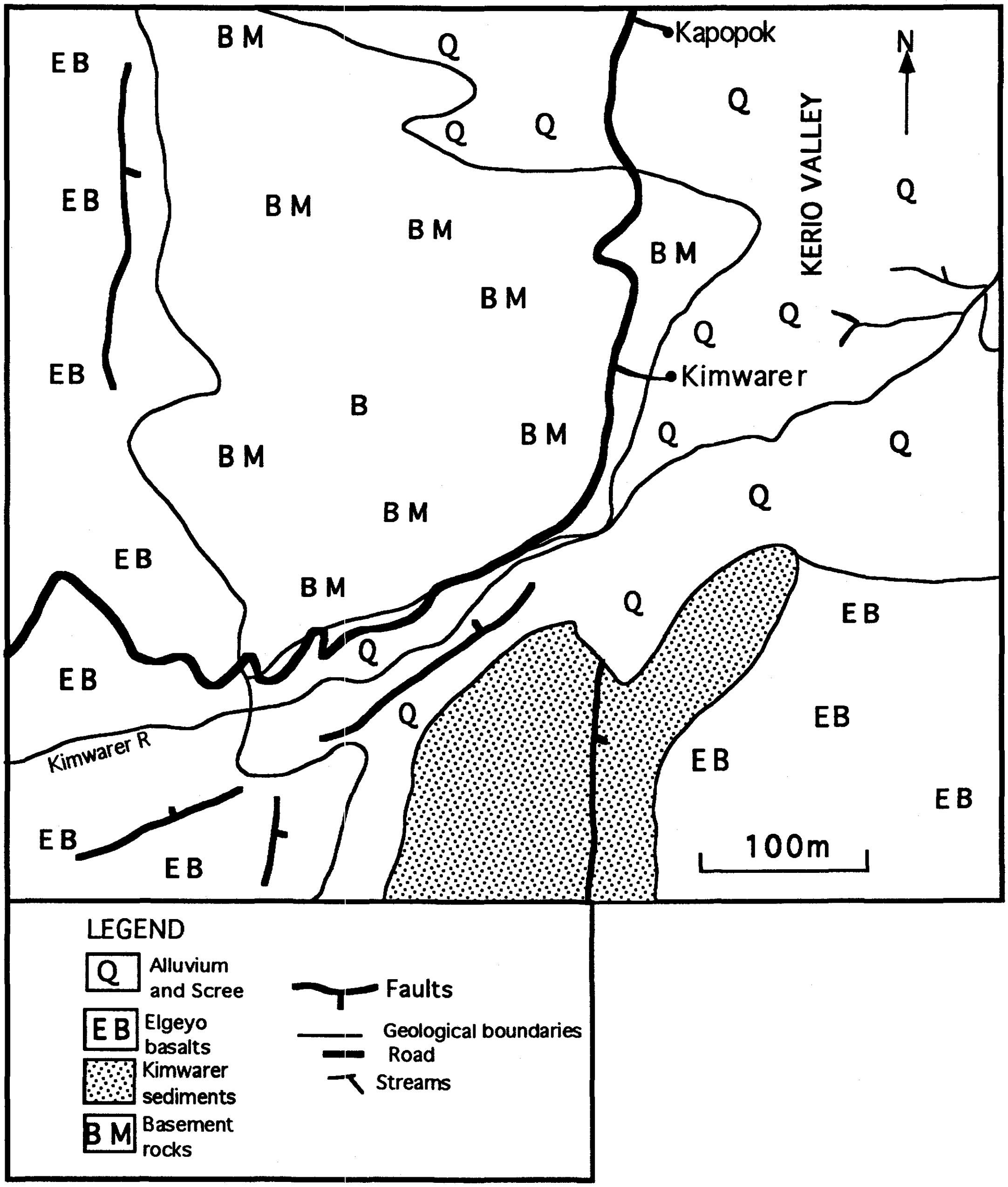


Fig.3.4. Geological map of Kimwarer area showing location of sediments in the basin (modified from Nyambok & Gaciri, 1975).

consists of a series of basic volcanics that were named Elgeyo basalts by Walsh (1969). Lippard (1972) showed that the basalts are absent in the Elgeyo Formation and that the sediments in this formation were younger than the Kimwarer sediments. He, therefore, changed the name to Elgeyo Formation. The rocks are mainly breccia-agglomerates and lavas. Overlying these rocks is the extensive Uasin Gishu phonolite, which is divided into the lower member, generally a non-porphyritic type, and an upper porphyritic type (Nyambok & Gaciri, 1975).

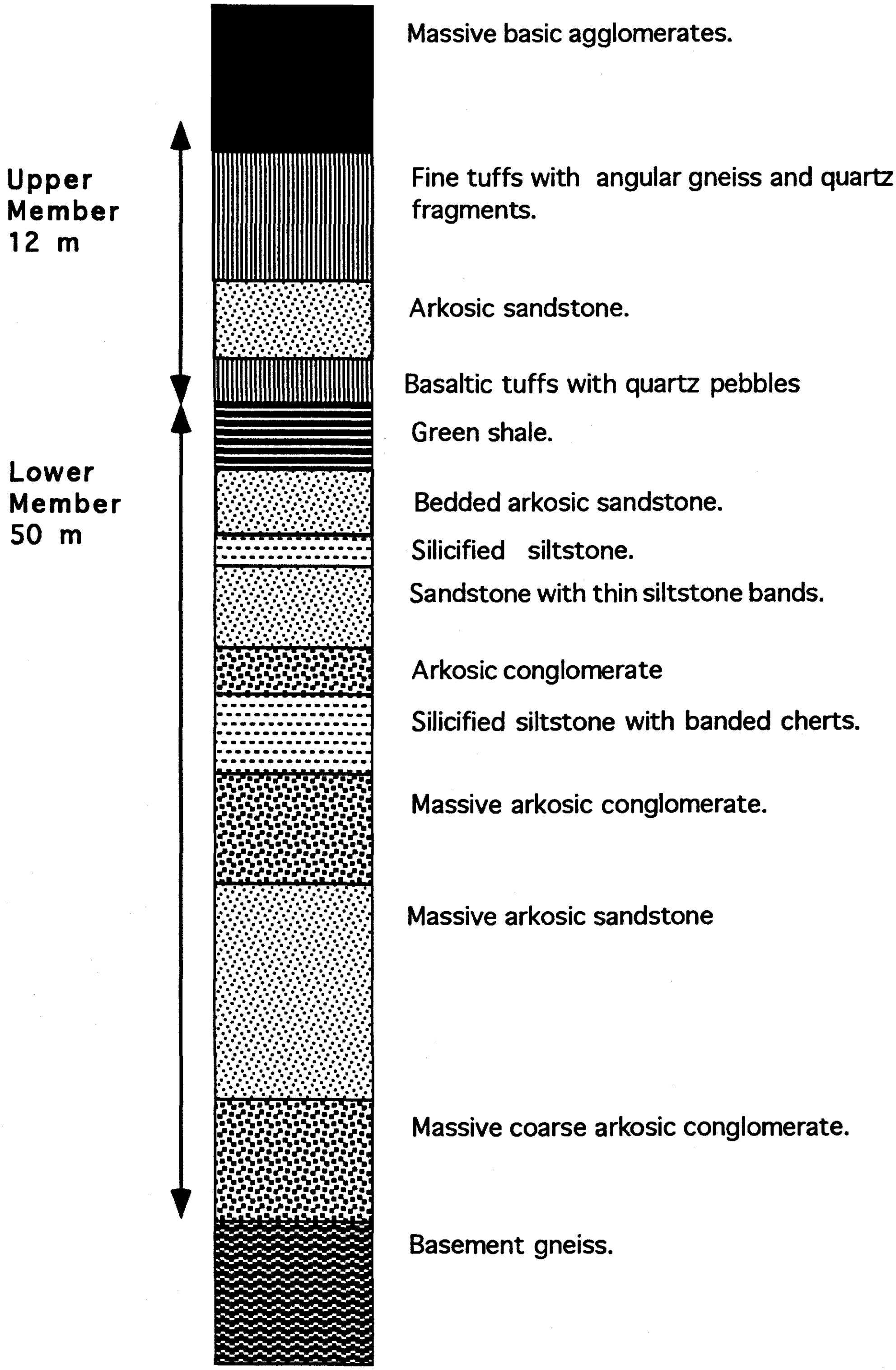


Fig. 3.5. Stratigraphy of Kimwarer Formation showing both the upper and lower members (adapted from Lippard, 1972).

3.3 NGORORA FORMATION.

INTRODUCTION

The Ngorora Formation is a mid-Miocene sedimentary sequence found in the central part of the Kenya Rift between latitude $0^{0}30'$N and 1^{0}N. The formation is defined as those sedimentary and volcaniclastic rocks bounded below by the Tiim Phonolite Formation and above by the Ewalel Phonolite, exposed along tilt-block faults in the flanks of the Tugen Hills (Bishop & Chapman, 1970; Pickford, 1978a). The formation accumulated when faulting led to the formation of several small basins in the region. The major tectonic features that influenced sedimentation in the Ngorora Formation and were significant in the development of the Tugen Hills are : the Kito Pass Fault in the north, the Saimo Fault in the south of the Ngorora basin, and the Kaption Volcanic Centre (Fig. 3.8a). Movement on these faults elevated some parts of the region and controlled the pattern of sedimentation (Chapman *et al.*, 1978).

The sediments include fluviatile, lacustrine, colluvial and volcaniclastic deposits, that are interbedded with lava flows. Pickford (1978a) divided the formation into five members, termed members A, B, C, D and E. These sediments are exposed in the Kapkiamo, Poi, Bartabwa and Kabarsero sub-basins of the Formation (Fig. 3.6).

This study focuses specifically on Member C of the formation in the Kapkiamo and Poi sub-basins. Member C is composed mainly of lacustrine sediments that contain oil-shale units rich in black organic matter (up to 4% TOC) and are, therefore, considered potential source rocks. The aim of this part of the study was to examine the sedimentology and mineralogy of these sediments, in order to understand the

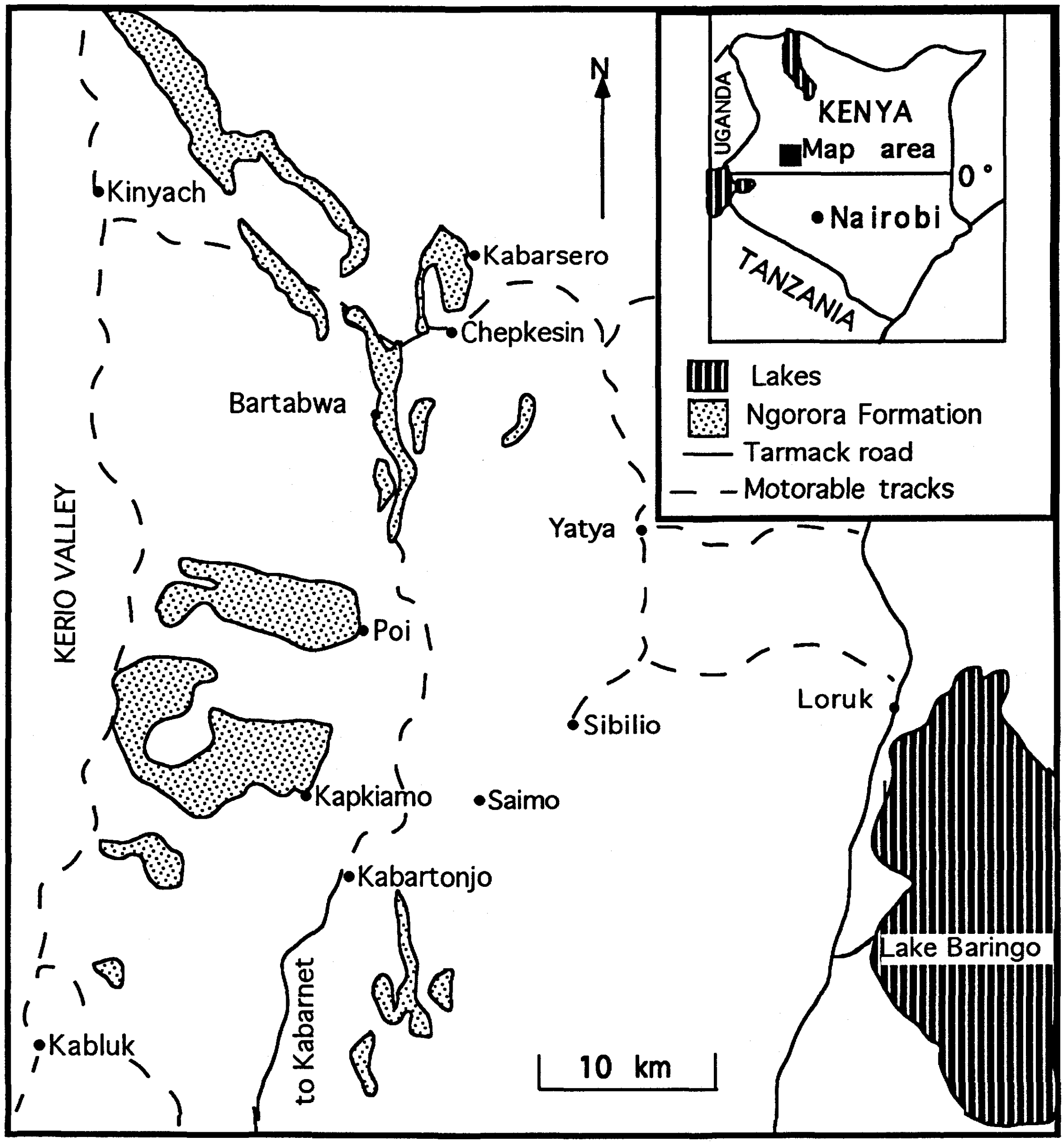


Fig.3.6 Map of the central Kenya Rift, showing outcrop localities of Ngorora Formation.

environments and processes in which the organic-rich shales and mudstones were deposited.

3.3.1 Stratigraphy of the Ngorora Formation

The stratigraphy of the Ngorora Formation has been studied extensively because it has yielded an abundant mammalian fauna, including an early hominid (Bishop & Chapman, 1970; Bishop *et al.*, 1971; Bishop & Pickford, 1975; Pickford, 1975, Pickford, 1978a). In these studies the Kabarsero sub-basin was designated as the type area of the formation as all five members are exposed in vertical succession (Fig. 3.7). However, several other localities within the Tugen Hills area have been assigned to the Ngorora Formation based on lithostratigraphic or faunal similarities (Fig. 3.6). The members were named according to the predominant depositional processes. At Kabarsero locality, Member A (92 m thick) is composed mainly of fluviatile deposits, lahars and phonolite lavas, which accumulated in the subsiding rift. The sediments in this member are mainly clay, and coarse boulders deposited by rivers flowing from uplands to the east of the formation. During deposition of this member, the Saimo Horst, which was later to develop as a major physiographic feature, began to form. Member B (42 m thick) is composed mainly of fluviatile sediments similar to those of Member A, but during the time of deposition, lahar activity stopped.

At the end of deposition of Member B, major faulting along the Elgeyo Escarpment and the Tugen Hills, and the uplift of the Sidekh and Saimo Horsts, led to formation of the Kapkiamo, Poi and Kabarsero sub-basins and the establishment of lacustrine sedimentation. In the Kabarsero sub-basin, Member C has a maximum exposed

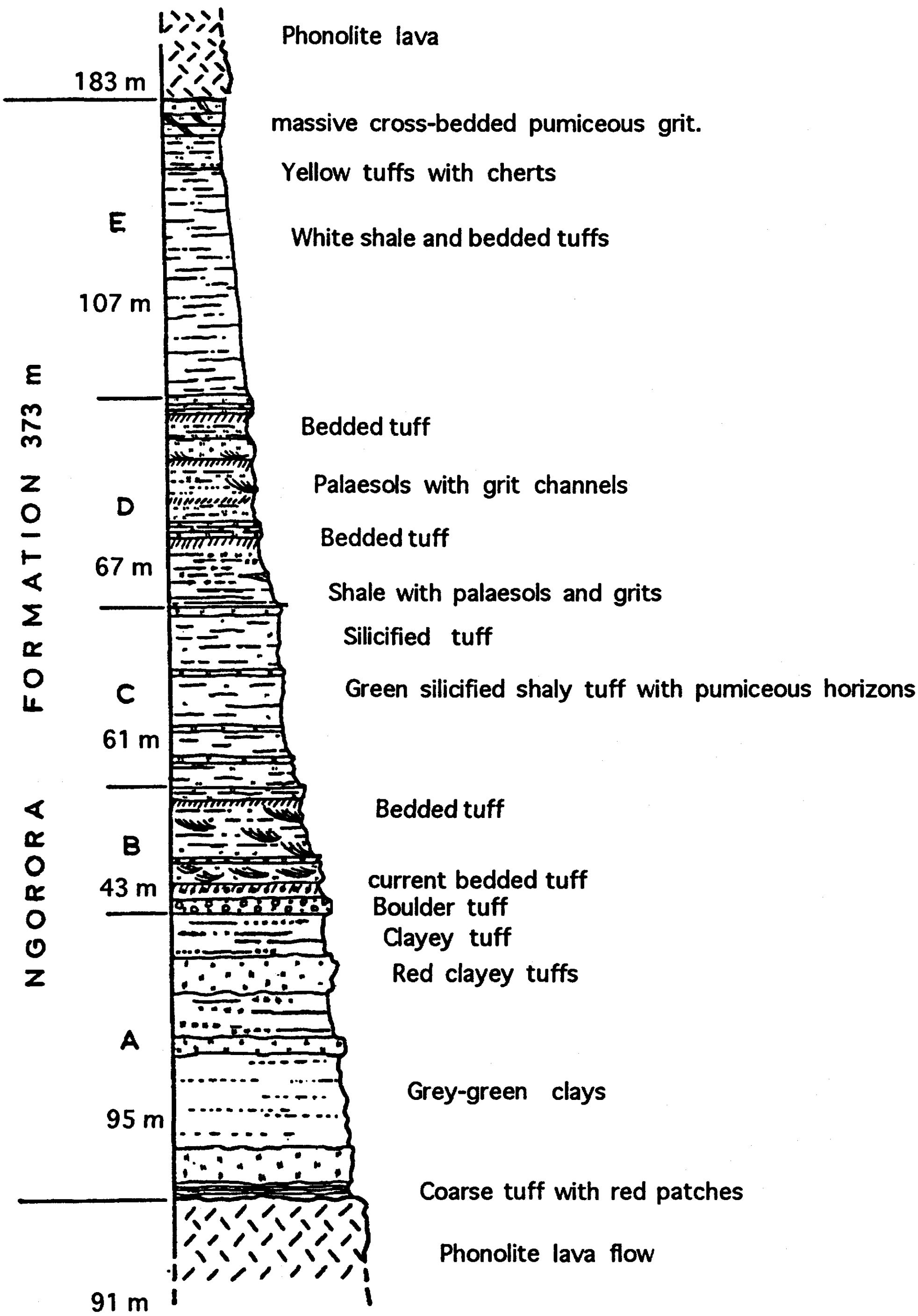


Fig.3.7. Lithological division of the Members of Ngorora Formation in the section at Kabarsero (adapted from Bishop & Chapman, 1970).

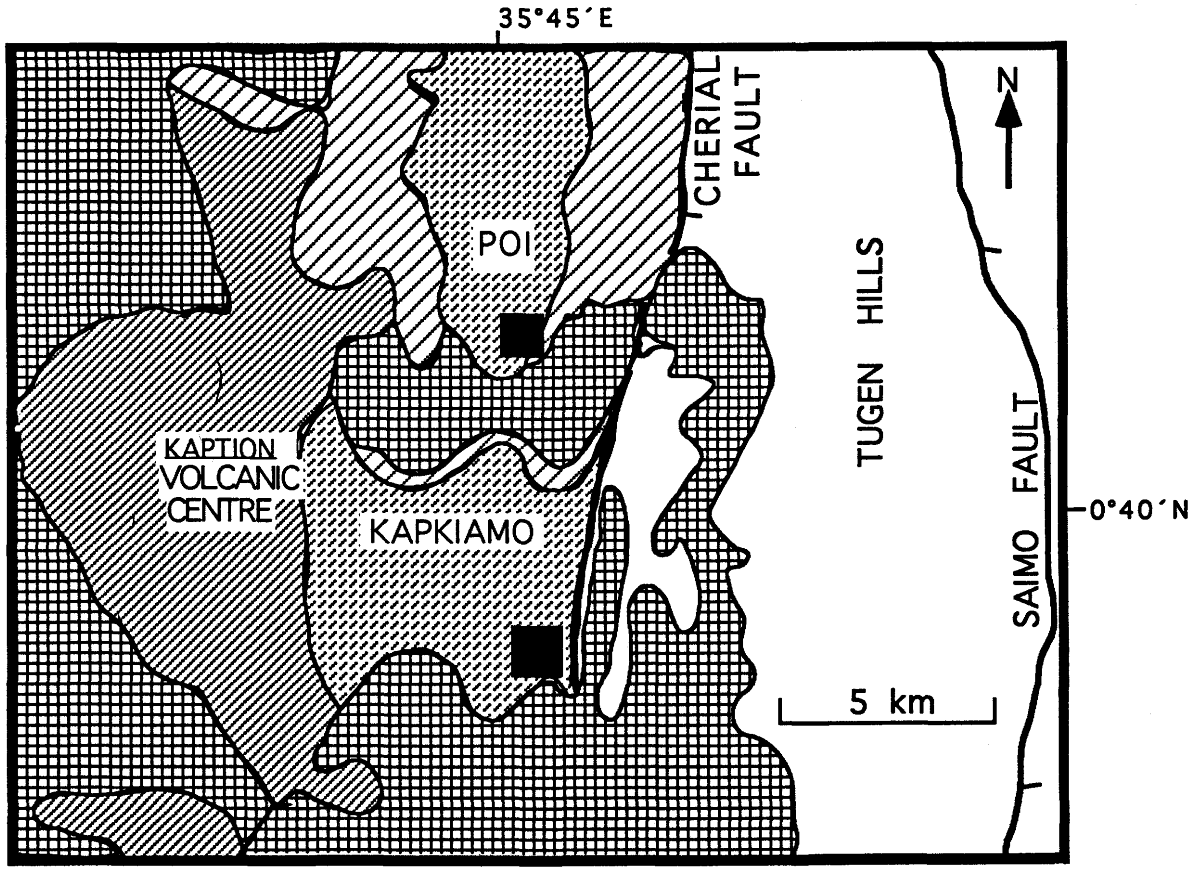
thickness of 60 m with clay palaeosols that contain mammalian faunas (Pickford, 1978a; Owen, 1981). By the time this member was forming, the Kaption Volcanic Centre (Fig. 3.8a) had become extinct and gradually eroded. After Member C was deposited, the lake at Kabarsero dried up and the predominant sedimentation in the sub-basins changed to floodplain and shallow lakes, in which fossiliferous coarse clays, sands and conglomerates (60 m thick) of Member D where deposited. At the same time, subsidence in the Kapkiamo basin was keeping pace with deposition. Further faulting along the Elgeyo Escarpment and the Tugen Hills led to a return to lacustrine sedimentation during Member E, when shales (160 m thick) were deposited.

