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Geology of the Marsabit area

Report 108 (Reconnaissance)

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MINISTRY OF ENVIRONMENT AND NATURAL RESOURCES
Mines and Geology Department

Report 108 (Reconnaissance)

Geology of the Marsabit area

Degree Sheet 20
with coloured 1:250 000 geological map and
results of geochemical exploration

R. M. Key

with contributions by
B. K. arap Rop and C. C. Rundle

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MAP

1:250 000 geological map of Degree Sheet 20 (in back pocket)

PREFACE

This report documents the geological reconnaissance of a remote area, the Marsabit degree-square, including the southern half of the Chalbi Desert and the desolate Koroli Desert – Hedad area, which extends south to the Proterozoic massifs of the Ndoto Mountains.

As an integral aim of a Kenyan – British Technical Co-operation programme, the Samburu – Marsabit geological mapping and mineral exploration project, the report describes, and accompanies, a new 1:250 000 geological map for an area which had not previously been geologically surveyed.

Of especial interest is the light which is thrown on the regional structure and volcanic stratigraphy of the eastern shoulder of this part of the Rift Valley: the spectacular 'maar' craters, or 'Gofs' on the Marsabit Shield are considered to have resulted from magmatic reaction with groundwater, associated with a pre-volcanic sedimentary basin which is, at the time of writing, a target for petroleum exploration. Whatever the outcome of these investigations, this report contributes significantly to the understanding of the geology of northern Kenya. Although no indications of metallic deposits have been found, Dr Key's assessment of the groundwater situation (and his discovery of an underground river) offer important background information for future development prospects.

B. D. Hackman
Samburu – Marsabit Project Leader
1 September 1986

Geology of the Marsabit area

Abstract Sheet 20 (a remote 12 200 km^2 tract of northern Kenya) was geologically mapped, and locally, geochemically surveyed, at reconnaissance scale in late 1984, using helicopter support. The area lies east of the Kenyan Rift Valley System and is founded on Proterozoic sedimentary and igneous rocks altered during the polyphase Late Proterozoic–Cambrian Mozambiquian Orogeny. Granulite Facies metasediments of the Kotim Gneisses are exposed in the south-west, to define upright NNW-trending (Baragoian) folds cut by NNW and NNE (Barsaloian) shear zones. Further east are the lower grade rocks, including altered mafic lavas and peridotite, of the Korr Complex. These form an exotic tectonic slice preserving older (Samburuan) ENE-trending structures.

Coarse clastic sedimentary rocks of the Maikona formation were deposited on an eroded surface of the crystalline basement, locally infilling a NW-trending graben. Subsequent, sub-Miocene, regional warping produced the Chalbi Basin, superimposed on the infilled graben, and itself partly infilled by lacustrine sediments (of the Karole formation).

Volcanism commenced in the Late Miocene with fissure eruption of flood basalts, preceding major Plio-Pleistocene alkali basalt shield volcanoes. These include Marsabit Shield with a surface area of c.6300 km^3 and a volume of c.910 km^3 of basalt lavas and subsidiary basaltic pyroclastics. Shield volcanism was controlled throughout by underlying fractures; either reactivated older faults or contemporaneous (Rift) structures. Their configurations reflect this control, as do lines of cones and *maars*. Quaternary reworking of adjacent superficial material accompanied the growth of the shields.

No metallic mineralisation was discovered and the only resources of note are abundant supplies of sand and aggregate and major marble hills near Korr. Four aquifers are presently being exploited, of which the Maikona formation is potentially the most important. An air vent located on the eastern flank of Kulal pinpoints a groundwater discharge which warrants investigation. The Maikona formation may also be a source rock for hydrocarbons. The area has no indications of geothermal energy.

1 Introduction

Sheet 20 (Marsabit) forms the SE quadrant of the phase 2 area of the Samburu–Marsabit Geological Mapping and Mineral Exploration Project: a Technical Co-operation project between the British (British Geological Survey) and Kenyan (Mines and Geological Department) Governments. The principal objective of this phase of the project was to produce reconnaissance geological maps (of degree squares), on a scale of 1:250 000, of a previously geologically unsurveyed part of northern Kenya between latitude 2°N and the Ethiopian border, and between longitudes 36° and 38°E. Selected stream sediment samples were collected during the mapping to provide data for regional geochemical atlases.

Most of the area was covered by helicopter-supported fieldwork in late 1984 from a base camp 10 km north of Marsabit, adjacent to the Maikona track and below the daily cloud base for Marsabit. Foot traverses with Mr Bernard Rop (Kenyan counterpart geologist) complemented the helicopter-supported fieldwork immediately around Marsabit.

1.1 LOCATION

The Marsabit sheet is bounded by latitudes 2° and 3°N and longitudes 37° and 38°E, an area of 12 210 km^2 (Figure 1). It is part of the Marsabit District of the Eastern Province with the district administrative headquarters at Marsabit. The following topographic maps cover the sheet area:

1:100 000 (incompletely contoured at 100 ft intervals), Series Y633, editions 1 and 2—GSGS, sheets 42 (Balesa Kulal), 43 (Maikona), 54 (Hedad), 55 (Marsabit). These cover the NW, NE, SW and SE quadrants respectively of sheet 20.

1:250 000 (contoured at 500 ft intervals), Series Y503, editions 1 and 2, sheets NA-37-5 (South Horr) and NA-37-6 (Marsabit). The South Horr sheet covers the western half, and the Marsabit sheet the eastern half of sheet 20.

1.2 ACCESS

A network of poor unsealed tracks connects the main population centres (Figure 1); all are impassable during heavy rains including the major track south from Marsabit towards Nairobi. The track from Kargi towards Olturot is the only direct link between the eastern and western parts of the map. During prolonged dry spells, vehicles may be driven across the flat surface of the Chalbi playa.

A surfaced airstrip at Marsabit enables regular communication to be maintained for light aircraft from Nairobi. Unsurfaced airstrips exist at all the major population centres (Maikona, Korr, Olturot and Kargi) and also at Segel which is used when the main Marsabit airfield is cloud-covered.

1.3 PREVIOUS WORK

Randel (1970) in his account of the geology of the area immediately south-east of sheet 20 chronicles the early explorers and administrators who trekked across this part of northern Kenya (Donaldson-Smith, 1900; Wickenberg,

1903; Archer, 1913; Parkinson, 1920, 1924, 1939). Dixey (1944, 1948) and Pulfrey (1960) provide regional descriptions of the geology and geomorphology. As a result of all this work it was established that the geology of sheet 20 was founded on Precambrian metamorphic rocks covered by younger (Tertiary) volcanic shields and plateaus, with the Sub-Miocene Chalbi Basin infilled by various superficial unconsolidated sediments.

Subsequent geological work has also been of a regional nature. This includes the series of papers by Williams on the basaltic volcanics (summarised *in* Williams, 1978), broadly describing the volcanism of the various shields. Brotzu and others (1984) provide a geochronological framework for all the volcanism of northern Kenya and established a Miocene age for the plateau basalts and Plio-Pleistocene ages for the shields.

An on-going UNESCO (latterly Kenya Government) integrated project on arid lands (IPAL), an investigation of the Rendille area, covers the whole of sheet 20. The series of reports (e.g. IPAL Technical Report, A-6 (Lusigi, 1984); IPAL Technical Report, B-2, 1983) includes a wealth of data on population, climate, land-use, livestock, etc. but very little on geology. However, this project was the first to recognise the presence of a sedimentary rock unit SE of Maikona. Nyamweru (1984) provides a detailed account of the geomorphology of the Chalbi Basin.

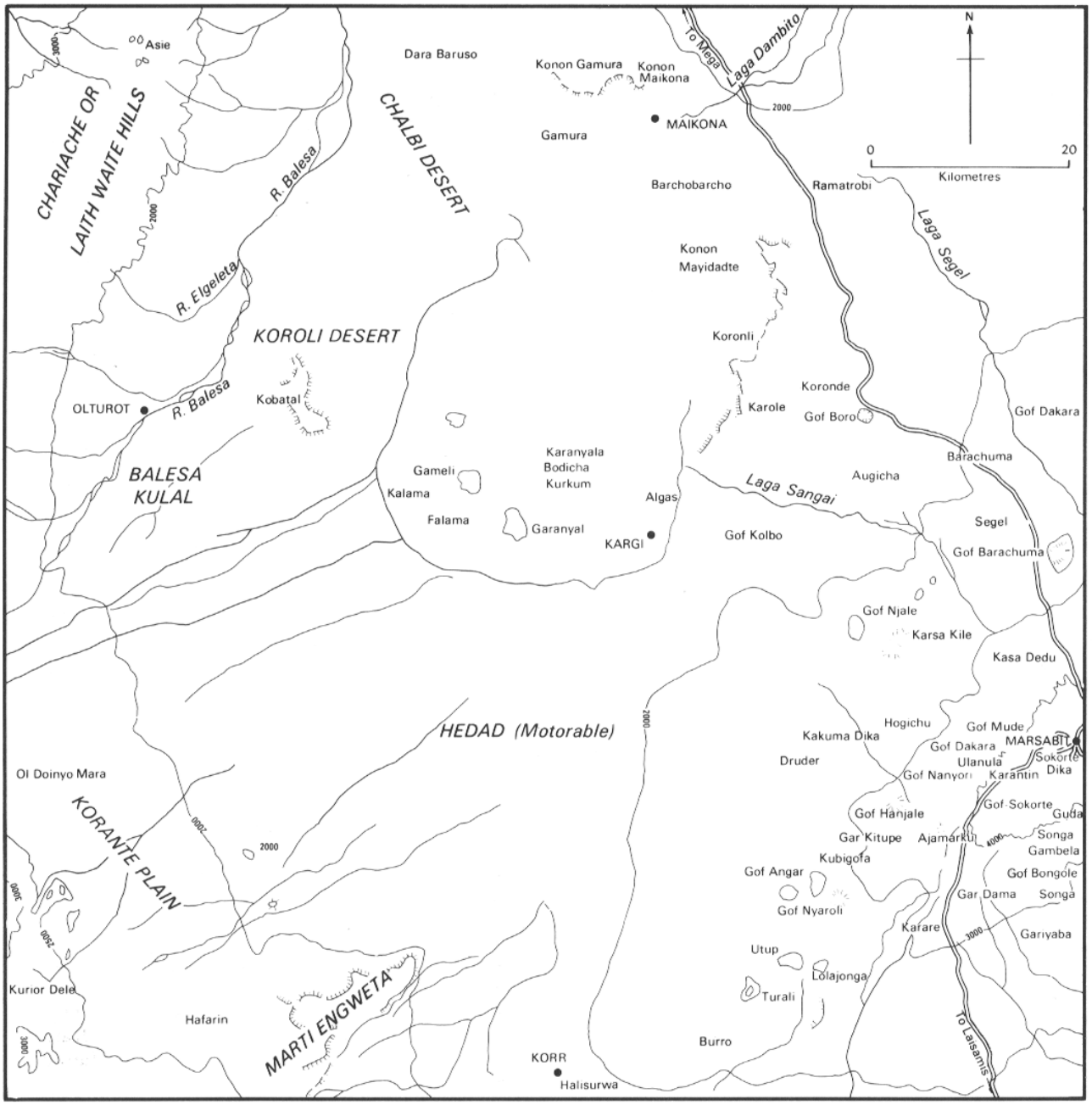


Figure 1 Location map with main track



Plate 1
The Korante Plain in the Hafarin area, looking south over the Marti Engweta plateau



Plate 2
The Koroli Desert, extreme north-west with fossil drainage channels



Plate 3
The Chalbi playa, looking west towards Kulal



Plate 4
Degraded dune field south of the Chalbi playa, looking west



Plate 5
Interface of Marsabit Shield and the Chalbi playa, Koronli waterhole



Plate 6
Southern margin of the Chalbi playa

2 Geomorphology

Bedrock lithologies and their relative ages are reflected in the scenery. Six contrasting physiographic provinces are recognised (Figure 2): the mature lowlands of the centre and south (Korante Plain, Hedad, Koroli Desert and Chalbi Basin) and the immature (Cenozoic) shield volcanoes of the north-west and east. The older provinces are basically Tertiary landscapes modified slightly during the Quaternary, whereas the shields remained volcanically active into the Quaternary.

Drainage systems within the six provinces reflect their relative maturity: the Tertiary landscapes have a largely fossil system of meandering watercourses and ancient pans or playas. Linear watercourses with short tributaries follow maximum slopes radially off the summit plateaus of the shield volcanoes. (The east-facing wetter sides are scarred by a concentration of such watercourses, forming impressive, narrow ravines.)



Figure 2 The major physiographic provinces. Arrows indicate mean directions of surface slope

2.1 KORANTE PLAIN

The Korante Plain descends from the eastern edge of Ol Doinyo Mara (immediately west of the map-area) with a very gentle easterly slope from c.920 m (3000 ft) to c.615 m (2000 ft) over a horizontal distance of about 24 km. It has a residual sandy soil cover from which rise numerous inselbergs composed of resistant 'basement' lithologies, mostly quartzofeldspathic gneisses. These bare rock edifices are rarely in excess of 100 m in height, except in the extreme west on the lower slopes of Ol Doinyo Mara. The highest inselbergs are Kurior Dele (over 1070 m), Hafarin (815 m) and the eastern extremity of Ol Doinyo Mara (over 1500 m). The surface outline of these rocks is controlled by the bedrock structure: most are narrow ridges trending N to NNW parallel to the strike of metamorphic fabrics (gneissosity). Some inselbergs such as Kurior Dele, are broader with several ridge-features related to limbs and noses of fold closures.

The Marti Engweta basalt-capped plateau rises less than 50 m above the sand covered plain. The basalt cap is Late Miocene in age, showing that the Korante Plain is essentially a sub-late Miocene surface. Subsequent erosion has merely stripped less than about 20 m (vertical scarp height beneath basalt cap) of material off an already planar surface. On the Marti Engweta the basalts rest directly on exposed gneiss pavements (there is no thick soil interface preserved) indicating that, at least locally, the proto-plain was a bare rock surface. Presently, the Marti Engweta Plateau only has a very thin and sporadic (volcanic) soil cover.

A dendritic drainage north-east of the Ol Doinyo Mara range diversifies the Korante Plain. Individual watercourses have sandy channels well-defined by flash floods caused by the relatively good rainfall on the western mountains (Plate 1). The Marti Engweta Plateau lacks an internal drainage system: rainwater collects in natural hollows on the uneven basalt surface.

2.2 HEDAD

The Hedad is essentially a continuation of the Korante Plain at slightly lower elevations (about 600 m) extending as far as the Marsabit Shield. It is a remarkably monotonous, flat area overlain by a residual sandy soil and flash-flood deposits washed in by the north-east flowing drainage off Ol Doinyo Mara. There are no rock outcrops except in the south-east around Korr where gentle hills are underlain by the metamorphic Korr Complex. The Hedad almost certainly is genetically related to the sub-Late Miocene development of the Korante Plains with very little subsequent erosion.

The well-defined drainage channels of the Korante Plain rapidly loose their identity in the Hedad where the flood water overspills on to the sandy plain (see geological map). However a good peripheral drainage channel borders the Marsabit Shield and is directed north into the Chalbi Basin. In the Korr area a radial drainage network off the gentle hills is kept open by flash flooding. The majority of these streams are directed to the north-east and are blocked by the younger Marsabit Shield.

2.3 KOROLI DESERT

The Koroli Desert is a northern extension of the Hedad between Kargi (east) and the Asie Shield. The land surface remains at about 600 m and apart from the presence of basalt capped mesas and an unusual drainage scheme, the Koroli Desert has the same aspect as the Hedad. The mesas never rise more then 50 m above the adjacent plain and consist of a thin (less than 20 m) basalt cap invariably overlying sedimentary rock (poorly exposed because of basalt scree). There are no outcrops of metamorphic rock in the Koroli Desert. The mesas occur in two groups: as a NW-trending chain between Garanyal and Kobatal and a more northerly unnamed and topographically lower group. There is only a thin volcanic soil over the basalts which nevertheless supports a thick thorn scrub vegetation.

A monotonous sand-rich soil mantles the flat desert floor. However there are subdued sand mounds (parallel to the dunes of the Chalbi Basin dune field) which suggests that this area may formerly have been part of an extensive dune field. These mounds show up on aerial photographs. Around Kargi reactivation of the sand is producing new dunes. These are relatively small longitudinal dunes parallel to the prevailing WNW-directed winds.

The most interesting feature of the Koroli Desert is its drainage system. In the west the Balesa River follows the perimeter of the Asie–Kulal Shield and has a wide, well-defined bed, directed northwards into the Chalbi Basin. Present day active drainage in this river is confined to flash floods which rarely utilise the whole bed-width, which must have therefore been formed during an earlier (wetter) Quaternary time. Other watercourses in the Koroli Desert are poorly defined and essentially fossilised (Plate 2). They are generally directed north-east towards the Chalbi Basin. However many of the watercourses are tributaries of a circular drainage channel enclosing Falama, etc. This major (but also fossilised) drainage is very reminiscent of the drainage which mimics the outlines of the Asie–Kulal and Marsabit Shields. It is postulated that an older shield (late Miocene) existed on the concave side of the circular drainage and that the basalt-capped mesas in this area are erosional remnants of this early volcanic complex.

2.4 CHALBI BASIN

This is a closed lacustrine basin at an elevation of only 400 m centred on the NW-trending playa through Dara Baruso (Plates 3–7). The playa is usually a dry, salt-encrusted mud flat with minor sand bars. However, whenever the long rains of April do eventuate the playa still floods to form an extensive lake. This happened in 1985 when the total area of the playa was under water. Vegetation is completely absent and there are no interior drainage channels, not even along the periphery of the Huri Shield in the north. The entire SW margin of the playa is defined by a relatively high (over 10 m) sand-bar which preserves strand lines (Plate 7) related to the original (Tertiary) lake. The development of the sand-bar must be related to the original lake where it formed a marginal 'barrier beach' deposit. It may have been caused by longshore drift (see Grove and Pullan (1963) on similar deposits in the Kalahari Desert).

Deflated sand-dune fields flank the playa to the north-east (in the area south-east of Maikona) and to the south-west behind the aforementioned sand bar. In the extreme north-east the dunes are rather complex polybarchans (Glennie, 1970) which indicate a wind direction from the north-east during dune growth. Adjacent to the playa (on

both sides) the dunes coalesce and lack any pronounced linearity. Interdune areas define numerous pans and it is thought that these complex dunes formed in areas susceptible to flooding (see below). To the south-east of the most southerly strand line (shown on the geological map) the dunes are longitudinal and have a pronounced N–S orientation, indicating winds of that direction. Pans in interdune areas result from the combined effect of topography and clay eluviation. A sparse grass and scrub cover presently stabilises the deflated dunes.

In the north the playa margin is defined by the elevated edge of the Huri Shield. There is no evidence (such as strand lines) for former high lake levels on the volcanic cliffs: it is thought that the volcanic rocks post-date the main lake development.

The Chalbi Basin is closed: all drainage channels are directed into the playa. The principal watercourses are the Balesa River (from the south), Laga Dambito (from the Huri Shield) and Laga Sangarta (from the Marsabit Shield). All have well-defined channels due to flash flooding. The south-east dune field is cut by several well defined watercourses which are never blocked by individual dunes. This suggests that during the dune formation the watercourses (1) contained perennially flowing water or (2) were kept open by intermittent flash floods.

The linear south-west margin of the playa is thought to mimic a SW-trending fault in the underlying bedrock. Basal argillaceous material is confined to the playa side of the fault: either lacustrine or alluvial silts or as an argillaceous bedrock. Tertiary and/or earlier erosion lowered the land surface into contact with these argillites. During subsequent wet periods the argillites formed a perched aquifer, to produce a lake.

The (northerly) source of the sand dune material was presumably the adjacent quartz-rich Maikona formation (next chapter). The UNESCO-IPAL technical report A-6 (Lusigi, 1984) also records a volcanic ash component in the aeolian dunes. The dunes are thought to have formed during the arid period when the land surface was reduced to the argillaceous unit in what subsequently became the playa. Flint (1959) notes that longitudinal dunes are limited to the 10 in (250 mm) isohyet. Therefore the following chronology for the various landforms is proposed:

1 Erosion under arid conditions to form the sub-Late Miocene flat surfaces (e.g. Korante Plain, Hedad, Koroli Desert), and reduction of the land surface to the argillaceous unit under what subsequently became the Chalbi playa. At this time the dune fields of the Chalbi Basin formed.

2 Wetter period(s) to produce a lake in the Chalbi Basin. Part of the dune field became engulfed in the lake with resultant reworking.

3 Pliocene inception of the Huri Shield which encroached onto the northern part of the Chalbi Basin after the main development of the lake.

