

GEOLOGY OF THE MOYALE AREA

DEGREE SHEET 14
(with coloured geological map)

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CONTENTS

	PAGE
ABSTRACT	
I—Introduction and General Information	1
II—Previous Geological Work	3
III—Physiography	4
IV—Summary of Geology	6
V—Details of Geology	6
1. Basement System	6
(a) Quartzites	7
(b) Quartzo-felspathic gneisses	8
(c) Biotite gneisses and migmatites	8
(d) Granitoid gneisses	9
(e) Graphitic gneisses	10
(f) Hornblende gneisses	10
(g) Crystalline limestones	10
(h) Charnockites	11
(i) Plagioclase amphibolites	12
2. Granitic rocks	13
(a) Granites	14
(b) Adamellites	15
(c) Granodiorites	15
(d) Microgranites	15
3. Intrusive rocks	16
(a) Major intrusions	16
(b) Minor intrusions	18
4. Volcanic rocks	19
5. Pleistocene and Recent Superficial Deposits	20
VI—Metamorphism and Granitization	21
VII—Structure	26
VIII—Economic Geology	28
IX—References	32

ILLUSTRATIONS

Fig. 1—Erosion surfaces in the Moyale area	4
Fig. 2—Granite/gneiss contact, Godana Odo	23
Fig. 3—Structures in the Moyale area	26
Fig. 4—Chromite at Debel	28

PLATES

Plate I—(a) Well at El Dera	}	at cente
(b) Granite tors, Jara		
Plate II—(a) Contorted biotite migmatite, Walmurra		
(b) Porphyroblastic granite, El Roba		
Plate III—(a) Tongue of olivine basalt south of Darandiri		
(b) Stringers of pink adamellite in grey granodiorite, Fugugo		

MAP

Geological map of the Moyale area (Degree sheet 14) Scale 1:250,000	at end
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ABSTRACT

The report describes an area in northern Kenya of about 2,550 square miles, bounded by meridians 39° and 40°E., and by latitude 3°N. and the Kenya-Ethiopia border. The area consists of a gently sloping plain, correlated with the end-Tertiary peneplain, studded with hills and mountains rising to over 4,000 feet O.D., some of which are correlated with the older sub-Miocene and end-Cretaceous surfaces. The solid rocks of the area consist of Basement System (Precambrian) paragneisses and granitic rocks, ultrabasic and basic intrusives and Quaternary volcanics. Evidence is given to show that the granitic rocks have resulted from granitization *in situ* and are not intrusives. Superficial deposits of Pleistocene and Recent age include soils, grits and alluvium. The structure of the area suggests at least two periods of folding. Large deposits of chromite and talc occur, but are unlikely to prove of economic importance. The water supplies of the area are described, and potential supplies suggested.

GEOLOGY OF THE MOYALE AREA

I—INTRODUCTION AND GENERAL INFORMATION

GENERAL

The area described in this report is of approximately 2,550 square miles, and lies between meridians 39° and 40°E., being bounded on the south by parallel 3°N. and in the north by the Kenya-Ethiopia border. This border in places follows a line cut in the early 1950s by a joint Kenya-Ethiopia boundary commission, but not yet ratified. Where the tacitly accepted border between the two countries differs from the cut line, mapping was continued up to this imaginary line or as near to it as the local administration considered prudent. In the extreme north-east a small area of granite around El Roba is included in the map since at the time of survey of the adjoining area the cut line was accepted as the *de facto* border, but since then the El Roba Police Post was reopened by the Kenya Police. That part of the area east of meridian 39°30'E. was mapped between November 1960 and March 1961, and the western part between July and October 1962.

The western part of the area lies within the Marsabit District of the Eastern Province, the centre and east falling within the Wajir and Mandera Districts respectively of the North-Eastern Province. The district boundaries are also tribal boundaries separating the Gureh in Mandera District and the Degodia in Wajir District from the Adjuran in Marsabit District. The latter are separated from the Boran, also in Marsabit District, by the motor-track running southwards from Kara Arba and passing in a south-westerly direction to the North of Korondil. A sprinkling of Sakuye is found intermingled with all the tribes mentioned. All are Hamitic and all nomadic, travelling wide distances with their camels, cattle, goats and sheep to follow available water and grazing. The only agriculture noted outside of the fairly intensive cultivation within a radius of three miles of Moyale township was a few acres near Gurar Police Post and small plantations marginal to red and valley soils at Galticha and Gader, and near Debel shop. Maize is the only crop planted.

Game is plentiful, animals seen including elephant, reticulated giraffe, lion, leopard, cheetah, zebra, ostrich, kudu and various species of smaller buck. Guinea fowl are particularly numerous.

CLIMATE AND VEGETATION

Rainfall records are kept at Moyale, Gurar and El Roba within the map area, and at Buna 10 miles south of the area. Average annual rainfall figures supplied by the East African Meteorological Department are.—*Moyale*, alt. 3,650 ft., 688.9 mm. (27.14 in.) over 48 years: *Gurar*, alt. 2,950 ft., 573.7 mm. (22.60 in.) over 6 years: *El Roba*, alt. 2,740 ft., 335.6 mm. (13.20 in.) over 12 years: *Buna*, alt. 1,725 ft., 271.2 mm. (10.69 in.) over 6 years. The higher figures for Moyale and Gurar reflect the altitude of the stations and the proximity of the high tableland of Ethiopia to the north, whose influence does not extend to the more distant El Roba. Over most of the map area the rainfall approximates to that of El Roba and Buna, about 10 in. per year. Two short rainy seasons from March to May and from September to November account for the majority of the rainfall, only rare showers occurring outside those months.

None of the rivers mapped contains water for more than a few hours after heavy rain and none has sufficient alluvium to hold sub-surface water for more than a few weeks. At widely scattered localities are natural water pans, as at Kudama,

Okote and near the eastern border of the lavas, which hold a considerable quantity of water in the rainy seasons, as do the several water-tanks (*balehs*) which are artificially constructed, often on the sites of existing pans, by mechanical excavation, the soil dug out being built up around the tanks as levees, with channels angled out across country to divert nearby streams and surface run-off into the tanks. The water in the smaller pans and tanks may have a very short existence, as, after rain, stock is driven in from many miles around. In December 1960, when the writer was camped at El Roba, an unseasonal heavy shower was seen passing to the south one evening. Early next morning on every road and track in the neighbourhood herds of camels were converging on Kosaye tank from as far afield as Takabba, 25 miles to the north-east. At 9 a.m. the tank, about an acre in extent and which had been dry for several weeks, was seen to contain about a foot of water. By late afternoon it had been drunk dry.

Permanent water, usually in small amounts in dry seasons, is available in hand dug wells at Debel, El Dera, at several places near Moyale township, and at Gurar, though the water from many of the Gurar wells is too saline for human consumption. The wells at El Dera, in the Debel Hills, are typical of those used by the Boran, the walls being tortuous and far from plumb, so that water cannot be drawn up by bucket and rope. Instead a succession of men and women (15 in the El Dera well pictured in Plate I (a)) stand one below the other on perches or platforms of branches and pass skin buckets of water up to the surface and empty buckets back down with surprising speed and rhythm, helped by continuous singing. Perhaps the speed of the operation is rather overdone, since the buckets are seldom more than half full when they reach the surface, and the lower workers are subjected to a continual downpour from spillage.

Around the foot of many of the hills are small wells (*adadi*) dug in the soil or grit, some of which give a trickle of water throughout the dry season, when it is normally reserved for human consumption, being too little to water even the smallest herd of stock. On some of the mountains and hills are natural water catchments in fissures and cleavages in the rock which due to their very small and sheltered surface areas may hold a few gallons of water for many weeks. These, too, are not used for stock, but are looked upon as emergency supplies for travellers. At Moyale and on Fugugo and Saki Gamada wells are dug in joint fissures up to 30 feet wide, whose detritus infilling holds a considerable amount of water for long periods, but are generally too small to water stock for more than a few weeks. In dry seasons the stock remaining in the map area is watered at Gadaduma, a few miles north of Gurar, or at the wells and borehole at Buna, to the south of the area.

Fairly dense thorn bush covers most of the area, high over the red soils but seldom more than three or four feet high on areas of the finer valley soils, where it is often so dense that walking is possible only on existing tracks. Grass cover is generally fair over the valley soils but sparse and often completely lacking on the red soils. Despite this the low average rainfall and very low gradients prevent any serious degree of erosion.

COMMUNICATIONS

Three main roads converge on Moyale township; from Marsabit via Sololo, from Wajir via Buna, and from Mandera via Derkali. The first two are well maintained, but the latter is little used east of Bamba Gurari where the road branches north to Gurar Police Post. Similarly the road from Buna to Takabba, which cuts the south-eastern corner of the area, receives only a minimum of maintenance. All the other motor tracks mapped are mere clearings through the bush, passable only with difficulty in dry weather and not at all when wet. Some tracks date back

to wartime when Italian forces occupied this part of Kenya for a few months, and others were cut by Desert Locust Control officers to provide access to areas otherwise only to be reached on foot. Where such tracks cross areas of black cotton soils (the valley soils of the map) they are particularly prone to damage. The track running south from Kara Arba runs over such soil for most of its length, and in 1962 was almost impassable owing to the work of one thoughtless elephant who had wandered from side to side of the track in wet weather, leaving a ten-mile-long trail of huge footprints a foot deep.

The migratory nature of the local tribesmen has led to the development of a good network of camel tracks over which walking is always easy.

Moyale township has grown around the administrative offices of the former Moyale District, and has a post and telegraph office, police headquarters, school, hospital and several well stocked shops. Elsewhere in the area the only permanent buildings are the police posts at Gurar and El Roba and small shops at Gurar and Debel.

Moyale has two airstrips, one adjacent to the township which is suitable only for single-engined aircraft, and a larger strip, on the flats below the hills, which is used by twin-engined planes.

MAPS

The area is covered by sheets 18, 32, 32a and 33 of the 1:100,000 Y633 Series of the Survey of Kenya. These maps were compiled from R.A.F. air photographs taken in 1957 at a scale of approximately 1:80,000. Where place names on the maps were found not to conform to local usage, such names have been amended on the geological map. Much of the Kenya-Ethiopia border is also covered by R.A.F. photographs taken in 1947 at a scale of 1:30,000. Geology was plotted directly on to photographs, at the larger scale where such photographs were available, and transferred to a field map at 1:80,000, the final map being drawn at 1:150,000 for mechanical reduction to the printed scale of 1:250,000. Contours over the flatter areas are sketched, being controlled by spot heights taken by an aneroid barometer and suitably corrected. Mountainous areas were contoured from air photographs with the aid of a Kalk Stereo Plotter. No accurate altitudes have been calculated in this part of Kenya, and all heights on the map are based on the D.C's. office at Moyale, which is accepted as 3,650 feet O.D. When mapping the adjacent area to the south, Williams (Williams and Matheson, Report No. 95) based the topography on the assumed altitude of Wajir, and heights calculated along the common border are shown as nearly 100 feet higher to the north than those in the area mapped by Williams.

II—PREVIOUS GEOLOGICAL WORK

In 1902/03 P. Maud (1904*) passed through the area, and his report discussed the Ethiopian (Dirri) escarpment which runs south-eastward through the present-day Moyale and dies away near Gurar.

Captain C. N. French (1913) in the course of his travels in 1911/12 crossed the north of the area from Gader to Gadaduma and thence to Moyale, and mentioned the polluted water at Gader, and the arc of hills along the present border.

In the first year of the 1914-18 war, J. Parkinson (1920) made a geological reconnaissance of much of northern Kenya. He too mentioned the Ethiopian (Goro) escarpment, and later referred to the metamorphosed sediments near Ajao, just south of the southern border of the map, which he correlated with the Turoka series of southern Kenya. He also mentioned a boss of granite five miles north of Ajao—obviously Dhuhumu, the Moyale granodiorite and ultrabasics at and near Debel.

*References are quoted on page 32.

F. Dixey (1948) traversed the area in 1943, and his work is dealt with later in this report.

A summary of a paper presented to the 19th International Geological Congress at Algiers by E. O. Teuscher (1953) briefly discussed the crystalline rocks in southern Ethiopia near the present area, mentioning adamellite and granitic material seemingly mobilized in the quartzose and biotite gneisses.

The area east of the northern part of the present map was surveyed by E. P. Saggerson and J. M. Miller (1957), and the area east of the southern part by A. O. Thompson and R. G. Dodson (1958). Reports on the areas to the south (Williams and Matheson, Report 95) and west (Dodson and Matheson, Report 94) are in preparation.

III—PHYSIOGRAPHY

The main feature of the area is a plain sloping gently away from the Ethiopian Plateau, which lies mainly outside the area to the north and west, tongues of which thrust southwards at Moyale, Chalalaka and Fugugo. The plain is broken by hills which are outliers of the plateau, the larger of which are composed of the more resistant