Precise age determinations of volcanic rocks within the Ngorora Formation have been made using a laser-fusing, single-crystal $^{40}Ar/^{39}Ar$ method (Deino *et al.*, 1990). The results show that the Tiim phonolite flow ended in the area about 13.2 Ma and that sedimentation in the basin ensued 0.1 to 0.3 Ma after the cooling of the phonolite flow. By 9 Ma, sedimentation had ceased and the formation was covered by the Ewalel phonolite flow. The Ngorora Formation thus represents a time span of about 4 million years.

3.3.2 SEDIMENTOLOGY OF MEMBER C:
KAPKIAMO SUB-BASIN.

The Kapkiamo sub-basin is an asymmetric half-graben, bounded to the east by the Saimo Horst and to the west by the Kaption Volcanic Centre (Fig. 3.8a). The geomorphological and geological evolution of the basin were controlled largely by tectonics and volcanic activity. Sedimentation in the Kapkiamo sub-basin was terminated by volcanism and uplift of the Sidekh and Saimo blocks. The opposing effects of subsidence and sedimentation occurred simultaneously, resulting in lacustrine sedimentation of fissile shales, mudstones and siltstones. Fluviatile sedimentation in the basin was minimal, and confined to the narrow subaerial margins of the lake. The sediments are exposed in small cliffs and in small steep, ephemeral stream channels.

Although the basal contact of the sediments with the underlying phonolite is rarely exposed, a sequence of about 35 m of lacustrine sediments that crop out in the sub-basin was logged in detail and sampled (Fig. 3.8b). At the base of the sequence, which is believed to be close to the base of the member, the sediments are predominantly pale green, mud-cracked fissile shales (2.2 m thick) visibly rich in black organic matter. These are overlain by shales with intercalations of mudstones and siltstones (4.2 m thick). The siltstones are made up of fine mud-chips and are locally intruded by clastic dikes, indicating early cementation. Above these siltstones are grey-green laminated mudstones with thin lensoid beds (7 cm thick) of fine-grained sandstone. The facies above the siltstones are white poorly consolidated fissile shales (1.2 m thick, Plate 4). Above the white shales lie intercalations of grey-green mudstones with fish fossils, siltstones and



LEGEND

Rocks younger than Ngorora Formation.

Member D

Member C

Member A

Rocks older than Ngorora Formation

Positions where sections were measured.

Fig. 3.8a. Geological map of part of the Ngorora Formation showing lacustrine sub-basins of Kapkiamo and Poi.

sandstone about 5 m thick, which progressively change to green waxy shales (1.5 m thick). The facies coarsen upward to brown, poorly consolidated tuffaceous siltstones (2.6 m thick) with root-marks. The top of the sequence is an erosional surface capped by white laminated mudstones with thin (2 cm) chert veins.

MEMBER C AT POI SUB-BASIN

The sediments of the Poi sub-basin of the Ngorora Formation, which occurs about 3 km north of the Kapkiamo sub-basin, also belong to Member C and are bounded to the east by the Cherial Fault (Fig. 3.8a). The basin is filled by a thick sequence of lacustrine shales, mudstones, and siltstones, with tuffaceous fluvial deposits, mainly sandstones and conglomerates with some intercalated lahar deposits. The lacustrine shales are mainly fissile and green, locally waxy with mud-cracks, and progressively coarsen upward, forming siltstones with erosional contacts below the siltstones. Some siltstones show evidence of reworking and have carbonaceous plant remains. The sediments, mainly fissile green-brown shales, are exposed where they have been uplifted or incised.

Because of difficult access and limited time, the full sedimentary sequence at Poi sub-basin was not studied, but selected lacustrine sediments were sampled, mainly for mineralogical and diagenetic analyses, and comparison with the Kapkiamo deposits. The basal contact of the Poi sediments with the underlying Tiim phonolite, as in the Kapkiamo basin is not exposed. A short logged stratigraphic sequence of about 7.7 m thick near the base of the member shows a generally upward-fining sequence (Fig. 3.8c). The lower part of the exposed sequence is composed of white to beige weakly laminated mudstone (0.5 m thick). These are overlain by 1 m thick grey massive tuffaceous siltstones, which are

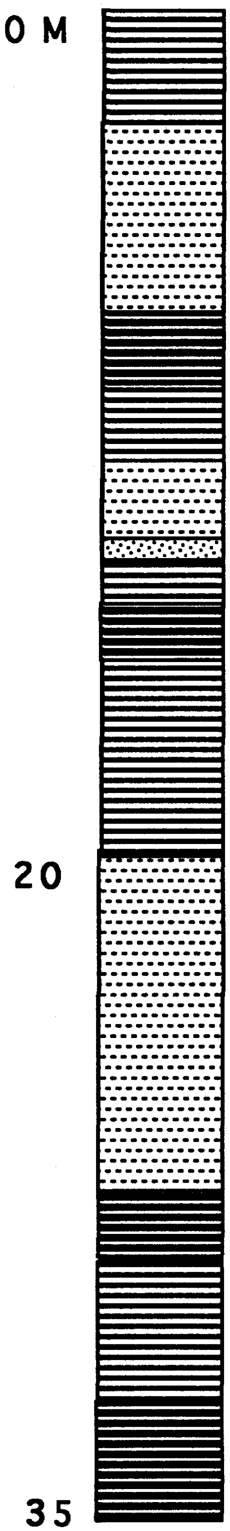


Fig. 3.8b Stratigraphic section of Member C, Ngorora Formation at Kapkiamo sub-basin.

granular at the top. The facies then changes to green waxy brecciated shales (0.9 m thick), which are overlain by orthoconglomerates with basal erosional contacts. The conglomerate facies (0.5 m thick) has a coarse sand matrix with round pebbles.

Above the conglomerate facies the sediments show some upward fining, from fine to medium grained sandstone through indurated siltstone to grey-green shale facies, with a lens of porcelaneous mudstone. The top of the sequence is covered by a paraconglomerate facies (2.5 m thick), which is poorly sorted, and probably formed from a debris flow or lahar flow (Plate 5). The deposits to the east of the lacustrine Poi sediments are lake marginal to fluvial deposits, representing higher energy depositional environments. They are composed of silty and tuffaceous sandstone overlying the lacustrine facies. Generally, the lacustrine facies of member C are similar in both the Kapkiamo and Poi sub-basins.

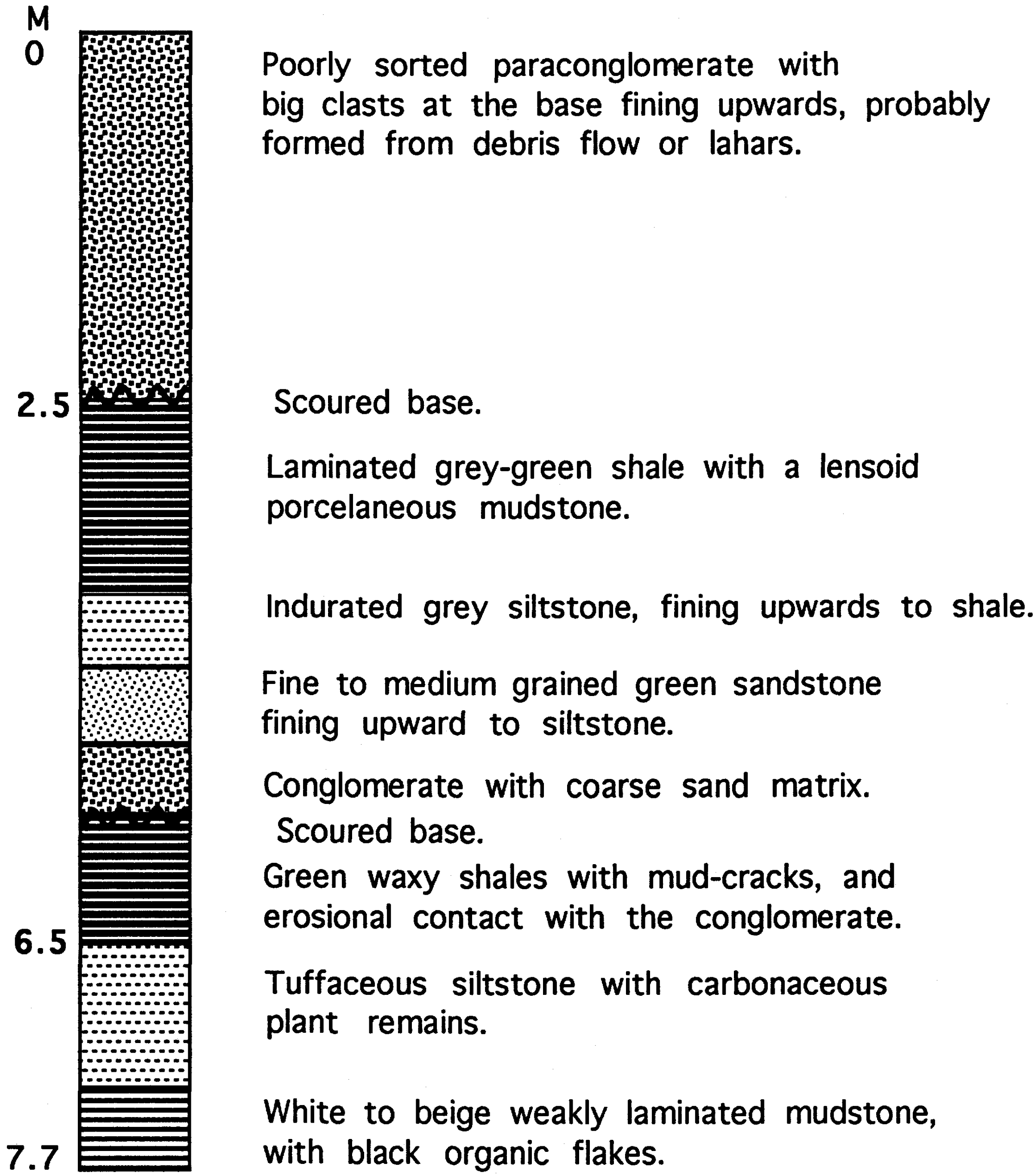


Fig. 3.8c. Stratigraphic section of Member C, Ngorora Formation at Poi sub-basin.

3.3.3 Facies and Environments of deposition of Member C Ngorora Formation

Four distinct lithofacies can be identified in Member C of the Ngorora Formation. These are:

Fissile shale/ Mudstone facies;

Tuffaceous Siltstone facies;

Sandstone/Conglomerate facies; and

Paraconglomerate facies.

These facies represent deposition in lacustrine, floodplain fluviatile and colluvial environments, respectively. The facies are intricately linked to the level of the paleolake, which in turn was controlled both by variations in climate and syndepositional tectonics. Mineralogical studies show conclusively that the paleolakes were, at times, strongly saline and alkaline, but during less saline phases were dilute and rich in fish and planktonic organisms.

Fissile Shale/Mudstone Facies.

The fissile shale and mudstone facies predominates in each sub-basin, with a logged total thickness of about 20 m of the sequence at the Kapkiamo basin and, although not measured, visibly accounts for much of Member C in the Poi sub-basin. The shales and mudstones are white to pale-green, laminated, and rich in organic matter, fish fossils and *in situ* plant remains. Mud-cracked horizons are common throughout the sequence indicating frequent subaerial exposure. The mud-cracks are mostly small (1-3 cm across), subrectangular to polygonal, and cut the sediments to depths of 0.5-3 cm (Plate 6). The upper boundaries of these facies are gradational, and coarsen to form tuffaceous siltstones.

X-ray diffraction analysis of these shales and mudstones shows that they are rich in quartz, smectites, sanidine, and the authigenic zeolites, analcime and clinoptilolite (see Chapter 4).

The fine grain size, lamination, and abundant mud-cracks indicate deposition under low energy conditions in a lake that fluctuated in level, periodically exposing the sediments. The abundant authigenic zeolites show that the paleolakes were at times strongly saline, and alkaline especially during regressive phase. This indicates that the lake was hydrologically closed with alkaline brines forming by evaporative concentration (Hay, 1966; Surdam & Parker, 1972; Surdam & Eugster, 1976). However, the abundant black organic matter and beds rich in fish debris indicate periods of relatively dilute surface waters, and high organic productivity. The preservation of organic matter, in contrast, suggests that the bottom waters may have been anoxic. The paleolake could at times have been chemically stratified or meromictic. A partly analogous situation can be found at modern Lake Bogoria, which lies about 45 km southeast of the Ngorora Formation. The lake is hydrologically closed and highly saline and alkaline, with a pH of 9.5 to 10.5 (Renaut & Tiercelin, 1993, and in press). The lake is meromictic and its sediments contain up to 7% total organic matter (TOC). The paleolakes at Kapkiamo and Poi, in which a TOC of up to 4% has been recorded (National Oil Corporation of Kenya, unpublished report), may have been similar, but the abundant mud-cracked surfaces suggest shallower margins than Bogoria, which has steep marginal slopes. These paleolakes were probably at times relatively deep and stratified; at other times they were ephemeral, drying up frequently. The organic matter is probably mainly from algal blooms in the monimolimnion when the lake levels were high. However, the lakes were probably no more than 10 to 20 m deep at their maxima as they frequently dried up. In morphology, they may have resembled the present Lake Nakuru, which is bordered by broad alkaline mudflats.

Tuffaceous Siltstone Facies

The siltstones are grey-green to brown, and vary from thinly laminated, to massive and indurated, especially those in the Poi sub-basin. They are tuffaceous and have a total thickness of 15 m in the Kapkiamo sub-basin. Their basal contacts are generally erosive and sharp, while their upper boundaries are gradational, and they tend to coarsen upward to form lenticular sandstone bodies. Fossils are rare in this facies compared with the shale/mudstone facies. Petrographic analyses show that these rocks are lithic arenites, rich in volcanic glass shards, rock fragments, and feldspars. The sand grains are angular to subangular, and the rocks are both compositionally and texturally immature.

This facies is interpreted to represent, sedimentation in shallow laterally shifting, ephemeral channels and washes near lake margins. Similar deposits are forming today in the littoral zones of Lake Bogoria (Renaut & Owen, 1991).

Sandstone and Conglomerate Facies.

In the Kapkiamo sub-basin, this facies occurs as thin lenticular bodies of fine to medium grained tuffaceous sandstones with a thickness of about 0.5 m, and is found as intercalations within the shale/mudstone facies. The sandstone and conglomerates both show small-scale planar cross-stratification. At Poi, this facies is typically about 1 m thick, and shows fining-upward sequences from conglomerate to the overlying green sandstone. The conglomerates have a coarse sand matrix with rounded lava pebbles, while the sandstones are fine to medium grained, with angular to subangular clasts. The primary bedding structures, poor sorting, lenticular geometry and erosive contacts of the sandstones suggest that deposition of sediments was in ephemeral braided streams. Petrographic examination shows that the coarse clasts have a groundmass of feldspars, quartz and lithic arenites rich in volcanic shards. The angularity and tuffaceous nature of the detrital grains implies that the sediments were shed from the local volcanic catchments and deposited by the ephemeral rivers that used to flow into the paleolakes.

Paraconglomerate Facies

The paraconglomerate facies, with a thickness of 1.2 m where logged, caps the sequence at the Poi sub-basin. The sediments are stained red by iron oxides and are upward fining, with angular to subangular poorly sorted clasts, averaging about 10 mm in diameter. They are composed of volcanic pebbles within a lithic arenite matrix. This facies probably represents sedimentation by debris flows on the steep slopes around the margins of the basin.

3.3.4 Depositional History of the Ngorora Formation.

During the period when Member A was forming sediments were mainly derived from the north and east of the basin, with some local volcanic centres contributing phonolite flows and agglomerate tuffs. Most of the sediments in this member of the formation are fluviatile. Member B, like Member A, is composed primarily of fluviatile and volcaniclastic deposits, but during deposition of this member the deposition of lahars stopped. Major faulting along the Elgeyo Escarpment and the Tugen Hills led to the deposition of lacustrine facies in Member C on the downthrow areas. During Member D a return to fluviatile depositional environment took place, with deposition of coarse clays and siltstones. Member E represents a lacustrine depositional phase like Member C, and the facies are mainly laminated shales.

The sediments of Member C in the Kapkiamo and Poi sub-basins are principally lacustrine, with minor shallow ephemeral stream deposits. The lacustrine facies are predominantly grey-green shales, rich in organic matter. Due to tectonic and climatic changes in the region, both paleolakes frequently experienced desiccation, as shown by the numerous mud-cracks. At low stages, the paleolakes were highly alkaline and saline ($pH > 9.5$), as indicated by the abundant authigenic zeolites. The mineralogy of the Kapkiamo basin sediments shows a zonation in response to the salinity (Chapter 4), the highly saline sediments are those at the centre of the basin marked by the presence of authigenic analcime and K-feldspar. The lakes were probably shallow (0- 20 m deep) and during deeper stages could have been meromictic, as shown by the presence of black organic matter and fossil fish which used to thrive on the upper fresh water above the chemocline. The paleolakes remained hydrologically closed for most of their history.

3.4 Kapthurin Formation

Introduction

The Kapthurin Formation is a 127 m thick sequence of Pleistocene sediments and pyroclastics deposited west of Lake Baringo in a linear, almost north-south trough (Fig. 3.9). These deposits are mainly fluviatile, deltaic and lacustrine sediments deposited in a downwarped basin initiated by tilting and faulting in the eastern part of the basin, along the older Chemeron Formation and the Kaparaina Basalt Formation (Tallon, 1978). The Kapthurin Formation is bounded to the north and south by basalts and trachytes, and to the west by the Tugen Hills. The eastern part is covered by the late Quaternary Loboi silts. The catchment area is made almost entirely by volcanic rocks (trachytes and basalts) and the sediments deposited were mainly tuffaceous sands, silts and gravels. The sediments in the south and central part of the basin are mainly fluviatile, while in the northeastern region towards Lake Baringo, they are mainly lacustrine.

Stratigraphy and depositional environment of the Kapthurin Formation

The sediments in this formation are mainly silts, gravels and tuffaceous sandstones. Tallon (1978) divided the formation into five members from top to base:

1 the Lower Silts and Gravels;

2 Pumice tuff;

3 Middle Silts and Gravels;

4 Bedded tuff; and,

5 the Upper Silts and Gravels members, respectively.

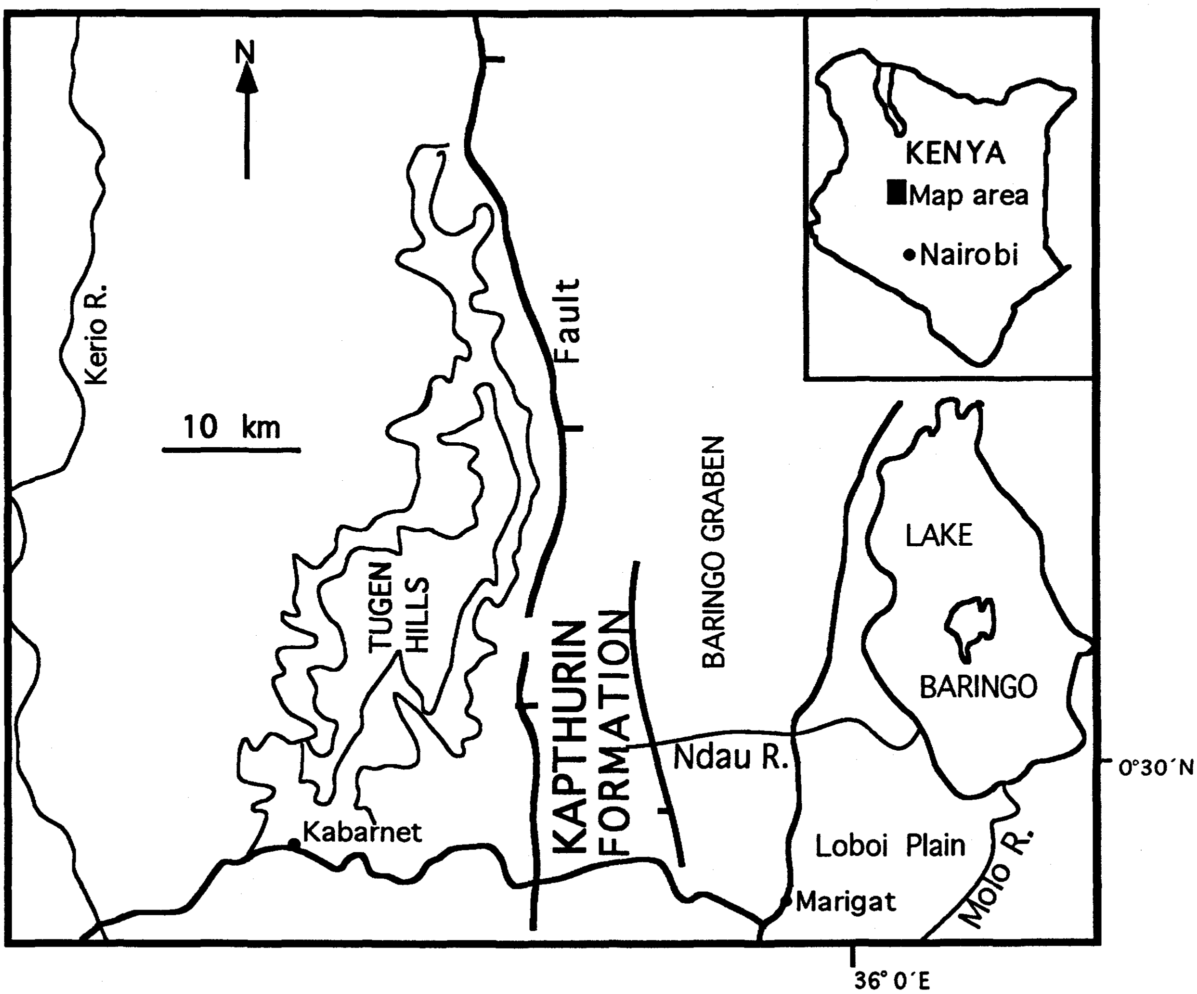


Fig.3.9 Map showing location of the Kapthurin Formation in the Tugen Hills, Baringo area and lines of principal faults in the basin.

The Lower Silts and Gravels Member (35 m thick) is composed of mainly fluvial and lacustrine sediments deposited in a pre-existing fault trough. The sediments in this member are relatively well sorted, and a large outcrop (10 m thick) of cross-bedded tuffaceous sandstone is exposed near Marigat in the southern part of the basin (Plate 7). This member was deposited by braided streams. The grain size of these sediments varies from coarse to fine and the sediments are rich in volcaniclastic detritus, and some reworked root casts.