2.5 NORTH-WEST VOLCANIC PROVINCE

The north-west Volcanic Province is defined at its lowest (eastern) level by the c.500 m (1600 ft) contour. It comprises the southern part of the Asie Shield and only the lowermost eastern slopes of the Kulal Shield. The Asie Shield defines the NNE-trending Chariache (or Laithwaite) Hills with a maximum elevation of 1084 m (3522 ft) on Asie Hill. It has an 'inverted-saucer' E–W profile rising c.500 m over horizontal distances of c.8 km on both flanks (see Figure 3). The summit ridge is relatively flat (Plate 8) with a thin soil cover and abundant basalt debris. However numerous rounded cinder cones, including Asie Hill itself, are concentrated along the summit together with, relative to Marsabit, few craters (*maars*). The eastern side of the Asie Shield is incised by linear ravines with vertical walls locally in excess of 100 m deep. All these eastern watercourses drain into the Balesa River. The cones are being eroded by numerous run-off channels and the *maars* have a thin lacustrine infill. Aeolian sand is presently being banked on the lower eastern slopes by the prevailing WNW directed winds.

Mount Kulal has a maximum elevation of 2230 m immediately west of the map-area along the N-trending summit ridge. Both eastern and western flanks are cut by major ravines, locally penetrating the entire height of the volcano, i.e. vertical walls in excess of 1000 m deep. Only the lowermost eastern slopes extend into the map-area where gullies are generally several metres deep. A thin soil cover is present on the interfluves, which are characterised by basalt debris. East–west master joints

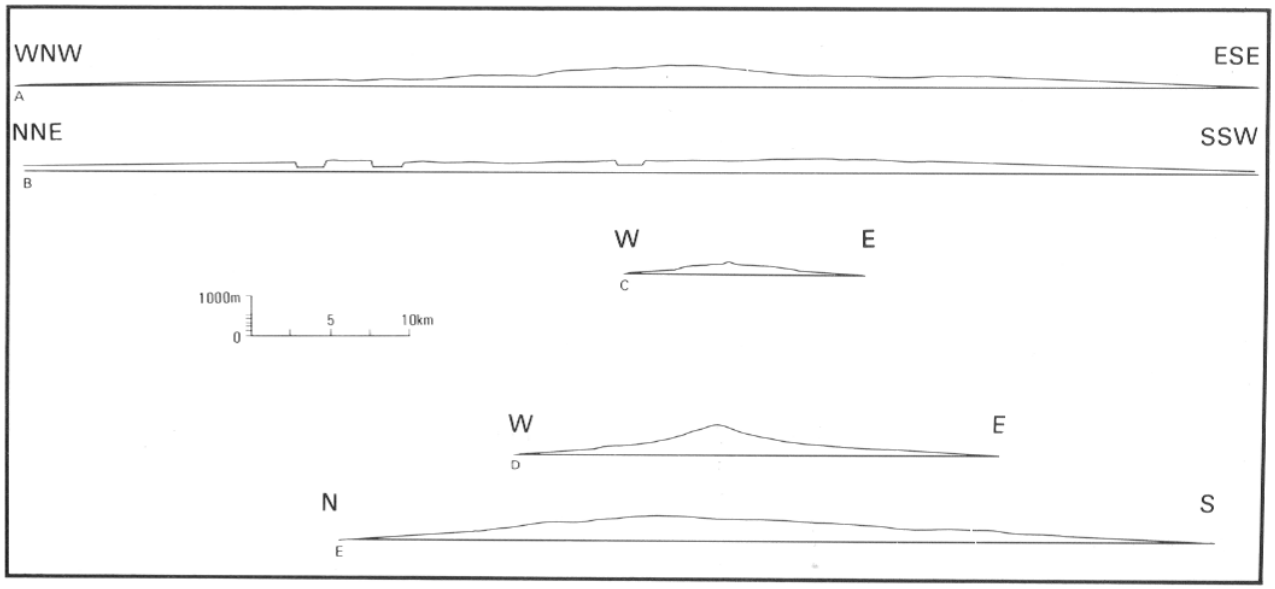


Figure 3 Shield profiles: A–B Marsabit, C Asie, D–E Kulal

locally control the drainage which form west bank tributaries of the Balesa.

2.6 EASTERN VOLCANIC PROVINCE

This is founded on an elevated basalt plateau defining the eastern margin of the several physiographic provinces originating in the Tertiary and described earlier. The dome-like edifices of Marsabit and Huri Shields rest on the basalt plateau. Only the southernmost extremity of the Huri Shield is seen north of Maikona where it forms a rocky plateau less than 30 m higher than the Chalbi Basin. It is poorly drained with natural rock hollows infilled by a mixture of aeolian sand and ponded silt.

The Marsabit Shield rises from below 615 m (2000 ft) along its eastern flanks to over 1700 m (5600 ft) at its summit in Marsabit town. Its slope angle increases as the summit is approached (Figure 3) but never exceeds gradients of greater than 1:6. Below 1200 m (4000 ft) the shield has a thin soil cover with numerous low mounds of angular basalt boulders separated by hollows with a mixture of sand and silt. The youngest lava flows form easily identifiable elevated features, often emanating from breached cinder cones, and lacking any soil or vegetation cover. Linear depressions in the northern part of the shield are infilled by aeolian sand. Above 1200 m (4000 ft) there is a thick red soil cover and a natural forest cover (except where cleared around Marsabit town).

Rounded cinder cones and deep *maars* are both common along axes trending NE and NW through the shield summit (Plate 9). The cones and *maars* tend to be more impressive than their equivalents on the Asie Shield. The cones often rise 100 m or more above the shield basalts (e.g. Hogichu) with the *maars* depressed by similar amounts, e.g. Gof Bongole's walls were measured as 210 m. The basal diameters of the cones and *maars* often exceed 1 km.

A radial drainage is variably developed on Marsabit Shield: the wetter SE flank features a closely-spaced series of deep gorges cut by ephemeral streams. By contrast the western slopes are poorly drained except in the summit areas near Marsabit town. The main control on drainage channels is the natural surface slope. Local control is provided by the cones and *maars* and also by the upstanding, youngest lava tongues. The influence of fractures such as master joints is minimal (in the extreme south-east corner the actual margin of the Marsabit Shield appears to be controlled by a series of faults trending NE). The *maars*, which are referred to as 'Gofs' by the local Rendille, contain thin lacustrine deposits.

2.7 SUMMARY

The following history of landform development is suggested from the description of individual physiographic province.

1 Pre-Late Miocene development (erosional) of the Korante Plain, Hedad, Koroli Desert and Chalbi Basin. These four provinces are genetically related and formed the SW slope of a regional (sub-Miocene) erosional basin trending NW through northern Kenya (see Pulfrey, 1960). The Chalbi Basin corresponded to the axial trough of this feature. The erosional event reduced the ground surface in the Chalbi Basin to an argillaceous unit. According to Holmes (1965) this would indicate that groundwater levels at that time must have been similar to present-day levels, i.e. near surface in the Chalbi playa which prevented further erosion of the argillites. At this time the dune fields of the Chalbi Basin started to form.

2 Late Miocene volcanism to form the basalt plateaus (e.g. Marti Engweta) locally preserving the sub (late) Miocene surface, and possibly an older shield in the Koroli Desert.

3 Pliocene erosion to produce dune fields (? from the Maikona formation's quartz-rich sediment) and a later development of a Lake Chalbi (evidence of the strand lines, major sand bar and major drainage channels from the south-west).

4 Plio-Pleistocene volcanism to produce the E and NW volcanic provinces.

5 Holocene erosion of unstable volcanic features (cinder cones and east-facing sides of the shields).

The non-volcanic landsurfaces are presently stable apart from local sand dune movement in the Kargi area and the banking of aeolian sand by winds blowing towards the west-north-west.

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3 Stratigraphy

The stratigraphy of the area (Table 1) can be considered in terms of three major phases: the Late Precambrian–Early Phanerozoic Mozambique Orogeny; cycles of subsequent uplift, erosion and localised continental sedimentation until the Pliocene; Late Tertiary–Quaternary basaltic volcanism. Metamorphic rocks of the first event are only exposed in the SW quadrant in two distinct provinces. These are the more westerly quartzofeldspathic gneisses and associated biotite, hornblende and hypersthene gneisses with NNW strikes typical within the orogenic belt in northern Kenya. To the east is the Korr Complex, anomalous with regard to (1) its ENE-striking structures, (2) its lithologies, with dominant hornblende-rich gneisses, related fissile leucocratic gneisses and pods of various ultrabasics and ultramafics including altered peridotites, and (3) its metamorphic grade: kyanite as well as sillimanite is the stable Al_2SiO_5 phase whereas only sillimanite is present in adjacent gneisses.

The succeeding period had a largely negative effect on the geology due to the predominant role of regional uplift and erosion. However, remnants of two sedimentary units are preserved in the north beneath plateau basalts. The age of the older unit (Maikona formation) is enigmatic—lithologically they resemble Cretaceous rocks west of Lake Turkana.

The Late Tertiary through Quaternary volcanism is manifested as plateau basalts upon which are founded major alkali basalt shield volcanoes. The orientation of the shields is structurally controlled on axes parallel (Kulal) and discordant (Asie, Marsabit) to the c.N–S orientation of the Rift Valley in northern Kenya. The map area lies just 40 km east of the Rift with Kulal essentially forming its eastern shoulder. Concomitant with the volcanism were minor sedimentation and reworking of older superficial deposits of the intershield areas.

Intrusive rocks are rare in the metamorphic, sedimentary and volcanic provinces.

The descriptions of lithostratigraphic units include sections on: nomenclature, geography, morphology and photogeology, reference sections, fossil content, age, structure, thickness, lithologies, petrology, sedimentation or petrogenesis in that order.

Table 1 An outline of the stratigraphy

Lithostratigraphic Unit	Lithologies	Age
	Unconsolidated superficial deposits and and calcrete	Quaternary (reworking of Tertiary material)
	Poorly consolidated calcareous sediments	Pleistocene
Asie Shield Huri Shield Kulal Shield Marsabit Shield	Alkaline basalt, tephrite, basanite and hawaiite lavas, alkali basaltic pyroclastics related to *maars* (block-and-ash cones) and cinder cones	Plio-Pleistocene
	Plateau alkali basalts and hawaiites	Mio-Pliocene
Karole formation	Poorly consolidated, fossiliferous bedded sediments	Miocene
Maikona formation	Flaggy, red-weathering gritstones and blue-grey shales	?Cretaceous/ Miocene
	Major unconformity	
	Augen gneiss	Early Phanerozoic to Late Precambrian (part of Mozambique Orogenic Belt)
Kotim Gneisses	Quartzofeldspathic gneisses, biotite gneisses, hornblende gneisses, hypersthene-bearing felsic rocks, garnet gneisses	
Korr Complex	Quartz-hornblende-plagioclase (with or without garnet) gneisses, fissile leucocratic gneisses), and slivers of marble, metaquartzite, amphibolite, ultramafic rocks	
	Intrusives	
	Basalt plug and dyke (west of Kargi)	Cenozoic
	Quartz reefs Pegmatitic granite	Late Precambrian
	Foliated granodiorite	

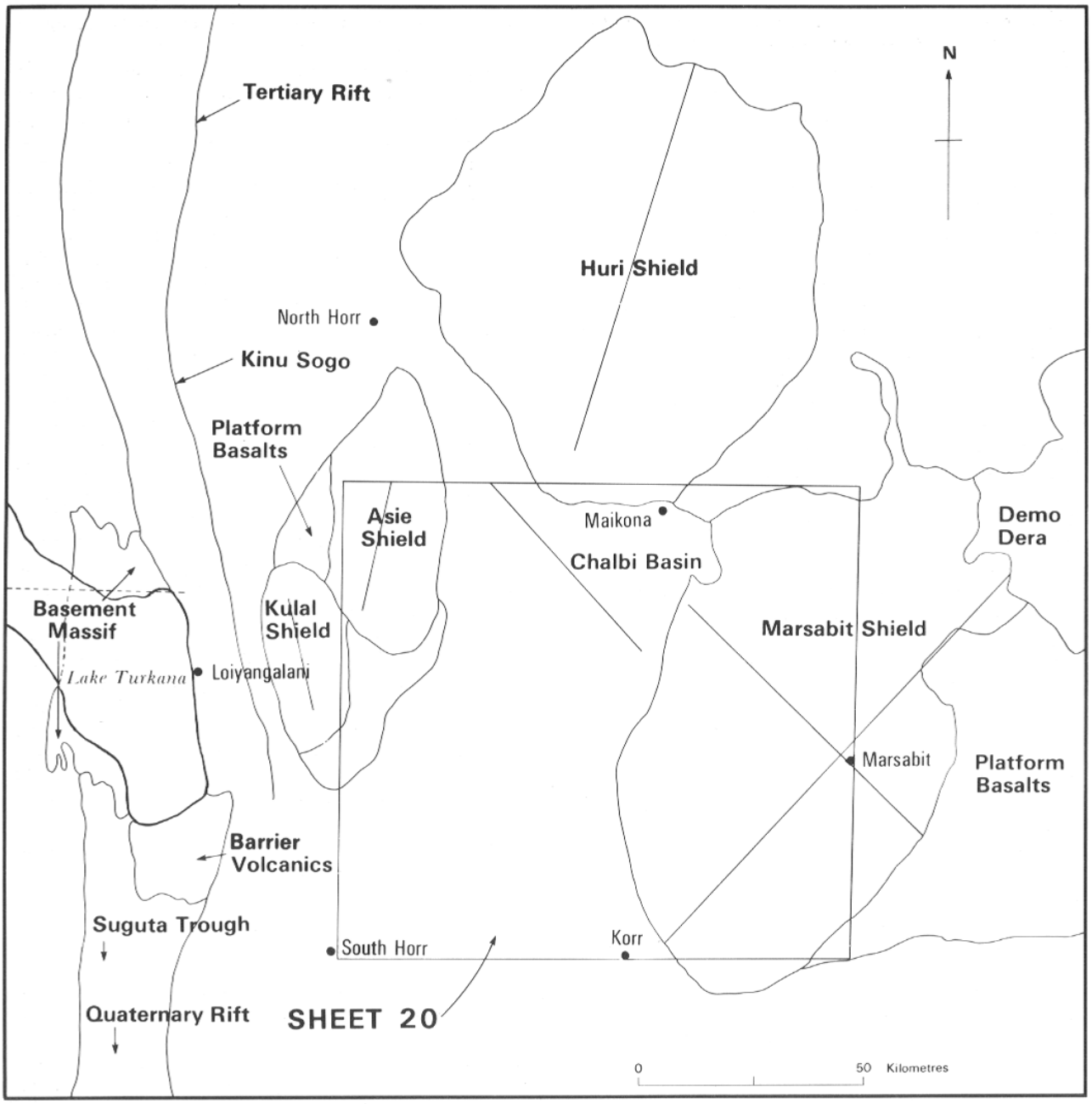


Figure 4 The four major volcanic shields and their position relative to the Rift faulting. Trends of pyroclastic centres within shields shown by continuous straight lines

3.1 METAMORPHIC ROCKS OF THE MOZAMBIQUE OROGENIC BELT

The Korr Complex

The Korr Complex takes its name from the small Rendille settlement of Korr nestling amongst the low, barren hills underlain by this unit. This province was initially identified during a Landsat imagery interpretation prior to fieldwork. It forms a circular feature about 16 km in diameter at the south-west extremity of the Marsabit Shield, with patchy dark tones.

Subsequent photo-interpretation again showed the area underlain by the Korr Complex as tonally dark. The fieldwork revealed that this distinguishing feature is due to (1) the absence of a thick soil cover unlike adjacent parts of the Hedad, (2) the abundance of mafic minerals in the thin soils, and (3) good outcrop and sub-outcrop of black hornblende-rich rocks.

As noted above, the Korr area is characterised by gentle rounded hills with good rock outcrop, and well-defined watercourses which locally expose bedrock. Numerous quartz reefs either form low bare rock ridges or provide abundant quartz float in their vicinity. In both cases they are readily visible on the ground and on aerial photographs.

The eastern part of the unit is unconformably overlain by the Marsabit Shield. However hilly inliers of marble, ultrabasic and ultramafic rocks protrude through the mantling basalts. The two marble hills (Plate 10) are readily recognisable because of their pale colours and mantles of pale hillwash. However the ultrabasic and ultramafic hills are indistinguishable on aerial photographs from nearby cinder cones. Lineaments in the main part of the complex are due to the gneissosity.

No contact between the Korr Complex and adjacent gneisses is exposed. The marked differences in lithology,

structure and metamorphism between them strongly suggest a tectonic contact (see Charsley, 1985). The Korr Complex is regarded as an exotic tectonic slice with a basal low angle tectonic interface (see map cross-section and Chapter 4). This necessitates a shallow present thickness for the unit as a whole.

The two major lithologies are melanocratic, hornblende-rich gneisses and leucocratic, quartzofeldspathic gneisses with subordinate metaquartzites, marbles, biotite-schists and gneisses, pyroxene-amphibolite, ultrabasic and ultramafic rocks. The melanocratic gneisses are invariably massive, dense, medium- to coarse-grained rocks which may be banded or speckled. Any (mineral) banding is folded and cut by brittle fractures. Almandine garnets are common and may constitute up to 30 per cent of the rock volume. The proportion of hornblende to felsic minerals varies on outcrop scale so that these rocks grade into leucocratic gneisses. Ultramafic rocks form concordant units up to several metres thick.

In thin section the melanocratic rocks are seen to consist of equigranular green hornblende prisms and plagioclase (andesine-labradorite) laths with minor quartz and diopside. Garnet grains are anhedral, poikilitic (quartz and ore inclusions), badly fractured and cut by hornblende seams. Magnetite, epidote (zoisite) and sphene are present in trace amounts. Average grain sizes may be up to 5 mm.

The leucocratic gneisses are grey to off-white, weathering yellow-brown, fissile and massive rocks always containing a discordant felsic vein and/or dyke phase. The banding reflects variable quartz: plagioclase ratios and seams rich in hornblende and/or biotite. Pods of marble, metaquartzite and biotite-schist or gneiss were noted.

In thin section, oligoclase laths were seen to be generally dominant over strained quartz grains. Any garnet phase forms anhedral porphyroblasts (less than 1 mm in size and therefore smaller than garnets in the melanocratic gneisses). Hornblende prisms occur in clusters with biotite plates aligned to define foliation planes. Magnetite, epidote and white mica occur in minor amounts.

The metaquartzites are massive, coarse-grained and predominantly composed of translucent quartz grains. A semi-penetrative foliation may be seen on weathered surfaces, which are patchily stained by weathering of iron phases (pyrite and magnetite). White mica flakes and ragged kyanite blades are locally present.

Marbles form thin seams in leucocratic gneisses, e.g. south-west of Korr Mission, and more impressively two major hills through the Marsabit Shield. In the larger exposures the marbles are seen to be lithologically varied with massive, coarse-grained, badly jointed pure rocks — banded, fine-grained siliceous marbles (with calc-silicate minerals) — graphitic grey marbles. Minor carbonate veins are present in all these lithologies. Chemical analyses (see Chapter 6) indicate that all the marbles are mixtures of dolomite and calcite.

As expected, equant carbonate grains dominate the modes with minor amounts of tremolite (skeletal grains), graphite (serrated flakes), talc, white mica, apatite and opaques. The grain size of the marbles varies up to 1 cm.

Biotite-schists are exposed in a well in the river bed south-west of Korr Mission and consist entirely of puckered black-brown biotite flakes.

The pyroxene-amphibolites are black, massive rocks which form low hills covered by angular boulders. Red garnets are common in these medium- to coarse-grained rocks which lack any orientated fabrics. Associated lithologies are quartz reefs, quartz-epidote pods, ultramafic schist and leucocratic gneiss seams.

Hornblende and diopside are the principal phases with hornblende locally replacing diopside. Garnet (up to 30 per cent of the mode), labradorite and (primary) hypersthene may also be present in equigranular textures.

Ultramafic and ultrabasic rocks underlie four hills south of the two marble hills through the Marsabit Shield, as well as forming minor bands or pods in the main area of the Korr Complex. The ultramafic rocks are fine- to medium-grained with felted texture of interlocking acicular or platy minerals. The commonest lithology is a black-green chlorite-rich rock with or without hornblende and/or magnetite octahedra. They may have a crenulated schistosity. Less common are hornblende-epidote rocks. A relatively coarse altered ultrabasic (peridotite) underlies the lowest of the four hills. This is massive, homogeneous dark (almost black) and cut by a network of white magnesite veins (trenches into the veins drew attention to the hill during the helicopter-supported fieldwork). In thin section the peridotite is seen to consist of olivine grains strongly altered to iddingsite and antigorite. Minor amounts of tremolite, talc, carbonate and red-brown opaque (?chromite) are also present. The average grain size of all the rocks is about 2 mm with the magnetite octahedra up to 6 mm across.