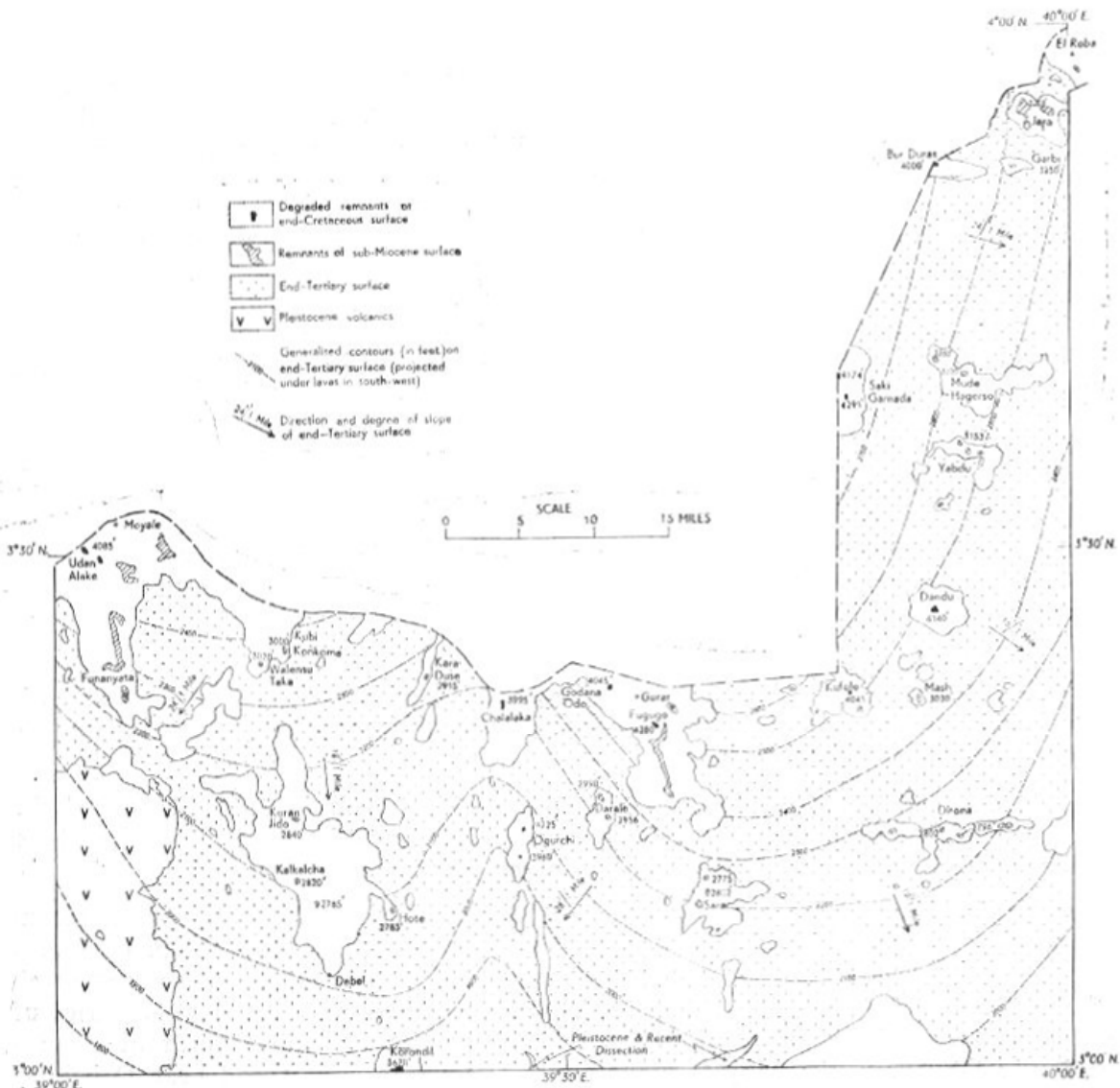


Fig. 1—Erosion surfaces in the Moyale area

rocks, granitic and granitoid varieties generally forming steep-sided and craggy hills and tors, particularly well shown at Jara (Plate I (b)). Metamorphosed basic intrusions and quartzites and limestones usually form much less distinctive features, of rounded outline. In the south-west is an area of about 145 square miles of Quaternary volcanics in which remnants of five craters can be seen. Outside of the hilly areas outcrops are rare and float, where found, is almost always of vein quartz, so that over much of the country no indication can be seen of the nature of the underlying solid rock. The plain is part of the end-Tertiary surface of Dixey (1948, p. 18), which here shows fairly steep slopes as compared with that surface over most of Kenya, and can be regarded as a pediment rather than a peneplain proper. There is no evidence to show whether the surface has been tilted subsequent to maturation. The generalized contours of the end-Tertiary plain show marked valleys running southwards in the centre and west, the latter being obscured to a great extent by lava flows. The lack of marked breaks of slope in these valleys suggests that they were a feature of the original surface, and not caused by later downcutting. The only important dissection of the surface is in the extreme south, in the valleys of Laga Jarti Guda and Laga Jara, where the dry river beds lie as much as 30 feet below the level of the plain. Exposed in the steep valley sides of these two rivers are deposits of secondary limestone (kunkar) in nodules and lenses varying in thickness from a few inches to over two feet. Similar kunkar deposits were found in the poorly marked valley west of Dandu, at a few places in the south-centre of the area and sporadically in the valley soils elsewhere. They were formed by down-leaching and redeposition of the calcareous elements in the soil over long periods of time when erosion on the surface was virtually at a standstill, as it is today.

Above the end-Tertiary surface remnants of a higher surface can be traced—the mid-Tertiary peneplain of Dixey (1948) now known in Kenya as the sub-Miocene surface. It is here represented by a concordance of summit heights and bevels varying from over 3,250 ft. O.D. in the north to about 2,750 ft. towards the south. Remnants of this surface are more obvious in the eastern half of the map area, those in the west and particularly in the south-west being much less certain, and for this reason it is not possible to decide whether the marked central valley in the end-Tertiary surface is repeated in the higher surface. The sub-Miocene, like the end-Tertiary surface, never reached full maturity, as is shown by the hills which still rise above the remnants of the surface, as at Dirona and Sara in the east. Differences in elevation of these higher peaks and the sub-Miocene bevels on them vary widely, except in the group of hills centred on Dirona, where several peaks reach an altitude of almost 100 feet above the sub-Miocene remnants, and just possibly represent a slightly older surface. On most of the larger hills near the Ethiopian border only a few traces of the sub-Miocene bevel were found, notably a broad flat-bottomed valley in the south of the Kufole Hills, a well marked bench on the eastern slope of the Fugugo block and shelves and cols in the Moyale Hills.

The fair accord of summit levels of these larger hills, at about 4,000 ft. O.D. suggests that they are remnants of Dixey's end-Cretaceous surface. Only at Fugugo (shown as Gurar on Dixey's map) is there any wide extension of this surface. There, over an area of half a mile square, several minor peaks reach within a few feet of the elevation of the highest point, 4,280 ft. which probably represents the true elevation of the surface.

The difference in elevation between the end-Cretaceous and the sub-Miocene surface in this area is in the order of 1,200 feet, and the difference between the latter and the end-Tertiary surface varies from 650 feet in the north-east to about 550 feet in the south-east.

IV—SUMMARY OF GEOLOGY

The consolidated rocks of the area are divided into four main divisions, metamorphosed bedded rocks (mainly sediments) of the Basement System, Precambrian in age, granitic rocks, intrusives, and Quaternary volcanics. Most of the plain areas are masked by superficial deposits of Pleistocene and Recent age.

Basement System

The most abundant Basement System rocks are limestones, quartzites and plagioclase amphibolites, with lesser amounts of granitoid gneisses, biotite gneisses and migmatites, hornblende gneisses, graphitic gneisses, quartzo-felspathic gneisses and charnockites. They closely resemble the Turoka Series of Parkinson (1913, p. 534). The division between biotite gneisses and migmatites and granitoid gneisses is a gradual one, and examination of thin sections proves the granitoid gneisses in turn to grade into rocks of the granitic group.

Granitic Rocks

Under this heading are described granites, adamellites and granodiorites, all of which represent sediments granitized *in situ*. The few small outcrops of microgranite are thought to mark local mobilization of parts of the granitic rocks.

Intrusive Rocks

The main representatives of this class are the metamorphosed ultrabasic rocks in the west of the area. The only other larger intrusion is the gabbro boss or bosses which form the Mash Hills. Small outcrops of gabbro occur near Korondil, and float of olivine gabbro was found south of Gader. Minor intrusives are few, and consist of metadolerites, patches of acid pegmatite and quartz veins, only a few of which are large enough to justify their inclusion in a map of this scale.

Quaternary Volcanics

In the south-west an area of olivine basalt can be mapped as two separate flows, the older of which was extruded from craters which still remain, while the later and coarser flow takes the form of plateau eruptions from fissures which are not seen.

Pleistocene and Recent deposits

These comprise the soils of the area, which have been sub-divided into red, sandy soils and the finer, dusty valley soils, usually grey or black and occasionally brown in colour. Less important deposits are coarse semi-consolidated grits around some of the granitic hills, and small deposits of quartz gravel and secondary limestones.

Rocks of the Ablun Series, a group of sediments metamorphosed to a lower degree than the Basement System rocks and presumed younger than that System (Thompson and Dodson 1958, pp. 12-15) which outcrop a few miles east of the northern part of the present area were not found in the map area, nor were Mesozoic sediments, which cover most of the area of Kenya lying to the east.

V—DETAILS OF GEOLOGY

1. Basement System

The Basement System rocks are classified as follows:—

- (a) Quartzites
- (b) Quartzo-felspathic gneisses
- (c) Biotite gneisses and migmatites

- (d) Granitoid gneisses
- (e) Graphitic gneisses
- (f) Hornblende gneisses
- (g) Crystalline limestones
- (h) Charnockites
- (i) Plagioclase amphibolites

(a) *Quartzites*

The quartzites of the area have been subdivided into three types:—

- (i) Coarse white quartzites—Xq₁
- (ii) Iron-bearing quartzites—Xq₂
- (iii) Fine-grained white and purple quartzites—Xq₃

Outcrops of quartzites usually form steep-sided prominent hills, with the exception of the iron-bearing quartzite (Xq₂) which was seen only as a single exposure a few feet across. The coarse-grained varieties (Xq₁) show a rather rounded outline from a distance, but the surfaces of the outcrops are usually littered with boulders, and difficult to traverse. The fine-grained quartzites (Xq₃) form massive tors, closely simulating granite, due to very strong jointing which at Bur Duras leads to the formation of vertical cliffs exceeding 50 feet in height.

(i) *Coarse white quartzites*

These occur only in the south-eastern quarter of the area. In hand specimen they are white or very pale grey, occasionally with red or brown iron-staining picking out individual grains, which locally reach half an inch across. In thin section the quartz is seen to occur as interlocking anhedral grains, and in specimen 14/106* from Dirona many of the grains show a shadowy outline of the original sand grain upon which the quartz recrystallized. Strain shadow in the quartz is usually faint or absent, pointing to total recrystallization of the rock, as is also indicated by the coarseness of grain. Many of the quartz grains of specimen 14/113 from Kubi Makagaad are distinctly biaxial, with a 2V of up to 10°. The quartz in this particular slide shows no strain. Accessory minerals identified are always in trace amounts, and consist mainly of iron ore, both as opaque magnetite and ilmenite and as red or brown iron oxides. In lesser amounts are micas, generally white or pale green muscovite and sericite, occasionally biotite. Specimen 14/145 from Anagasile contains specks of tourmaline in addition to mica.

(ii) *Iron-bearing quartzites*

Only one solid exposure of these quartzites was found, north-east of Bur Duras on the cut line marking the Kenya-Ethiopia border in the north-east of the area. The occurrence of float blocks of very similar appearance on the northern slopes of Bur Duras suggests that it is a local variation of the Bur Duras quartzite. The hand specimen, 14/76, is almost black in colour, with streaks of red-brown iron oxide picking out the foliation of the rock. In thin section it is seen as an interlocking mesh of fine-grained unstrained quartz, shot with semi-radiating clusters of needles of red-brown iron oxide and blebs and dusty patches of opaque iron ore. Where the iron content of the slide is highest the remaining interstitial quartz is seen as an extremely fine-grained, almost amorphous, aggregate. No minerals other than quartz and iron ore were seen. At Mado

*Numbers 14/106, etc., refer to specimens in the regional collection of the Mines and Geological Department, Nairobi.

Goda float blocks of a rock of similar appearance, though of coarser grain, were found. But in thin section (14/63) the Mado Goda rock is very different in appearance, the opaque iron ore being roughly equigranular with the quartz, which is coated with transparent yellow oxide, and associated with deep green chloritized biotite and smaller amounts of pale green hornblende. Apatite occurs in trace amounts. This rock may represent a metamorphosed intermediate dyke rather than a metasedimentary quartzite.

(iii) *Fine-grained white and purple quartzites*

These occur only at Bur Duras and its outlier Garbi. In hand specimen the rock is of medium to light grey colour, with streaks and patches of brownish-purple iron staining, with a very distinct foliation often picked out by layers of colourless sericite, which locally becomes so abundant as to produce a quartz-sericite schist. A typical slide, 14/77 from Bur Duras, shows a fine-grained mesh of anhedral quartz grains, all showing strain shadow, and all elongated along the foliation, as are the flakes of sericite. Iron ore is seen in the slide only in trace amounts, both as opaque grains and as red-brown oxide. A few stubby prisms of tourmaline also occur, dichroic in shades of brownish grey. These quartzites compare very closely with the Kisii quartzites of western Kenya (Shackleton, 1946 p. 45 and Huddleston, 1951 pp. 26-30), of the Bukoban System, which is younger than the Basement System. In the present area the fine-grained quartzites are nowhere seen in contact with other solid rocks, though farther east Thompson and Dodson (1958, map and p. 9) show a quartzite which is clearly a continuation of the Bur Duras quartzite in contact with a typical Basement System crystalline limestone. Thus, while the age of the Bur Duras quartzite is not certain, it is more likely to be of Basement age than Bukoban. These quartzites bear little resemblance to those of the Ablun Series a few miles farther east. (Thompson and Dodson, 1958, p. 13).

(b) *Quartzo-felspathic gneisses*

In hand specimen the quartzo-felspathic gneisses, which are exposed only near Kubi Konkoma south-east of Moyale, closely resemble the more leucocratic facies of the granitoid gneisses, but they lack the craggy, tor-forming aspect of those rocks. In thin section microcline, a ubiquitous constituent of the granitoid gneisses, is seen to be lacking. Specimen 14/192 is dark fawn in colour, of medium grain, and well foliated. Its chief constituents are quartz and sericitized albite, with very small amounts of pale greenish brown biotite, locally completely chloritized and associated with iron ore and rare white mica. Almost colourless subhedral and anhedral garnets are also seen in the slide, with trace amounts of apatite.

(c) *Biotite gneisses and migmatites*

Distinction between biotite gneisses and migmatites and granitoid gneisses was made on their appearance in the field rather than on petrological grounds. The biotite gneisses generally occur in the form of rounded outcrops, as against the craggy and tor-forming granitoid gneisses. Where feldspar porphyroblasts occur in more than trace amounts the rock is referred to the granitoid gneiss division. The migmatites are clearly banded alternations of mafic biotitic rock, often schistose, with white or off-white quartzo-felspathic layers up to four inches in thickness, but usually less than two inches, and always strongly contorted (Plate II (a)). In hand specimen the biotite gneisses are of fine to medium-grain, medium to dark grey in colour dependent upon their biotite content, and show a marked foliation due to parallel alignment of mica flakes. In thin section biotite is generally strongly dichroic in shades of brown, except in 14/111 from Kotich where the biotite is greenish and locally chloritized, with magnetite thrown out. Specimen 14/122 from Walmurra shows alteration of red-brown

biotite to aggregates of sericite and magnetite. Quartz is an important constituent of all the slides examined, together with plagioclase feldspar, usually oligoclase but sometimes oligoclase-andesine. Microcline is rare, but occurs locally as an alteration of plagioclase and sometimes as small porphyroblasts. Accessory-minerals include pale-green, bleached hornblende and pleochroic red-brown sphene, both associated with biotite in specimen 14/119 from Walmurra, apatite, and occasionally zircon, which in 14/130 from Borambor occurs in large grains, sometimes with pleochroic haloes in biotite. In this last occurrence the biotite gneiss is cut by streaks and lenses of granite, which do not disturb the foliation of the gneiss but have grown slowly at the expense of the gneiss.

In the typical migmatites, as at Walmurra (where migmatite makes up only a few per cent of the bulk of the biotite rocks) the leucocratic layers make sharp contacts with the schistose biotitic component, but with no evidence of thermal alteration. In thin section the leucocratic layers are seen to consist of quartz, oligoclase-andesine and microcline, with only trace amounts of biotite. The leucocratic layers are segregations of the original rock material, probably with addition of small amounts of potassic material (as evidenced by the development of microcline) and not of material injected into the existing rock mass.