The Middle Silts and Gravels Member (40 m thick) is separated from the lower member by the Pumice Tuff Member (20 m thick). The facies in this middle member are mainly poorly sorted brown silts. This member is separated from the Upper Silts and Gravel Member (20 m thick) by the Bedded Tuff Member. The Upper Silts and Gravels Member is composed of poorly sorted, pebble and boulder, fluvial deposits that crop out extensively in the western part of basin.

Early sedimentation in the Kapthurin Formation was in a large precursor basin of the present Lake Baringo. The paleolake was initially fresh but it became closed, with saline, alkaline brines at times. During the alkaline phase authigenic analcime, fluorite and dolomite formed in the sediments (Renaut & Owen, 1987). The salinity and alkalinity of the paleolake could have been due to hydrological closure of the basin and or due to climatic changes, which may have caused the regression of the paleolake.

Study of the Kapthurin Formation was not a major focus in this research. However, some of the fluviatile sediments were examined for diagenetic features. Thin section studies of the tuffaceous sandstones show that they are rich in volcanic shards, lithic rock fragments and detrital feldspars, which are undergoing extensive dissolution. The detrital grains are cemented by early calcite, which has been succeeded by iron oxide cements in places. X-ray diffraction analyses of the silts show that their mineralogy is principally sanidine and smectites, while calcretes in the formation are calcite.

CHAPTER-4. PETROGRAPHY AND DIAGENESIS.

4.1. Petrography of the Tambach Formation sediments.

The fluviatile facies of the Miocene Tambach Formation are mainly conglomerates and sandstones derived from both metamorphic basement and volcanic rocks. The sandstones and matrix in the conglomerates are typical lithic and arkosic arenites, with the lithic grains being derived mainly from volcanic rocks. The coarse clastics in the conglomerates lie within a framework of quartz and feldspar grains. Most arkosic sandstones are moderately well sorted, fine to medium grained, with angular detrital grains that reflect their local derivation from underlying basement rocks. The feldspars, which are common in the sediments, were analyzed by X-ray diffraction, and are mainly detrital sanidine, albite, microcline and anorthite. Detrital plagioclase is undergoing extensive dissolution in some samples to form clay minerals, commonly seen along cleavage planes (Plate 8). Although dissolution of feldspars is generally expected to increase porosity, it has not produced significant secondary porosity in most Tambach sediments due to its replacement and secondary pore-filling by clay minerals. In some samples, compaction is extensive, resulting in the flattening of the detrital grains. Detrital clays in the sandstones include both smectites and illite.

The diagenetic mineral suite in the sandstones includes calcite, montmorillonite, and iron oxides. Sparry calcite is an early pore-filling drusy cement in the sandstones, mostly predating authigenic clays. In thin section, calcite occur as patchy cement (Plate 8), which is stained red by Alizarin red S, using the method of Dickson (1965).

Authigenic smectite cements and partially fills pores in some sandstones with well-developed honeycomb and flaky structures (Plate 9). This morphology confirms that it is authigenic, and it is probably a secondary mineral derived from alteration of feldspars and other silicate minerals. The cements have reduced the porosity from an estimated original intergranular porosity of about 35% to about 10%. In most sandstones and conglomerates examined, both detrital and authigenic clay matrix accounts for 10-15%, and the sandstones are compositionally immature. The cementation sequence commonly seen starts with early precipitation of calcite, followed by authigenic clays minerals, then iron oxide. Some of the iron oxide is undoubtedly late, due to surface exposure at outcrop, but early iron-oxide cements are common in modern rift floor sediments (Renaut, pers. comm., 1993). The analcimes in the claystones are associated with montmorillonite, illite, calcite and detrital albite (Fig. 4.1).

4.1.1 Environments of diagenesis of the Tambach Formation sediments

Diagenesis of sediments is controlled by the preburial factors of provenance, depositional setting and climatic regimes. Early diagenetic processes affected the various lithofacies in the Tambach Formation differently. The early deposits are fluvial, consisting of conglomerates and sandstones derived mainly from quartzo-feldspathic basement rocks. These clastics were partially cemented by early calcite. Calcite precipitation is common in modern soils in the vadose and in shallow phreatic zones, and forms as a result of capillary rise, evaporation, evapotranspiration and evaporative pumping of shallow dilute groundwaters (Renaut, 1993). With gradual sedimentary fill, the Tambach basin evolved

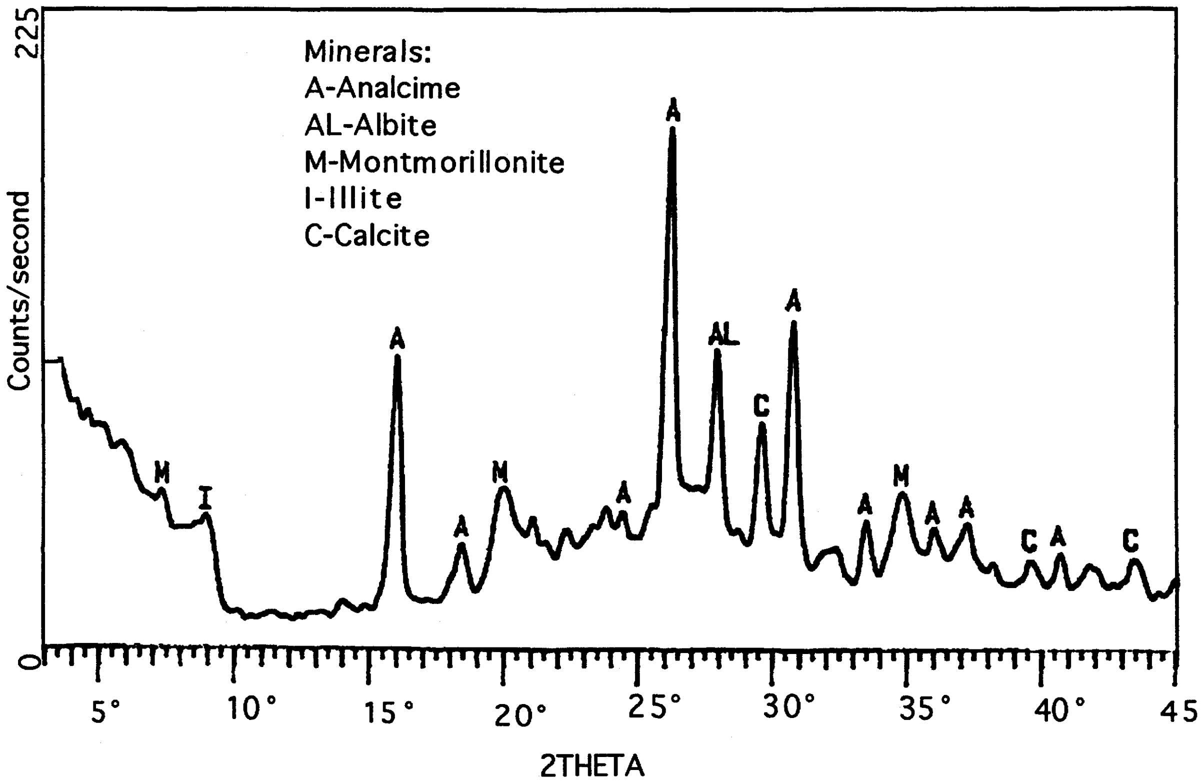


Fig.4.1 X-ray diffraction of lacustrine Tambach sediments at Kessup locality, analcime in these sediments is associated with calcite. Scanning was done at 40kV, 80mA and 3°/min.

progressively to become a closed lacustrine basin, with deposition of siltstones, claystones and fissile shales. Increasing overburden compaction resulted in the flattening of detrital grains in the sandstones and conglomerates. The sparry calcite cement locally was partly dissolved to produce secondary porosity that in places, was later filled by authigenic smectites.

Diagenesis continued when the basin subsided due to the further faulting that gave rise to the Elgeyo Escarpment. The exposed Tambach sediments were probably buried to a depth of up to about 2 km, but could be deeper below the Kerio Valley alluvial sediments. At one time they were overlain by extensive phonolite flows, now eroded. Formation of iron oxides is extensive in the samples, replacing and staining clays, but since all the samples studied are from outcrops, some iron oxide could be due to surface weathering or alteration of mainly iron-rich minerals by circulating groundwater in an oxidising environment.

Toward the centre of the basin, the depositional facies became lacustrine. Authigenic analcime crystals in the lacustrine claystones are well developed with euhedral morphology. Most crystals are submicroscopic, ranging in length from 7-20 μm across (Plate 10). The analcime occurs as pore-filling cement and is found between detrital clays. The possible mechanisms for analcime formation are (i) direct precipitation from interstitial pore fluids (e.g., Gall & Hyde, 1989) or (ii) by the reaction of saline, alkaline pore water with detrital silicates (e.g., Hay, 1970; Remy & Ferrell, 1989). The possible detrital precursors of analcime in the Tambach basin are volcanic glass, plagioclase feldspars and clay minerals. Although volcaniclastic materials (glass) are common in the basin and underlie the analcimic sediments, the Si/Al ratios of the analcimes show that volcanic glass are probably not the main reactants. Analcime normally forms from volcanic glass through an intermediate, more siliceous and hydrous alkali zeolite (Surdam and Sheppard, 1978). In the Tambach sediments, no other zeolites were found. The mean Si/Al ratio of the analcime as determined by electron microprobe analysis on 6 grains is 2.21 (Tables 4.1a & 4.1b). The Si/Al ratios of the analcime show that the Tambach analcimes belong to the silica-poor category (Group C) of sedimentary analcimes of Coombs and Whetten (1967). The analcimes in these sediments are not associated with quartz like those of the Ngorora Formation (Section 4.3), and are poor in silica and associated with calcite cements (Fig. 4.1). Similar characteristics led Gall and Hyde (1989) to conclude direct precipitation for the formation of analcime in the lacustrine sediments of the Carboniferous Rocky Brook Formation, in western Newfoundland, Canada.

In the Tambach Formation, analcime either formed by direct precipitation or by reaction of saline, alkaline water with detrital clay minerals. The analcime is associated with detrital clays, some of which seem to be illuvial and have been washed into the pores of the sediments. Direct precipitation of analcime is unlikely because of the low amount of Al^{3+}, in the fluids of the sediments in the central Kenya Rift (Renaut, 1993). Detrital clays are the most likely main precursors of analcime, although other potential sources such as plagioclase feldspars, which show considerable etching, may have also contributed. Some analcime is itself etched, probably due to very high alkalinity when the lake was undergoing regression.

Table 4.1a Compositions of Tambach analcimes analysed by electron microprobe.

Sample Ta-38						
Analysis no.	1	2	3	4	5	6
Oxide Weight%						
SiO_2	58.04	59.34	58.13	57.42	56.45	56.00
Al_2O_3	21.81	22.66	22.63	21.66	21.79	22.02
Na_2O	9.94	10.36	11.51	12.03	11.04	11.11
Fe_2O_3	0.04	0.18	0.03	0.01	0.05	0.09
K_2O	0.05	0.03	0.01	0.02	0.04	0.02
CaO	0.00	0.00	0.01	0.02	0.00	0.02
MgO	0.00	0.05	0.00	0.00	0.00	0.00
Total	89.88	92.62	92.32	91.16	89.37	89.26

Table 4.1b. Compositions of Tambach analcimes analysed by microprobe.

Sample Ta-38						
Analysis no.	1	2	3	4	5	6
Atoms per 96 oxygens						
Si	33.90	33.70	33.32	33.44	33.41	33.22
Al	15.01	15.17	15.29	14.87	15.20	15.40
Na	11.26	11.41	12.79	13.58	12.67	12.78
Si/Al	2.26	2.22	2.18	2.25	2.20	2.16

4.2 Petrography of the Kimwarer Formation Sediments.

The Kimwarer sediments are probably among the oldest and most compositionally mature sediments in the central rift system of Kenya. The sediments were shed from metamorphic basement rocks including hornblende gneiss, biotite gneiss, quartzo-felspathic gneiss, quartzites and granitoid gneiss. Petrographic analysis of twelve thin sections revealed fairly clean arkosic sandstones. The sandstones are typically arkosic arenites with a framework of detrital feldspars (mainly microcline and sanidine) and quartz, and grain size ranging from medium to coarse sand, with angular contacts. They show moderate sorting with most subangular to angular grains, some with preferred orientation, parallel to bedding. The angularity and abundance of the feldspar grains confirm a local source for the sediments in the basement rocks; the grains have not suffered much abrasion during transportation. Detrital grains are well packed in some samples, reducing porosity. Compaction seems to have been intense as shown by flattened grains. The sediments may possibly have been overlain by several hundred metres of sediments and lavas, which have been subsequently eroded.

The sandstones are cemented by quartz, which in some places is apparently replacing earlier clay cements. The quartz cements are microscopic (mainly between 30-50 μm in length) with well-developed euhedral crystals that partly fill the pores and have reduced the primary porosity to less than 30% (Plate 11). Petrographically, the quartz cements appear to be of one generation. In some sandstone samples interstitial fluids have caused etching of feldspars grains, that were later filled by iron oxide. The shales and siltstones in the basin are rich in detrital illite which was probably derived from altered mica (Fig. 4.2).

4.2.1 Environments of diagenesis of Kimwarer sediments.

The Kimwarer sandstones were deposited by fluvial channels in a depression at the southern end of the Elgeyo Escarpment. The earliest sediments in the lower Kerio Valley consist of conglomerate and sandstone facies, and are overlain by later lacustrine fissile shales and siltstones.

Unstable minerals, including some feldspars and micas, underwent early diagenesis to produce clays, mainly montmorillonite and illite, which cemented the conglomerates and sandstones. The fabrics of the sediments were not significantly altered by this early cementation; some samples still have an estimated primary porosity of about 30%, although in most it is less. The quartz cements may have formed during burial, given their euhedral morphology and petrographic evidence that shows that they postdate the early clay cements. The source of the silica is unknown, but the formation lies close to a major fluorite deposit which is believed to have formed from hydrothermal fluids that were mobilised through tensional fractures and subsidiary faults (Nyambok & Gaciri, 1975). In the subsurface, the fluids were at high temperature and under this regime, silica solubility is high. Fluids passing through tensional fractures formed by faulting may have precipitated quartz cement in the sandstones when the temperature dropped and led to supersaturation of silica.

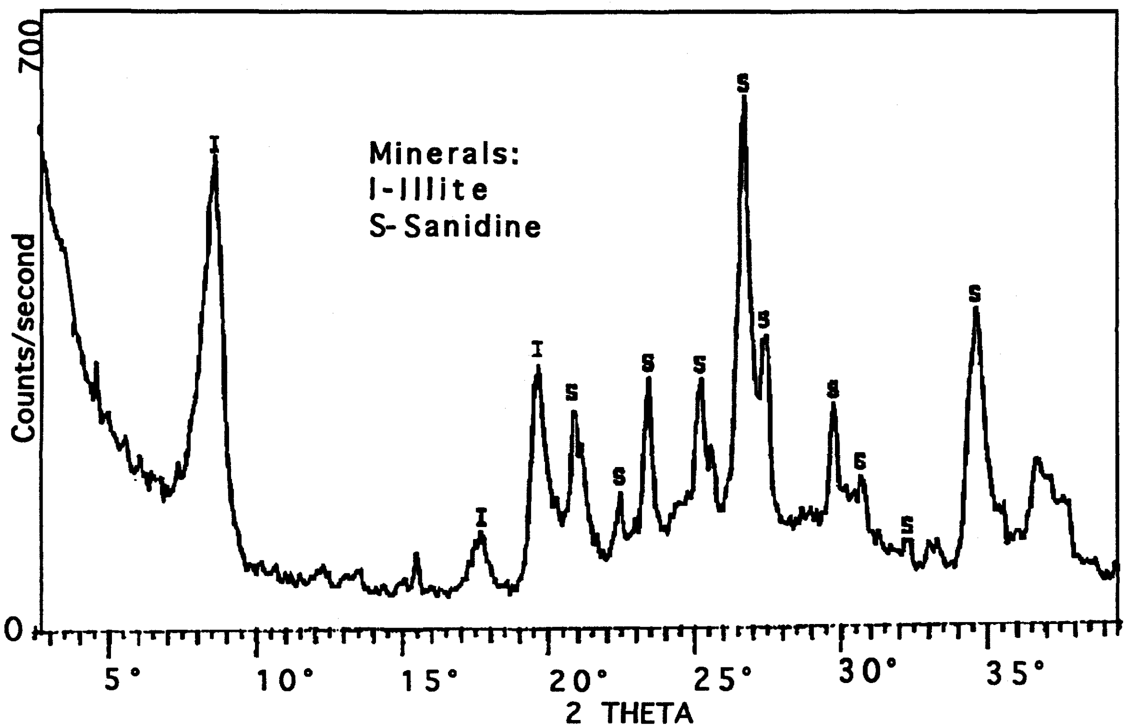


Fig.4.2 X-ray diffraction chart of Kimwarer silts. Air dried and scanned at 40kV, 80mA and 3°/min.

4.3 Petrography of Member C sediments Ngorora Formation

4.3.1 Kapkiamo sub-basin

The sediments of the Kapkiamo sub-basin of the Ngorora Formation were shed almost entirely from volcanic rocks, mainly phonolites, trachytes and basalts. The facies in this basin include thin lenticular sandstones, siltstones, mudstones and shales. The rocks are mainly composed of lithic grains, detrital clays and altered volcanic ash and are cemented by some clays, calcite, zeolites and iron oxide. The sandstones and siltstones are composed of fine grained angular to subangular detrital feldspars and quartz, with lithic fragments. XRD and SEM analysis of the mudstones and shales of the Kapkiamo sub-basin show an authigenic mineral suite that includes clays, calcite, zeolites and iron oxide.

The authigenic clay minerals are mainly smectite and illite; the smectite occurs as a relatively late cement in some samples, and partly coats earlier calcite cements and lines pores in the mudstones (Plate 12). It has a slightly crenulated morphology, with small pore-bridging ribbons, averaging 4-5 μm long. Authigenic illite occurs as thin interwoven filamentous ribbons, that in places coat authigenic clinoptilolite. The calcite cements are found in the mudstones near the top of the sequence in the basin. SEM examination of the samples reveal that the calcite crystals are blocky (about 10 μm across), pore-lining and pore-filling cements in the mudstones and show rhombic morphology (Plate 12). Authigenic quartz crystals in the Kapkiamo sediments are fine grained (commonly 1-2 μm) and are associated with analcime. With SEM examination they lack good crystal morphology, but as discussed below they are most likely authigenic. Even if the quartz was detrital, with the high pH demonstrated by the presence of chert and zeolites in the sediments, the silica would probably have dissolved and later recrystallized as another authigenic mineral, such as opal or quartz. In the Kapkiamo basin, the zeolites, analcime and clinoptilolite, were found in the mudstones and shales. Analcime is ubiquitous in the sediments near the former centre of the basin. In most of the mudstones, analcime is not visible in thin section, but X-ray diffractograms of the samples confirmed analcime, mainly associated with quartz (Fig. 4.3), both of which are probably authigenic. Some analcime occurs with authigenic smectites and clinoptilolite. By studying gold and carbon coated samples in SEM with EDS, microscopic clay-coated analcime was detected, both with and without euhedral crystal morphology (Plate 13). The well-developed crystals average 20 μm across. The most likely reason for crystals without euhedral form is due to masking by detrital clays. Clinoptilolite is found in the sediments associated with the former margins of the basin. Most crystals are euhedral with well-developed tabular or 'coffin shaped' morphology (50-100 μm in length). They partly fill pores in the mudstones and in some cases are coated with later wispy authigenic illite; etched parts of the zeolites are also filled by clay minerals (Plate 14).

From X-ray diffraction analysis the common K-feldspar in the mudstones and shales of the Kapkiamo sediments is sanidine, which is commonly associated with quartz. From SEM and EDS analysis, it appears that some of the K-feldspars are authigenic and formed later than iron oxide cements. The authigenic K-feldspars are well developed and planar in morphology (10-20 μm across) and have grown into

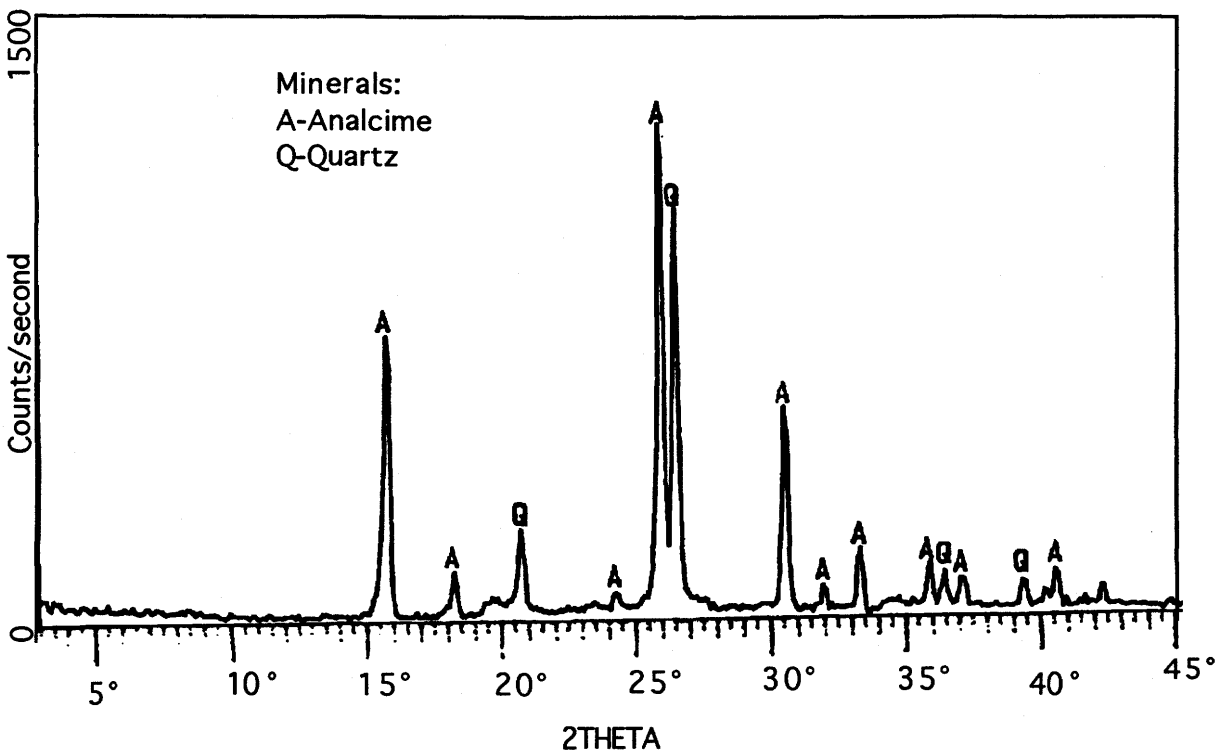


Fig.4.3 X-ray diffraction of lacustrine sediments at Kapkiamo sub-basin of Ngorora Formation, showing typical analcime-quartz association, sample air dried and scanned at 40kV, 80mA and 3°/min.

pores between older iron oxide (Plate 15).