The origin of the Korr Complex is enigmatic. The pyroxene-amphibolites are unlikely to have been eclogites (Randel, 1970) as all the diagnostic minerals are metamorphic. The presence of altered peridotites and abundance of probable basic metavolcanics (the melanocratic gneisses) suggest that the complex may be a dismembered ophiolitic unit. The metasediments would not be out of place in such an environment. However, these rocks have been tectonically emplaced into their present setting and this fact will alway pose a question mark over any discussion on their origin.

The western gneisses

The western gneisses are lithologically similar to the Kotim Gneisses which are extensively developed to the south, underlying major mountain ranges (Key, 1984). They are therefore placed within this lithostratigraphic formation. On the map-area they are confined to the south-west corner where they are poorly exposed on the Korante Plain. Outcrop is confined to the inselbergs, the lower slopes of the Marti Engweta and the easternmost hills of Ol Doinyo Mara. There is no outcrop on the low ground or in the numerous river beds. Photogeological lineaments are confined to the high ground and consist of finely spaced lineaments related to gneissosity and negative features, presumably traces of joints or faults. The morphology of individual hills is controlled by the trend of bedrock gneissosity (see Chapter 2).

Reference sections for the Kotim Gneisses are taken from more accessible southerly areas (Hackman and others, 1986). The inselbergs adjacent to the only track across the Korante Plain afford outcrops of typical quartzofeldspathic gneisses. A traverse across the northerly E–W-trending rib of Ol Doinyo Mara would encounter all other lithologies apart from the augen-gneisses and hornblende-gneisses. The augen-gneisses form a prominent rib (on the main easterly extent of Ol Doinyo Mara) slightly discordant to the gneissosity. Hornblende gneisses underlie low kopjes in the extreme south-west and immediately north of Marti Engweta.

The gneisses define a series of regional antiforms and synforms (wavelengths of about 10 km) with NNW axial traces, and cut by NNW- and NNE-trending shear zones. Several faults are inferred from major negative lineaments trending NE to ENE. The relationship between the Kotim Gneisses and Korr Complex has already been discussed. Miocene basalts overlie a planar erosion surface of the Kotim Gneisses on the Marti Engweta.

The thickness of these gneisses is not known: repeated tectonic thickening has taken place so that present thicknesses of individual units are misleading with regard to original (sedimentary) thicknesses, e.g. the biotite gneiss unit exposed on Ol Doinyo Mara is c.4000 m thick.

The quartzofeldspathic gneisses display subtle variations in texture. They are greyish-white to translucent grey rocks patchily weathering to shades of white-brown to pink. Grain sizes vary from less than 1 mm to about 3 mm. They tend to be massive with a variably defined gneissosity (by mafic seams or aggregates, grain size variations, shape orientation of felsic and mafic grains, or non-existent). If the gneissosity is defined by shape orientation of quartz the rocks are flaggy. Alternatively where the gneissosity is weakly defined the rocks resemble massive granites. *Lit par lit* felsic veins are generally present and may be a major component. Pegmatites are rare. The gneissosity is folded on outcrop scale, especially in M-zones of regional folds. The style of the small-scale structures varies from isoclines to open warps, i.e. several generations of minor folds are preserved. Joints are prominently displayed, especially NNW sets.

Thin sections show that the dominant feldspar phase varies from plagioclase to K-feldspar (orthoclase, microcline and microperthite might co-exist). Generally one or other is dominant with only minor amounts of the other phase, i.e. the rocks are either granites *sensu stricto* or granodiorites. In only one case was a myrmekitic intergrowth of plagioclase in orthoclase noted. However all the rocks have cataclastic textures, which, in extreme cases (the flaggy gneisses), are mylonitic. Quartz grains are strained, granulated or tabular when completely recrystallised. K-feldspar porphyroblasts are variably sericitised or replaced by muscovite flakes and may also be granulated or internally cracked. Plagioclase grains may be zoned. The feldspars are generally present in greater modal amounts than quartz. Other minerals (green hornblende, brown biotite, muscovite, apatite, hematite, magnetite) are only present in minor amounts. Biotite flakes may be aligned to define a foliation, or randomly orientated along felsic grain boundaries. In one case chlorite and sericite were seen replacing biotite.

Biotite-gneisses are medium-grained (up to 2 mm grains), well-banded or speckled rocks with *lit-par-lit* felsic veins. Red garnets are usually present. One thin section showed a weakly cataclastic texture with a matrix of strained quartz grains, oligoclase laths and equant magnetite grains. A planar fabric is defined by orientated green biotite flakes. Almandine garnet occurs as relict poikilitic grains, with quartz chadacrysts.

The metasedimentary unit (mgs) consists of fissile, finely banded, fine-grained biotite-gneisses with thin concordant metaquartzite and ultramafic schist bands. Red garnets are ubiquitous in the metaquartzites and gneisses and may constitute in excess of 20 per cent of the rock volume. The metaquartzites are fissile, translucent-grey rocks weathering to shades of yellow and purplish-brown. Sillimanite and garnet may be seen in hand specimens as well as minute pyrite flecks. The ultramafic schists are coarse felted aggregates of vivid green plates weathering strongly to shades of brown.

In thin section the metaquartzites are seen to consist of strained, embayed and anhedral quartz grains up to 2 mm in size with minor amounts of sericitised microperthite, plagioclase, garnet and sillimanite. The last occurs as orientated fibres and as massive grains.

The ultramafic schists consist principally of tremolite plates with anthophyllite and minor amounts of magnetite and chlorite in a felted matrix.

An impure metaquartzite underlying the hill in the extreme south-west lies within a major shear zone and consequently has a strong foliation. It has a grey colour and contains more feldspar than the metaquartzite seams described above. A breccia within the same shear zone is a dark grey, fine-grained massive rock with folded pseudotachylite veins and angular (upstanding on weathered surfaces) black quartz grains. In thin section a fine network of opaque material along brittle microfractures cuts strained quartz grains, strongly sericitised K-feldspar, rounded zircons, reddish biotite, plagioclase and hornblende clusters.

Hornblende gneisses are rare and are dark grey, fissile to flaggy, medium-grained rocks in which hornblende, plagioclase and minor quartz are visible to the naked eye.

The hypersthene-bearing rocks underlie two rounded hills on the Ol Doinyo Mara and are distinctive red-brown weathering, dark green, massive, homogeneous, medium-grained rocks. They lack any orientated fabric. In thin section they were seen to have a matrix of quartz and plagioclase with minor orthoclase. Relict hypersthene grains (partly replaced by hornblende) and poikilitic garnets and biotite flakes are disseminated in the felsic matrix.

The augen-gneiss, forming a distinctive (discordant) rib on Ol Doinyo Mara, is a fissile, translucent-grey rock containing numerous pink feldspar augen up to 0.5 cm in size. Muscovite, biotite and opaques are also visible in hand specimens. In thin section the augen are found to be microperthite, sheared by mylonitic quartz stringers in a granulated matrix of these two minerals. Microfractures cut the augen.

Evidence from the type area (to the south) of the Kotim Gneisses suggests they are predominantly metasedimentary (meta-arkoses). However in the present area the extreme (granulite facies) metamorphism has recrystallised the quartzofeldspathic rocks so that in places they resemble foliated granites or granodiorites. The homogeneous nature of the hypersthene-bearing rock implies it was originally a concordant intrusive sheet, i.e. in the map-area the Kotim Gneisses are a composite igneous/sedimentary unit. Dodson (1963) comes to the same conclusion for the adjacent rocks westwards. He records abundant K-feldspar and diopside in the hypersthene-bearing rocks, i.e. they are two-pyroxene granulites (charnockites).

3.2 MAIKONA FORMATION

This sedimentary unit is named after Maikona because good exposures of typical gritstones occur in river gullies at the south-east end of that settlement (Plate 11). These rocks crop out in two distinct belts: south-east from Maikona to the edge of the Marsabit Shield, and secondly on the basal slopes of the mesas of the Koroli Desert. It is probable, that the intervening Chalbi Basin is underlain by a more argillaceous facies of the Maikona formation.

The present morphology of the formation is subdued.

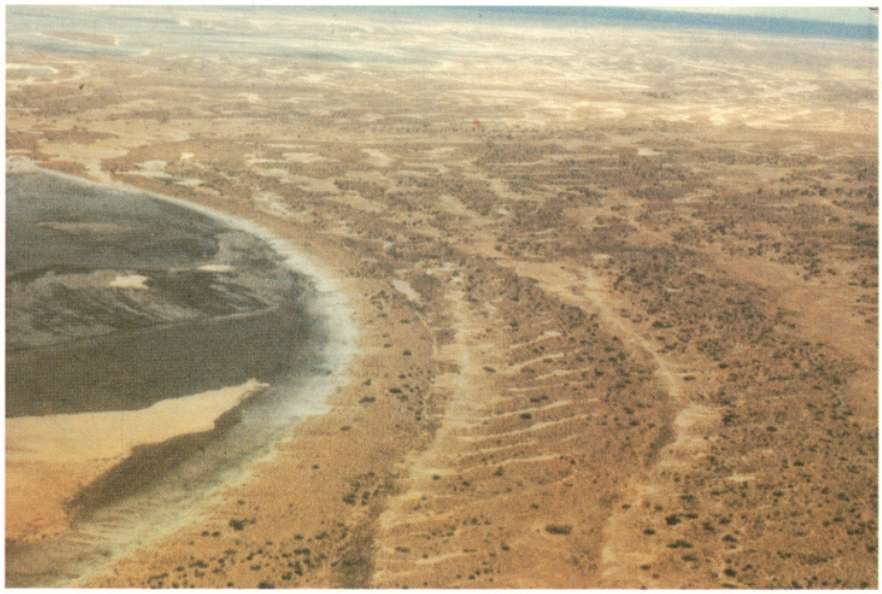


Plate 7
Strandlines along south-west margin of Chalbi playa



Plate 8
The summit area of the Asie Shield with Kulal in the background



Plate 9
The summit area of the Marsabit Shield looking north

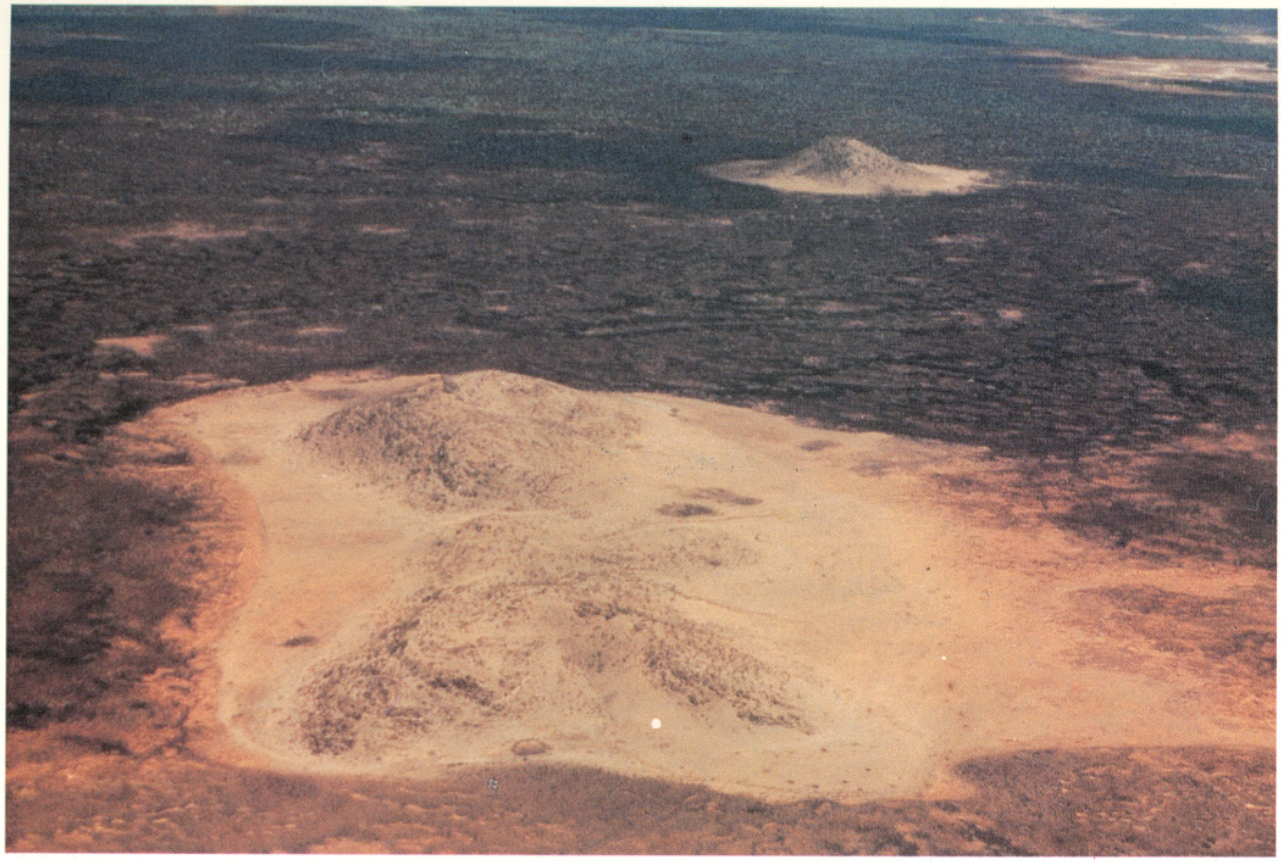


Plate 10 The marble hills of the Korr Complex



Plate 11 Maikona formation outcrop in the Laga Dambito

In the area south-east of Maikona a bevelled gritstone surface is either overlain by basalts or by aeolian sand. Locally the basalts may be seen to have infilled hollows in the gritstone surface (e.g. exposures in the Laga Dambito, Plate 11). The gritstone embayment into the Marsabit Shield along the main Maikona to Marsabit track suggests that the gritstones formed a more positive feature during the volcanism, which diverted the lavas. Impressive gullies are still present in river sections in this area (Plate 12). In the Koroli Desert the gritstones form a level surface overlain by either basalts or unconsolidated (Karole formation) sediments. Where these gritstones are not masked by basalt scree they form bright, highly reflective areas on photographs in contrast to the basalts and the unconsolidated superficial deposits. However, in the Maikona belt the gritstones have a more variable reflectance principally caused by variations in the thickness and type of overburden. Outcrop produces a monotonous grey photo-tone due to dark-reddish weathered surfaces. Paler tones are caused by thin sand mantles which become more reflective (brighter white) as the sand becomes thicker. Negative lineaments in this belt are related to master joints or faults.

Formalisation, by defining type sections, will have to await drill-hole information. The following (reference) sections provide good outcrop of gritstone.

1 River sections at the south end of Maikona where gritstone 'windows' through basalt are exposed (Plate 11).

2 The (more extensive) river section immediately north of Konon Mayidadte where cliffs up to c.10 m high are exposed (Plate 12).

3 Along the main Maikona to Marsabit track at the edge of the Marsabit Shield. Gritstone pavements are well exposed.

4 The northern slopes of the mesa at Garanyal where about 30 m of sedimentary rocks are exposed.

5 Around north-north-west of Kargi where as much as 70 m of bedded sedimentary rock is exposed.

No fossils were found in the Maikona belt although spores might be present in mudstone clasts in the gritstone (Plate 14). Petrified wood occurs in the Koroli Desert outcrops. Five pieces of angiosperm wood submitted by Professor Nyamweru (Kenyatta University College, Nairobi) to the British Museum (Natural History), London, were identified as follows (Crawley, *pers. comm.*): '5 pieces of permineralised angiosperm wood. All the specimens consist of secondary wood. Four of these show similarity to the living genera *Afzelia, Dichrostachys, Macrolobium* and *Piptadenia* (all Leguminosae Family). These would be assignable to the fossil form genera *Pahudioxylon, Dichrostachyoxylon, Berlinioxylon* and *Mimosoxylon* respectively. The fifth specimen shows similarities to *Copaifera* and *Guibourtia* (both Leguminosae) but also *Chukrasin* (Maliaceae Family). At present I would assign this to ?*Copaiferoxylon* form genus. The age of these specimens would be Cainozoic and I would suspect more precisely Neogene (Mio-Pliocene) from the type of wood and strata present in Northern Kenya'.

Uncertainty exists over the exact age of the Maikona formation whose age limits are set by the overlying Late Miocene–Pliocene basalts and the end of metamorphism in the Mozambiquian orogeny in northern Kenya (c.510 Ma). Its most likely age is either (1) Cenozoic from the fossil wood evidence or (2) Cretaceous, as the gritstones are lithologically identical to the dinosaur-bearing Turkana Grits from west of Lake Turkana (Walsh and Dodson, 1969).

The gritstones are ubiquitously subhorizontal (except for major planar cross-beds with dips up to 20°). Their upper contacts have already been described. Basal contacts are not exposed. The present southern outcrop limit is the Koroli Desert: as in the Korante Plain the Late Miocene basalts rest directly on metamorphic rocks. Lineaments related to fractures trend c.NW and c.NE.

The thickness of the Maikona formation is not known. A maximum exposed thickness is about 70 m in the Kargi area. A borehole at Kargi stopped in sandstone after 95.7 m (Chapter 6).

The major lithology in the Koroli Desert is a brownish, red-weathering, medium- to coarse-grained gritstone. It is well-bedded, locally with planar cross-beds and graded units, and is consequently flaggy. Rounded quartz (clear, white, yellow and red) and angular feldspar (white, pink) clasts up to several centimetres in diameter are common. These larger fragments form a diagnostic float in a pale grey soil. For c.1 m beneath the capping of basalts the gritstone is stained a bright red.

Similar gritstones in the Maikona belt (see Plates 12–14) contain pebble beds, usually characterised by rounded quartz but with angular feldspar, and aligned mudstone and sandstone clasts, to accentuate a pronounced flaggy character. Planar cross-beds (foresets dipping at up to 20°) and less commonly, low-angle festoon cross-beds are present. No obvious volcaniclastic material was observed.

In thin section the gritstones are seen to have a hematite-rich matrix, supporting angular quartz grains (0.2 mm average diameter) with minor sericite, white mica and vermiform chalcedony.

The nature of the sedimentary structures would suggest that the gritstones represent deposition at the distal end of a braided stream system (see Key, 1983). However, the angularity of the matrix quartz indicates that the source area was close. Presently quartz-bearing gneisses (the most likely source rock) are exposed within 25 km to the south of the Koroli Desert, and in fact underlie most of this part of Kenya. If the present SE alignment of the Maikona belt reflects the trend of a former range of hills (rather than being fortuitously controlled by basalt erosion), it would suggest SE orientated faulting. The linearity of the southern margin of the Chalbi Basin also indicates SE faulting which could have influenced sedimentation of the Maikona formation within a (Chalbi) basin, with infill from both the south-west and north-east along braided rivers. Drillholes into the gritstones and into the Chalbi Basin are required before a more definite statement on this formation's origins can be made.

Confidential oil-exploration geophysical data (Ministry of Energy) confirm the idea of a NW-trending graben under the Chalbi Basin.

3.3 KAROLE FORMATION

Poorly consolidated, fine-grained sediments are locally exposed beneath the basal basalts of the north-west and west parts of the Marsabit Shield. The best exposure (Plate 15) seen by the author was at Karole waterhole so they are informally referred to as the Karole formation. They were seen at the following locations (others certainly exist along most of the western edge of the Marsabit Sheild, but are largely masked by basalt debris):

1 Near the Marsabit to Maikona track where it crosses the northern part of the Marsabit Shield.

2 Mayidadte waterhole.

3 Koronli waterhole.
4 Karole waterhole.
5 Algas (see Nyamweru, 1984).

Similar deposits are locally present on mesas in the Koroli Desert sandwiched between the gritstones of the Maikona formation and basalts.

Exposure is confined to scarp slopes overlain by basalt flows. As such the photo-expression of the sediments is largely masked by a cover of basalt scree. However their presence may be detected by their high reflectance on the edges of the Marsabit Sheild. It is also true that wherever there is water seepage at the edge of the Marsabit Shield there is outcrop of the Karole formation. Therefore observation of springs on photographs is a good indication of the presence of the Karole formation sediments.

No type section was measured in these thin deposits. Nowhere were they seen to be more than 15 m thick. The best place to define a type section would be at Karole where good exposures of a variety of lithologies are exposed in a major gully.