(d) *Granitoid gneisses*

As already stated, outcrops of granitoid gneisses in the area form craggy hills, with tors and huge joint blocks, very similar to the granitic outcrops. Gneissosity in the granitoid gneisses, which was used as a criterion to distinguish them from the non-foliated granitic rocks, is always less marked than in the biotite gneisses, and in almost all the outcrops examined feldspar porphyroblasts are prominent. The granitoid gneisses are of medium to coarse grain, varying in colour from pale to dark grey with increasing biotite content, and with pink or pinky-brown feldspar porphyroblasts. Thin sections all show abundant quartz, usually with strain shadow, and sometimes myrmekitic against the feldspars. Plagioclase feldspar varies in different exposures from oligoclase to andesine, and is usually coarsely perthitic. Microcline occurs mainly in the form of porphyroblasts which have grown at the expense of existing rock minerals, without developing augen structure across the foliation. A small amount of microcline also occurs in the main mass of the rock, where it is usually clearly an alteration of plagioclase feldspar, being clear and unaltered as contrasted to the cloudy and saussuritized original feldspars. Orthoclase is lacking in all the slides examined. In specimen 14/64, from Diniko Diko on the Ethiopian border, the plagioclase feldspar of the groundmass is albite, which also occurs as porphyroblasts in addition to the more numerous microcline porphyroblasts. The predominant ferromagnesian mineral present in the granitoid gneisses is biotite, usually of a greenish tinge and usually more or less chloritized. Epidote is a common alteration product of the biotite and feldspars, and becomes an important constituent of the rock at Kubi Halo (14/82) and Kubiyo (14/103). In specimen 14/118 from Kubi Kuyara the dominant ferromagnesian is dark blue-green hornblende, which is locally altered to red-brown biotite. Sphene occurs in trace amounts in many of the slides examined, and in 14/38 from Godana Odo forms two to three per cent by volume of the rock mass, in grains exceeding a millimetre in length. Other accessory minerals are muscovite and sericite, iron ore usually associated with biotite, and apatite. Garnet was seen in trace amounts in 14/202 from Udan Alake.

The granitoid gneiss of Abiyu and Dudubatu (14/170) is strongly quartzose. In hand specimen it is of fine to medium grain, the foliation being well marked by alternating layers of pink and grey colour, with lenses and lenticles of white quartz. In thin section nearly 80 per cent of the rock is seen to be quartz in two generations, the earlier fine grained and iron stained, with streaks of the later clear recrystallized

quartz of much coarser grain. Microcline makes up about 15 per cent of the total and oligoclase-andesine 5 per cent. Other minerals, all in trace amounts, are wisps of green chloritized biotite, opaque iron ore, muscovite and sphene. The original rock was a fairly pure sandstone or quartzite.

(e) *Graphitic gneisses*

The main occurrences of graphitic gneisses are some 12 miles south-east of Moyale at Harage and Walensu Taka, and near Waldiri, a further 12 miles south-south-east of those outcrops. Other small occurrences are at and near Kubi Mata Sadeni, eight miles east-south-east of Moyale and at Funanyata south of Moyale. The gneisses are generally of fine grain, and flake size of the graphite is generally very small, though at Kubi Konkoma flakes up to 3 mm. across were seen. In this outcrop graphite content locally reaches 20 per cent of the volume of the rock, though throughout the outcrop the average is only three to four per cent. A thin section from there, 14/190, shows graphite associated with iron ores and pale green mica, probably phlogopitic. Other minerals identified are quartz and strongly saussuritized feldspars of the composition of oligoclase-andesine. Rutile occurs in trace amounts. Specimen 14/232 from north-east of Waldiri is of very fine grain, approximating to slate in appearance. The slide of this rock has a mylonitic texture almost certainly due to shearing, and the graphite is seen as fine dust in a groundmass of granular quartz and unidentified feldspar, with trace amounts of colourless mica. A few blebs of clear quartz and microcline are clearly of secondary growth.

(f) *Hornblende gneisses*

A few small outcrops of hornblende gneiss are associated with the graphitic gneisses at Kubi Mata Sadeni and Kubi Konkoma. They are of medium to coarse grain, dark greenish grey speckled with white, and with well marked foliation. A typical specimen, 14/250 from Kubi Konkoma, shows some 60 per cent of the rock to be pale brownish-green hornblende associated with quartz, strongly saussuritized oligoclase, and clinozoisite. The lack of iron-ore in association with the clinozoisite points to the latter being an alteration product of feldspar, not hornblende. Specimen 14/194 from Kubi Mata Sadeni is very similar except that the hornblende is clearly secondary after very pale green diopside. These gneisses are considered to be of sedimentary origin—probably metamorphosed derivatives of lime-rich siltstone, as evidenced by the occurrence of quartz and the good foliation of the rocks, which closely parallels the contacts with adjacent graphitic gneisses and therefore almost certainly marks the original bedding of the sediments.

(g) *Crystalline limestones*

These rocks are widely developed in the centre of the area, with lesser amounts in the south-east. Other solid exposures are seen south-east of Moyale, and a few patches of float were found along the Ethiopian border in the north-east. Their outcrops always form positive features, either fairly steep ridges and hills or, as at Danicha in the south-east, as almost flat platforms raised two or three feet above the surrounding plain soils. The outlines of such outcrops may often be traced on air photographs by the change in vegetation, which is usually much denser on the limestones than on the red soils. The limestones are generally white in colour, less often of shades of pink or grey, and of coarse or very coarse grain, individual calcite crystals reaching up to 6 mm. across. In the many slides examined the most common minerals present after calcite are phlogopite mica, either colourless or very pale brown, and colourless forsterite, usually altered marginally and along cracks to colourless or pale yellow serpentine (ophicalcite), though in specimen 14/142 from Sara the forsterite appears to have altered to a fine-grained aggregate of calcite, and serpentine is not seen. Blue

spinel occurs in 14/43 from Mado Goda and 14/125 from Sigide, in both cases in addition to forsterite and serpentine. Graphite, which is very common in crystalline limestones in the south of Kenya, was seen only in those exposures near Moyale and in 14/67 from Mado Goda, in trace amounts. The latter specimen is unusual in that it is of a medium red colour in hand specimen, and under the microscope the calcite is seen to occur in separate generations, a larger and older generation free of iron-staining, and streaks of much fine calcite, with each individual rounded grain coated with translucent iron oxide. There is a further generation of even finer calcite grains in thin streaks. The appearance of the slide suggests recrystallization of the original coarse-grained calcite along shear planes, and a further deposition of very fine-grained calcite from solution along opened cracks and joints, accompanied by iron oxide in solution which has coated the calcite grains in the weaker portions of the rock. Accessory minerals seen in this slide, apart from graphite and iron oxide, are quartz, scapolite (which also occurs in 14/107 from Dirona) and colourless phlogopite. Other minerals recognized in the limestones are diopside and wollastonite, both in specimen 14/43 from Mado Goda, tremolite in 14/191 from Kubi Konkoma, zoisite in 14/193 from Kubi Mata Sadeni, muscovite and biotite.

Where crystalline limestones are in contact with granite just east of the main road at Mado Goda blebs and streaks of calc-silicate rock are sometimes developed within two or three feet of the contacts, very sparsely distributed, so that in most of the places where a clear contact can be seen no interaction between the two rock types could be recognized. Specimen 14/147 was taken from a knot of limestone a foot long caught up in granite. In hand specimen it is of coarse grain, green and white in colour, speckled with fine blue-black crystals of diopside. In the two thin sections examined the constituent minerals are calcite, almost colourless epidote, blue-green diopside, salmon-pink garnet, strained quartz, a small amount of plagioclase feldspar (oligoclase-andesine) and scapolite. Where granitic material is seen as enclaves in limestone, usually in angular blocks only a few inches across, the limestone immediately adjacent to the granitic material always shows a strong development of epidote, as in specimen 14/154. The granitic enclave consists of quartz and albite-oligoclase, the only accessory mineral being epidote. Microcline is lacking, in contrast to the main body of the granite where it forms the dominant feldspar.

Where the road at Mado Goda crosses the most westerly outcrop of limestone the rock contains well-scattered schlieren up to two feet in length of a fine-grained black and white rock with a marked foliation concordant with that of the limestone. In thin section one such schlieren, specimen 14/42, shows pale blue-green slightly pleochroic augite, altering marginally to brownish-green strongly pleochroic hornblende, with andesine-labradorite and trace amounts of sphene. The origin of this rock is not clear—it may represent part of a minor basic dyke intruded into the limestone prior to folding (though no basic dyke was found within many miles of this exposure) or perhaps patches of muddy sediment laid down with the limestone.

(h) *Charnockites*

Charnockites are found only in the southern part of the Sara Hills, where they form a fairly large hill and three small, low outliers. In the large hill the rock is of coarse grain, dark brownish-grey in colour, with red garnets up to half an inch across, and with a distinct foliation marked by a tendency to segregation of the dark and light minerals in discrete bands. In thin section 14/141 the most important ferromagnesian is hypersthene, pleochroic in pink and green, with marginal fringes of green antigorite. Much of the hypersthene shows alteration to red-brown biotite in ragged flakes, often bent and twisted, and opaque iron ore. Anhedraal garnets are common, pale pink in colour and heavily fractured. Leucocratic minerals are quartz and andesine-labradorite, with apatite in trace amounts.

The rock of the three outliers to the west, where charnockites occur interfingering with biotite granitoid gneisses, is very similar in hand specimen, but under the microscope (specimen 14/139) the hypersthene is seen partly altered to brownish-green hornblende with a good deal of opaque iron ore, and garnet is missing. The felsic minerals are quartz and plagioclase feldspar, with some development of myrmekite between the two. In this section the plagioclase is much more sodic, being oligoclase, with albite-oligoclase occurring in the accompanying granitoid gneiss. Apatite again occurs as a trace accessory.

The two specimens described both fall into the Intermediate Division of the Uganda charnockites described by Groves (1935, pp. 162-168), 14/141 being the more basic of the two as evidenced by the composition of the plagioclase feldspar. Groves (*ibid.* pp. 198-200) cites a considerable bulk of evidence pointing to the production of the charnockitic rocks by plutonic metamorphism, usually in a dry environment, of a series of normal plutonic rocks, but elsewhere he notes that paragneisses occur in association with charnockites, and it appears that they, too, may give rise to true charnockites under plutonic metamorphism. In the present area the origin of the charnockites is obscure largely due to their small and virtually isolated outcrops. The occurrence of interfingering charnockites and granitoid gneisses points to more than simple plutonic metamorphism, since under such conditions it is difficult to believe that the production of charnockites would be selective in such a small space, the rock types changing over a distance of only a few inches in places. Similarly the metamorphosed sediments and granitic rocks elsewhere in the Sara Hills show no charnockitic affinities, though they must have been subjected to much the same degree of metamorphism. The charnockites of Sara therefore appear to have been derived from the metamorphism of rocks somewhat different to the sediments which gave rise to the nearby rocks, but whether they were of plutonic origin or argillaceous sediments is not clear.

(i) *Plagioclase amphibolites*

The most important developments of plagioclase amphibolite in the area are near Moyale and at Kufole, where it occurs in contact with granite, and smaller exposures to the west of Kufole. In the north of the Sara Hills a few discontinuous outcrops occur in contact with granodiorite and at Iladu and Kara Arba plagioclase amphibolite is associated with ultrabasic intrusives. A typical specimen from Kufole, 14/99, is of medium grain, speckled black and white and well foliated. In the thin section the main mineral is hornblende, pleochroic from yellow-brown to deep blue, pointing to a fairly high soda content. The hornblende is locally associated with clusters of sphene and apatite. The plagioclase feldspar is andesine, often saussuritized and enclosing fragments of pale green augite, with trace amounts of microcline locally replacing andesine. Quartz was not found in the slide, the only other mineral present being opaque iron ore. A small exposure north of Garsa Abula, specimen 14/151, again has hornblende as its chief constituent, but of a green colour with much opaque iron ore and rare sphene. Other minerals seen are andesine, a few per cent of quartz and trace amounts of apatite. The plagioclase amphibolite in the Sara Hills is very similar in appearance to the Kufole rock, but with much less distinct foliation. In thin section, 14/126, the main mafic mineral is pale blue-green diopside altering to brownish-green hornblende and iron ore. Interstitial to the mafic minerals are plagioclase feldspar (andesine-labradorite) and quartz. Streaky inclusions of this same plagioclase amphibolite are found in the granodiorite for a distance of several hundreds of feet uphill from the main contact of the two rocks.

A lens of plagioclase amphibolite 20 inches long and four to five inches in width was seen in granodiorite at Sigide. The mafic minerals in that inclusion, specimen 14/123a, are pale blue green diopside altering to green hornblende, which in turn is partly altered

to red-brown biotite. The volumetric percentages of these three minerals in the whole rock were estimated as diopside 2 per cent, hornblende 55 per cent and biotite 8 per cent. The remaining minerals are oligoclase-andesine, a small amount of quartz and traces of apatite and iron ore.

The plagioclase amphibolites in the vicinity of Moyale differ somewhat in composition from those just described. Specimen 14/201 from west of Moyale township is typical. It is of fine to medium-grain, clearly foliated, and in thin section the only amphibole seen is pale green actinolite, though in other slides from nearby outcrops a few per cent of brownish green hornblende sometimes accompanies the actinolite. The felspar is oligoclase, much of which is altered to clinozoisite, and quartz is lacking. Farther south, at Funanyata, lenses of slightly darker colour occur in the plagioclase amphibolite strata. One such lens was sampled (14/209) and the slide was seen to be totally lacking in felspar, its place being taken by clinozoisite. Both hornblende and lesser amounts of actinolite are present. Again in 14/214 from Iladu clinozoisite has completely replaced felspar in the section examined, and calcite is present in trace amounts. This particular rock is strongly schistose, probably due to shearing. The last three localities are all near or in contact with ultrabasic intrusive rocks, and probably are metamorphic derivatives of lavas or dykes. However, the plagioclase amphibolites farther east, described earlier, are all interbedded with or in contact with metasediments, and this fact, together with the occurrence of quartz in most of the slides examined, points to a probable metasedimentary origin, possibly a calcareous mudstone.

Specimen 14/184 from Kara Arba is anomalous in so far as it occurs as a single outcrop in an ultrabasic environment, yet quartz makes up several per cent by volume of the slide, and garnet is present in the hand specimen. The amphibole is blue-green hornblende and the plagioclase is andesine-labradorite, locally replaced by clinozoisite. Apatite and iron are present in trace amounts.

2. Granitic Rocks

The granitic rocks are mapped under four classifications,

- | | |
|-----------------|-------------------|
| (a) Granites | (c) Granodiorites |
| (b) Adamellites | (d) Microgranites |

The first three are all coarse-grained rocks, sub-divided according to the ratio of alkali-felspars to plagioclase. Where the ratio exceeds 2:1 the rocks are shown as granites, between 2:1 and 1:2 as adamellites, and where plagioclase exceeds 2:1 as granodiorites. The finer-grained equivalents are all mapped as microgranites, though two of these are more correctly microgranodiorites, due to the predominance of plagioclase over alkali-felspars.