4.3.2 Petrography of Poi sub-basin Sediments.

The sediments in the Poi sub-basin are composed of shales, mudstones, siltstones, tuffaceous sandstones and conglomerates. Petrographic examination of the siltstones, sandstones and conglomerates supports the field observation that the rocks are generally derived from volcanic sources. In thin section, the siltstones are composed of evenly disseminated brown silt grains, a few fine-grained angular detrital feldspars and quartz grains, and some volcanic shards. Scanning electron microscopy (SEM) with EDS analysis of the siltstones in the Poi sub-basin show well-developed, euhedral, authigenic K-feldspar crystals (50-100 μm across) which have filled pores in the sediments (Plate 16). In places the authigenic K-feldspar occurs as small (10-25 μm long) elongate pore-lining crystals. Some of the authigenic K-feldspars occur as blocky euhedral crystals on the dissolved surfaces of detrital plagioclase feldspars that have been etched preferentially along crystallographic axes (Plate 17).

The sandstones in the Poi sub-basin are fairly well sorted, fine grained, lithic arenites, with angular to subangular detrital feldspars and quartz grains that are cemented by calcite, smectites and iron oxide. The calcite cement is poikilotopic and occurs as patches between detrital feldspars and quartz. It is seen to be an earlier cement than the clays and iron oxide. and, in some samples, replaces volcanic shards (Plate 18). The conglomerate facies are generally composed of medium to coarse grained monocrystalline detrital quartz and feldspars, which are subrounded to angular, and are cemented by smectites, iron oxide and analcime. Authigenic smectites cementing the conglomerates show flaky to crenulated morphology and generally fill pores. In places, the clays are coated by later iron oxide cements. Authigenic analcime is a common cement in the conglomerates. It occurs as well-developed cubo-octahedral crystals with euhedral morphology. The crystals are microscopic, ranging in size from approximately 50-100 μm across. They occur as pore-filling and pore-lining cements in the conglomerates and some predate authigenic smectites (Plates 19).

Bulk X-ray diffraction analyses of the mudstones and shales of the Poi sub-basin show that the minerals are principally analcime, quartz, sanidine and smectite, which are similar in composition to those of the Kapkiamo sub-basin, except that clinoptilolite was not found in the Poi sub-basin.

4.4 Environments and diagenesis of Member C deposits Ngorora Formation

The diagenetic mineral suite found in Member C of the Ngorora Formation in both the Kapkiamo and Poi sub-basins, suggests that the lakes were at times strongly saline and alkaline. A schematic reconstruction of the distribution of authigenic minerals in the lacustrine deposits in the Kapkiamo sub-basin shows a lateral zonation, with clinoptilolite, calcite and montmorillonite at the margins of the basin, followed by analcime and K-feldspar at the centre of the basin (Fig.4.4). A similar zonation of authigenic minerals has been described in the Eocene Green River Formation of Wyoming (Hay, 1966; Surdam & Parker, 1972) and in the Miocene Barstow Formation in California (Sheppard & Gude, 1969). This systematic pattern of mineral zonation is characteristic of authigenic zeolite minerals in saline, alkaline lakes where interstitial pore waters react with solid materials (Surdam & Sheppard, 1978). The mineral distribution reflects the progressive increase in salinity and alkalinity of the pore and surface water toward the basin centre. The paleolakes of Member C of the Ngorora Formation probably fluctuated from fresh, when they supported a thriving plankton and fish population, to highly saline and alkaline with formation of authigenic analcimes and K-feldspars during regression. These fluctuations could have been caused by tectonics or climatic changes.

Thin chert veins near the top of the sequence in the Kapkiamo sub-basin confirm the high salinity and alkalinity of the paleolake. The chert occurs as thin horizontal veins (2-5 cm thick) that are white to cream in colour, and consist of finely crystalline quartz. The origin of the cherts is uncertain, but they lack the nodular morphology, reticulation and laminae that are characteristic of Magadi-type cherts, which form from sodium silicate minerals such as magadiite and kenyaite (Eugster,1967, 1969; Hay, 1968). The solubility of silica increases with increase in pH (i.e., pH > 9). It is possible that some silica produced by dissolution of volcanic glass and other minerals during the highly alkaline phases of the lake recrystallised to form the cherts when the pH was abruptly lowered.

Another possible mechanism for chert formation is through a gelatinous precursor (e.g. Eugster & Jones, 1968; Eugster, 1980; Renaut & Owen, 1988). The fine grained and vein-like structure of the cherts might favour this mechanism. It is possible that seepages of alkaline hot water along fault lines reacted with volcanic

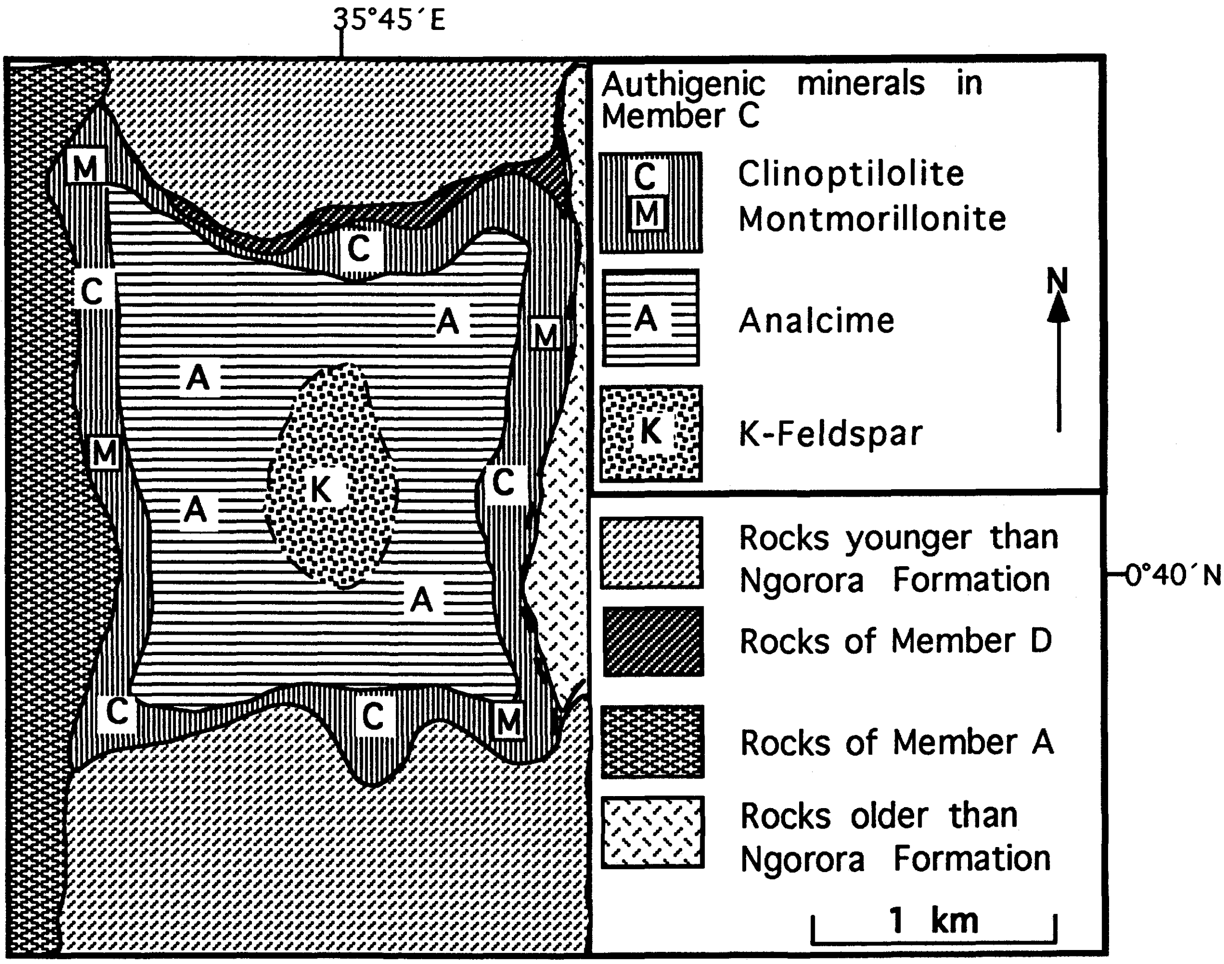


Fig.4.4 A schematic reconstruction of the diagenetic mineral zonation at Kapkiamo sub-basin (Member C) using distribution of authigenic minerals in the mapped section of the basin. The distribution of the minerals is a function of salinity in the basin. At the less saline margins of the basin clinoptilolite and montmorillonite is present, while at the hypersaline centr of the basin authigenic K-feldspars are found.

detritus to form a siliceous gel that was the precursor of the cherts, but direct evidence for former hot springs, though likely present, is lacking.

Poikilotopic calcite cements sandstones of the Poi sub-basin, and in places calcite replaces volcanic glass. Petrographic observations of the calcite cements indicate that they are early and probably formed from shallow circulating groundwater. In the Kapkiamo sub-basin, calcite fills pores in mudstones near the margins of the basin and is associated with smectites and quartz. Its occurrence mainly in the peripheral sediments suggests that it could originate from shallow dilute groundwaters flowing in from the basin margins, or possibly by mixing of fresh runoff with more saline, alkaline lake water.

Zeolites

Zeolites are both common and widespread in saline, alkaline lakes (Hay, 1966, 1978; Surdam, 1977; Hay, 1978; Gall & Hyde, 1989). Several materials can react with interstitial brines to form zeolites, but the most common are volcanic glass, biogenic silica, poorly crystalline clays, montmorillonite, plagioclase, and quartz. The formation of late Quaternary zeolites has been reported from modern Lake Magadi (Eugster & Jones, 1968, Surdam & Eugster, 1976) and Lake Bogoria (Renaut *et al.*, 1986; Tiercelin *et al.*, 1987; Renaut, 1993). The Miocene Ngorora Formation could, in part, be an ancient process analogue of these basins. The Ngorora basins were hydrologically closed by the fault blocks of the Tugen Hills, while the climate was similar to the present, varying from arid to semi-arid (Pickford, 1978a), thus making it an ideal environment for the formation of saline, alkaline lakes. In the lacustrine

Member C, two types of authigenic zeolites were found; analcime and clinoptilolite in the Kapkiamo sub-basin, and only analcime in the Poi sub-basin. The formation of the authigenic zeolites in the Ngorora basins is related to the interaction of the interstitial pore fluids with one or more of the above mentioned solid materials; however, some are more viable candidates than others. The abundance of the volcanogenic material in the catchment area and the presence of clinoptilolite, which is commonly considered a precursor zeolite of analcime (Surdam & Parker, 1972), makes volcanic glass a plausible precursor. Clay minerals, both authigenic and detrital, are found in the sediments, mainly smectite and some illite; some of the authigenic clays clearly postdate the zeolites and are thus unlikely to be the precursors of the zeolites. From the SEM analysis of the Kapkiamo and Poi sediments, no biogenic silica (e.g. diatoms) was detected and there is no evidence to show that it has been dissolved to form the zeolites. However, the opal-A of diatom frustules is highly soluble in alkaline fluids, so complete dissolution cannot be ruled out. Diatoms were probably present in the lake, given the silica-rich waters and presence of fish-bearing horizons. The other possible precursors are feldspars; both potassium feldspar and albite are stable at and near earth surface temperatures and at high pH, and do not easily undergo dissolution. Plagioclase, however, was found to be etched, but is mainly associated with clays and authigenic K-feldspars and not the zeolites.

Clinoptilolite is the zeolite found in the mudstones interpreted to be associated with the former margins of the Kapkiamo sub-basin. It could have formed from direct reaction of alkaline pore fluids with volcanic glass (cf. Surdam & Parker, 1972). The formation of the associated authigenic illite may be a result of clinoptilolite changing into analcime, releasing K^+ cations which then reacted with smectite to form illite (see below). Variations in pH, salinity and the cation content of the water are responsible for the zonation of zeolites in closed basins. The siliceous and more hydrous zeolites like clinoptilolite form near the edge of the basin where fluids are less saline, whereas analcime develops as salinity increases, with authigenic K-feldspar forming in the centre of the basin.

Analcime is a common diagenetic mineral in saline, alkaline lake deposits (Hay, 1966; Surdam & Eugster, 1976; Surdam & Parker, 1972). In Member C of the Ngorora Formation, analcime is ubiquitous in the sediments at Kapkiamo and Poi sub-basins. There are five possible explanations for the origin of analcime in the Member C of the Ngorora Formation:

1) direct precipitation from lake water;

2) formation from a gel precursor;

3) formation from clay minerals;

4) formation from plagioclase; and

5) formation from a zeolite precursor.

Although direct precipitation of analcime has been achieved experimentally (Cournayer *et al.*, 1975), there are few documented cases in lacustrine basins. The presence of other zeolites, commonly considered precursors for analcime, suggest that formation from direct precipitation is unlikely. The formation of analcime from a gel precursor has been documented near hydrothermal springs at Lake Magadi in Kenya by Eugster and Jones (1968) and at sites of hydrothermal alteration at southern Lake Bogoria (Renaut & Owen, 1988). At Magadi, these gels subsequently transform into analcime and chert. Although localised cherts are found in the Kapkiamo sub-basin, the wide distribution of the analcime in the sub-basins does not support a localised source. Clay minerals have been considered as possible precursors of analcime (Hay, 1970; Sheppard & Gude, 1973; Renaut, 1993). The reason for inferring formation of analcime at the expense of the clays has been the absence of certain clays associated with analcime. The clay minerals associated with analcime in the sediments are smectites and illite. Some of the authigenic clays are earlier than analcime and there is no evidence to suggest that they have reacted to produce analcime and the high Si/Al ratio in the analcimes (Tables 4.2a, 4.2b, 4.3a & 4.3b) do not support formation of analcime directly from clay precursors (e.g. Coombs & Whetten, 1967). Plagioclase is a possible candidate for the formation of analcime (Hay, 1966; Surdam & Sheppard, 1978). Little plagioclase was detected by the X-ray diffraction analysis of the samples from the Kapkiamo basin. Plagioclase probably underwent dissolution to produce authigenic clays. From SEM observations, the etched plagioclase grains are associated with clays and authigenic K-feldspars rather than analcime. Since analcime is not usually an early formed zeolite, it is unlikely that it is an alteration product from plagioclase.

Formation of analcime from precursor zeolites is well documented; typical examples are those of the Eocene Green River Formation in Wyoming (Hay, 1966; Surdam & Parker, 1972) and the Miocene Barstow Formation in California (Sheppard

& Gude, 1969). In these formations, tuffs are abundant and volcanic glass has reacted with saline, alkaline lake waters of increasing concentration to produce a systematic lateral zonation of authigenic minerals. In the Kapkiamo sub-basin of the Miocene Ngorora Formation, the detrital sediments are rich in tuffaceous material and a zonation of authigenic minerals is observed. Analcime was found in the sediments assumed to be near the centre of the basin, which was probably the more saline part of the lake. Analcime does not normally form directly from the reaction of volcanic glass and saline fluids, but from intermediate more siliceous and hydrous zeolite precursors (Surdam & Sheppard, 1978). In the Kapkiamo sub-basin the most likely precursor is clinoptilolite, which is found in the sediments at the margins of the basins and, in places, shows etching. The Si/Al ratio of the analcimes as determined by XRD using the d-value of 639 analcime peak and electron microprobe analysis support formation of analcime in the Member C of the Ngorora Formation from a zeolite precursor, that originally derived from alteration of volcanic glass.

Composition of the analcimes

To help to determine the origin of analcime in the Kapkiamo and Poi sub-basins, the Si/Al ratios of analcime from the sub-basins were analysed by XRD using the d-value of 639 analcime peak and electron microprobe analysis. Ten samples from the Kapkiamo sub-basin (Table 4.2a) containing analcime and quartz were analyzed by XRD using a Cu-K alpha radiation set at 40kv and 80mA, and scanned at 0.5 degree per minute. Ideal analcime has a structural formula of $Na_{16}Al_{16}Si_{32}O_{96}.16H_2O$ with a

Si/Al ratio of 2.0 (Coombs & Whetten, 1967, Remy & Ferrell, 1989). The value of the Si/Al ratio can be used to determine the origin of analcime. The mean Si/Al ratio of analcime was determined by using the technique of Saha (1959, 1961) and the calibration curve of Remy and Ferrell (1989), which is modified from Coombs and Whetten (1967). In this study, the quartz 203 peak (68.130, 2Ø) was used as an internal standard. The modified correlation curve of Remy and Ferrell (1989) was then used to determine the Si/Al ratio by converting the position of the analcime 639 peak.

The composition of analcime provides information on the conditions in which it formed (Saha, 1961, Coombs & Whetten 1967). The Si/Al ratio, as determined by the average position of the analcime 639 XRD peak (78.48, 2Ø), is 2.81. Shale and mudstone samples containing analcime from the Poi sub-basin were analysed, and a Si/Al ratio of 2.69 was obtained by XRD analysis (Table 4.2b) and 2.38 by using electron microprobe (Tables 4.3a & 4.3b). Differences in the compositions according to methods used have been found by several other authors (e.g. Remy & Ferrel, 1989; Renaut, 1993). The Ngorora analcimes fall under the group A of silica-rich analcimes (Coombs & Whetten, 1967) that form from a precursor zeolite after volcanic glass that has reacted with saline alkaline water.

Table 4.2a Determination of the Si/Al ratio in analcime from the Kapkiamo sub-basin, Ngorora Formation by XRD analysis.

Sample.	**2Ø Quartz 203 peak.**	**2Ø Analcime 639 peak.**	**Analcime corrected.**
Kapk 23	68.100	78.500	78.530
Kapk 24	68.200	78.500	78.430
Kapk 27	68.200	78.500	78.430
Kapk 28	68.100	78.500	78.530
Kapk 29	68.100	78.400	78.430
Kapk 30	68.100	78.500	78.530
Kapk 31	68.100	78.500	78.530
Kapk 32	68.200	78.500	78.430
Kapk 33	68.100	78.500	78.530
Kapk 36	68.200	78.500	78.430

In these analyses the standard 2Ø quartz 203 peak used is 68.13 and the scanning was done at 0.5°/min. The mean value of the 2Ø analcime 639 peak is 78.48. From correlation curves of Coombs and Whetten (1967) and Remy and Ferrell (1989), analcimes from Kapkiamo belong to group A, which is rich in silica (Si/Al 2.81) and are derived from the reaction of siliceous volcanic glass with saline, alkaline water.

Table 4.2b Results of determination of Si/Al ratio in analcimes from Poi sub-basin, Ngorora Formation analysed by XRD using the 639 peak analcime.

Sample	Quartz 203 peak 2Ø	Analcime 639 peak 2Ø.
Poi-1	68.10	78.43
Poi-8	68.10	78.33
Poi-12	68.20	78.43
Poi-13	68.10	78.43

In these analyses the method used in table 4.2a was applied and scanning was done at 0.5°/min using the position of the quartz 203 peak (68.13°, 2Ø) as an internal standard. From these results the mean Si/Al ratio was 2.69.

Table. 4.3a Compositions of analcimes from Member C of the Ngorora Formation in the Poi sub-basin, as determined by electron microprobe.

Sample Poi-11					
Analysis no.	1	2	3	4	5
Oxide weight%					
SiO_2	58.66	60.36	58.05	59.34	58.56
Al_2O_3	21.15	20.85	21.35	21.03	20.97
Na_2O	9.00	9.34	12.02	10.91	11.37
Fe_2O_3	0.12	0.22	0.12	0.16	0.08
K_2O	0.00	0.00	0.00	0.00	0.00
CaO	0.00	0.00	0.00	0.00	0.00
MgO	0.01	0.00	0.00	0.00	0.02
Total	88.94	90.77	91.54	91.44	91.00

Table 4.3b Compositions of analcimes at Poi sub-basin analysed by electron microprobe.

Sample Poi-11					
Analysis no.	1	2	3	4	5
Atoms per 96 oxygens					
Si	34.43	34.74	33.65	34.20	34.01
Al	14.63	14.14	14.59	14.29	14.35
Na	10.25	10.42	13.52	12.19	12.81
Si/Al	2.35	2.46	2.31	2.39	2.37

CHAPTER 5

DIAGENETIC PROCESSES OF RIFT SEDIMENTS

Diagenetic pathways of rift sediments can be elucidated by considering the prevalent factors that control their diagenesis. The most important aspects are the physical and chemical properties of groundwater, sediment composition and texture, and temperature. Almost all chemical reactions take place in the fluid phase and thus groundwaters play a primary role. In the Kenya Rift, many of the sediments are derived from weathering of volcanic rocks (lavas) and volcaniclastic materials (tephra), mainly of basaltic, phonolitic, and trachytic composition. These rocks contain highly reactive materials, including volcanic glass, plagioclase, and mafic minerals that are highly susceptible to diagenetic alteration when in contact with waters of different compositions. Analyses of the composition of dilute surface waters in the Kenya Rift show that they are rich in Ca^{2+}, Na^{+} and HCO_3^- ions (Table 5.1), while the groundwaters and hydrothermal fluids contain mainly Na^{+}, HCO_3^- and Cl^- and SiO_2 (Kilham, 1971; Jones *et al.*, 1977; Renaut *et al.*, 1987; Cioni *et al.*, 1992; Renaut, 1993). These analyses show that most near-surface waters in the rift basins are alkaline, reflecting the sodic nature of the volcanic rocks through which the groundwaters percolate. Neutral and acidic groundwaters occur locally on basement rocks, and at some hydrothermal sites with high CO_2 concentration. Reactions between the alkaline fluids and sediments give rise to many authigenic minerals (Surdam & Eugster, 1976; Hay, 1970). Volcaniclastic sands derived from these terrains, composed mainly of K-feldspars, are unlikely to dissolve to produce secondary porosity, as these

Table 5.1 Selected chemical analyses of Lake Bogoria basin waters (From Renaut, 1993).

