

FOREWORD

Massive easily workable kyanite was first discovered in Kenya in 1942 and production started in 1944. Six years later Kenya was the world's chief producer of kyanite. Since then there has been a fall off in production as the more accessible rich ore was worked out, but as a process for the extraction of kyanite from less rich material has been evolved, it may be expected that the production will once again rise. The kyanite now extracted is calcined and converted to mullite before export.

Dr. Temperley in this, the first memoir published by the Geological Survey of Kenya, gives a full account of the history of development of the industry and of the kyanite deposits that are either worked or known in various parts of Kenya. He also gives an account of kyanite deposits throughout the world, providing a classification of the various types of deposits, and attempts to solve the problems of the genesis of their rocks. To assist prospectors early chapters of the memoir deal with the properties of kyanite and allied minerals, and the specifications for saleable material. The work entailed in the preparation of the memoir was made possible by means of a grant from the Colonial Development and Welfare Vote.

Mr. A. L. Stewart, Metallurgist in the Mines and Geological Department, contributed sections on the laboratory investigation of newly discovered deposits. Other colleagues in the department assisted by discussion and in the search for literature.

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KYANITE IN KENYA

I—INTRODUCTION

Kenya has produced in the last eight years 80,000 tons of kyanite valued at approximately £570,000. In 1949, the year of maximum production, kyanite was third in value among the mineral products of Kenya, being exceeded only by soda ash and gold. In this memoir the Murka-Loosoito kyanite belt, which has yielded the whole kyanite output, is described in considerable detail but chapters are also included giving some information bearing on the potentiality of other kyanite occurrences in the Colony.

In order that the Kenya kyanite deposits may be seen in their true relationship to those of other countries a summary review of all the literature on kyanite available in the library of the Mines and Geology Department has been included. Throughout the study the question of the origin of kyanite has been kept in mind and, in the hope that the work might throw some light on this problem, the deposits described have been classified according to the mode of occurrence of the kyanite rather than their economic value. In a final chapter on the origin of kyanite the facts that have emerged from this study are summarized, but it has not proved possible to propose any completely satisfactory theory to account for the features of those deposits that have yielded the greatest tonnages of kyanite.

The author wishes to thank Dr. J. A. Dunn for a most interesting letter expressing his views on the origin of the Indian kyanite deposits. He is grateful for hospitality kindly afforded to him by Messrs. Kenya Kyanite Ltd. at Murka and by Messrs. East Africa Minerals Ltd. at Kevas during the several visits he has paid to the Murka-Loosoito kyanite belt. The author is also indebted to Mr. P. H. Cull of Sultan Hamud for both hospitality and the provision of guides when he visited the numerous kyanite occurrences discovered by Mr. Cull in that vicinity. The Director and the Game Wardens of the Royal National Parks of Kenya have been most helpful in the facilities placed at the author's disposal during his work in the Tsavo Park, especially during his exploration of the Longalonga-Signal Hill kyanite belt.

II—USES AND PROPERTIES OF KYANITE

1. INDUSTRIAL USES AND PROPERTIES

(1) *Name and Mineral Group*

The name kyanite or cyanite is derived from the Greek word for blue. Another name for the mineral is disthene, derived from the Greek words for double strength, which refers to the fact that the hardness and electrical properties of the mineral vary according to the direction in which tests are made.

Kyanite is a member of a group of minerals, known in industry as the "sillimanite group", all of which possess important refractory properties. The group includes kyanite, andalusite, sillimanite, dumortierite, topaz and mullite. All are naturally occurring minerals but the mullite used in industry is artificial and produced when any of the other five is heated at temperatures above 1,545° C. Mullite is often referred to in industry as "artificial sillimanite", irrespective of the mineral from which it is derived, and the name sillimanite is sometimes applied loosely to any member of the group.

The value of all these minerals as refractories depends on the high decomposition temperature (1,810° C.) of mullite into which they are converted during use. Besides its high decomposition temperature mullite imparts to the products in which it is formed such highly desirable properties as low thermal expansion with resultant resistance to heat-shock, moderate thermal conductivity, high refractoriness under load even at high temperatures and resistance to chemical corrosion, particularly by acid slags. A list of the most refractory minerals with their melting points or decomposition temperatures is given in appendix No. 2.