In the field a broad classification can be made on colour, the granites being predominantly red or pink, the adamellites grading from pink to pinky-brown, and the granodiorites being brown to grey. The colour gradation does not always hold, since some specimens of granodiorite are lighter in colour than some adamellites. In most of the smaller exposures the rock type has been determined by a single thin section, but slides were made from several specimens taken at scattered localities on the larger outcrops. All the rocks discussed in this section are non-foliated, or show only a vague gneissosity over very small areas, the foliated varieties having already been described under granitoid gneisses.

In none of the granitic rocks was orthoclase identified. Much of the felspar is untwinned, simulating orthoclase, but all the grains tested proved to be plagioclase. There is little evidence of typical granite mineralization, tourmaline and topaz being absent, fluorite occurring in two specimens and pyrites in one. The pegmatite phase of normal intrusive granites is also lacking. Many of the granitic rocks enclose remnants

of gneissose rocks, most of which prove to be of similar composition to the host rock but deficient or lacking in microcline. One such inclusion, a few inches long, in the Kufole granite (14/94a) was sectioned, and seen to consist of a mosaic of quartz, oligoclase and greenish brown biotite, with abundant iron ore and apatite. Other inclusions noted in granitic rocks are plagioclase amphibolite and calc-silicate, both already described, and epidiorite, described later with the minor intrusions.

(a) *Granites*

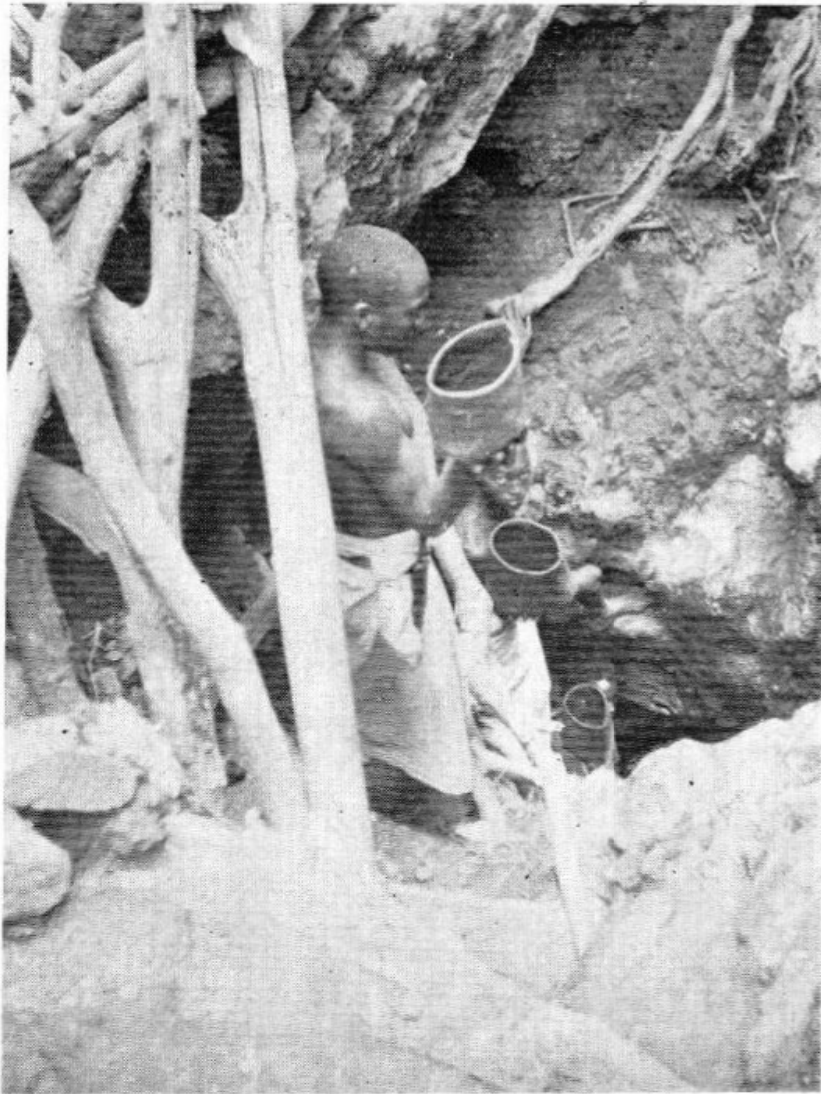
The granites are all of coarse grain, generally of shades of pink, more rarely red, and sometimes with a white or grey groundmass with pink or red feldspar porphyroblasts. The rocks sampled are divided evenly into porphyroblastic and non-porphyroblastic types, the porphyroblasts being generally of microcline, though specimen 14/129 from Borambor contains porphyroblasts of quartz and oligoclase in addition to microcline. Often both porphyroblastic and non-porphyroblastic types alternate in the same outcrop.

A typical specimen of porphyroblastic granite is 14/72 from Saki Gamada. It is red in colour, with brown quartz and black mica, some of the red feldspar porphyroblasts exceeding 25 mm. in length. In thin section the porphyroblasts were identified as coarsely perthitic microcline, with both rounded and angular inclusions of quartz and plagioclase. The groundmass minerals are quartz, microcline and plagioclase in the oligoclase range, often cloudy and sericitized. The ferromagnesian is strongly pleochroic biotite, generally in shades of green with relics of red-brown biotite, the green colour being due to incipient chloritization. Iron ore is common, both in opaque form and as red-brown oxide staining. Accessory minerals identified are sphene and apatite. Specimen 14/75 from El Roba Police Post (Plate II (b)) is rather similar, though somewhat lighter in colour, and with pink feldspar porphyroblasts sometimes reaching 50 mm. in length. Spectrographic analysis of a crushed sample of the El Roba granite showed it to be higher in soda than potash. The explanation of this rather surprising result probably lies in the amount of soda feldspar occurring as perthite in the microcline, added to the soda of the plagioclase feldspars.

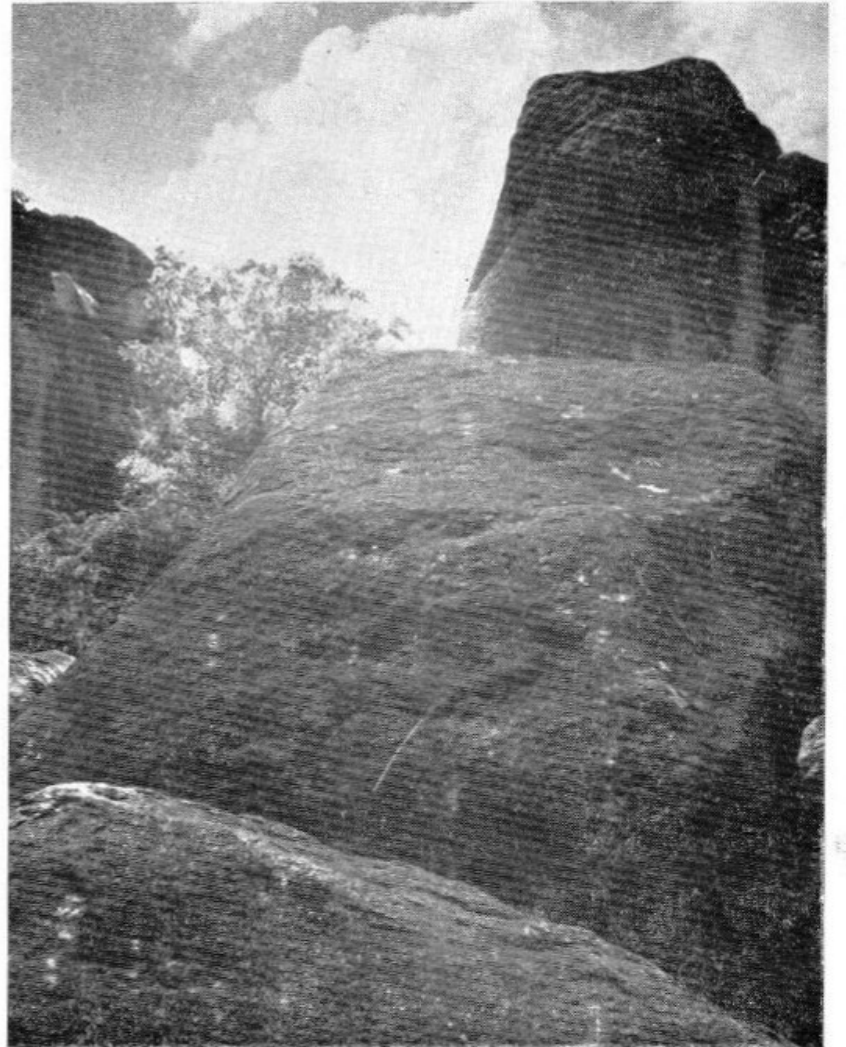
In all the thin sections of porphyroblastic granites examined the alkali feldspar is microcline and the plagioclase feldspar oligoclase, much of it untwinned and simulating orthoclase. In addition to the minerals already mentioned epidote occurs in small amounts in 14/57 from Adile, 14/58 from the southern end of Kufole, and 14/152 from Koloba Diriba.

A typical specimen of non-porphyroblastic granite is 14/89 from Dandu. It is light red in colour, with dark quartz and a few per cent of biotite in large irregular flakes. The main constituents of the rock are quartz, coarsely perthitic microcline and plagioclase of the composition albite-oligoclase (An_{12}) much of the plagioclase being cloudy and sericitized. The chief mica present is biotite, much of it chloritized and deep green in colour, with a few remnants of red-brown biotite. Associated with the chloritized biotite is a great deal of opaque iron ore. Some zircon inclusions occur in the biotite, with strong pleochroic haloes. Muscovite and sericite are also present, in subordinate amounts to biotite, and sphene and apatite are present in trace amounts. In specimen 14/90, also from Dandu, the plagioclase feldspar is albite, and in 14/37, from Godana Odo, oligoclase. In specimen 14/37 much of the quartz shows strain shadow, and some grains are distinctly biaxial. Epidote was found in 14/227 from Korondil, 14/242 from Darandiri and 14/153 from Fugugo. In the latter slide there is a good deal of myrmekitic quartz associated with the microcline. In seven thin sections made from the non-porphyritic Chalalaka and Ogurchi granites the plagioclase of six is oligoclase-andesine and the seventh andesine. Again the ferromagnesian is biotite, of greenish-brown colour with incipient chloritization.

PLATE I

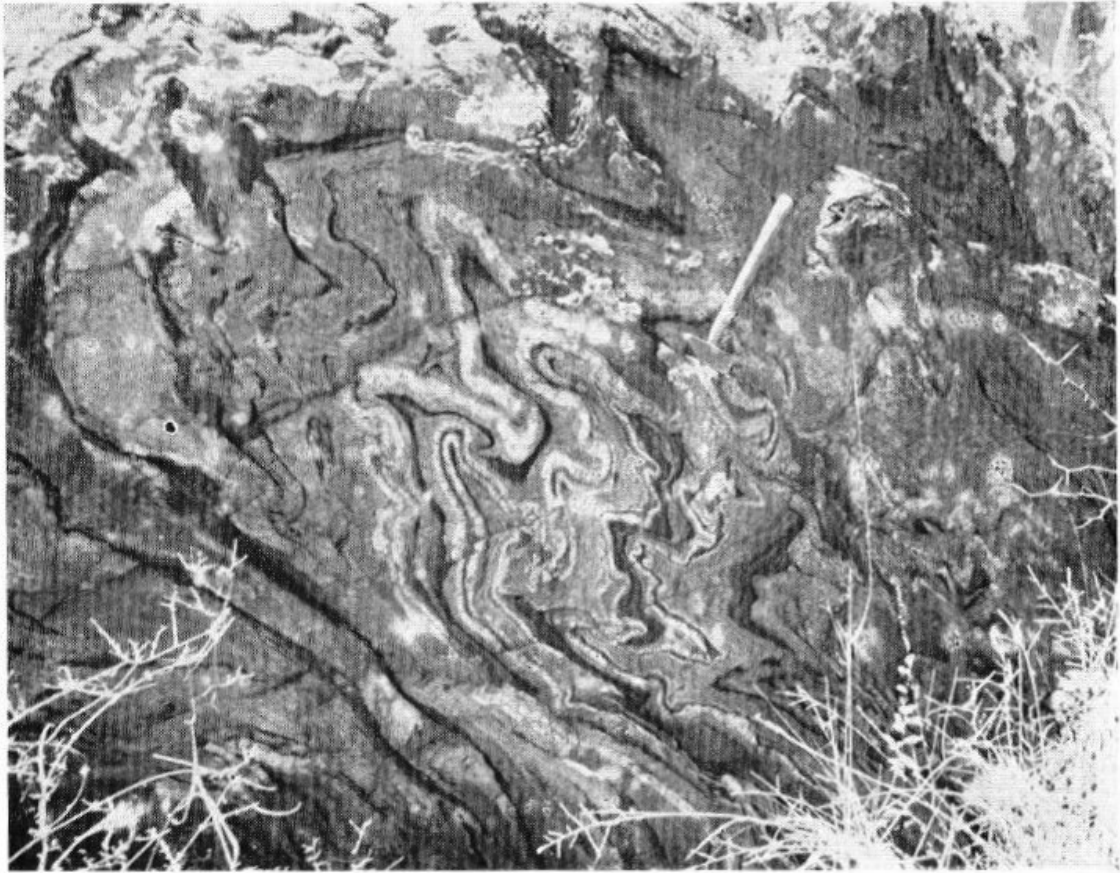


(a) Mouth of well at El Dera. The picture shows three of the fifteen workers needed to bring water to the surface