Sample†	Date	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	CO_3^{2-}	Cl^-	SO_4^{2-}	F^-	SiO_2
Rivers, rain												
RF1	Aug 1977	6.2	2.34	0.33	2.68	0.21	5.99	0	4.12	0	nd	0
SR1	Aug 1977	6.9	58	3	20	3	175	0	43	5	0.9	31
BW1	Oct 1991	7.2	80	4.5	27	6.5	240	0	42	4.7	2.3	60
BW3	Oct 1991	7.1	125	7	13	3	305	0	48	2.3	7.2	65
Lake water												
K1	Jan 1970	10.6	24400	387	0	2.2	5675	26165	6390	216	1064	260
BW6	Oct 1991	9.9	23000	450	8	1	4800	22500	5400	290	60	170
BW2	Oct 1991	9.9	24600	435	12	<1	5500	24500	5680	330	110	225
Groundwater												
BWG	Oct 1991	9.3	10560	15	0	1	3500	9600	3260	103	23	95
GD1	Aug 1976	8.3	430	14	6.5	1.2	925	tr	156	16	3.1	62
GW1	Jul 1977	9.7	4130	90	6	tr	*142		1290	105	16	18

All analyses expressed in mgl^{-1}, except alkalinity (HCO_3 + CO_3) for GW1(*), expressed in $meql^{-1}$. Field pH given except for RF1, which is laboratory pH. nd: not determined. tr: trace.

† SR1 and BW1: Sandai river at Sandai Plain; BW3: Loboi swamp (partly fed by warm springs); RF1: rainwater, sampled on Sandai Plain; K1: Lake Bogoria (from Kilham, 1971); BW6: Lake Bogoria, north basin, surface water; BW2: Lake Bogoria, central basin, surface water; BWG: groundwater from pit, GD1: shallow groundwater, GW1: Lake Marginal groundwater.

minerals are relatively stable in alkaline conditions. The potential for early maturation of hydrocarbons in the rift sediments is enhanced by the high regional geothermal gradient, that ranges from 64.7 to 66.2°C/km, in places (Nyblade *et al.*, 1990). Under these high geothermal gradients, sediments buried only to about 2 km can be expected to have matured organically and lie within the oil window.

5.1 Early diagenesis of rift sediments

Early diagenesis of the Kenya Rift sediments is controlled predominantly by chemical processes that involve shallow groundwaters that are responsible either for dissolution or precipitation of mineral phases in the sediments. Seasonal climatic variations change the level of the water table, the salinity, and the level of the groundwater-sediment interactions. During the dry season, the water table drops and, where shallow (< 1 m), the salinity of the groundwater commonly increases by evaporative concentration. Pore-waters that percolate through sediments derived from sodic volcanic rocks become highly alkaline. During early diagenesis mechanical compaction is of minor importance compared to chemical processes.

The few previous studies of diagenesis of the rift sediments in East Africa show that several authigenic minerals form during early diagenesis. In the Plio-Pleistocene Kubi Algi and Koobi Fora sediments of north-east Lake Turkana, Cerling (1979) found contrasting assemblages of authigenic minerals that define diagenetic zones within the sediments. A gypsum-hematite-cristobalite zone was interpreted to represent reduced sediments that were oxidised *in situ*, whereas an authigenic mineral suite of calcite-dolomite-zeolite-halite represents highly saline, alkaline environments. In the older siliciclastic sediments of the Karoo rift basins of Tanzania, early diagenetic minerals are mainly calcite, dolomite and hematite (Dypvick & Nesteby, 1992). The carbonate cements in these sediments formed in flood-plain environments, some originally as calcretes, which probably dissolved and later reprecipitated as late diagenetic cements.

Calcite

Field, petrographic and chemical data from the Central Rift basins of Kenya reveal that early diagenesis of sediments has occurred in a near surface, open leaching system, through the action of percolating dilute groundwaters. The earliest cements precipitated in the sandstone facies are mainly sparry calcite. Early calcite cements are common in the Quaternary sediments of the East African Rift, and are precipitated by evaporation, evapotranspiration, and possibly carbon dioxide degassing (Hay & Reeder, 1978; Renaut, 1993). Although the latter modes of calcite precipitation are plausible, some calcite cements in the Miocene siliciclastics of the central Kenya Rift are also likely precipitated by groundwater rich in Ca^{2+}, locally supplied by the dissolution of plagioclase feldspars and other calcium-bearing minerals in the phreatic zones. The ease of precipitating calcite cement in the sandstones increases with burial depth and at high pH, as calcite solubility decreases with increasing temperature. The paucity of dolomite cements in the sediments studied could be attributed to the low Mg/Ca ratio in most groundwaters in the Rift (cf. Renaut, 1993). In the Miocene

Tambach sandstones, calcite cements have undergone dissolution and are being replaced by iron oxide or clay mineral. This phenomenon is probably brought about by the increase in carbon dioxide in the pore fluids.

Clays

Clay minerals are common authigenic minerals in the Kenya Rift sediments. From SEM examinations, the clays occur principally as pore-lining and pore-filling cements. The most common authigenic clay minerals in the Kenya rift sediments are smectites and illite. These clays are probably produced by dissolution of detrital minerals, especially plagioclase by groundwaters, and are precipitated in the sediment pores. The formation of smectites is favoured in shallow sediments, where fluids are generally poor in K^+, but at greater depths where there is an increase in temperature, illite forms usually through a series of mixed-layer illite/smectites clays (Hower *et al.*, 1976). In the Tambach Formation, the sandstone and conglomerate facies are cemented by authigenic smectites. The sequential development of these cements has resulted in a reduction of primary porosity and permeability.

Zeolites

Authigenic zeolites have been reported in several basins of the Kenya Rift (Surdam & Eugster, 1976; Cerling, 1979; Renaut, 1993). These zeolites normally form by reaction of interstitial pore-waters with silicate detritus. In the volcanogenic sediments of the Ngorora Formation, the zeolites were found to form by reaction of volcanic glass with saline, alkaline waters (Chapter 4). In these basins clinoptilolite is considered a precursor of analcime; the formation of these zeolites is determined by the salinity and composition of the fluids, with analcime forming in the more saline part of the sub-basins. In the Member C sediments of the Ngorora Formation, some of the zeolites predate authigenic clays and are associated with sub-microscopic quartz. The zeolites occur as pore-lining and pore-filling cements.

In the Miocene Tambach sediments, the lacustrine claystones and shales contain euhedral analcimes with a low Si/Al ratio that probably formed by reaction of saline, alkaline fluids with detrital clay minerals.

Quartz

Authigenic silica is a common cement in the sandstones of the Kimwarer Formation, occurring as microscopic euhedral crystals, and in some places as replacement of earlier authigenic clays. In the latter example, the silica is probably derived from hydrothermal fluids, that were mobilised upward through faults with slow crystallization in the pores of the sandstones, allowing for growth of large silica crystals.

In the Ngorora basins, sub-microscopic quartz is found associated with zeolites, although in most of the crystals euhedral morphologies are poorly developed. The quartz is almost certainly authigenic, as the zeolites must have formed under highly alkaline conditions ($pH > 9$). Under high pH, detrital quartz would dissolve. The fine crystalline quartz could be attributed to rapid crystallization of SiO_2, probably due to abrupt lowering in pH. The silica is likely derived from reaction of detrital silicates and saline, alkaline fluids.

K-feldspar.

Authigenic K-feldspar is found in the sediments of the Ngorora Formation lining pores, where it postdates zeolites and iron oxide cements. In the Kapkiamo sub-basin, authigenic K-feldspar is found in the more saline centre of the basin, and has a well formed euhedral morphology, with an average crystal size of 20-30 μm. In the Poi sub-basin, some of the authigenic K-feldspars are prismatic and developed in open pores in the sediments. Due to the ubiquitous presence of volcaniclastic detritus in the Ngorora Formation, the authigenic K-feldspar probably formed from original volcanic glass through intermediate zeolite precursors. At high pH and salinities, analcime can change to K-feldspar (Surdam & Parker, 1972). The following chemical reaction is proposed for the mineral authigenesis in the lacustrine sediments of the Ngorora Formation:

Volcanic glass→ Clinoptilolite→ Analcime→ K-feldspar.

Iron oxide

Iron oxide is a common diagenetic cement in the sediments of the studied basins. In the sandstones, iron oxide occurs as a matrix-staining component and has grown in pores in feldspar produced by dissolution. The iron oxide probably formed when the Fe^{2+} in the meteoric water passing through grain pores was oxidised to Fe^{3+}. The iron oxide cements mainly postdate calcite, authigenic clays and K-feldspars.

The precipitation of authigenic minerals in the central Kenya Rift sediments is a reflection of the diagenetic conditions in the various basins. High salinities and alkalinities of the fluids in the closed lacustrine basins led to precipitation of calcite, zeolites, authigenic K-feldspars and some clays. Iron oxide cements reflect oxidizing conditions in the region that resulted from precipitation of iron mobilized under reducing conditions. A summary of sequential cement development in the sediments of some of the Miocene formations in the central Kenya Rift are shown in Table 5.2.

Table 5.2 Summary of sequential cement development in the Miocene sediments of some formations in the central Kenya Rift.

Formations	Cement development from early to late in the sediments.				
Tambach	Calcite	Clays	Iron oxide		
Kimwarer	Clays	Quartz	Iron oxide		
Ngorora	Calcite	Zeolites	Clays	Iron oxide	K-feldspars

5.3 Burial diagenesis of rift sediments

Burial diagenesis of the modern Kenya Rift sediments remains poorly understood due to lack of deep drilling. However, from studies of the exposed, Miocene sediments in the central Kenya Rift, speculations on the types of the processes can be made. In the subsurface, both chemical and physical processes take place. Less stable mineral phases are dissolved, including some feldspars and volcanic glass, probably leading to some secondary porosity, but with a lower permeability due to precipitation of clays which bridge pores in the sediment grains.

The high geothermal gradients and common alkaline groundwaters in the Kenya Rift, could lead to silica mobilization in the subsurface and generate secondary porosity, and probably some authigenic silica cements where the pH is lowered, as inferred for the Kimwarer sediments. The effect of compaction on sediments buried to several kilometres would probably result in quartz and K-feldspar overgrowths due to pressure solution at the grain contacts. At great depths, authigenic smectites may undergo dehydration and form illite cements, if there is K^+ in the system, which is common in the rift. Illitization will result in the release of silica and the system could be enriched in quartz, which may reduce porosity of the sediments.

Predictions of subsurface diagenetic processes, depend mainly on the type of the depositional basin, provenance and depth of sediment burial. Sandstones derived from volcaniclastic sediments have a large amount of lithic fragments, and are likely to suffer greater compactive porosity loss in the subsurface than quartz or arkosic arenites due to the more ductile lithic fragments in the lithic arenites.

Recent studies of the Karoo (Late Carboniferous/Permian) rift sediments in Tanzania show that dissolution and precipitation of cements have occurred in the sediments with burial. Precipitation of authigenic quartz and K-feldspar overgrowths have not reduced the porosity substantially due to high secondary porosities as a result of late dissolution of feldspar and rock fragments. However, the cementation has reduced permeabilities to less than 6 mD (Dypvik & Nesteby, 1992). Burial diagenesis of the Campanian-Maastrichtian sandstones in the Anza Graben basins of the northern Kenya has been studied using well cuttings, log data and palynological analyses from several exploration wells in the late 1980's. The sandstones in the Anza basins are cemented by the zeolite, laumontite, that was found to fill pores and replace detrital feldspars (Winn *et al.*, 1993). Laumontite cements were not found in the Tertiary sediments of the Anza Graben, which suggests that cementation of the sandstones by the laumontite occurred during the Late Cretaceous. These results could be used as a predictive model for the burial diagenesis of the Neogene sediments of the Kenya Rift.

CHAPTER 6: IMPLICATION FOR PETROLEUM EXPLORATION.

6.1 Reservoir Potential in Kenya Rift.

Economic petroleum accumulations have been found in rift basins in formations of many geological ages, for example, in the North Sea (Glennie, 1987), the Campos Basin in Brazil (Abrahào & Warme, 1990) and in southern Sudan (Schull, 1988). In the East African Rift System, the potential for source rocks is high in many lacustrine basins (Johnson & Ng'ang'a, 1990). Most studies of the hydrocarbon potential have been made in the western branch of the East Africa rift system, especially Lake Tanganyika, where up to 12% TOC has been found in modern sediments, and oil seeps occasionally occur at the lake surface (Tiercelin *et al.*, 1992). This richness in organic matter is attributed to the meromictic regime of the lake and the anoxic conditions which prevail below 100-200 m water depth.

In the eastern branch of the East Africa system both modern and ancient stratified lakes occur, but are much smaller, and of widely different salinity. These include Lake Bogoria, which is a meromictic closed lake with saline, alkaline water, and has sediments with up to 6% TOC (Tiercelin *et al.*, 1980, 1982). The sedimentological and mineralogical analysis of the sediments from the Ngorora and Tambach paleolakes suggest that these lacustrine basins were also saline and alkaline, and although shallow, were probably meromictic during some stages. Sedimentation in the deeper parts of these basins was mainly by algal (sapropelic) organic material and fine silt and clay particles. Unlike Bogoria, definitive evidence for former evaporites (e.g., pseudomorphs) is absent, but salts could have dissolved. In places where clastic input was minimal, these Neogene sediments may have formed potential source rocks. The maturation of these source rocks depends on their age, burial and geothermal gradients. Although these sediments are relatively young, the Kenya Rift System has a regionally high geothermal gradient of about 65°C/km of burial (Nyblade *et al.*, 1990). Such high geothermal gradients could cause maturation of the sediments despite their young age. For a reservoir to occur, the tectonic setting must also be favourable. In a lacustrine basin, large axial and lateral littoral platform fluvial sediments can present lithological characteristics that are highly favourable to the formation of adequate rock reservoirs (Cohen, 1989).

6.1.1 Hydrocarbon potential of the Tambach Formation

The sandstone bodies in the Tambach Formation are mainly fluvial deposits that were deposited by rivers flowing mainly from the west, although some probably were flowing from the eastern ramp margin of the half-graben. The effectiveness of these sand bodies as potential reservoirs depends on the provenance and the diagenesis of the sediments. As demonstrated here, most sandstones in the Tambach Formation are arkosic to lithic arenites with fairly significant clay matrix and authigenic clays; most were derived from quartzo-feldspathic, metamorphic basement rocks. Their potential as hydrocarbon reservoirs is partially diminished by the high clay content that has reduced porosity to an estimated 10% from primary values of about 30% (visually estimated from thin sections). Although many of these sands are poorly to fairly well sorted, some show evidence of deposition by strong currents, and are thus much cleaner. If these sands have characteristics of sandy braided streams (Chapter 3) and are laterally extensive, they could form good reservoirs, especially where capped by impermeable shales of floodplain or lacustrine origin. The effectiveness of these sands as hydrocarbon reservoirs depends on their composition. Where volcanic rocks constitute a major proportion of the source rocks, there will probably be an early loss of porosity due to the diagenetic alteration of feldspars and volcanic rock fragments to clay minerals and zeolites. In contrast, high to moderate energy sands, derived from rocks rich in quartz, like the metamorphic basement rocks, are generally cleaner with better petroleum reservoir potential.

The effects of compaction on the subsurface sediments of the Tambach Formation are unknown. Although no exploration wells have been drilled to date, it is expected that porosity will decrease with increasing overburden. However, the extensive dissolution of detrital feldspars observed in the sandstone samples of the Tambach sediments, has produced secondary porosity and increased the intergranular porosity of the sandstones. This has occurred despite the pore-filling and bridging by authigenic clays, which tend to reduce permeability and the effectiveness of the sandstones to act as hydrocarbon reservoirs. There is, therefore, still the chance of favourable reservoirs in the fluvial sands of the Tambach Formation that have not been affected extensively by diagenesis or in those sandstones in which detrital feldspars and calcite cements have undergone dissolution, producing secondary porosity.

The hydrocarbon potential of these rift basins also depends on the lateral extent and quality of the reservoir rocks. In the Tambach Formation the lateral extent of the sandy facies cannot be ascertained due to the difficult terrain and the fact that across the eastern side of the basin the sediments are covered by the thick alluvial sediments of the Kerio Valley. Nevertheless, the fact that most of the sediments are derived from basement rocks, and are rich in quartz, makes those Miocene sand bodies that predate extensive volcanic eruptions in the area the best potential hydrocarbon reservoirs. The source rocks for the generation of hydrocarbons could come from adjacent or downfaulted Miocene lacustrine shales, rich in sapropelic organic matter. Both stratigraphic and structural traps are probably present in the Kenya Rift. Impermeable shales could induce stratigraphic traps in fluvial and marginal lacustrine deposits, where they are laterally extensive, whereas faults control many types of structural trap.

6.1.2 Hydrocarbon potential of the Kimwarer Formation sediments

The Kimwarer Formation sediments, south of the Tambach Formation, are older than the Tambach sediments; they are fluvial and lacustrine sediments also derived mainly from basement rocks. The sandstones are coarse arkosic arenites and petrographic analyses rocks reveal that they are clean sandstones with few lithic fragments, and are fairly well sorted. They could make good potential reservoirs although their lateral extent in subsurface is unknown. However, where sampled, the rocks have undergone secondary silica cementation, possibly from hydrothermal fluids. While this has reduced their porosity, some primary porosity has remained as quartz cements have acted to "prop open" pores. Other limitations are due to the small lateral extent of the potential reservoir sand body, which is about 45 m thick, and an apparent paucity of source rocks in the basin. The shales and the siltstones in the Kimwarer Formation appear barren of organic matter in thin section and are essentially cream or yellow in colour with no obvious carbonaceous material. Mineralogically, these sediments are rich in quartz, K-feldspar, illite and montmorillonite, and show moderate sorting. The paucity of source rocks and the effect of secondary cementation of sandstones by silica, tends to diminish the hydrocarbon potential of Kimwarer sediments compared to those of the Tambach Formation.

6.1.3 Hydrocarbon potential of the Ngorora Formation

The Ngorora Formation in the Tugen Hills is composed of fluvial and lacustrine facies of Middle Miocene age (Deino *et al.*, 1990). The Member C deposits of the Kapkiamo and Poi sub-basins were formed in lakes that were closed, and highly saline and alkaline at certain stages. The Kapkiamo sub-basin is almost entirely lacustrine, and bounded by the Saimo Horst to the east and the Kaption volcano to the west. These topographic features sealed the basin from major siliciclastic input and the paleolake became saline, alkaline, and probably meromictic. This could have produced a thriving environment for planktonic micro-organisms, which could produce good source rocks in the deep water environment. However, a problem in this basin, as in other basins in the Ngorora Formation, is identifying good reservoir rocks. Siliciclastic input was minimal, limited to small littoral sand bodies. The detrital sediments are mainly of volcanogenic origin and diagenetic reactions are extensive. Volcanic glass, plagioclase and volcanic lithic fragments underwent dissolution and replacement, and formed several diagenetic phases, including clays and zeolites. These reactions produced cements which reduced the porosities of the coarser sandstones, making them less effective as a potential petroleum habitat.

The Poi sub-basin of the Ngorora Formation is mainly a lacustrine basin, with fissile shales, silts and tuffaceous sandstones and conglomerates. The sandstones and conglomerates are poorly sorted deposits of debris flows and lahars. This, coupled with high cementation by clays and zeolites, has reduced the potential of the fluviatile facies as hydrocarbon reservoirs. The resource potential of littoral facies in the Kenya Rift depends on the size and extent of the littoral sand bodies. Extensive sand bodies with coarse arkosic or quartzitic arenites are more likely to form good hydrocarbon reservoirs. While the Ngorora Formation can be considered a prospective source rock, it lacks good local potential reservoir rocks. Any hydrocarbon generated would have to migrate to other formations to be prospective. The intense faulting, particularly during the last 2 million years, would have provided many permeable conduits for escape of fluids. Thus conditions are probably unfavourable.

6.2 Exploration Strategies.

Knowledge of facies relationship and diagenetic processes of siliciclastic sediments in the Kenya Rift can be used to gain an insight of probable hydrocarbon reservoirs and source rocks. After the formation of the rift system within Kenya, several episodes of volcanic activity occurred, providing a substantial portion of the detritus in the developing basins. The basinal facies were controlled by tectonic structures of the rift. In the floor of the rift, lacustrine basins, with lakes ranging from fresh and brackish to saline formed. These lacustrine sediments are possible hydrocarbon source rocks. In high energy settings, coarse siliciclastic deposits of conglomerates and sandstones facies were deposited. Sediments shed from basement rocks and deposited in high energy areas, tend to be fairly clean arkosic or quartz arenites and, in places, where large lateral sand bodies are found juxtaposed to lacustrine organic-rich sediments, they are potential reservoir rocks. However, their ability to host hydrocarbons depends on the presence of structural or sedimentological traps, for example, extensive impermeable shale bodies or evaporites. Throughout most of the rift system, potential structural traps are common due to faulting. The diagenesis of basement-derived clastics reveals that, despite early cementation, they still have some porosity.

Volcaniclastic sediments are ubiquitous in the Kenya Rift and are shed from trachytes, basalts and phonolites. These sediments are characterised by highly reactive materials such as volcanic lithic fragments, glass and plagioclase. These minerals are diagenetically altered to clay minerals and zeolites, which greatly reduce their porosity and permeability. In contrast to basement-derived sediments, they are characterised by poor sorting and detrital muddy matrix, which gives a low reservoir potential.

Hydrocarbon source rocks in the rift system are mainly lacustrine shales and claystones. The distribution of organic matter in these sediments reflects the depositional environment. In the littoral zones most organic matter is derived from land plants; in the deepest parts of the lakes, where the influence of siliciclastics is minimal, organic matter is mainly derived from planktonic organisms, including cyanobacteria, algae and diatoms. In saline lake environments, which are commonly stratified, anoxic bottom waters favour the preservation of their organic remains. This preserved organic matter may generate hydrocarbons (Type 1 or 11 Kerogen) when deeply buried. Talbot (1988) demonstrated that favourable conditions for oil source rock accumulation in tropical African lakes are favoured by humid climate and reduced wind activity, and that these conditions are likely to occur in deep, fresh to mildly alkaline lakes and *not* only in shallow saline lakes like Lake Bogoria.

Hydrocarbon discoveries have been made in the older Jurassic-Cretaceous rift basins of southern Sudan, in the Unity and Higlig areas, with estimated recoverable reserves of between 250-300 million bbl of oil (Schull, 1988). The reservoir rocks in these basins are alluvial and fluvial sandstones, mainly quartz and arkosic arenites derived from Precambrian and Cambrian gneiss, while the source rocks are lacustrine claystones and shales (Schull, 1988). These rift basins are early partial analogues for the Kenya Rift, although they differ in geological ages. The Kenya Rift is a relatively young geologic feature of late Cenozoic age in which rifting was associated with volcanism. No volcanic activity is known to be associated with early rifting phase in the Sudan. Compared to the resource potential in Kenya, better hydrocarbon prospects are probably associated with fluvial facies shed from basement rocks juxtaposed to lacustrine claystones and shales.