Fossil bones and teeth are present and Nyamweru (1984) listed an extensive fauna from Algas to include: *Lates niloticus*, Clariidae, *Trionyx, Pelusios, Crocodylus niloticus, Euthecodon*, Cercopithocinae, *Elephas recki, Deinotherium bozasi*, Rhinocerotidae, *Equus olowayensis, Mesochoerus limnetes, Metridiochoerus andrewi* (II), *Hippopotamus* cf. *imaguncula, Camelus, Sivatherium maurusium*, Tragelaphini, Alcelaphini, *Menelikia*, Lyrocera.

At Karole the basal unit is a shelly limestone almost entirely composed of complete and fragmented molluscs.

These sediments predate the basalts of the Marsabit Shield. Nyamweru (1984) quotes an age of 2.5 + 0.3 Ma for the basalt immediately above the sediments at Algas. The present author regards the Karole formation as part of the infilling of a former Lake Chalbi in Late Miocene–early Pliocene times (see Chapter 2) which would agree with a pre-2.5 Ma age.

The Karole formation sediments are horizontally bedded and are sandwiched between the subhorizontal strata of the Maikona formation and the basal basalts of the Marsabit Shield or the basalt caps of the Koroli Desert mesas.

No exact measurements of this formation's vertical thickness were made but it is of the order of 15 m.

The soft sediments show some variety, although white and brown unconsolidated silts are dominant. At Karole there is a basal shelly limestone, almost entirely composed of fragmented (rarely complete) gastropods. It forms a pavement to the gully floor and is overlain by c.12 m of a very pale brown unconsolidated silt exposed in the gully wall. Numerous, horizontal hardpan calcrete seams up to c.10 cm thick are present in the silt (Plate 15). They are locally nodular, where they appear to be secondary after bones. Fossil fragments were not seen *in situ* but weather out of the soft sediment to collect in the gully floor. An uppermost 2.4 m of dark brown silt immediately underlies basalt. Elsewhere green laminae are present in the sediments which may be more consolidated and fissile.

No petrology was attempted on the unconsolidated silts. One of the large calcrete nodules was sliced (in an attempt to locate a bone nucleus) and was composed entirely of carbonate material.

The Karole formation is regarded as lacustrine in origin and part of the proto-Lake Chalbi. Nyamweru (1984) notes that the Algas fossil assemblage indicates a deep body of water with Nilotic affinities, with adjacent grassland.

3.4 CENOZOIC VOLCANIC ROCKS

Basalts of the Korante Plain and Koroli Desert

Basalts cap mesas and plateaus in the Korante Plain and Koroli Desert. They have dark photo-tones with numerous, irregular paler patches caused by the superficial infills to natural hollows in the basalt surfaces. Rare negative lineaments are due to joints and minor faults. No reference sections are defined but the most accessible places to examine the basalts are the west end of Marti Engweta and the south end of Falama. Both are close to motorable tracks.

K-Ar dates of 7.7 ± 0.4 Ma (Brotzu and others, 1984) and 3.44 ± 0.4 Ma have been obtained from basalts from Marti Engweta and Garanyal respectively (see Appendix 1).

The basalts are horizontal and were deposited on planar surfaces (see previous sections). They are well jointed, locally with columnar joints, and cut by minor faults. At the north-east end of Marti Engweta a NNW fault downthrows basalt eastwards. On Falama a NNE lineament is thought to be due to a dyke (Kargi inhabitants report a 'very heavy rock weathering into circular pieces which form a straight line' in this area).

The basalts are never in excess of 30 m thick and commonly less than 5 m thick. They are erosional remnants and commonly only the lower scoriaceous parts of a basal flow are now preserved. In thicker sections several flows are still present. Typically the basalts have scoriaceous basal zones (which may also have blocky textures) with fissile aphanitic, homogeneous centres. Columnar joints are well developed in the fissile parts. In cases where tops of flows are preserved they are vesicular. Complete flows are c.10 m thick. Minor secondary calcrete is present along joints (notably in the Kargi area).

Petrographic examination of the base and centre of the basalts show them to be relatively coarse rocks (compared to the younger Shield basalts) with no microcrystalline matrix. Dominant phases are unorientated labradorite laths (max. An value = 64), augite and variable altered (to iddingsite) olivine grains, all from 0.1 to 0.7 mm in size. The only other phase noted was magnetite. Larger plagioclase laths are zoned.

According to Brotzu and others (1984) the basalts underlying Marti Engweta are tholeiitic. However, a single whole rock analysis of the upper flow capping Garanyal plateau (Table 2) showed the lava to be an alkaline basalt. In common with all basalt analyses from sheet 20, this rock (RK/20/75) has high Na_2O and low Al_2O_3 relative to standard basalts (e.g. see the table of average Rift basalts from Kenya *in* Weaver, 1973). However on a SiO_2 vs alkali plot (Figure 7) the analysis plots in the basalt field and on an AFM diagram (Figure 6) lies within the alkali basalt range (confirmed on a Peacock diagram and by a low Grasso index, Peacock, 1931; Grasso, 1968).

The basalts are erosional remnants and originally may have formed major platforms supporting shield volcanoes similar to the (later) Marsabit, Huri, Asie and Kulal shields. They are thought to have fissure sources (cf. Williams, 1978) although no infilled fissures were seen during the present survey.

North-west Volcanic Province

Portions of two major shield volcanoes resting upon a common basalt platform extend into the north-west of the

Table 2 Whole rock analyses from Marsabit area

Sample No.	75	102	71	67	35	49	77	43	96	32	23	33
wt%												
SiO_2	49.3	45.4	53.9	48.3	48.7	47.5	44.6	47.4	43.5	44.8	44.2	53.00
Al_2O_3	12.77	10.99	6.77	10.77	12.77	10.10	13.88	15.32	12.70	15.09	13.43	1.04
CaO	8.40	11.20	9.52	10.08	10.08	9.52	10.36	7.84	10.08	8.40	9.24	1.96
MgO	5.44	8.87	10.28	9.47	8.47	13.19	6.25	5.24	7.86	4.03	6.85	37.09
FeO	6.90	7.76	8.91	8.91	10.49	8.91	8.91	6.61	7.17	3.30	5.75	6.03
Fe_2O_3	6.44	3.77	2.14	2.61	1.84	2.81	4.03	6.02	5.13	7.47	5.04	—
K_2O	0.66	1.27	0.72	1.39	0.60	0.72	2.14	1.39	0.66	2.05	1.69	—
Na_2O	4.85	5.32	3.23	3.10	2.69	3.03	4.85	3.77	4.65	6.81	6.33	1.13
MnO	0.23	0.19	0.32	0.32	0.26	0.29	0.23	0.29	0.22	0.36	0.32	0.1
P_2O_5	0.37	0.49	0.26	0.44	0.40	0.18	0.37	0.41	0.61	0.63	0.74	0.11
TiO_2	3.29	2.54	1.63	2.38	1.67	1.46	3.25	2.67	2.88	2.29	2.25	—
L.O.I.	1.2	1.9	2.1	2.4	1.4	2.4	1.0	2.8	4.8	4.3	4.0	0.6
Total	99.85	99.70	99.78	99.45	99.37	100.11	99.87	99.76	100.27	99.53	99.84	101.06

TRACE ELEMENTS	75	102	71	67	35	49	77	43	96	32	23	33
ppm												
BaO	447	335	279	447	391	223	223	279	223	502	447	—
Cr_2O_3	146	380	482	336	263	336	117	88	263	73	263	1700
SrO	331	485	331	473	438	272	497	627	887	922	721	—
V_2O_5	1786	1429	1072	1607	1072	1429	1607	1607	1607	1607	1429	—
Co	35	49	55	51	51	53	51	46	51	34	36	108
Cu	70	72	81	69	72	75	49	30	51	39	42	12
Ni	83	233	341	227	204	354	104	70	202	74	123	1740
Pb	<1	<1	<1	<1	38	<1	<1	<1	3	7	3	<1
Zn	141	102	104	107	135	93	109	105	132	115	125	56
Solidification Index	22	33	41	38	35	46	24	23	31	17	27	86

CIPW NORMS	75	71	67	35	49	43	96	32	33
Quartz		1.11							
Orthoclase	3.90	4.26	8.22	3.55	4.26	8.22	3.90	12.12	0.18
Albite	41.04	27.33	24.53	22.76	31.90	31.90	19.34	21.32	1.10
Nepheline			0.82		1.76		9.62	17.45	
Anorthite	11.13	1.85	11.37	21.00	11.83	20.78	11.83	4.55	2.17
Diopside	22.27	35.34	28.80	21.65	27.49	12.30	27.20	21.65	5.37
Hypersthene	0.19	20.99		11.75		5.33			66.82
Olivine	3.68		13.90	10.85	22.91	3.69	8.03		21.55
Wollastonite								2.17	
Magnetite	9.34	3.10	3.78	2.67	4.07	8.73	7.44	5.17	2.17
Hematite		3.10						4.17	
Ilmenite	6.25		4.52	3.17	2.77	5.07	5.47	4.35	0.08
Apatite	0.88	0.62	1.04	0.95	0.43	0.97	1.44	1.49	0.26
Water	1.18	2.09	2.38	1.38	2.39	2.78	4.77	4.27	0.06
	99.86	99.79	99.36	99.73	99.89	99.77	99.04	98.71	99.69

75 Basalt*, Garanyal Plateau
102 Hawaiite, Olturot
71 Basaltic andesite, eastern base of Asie Shield
67 Basalt, western side of Asie Shield
35 Basalt, north base of Marsabit Shield
49 Basalt, north-west base of Marsabit Shield
77 Basanite, south-west base of Marsabit Shield
43 Basalt, Gof Kolbo, west centre of Marsabit Shield
96 Basanite, summit area of Marsabit Shield
32 Tephrite, summit area of Marsabit Shield
23 Basanite, lava tongue, west part of Marsabit Shield
33 Peridotite nodule, Marsabit Shield
* Lithological nomenclature based on alkali and silica content of soils.

area. One forms Kulal mountain, mainly developed westwards. and is referred to as the Kulal Shield (Williams, 1978). The other defines a lower range of hills and is given the name Asie Shield, after the highest peak (a cinder cone). The range of hills is variously referred to as the Chariache or Laithwaite on maps.

The morphology of the province has been described in Chapter 2. On aerial photographs the dominant basalt lavas have relatively dark tones contrasted to the various pyroclastic material along the Asie Shield summit plateau. All the cinder cones are easily recognised on the photographs by the characteristic shape (they have basal diameters of up to 800 m). Only three *maars* are present which form prominent photofeatures up to 1.2 km in diameter. Negative lineaments, often accentuated by drainage channels, are related to traces of minor faults. Aeolian sand areas banked against upstanding features (e.g. burial mounds) on the NE basalt platform have white, reflective photo-tones.

The following sections provide good outcrops of the three principal lithologies comprising the Asie Shield.

Basalt lavas any of the eastern gorges, e.g. the gorge at g.r. 295 322 exposes c.16 flow units (Plate 16).
Cinder cone pyroclastics Asie Hill (Plate 17) or any of the cones along the summit plateau (Plate 18).
Block-and-ash cone pyroclastics the stream section at g.r. 278 324 (Plate 19).

No reference sections are defined for the Kulal Shield which is mainly developed on sheet 19 to the west. The platform basalt is well exposed in pits at Olturot.

Four suites of samples were collected for K-Ar dating to include a platform basalt from Olturot, a basal lava from the gorge at g.r. 295 322, an upper lava from g.r. 278 324 (the flow shown in Plate 20), and an uppermost flow from the summit area of the Asie Shield at g.r. 286 320. The ages obtained are as follows:

Uppermost lava (g.r. 286 320) = 2.07 ± 0.13 Ma
Upper lava (g.r. 278 324) = 2.04 ± 0.60 Ma
Basal lava (g.r. 295 322) = 2.70 ± 0.35 Ma
Platform lava (Olturot) = 1.91 ± 0.21 Ma

i.e. a time span of about 0.70 Ma for the development of the Asie Shield. Nyamweru (1984) quotes unpublished K-Ar whole rock ages of between 2.0 and 2.4 Ma for basalt lavas from the southern slopes of Kulal.

Asie Shield has an oval surface shape with a c.65 km long axis orientated towards 018°, and a short axis c.15 km long. This shape together with the concentration of later eruptive centres along its long axis indicates an underlying fissure controlled the Shield volcanism. Late fractures trend N or NNW with the N set possibly related to Rift tectonism. As mentioned in Chapter 2 the Kulal Shield effectively defines part of the eastern shoulder of the Rift Valley in northern Kenya.

Based on its topography, the Asie Shield has a maximum (crestal) thickness of c.500 m of basalt lavas and intercalated pyroclastics. This thins to zero radially towards shield margins with a related rapid reduction in the amount of pyroclastic material. The Asie Shield covers a surface area of c.1000 km^2. Individual basalt lava flow units have remarkably uniform thickness of c.8 m (Plate 20). The cinder cones have a present maximum height of c.161 m (Asie Hill) with radial dips and surface slopes of up to 28°. By contrast the rarer block-and-ash cones of the *maars* are presently less than 100 m in height with radial dips away from the *maars* of up to 19°.

The part of the Kulal Shield present on the map-area has a vertical thickness of c.100 m of basalt lava. The platform basalt is less than 30 m thick.

The basalt flow units of the platform and the shields typically have rubbly bases overlain, with sharp uneven contacts, by fissile centres with poor developed vesicular tops. On Asie Shield they weather to a distinctive orange-brown colour. The rubbly bases are up to 3 m thick, supported by angular scoriaceous basalt debris ranging in size up to 1 m. The larger blocks have quenched marginal textures. Both a brown soil matrix and minor secondary carbonate are generally present. Upper contacts of this unit are irregular and locally overlain by the rubble base of the next flow unit with no intervening fissile lava. Generally however the central parts of the flows are c.5 m thick, consisting of massive aphanitic rocks with conchoidal fractures (Plate 20). Olivine phenocrysts are ubiquitous (petrographic examination, see below) but rarely large enough to be seen by the naked eye. The massive centres grade upwards into vesicular flow tops up to 0.5 m thick. Individual vesicles are circular and less than 2 mm in diameter. Red soil pockets are locally intercalated between flow units. Individual flow units are laterally continuous in the walls of the eastern gorges maintaining constant (c.8 m) thicknesses over several kilometres of exposure. Narrow lava 'tongues' emanating from summit cones are rare (compared to the Marsabit Shield). Lava surfaces are featureless with no signs of *pahoehoe, aa*, or pillow textures.

The cinder cones consist almost exclusively of very thickly or thickly (Ingram, 1954) bedded, friable lapilli breccia (terminology of MacDonald, 1972). Individual lapilli consist of angular scoriaceous basalt, the majority of which are fragments of fusiform bombs. No matrix is present but 'cow-dung' bombs do form a minor constituent. Within a single cone, lapilli size does not vary from layer to layer (separate showers of fragments) and within layers the lapilli are well sorted. Rarely a basal splatter unit is composed of welded cylindrical ribbon bombs. Thin aphanitic basalt flows may have conformable basal contacts but eroded tops. No summit craters occur on the cinder cones of the Asie Shield in the map-area (Plate 18 shows a typical profile). Most cones have a peripheral apron of weathered (hillwash) lapilli breccia.

The *maars* have composite walls consisting of (basal) basalt flows overlain by block-and-ash cones which define summit rims. The sides of the cones facing *maar* centres are steep whereas the outer sides dip gently towards the summit plateau so that these cone deposits define radial wedges (see plates of Gof Barachuma, Marsabit Shield). Only the cone deposits are elevated above the general ground level, i.e. there is no build up of lava around the *maars*. The block-and-ash cones are composed of thinly bedded, brown, friable ashes with a variable clast content between beds as well as within beds (where sets and co-sets may be identified by the variation in lapilli: and block content). Where the block content increases above 25 per cent the deposits are relatively well consolidated to form tuff-breccias. Minor amounts of fusiform bombs and individual crystals of olivine, clinopyroxene are also present. However the deposits are always matrix-supported. Minor sedimentary structures include ubiquitous cross-bedding, local unconformities, distortion of beds around large blocks or bombs. Secondary calcite is patchily developed.

Gully sections into the summit plateau expose intercalations of various horizontal pyroclastic deposits between basalt lava flows. These include lapilli breccia (of cinder cone deposits), thinly bedded ashes with minor amounts of equant clinopyroxene crystals and (?) black

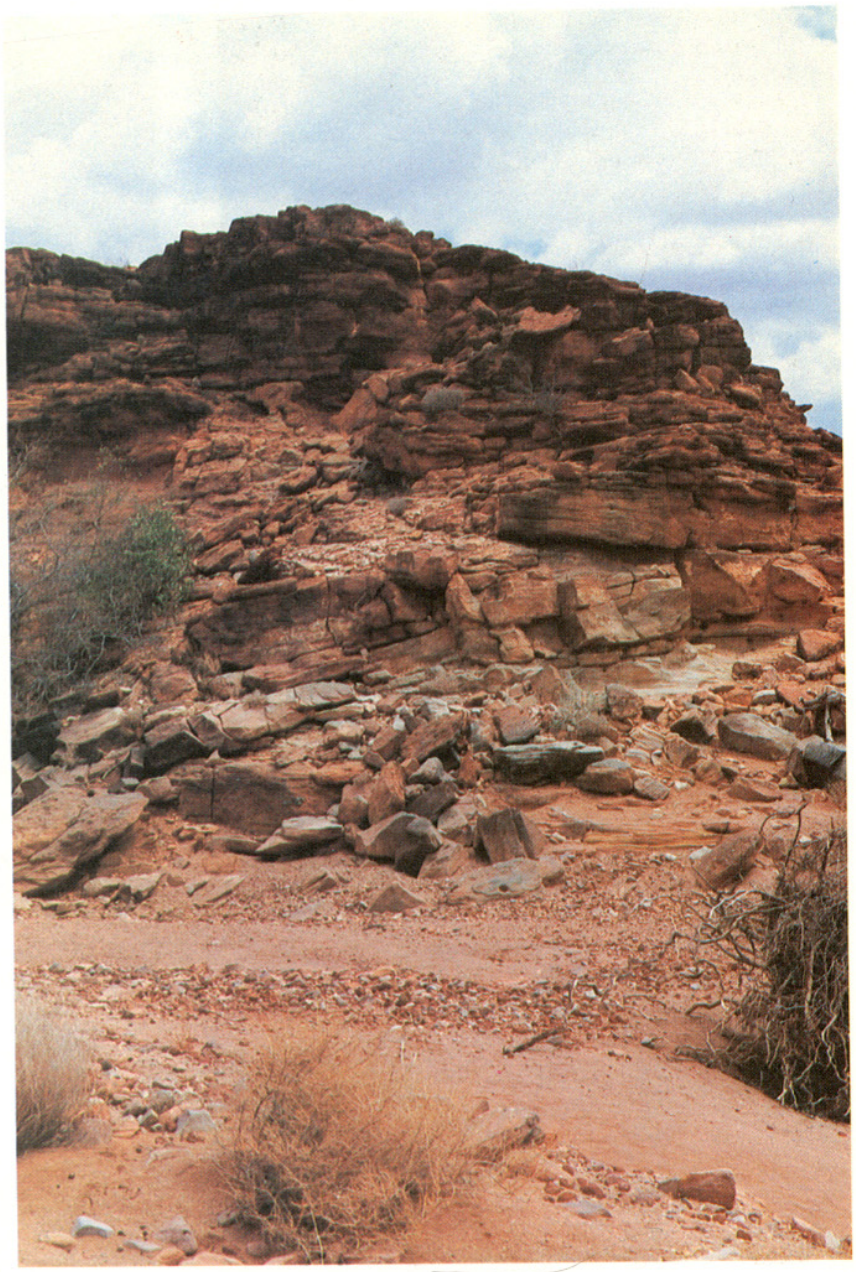


Plate 12
Maikona formation outcrop, Konon Mayidadte area



Plate 13 Detail of the typical gritstone, Maikona formation



Plate 14 Mudstone clasts in gritstone of the Maikona formation, Konon Mayidadte



Plate 15 Section through the Karole formation, Karole waterhole



Plate 16 Gorge section into the eastern side of the Asie Shield



Plate 17 Asie Hill (cinder cone)



Plate 18 Radially dipping cinder cone deposits, summit of Asie Shield



Plate 19 Bedded pyroclastics containing a single basalt lava, summit of Asie Shield