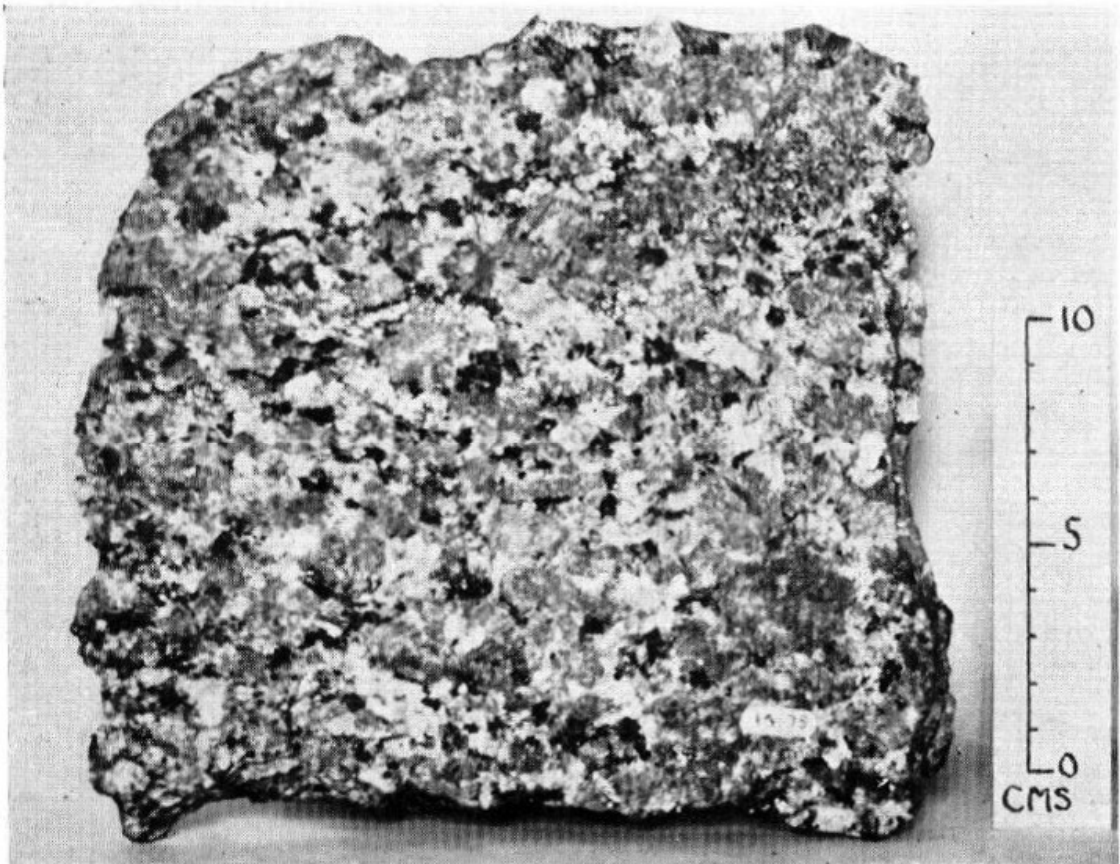


(b) Granite tors at Jara

PLATE II

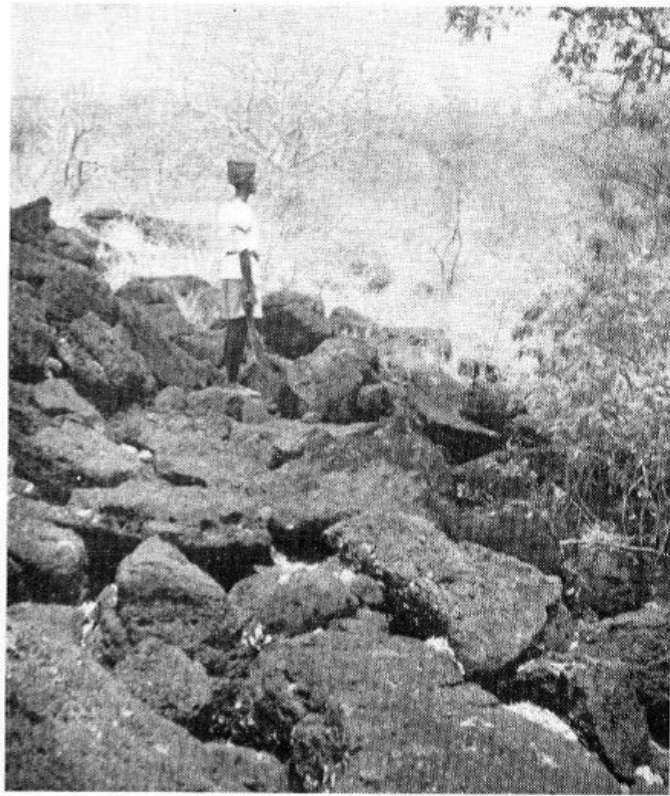


(a) Contorted biotite migmatite, Walmurra



(b) Porphyroblastic granite from El Roba Police Post

PLATE III



(a) Tongue of olivine basalt south of Darandiri



(b) Stringers of pink adamellite in grey granodiorite, Fugugo

(b) *Adamellites*

The adamellites of the area vary in colour from pink to pinky-brown, are all of coarse grain and only rarely strongly porphyroblastic, though pink felspar porphyroblasts occur sporadically in most of the outcrops examined. A typical specimen, 14/121 from Birte, is seen under the microscope as a coarse aggregate of mutually interfering grains of quartz, microcline and cloudy oligoclase, the latter seen in varying stages of alteration to microcline. The mica is very dark brown biotite, locally almost black, showing a small degree of chloritization. Sericite, epidote and iron ore occur in trace amounts. The common plagioclase felspar in the adamellites is oligoclase, though both albite and albite-oligoclase were recorded. Epidote occurs in many of the thin sections, and in 14/138 from Katama can be seen to have replaced biotite. Other minerals noted in these rocks are muscovite, which occurs in addition to biotite in 14/101 from Halati, sphene, and trace amounts of fluorite in 14/55 from Garsa Abula and 14/50b which was taken from a stringer of adamellite which cuts the small granodiorite outcrop two miles north of Fugugo (Plate III (b)). The hand specimen of the last mentioned rock shows iron pyrites in small scattered crystals. This occurrence is described at greater length on p. 24.

(c) *Granodiorites*

Although generally darker in colour than the granites and adamellites, the granodiorites of the area contain rather less biotite, often little more than one per cent by volume of the whole rock. An exception is the Moyale granodiorite where biotite locally exceeds five per cent of the rock. That of Darale, specimens 14/137 and 14/144, contains quartz, albite-oligoclase and only a small amount of microcline, which also occurs as rare porphyroblasts. The biotite is greenish brown in colour, showing alteration to epidote and sericite and trace amounts of chlorite. Other trace minerals noted are apatite, sphene and opaque iron ore. In most of the slides of granodiorite examined the plagioclase felspar is oligoclase, though albite, albite-oligoclase and oligoclase-andesine were all recorded. No alkali felspar was found in 14/127 from Garari, nor in 14/128 from Lefend and most of the specimens of the Moyale granodiorite, which can therefore be classified as trondhjemites. All the trondhjemites contain brownish green hornblende, locally altered to biotite. Specimen 14/123 from Sigide contains both hornblende and diopside in addition to biotite, and in 14/109 from Kudama the biotite encloses relict grains of hypersthene. Pale pink garnets were found in only one slide, 14/135a from Garkilo.

(d) *Microgranites*

Most of the microgranites exposed in the area occur as veins and segregations in other granitic rocks, but two isolated outcrops, one near Kudama and another south of Gairamsa, are in the form of flat sheets, partly hidden by soils, which make no recognizable feature, as contrasted to their coarse-grained equivalents which always form bold features. All are pink to grey in colour, with only minor amounts of mafic minerals. In thin section the microgranites are seen to contain the same minerals as the granites, quartz, microcline and plagioclase feldspars ranging in composition from albite to oligoclase, usually cloudy and strongly perthitic. All contain greenish-brown biotite, often chloritized, with muscovite, sericite and epidote. Apatite, sphene and iron ore are common accessories, and 14/62, a segregation in granite at Mado Goda, contains trace amounts of very pale pink garnet. The rock of the exposure south of Kudama, 14/117, is a microgranodiorite, containing quartz, zoned plagioclase feldspar, with cores of oligoclase rimmed with albite, and only a small amount of microcline. No biotite occurs in this slide, its place being taken by ragged aggregates of muscovite, sericite and iron ore.

3. Intrusive Rocks

(a) Major Intrusions

In the western part of the area are outcrops of metamorphosed ultrabasic rocks totalling tens of square miles. They have been subdivided on the map into amphibolitic rocks, serpentinites and talc schists, although there is a degree of gradation between all three types. The original rock type which gave rise to all these varieties was a peridotite, and the various processes involved in the differentiation and metamorphism of the peridotite are discussed in a later chapter. Outcrops of ultrabasic rocks generally form high and conspicuous features, but with smooth and rounded outlines.

The next largest intrusion in the area is the gabbro of the Mash Hills which outcrops in five separate exposures over an area of three miles by two. The solid rock between separate exposures is masked by soil, with no float of any kind, and it could not be determined whether the outcrops represent exposures of one continuous boss or are cupolas of a larger buried mass. The hills, which rise steeply from the plain, have rounded outlines and very thick vegetation cover. Under surface weathering the exposed rock exfoliates to rounded boulders.

At Rapsul, near Korondil on the southern border of the map, is a small outcrop and patches of float of hornblendic gabbro, and a few rounded boulders of olivine gabbro were found on the soil cover south of Gader in the east of the area.

(i) Amphibolitic ultrabasic rocks

These are always of medium to coarse grain and greenish-grey in colour. They are never foliated. A typical thin section, 14/172 from Kara Duse, shows large sutured grains of pale green actinolite partly altered to colourless clinzoisite, actinolite slightly exceeding clinzoisite in volume. Coarsely crystalline secondary calcite makes up some five per cent of the rock, with trace amounts of quartz. No feldspar was seen. Specimen 14/181 from Dololo Halo, south of Kara Duse, is very similar except that about four per cent of andesine occurs in the slide. Plagioclase feldspar, always in minor amounts, was seen in one fifth of the slides examined, albite in 14/188 from Kubi Danicha, albite-oligoclase in 14/235 from Kochore Diko, and labradorite in 14/216 and 14/217 from Iladu. In the first two slides the plagioclase is strongly saussuritized and sieved with grains of clinzoisite, pointing to derivation from a much more calcic feldspar. In specimens 14/186 from Kara Arba and 14/187 from Kubi Danicha some of the larger actinolite grains have cores of very pale green diopside. In other slides the amphibole is tremolite or tremolite-actinolite. Specimen 14/216 from Iladu shows actinolite secondary after very pale brown augite, the actinolite itself altering marginally to brownish green hornblende, and in 14/203 from Dirona, south-west of Moyale, colourless diopside is seen to have altered directly to green hornblende, and actinolite does not occur in the slide. Clinzoisite is an important constituent of all the slides examined except 14/183 from Kara Arba, where its place is taken by almost uniaxial zoisite. Accessory minerals are serpentine, iron ores and sphene.

(ii) Serpentinites

The serpentinites are fine-grained, rarely foliated, and vary widely in colour, usually in shades of fawn and grey but occasionally red, purplish or green. The most common minerals seen in thin sections are massive serpophite and fibrous antigorite. They are invariably found together, and serpophite usually exceeds antigorite in volume. Iron ores, both opaque and translucent, accompany the serpentine minerals, and nearly every slide shows amorphous calcite in veins and local segregations. Two slides, 14/231 from Kalkalcha and 14/247 from Sukela Lame, show original pyroxene. In each case the colourless pyroxene occurs as tiny relict grains. The former slide contains talc in

excess of serpentine, and is taken from one of the very few localities where patches of talcose rock, usually only a few feet across, occur in serpentinite. Such localities were found only in the Debel Hills and south of Kalkalcha, and in one locality at the northern end of Misa Hill where plates of talc occur in a matrix of colourless orthopyroxene (enstatite) which is marginally altered to bastite and serpophite.

Chromite, a common accessory in serpentinites in many parts of the world, is rare in the mapped area, being seen only at Debel, Dudati and in the north of Raboli. In the two latter exposures it was found only as float fragments but over a wide area near the wells at Debel it occurs as veins and segregations in the serpentinite. This chromite occurrence was investigated in 1950 by D. K. Hamilton (1951) and its economic potential is discussed in a later chapter. In an appendix to Hamilton's report W. Pulfrey discussed the petrology of the chromite-bearing serpentinite, and concluded that chromite was an original constituent of the ultrabasic rock, since in some of Hamilton's Debel slides, notably 14/10, veinlets of antigorite cut across chromite veins. In some of the earlier slides Pulfrey identified relics of olivine, which was not seen in any of the slides of specimens collected by the writer, and also cited chlorite as an alteration product of some of the pyroxene relics.

Asbestos veins are completely lacking in these serpentinites, though asbestiform tremolite-actinolite occurs locally in small grains.

A common secondary product of the serpentinites is magnesite, which is generally found only in patches marginal to the larger outcrops, as towards the north end of Misa Hill. In hand specimen it is massive and usually white, but occasionally reddish due to iron-staining. A slide from that locality, 14/222, shows in addition to magnesite small amounts of serpentine, amorphous carbonate (probably calcite) and small grains of spinel.

In the south-west of the Gode Hills patches of serpentinite sometimes reaching tens of feet across occur marginal to the main outcrop of actinolite-clinzoisite rock. All these patches are partly masked by secondary magnesian products. One such product, specimen 14/218, is of very fine grain, buff and light red in colour with white veining. In thin section the bulk of the rock is seen to be iron-stained magnesite and limonite, with a few per cent of serpentine. The white veins are of chalcedony with marginal amorphous calcite.

On the very small outcrops of serpentinite east of Funanyata were found scattered float fragments of fine to medium-grained fawn-grey rock closely resembling crystalline limestone. In thin section 14/210a the rock is seen to consist of roughly equal amounts of crystalline calcite and clinzoisite, with a few clear grains of secondary quartz and needles of rutile. The surrounding serpentinite contains a good deal of clinzoisite, and the serpentine is associated with heavy concentrations of opaque iron ore.

(iii) *Talc schists*

Talc schists form only a small fraction of the ultrabasic rocks exposed in the area, and are concentrated in and near the hill mass south of Moyale township. The rock is of coarse grain, and usually grey and buff in colour due to fairly heavy iron staining. A typical slide, 14/211 from Funanyata, shows a fibrous aggregate of talc with red-brown iron staining, minor amounts of opaque iron ore and a single euhedral crystal of calcite one millimetre across.

In the elongated outcrop of talc schists west of Moyale township are enclaves, sometimes hundreds of feet long, of amphibolitized rock free of talc. In hand specimen 14/205 this rock is of medium grain, dark grey-green in colour with pink

porphyroblasts up to 10 mm. long closely resembling the microcline porphyroblasts common in the granitic rocks of the area. In thin section however, the porphyroblasts are recognized as clusters of granular clinozoisite with small amounts of quartz. The remainder of the rock consists of pale green actinolite or tremolite-actinolite, much of it asbestiform with bent and twisted fibres, sometimes altering marginally to green hornblende and smaller amounts of interstitial clinozoisite. Anhedral blebs of opaque iron ore also occur, usually with coronas of calcite.

(iv) *Gabbros*

The gabbro of the Mash Hills is of a dark blue-grey colour, non-foliated and equigranular, grain size averaging 1.0 to 1.5 mm. in the north of the hills and 2 mm. in the south. In thin sections 14/97 and 14/98 the rock is seen to have an ophitic texture, elongated laths of felspar enclosing ferromagnesian, the felspar being andesine-labradorite, strongly twinned. The main ferromagnesian is pale green augite, often dusty with microscopic inclusions of iron ore and thin sheets probably of orthopyroxene. The augite is marginally altered to green hornblende associated with opaque iron ore. The only accessory mineral seen is apatite. Quartz and olivine are wanting, and the rock is a typical orthogabbro.

A typical specimen of the Rapsul gabbro, 14/226, is dark blue-grey in colour, generally even grained but with occasional phenocrysts of black amphibole reaching 10 mm. across. The phenocrysts were identified in thin section as pale blue-green hornblende, which also forms 60 per cent of the groundmass where it is associated with andesine-labradorite, much of it altered to clinozoisite. Clear anhedral quartz, often in large grains, makes up some five per cent of the rock. Much of it no doubt originated in the epidotization of the original feldspars, but its relatively large quantity suggests that there has been some influx of silica into the rock, probably during the granitization of the nearby Korondil mass.