Another example of a productive continental rift basin is the Campos basin in offshore Brazil. The evolution of this basin is linked to the Mesozoic rifting that separated Africa and South America (Abrahào & Warme, 1990). The major oil discovery in this basin is in the Lagoa Feia Formation. This rift basin provides some similarities with the East Africa Rift System, although they differ in age and experienced different sedimentary processes. The Lagoa Feia Formation formed as a result of subsidence accumulating fluvial and lacustrine sediments, and was later sealed by evaporite deposition that formed the cap rocks (Abrahào & Warme, 1990). Both the Campos basin and Kenya Rift had extensive volcanic activity. The reservoir rocks in the Lagoa Feia Formation are mainly coquinas and the source rocks are organic-rich lacustrine shales.

Comparing the similarities of these two rift basins provides a model of exploration targets in the Kenya Rift, where some potential siliciclastic reservoirs have high volcaniclastic detritus and are cemented by zeolites. In the Campos basin similar volcaniclastic sediments are poor reservoirs and better prospects exist in areas where provenance is gneiss and granitic (Abrahào & Warme, 1990). In the Kenya Rift Valley System such prospects are thus likely in the Miocene Tambach and the Oligocene-Miocene southern Turkana basins where sediments are also derived from basement rocks (Morley *et al.*, 1992).

CHAPTER-7: CONCLUSIONS

7.1 Conclusions

This study has incorporated evidence both from fieldwork and laboratory analysis of the sedimentology and diagenesis of selected Neogene deposits in the central rift system of Kenya. The formations studied are the Miocene sediments of the Tambach, Kimwarer and Ngorora Formations, with minor examinations of the Pleistocene Kapthurin Formation and the Late Quaternary Loboi silts. As in all rift basins in Kenya, sedimentation was strongly influenced by tectonics, volcanism and climate. Faulting and subsidence led to the deposition of lacustrine facies in the downthrow areas of half-graben basins, while fluviatile systems deposited sediments at the lake marginal and littoral areas, both on the ramps and along the axes of the half-grabens. Lacustrine sedimentation was controlled by changing topographies resulting both from tectonics and erosion. Lakes were formed and destroyed many times in the central Kenya Rift since the Miocene epoch. Termination of lacustrine sedimentation was caused by both volcanism and tectonics (e.g., Ngorora Formation) climatic changes and basin filling (e.g., probably the Tambach Formation). During phases of volcanic activity, some basins, were flooded by lavas that, in some cases, terminated sedimentation. Predominant semi-arid climates led to periodic desiccation of the lakes and cessation of sedimentation.

Early diagenesis of the sediments in the Kenya Rift basins is controlled mainly by sediment composition and groundwater. In areas where the source rocks are predominantly volcanic, as for the Ngorora Formation, unstable mineral phases, such as plagioclase, volcanic glass, and volcanic lithic fragments have undergone early diagenesis by reacting with shallow groundwater of variable salinity and composition to produce clays, zeolites, and authigenic K-feldspar. In contrast, sandstones derived from metamorphic basement rocks in the Tambach and Kimwarer Formations, have not reacted so extensively and are commonly fairly clean, but are cemented by calcite, clay minerals and silica (quartz). Dissolution of plagioclase feldspar is common both in basement-derived clastics and in volcanogenic sediments, forming authigenic clays that cement and partially to totally fill pores in the sediments.

The paleolakes of the Tambach and Ngorora Formations (Member C) were saline and alkaline during some phases of their existence, as shown by the presence of authigenic zeolites in the sediments. In the Kapkiamo sub-basin of Ngorora Formation, authigenic minerals show lateral zonation from smectite, calcite and clinoptilolite near the lake margins, followed by a zone with analcime, and finally authigenic K-feldspars in the more saline centre of the basin. This early diagenetic sequence is due to shallow alkaline groundwater moving toward the basin depocentre undergoing progressive evaporative concentration. These fluids, with high pH, reacted with volcaniclastic debris and older authigenic minerals, with K-feldspar forming in the most saline brine. The effect of temperature is not great during early diagenesis (except near hydrothermal sites), but may be pronounced in subsurface because of the high geothermal gradient in the rift.

Overall, the hydrocarbon potential of the Kenya Rift sediments depend on the provenance, basin type and diagenesis. Those sediments derived from basement rocks are commonly quartzose, and are mineralogically stable. Sand bodies formed by high energy fluvial systems draining catchments in these areas are fairly clean and well sorted. Where these sands are extensive and not highly cemented, they form potential hydrocarbon reservoir rocks. In contrast, volcanogenic sands, like those in the Ngorora Formation, are tuffaceous and rich in volcanic rock fragments; these suffer early diagenesis to form clays and zeolites, which reduce their porosities and permeabilities. Potential source rocks in the Kenya Rift basins are the lacustrine shales and claystones with microbial organic matter. The best quality source rocks are more likely to be found in the saline, meromictic lakes with little siliciclastic input in which remains of planktonic organisms are well preserved. Potential exploration targets for hydrocarbons are those areas in which lacustrine sediments are buried deeply enough to generate hydrocarbons, and are juxtaposed to clean sands with structural hydrocarbon traps. Such prospects exist in the Tambach Formation, and possibly in the Upper Oligocene-Miocene basins of south Turkana where source rocks in the basins are derived predominantly from quartzo-feldspathic basement.

To better assess the petroleum potential of the Kenya Rift basins, more seismic work is required to help delineate the thickness of the sedimentary units and possible entrapment structures in these basins. Drilling is essential to understand burial diagenesis, and further research is also required in the geochemical analysis of the type and richness of organic matter in the shales and claystones; this should include rock pyrolysis and total organic carbon content.

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Plate 1

A. The Elgeyo boundary fault showing Torok waterfall (arrow) cascading down the Elgeyo Escarpment. The bottom of the waterfall marks the contact of the Uasin Gishu phonolite (P) and the Tambach sediments, which are covered by the vegetation. The waterfall is about 80 m high.

B. Looking east from the Elgeyo Escarpment at Iten View Point: in the foreground is the north-south Tambach trough at Anin. Between this trough and the Tugen Hills Range (arrow) in the background is the Quaternary Kerio Valley alluvial fill (K). Note the buildings for scale.


A
P


B
K
91 9 27

Plate 2

A. Lake marginal sandstone facies (pen lying on) with low-angle planar foresets, overlain by the lacustrine claystones in the Tambach Formation.

B. Fining upward fluviatile sequence of the Tambach Formation at the type section. The sequence at the base is composed of paraconglomerates followed by sandstones in the upper section.


A


B

Plate 3

A. The upper lacustrine sequence of the Miocene Tambach Formation. The facies are intercalated green tuffaceous claystones and shales.

B. Sandstone deposits of the Miocene Tambach Formation. The sandstones show planar and trough cross-bedding (left of the hammer). These deposits underlie the lacustrine facies in (A).

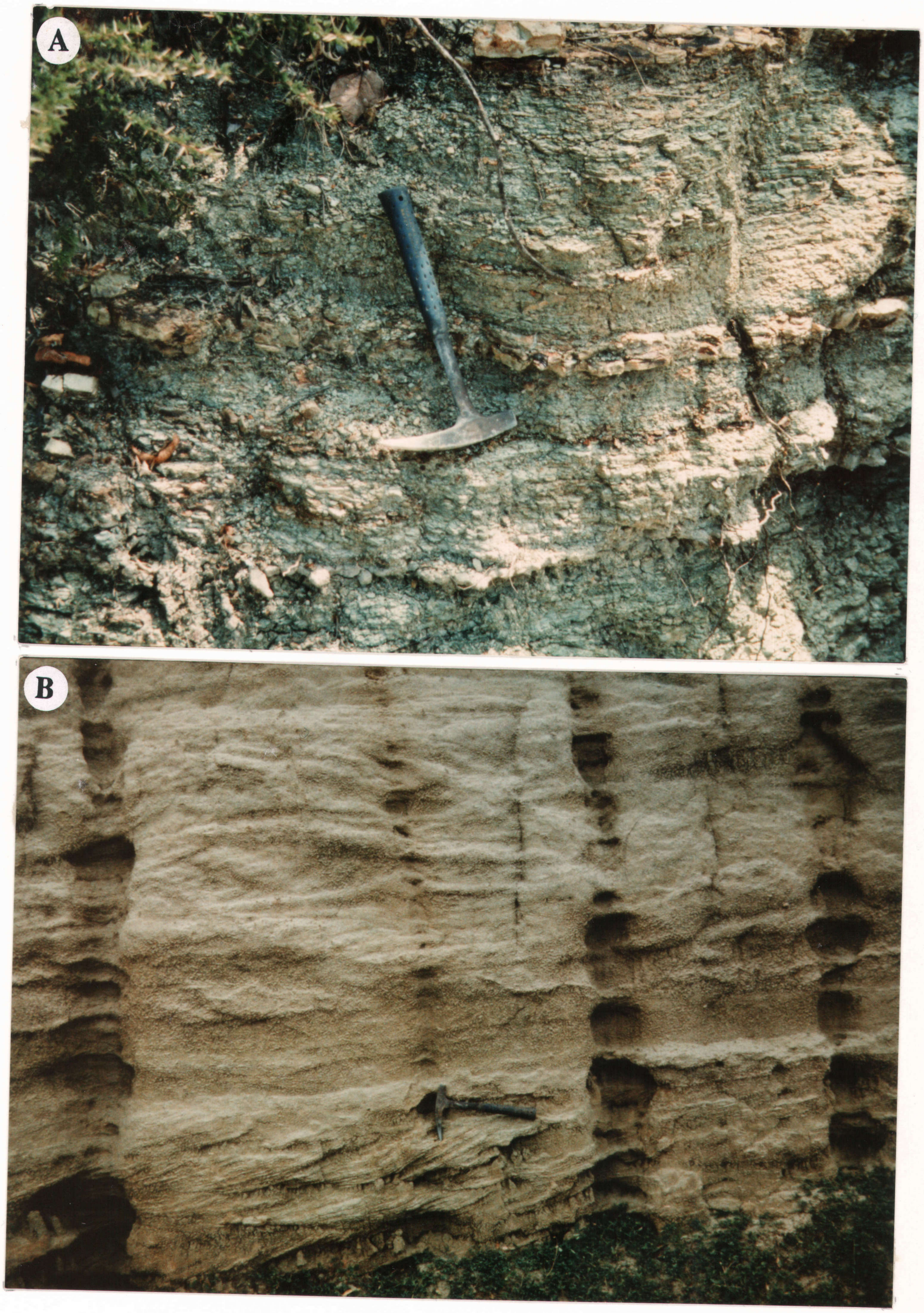

A
B

Plate 4

A. Zeolitic white shales of the Member C, Ngorora Formation at Kapkiamo sub-basin.

(The shales were deposited in a saline, alkaline lake.)

Plate 5

A. Poorly sorted, beige paraconglomerates resting on the Poi lacustrine shale. The paraconglomerate is a debris-flow or lahar deposit.

B. Fissile shales of Poi sub-basin of the Ngorora Formation overlain by thin lava flow (contact at the hammer).

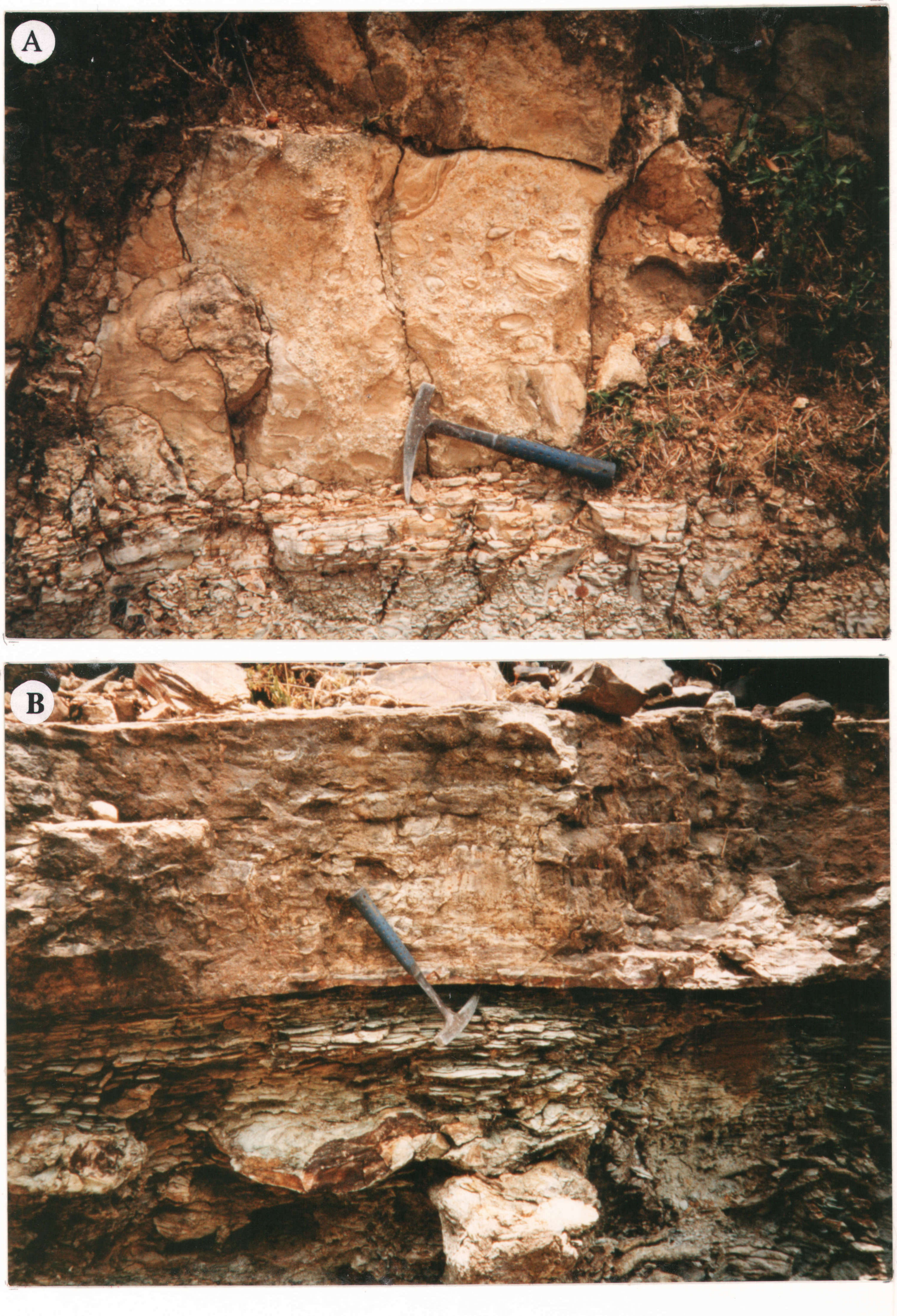

A
B

Plate 6

A. Fissile shales exposed in a stream cut in the Poi sub-basin of the Ngorora Formation. These shales are rich in zeolites (analcime).

B. Subrectangular to polygonal mud-cracks exposed on bedding plane of lacustrine sediments in Poi sub-basin of the Ngorora Formation.


A


B
Nikon

Plate 7

A. Fluviatile cross-bedded sandstone deposits of the Pleistocene Kapthurin Formation at Pole Pole corner near Marigat in the Baringo basin. The rocks are rich in volcaniclastic detritus. The total exposed sequence of deposits is about 10 m thick.

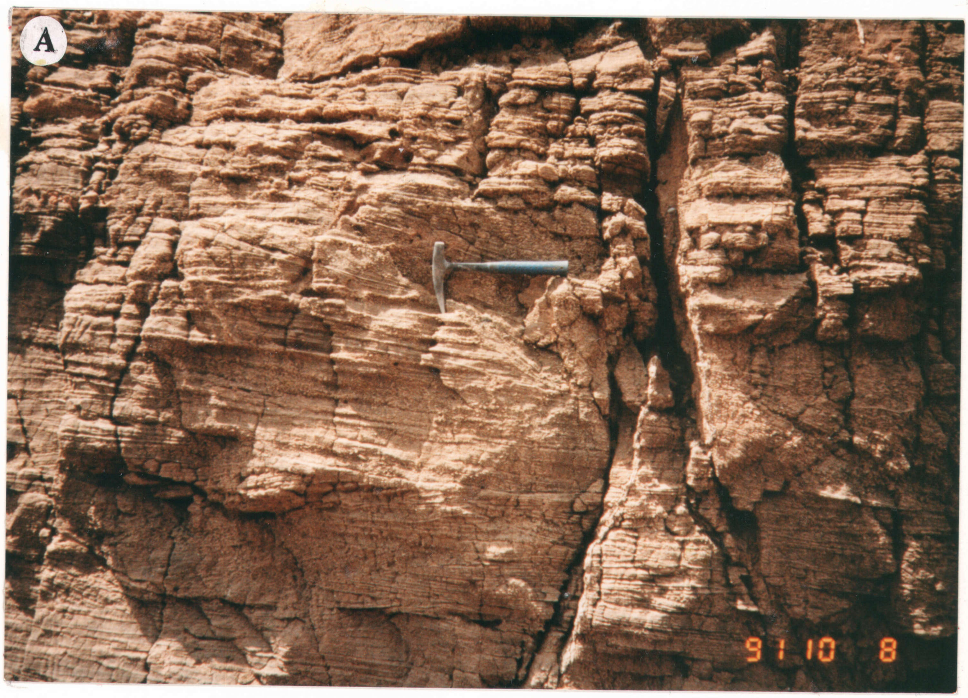

A
91 10 8

Plate 8

A. Thin section photomicrograph of detrital plagioclase feldspar (P) from sandstone of the Tambach Formation which has undergone extensive dissolution mainly along cleavage planes. Plane polarised light. The scale bar is 0.25 mm.

B. Photomicrograph of patchy calcite (C) cementing sandstone of the Tambach Formation. The calcite is stained red by Alizarin red S. Plane-polarised light; Scale bar is 0.1 mm.

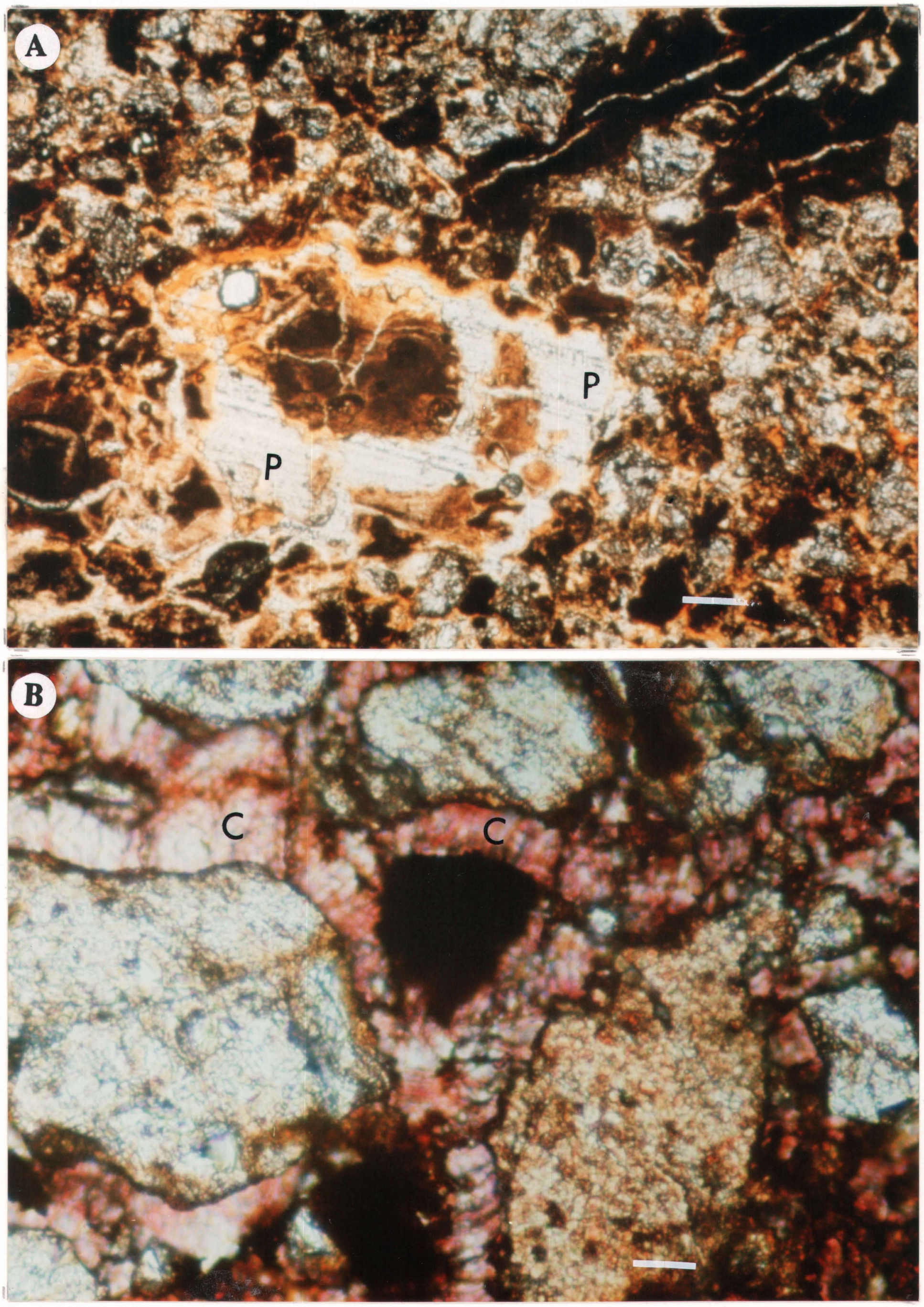

A
P
P
B
C
C

Plate 9

A. Scanning electron micrograph of authigenic smectite cements in sandstones in the Tambach Formation. These smectites have well developed honeycomb structures and partially fill pores in the sandstones.