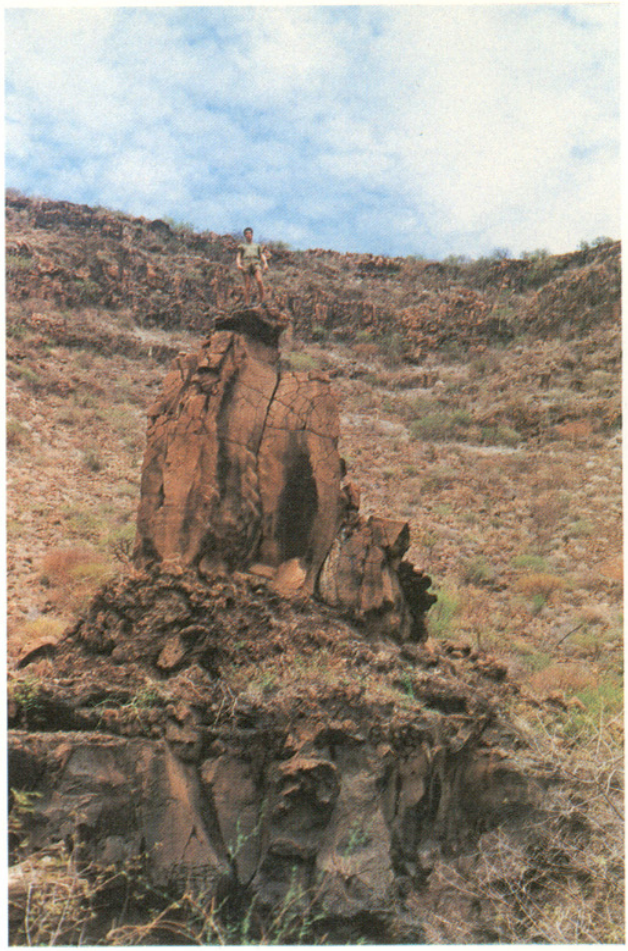


Plate 20
Complete flow unit, east side of Asie Shield

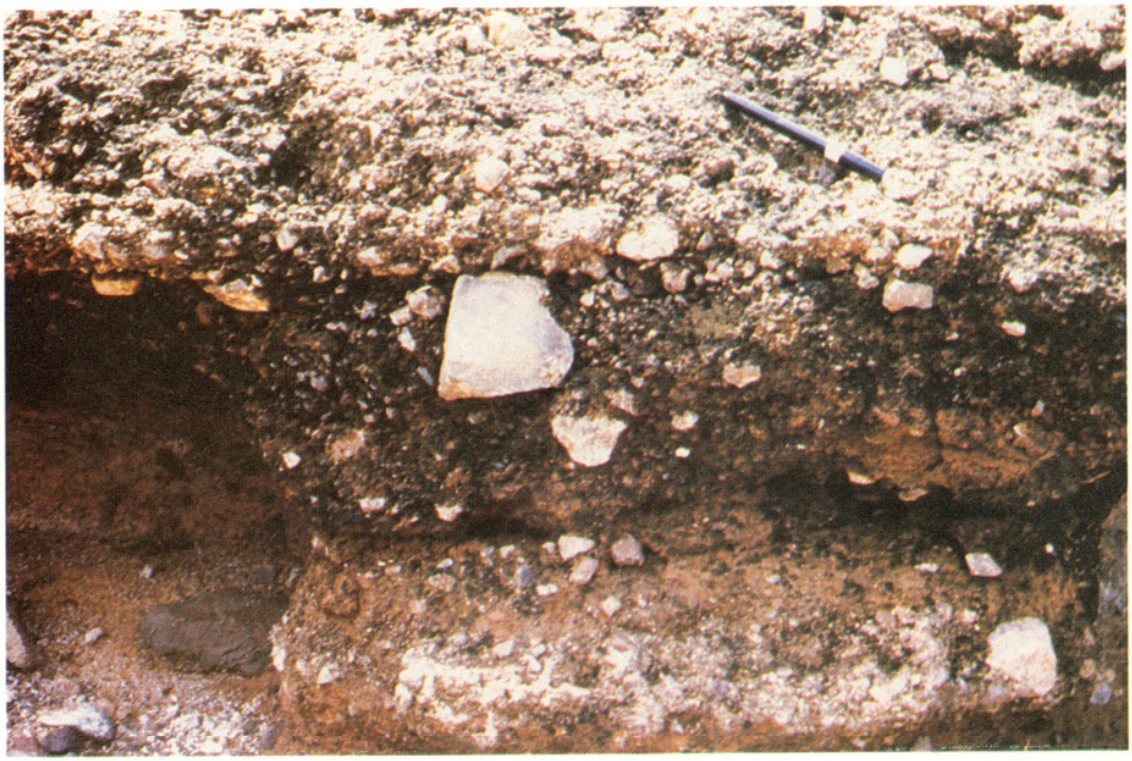


Plate 21 Block-and-ash cone deposit, Asie Shield

glass fragments as well as variable basalt lapilli. All the observed pyroclastic deposits were brown except for an ochreous unit at g.r. 278 308 adjacent to a crystal ash. Secondary calcite cement is again present in minor amounts.

A systematic petrographic study of the basalts revealed a gross compositional trend. The platform basalts are olivine basalts or hawaiites with olivine phenocrysts embedded in a fine matrix of randomly orientated plagioclase laths (An 50–60), microlitic clinopyroxene (probably pigeonite), magnetite and secondary calcite. The olivine phenocrysts are subhedral, variably altered to iddingsite and c.0.3 mm in diameter.

The lower lavas of the Asie Shield are relatively coarse-grained (up to 0.6 mm for silicate phases) ankaramitic basalts with euhedral to anhedral phenocrysts of olivine and augite. Plagioclase (An 67–68) laths of similar size to these phenocrysts may or may not be shape-orientated and are ophitically enclosed by augite grains. Due to the reconnaissance nature of the fieldwork not enough samples were collected to quantify exactly the relative amounts of the different lithologies.

Olivine grains are variably altered (to indicate internal zoning) to iddingsite and the augite grains are asymmetrically zoned. Secondary calcite and magnetite blebs are disseminated amongst the silicates. Calcite also partly infills any vesicles.

The upper lavas of the Asie Shield are analcime-bearing olivine basalts with euhedral to anhedral olivine phenocrysts in a matrix of plagioclase (An 54–68), clinopyroxene (augite), magnetite, analcime and secondary calcite. Once again olivine grains are variably altered to iddingsite with smaller phenocrysts (c.0.2 mm) completely pseudomorphed. The larger phenocrysts (c.1 mm) may be internally strained. Plagioclase laths may or may not be orientated. Analcime infills interstices between the three main phases. Calcite occurs as aggregates, veinlets and infilling vesicles.

From the North-west Volcanic Province, a platform lava at Olturot (RK/20/102), a basal eastern lava (RK/20/71) and lower western lava (RK/4/67) from the Asie Shield were analysed (Table 2). The analyses are sufficiently different to plot in three separate fields in Figure 6: the platform basalt in the hawaiities (agreeing with the petrology), the shield lavas in the basalts and basaltic andesites. However all three plot in the alkali basalt fields on AFM and Peacock diagrams and have alkaline (low) Grasso indices.

The evolution of the Asie Shield appears to have taken place in three major phases.

1 *Hawaiian*-type volcanism to produce a basalt/hawaiite platform and the lower, laterally extensive, thin ankaramitic basalt flow-units. It is deduced that these lavas were erupted from fissure systems trending NNE (and N) parallel to the long axes of Asie (and Kulal) Shields. K-Ar whole rock ages indicate that this volcanism took place in the Late Pliocene. The eastern side of Asie Shield is depressed relative to the western side and this probably reflects on original slope to the surface on which the shield developed.

2 *Strombolian*-type volcanism which produced cinder cones along the axial ridge together with olivine basalt lava flow units which remained laterally extensive. Pyroclastic intercalations are confined to the vicinity of the cones.

3 *Ultravulcanian*-type and *Strombolian*-type volcanism to form the block-and-ash cones and summit cinder cones respectively. Lava flows were rare and confined to short 'tongues' (and also give a Late Pliocene age, Appendix 1).

The only sign of any geothermal activity is the ochre related to phase 2. The small-scale structures of the block-and-ash cones indicate that they were formed as surge deposits (Fisher and Schmincke, 1984).

Eastern Volcanic Province

The Eastern Volcanic Province includes the southern tip of the shield (Huri Shield) forming the NNE-trending Huri Hills and the western side of the shield (Marsabit Shield) centred on Marsabit (Figure 4). They share a basalt platform, the south end of which is referred to the Kaisut Plateau by Randel (1970). The south end of the Huri Shield forms a raised plateau abutting into the Chalbi playa. The Laga Dambito drains into the playa from the north-east with the river channel following the Huri Shield's south-east periphery. Elevated piles of basalt blocks (dark photo-tones) are separated by irregular hollows partly infilled by unconsolidated sediments (pale photo-tones).

The Marsabit Shield has a more varied morphology caused by the different weathering characteristics of the assorted volcanic lithologies. The shield itself has a typical shallow-dome shape profile (Figure 3) with overall surface slopes of less than 6°. The laterally extensive basalt lavas, underlying much of the shield (mainly below the 4000 ft contour), define a flat plateau with a thin soil and scrub cover. Contrasting photo-tones are again (as on Huri) due to accumulated basalt blocks and intervening depressions with unconsolidated sediments. Upper flows locally show black photo-tones (south-west area of shield). However the youngest lavas form narrow tongues which flowed down-slope usually from cinder cone sources. These flows are characterised by elevated flow margins with collapsed centres, an absence of vegetation, and an internal drainage network. Cinder cones, block-and-ash cones and *maars* are concentrated in NW- and NE-trending belts through the shield summit. They have classic profiles (Chapter 2 and Plates 23–26) with many of the cinder cones having breached summit craters in contrast to the Asie Shield cones. Related pyroclastic deposits have pale photo-tones relative to all basalt lava flows. The thickly vegetated summit area, around Marsabit, is notably hilly due to an abundance of weathered (i.e. rounded) pyroclastic cones.

The influence of fractures on the morphology is not significant except where WNW-trending fractures (in the north) are parallel to the prevailing winds and are accentuated by sand blasting. Aeolian sand (highly reflective photo-tones) infills linear depressions related to the fractures. In the south-east corner a series of ENE faults have produced a 'step' effect along the shield margins.

The basal platform is exposed east of Maikona where its most distinguishing features are a massive concentration of dark circles on aerial photographs. Fieldwork showed that these are due to the abandoned rock foundations of former Rendille settlements.

Good ground access is limited to the main tracks through Marsabit (north to Maikona, south to Laisamis, west to Kargi, and tracks in the Marsabit Park). The following reference sections are on, or close to, these tracks.

Platform basalts exposures in the Laga Dambito at Maikona (g.r. 417 823).

Marsabit Shield:

Extensive lava flow-units the *maar* wall in Gofs Barachuma, Bongole and Boro; southwards for 20 km from Marsabit along the Laisamis, track with blasted exposures through the summit basalt lavas.

Uppermost lava tongues the flows at Koronde (near Gof Boro), north of Gof Barachuma and north from Hogichu on the Kargi track.

Cinder cone pyroclastics Hogichu

Block-and-ash-cone (maar) pyroclastics section at Gofs Barachuma and Boro.

Summit lavas and pyroclastics wedges track-side hills and cuttings between Marsabit and Karare.

For details of *Huri Shield* reference sections see Charsley (1986). According to Brotzu and others (1984) the platform basalts underlying the shields were extruded from fissure sources during the Late Miocene (K-Ar basalt ages of c.7.3 to c.5.4 Ma). Volcanism in the Marsabit Shield commenced in the Pliocene (a basal basalt from the west has been dated at c.2.5 Ma, quoted in Nyamweru, 1984) and continued into the Quaternary. Brotzu and others (1984) record K-Ar ages from basalts of c.0.6 Ma (north-west margin) to less than 0.5 Ma (north summit). Five basalt samples collected during the present survey (Appendix 1) give K-Ar ages of c.1.78 Ma to c.0.68 Ma. These include dates of basal basalts (1.70 ± 0.12 Ma) from the north and uppermost basalt tongues (0.68 ± 0.16 Ma, 0.76 ± 0.17 Ma) from the north-west and summit areas. The age of the Huri Shield is discussed by Charsley (1986).

Marsabit Shield has an oval plan (Figure 4) with a NE–SW long axis which is about 115 km long and a SE–NW axis about 90 km long. Volcanic centres (cones and *maars*) are concentrated in two belts, about 15 km wide, trending NW and NE through the summit of the shield. The north-west edge of the NE-trending belt defines a strong lineament on Landsat imagery to suggest a major structural control (contemporaneous with volcanism) to this belt. The north-west belt parallels major faults in the subvolcanic bedrock (Ministry of Energy confidential geophysical data). Smaller fractures either parallel the two major structures or trend N–S or E–W. There is in fact, little faulting within the shield itself. The south-east margin of the shield is controlled by step faults trending NE and downthrowing to the south-east.

The Marsabit Shield has a surface area of about 6300 km^2 (in the east it is locally overlain by younger flood basalts of the Demo Dera) with a total volume of c.910 km^3 of basaltic material. At its summit the shield has a total thickness of c.1200 m of intercalated basaltic lavas and pyroclastics. Individual flow-units have thicknesses from about 5 to 20 m whereas the various pyroclastic wedges may be up to 200 m (maximum) thickness.

The platform basalt exposed south-east of Maikona is a homogeneous well-jointed (locally well-developed, vertical columnar joints) aphanitic basalt weathering to shades of dark brown. According to Brotzu and others (1984) both hawaiites and olivine basalts are present (cf. the Asie–Kulal platform).

Immediately north of Maikona the Huri Shield consists of several flows (individually c.5 m thick) stacked on top of each other to define a scarp which is about 30 m high. The basalts are well jointed (locally columnar), vesicular rocks with a ferromagnesian phase weathering to orange-brown against a dark brown background. Secondary carbonate is common along joint planes. A single thin section showed an ophitic texture with clinopyroxene (pigeonite) plates enclosing well-formed and twinned plagioclase (An 62) laths. Olivine grains are altered to iddingsite and also have augite rims. Magnetite grains are disseminated in this rock (average grain size: clinopyroxene 0.7 mm, olivine 0.1 mm, plagioclase 0.4 mm), and secondary calcite occurs interstitially to the silicates. Equant plagioclase grains are zoned with acicular, colourless inclusions.

Individual flow-units in the Marsabit Shield have variable thicknesses (5 to 20 m) but the thickness of a single flow unit is remarkably constant with essentially planar upper and basal contacts. Individual flow-units consist of basal blocky units (Plate 27), fissile aphyric centres and scoriaceous, locally chilled tops. Thicknesses of these zones vary, with some flow-units being wholly composed of basalt blocks in an unconsolidated, orange-brown basaltic powder. The basalts are invariably jointed with vertical, columnar, conchoidal (fissile centres) and horizontal joints. Textural variations include the presence of horizontal vesicle trails, angular peridotite nodules, ferromagnesian clots, clinopyroxene phenocrysts, overall coarse grain size with the major silicate phases visible to the naked eye. Upper flow surfaces are generally featureless. However pillows are relatively common in the NW quadrant in flows overlying cinder cones. Individual pillows vary in size up to a maximum length of 5 m. Pressure ridges are also present (trending 020°) in this area, e.g. at Gof Dakara. In the summit area the flows commonly show spheroidal weathering and locally weather to shades of orange-brown (cf. Asie Shield). Elsewhere the basalt flows weather to darker brown and greys (in stream beds). Secondary carbonate locally infills joint planes. Red soil, up to 1 m thick, is present between two flow units at g.r. 357 274. In the same area a 1 m thick feeder dyke is exposed; where it cuts a pyroclastic wedge the dyke has 1 cm thick chilled margins.

A road cutting at Ulanula (2 km south from Marsabit) exposes distinctive pale grey-brown weathering lavas interbedded with pyroclastics. The lavas are aphyric with a brecciated texture (matrix-supported), with angular clasts of aphanitic grey rock several centimetres in length. In thin section the lavas are seen to be highly altered with secondary amorphous material masking original phases. No olivine was identified.

The uppermost lava tongues have elevated well-defined flow sides and fronts. In several cases the flows may be traced back to a source cinder cone. In these cases as the cone is approached the lava passes proximally into an agglomerate with welded 'cow-dung' bombs composed of scoriaceous basalt. At the cone the agglomerate in turn passes proximally into the typical lapilli breccia (see below). The tops of the lava flows are blocky with joints orientated at right angles to the flow surface. Flows are of the order of 10 m thick with blocky bases up to 2 m thick. The basalts are massive aphyric rocks, locally scoriaceous, and have a distinctive charcoal-grey colour, i.e. they appear fresher than the underlying browner basalt flows. Secondary calcite infilling vesicles and joints is common.

There is a change in the petrology of the basalt lavas vertically in the Marsabit Shield (see also Randel, 1970). The older flows (i.e. lavas below the 3000 ft contour) are relatively coarse, clinopyroxene with plagioclase with or without olivine basalts (mostly ankaramitic basalts). These rocks have bimodal clinopyroxene and plagioclase grains with the larger (0.3 to 1.0 mm) plates and laths in a matrix of unorientated plagioclase laths and microlitic clinopyroxene. The clinopyroxene phase is either augite (locally zoned) or pigeonite, ophitically enclosing plagioclase laths varying (between rocks) from An 56 to An 74 (mean of all samples of An 65). Olivine phenocrysts are smaller (up to 0.8 mm) than the clinopyroxene and plagioclase phenocrysts and are variably altered to id-

dingsite. Magnetite blebs are ubiquitous and rarely an opaque dust is also present. Secondary calcite is common, notably infilling vesicles.

The overlying flows (to include the uppermost basalt tongues) are olivine basalts except for the rare, highly altered, summit lavas (see above). Euhedral to anhedral olivine phenocrysts vary in size from 0.3 to 2 mm with rare microphenocrysts (<0.3 mm). They are variably altered to iddingsite. Plagioclase laths may or may not be orientated in the matrix (grain size <0.3 mm) and rarely also form phenocrysts up to 1.6 mm in length. They vary from An 50 to An 69 with a mean value of An 62 (17 rocks). Clinopyroxene is present as microlitic pigeonite with rare augite phenocrysts up to 4.4 mm in size. Magnetite grains are ubiquitous together with secondary calcite. Analcime, sericite (secondary), chlorite (secondary) and chalcedony (amygdales) are rare. Randel (1970) refers to these rocks as analcime basalts whilst admitting that analcime is not ubiquitous. Brotzu and others (1984) record tephrites as well as olivine basalts from summit lavas.

The cinder cones (about 180 on sheet 20) consist of red-brown weathering, thickly-bedded lapilli breccia. The beds have radial dips of up to 40°, although basal beds tend to subhorizontal, i.e. the dip angles increase up the succession. Angular scoriaceous basalt lapilli are the principal component of the breccias with minor convoluted bombs ('cow-dung' and cylindical) and blocks of the same material up to c.40 cm in length. A secondary carbonate cement is ubiquitous; a friable red-brown matrix is confined to discrete beds. Sets and co-sets defined by variable clast size and content occur in the matrix-supported breccias.

Sedimentary structures other than the uniform radial bedding, are rare. In one cone (Lolajonga Hill, g.r. 429 735) a coarsening upwards of clasts was noted from a basal lapilli tuff containing rare 'cow-dung' bombs. Intraformational cross-cuts exist in cones containing matrix-bearing beds. Upper conformable pillow lavas are present at about the same stratigraphic level in several adjacent cones in the north-west.

Around Hogichu the development of the cinder cones appears to have taken place simultaneously with extensive extrusion of basalt. River sections in this area show intercalations of lapilli-breccia between several lava flows. This is shown schematically in Figure 5.

A feature of the Marsabit Shield is the abundance of *maars* (22 on sheet 20) and their related block-and-ash cone deposits. The *maars* are up to 2.5 km in diameter and locally (Karsa Kile) coalesce to form composite craters up

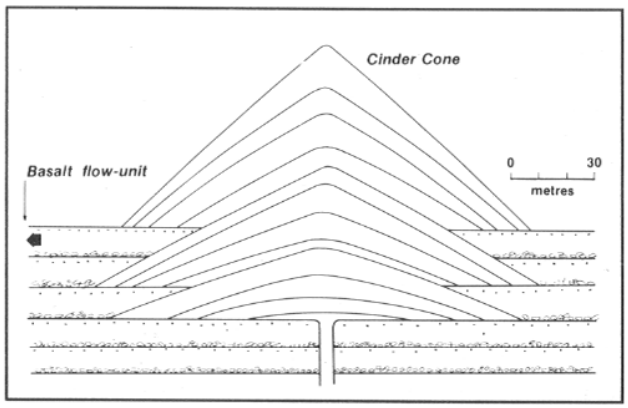


Figure 5 Contemporaneous basaltic lava and basaltic pyroclastic eruptions, Hogichu

to 3.0 km long. They are up to 300 m deep (Gof's Boro and Bongole) and in almost all cases the vertical walls to the general surface area are made of the laterally extensive basalt flows. Exceptionally, e.g. at Gof Hanjale, a basal breccia beneath basalt lavas is exposed, which is well-bedded and consists of angular lapilli, rare blocks and cow-dung bombs (all scoriaceous basalt) in a friable red-brown weathering matrix. The size of clasts increases upwards.