(v) *Olivine gabbros*

A few well-rounded boulders up to three feet across were found south of Gader, and proved on examination to be of olivine gabbro. In hand specimen the rock is very dark grey, non-foliated, with individual grains reaching 3 mm. in length. In thin section 14/84 ophitic texture is very marked, the plagioclase laths again being andesine-labradorite, somewhat cloudy due to sub-microscopic inclusions, apparently of iron ore. Large anhedral grains of olivine occur, with opaque iron ore marking the fractures. The olivine itself is thickly dusted with microscopic needles of an unidentified mineral, all aligned along the c-axis and giving the mineral a distinct pleochroism from blue-grey to brownish grey. The olivines have a double reaction rim, an inner fringe of colourless antigorite followed by pale green chrysotile. Pale purple-brown augite is a major constituent of the rock, locally altered to hornblende pleochroic in shades of pale blue and green, with trace amounts of biotite developed from the hornblende, throwing out much opaque iron ore in the process. A few prisms of apatite were recognized. No quartz occurs in the slide.

(b) *Minor Intrusions*

Minor intrusions in the area are few and small and consist of coarse acid pegmatites, metadolerites and quartz veins.

(i) *Acid pegmatites*

Pegmatite occurs as knots and lenses, seldom exceeding two feet across, in the crystalline limestones of Gairamsa, near the motor track running south-east from Gurar. The pegmatite, specimen 14/149, contains only quartz, bright green felspar and mica, felspar crystals reaching six inches across, but generally no more than two inches. The mica, predominantly a discoloured muscovite simulating biotite in hand specimen, is in fractured books seldom larger than a postage stamp. In thin section two feldspars are recognizable, large crystals of microcline (amazonite), and albite as small inclusions

in quartz. The slide also shows large flakes of muscovite and small knots of ragged flakes of brown and green biotite, with a few flakes of secondary chlorite.

At Kubi Danicha, 16 miles south-east of Moyale, two subparallel pegmatites 100 feet apart and each about 20 feet wide cut amphibolitized ultrabasic rock. Only albite, quartz and muscovite were identified, the latter mineral being in crumpled books seldom exceeding one inch across.

(ii) *Metadolerites*

Just north of Mash float of metadolerite covers an area of about 50 feet by 10 feet in red soil. This occurrence has been exaggerated on the map for clarity. In hand specimen 14/81 the rock is dark blue-grey in colour, non-foliated, with a grain just coarse enough to be distinguishable to the unaided eye. In thin section it shows a typical doleritic texture, with laths of andesine-labradorite enclosing anhedral grains of faintly pleochroic pale green augite with inclusions of opaque iron ore picking out the cleavages of the mineral. The augite is marginally altered to green hornblende with opaque iron ore. Apatite occurs in trace amounts.

Between Oda and Kilta, south of Moyale, a dolerite dyke was traced over a length of strike of more than 300 feet, cross-cutting plagioclase amphibolite. At its widest point it reaches 20 feet across, but generally it is no more than five feet, and is too small to show at the scale of the map. The rock is very similar in appearance to that just described, but in thin section 14/206 the pyroxene is seen to be pale brown augite, and amphibole does not occur. Subhedral crystals of olivine, almost completely serpentinized, almost equal the pyroxene in volume. Veins and blebs of calcite and quartz grains are late alteration products.

The granodiorite at Garkilo is cut by a single lens, about 12 feet by 2 feet, of epidiorite, a dark grey rock with a very fine-grained saccharoidal texture. In thin section 14/135b the original pyroxene is seen as relict grains of colourless hypersthene, the bulk of the pyroxene having altered to strongly pleochroic brown hornblende, with interstitial patches of iron ore. The feldspar is andesine-labradorite, much of it untwinned, which locally encloses small crystals of apatite.

(iii) *White quartz veins*

In the gabbro at Mash and at several localities in the western part of the area, where they are emplaced in red sandy soils, are barren white quartz veins up to ten feet in width, with no trace of accessory minerals other than very minor patches of red iron staining, probably derived from the enclosing soils. Float of vein quartz is also fairly common in the red soils of the area.

4. Volcanic Rocks

Volcanic rocks occur only in the south-west of the area where they are emplaced in a wide, shallow valley which formed part of the end-Tertiary erosion surface. Two major episodes of volcanicity can be recognized, the rock of both being olivine basalt, the older designated $P1b_2$ on the map and the younger $P1b_3$. These designations have been used to conform with the mapping of the adjoining area to the west (Dodson and Matheson, Report No. 94) where a lower $P1b_1$ basalt occurs. The limits of the flows of the upper $P1b_3$ basalt form a continuous scarp face up to 30 feet in height. The emplacement of the basalts on the mature end-Tertiary surface and their relative freedom from erosion makes it possible to date the lower of the two flows as Pleistocene and the upper as Pleistocene or more probably Recent.

The lower $P1b_2$ basalt is generally of very fine grain, sometimes glassy, with only occasional visible phenocrysts, and locally vesicular. Its colour varies from deep purple to bluish grey, but is generally brownish-grey. It was extruded from a series of small craters, now calderas, some (perhaps all) of which can still be recognized. Some, as Bule Guda and Dulei, are in a good state of preservation, with only a small central

section of the original cone collapsed; one, Bule Diko, is almost completely engulfed by the later Plb₃ lava; Toi and Mukorori are incomplete due to much more extensive collapse. All the calderas except Bule Diko, of which only part of the rim is exposed, show in the almost vertical inside walls that the earliest extrusions were of solid well-crystallized lava, which was followed by a final semi-explosive phase which mantled the earlier rocks with grey and red bombs, lapilli and cinders, of glassy texture. The semi-explosive episode was relatively minor as fragmentary rocks are never found more than a few hundred feet from the craters.

A typical slide, 14/240 from Dulei, shows phenocrysts of euhedral and subhedral olivine and rare phenocrysts of pale purple-brown augite in a very fine-grained groundmass of labradorite, almost colourless augite and olivine, all heavily dusted with iron ore. Some of the cavities contain zeolites—large crystals of heulandite with outer rims of a fibrous mineral, probably stilbite. This specimen and several others from Dulei and Mukorori, notably 14/243, contain angular fragments of red, sometimes yellow and green, peridotite, consisting mainly of olivine and augite with lesser amounts of picotite, always with iron ore. A reaction rim of uralite marks the contact between peridotite and the enclosing basalt. The lava of the crater rim at Mukorori is particularly rich in xenoliths, which sometimes reach ten inches but are more usually one or two inches across, among which were identified, in addition to peridotite, well-foliated plagioclase amphibolite, biotite gneiss and granite. All these xenoliths (with the exception of peridotite) are very similar to their equivalents elsewhere in the area, and in thin section show no thermal contact phenomena or assimilation of basaltic material, proving them to have been caught up in the magma during eruption, the magma having cooled too quickly to allow any alteration or assimilation. The peridotites came from greater depths, and can be considered as solidified portions (perhaps the heavier differentiate) of the magma chamber which gave rise to the basalt magma, and may, of course, be remnants of the original magma chamber which gave rise to the ancient ultrabasic rocks which outcrop nearby.

The upper olivine basalts, Plb₃, are of a grain size coarse enough to be readily visible to the unaided eye, of a medium grey or blue-grey colour, always coarsely vesicular and usually with small phenocrysts which hardly exceed in size the groundmass minerals. In specimen 14/220, from the north of the flow near Koloba, the phenocrysts are mostly of olivine, with lesser amounts of very pale grey-green enstatite-augite and rarely plagioclase. The bulk of the groundmass consists of ragged laths of andesine enclosing purple-brown augite, a small amount of olivine, and iron ore. Zeolite infilling to the vesicles is rare, an occasional veneer of stilbite being seen. Extrusion of the upper lava was from fissures, none of which can now be traced, though individual flows and tongues can be seen everywhere. Plate III (a) shows a flow south of Darandiri, a tumbled mass of angular boulders of very scoriaceous lava which have been broken after solidifying and carried along by the still molten underlying lava.

Comparison of heights on the surface of the lava with contours on the end-Tertiary erosion surface projected under the lava show that the lava reaches its greatest thickness, about 200 feet, to the north of Mukorori, with a second maximum of about 150 feet near Bule Diko.

5. Pleistocene and Recent Superficial Deposits

Soils in the area have been divided into two groups on the map, red sandy soils and black and grey valley soils. Both appear to be residual, the difference in appearance being largely due to the poorer drainage in the valley deposits, with subsequent lesser formation of red iron oxides. The red soils generally have a higher proportion of coarse mineral grains, largely quartz with rare individual grains of feldspar and amphibole, than the valley soils. Such grains are semi-rounded or sub-angular, never well rounded. This higher proportion of coarse material probably results from the washing

out of some of the finer material from the red soils under the better drainage conditions, and its retention in the valley soils. Washed samples of the two types of soil showed that all of the mineral grains in the red soils are deeply stained with red iron oxide, and that black iron minerals are absent. In the valley soils, grains of black iron ore, mostly non-magnetic, are common, and few of the quartz grains have oxide staining, showing that reducing conditions pertain in the valley soils, and oxidizing conditions in the red.

At intervals over the red soils are patches of angular gravel of vein quartz, fragments averaging one to one-and-a-half inches across, the largest patches reaching two or three hundred feet in extent. Such gravel was not seen on the valley soils, though nodules of off-white secondary limestone (kunkar) are sometimes found. The best exposures of kunkar are in the infrequent gullies, where it can sometimes be seen in discontinuous layers up to two feet in thickness, at a depth of one to two feet below the general surface of the ground. Solid sheets of kunkar limestone mask some of the crystalline limestone outcrops, particularly level outcrops raised only a few feet above the plain. A specimen taken from such a sheet at Danicha, 14/114, is pisolitic in texture, with rounded nodules of off-white calcite varying in diameter from a tenth to half an inch, cemented in a matrix of light red calcite, the colour being due to iron staining.

Around several of the granitic outcrops are deposits of coarse grit, off-white to pink in colour, consisting of a generally poorly cemented aggregate of angular quartz and felspar in a fine-grained siliceous matrix, as in specimen 14/87 from Mude Hagero. Biotite is not seen in the grits. The material of these deposits is clearly derived from the breakdown of the granitic rocks, the decomposition products having been redeposited in the form of discontinuous outwash fans from the main outcrops. Such deposits dip outwards at from two to four degrees. At Mude Hagero 40 feet depth of grits can be measured in gullies, the base not being seen. It occurs in layers varying from six inches to four or five feet in thickness, the distinct layering being due to variations in hardness and colour in different bands. The persistence of the better-marked bands over a lateral distance of hundreds of yards suggests that the grits were laid down in shallow lakes or ponds, which points to much wetter conditions at the time of their deposition than today. The grits can be seen to feather out over the red soils at their farthest extent from the outcrops which gave rise to them. The very recent geological age of the grits is shown by the fact that in many of the outcrops chert artefacts were found embedded in the grits. All of these artefacts were identified by Mrs. S. C. Coryndon of the National Museum, Nairobi, as belonging to the Levalloisian culture, which lasted throughout Upper Pleistocene times.

In the Mansile Valley and at Oda, east and south-east of Moyale, are wide stretches of sandy alluvium which had its origin in outwash fans from the Moyale Hills. The main constituent of the alluvium is quartz in small semi-rounded grains, with only minor amounts of felspar and mafic minerals. Thin layers of bouldery and pebbly material in the alluvium mark periods of heavy rainfall when the transporting power of the outwash streams was greatly increased. In a few other places, notably in the lower reaches of the Laga Jara and some of the streams draining the Fugugo massif, fine black alluvium is seen in river beds and occasionally in narrow bands flanking the rivers.

VI—METAMORPHISM AND GRANITIZATION

The metamorphic grade of the Precambrian sediments falls in the staurolite-kyanite subfacies of the amphibolite facies of Turner and Verhoogen (1951, pp. 452-456), with a typical assemblage of plagioclase-hornblende-biotite-epidote-microcline-quartz. The occurrence of muscovite subsidiary to biotite in many of the rocks is quite consistent with this grade, as is the occasional presence of wollastonite in the crystalline limestones of Mado Goda. Hornblende is seldom an important constituent of the rocks,

but where it does occur it is clearly being replaced by biotite, and much of the biotite in rocks now free of hornblende must have had its origin in hornblende. This is to some extent accounted for by potash metasomatism, but also infers a degree of retrograde metamorphism, which is also reflected in the frequent occurrence of chlorite replacing biotite. Retrograde metamorphism in this area can be explained by relief of the high pressures involved in amphibolite-grade metamorphism on unloading under erosion conditions.

Kyanite was not found in the area, perhaps due to the absence of original sediments with a sufficiently high percentage of alumina, but Parkinson (1920, p. 27) recorded its higher grade equivalent, sillimanite, at Buttellu, 12 miles south of the southern border of the map.

The high pressures attained under regional metamorphism to the amphibolite grade, due both to deep burial and folding, gives a clear pointer to the origin of the granitic rocks of the area. Such conditions, prolonged for great periods and accompanied by an influx of potassic fluids or vapours, have inevitably led to a thorough "soaking" of the original sediments, and by rearrangement of the more mobile elements of the minerals of those rocks have led to a degree of homogeneity which has produced granites. The influx of potash cannot be doubted, being demonstrated in the transformation of plagioclase feldspar into microcline, the production of microcline porphyroblasts in otherwise even-grained gneisses, and the scarcity of hornblende, which under potash metasomatism readily alters to biotite.

V. Marmo (1955) discusses such synkinematic "granites", distinguishing them from late- and post-kinematic granites of intrusive origin, and lists (pp. 431-432) the principal points of recognition of such "granites". These are:—

- "(1) Predominantly gneissose, and forming concordant bodies with the enclosed schists.
- "(2) Contacts are usually gradational, and the appearance of these granites as meta-contacts of migmatites is unusual.
- "(3) Basic inclusions are frequent, and are typical of the synkinematic granites, as also are the lenses and strips of all kinds of basic rocks; they are concordant to the gneissosity of the "granite".
- "(4) They are usually comparatively coarse-grained, often related to the veined and augen gneisses, and varieties containing large quartz inclusions occur.
- "(5) Most of the field evidence suggests that they were formed by granitization of older rocks.
- "(6) In their composition the synkinematic "granites" tend to be granodiorites and even quartz-diorites."

In a later paper Marmo (1958) points out that in Precambrian synkinematic granites the only potash feldspar present is microcline, and that orthoclase occurs only in later intrusive granites.

Applying Marmo's points in order:—

- (1) It has already been explained that in the map the gneissose varieties of the granitic rocks are separated, and classified as granitoid gneisses, whereas Marmo would have classified them with the granites. The map clearly shows the concordance of granitic rocks and granitoid gneisses with neighbouring paragneisses wherever the two are in contact.

(2) In this area contacts between granites or granitoid gneisses and biotite gneisses are almost always gradational; only where granitic rocks are in contact with "resisters" such as limestones, and to some extent quartzites, are contacts sharp. The leucocratic layers in the biotite migmatites are very different in appearance to the granites and granodiorites, being white or off-white in colour, as against predominant pinks, browns and greys of the granitic rocks.