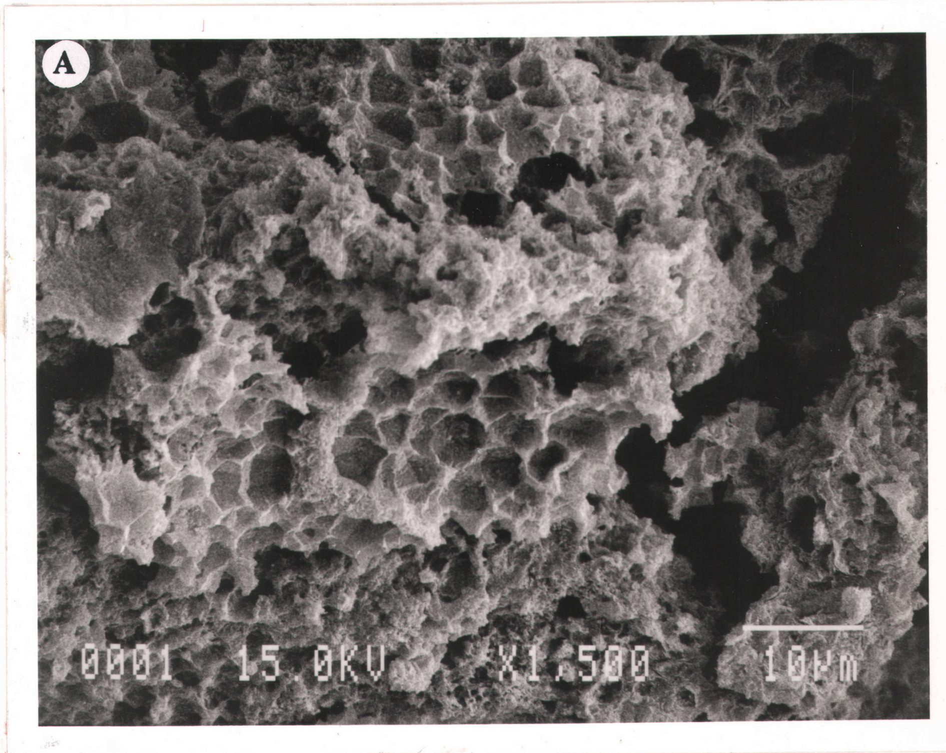

A
0001 15.0KV X1,500 10µm

Plate 10

A. Scanning electron micrograph of euhedral authigenic analcime in the lacustrine claystones of the Tambach Formation. The analcime is surrounded by later clays.

B. Scanning electron micrograph of etched authigenic analcime (centre right) in the claystone facies of the Tambach Formation. The dissolution of analcime is probably due to exceptionally high salinity and alkalinity of the fluids when the lake was undergoing final desiccation.

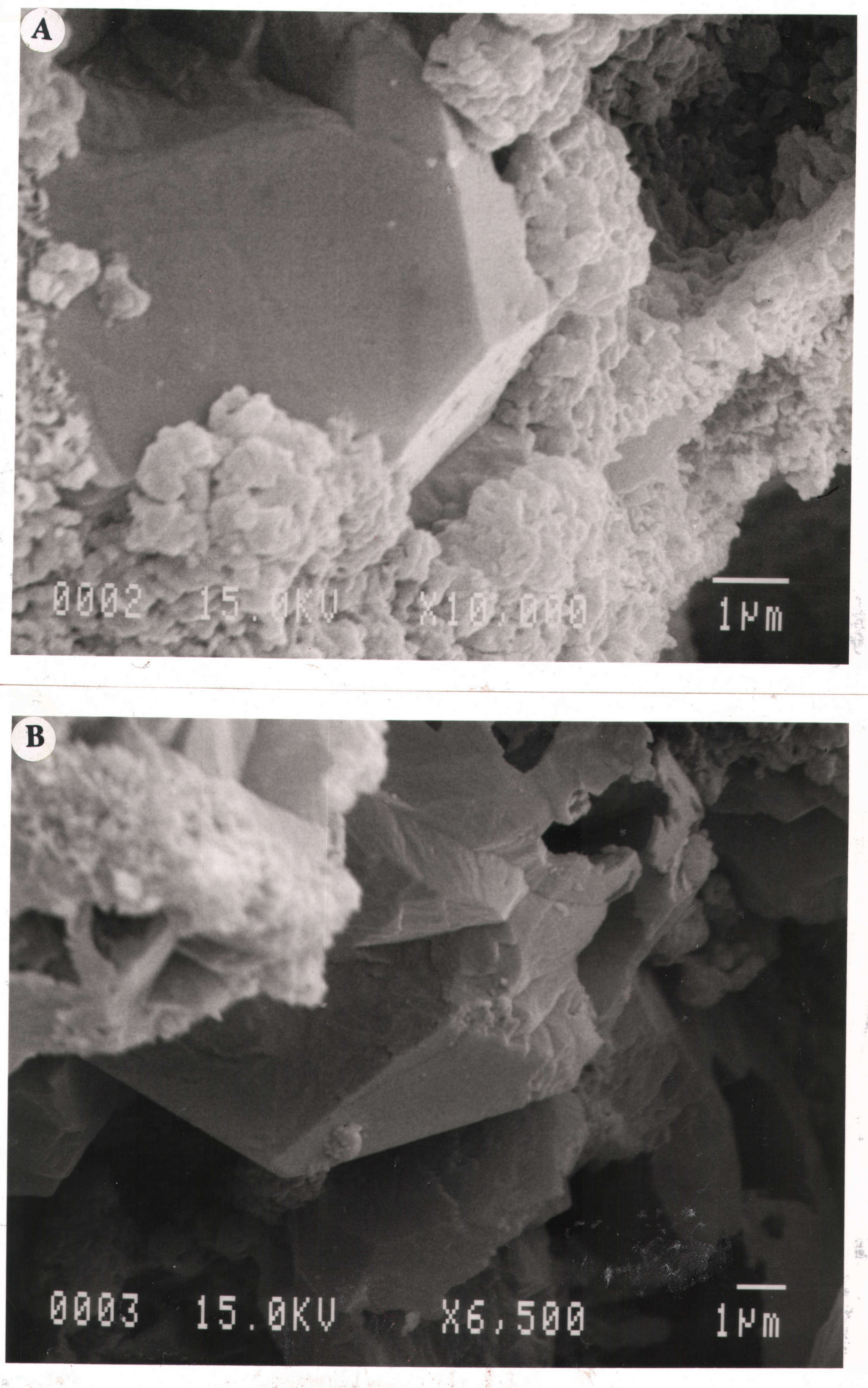

A
0002 15.0KV X10,000
1µm
B
0003 15.0KV X6,500
1µm

Plate 11

A. Scanning electron micrograph of authigenic quartz cementing sandstone in the Kimwarer Formation. The quartz crystals interlock and have tended to stop further cementation of the sandstones.

B. Scanning electron micrograph of early clay cements (illite and smectite) in the Kimwarer sandstones. The authigenic clays act as pore-filling cements with small ribbon like structures bridging pores.

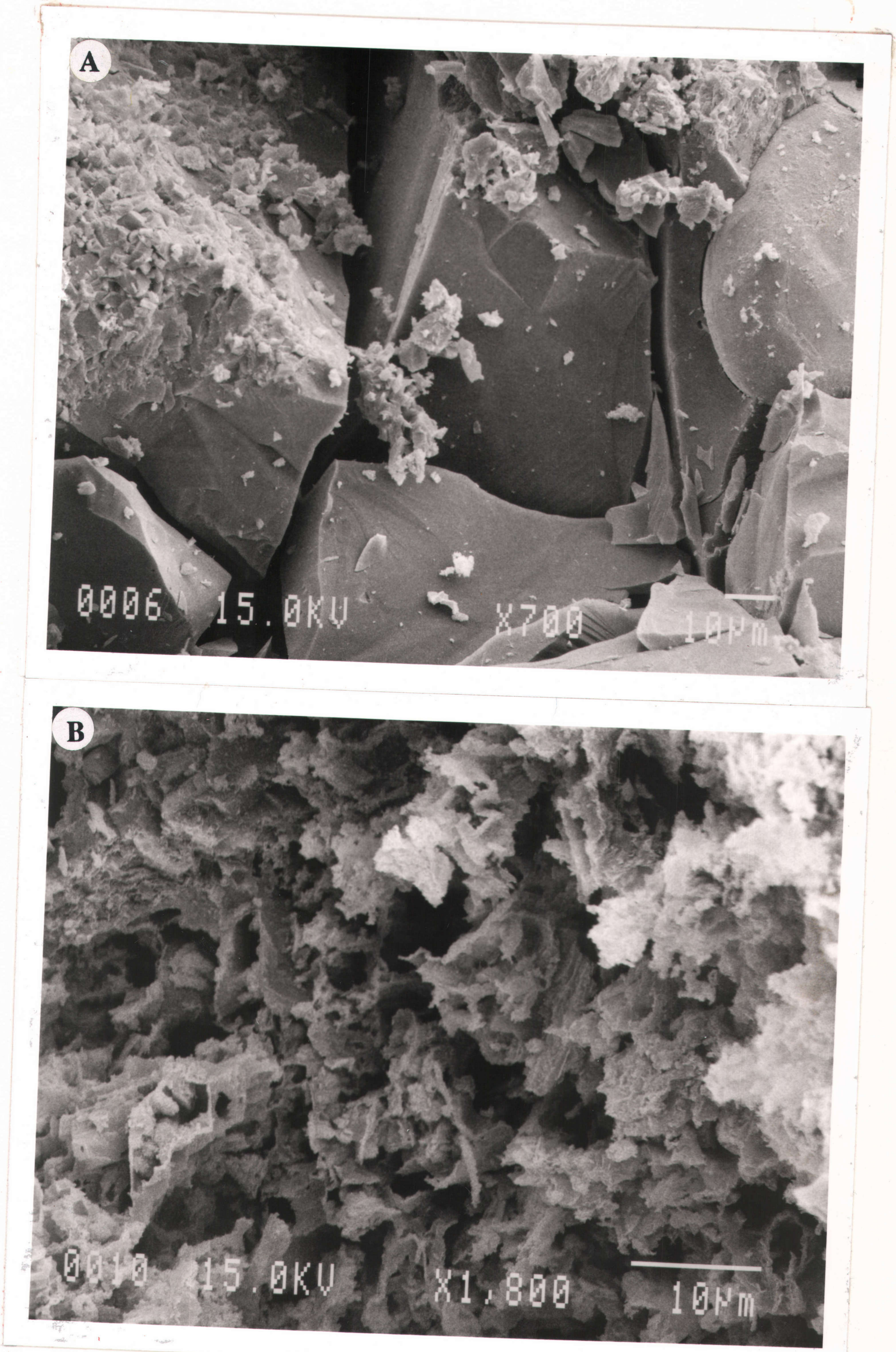

A
0006 15.0KV X700 10µm
B
0010 15.0KV X1,800 10µm

Plate 12

A. Scanning electron micrograph of smectite filling pores (S) and coating calcite (C) which is lining pores in the lacustrine mudstones of the Kapkiamo sub-basin of the Ngorora Formation.

B. Scanning electron micrograph of blocky pore-filling and pore-lining calcite cements in the mudstones of the Kapkiamo sub-basin.

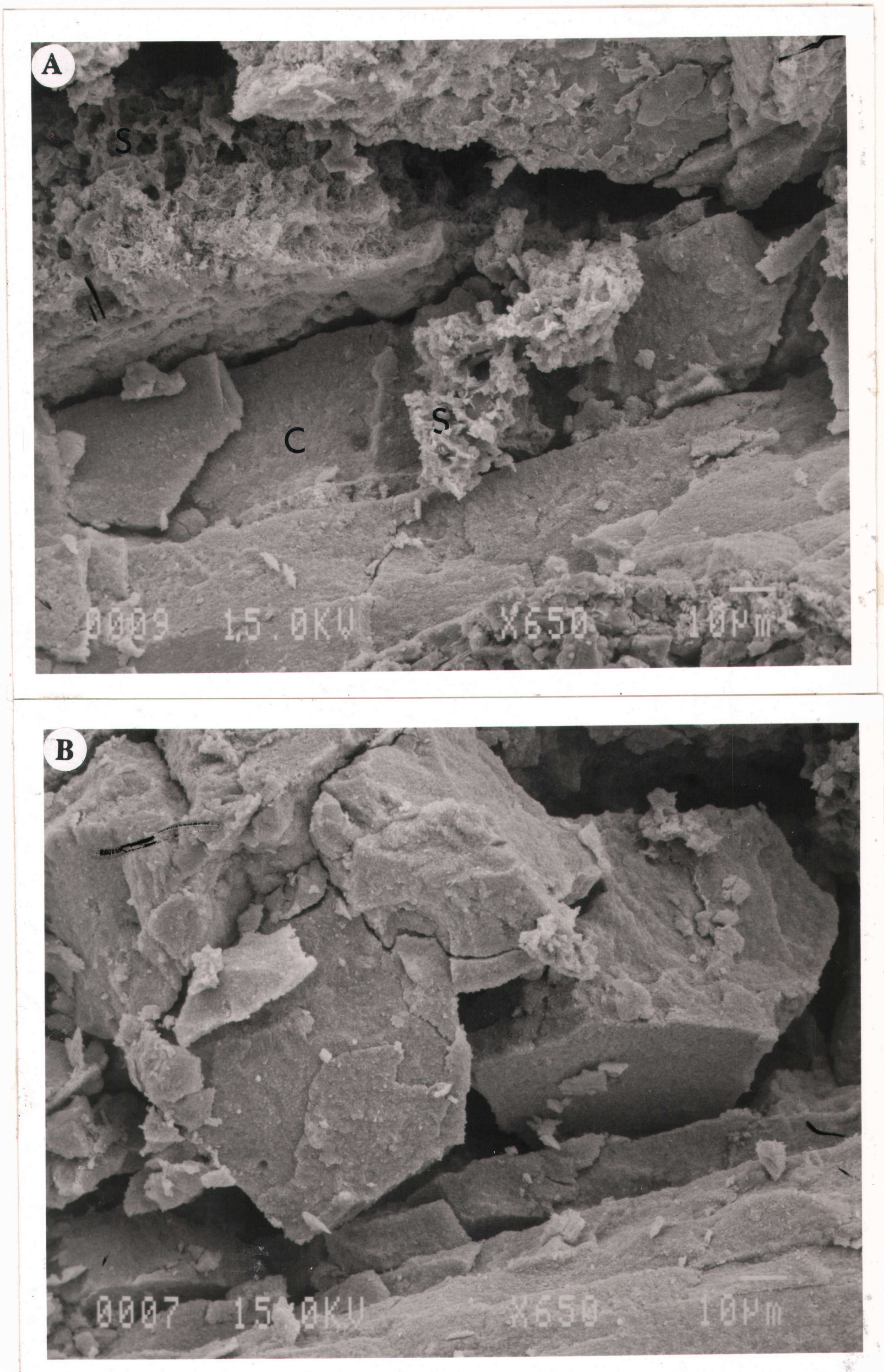

A
S
C
S
0009 15.0KV X650 10µm
B
0007 15.0KV X650 10µm

Plate 13

A. Scanning electron micrograph of euhedral authigenic analcime in the mudstones of the Kapkiamo sub-basin. The zeolites are partially coated by probable detrital clays.

B. Scanning electron micrograph of subhedral analcime from the mudstones of the Kapkiamo sub-basin. The zeolites are coated with films of detrital clay that are masking the zeolite crystal morphology.

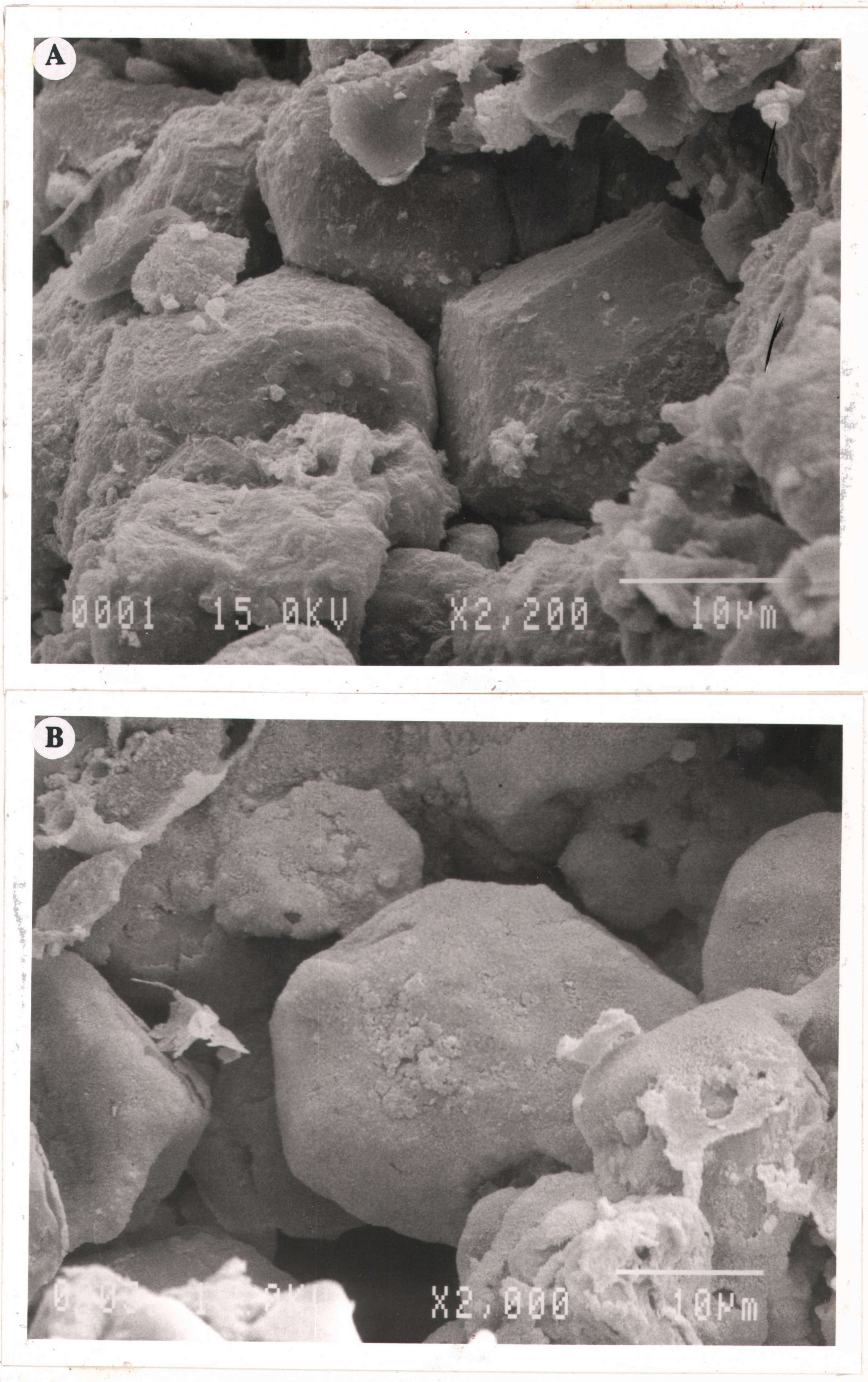

A
0001 15.0KV X2,200 10μm
B
X2,000 10μm

Plate 14

A. Scanning electron micrograph of authigenic clinoptilolite found in the mudstones of the Kapkiamo sub-basin. The individual clinoptilolite crystals are microscopic and fill pores in the sediments. The crystals show tabular ''coffin'' morphology and some are etched and filled by clays (lower right).

B. Scanning electron micrograph of authigenic clinoptilolite coated with late authigenic illite in the mudstones of the Kapkiamo sub-basin.

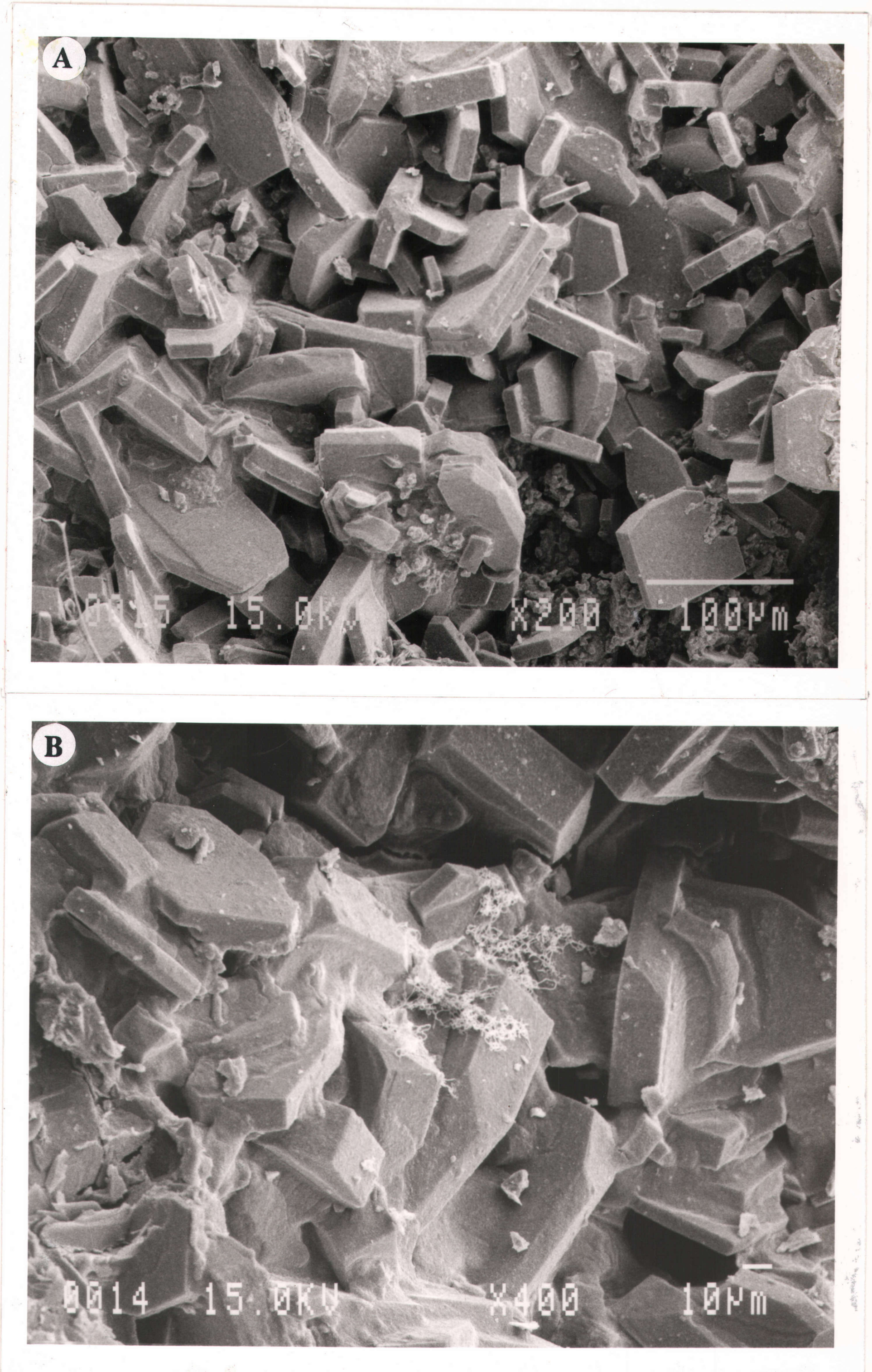
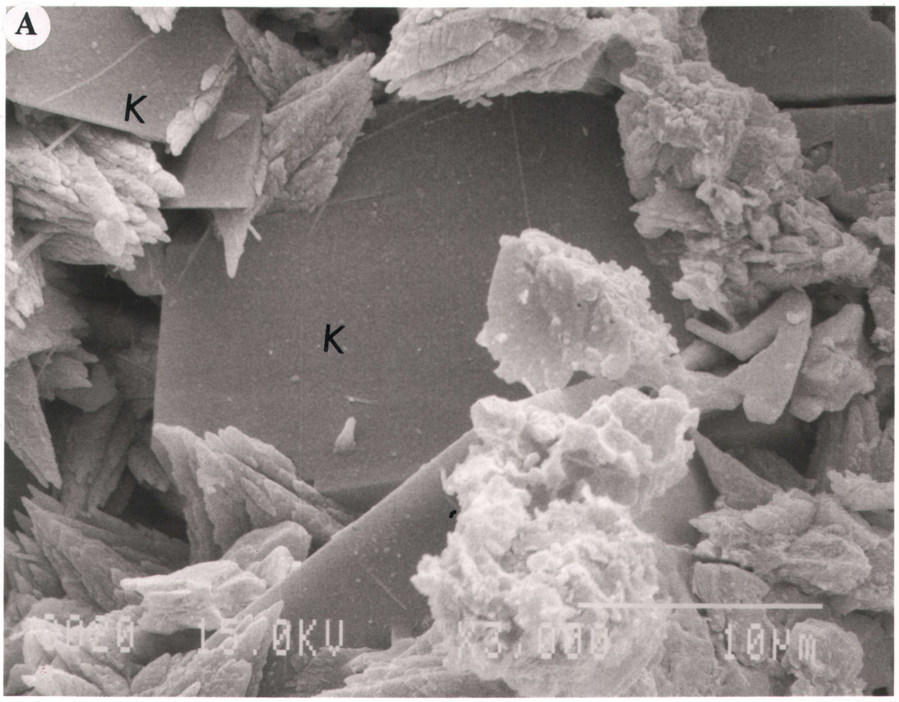

A
0015 15.0kV X200 100µm
B
0014 15.0kV X400 10µm

Plate 15

A. Scanning electron micrograph of pore-filling euhedral clean authigenic K-feldspar (K) in the mudstones of the Kapkiamo sub-basin. The K-feldspars have grown in pores between early iron oxide cements.