Block-and-ash cones ring the *maars* and define the upper parts of the vertical *maars* walls (Plates 23 and 24). They are up to 100 m high and taper to nothing radially away from the *maars*. The dominant lithology (Plate 25) is a bedded lapilli ash with or without basalt blocks and bombs. It is matrix-supported with friable, grey to brown basaltic powder in which the assorted clasts are embedded. The commonest clasts are angular to subrounded lapilli of scoriaceous basalt weathering to all shades of brown, red, purple, grey or green. Many clasts are fragments of spindle bombs. Other clasts consist of quartz, jasper, peridotite (with melanite garnet as a modal constituent) nodules and clinopyroxene (notably at Gof Barachuma where black augite fragments are common and derived from a basalt horizon in the Gof wall containing 4 mm diameter augite phenocrysts). The lapilli grade in size into the matrix. 'Cow-dung' and cylindrical bombs and blocks of scoriaceous basalt are ubiquitous in minor amounts.

Sedimentary structures include planar and cross-bedding, 'cut-and-fill' channels, wash-outs, local unconformities, sets and co-sets delineated by variations in lapilli concentration in single beds, grading (commonly inverted). Bedding is on all scales from thickly laminated to thickly-bedded. Bedding is not disrupted by blocks. The beds dip away from the *maars* parallel to the cone slope, i.e. angles of less than 20°. The degree of sorting is generally good, but can be variable with some horizons having a chaotic accumulation of lapilli and blocks.

Other lithologies interbedded with the lapilli ashes are basalt lava flows, massive ashes, lapilli-block-bomb breccias, and accretionary lapilli rocks (Gof Hangale) and pumiceous rocks (summit). The basalt flows are conformable to bedding and c.5 m thick. The other (pyroclastic) lithologies tend to form wedges. Secondary carbonate is ubiquitous. Most of the block-and-ash cone deposits are therefore composite although the well-bedded lapilli ash is always dominant. In many cases an uppermost, relatively well-consolidated lapilli-block tuff caps and preserves the pyroclastic sequence. There is a tendency for these sequences to coarsen upwards (the massive ash at Lolajonga Hill is a basal unit). The basal contact of this sequence with the basalt lavas varies from conformable (e.g. Gof Dakara), unconformable (Gof Njale) to gradational with the scoriaceous basalt top becoming brecciated with an upward increase in matrix (Gof Angar).

In the summit area there is a variety of pyroclastic material interbedded with basalt flow units. A feature of the pyroclastics is the relative coarseness of the basalt lapilli (>2.5 cm) in lapilli ashes, lapilli tuffs and lapilli breccias. These rocks may be bedded or massive. Flow textures were noted in one ash unit (Ulanula). Bombs are rare, but large, with cylindrical pumiceous bombs up to 2.5 m noted. These are zoned by lines of vesicles parallel to the bomb outlines. Secondary calcite is common as a cement.

Seven whole rock analyses (Table 2) of lavas from various stratigraphic levels in the Marsabit Shield show systematic elemental variation in accord with the de-

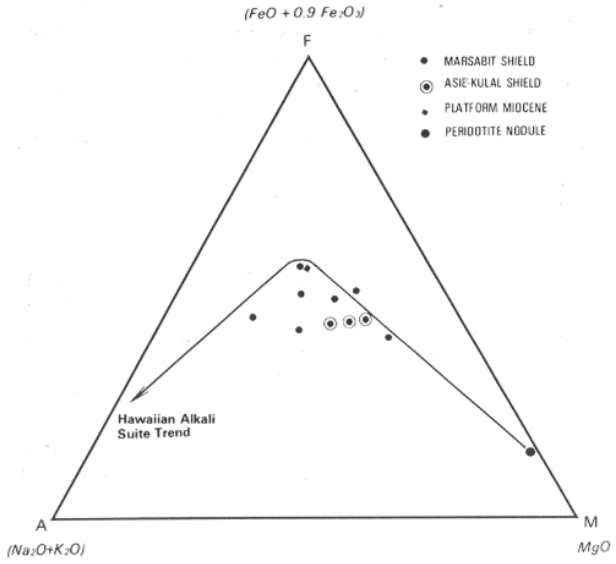


Figure 6 A 'F' M plot of whole rock analyses of the volcanics

scribed petrological changes. The older (ankaramitic) lavas plot within the basalt field of Figure 7, whereas the more alkaline younger flows plot as basanites or tephrites (agreeing with Brotzu and others, 1984). All the lavas classify as alkali basalts on AFM, Peacock and Grasso plots. In Figure 6 the rocks follow an alkali basalt fractionation path (ferrofemic index 68, Coats, 1968) with the basal lavas plotting close to the ankaramite source. This is confirmed by the overall decrease in Solidification Index with time: the youngest rocks being the most fractionated (Figure 8). The increase in the P_2O_5 content of the lavas with time highlights this trend. However, whilst binary *vs* element/or element ratio (e.g. Solidification Index) show linear positive or negative correlations, there is sufficient scatter of individual plots to indicate that magma fractionation was not simple. The presence of peridotite nodules (analysis in Table 2) and olivine xenocrysts in lavas also indicates that at least two fractionation processes may have been involved: the removal of melt to build up the shield volcano and *in situ* crystallisation of silicates. The chemical and petrographic data indicate an upper mantle source magma of ankaramitic basalt or peridotite composition for the Marsabit Shield. The

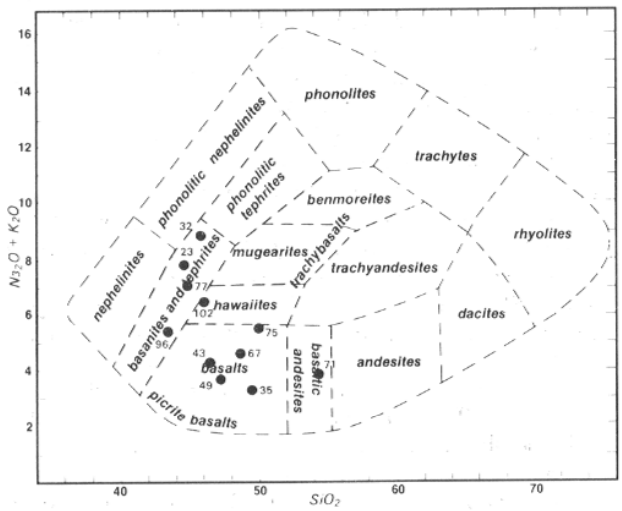


Figure 7 SiO_2 vs Na_2O + K_2O plot of whole rock analyses of the volcanics

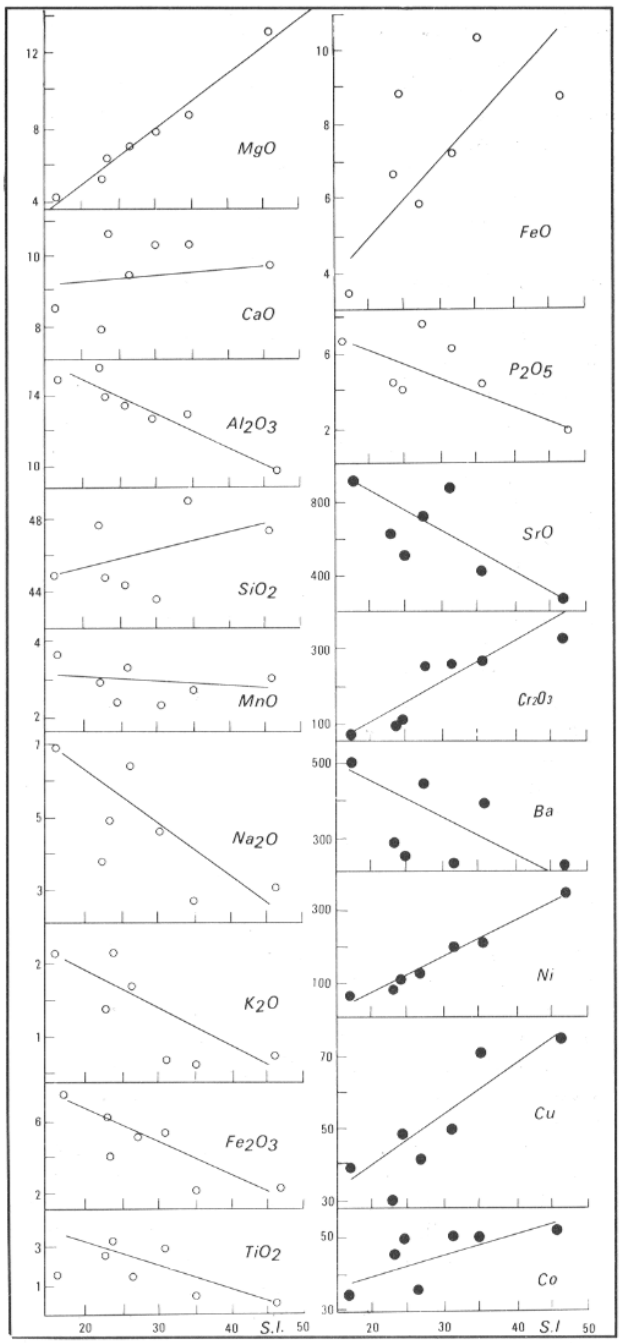


Figure 8 Plots of major and trace elements against solidification index

relatively high sodium contents of the lavas may be due to crustal contamination (? the presence of a salt layer in the underlying Maikona formation lacustrine deposits). Otherwise there is no evidence for any crustal contamination of the magma.

The evolution of the Eastern Volcanic Province took place in four stages as follows:

1 Late Miocene to Pliocene fissure-controlled eruption of the flood basalts (comprising the basal platform basalts).

2 Pliocene inception of the shields with Hawaiian-type volcanic activity producing the laterally extensive basalt flows. The Marsabit Shield has a pronounced north-east elongation which is taken to indicate a major underlying fissure control. No contemporaneous pyroclastic ejectamenta accompanied the fissure basalt activity which appears to have been almost continuous, i.e. general absence of interflow soil horizons. This was the main phase of volcanism (ankaramitic basalts) in terms of

volume of basalt erupted (over 70 per cent of the shield volume).

3 During the Quaternary the style of volcanism changed from the continuous gentle eruption of monotonous basalt flows to violent (Strombolian and Ultravulcanian) ejection of pyroclastic debris building the cones and blasting the *maars*. Initially this build up of pyroclastics was concomitant with further eruption of extensive lava flows (olivine basalts). There was a strong tectonic control on the siting of cones and *maars* which are concentrated in north-east and north-west belts through the summit of the Marsabit Shield. Contemporaneous faulting accompanied the volcanism, the most striking example being the major fault (now concealed by later flows but defined by a Landsat lineament) along the north-west edge of the major north-east belt of cones and *maars*. Most of the faults active at this stage were reactivated structures in the subvolcanic 'basement'. The preferential building of the summit area commenced at this time.

4 Final phase (Quaternary and post 0.5 Ma) of explosive (Strombolian and Ultravulcanian) volcanism to produce more cones and *maars* with eruption of narrow lava tongues (analcime-olivine basalts) mainly from cone sources. There was an overall coarsening of clast size with decreasing age which indicates a lessening of the explosive force of eruptions (MacDonald, 1972). No contemporaneous faulting accompanied this dying phase of the shield. Volcanic activity was again concentrated in the major north-west and north-east belts, notably in the summit area where the belts intersected.

The Marsabit Shield *maars* are identical to the type *maars* (*of* MacDonald, 1972) in all aspects: shape, size, pyroclastic associations (basal surge deposits) and basalt shield setting. The Ultravulcanian activity necessary to blast the *maars* is generally attributed to a mixing of water (groundwater) and the volcanic magma at relatively high crustal levels. The Marsabit Shield straddles the Chalbi Basin (a sub-Miocene regional depression), which accumulated ground and surface water. It is therefore logical to attribute the abundance of *maars* on the Marsabit Shield relative to the other shield volcanoes of northern Kenya to the sporadic mixing of the source magma and groundwater (Williams, 1978 arrived at a similar conclusion). The magma itself has a deep (? mantle) source and was not greatly contaminated by the underlying basement (metamorphic and sedimentary). No fragments of this material are present in any of the Gofs, other than quartz and rare jasper pebbles.

3.5 QUATERNARY SEDIMENTS

Pleistocene lacustrine deposits at Olturot

A pan-like depression in basalts on the margin of the NW Volcanic Province at Olturot contains two low, flat mounds above the silt and gravel pan floor. The mounds are c.1 m high and composed of a dull white, earthy calcareous (micritic) sediment containing fine root strands and complete mollusc shells. *Melanoides tuberculata* dominates the fauna with *Biomphalaria, Lymnia, Opeas suavissima, O.marsabitensis, segmentina* or *segmentorbis, Succinea, Achatina* and *Cyraulus* (Nyamweru, 1984). This is a fresh-water assemblage. A radio-carbon age of 10 430 + 250 years BP was obtained from one gastropod sample (Nyamweru, 1984).

The two mounds are erosional remnants of a deposit which is thought to have formed in an overspill from the adjacent Balesa River during the wetter end-Pleistocene period. Nyamweru (1984) notes that Olturot is too high to have connected to a large Lake Chalbi at this time. Artefacts are common on the pan floor and have been identified as Lower and Middle Stone Age (Merrick *in* Nyamweru, 1984).

In the two major volcanic provinces the main Quaternary superficial deposits (soils) are residual, *in situ*, weathering products of the underlying basalts. However, in the intervening, central terrains the superficial mantle consists of a variable mixture of (aeolian, alluvial and lacustrine) transported and residual weathered material. It was noted in Chapter 2 that the accumulation of surface sediments in this central area has been continuing since the Miocene and many of the physiographic features, e.g. dunes, are stabilised and relatively old. The Quaternary influence in these cases was mainly a reworking of uppermost units. Therefore these superficial deposits are generally layered to record a history of changing Quaternary (and older) climates. Unfortunately vertical sections are rare and mainly confined to the banks of major rivers. For example the River Balesa's present banks expose bedded deposits (Plate 31) related, in part at least, to the Late Pleistocene (c.10 000 years BP) flooding of this river (see Nyamweru, 1984, for references).

Soils and superficial sediments

North-west Volcanic Province

Overlying the platform basalts between the Asie and Kulal Shields is a relatively deep, friable, strongly calcareous and sodic, stony or gravelly, sandy clay-loam to clay soil with a stony or gravelly surface layer (all soil descriptions are from Lusigi, 1984). A similar soil continues over the hills; illite and montmorillonite are the major clay minerals in all volcanic soils. In the north-east the upper stony layer locally has a thin veneer of white aeolian sand with or without a silt fraction. The sands are derived from the east (prevailing wind direction) and are banked against boulder mounds (Plate 28).

Eastern Volcanic Province

The summit area (above the 4000 ft contour) of Marsabit Shield has a deep, friable clay soil which is locally stony. On the lower slope there is a thinner, strongly calcareous, very stony clay loamy soil with an overlying stony or gravelly layer. In many areas, especially on the youngest lava tongues the soil layer may be absent. Natural hollows, notably the northern linear depressions, are partly infilled by a veneer of aeolian sand and silt (mud cracks common). All the *maars* are partly infilled by lacustrine silts of unknown thickness. The prevailing ESE winds have dispersed the pyroclastics over small areas on the western (leeward) sides of the cones.

Chalbi playa sediments

The playa has a brown, strongly calcareous, strongly saline, strongly sodic, fine-grained, sand loam to clay soil cover. Salt films (Plate 29) are ubiquitous together with veneers of aeolian sand. Chippings from a water borehole at Maikona indicate over 100 m of sediment or sedimentary rock beneath the playa. The south-west playa margin is well defined by sand banks, bars and spits. The playa shores have a rounded quartz (c.0.5 cm in diameter) beach sand containing rounded basalt fragments of the same size. Sub-outcrop of gritstone (?Maikona formation) is locally present. The sand banks, bars and spits have two sand components: an older, brown well consolidated and stratified sand and white, unconsolidated aeolian sand (Plate 30). According to Lusigi (1984) the older material is a moderately to strongly calcareous,

strongly sodic, medium to fine sand soil. Quartz grains predominate and are identical to the quartz component of the gritstones of the Maikona formation — the obvious source material.

In the dune fields to the south-west of the playa the material of the dunes is identical to the older sand described in the last paragraph. The interdune areas are infilled by eluviated silts. A very deep, moderately to strongly calcareous, stratified sand to loam soil with a top soil of silt loam to loam infills the fossil watercourses and pans. Basalt and 'basement' pebbles are ubiquitous in well defined beds, as well as defining sets and co-sets (Plate 31). The large alluvial fans off the NW Volcanic Province into the Chalbi Basin have a major basalt boulder content.

Hedad, Koroli Desert and Korante Plain sediments

The dunes and interdune eluviated zones of the north are composed of identical sands and silts to the Chalbi Basin dune fields. The monotonous plains have a deep, slightly to moderately sodic, sandy loam to sandy clay loam soil with a top soil of sand to sandy loam. Aound Kargi a more calcareous sandy loam overlies a calcrete (petrocalcic material of Lusigi, 1984) with a basalt gravel surface layer. The basalt plateaus of the Koroli Desert and Korante Plain have a shallow, very strong clay loam soil with an exceedingly stony surface layer. Similarly, the inselbergs of the Korante Plain have a thin soil cover; in these cases a stony or sandy loam soil. The metamorphic rocks of the inselbergs are a major source for the plain soil which contains quartz, mica and feldspar as well as their breakdown products: palygorskite, illite, montmorillonite, vermiculite and kaolinite. A relatively deep, friable sandy loam or sandy clay loam locally overlies the Korr area; it may contain a major stony phase, and is saline.

3.6 INTRUSIVES

Korr Complex (excluding the metamorphosed ultramafics/ultrabasics descriptions in Section 3.1)

The largest intrusive is the discordant, vertical granite sheet cropping out on the northern summit of Halisurwa. This is a massive, pink-weathering, feldspathic rock with euhedral quartz grains visible in hand specimen. In thin section it is seen to consist of coarse (2.5 mm) microcline and microperthite grains (minor sericite alteration) with minor quartz, magnetite, oligoclase and sphene. No mafic phase is present.

Minor intrusives include quartz reefs and stringers, carbonate veins in marbles, white mica-bearing felsic veins, quartzofeldspathic pegmatites and grey microgranite dykes. The latter are relatively common, especially to the east of Korr Mission. They have sharply discordant contacts with the host gneisses and are c.1 m thick. Quartz, microcline and orthoclase are the dominant phases with biotite and plagioclase, and traces of sphene and apatite. Sericite partly replaces the larger K-feldspar grains. The average grain size is c.0.1 mm

Western gneisses

Apparently conformable pegmatitic granite and charnockitic gneisses (described in Section 3.1) are present in the gneisses on the north-eastern ridge of Ol Doinyo Mara. The granite underlies the summit of the ridge and is poorly exposed with limited outcrop and float of a pegmatitic, leucocratic rock. Strained microperthite plates cut by sericite stringers and dark grey microcrystalline seams are the principal phase, with quartz and rounded ore blebs. *Lit par lit* felsic veins and quartzofeldspathic pegmatites are common in most outcrops of the quartzofeldspathic gneisses.

Volcanic rocks

Intrusive rocks are rare in all the volcanic provinces. A small plug cuts the southern end of the Asie Shield (g.r. 286 303) and consists of an aphyric homogeneous basalt identical to the adjacent basalt lavas. It is also petrographically identical to the later olivine basalts of this shield with olivine phenocrysts (0.6 mm diameter) in a matrix of labradorite, microlitic clinopyroxene and magnetite. Iddingsite replaces the olivine phenocrysts in well-defined rims.

A photo-lineament trending NNE through Falama is thought to be related to the dyke reported from this area by Kargi inhabitants.

In the north-west part of the Marsabit Shield (g.r. 358 269) a small aphanitic basalt plug forms a low hill. As with the Asie plug, it is olivine basalt with olivine (0.3 mm diameter) and plagioclase (1 mm long) phenocrysts in a matrix of plagioclase, microlitic clinopyroxene, ore and minor chlorite. In the same general area a feeder dyke (c.1 m thick) trending 115° and dipping 65°S was noted to one of the regular flow units.