(3) Basic inclusions are not common in the area, unless the plagioclase amphibolites in contact with the Kufole granite are considered. However, inclusions of unaltered or relatively unaltered country rock are very common in most of the exposures examined, the only large outcrops in which inclusions were not seen being Dandu and Saki Gamada. In every case the foliation of these inclusions, or their elongation where foliation could not be determined, is parallel to that of the country rock in their vicinity. Thus at El Roba all the inclusions strike within a few degrees of 275° , and a few miles further south at Omur Thompson and Dodson (1958 p. 26) recorded that inclusions in a granite outcrop are all aligned along 240° .

Thompson and Dodson interpreted this as showing that the granite was intruded as a magma, and that the contact (unseen) of this granite is nearby, and runs at 240° . Near the margin of an intruded granite, while it is likely that many of the xenoliths stopped off the country rock by the moving magma would be so aligned, it is extremely improbable that *all* the xenoliths would be so neatly arranged. At Godana Odo many inclusions of country rock are exposed in rock platforms on the foot track running east and north of the hill from Gurar Police Post. All these inclusions are aligned within a few degrees of 020° .

Similarly all the remnants of country rock seen at Garkilo strike at 360° . It will be seen from the map that in all these instances the enclaves are in good accord with the general strike of the metamorphic rocks in their vicinity. H. H. Read (1957 pp. 346-347) quotes a similar occurrence of "ghost stratigraphy" in Northern Ireland which can be explained only by granitization *in situ*.

On the north-east flank of Godana Odo an exposed platform of rock 20 by 10 feet shows granite making a cross-cutting contact with a strongly foliated granitoid gneiss (Fig. 2). The transition from granite to gneiss occurs over a distance of less than a



Fig. 2—Granite/gneiss contact, Godana Odo

quarter of an inch, with no trace of thermal changes in the gneiss. Enclaves of gneiss up to a foot long are seen in the granite at a distance of a few inches to ten feet from the contact, and in every case the foliation and dip of the enclaves exactly parallel that of the main body of the gneiss.

(4) All the granitic rocks examined, with the exception of the minor microgranites, are of coarse or very coarse grain. Many contain felspar insets and a few contain insets of quartz.

(5) All the field evidence so far cited points to a granitization origin for the granites. A few facts were observed, however, which can be interpreted as actual movement of magma in very restricted areas. First, at one of the contacts between crystalline limestone and granite at Mado Goda fragments of green and black calc-silicate rock in the granite and blebs of aplitic granite material up to a foot long in the limestone point to local stoping of the limestone, and an interchange of material. This was seen in only one contact of the many examined, and occurs over a distance of less than 20 yards along the strike and never more than three feet on either side of the contact. Secondly, at Fugugo pink adamellite veins up to three feet wide are seen cutting grey granodiorite (Plate III (b)), with a transitional contact covering about half an inch where photographed.

On following the veins to the east along a well exposed stream bed, within 50 yards the contacts become gradational over five or six inches, and the colour of each rock type begins to merge towards the other, until after 300 yards all trace of contact is lost, and the rock is a homogeneous pinky-grey granodiorite. This exposure is notable for containing one of the two examples of granite mineralization noted over the whole area—traces of iron pyrites and fluorite. The explanation of this dyke effect probably lies in an influx of vapour or liquid, particularly rich in potash and with traces of fluorine, along a line of weakness in the granodiorite, which locally upgraded the granodiorite to adamellite, and probably mobilized the rock to a small extent. Thirdly, the occurrences of microgranite probably had their origin in small local pockets of mobilized magma generated during the process of granitization.

(6) Many of the granitic rocks are granodiorites, and again the map clearly demonstrates a transition outwards from the main granite centres along the Ethiopian border from granite through adamellite and granodiorite to granitoid gneiss, migmatite and true paragneiss, indicating a lessening of granitization outwards from the main centres. Finally, Marmo's later points as to the character of the feldspars: in none of the slides examined was orthoclase determined, though much of the plagioclase is lacking in polysynthetic twinning and simulates orthoclase.

The almost total lack of coarse, mineralized pegmatites, so typical of the intrusive granites, has already been pointed out. A further point which militates against an intrusive origin of the granites is the occurrence of bands of limestone at Mado Goda enclosed for hundreds of yards by granite, with no sign of fracturing of the limestones or their invasion by granite, except the very minor occurrence just described.

One important facet of the granitization which remains to be explained is the replacement locally at Mado Goda of quartzite by granite. Harne (1959 pp. 49-53) quoted examples from Finland of quartzite being granitized by emanations rich in potash, in that case from an intrusive granite. He discussed the formation of feldspars, both microcline and plagioclase, in a relatively pure quartzite, with no visible "feeders" from the granite mass. It is probable that a similar process operated at Mado Goda, the only partial alteration of some of the quartzites being due perhaps to differential ease of access of the emanations due to folding and fracturing. The ubiquitous presence of biotite in the granitized quartzites is in part due to the nature of the granitic emanations, i.e. a sufficiently high content of Fe and Mg, and may also be due in part to variations in the mafic content of the quartzite from place to place in the same outcrop.

All the granitic rocks show an increase in radioactivity over the paragneisses, varying from about one and a half times background in the case of granodiorites to twice background or more over the granites, a further indication of the increasing influx of potassium in the granites as compared with the granodiorites.

Evidence as to the time interval between metamorphism and granitization is slight, but indicates that granitization followed the onset of metamorphism. This is shown by the resistance of the crystalline limestones, and in part the quartzites, to granitization.

These rocks must have recrystallized to a great extent before the major influx of granitizing agencies in order to have been able to act as barriers. Further, it has already been shown that much of the biotite of the granitic rocks had its origin in hornblende, itself a metamorphic product under these conditions. There is no evidence to show whether or not there was a time lag between the completion of metamorphism and the onset of granitization. It is likely that granitization was the final and most intense phase of metamorphism.

The abundance of actinolite-clinozoisite rock and serpentinites derived from ultrabasic rocks, together with the absence of unaltered ultrabasic rocks in the area, proves total metamorphism of the intrusives. The common products of metamorphism of ultrabasic rocks are, first, rocks rich in hornblende and/or anthophyllite, and finally serpentinites and talc schists. In the present area however, anthophyllite is lacking and hornblende rare, occurring usually as an alteration product of actinolite. Unusual, too, is the abundance of clinozoisite. In an attempt to reconstruct the composition of the original ultrabasic magma it was assumed that equal quantities of actinolite-clinozoisite rock and serpentinite are present in the area, and that the average composition of the former is two parts actinolite to one part clinozoisite. The bulk composition of such a magma, assuming it to be anhydrous, would be approximately:—

	per cent
SiO ₂	49
Al ₂ O ₃	6
FeO and Fe ₂ O ₃	7
MgO	29
CaO	9

Dakyns and Teall (1892 p. 115) give the following analysis of a peridotite from Loch Garabal, Scotland:—

	per cent
SiO ₂	46.0
Al ₂ O ₃	6.8
Cr ₂ O ₃	.2
Fe ₂ O ₃	3.0
FeO	7.5
MgO	23.9
CaO	8.1
Na ₂ O	.8
K ₂ O	.9
Loss on ignition	2.4
	<hr/> 99.6 <hr/>

Analyst—J. H. Player.

It can therefore be assumed that the original magma of the intrusives was a peridotite, and indeed angular fragments of olivine-augite-picotite peridotite are found caught up in the Pleistocene lavas in the south-west of the area. As discussed more fully later, the intrusion was syntectonic with the folding of the Moyale syncline, and the serpentinites are lower in the rock sequence than the actinolite-rich rocks, pointing to a gravity differentiation of the original magma into a heavy lower fraction rich in olivine (now the serpentinites) and a lighter upper fraction which has given rise to the actinolite-clinozoisite rocks. Metamorphism of the intrusion was probably virtually simultaneous with its emplacement, and the main metasomatizing agency water. Harker (1950 p. 276) states that pure magnesian serpentine contains 13.04 per cent water and talc

4.76 per cent. This fact would account for the occurrence of talc generally in separate outcrops from the serpentinites, marking areas where water was available in lesser amounts. It is most unlikely that meteoric water would be available in sufficient quantities to produce the amount of serpentinites now exposed, and the bulk must have been juvenile (magmatic) water.

VII—STRUCTURE

The paucity of exposures makes detailed interpretation of the structure of the Basement System rocks impossible, but Figure 3 indicates the probable structure of parts of the area. The single anticline in the north-east is evidenced by air photos of that

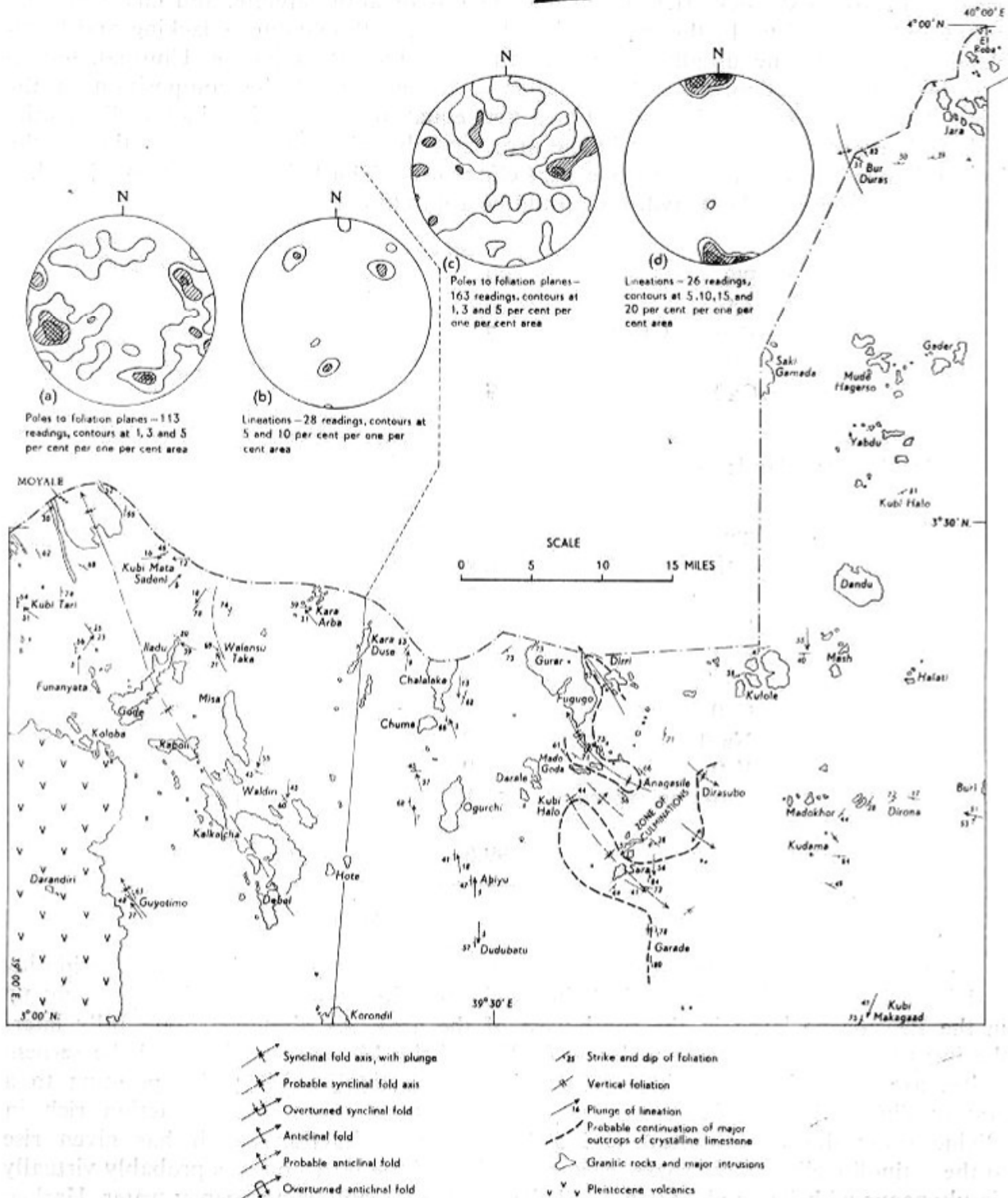


Fig. 3—Structures in the Moyale area

part of Ethiopia adjacent to the border, which show the Bur Duras quartzite swinging north-west and then south-east to make a sharp anticlinal closure. In the centre of the area Mado Goda and Anagasile form a major syncline plunging north-west, overturned gently to the south-west at Mado Goda and open at Anagasile. It is paralleled to the north-east by an anticline at Dirri, that one being overturned gently to the north-east. West of the Mado Goda-Anagasile syncline the north-south line of outcrops from Chalalaka to Dudubatu apparently forms a monocline dipping westwards, but the lack of exposures to either side makes it impossible to determine whether it is, as might be expected, a limb of an anticline/syncline repetition. With the exception of a doubtful syncline at Walensu Taka the only fold structure recognizable in the west is the northward-plunging syncline through Moyale. A very minor syncline, perhaps a mere pucker, is well exposed at the Guyotimo waterhole in a rock pavement only 100 feet across.

In Figure 3 an attempt has been made to project the continuation of the crystalline limestone outcrops south-east of the main Mado Goda and Anagasile limestones. The continuation of outcrops of Dirasubo and Sara is obvious, and the writer considers its extension to Kubi Halo to be justified on the little evidence available. The continuation from Kubi Halo to Garade is more conjectural, but it seems unlikely that the major outcrop at Garade should be a different stratum to that at Sara, and the symmetry of folding is preserved by the continuation as sketched. The syncline of Mado Goda-Anagasile and the Dirri anticline cannot be traced across the second limestone band, the first apparently reappearing as a south-east plunging anticline, and the second as a south-east plunging syncline. This can be explained if the two major limestones are, in fact, outcrops of one stratum. It is suggested that a first period of folding resulted in a south-west to north-east anticline passing through Sara, later refolded by pressure from south-west to north-east and impressing the present Mado Goda-Anagasile and Dirri folds on the earlier anticline.

In many respects the metamorphosed ultrabasic rocks in the western part of the area conform to the alpine-type peridotites first described by Benson (1926), and enlarged on by Hess (1955). Such peridotites are intruded during the first deformation of a mountain belt or geosyncline, the magma being generated by differential fusion of the peridotitic substratum under local impact of a segment of the overlying granitic crust. The relationship of the amphibolitized ultrabasic rocks and serpentinites to the Moyale syncline can be explained by the continuation of the axis of that syncline in a south-south-easterly direction through Gode and Kalkalcha to Debel. Assuming the persistence of the northerly plunge of the syncline the rocks exposed to the southwards become progressively lower in the succession. Thus differentiation of the original magma by gravity sinking of the olivine crystals would lead to the development of serpentinites in the lower strata and amphibolitic rocks in the upper strata where olivine formed only a small fraction of the magma.

Contoured stereograms of poles to foliation planes and lineations plotted on a Schmidt net are shown inset to Figure 3. The area was divided into two parts east and west of a line from Kara Duse southwards to Korondil. The wide scatter of poles to foliation planes shown in both Figure 3 (a) and (c) tends to confirm the existence of more than one episode of folding. Figure 3 (b) and (d) are constructed on relatively few readings (28 and 26 respectively) due to a general lack of measurable lineations in the area. However, contour intervals were chosen to avoid counting single points on the diagram, and the overall picture is considered to be fairly representative.