B. Scanning electron micrograph of detrital feldspar undergoing dissolution. The etching is causing secondary porosity in the siltstones of the Kapkiamo sub-basin.


A
K
K
0020 15.0KV X3,000 10Pm

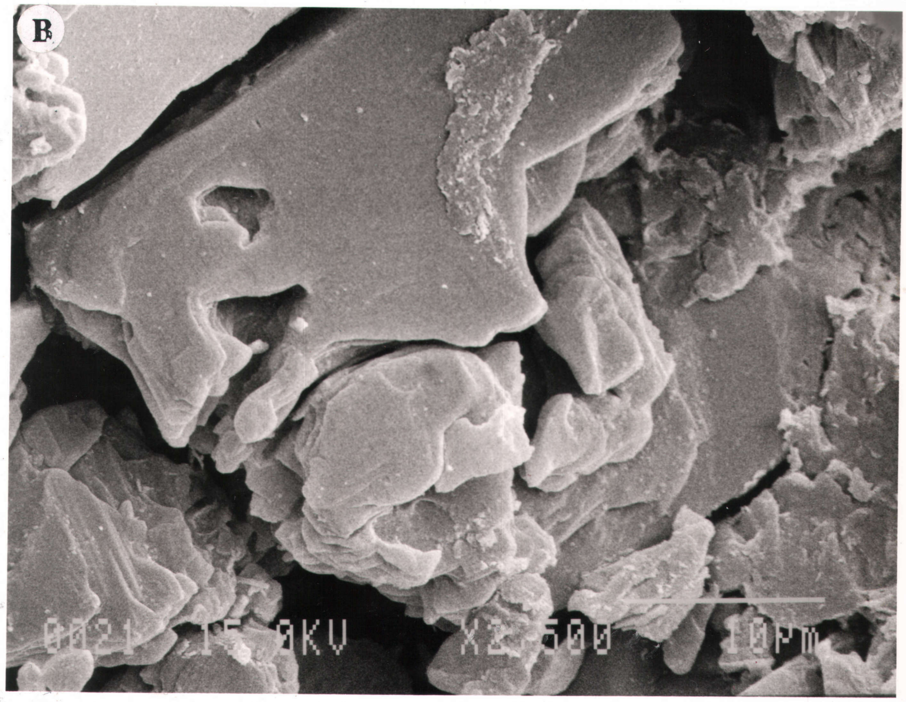

B
0021 15.0KV X2,500 10Pm

Plate 16

A. Scanning electron micrograph of pore-filling authigenic K-feldspar in the siltstone of the Poi sub-basin of the Ngorora Formation. The growth of interlocking crystals has completely filled the pores of the siltstones.

B. Scanning electron micrograph of authigenic K-feldspars lining pores in the siltstones of Member C (Poi sub-basin) of the Ngorora Formation. In places, the individual crystals are submicroscopic and euhedral.

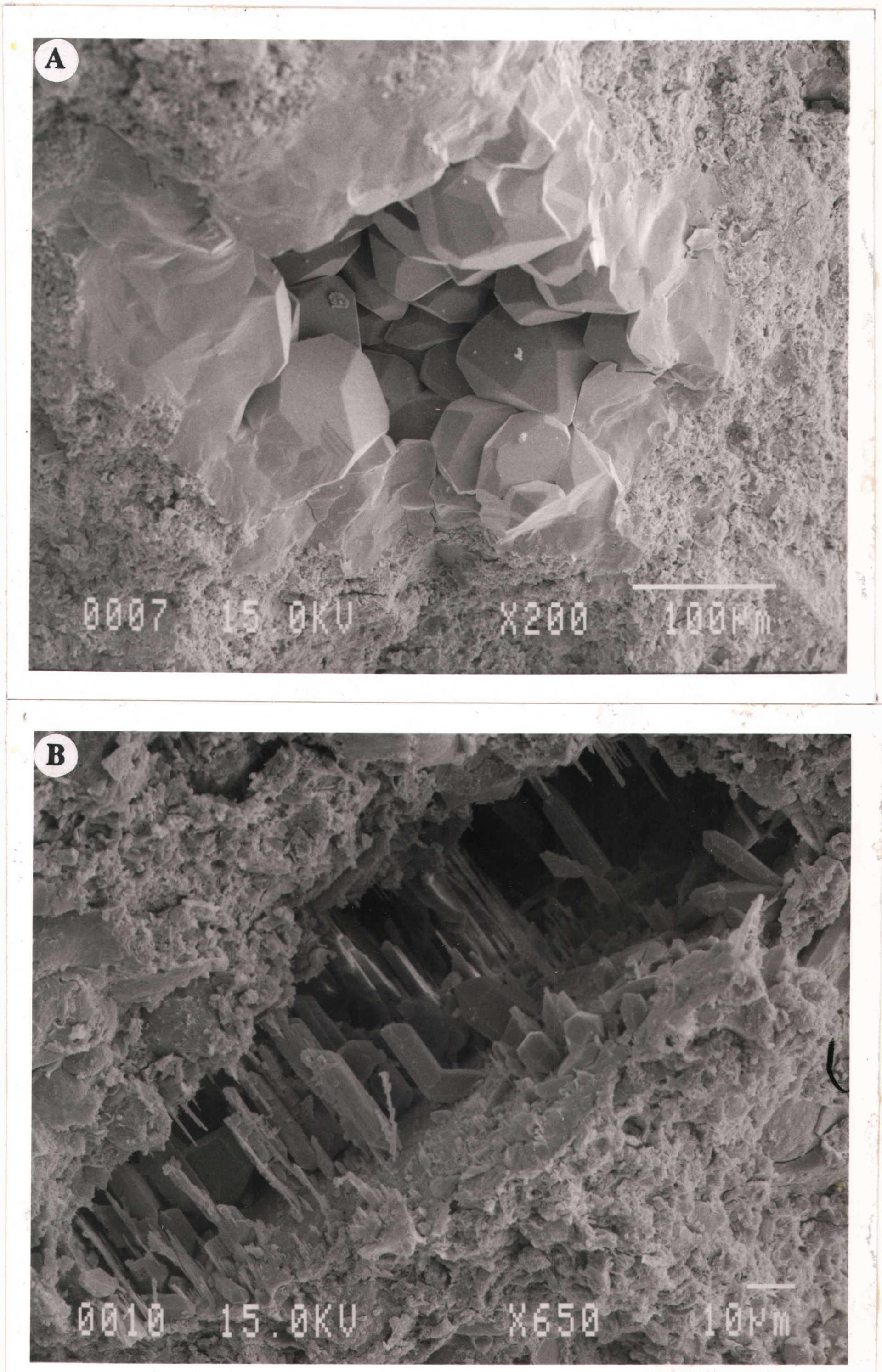

A
0007 15.0KV X200 100µm
B
0010 15.0KV X650 10µm

Plate 17

A. Scanning electron micrograph of euhedral analcime cementing conglomerate in the fluviatile facies of the Poi sub-basin.

B. Scanning electron micrograph of blocky euhedral K-feldspar crystals (K) on dissolved plagioclase (P) in the siltstones of the Poi sub-basin. Dissolution of the plagioclase grain is crystallographically controlled.

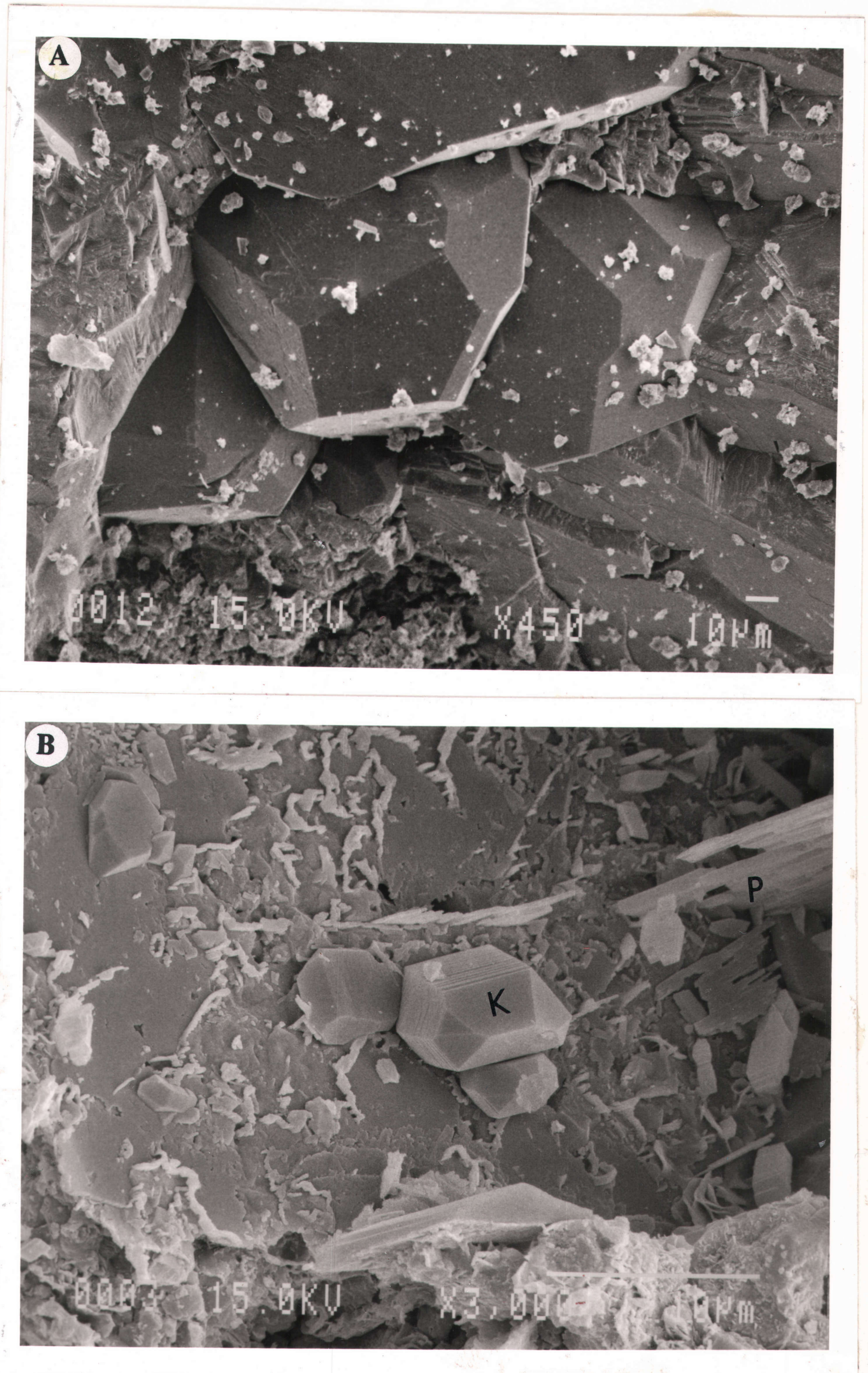
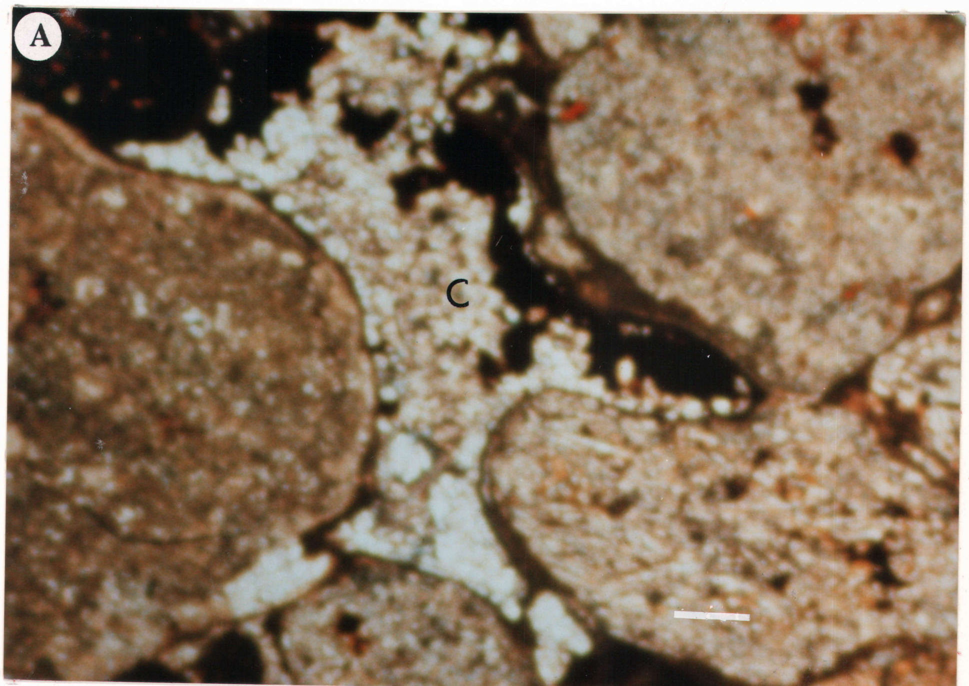

A
0012 15.0KV X450 10μm
B
P
K
15.0KV

Plate 18

A. Thin section photomicrograph showing calcite (C) cementing sandstones in the Poi sub-basin of the Ngorora. The calcite cement occur as patches and in places has been dissolved and replaced by iron oxide cements (plane-polarised light); scale bar is 0.25 mm.

B. Thin section photomicrograph of sandstone from Poi sub-basin. The calcite cement is replacing volcanic shards (V), which is rimmed by brown iron oxide cements (Fe) which is replacing calcite cement. Under plane-polarised light; scale bar is 0.25 mm.


A
C

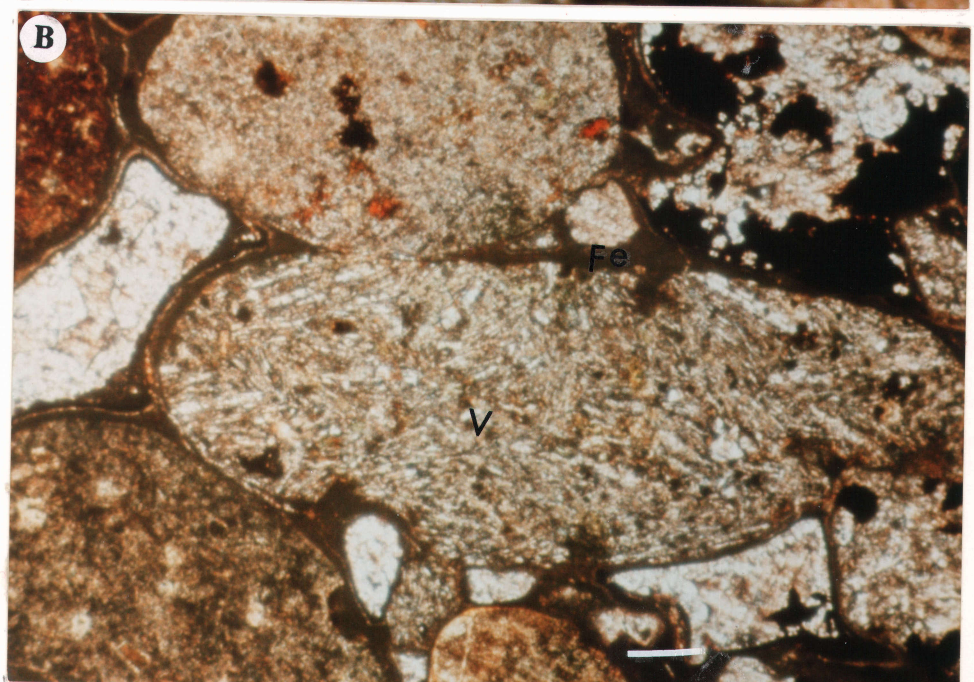
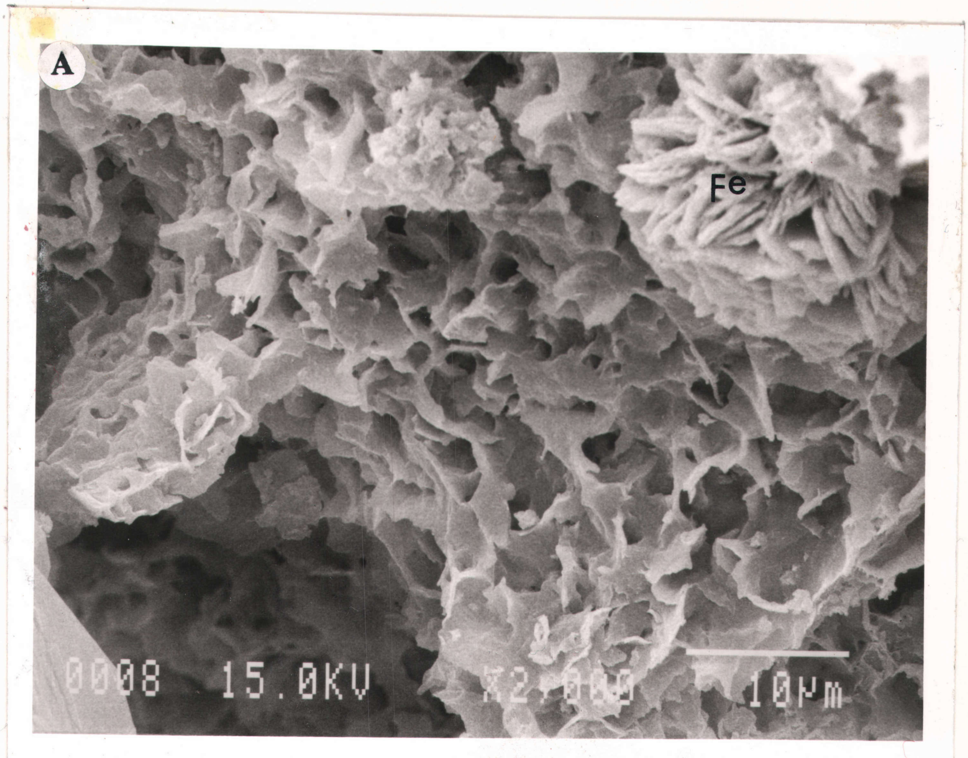
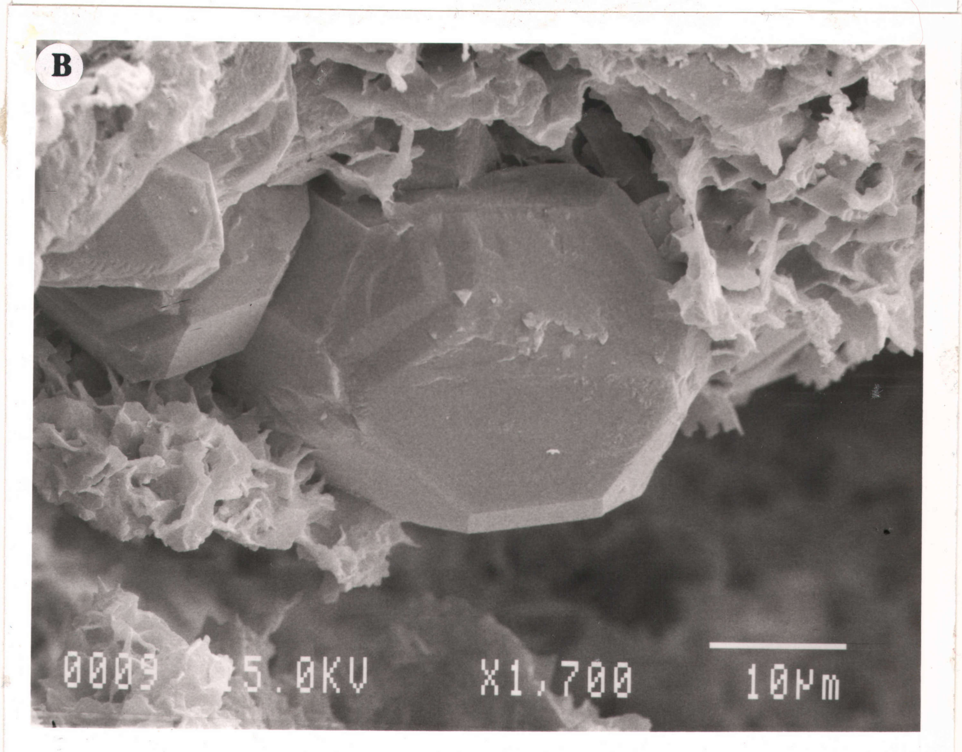

B
Fe
V

Plate 19

A. Scanning electron micrograph showing flaky to crenulated authigenic smectite filling pores in the conglomerates of the Poi sub-basin. The authigenic smectites are coated by a later iron oxide (Fe).

B. Scanning electron micrograph of authigenic cubo-octahedral analcime crystals lining pores in the siltstones of the Poi sub-basin. The analcimes predate authigenic smectites in the same pore.


A
Fe
0008 15.0KV
10µm


B
0009
X1,700
10µm