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Plate 22
Cinder cone flanked by later basalt flow units, Asie Shield



Plate 23
Aerial view of Gof Barachuma

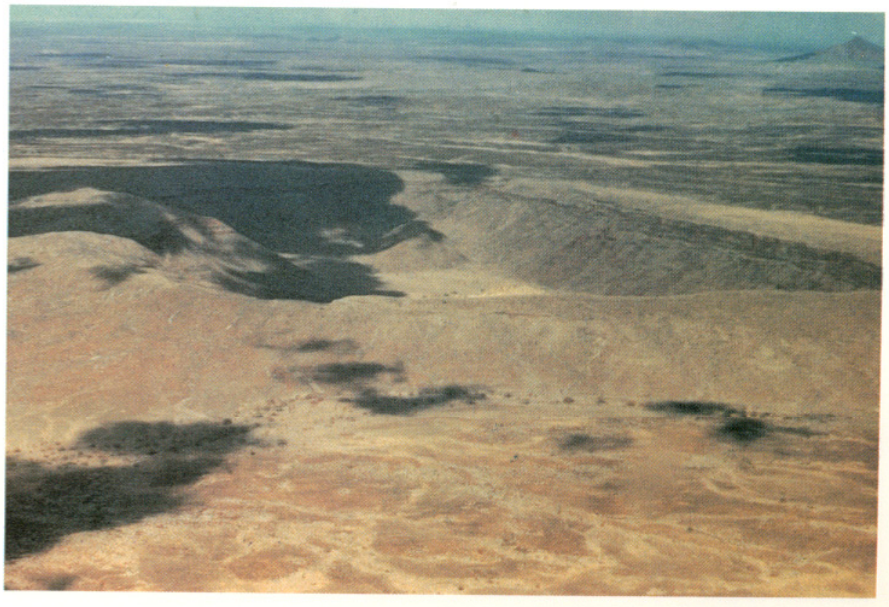


Plate 24
Aerial view of Gof Barachuma

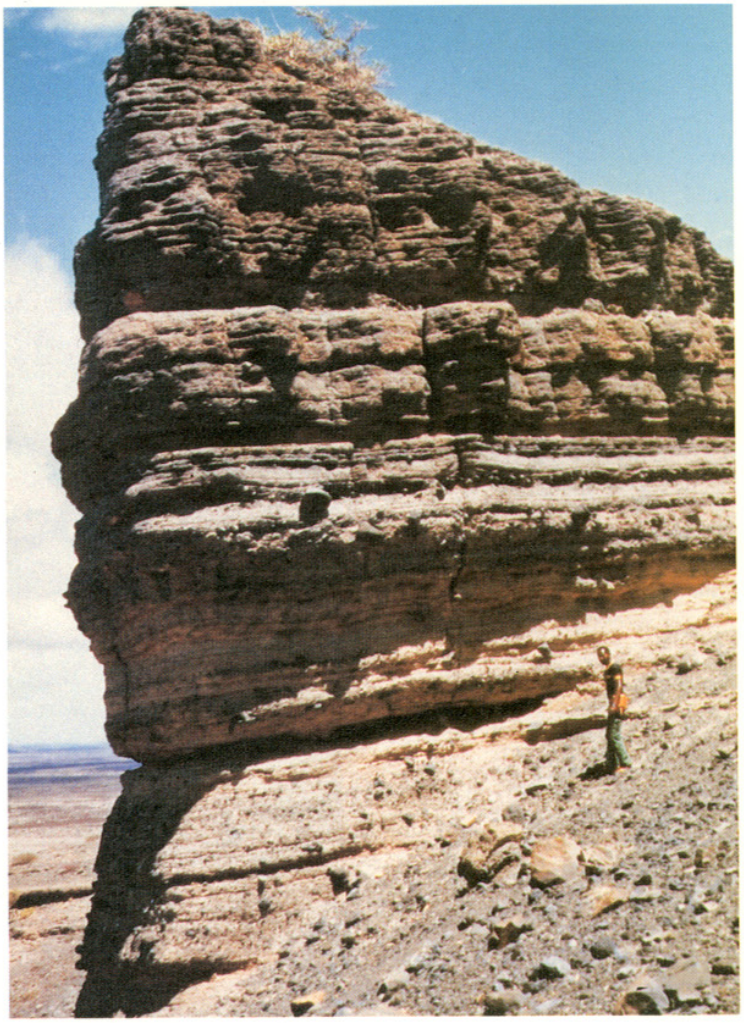


Plate 25
Bedded (surge) deposits peripheral to a *maar*



Plate 26 Typical cinder cone with breached summit crater, summit of Marsabit Shield



Plate 27
Blocky base to basalt flow-unit, Marsabit Shield



Plate 28
Aeolian sand mantle to basalt boulder field, east extremity of Asie Shield

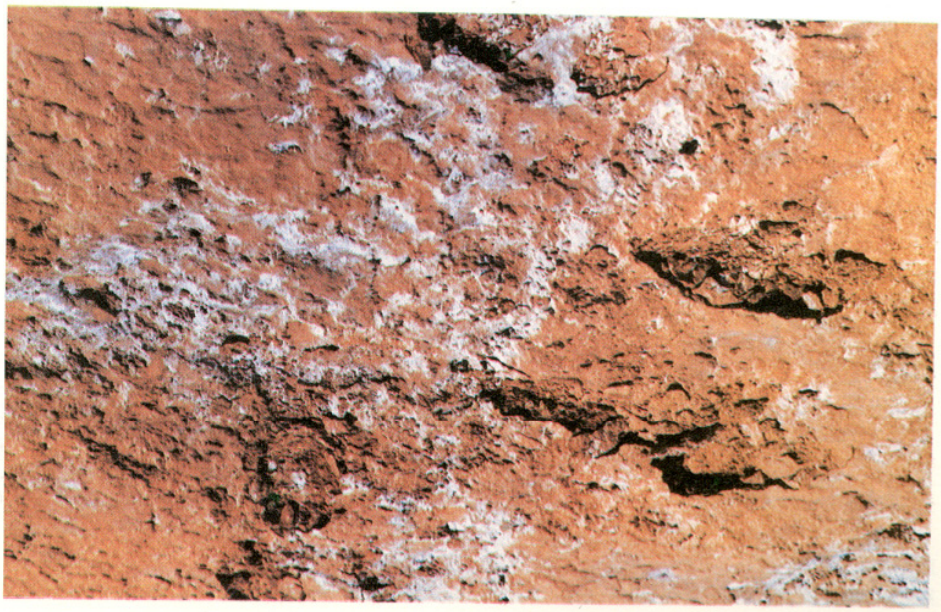


Plate 29
Salt crust of the Chalbi playa



Plate 30
Recent aeolian sand (white) against older, consolidated dune sand



Plate 31
Fluviatile sediments of the Balesa River



Plate 32
Koroli waterhole

4 Structure and metamorphism

4.1 KORR COMPLEX

The earliest tectonothermal event (DI/MI) recorded in this unit produced the coarse gneissic fabric. Diagnostic mineral assemblages defining the gneissic fabric include:

kyanite + quartz + white mica, hornblende + plagioclase + diopside + quartz + garnet, carbonate (calcite and dolomite) + tremolite + graphite + white mica + apatite, hornblende + chlorite + magnetite.

These components suggest an Amphibolite Facies metamorphism with P H_2O in excess of 3 Kbars and temperatures less than about 600°C (see petrogenetic grid in Pattison and Harte, 1985).

An upright synform (of gneissosity) with an axis plunging moderately towards 060° is the dominant major structure (D2) within the Korr Complex (fold axial trace shown on geological map). No parasitic folds were noted in outcrops although a co-axial lineation is common. New biotite growth and recrystallisation of hornblende (locally after diopside) accompanied this folding. Axial traces and axes of small-scale structures, noted in outcrop, are not parallel to the regional synform. Similarly a stereographic plot of foliations and lineations (Figure 9) produces a scatter of readings not compatible with this major fold. These observations, together with style variations of the small-scale folds (cylindrical and asymmetric tight) and shears (brittle and plastic) suggest a complex post-D2 tectonic history. All the small-scale folds are thought to be caused by movement along various steeply dipping shears. Individual shears were measured to trend NNW (dextral), NNE, ENE, E and ESE and may be infilled by quartz reefs. Fold axes plunge from 18 to 90°.

The Korr Complex is thought to have been tectonically transported into its present setting during the Sabachian deformation (see below). This followed the formation of the ENE synform. The NNW shears may be Baragoian structures (see below).

4.2 WESTERN GNEISSES (KOTIM GNEISSES)

An early tectonothermal event (Samburuan) produced the gneissic fabric. Granulite Facies conditions were attained during this prograde event; the mineral assemblages include:

sillimanite + quartz + garnet + plagioclase + microperthite, hypersthene + diopside + K-feldspar + plagioclase + quartz.

These indicate that the metamorphic temperatures exceeded 700°C in rocks presently exposed; local anatexis produced granitic textures in quartzofeldspathic rocks. The resultant gneissosity was subhorizontal (see Hackman and others, 1986; Key, 1986). Deformation outlasted the thermal peak to produce isoclinal recumbent folds of gneissosity (*Sabachian*), e.g. the closely spaced linear inselberg pair at g.r. 294 230 is interpreted as the two limbs of an isocline subsequently rotated. Horizontal tectonic transport accompanied this folding (cf. references above) and it is probable that the Korr Complex was moved into its present setting at this time.

The series of upright synforms and antiforms trending NNW (335°) shown on the geological map and cross-sections were produced during a regional tectonothermal event (*Baragoian* cf. above references). The folds have wavelengths of less than 10 km and plunge at moderate angles to the SSE (see plot of co-axial lineations, Figure 9). To the south, contemporaneous folds plunge NNW, to indicate a regional depression near latitude 2°N. Related minor structures are parasitic folds, M zones (g.r. 285 240), co-axial rodding, axial planar foliation (Kurior Dele). Contemporaneous major structures are the NW- to NNW-trending shear zones shown on the geological map. Repeated movement has taken place in these zones, cf. the folded pseudotachylite veins. A low grade metamorphism produced the hornblende and biotite Baragoian fabrics and the breakdown of K-feldspar to white mica may have been taking place at this time. The ubiquitous cataclastic fabrics defined by quartz and feldspar grains

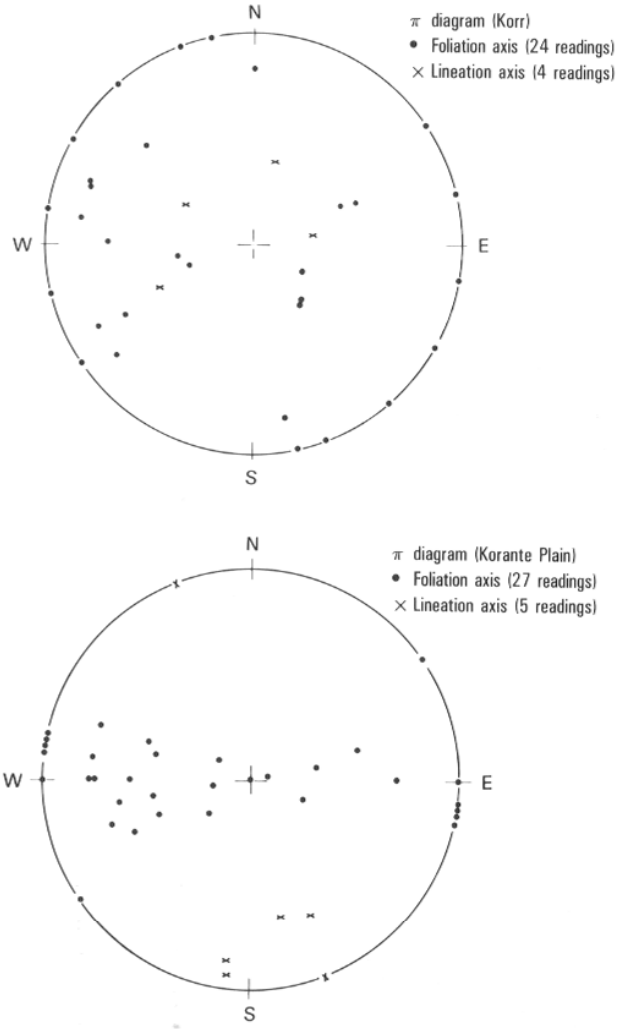


Figure 9 Stereographic plots of foliations and lineations in the metamorphic rocks

may be due to the Baragoian event or later shearing. As a result of this event the Kotim Gneisses generally have steep dips and a regional NNW strike (Figure 9).

Post-Baragoian structures include the major NNE-trending shear zone near the western map edge; faults trending ENE to NE; and horizontal joints.

4.3 SUBVOLCANIC SEDIMENTARY ROCKS

These rocks are not folded. However their outcrop distribution (cf. the Maikona formation) indicates a control by major faults trending NW (320°). This is confirmed by regional geophysical data (Ministry of Energy confidential reports) which show the Chalbi Basin as the north-west part of a major (Anza) Graben trending NW. The fault trending 060° cutting the Maikona formation, south-east of Maikona, is also parallel to a set of faults in eastern Kenya identified by the geophysical survey.

All the sedimentary rocks are unmetamorphosed.

4.4 CENOZOIC VOLCANIC ROCKS

Both the North-west and Eastern Volcanic Provinces are essentially undeformed. Asie Shield trends NNE, parallel to major, late, shear zones in the metamorphic rocks. Kulal Shield trends NNW parallel to the adjacent Rift System (Figure 4) suggesting it overlies a bounding Rift fault. Volcanic activity on the Marsabit Shield was controlled by fissures trending NW and NE. The NW fracture presumably reflects the Anza Graben structures in the underlying sedimentary strata. The NE fissure parallels the long axis of the Miocene Marti Engweta plateau as well as the regional trend of the Mount Kenya–Nyambeni Volcanic Provinces to the south. Together they might represent a fundamental set of (transcurrent) fractures related to the Miocene development of the Rift System.

Faults contemporaneous with the vulcanicity in the NW Province parallel the trend of the two shields with minor faults trending E and NE. The easterly faults are parallel to a major fault recognised to the west which controls the southern bend in Lake Turkana (Figure 4). Similarly the late faults in the Marsabit Shield mostly parallel the older fissures.

All the volcanic rocks are unmetamorphosed although secondary calcite and iddingsite alteration of olivine are widespread. Calcite growth is presumed to be due to circulating groundwater (low temperature) whereas the iddingsite alteration reaction may be high temperature (see Charsley, 1986).

5 Economic geology

Present exploitation of the mineral resources of sheet 20 is confine to small-scale manufacture of cement blocks at Korr using local river sand, and minor quarrying of pyroclastic material around Marsabit for roadstone. In the latter case, the pyroclastics, being poorly consolidated, are easily worked but are poor roadstone; during the rains they produce a very slippery surface. Alternative sources of better roadstone are widespread and listed below. Otherwise the area has a poor inventory of industrial minerals. Oil exploration is currently taking place in the sedimentary rocks in the Maikona area.

5.1 AGGREGATE (TO INCLUDE ROADSTONE)

All the *basalt* lava flow-units are ideal aggregate sources. Good quarry sites include the vertical walls of Gof Bongole (for Marsabit); basalt block mounds adjacent to the North Horr track north of Laga Dambito (for Maikona); the hill defined by the basalt stock g.r. 282 303 (for Olturot); the scarp edge of Marsabit Shield at Kargi (for Kargi) and at Halisurwa (for Korr). The *gritstones* of the Maikona formation are also an excellent source of aggregate. Good quarry sites are present west of the Maikona to Marsabit track, notably into the cliff faces near Konon Mayidadte, and on the scarp slopes of the Koroli Desert mesas. Alternative sources of aggregate are the *amphibolites* of the Korr Complex and the *quartzo-feldspathic gneisses* of the south-west. Both underlie hills and inselbergs which could be easily quarried.

5.2 CARBONATE

The two marble hills through the south-west part of the Marsabit Shield contain large reserves of impure dolomite. The northern hill is approximately 600 m long N–S) by 200 m wide (E–W) and has a maximum elevation of over 20 m. The southern hill is smaller 300 m x 200 m x c.20 m). Four analyses of the assorted marble lithologies (Chapter 3) are listed below.

Sample	% CaO	% MgO	% total as carbonate	Ratio of CaO:MgO
RK/20/1	37.5	10.4	91.8	3.6:1
RK/20/2	32.2	16.0	92.4	2.0:1
RK/20/3	31.4	19.5	97.6	1.6:1
RK/20/4	32.8	17.0	95.5	1.9:1
(pure dolomite)	30.4	21.7	100	1.4:1

Calc-silicates (e.g. tremolite) are present in samples RK/20/1 and 2 and graphite is disseminated in RK/20/4. These hills would also appear to be a potential source of facing stone (see para. 5.5) and/or lime.

The calcrete (petrocalcic soil layer) at Kargi forms pavements in the Koroli Desert floor and would be difficult to quarry. No analyses of this material are available.

5.3 CEMENT BLOCKS

During the fieldwork it was noted that a small number of cement blocks were being manufactured in Korr using sand from the small river south of Korr Mission. The blocks were of good quality.

5.4 CLAY

The topmost brown silt of the Chalbi playa may be suitable for a local clay-based industry (manufacture of pots, etc.). A thick clay-rich soil overlies the summit area of the Marsabit Shield and contains montmorillonite and illite (Lusigi, 1984).

5.5 FACING STONE

Locally the *marble* on the northern hill protruding through the south-west part of the Marsabit Shield is massive white, and poorly-jointed and thus has potential as facing stone. Similarly the *amphibolite* forming hills in the Korr area is locally massive and of equal potential (as 'black granite').

5.6 FOSSILS

The Karole formation contains a varied fossil assemblage (Chapter 3) and petrified wood is present in the Maikona formation from the mesas of the Koroli Desert. This material could be collected and sold either to tourists visiting Marsabit or sent to Nairobi.

5.7 GEMSTONES

Peridot nodules are common in all the pyroclastic deposits adjacent to the Gofs of the Marsabit Shield. Unfortunately individual peridot fragments are generally small (less than 0.5 cm diameter) and internally cracked. Therefore although they have an attractive yellow-green colour they would appear to have no potential as gem material. *Red (almandine) garnets* are widespread in rocks of the Korr Complex and are a major constituent of the top layer of the overlying sandy soil. Individual stones are too small to be considered for gemstones but collectively could be used as an abrasive. The *almandine garnets* of the western Kotim Gneisses are strongly fragmented and are an ugly orange-red translucent colour, i.e. they have no gem potential. No other gemstones are present in the south-west despite the presence of various beryl, corundum and tourmaline stones immediately to the west around South Horr.

5.8 MAGNESITE

Magnesite veins cut the peridotite hill protruding through the south-west part of the Marsabit Shield. They are too thin to be of economic value.

5.9 OIL

Oil exploration is currently being undertaken by Amoco in northern Kenya to include sheet 20. Drillholes are planned into the Maikona formation to ascertain its vertical thickness. A better understanding of the potential for oil discoveries should result.

5.10 SALT

The surface showings of the salt in the Chalbi playa (Plate 29) are too small to be worked. The exploration drillholes mentioned in the last section may discover subsurface evaporite concentrations. The surface salt is derived from groundwater evaporation.

5.11 SAND

The most easily accessible source of quartz-rich sand overlies the Maikona formation along the track from Maikona to Marsabit. It is generally in excess of 1 m thick, coarse, and locally is banked. Huge deposits of similar material are present in the major sand bank along the south-west margin of the Chalbi playa, albeit in a remote area. Small sand banks also exist near Kargi. Large reserves of river sand infill all the drainage channels of the west, e.g. the Balesa River.

5.12 STREAM SEDIMENT SAMPLES

Thirty-eight large (several kilogram) samples were collected from well defined drainage channels in the Korr area (6 samples), SW (22 samples), Asie Shield (10 samples). The aim of this sampling was to provide a regional geochemical picture rather than to identify anomalies. The bulk samples were sieved, with a −80 mesh fraction analysed (by Geosurvey, Nairobi) for Ag, Ba, Co, Cu, Fe, Li, Mn, Mo, Ni, Pb, Sr and Zn. The +80 mesh fraction was crushed to less than 200 mesh and analysed (by XRF at Nottingham University) for TiO_2, Fe_2O_3, MnO, As, Ba, Bi, Co, Cr, Cu, La, Mo, Ni, Nb, Pb, Sn, Sr, Th, U, V, W, Zn and Zr. A summary of the results is present in Table 3.

With regard to the −80 mesh fractions the ranges of values from the two metamorphic terrains are essentially identical for all elements. However, the Asie Shield drainage sediments have higher values for Ba, Co, Mn, Ni, Sr and Zn relative to the metamorphic terrains.