A plot of frequency of joint directions over all the diverse rocks of the area failed to show any clear-cut pattern.

No faulting was recognized anywhere in the area. It would be virtually impossible that no faulting occurred in such strongly folded terrain, and the explanation of the lack of visible faulting lies first, in the nature of the granitic rocks, where faulting, especially if prior to or contemporaneous with granitization, would be almost impossible to detect,

and secondly in the lack of exposures over much of the area. A fault line is always a line of weakness, and unless accompanied by strong brecciation and silicification is readily attacked by erosion, and under slow planation would become masked by soil cover.

VIII—ECONOMIC GEOLOGY

The only minerals of possible economic importance in the area are chromite, talc and graphite, but the relatively poor quality of all three and their distance from the railhead at Nanyuki (over 400 miles) or any important consumer area makes them of little or no potential value.

Chromite.—Deposits of chromite were found in serpentinites at Debel, Dudati and Raboli. Only in the first-named locality is there any likelihood of a significant tonnage of ore. The following account and map (Figure 4) are extracted from an unpublished report in the Mines and Geological Department, Nairobi, written by D. K. Hamilton in June 1951:—

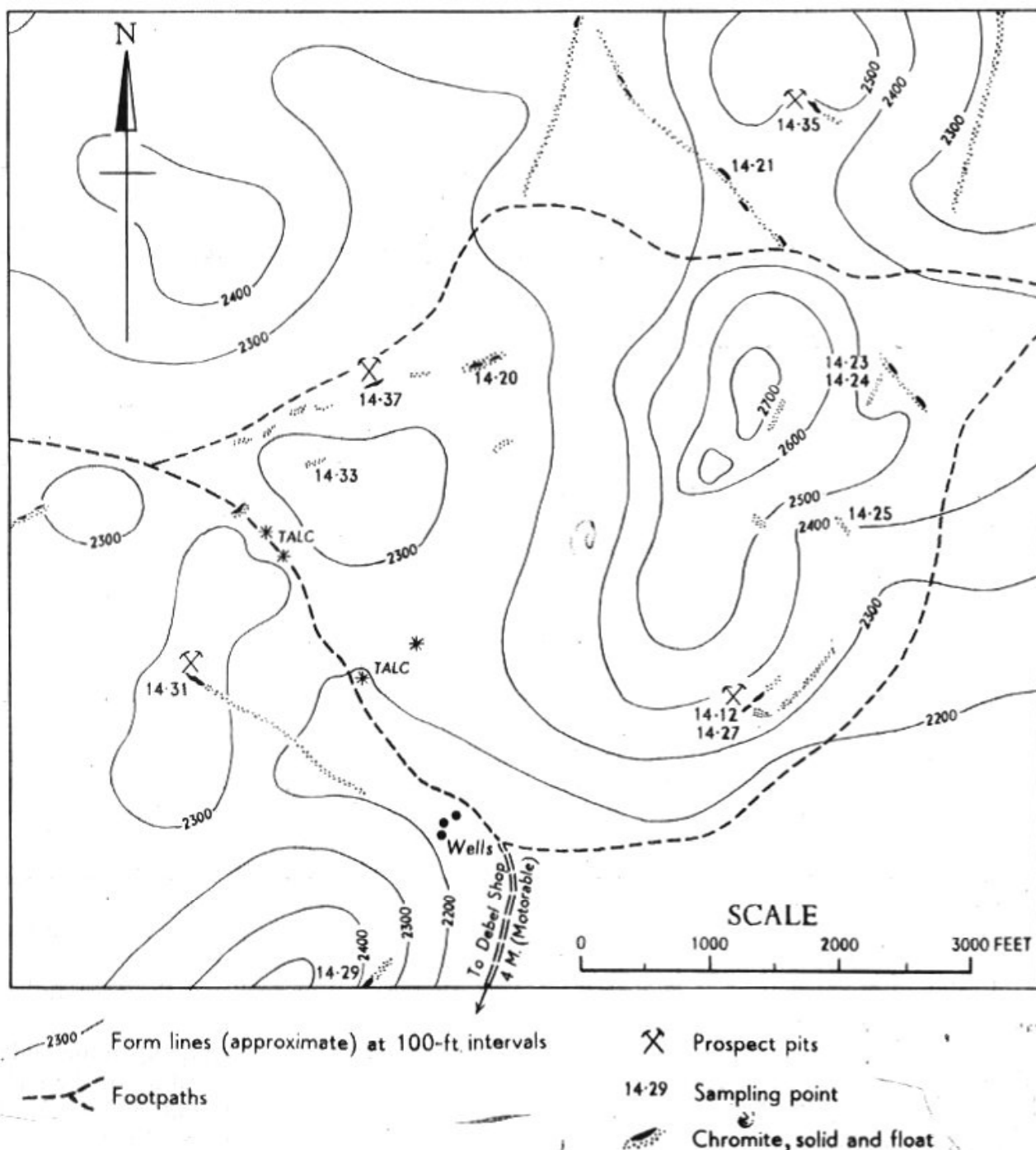


Fig. 4—Chromite at Debel (after D. K. Hamilton)

"All finds of chromite (in place and as float) were plotted on the map. It became evident that these finds tended to a linear pattern. Where the lines of float occurrence coincided with a steep slope there was negligible down-hill divergence of the chromite. The chromite, for some as yet unknown reason, rarely seems to be found as float at any great distance from the source dykes.

"Three general directions were indicated by these lines of chromite occurrence. Those directions, N.80°E. to E., N.30°W. to N.40°W. and N.50°E. to N.60°E., correspond generally to the joint directions within the intrusive mass. In but two cases do the dykes examined attain a width of two or more feet in thickness. In both of these cases a width of about 2½ feet is maintained for a distance of less than 10 feet. One of these swells from a width of about six inches to two feet, in a distance of about five feet. It then carries on for about five feet at a width of two to 2½ feet, to terminate abruptly against a joint plane. The other swells from a width of about four inches to 2½ feet over a distance of about five feet, then in the same distance decreases to about four inches again. In all other cases the veins hardly exceed six inches in width."

"Analyses.—Twelve analyses have been made from materials from the area. Three of the samples were paired in such a way as to determine the extent of chromite saturation of the dyke wall materials. Samples were taken from the central portion of the dyke and other samples taken from two or three inches into the enclosing wall rocks. In all cases a very pronounced drop in chromite content occurs. The points of sampling are indicated on the map (Figure 4). Analyses are as follows:—

Sample No.	per cent Cr ₂ O ₃	per cent Fe	Cr: Fe ratio
14/12—Wall rocks	14.65	9.71	10.02:9.71 (1.03:1)
14/20—Wall rocks	10.41	18.36	7.12:18.36 (1:2.55)
14/21—Chromite dyke	34.13	20.23	23.35:20.23 (1.15:1)
14/23—Chromite dyke	27.39	10.56	18.74:10.56 (1.77:1)
14/24—Wall rocks	19.43	14.97	13.29:14.97 (1:1.12)
14/25—Chromite dyke	34.76	15.68	23.78:15.68 (1.52:1)
14/27—Chromite dyke	47.53	15.32	32.52:15.32 (2.12:1)
14/29—Chromite dyke	33.71	15.20	23.64:15.20 (1.55:1)
14/31—Chromite dyke	32.85	21.64	22.48:21.64 (1.03:1)
14/33—Chromite dyke	15.11	9.43	10.34: 9.43 (1.09:1)
14/35—Chromite dyke	20.87	11.88	14.28:11.88 (1.20:1)
14/37—Chromite dyke	51.43	12.24	35.19:12.24 (2.87:1)

Sample 14/12 represents the wall rocks enclosing the dyke sampled as 14/27. The chromite content drops rapidly from 47.53 per cent in the dyke to 14.65 per cent in the wall rocks.

Sample 14/20 represents the wall rocks of an unsampled dyke.

Sample 14/24 represents the wall rocks enclosing the dyke sampled as 14/23. The chromite content drops from 27.39 per cent in the dyke to 19.43 per cent.

"Conclusions.—Present knowledge is limited to the materials observed at the surface. From these observations as much as 10,000 linear feet of dykes is implied (see map). Much of this length is implied by float. Under the circumstances of the float inference and the great amount of carbonate cover, such a figure must be regarded as a very hazardous guess. Where these dykes have been visible the average width

has been in the order of two or three inches. Thus, perhaps as much as 2,000 square feet of chromite might be implied in a surface area of slightly more than four square miles. If this condition were true to a depth of one foot below the land surface, it would represent 2,000 cubic feet of chromite—approximately 255 long tons of chromite.

“This figure is definitely on the conservative side. A few rich pockets could easily multiply this figure by four. It would not be unexpected for the top foot of the area to yield 1,000 long tons. To produce the material on a sustained basis, however, it would be necessary to restrict the workings to a small area, and mine dykes of less than six inches in width. At present prices* the cost of transport makes development at a profit impossible. Debel is about 405 miles by corduroy dirt road (part of it impassable when wet) from the railhead at Nanyuki, roughly 600 miles over similar roads from Mombasa, and roughly 625 miles over similar roads from Mogadishu in Somalia.”

Talc.—Talc schists were found in and near the hill mass centred on Moyale township, and in small pockets in the serpentinite rocks in the west of the area. The schist immediately west of the township exceeds 1,500 feet in width, but the talc is mostly of a brown or buff colour due to iron staining, and is unlikely to command a ready sale. In 1963 pure white talc was priced at about £7 per ton in Nairobi.

Graphite.—As already stated the graphitic rocks of the Moyale area are of poor grade due either to low carbon content or, where the carbon content is reasonably high, to the very small flake size. The scarcity of water in the vicinity of the outcrops would make extraction of the graphite a difficult business, and would probably entail crushing and winnowing the dry ore and carrying the beneficiated ore over long distances to water supplies sufficient to run a flotation plant for final separation.

Limestone.—The abundant limestones of the central part of the area could be burned for lime, and may be suitable for cement manufacture (the magnesia content was not measured) but the remoteness of the outcrops from a consumer market makes it unlikely that they will repay further investigation.

Other Minerals.—Gravels from streams draining outcrops of ultrabasic rocks were panned and examined for traces of platinum-group metals, but none was found. The ultrabasic rocks were found also to be totally lacking in asbestos mineralization. Muscovite occurs in the few small acid pegmatites mapped, but crystals never approach economic size. White quartz veins occur which would probably be suitable for the manufacture of clear glass, but again their remote position makes them worthless.

Water.—The natural water supplies of the area, described in an earlier chapter, are inadequate to support even the small nomadic population for more than a few months of the year, and in dry seasons all stock is watered at points outside the area.

Under the Northern Frontier Province and Samburu District Water Development Scheme 1950-58, of which a detailed account has been published by the consulting engineers Howard Humphreys and Sons (1958), a number of shallow water tanks (balehs) were constructed. Such tanks are excavated in suitable soils at the side of stream beds, the excavated material being built up as retaining bunds around the excavations. The tank is connected to the stream by a channel into which the water is diverted until the reservoir is full. Additional shallow channels are often angled out from the

*In early 1963 Rhodesian 48 per cent ore with a Cr:Fe ratio of 3:1 was priced at about £13 per ton c.i.f. Europe./J.W.

tanks to trap surface run-off in gently sloping areas. Evaporation losses are inevitably high, but seepage losses, provided the site is carefully chosen are small. However much damage has been done by tribesmen digging into the floor of a reservoir after the surface water has gone. Such "wells" may break through the carefully puddled soils of the bed and allow further inflow of water to drain away rapidly. Bamba Gurari tank was virtually useless in 1960 owing to seepage initiated in this manner, but when revisited in 1962 the floor of the tank had silted up sufficiently to again retain water.

Eight tanks were constructed under the scheme in the present area, as follows:—

Name of work	Capacity in Million galls.	Excavation in cubic yards
Urungu	3.5	20,000
Koran Jido	5.25	24,400
Badana	2.25	15,500
Funanyata	6.5	26,900
Kubi Tari	3	18,850
Kara Duse	6.75	28,800
Chufa	2.25	13,000
Bamba Gurari	8	34,200

The tanks at Arba Garse, Misa and Kosaye were built after the ending of the scheme.

There are three dams near Moyale, at Hara Bawr, and on the lagas Holali and Hosa. The former is a double dam, two earthen walls 200 yards apart spanning a narrow valley. When water supplies in the dam are good the water in the smaller (upstream) dam is tightly fenced off and reserved for human consumption, the larger dam being used for stock. The Howard Humphreys report (*op. cit.* p. 45) classifies the Hara Bawr dam as a dangerous structure as the spillway is unsatisfactory and the embankment is badly fissured and its slopes are much too steep. However in 1962 the embankment had a full vegetation cover which had prevented further fissuring, and the structure appeared quite sound. The Holali Dam is a well-built earth structure, but seepage rate in the reservoir is so high that it holds water only for a few days. It is probable that sooner or later the floor of the dam will seal itself with silt and provide a useful supply. The dam on the Hosa River is an almost vertical concrete wall some 20 feet high impounding about an acre of water which is said never to have dried up since the dam was built in January 1959. The river feeding the dam was dry when visited in August 1962, but the dam was full and a trickle of water was escaping over the spillway, proving the existence of a spring or springs below the surface.

Exploratory bore-holes have been drilled at Chufa (to a depth of 200 feet) and near Ogurchi (160 feet) but both were dry. A bore-hole was drilled in 1961 at Oda, on the alluvial flats south of Moyale, and on test yielded up to 500 gallons per hour of good water. It had been intended that the water should be piped to the township of Moyale, but for financial reasons the plan was never implemented and the bore-hole has since been sealed off.

The Howard Humphreys report (*op. cit.* p. 49) recommends the construction of further tanks at Lefend and Ogurchi (east of the hill) and bore-holes at Kufole and Gader (*op. cit.* Appendix B). These recommendations appear to have been made from considerations of desirability of water points at those places, after survey sufficient only to decide between the merits of tanks or bore-holes, and the success of such works cannot be estimated without further geophysical or soil surveys.

T. T. Bestow (1957) a geologist of the Water Development Department, Nairobi, made a geophysical survey in the neighbourhood of Gurar to find a source of permanent water for the police post there. Electric depth probes at the junction of two dry water-courses some 200 yards south-east of the post showed that up to 110 feet of sediments and weathered rock was likely to be present, and that water should be found at the junction. A depth of 180 feet was recommended as the minimum drilling depth. Similar conditions pertain by a dry water course some 300 yards east of the post, and that site was selected as a possible alternative to the above.

Two other bore-hole sites, again chosen by means of electric depth probes, exist at Bamba Gurari. The first is situated on the main road approximately one mile west of the Gurar turn-off, some 1,000 feet west of the point where a dry water course crosses the road. A total depth of 450 feet was recommended but there is a good chance of striking water at 60 feet. The alternative site is situated 1,500 east of the turn-off, and a depth of 300 feet was recommended.

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