Table 3 Summary of the stream sediment analytical data

Province	Range of values for individual elements (Atomic Absorption analyses)												(XRF analyses)					
	Ag	Ba	Co	Cu	Fe*	Li	Mn	Mo	Ni	Pb	Sr	Zn	TiO_2*	Fe_2O_3*	MnO*	As	Ba	Bi
Korr	<.3	50–90	11–13	14–23	1.9–4.2	2–5	230–360	<2	15–27	<1	26–47	17–37	0.77–3.81	11.91–30.15	0.41–1.08	0	98–587	0–1
W. metamorphics	<.3	40–120	7–23	10–24	1.8–10.8	1–6	280–450	<2	10–22	<1	23–56	16–39	1.35–22.19	6.14–68.58	0.15–0.91	0–2	0–667	0–9
Asie	<.3	140–360	29–41	19–35	2.9–6.5	3.5	700–1290	<2	17–122	<1	84–256	40–89	1.42–4.56	11.58–16.21	0.22–0.25	0–5	177–554	0–2

	Co	Cr	Cu	La	Mo	Ni	Nb	Pb	Sn	Sr	Th	U	V	W	Zn	Zr
Korr	11–41	352–551	14–56	5–38	0–3	15–42	5–21	4–12	11–18	117–466	0–13	0–3	200–420	0–11	57–116	110–443
W. metamorphics	14–72	251–1032	8–64	22–284	0–5	13–67	12–88	0–13	3–29	34–476	5–98	0–12	110–2093	2–34	46–482	163 3331
Asie	30–88	98–5488	30–49	18–62	0–3	27–1111	20–65	0–9	0–4	211–544	0–7	0–3	180–456	2–11	83–132	89–242

Values in ppm except * = %

6 Water resources

6.1 SURFACE WATER

Permanent supplies of surface water are rare and confined to spring-fed pools around the edges of Marsabit and Huri Shields and on the summit of Marsabit Shield. The most spectacular of these is the alkaline lake infilling Gof Sokorta Guda (Lake Paradise). The adjacent summit springs (Balesa Bongole, Songa Gambela, Aita Spring and Ulanula Spring) provide much of Marsabit town's water supply.

The peripheral springs appear to have two sources. (1) Water is confined within the shield volcanics and flows radially and downwards away from the summit areas for eventual discharge at the interface of the thin peripheral lavas and underlying sedimentary rock (e.g. Dafa Baruso Spring). (2) Artesian water is held in the sedimentary rocks where they are overlain by the shields, discharging where the confining volcanic overburden ends (e.g. Koroli, Plate 32). There must also be some other control on the location of these artesian-fed springs otherwise spring water would be ubiquitous around the entire north-west and south-west peripheries of the Marsabit and Huri shields. Either major fractures in the sedimentary rock, or the presence of an adjacent impermeable unit, are likely secondary controls. All spring water is slightly saline.

Ephemeral surface water is present in all the watercourses, the Gofs (*maars*), the springs at Kalama, and in the Chalbi playa following heavy rains. A small earth dam has been built at Kalama, otherwise all the water rapidly disappears by natural seepage and evaporation.

6.2 GROUND WATER

Twenty boreholes (seven of which were dry) have been completed on the sheet together with numerous shallow wells. All the boreholes are shown on the geological map and detailed (location, depth, depth to water, etc.) in Table 4. Five of the boreholes are operational: at Olturot (IPAL), Korr, Maikona, Kargi, and Marsabit, (near Balesa Bongole). Four aquifer types are utilised: perched aquifers in superficial unconsolidated sediments; metamorphic basement; Maikona formation; shield volcanics.

Perched aquifer in superficial unconsolidated sediments

This aquifer type is tapped by means of shallow, hand-dug wells, notably in the Balesa River and at Kurkum.

Table 4 Summary of water borehole data from sheet 20 (no information available on several boreholes)

Hole Number	Location	Depth (m)	Water Struck (m)	Water rest level (m)	Tested Yield (m^3/hr)	Specific capacity (m^3/hr/m)	Quality	Comment
SA60	Marsabit Summit	74.4	68	64				Aquifer is a soil unit in lava sequence
C3094	Marsabit Summit	154	50,143	47				Aquifers are weathered lavas
SA36	Marsabit Summit	108.8	—					DRY
SA39	Marsabit Summit	71	—					DRY
C4573	Marsabit Summit	130	76	72.5	8.1	8.62	Good	Aquifer is a pyroclastic unit in lava sequence
SA40	Marsabit Summit	8.6.6	—					DRY
C4073	Korr	96.9	38,78	29,27	0.5	0.008	Saline	
C4108	Korr	45	30	11.5	3.8	0.12	Good	
C4071	Korr	27	11,14	9.7,9.5	3.6	0.24	Good	
C4113	Marsabit Summit	70	22	14	0.3	0.007	Saline	Aquifers are fractures in the Korr Complex
C4119	Marsabit Summit	50	15,28,42	12			Good	
C4084	Marsabit Summit	26.3	12	8			Good	
C4073	Korante Plain	58	25,45	6.0	0.6	0.01	Good	
C4075	Korante Plain	108	—					DRY
C4080	Hedad	200	—					DRY
SA113	Hedad	61	—					DRY
C3960	Kargi	95.7	18,72	13.5	10.9	4.36	Saline	Aquifer is a sandstone of the Maikona Formation
C3962	Kargi	32	—					Abandoned in a dark, hard rock. DRY
SA112	Maikona	49.4	42.7	41.1	0.22		Good	Aquifer is a sandstone of the Maikona Formation

that wells dry up in periods of drought. For example in the Balesa River the depth to subsurface water in the bedded river sediments increases below 8 m during prolonged dry periods (IPAL technical report B-2, 1983). The wells cannot be extended to this depth because of wall-collapse caused by the unconsolidated nature of the river sediment, and hence dry up.

The perched aquifers all drain towards the Chalbi Basin ('the ultimate groundwater sink', IPAL, *op. cit.*). Large quantities of fresh water are thought to be present, but the problems of relatively deep well construction have severely curtailed exploitation.

Metamorphic basement

The three boreholes (to maximum depths of c.60 m) into the western gneisses were all dry. The holes are widely spaced which suggests that these gneisses are poor storage rocks (at shallow depths) for groundwater. In contrast all eight boreholes into the Korr Complex on sheet 20 have struck water at shallow depth, albeit with low yields (less than 4 m^3/hour). Boreholes stopped above 60 m have good quality water, whereas the two holes extended to greater depths (maximum 96 m) have saline water. In all cases, groundwater is stored in fractured gneisses of the Korr Complex. Those rocks are topographically high relative to the adjacent (Kotim) gneisses so that some recharge must take place from perched aquifers in the surrounding relatively thick superficial cover.

Maikona formation

Three boreholes have been sunk into coarse, clastic sedimentary rocks at Maikona (1) and Kargi (2). These rocks should be excellent aquifers (coarse grain size weakly consolidated) and the deepest borehole at Kargi (95 m) has the highest yield (over 10 m^3/hour) of any on sheet 20. An adjacent borehole at Kargi was abandoned for unknown reasons, at a shallow depth (32 m) before striking the aquifer. The borehole at Maikona was also stopped at a relatively shallow depth (c.50 m) and has a low yield of good quality ground water. The high yielding Kargi borehole has saline water.

Shield Volcanics

No details are available for the borehole and well (with hand pump) at Olturot into (? through) the platform basalt of the North-west Volcanic Province. The water is of good quality.

Of the six boreholes into the summit of the Marsabit Shield, the three which intersected interbedded pyroclastics, decomposed lava or soil in massive basalt flow-units all struck good quality groundwater in these friable horizons. The other three intersected montonous flow-units and were dry. Yields from these relatively deep (to 150 m) boreholes are variable (as expected from the nature of the aquifers), up to 8.1 m^3/hour.

6.3 RECOMMENDATIONS FOR FUTURE EXPLOITATION OF THE WATER RESOURCES

With regard to the *surface water* the status quo should be maintained. There are no obvious major dam sites and the groundwater, if exploited properly (see below), is more than adequate to meet the water requirements of the people and livestock.

In order to exploit the *perched aquifers in the superficial deposits* (of the Koroli Desert, Hedad and Korante Plains) the existing shallow wells need to be deepened with properly reinforced walls (see also IPAL, technical report B-2, 1983). Hand pumps fitted to the wells should increase yields. Similar wells could be sunk into the sandy river beds of the Hedad and Korante Plains.

The main hope of locating groundwater in the *western gneiss* area is from boreholes sited to intersect the north-easterly faults. The gneisses do not appear to retain groundwater at shallow depths. The *Korr* area is adequately supplied with water from boreholes and hand dug wells into stream beds (these could be properly lined).

The Maikona formation gritstone is a major aquifer and needs to be properly evaluated. The yield of the deeper borehole at Kargi is minimal because of the limitations of the presently installed pumping equipment. Several deep and properly equipped boreholes should be sunk into this formation and their yields, etc. correctly monitored. The aquifer has the potential to supply the whole of the NE quadrant of sheet 20 and an expanded Marsabit town with water. Extensive recharge must be continually taking place as the aquifer lies within the Chalbi Basin. At deeper levels the aquifer may be saline.

Groundwater in the Marsabit Shield is apparently confined within the lenses of friable material (pyroclastic, soils, weathered lava) interbedded in the massive basalt lava flow-water. Recharge must take place from rainwater percolating through interconnecting joints or along major fractures (higher yields). Therefore new boreholes on the shield should be confined to the NW- and NE-trending belts of pyroclastics through the summit area and drilled until a friable unit is intersected. Similarly, any boreholes on the Asie Shield should be confined to the summit plateau.

An important discovery during the fieldwork was an air vent to the west of Olturot on the slopes of the Kulal Shield. The air is expelled from joints in basalt lavas by pressure built up from a subterranean stream or river. The location of the air vent is shown on the geological map: either a well or borehole should be sunk to intersect the underlying flowing water. Major groundwater flows must exist off Mount Kulal because (1) it has an unusually high annual rainfall (averaging about 80 cm annually) and (2) no major surface flows exist. Therefore any indications of groundwater flow must be fully investigated. An analogous situation exists with regard to the Chyulu Hills (high rainfall, no major surface discharge and massive groundwater movement concentrated into major underground rivers, outletting at Mzima Springs).

6.4 GEOTHERMAL POTENTIAL

There are no surface indications of geothermal activity; volcanism has ceased in the shield volcanoes. Neither hot springs nor steam jets are present. Similarly no present-day tectonism has been identified and the area is seismically quiet.

Warm water is present in all the Kargi boreholes with quoted temperatures of 36° or 37°C (Ministry of Water Development records). Unfortunately no temperatures are given for other boreholes.

It would appear that there is very little likelihood of a source of geothermal energy on sheet 20.

7 Summary of the geological history

The area is founded on Proterozoic sedimentary and volcanic rock folded and metamorphosed during the Late Proterozoic–Cambrian Mozambiquian Orogeny. The dominant lithology throughout this part of northern Kenya is altered psammite (of the Kotim Gneisses). At an early stage in the orogeny a regional, prograde, granulite facies tectonothermal event (Samburuan) converted the psammites and related sedimentary rocks to quartzo-feldspathic and quartz-bearing gneisses respectively, and produced local autochthonous granite melts. Following erosion, a succeeding major tectonic episode (Sabachian) produced recumbent, tight folds together with horizontal tectonic transport of crustal slices. The Korr Complex was emplaced in the south-east and preserves a lower grade assemblage of altered sedimentary and igneous rocks including mafic lavas, peridotite, early granite sheets and marbles.

The rocks of the south-west were refolded by regional NNW-trending, upright folds plunging SSE and simultaneously cut by parallel shears. During this (Baragoian) event the Korr Complex was also cut by the shear zones. The major NNE-trending shear in the extreme south-west is the northern extremity of a major shear zone (Barsaloian) c.180 km long and up to 15 km wide (Charsley and others, 1984). Minor intrusives, mainly felsic veins accompanied these waning phases of the orogeny. No significant metal mineralisation is present in the metamorphic rocks.

Post-Cambrian uplift and/or erosion produced a planar land surface upon which the coarse clastic sediments of the Maikona formation were deposited. In part, the sedimentation took place in a NW-trending graben across the north-east of the area, fed by braided streams for both the south-west and north-east. Present information is insufficient to state the exact age or maximum thickness of these sedimentary rocks. Lithologically they are identical to the Cretaceous Turkana grits west of Lake Turkana. They are economically important both as a major aquifer and as potential hosts to hydrocarbons.

Further erosion and regional warping produced the regional sub-Miocene planar surface which defined the NW-trending Chalbi Basin. Fossiliferous lacustrine beds were deposited in this basin during the Miocene (the Karole formation) on top of the Maikona formation. Dune fields surrounded the lake.

Towards the end of the Miocene, contemporaneous with Rift System faulting to the east, major alkali basalt volcanism commenced with widespread outpouring of homogeneous, thin olivine-basalt lava floods. Fissure sources are assumed for these basalts which overlie all older rocks on sheet 20. They subsequently floored the major Plio-Pleistocene shield volcanoes (Kulal, Asie, Huri and Marsabit) and possibly an older (?Mio-Pliocene) shield in the Koroli Desert. All the shields are entirely composed of alkali-basaltic lavas and pyroclastics. Initial volcanism was controlled by regional fissures, either reactivated older faults in the underlying metamorphic or sedimentary rocks, or contemporaneous Rift faults (Kulal). Thus all the shields have elliptical surface plans. The oldest flows are uniformly thin, laterally extensive ankaramitic basalts erupted under Hawaiian-type conditions. In terms of volume they dominate all the shields. Succeeding volcanicity was progressively more violent to produce intervals of pyroclastic accumulation from cinder cones and *maars* (block-and-ash cones, i.e. Strombolian and Ultravulcanian activity). Initially uniformly thin, laterally extensive, olivine-basalt lavas were erupted, but the final lava flows were narrow tongues of olivine-basalt emerging from cones. During the final volcanic stage the intensity of the pyroclastic outpouring waned (i.e. coarsening of the pyroclastic debris). Throughout the life of the shields the initiating fissures controlled the sites of volcanic eruption, cf. the concentration of pyroclastic material in belts.

No hydrothermal mineralisation accompanied the volcanism. All volcanism has now ceased with no indications of present-day geothermal activity. The presence of pillow lavas in the north-west of the Marsabit Shield adjacent to the Chalbi playa suggests a high lake level contemporaneous with late volcanic activity.

Quaternary reworking of surface material, including the superficial mantles of the exposed sub-Miocene surface, overlapped with the final throes of the shield volcanoes. Fluctuating climate caused lake level changes in the Chalbi Basin. Present sedimentation is confined to flash flood deposits in the Hedad and aeolian sand banking caused by the prevailing winds from the east-south-east.

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Table 5 K-Ar results for basalts
Determinations by Dr C. Rundle, British Geological Survey (Isotope Geology Unit), London

Sample No.	%K (± 1%)	Rad. ^{40}Ar ± % S.D. (nl/g)	Atmos. ^{40}Ar (%)	Age ± 2 sigma (Ma)
RK/20/23a	1.449	0.0479 ± 25.0	95.8	
		0.0388 ± 17.4	94.3	
		0.0499 ± 9.0	89.3	
		mean: 0.0466 ± 6.9		0.83 ± 0.12
23b	1.270	0.0327 ± 10.3	90.8	0.66 ± 0.14
				mean: 0.76 ± 0.17
RK/20/29a	0.554	0.0399 ± 14.3	93.2	
		0.0418 ± 44.3	97.6	
		0.0358 ± 24.6	95.9	
		0.0343 ± 30.1	96.6	
		mean: 0.0381 ± 5.0		1.77 ± 0.18
29b	0.506	0.0379 ± 18.9	90.1	1.93 ± 0.73
				mean: 1.78 ± 0.27
RK/20/35a	0.504	0.0217 ± 71.1	98.3	
		0.0202 ± 50.9	97.9	
		*0.0118 ± 117.9	99.0	
		0.0221 ± 45.4	97.7	
		0.0251 ± 46.6	97.6	
		mean: 0.0222 ± 4.5		1.13 ± 0.10
35b	0.505	0.0217 ± 75.0	98.4	1.11 ± 1.66
				mean: 1.13 ± 0.04
RK/20/49a	0.478	0.0266 ± 20.2	95.1	
		0.0230 ± 80.1	98.5	
		0.0202 ± 19.7	94.9	
		mean: 0.0225 ± 6.4		1.21 ± 0.16
49b	0.487	0.0319 ± 20.5	95.2	
		0.0333 ± 53.4	97.9	
		mean: 0.0321 ± 3.3		1.70 ± 0.12
RK/20/67a	1.238	0.1013 ± 11.7	91.9	
		0.0937 ± 23.0	95.7	
		0.0998 ± 10.0	90.6	
		mean: 0.0997 ± 3.1		2.07 ± 0.13
67b	1.327	0.0854 ± 8.6	89.3	
		0.0869 ± 8.9	89.6	
		mean: 0.0861 ± 0.9		1.67 ± 0.04
RK/20/71a	0.533	0.0518 ± 9.2	89.9	2.50 ± 0.46
71b	0.657	0.0726 ± 6.6	86.4	2.84 ± 0.38
				mean: 2.70 ± 0.35
RK/20/72a	0.534	0.0396 ± 5.2	82.6	1.91 ± 0.20
72c	0.590	0.0553 ± 6.8	83.6	2.41 ± 0.33
				mean: 2.04 ± 0.60
RK/20/75a	0.609	0.0799 ± 3.9	78.7	3.37 ± 0.27
75b	0.804	0.1153 ± 7.0	86.9	3.68 ± 0.52
				mean: 3.44 ± 0.40

Table 5 *continued*

Sample No.	%K (± 1%)	Rad.^{40}Ar ± % S.D. (nl/g)	Atmos.^{40}Ar (%)	Age ± 2 sigma (Ma)
RK/20/101a	0.916	0.0244 ± 7.8	87.9	
		0.0236 ± 10.0	87.0	
		mean: 0.0241 ± 1.7		0.68 ± 0.03
101b	0.976	0.0223 ± 12.3	91.3	0.59 ± 0.14
				mean: 0.68 ± 0.16
RK/20/102a	1.078	0.0614 ± 7.4	87.8	1.47 ± 0.22
102b	1.103	0.0860 ± 5.8	84.9	
		0.0771 ± 7.0	85.6	
		mean: 0.0819 ± 5.5		1.91 ± 0.21
K2/1a	0.275	0.0496 ± 13.5	92.9	4.63 ± 1.25
1b	0.320	0.0595 ± 13.3	88.4	4.78 ± 1.27
1d	0.249	0.0453 ± 22.3	95.5	4.68 ± 2.09
				mean: 4.70 ± 0.08

NB ! = 2 σ error on age > 100 per cent.
★ = 1 σ error on vol. rad. Ar > 100 per cent — not used in mean calculation.

All mean values are the weighted mean and standard deviation calculated according to the formula:

$$\text{mean} = \frac{\frac{A}{a^2} + \frac{B}{b^2} + \frac{C}{c^2} \cdots}{\frac{1}{a^2} \quad \frac{1}{b^2} \quad \frac{1}{c^2} \cdots} \qquad \text{S.D.} = \left[\frac{(\bar{x} - x_i)^2 \times w_i}{(n - 1) \times w_i} \right]^{\frac{1}{2}}$$

where A, B, ... = x_i = measured value, and a, b, ... = w_i = standard deviation on x_i.

Table 6 Relationship between K-Ar age and stratigraphic position

Stratigraphic Horizon	Sample No.	Grid reference	Preferred K-Ar Age (Ma)	*Time Scale
Marsabit Shield				
Youngest Flows	23	4220 7530	0.76 ± 0.17	Pleistocene
Youngest Flows	101	4424 7438	0.68 ± 0.16	
Main shield	29	4220 7660	1.78 ± 0.27	
Main shield	35	4538 8210	1.13 ± 0.04	-c.1.6 Ma
Basal Unit	49(b)	4246 8083	1.70 ± 0.12	
Kulal Shield				
Basal Unit	102(b)	3550 7870	1.91 ± 0.21	
Asie Shield				
Upper Unit	67(a)	3451 8240	2.07 ± 0.13	Pliocene
Upper Unit	72	3530 8200	2.04 ± 0.60	
Basal Unit	71	3630 8220	2.70 ± 0.35	
Isolated Basalt Plateau	75	3960 7800	3.44 ± 0.40	
Isolated Basalt Plateau	K2/1	South end of Marti Engweta Plateau	4.70 ± 0.08	-c.5.3 Ma

* Time Scale according to Bergerren, Kent and van Couvering *in* Snelling, N. J. Editor. 1985. The Chronology of the Geological Record. *Spec. Pub. Geol. Soc. London.*

Miocene/Pliocene boundary slightly younger than the Gilbert/Chron 5 (magnetic) boundary at c.5.3 Ma; Pliocene/Pleistocene boundary slightly younger than the Olduvai Event at c.1.6 Ma.

MINISTRY OF ENVIRONMENT AND NATURAL RESOURCES

Minister: Hon. J. J. Nyagah
Permanent Secretary: Mr E. C. arap Lang'at

MINES AND GEOLOGICAL DEPARTMENT

Commissioner: Mr C. Y. O. Owayo
Chief Geologist: Mr F. G. Theuri

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