An account of the history of research on, and industrial development of kyanite and sillimanite as refractory minerals up to 1929 is contained in a memoir by Dunn (1929)* on the refractory minerals of Southern India.

(2) *Industrial Uses*

A useful account of the sillimanite group of minerals has been given by Riddle and Foster (1949). All the information on the industrial uses and thermal properties of these minerals given in this section of the present memoir has been taken, in part practically verbatim, from their contribution.

Kyanite, because of its more common occurrence in commercial quantities, has been the most widely used of the sillimanite group minerals. In the United States about half of the total kyanite products are used in the metallurgical industry, while the glass industry uses about 40 per cent. The remainder goes into miscellaneous products such as ceramic kiln furniture, electric furnace linings, spark plugs and chemical porcelain. Among metallurgical uses are furnaces for melting high-copper brasses and bronzes, copper-nickel alloys, some steels and ferrous alloys, and zinc-smelting, and in gold-refining furnaces. Appreciable amounts are used in parts of heat-treating furnaces and in the roofs of many small direct-arc electrical furnaces. Kyanite is also used in the superstructure of glass-melting tanks as well as below the slag line, and in plungers and other glassworks refractories. In addition, appreciable quantities of kyanite are used as a glass-batch constituent, to increase the alumina content.

Kyanite is excellent for the construction of laboratory kilns operating at unusually high temperatures, as well as general commercial kilns. It is used to line enamel melters and cement kilns, and in plastic ramming mixes, saggars, and other kiln furniture, special refractory shapes, and electrical porcelain. Fused-kyanite mullite has been used in spark plug insulators and as a grog in refractories. Electro-cast mullite has found its main use in monolithic glass-tank blocks and other glass-house refractories where erosion is particularly severe. High cost and spalling tendency react against its use in small cast shapes, although some has been used as grog in bonded refractories.

(3) *Thermal Properties*

The minerals of the sillimanite group differ slightly from one another in their thermal properties. There is no fixed temperature at which any of them decomposes for this depends on grain size. Kyanite breaks down between 1,100° C. and 1,480° C. Topaz and dumortierite are the most easily disassociated; followed in order by kyanite, andalusite and sillimanite. In practice andalusite has an advantage in that mullitization is gradual and progressive when it is heated to 1,390° C. (Searle 1950, page 144). Sillimanite is scarcely affected at such temperatures, whereas the others are too readily decomposed.

The volume changes on calcination affect the use of the minerals. All show a decrease in density, and hence, an increase in volume on the formation of mullite during calcination. For all except kyanite, the change is so slight that they are essentially volume-constant and can be used without pre-calcining. Kyanite undergoes a notable expansion. It is, therefore, normally calcined before use, although in some cases raw kyanite in low percentages has been tried with success. Once completely mullitized, no further volume change occurs in any of the minerals aside from the normal thermal expansion.

On calcination kyanite, dumortierite and topaz give an interlacing aggregate of mullite needles which is said to promote mechanical strength. Andalusite and sillimanite show a parallel orientation of mullite crystals. Kyanite, on account of its expansion, gives a highly porous product. On the basis of density decrease, this expansion should be about 16 per cent, but because of cracking and exfoliation it amounts to as much as 200 per cent. This is particularly true of the coarse, bladed kyanite mined

*References are quoted on p. 82.

in the U.S.A., which consequently has a high shrinkage when made into blocks and is difficult to bond. In contrast to the friable grog made from this type of kyanite, massive Indian kyanite yields a tough grog of considerably lower porosity.

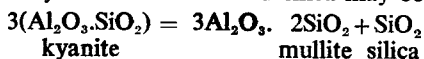
(4) *Gem Kyanite*

Herbert Smith (1950, page 387) classes kyanite among the rarer transparent and translucent stones. Kyanite of gem quality has been found in association with sapphire in India, Burma, Switzerland and Montana, U.S.A. It has sometimes been mistaken for sapphire (blue corundum) and aquamarine (blue-green beryl) but it can easily be distinguished from these minerals by specific gravity and refractive index tests. The specific gravities of the three minerals concerned are corundum 4.0, kyanite 3.6, beryl 2.7 and the refractive indices are corundum 1.77, kyanite 1.72 and beryl 1.58. The present writer found a few pounds of kyanite approaching gem quality at Idibo in the Central Province of Tanganyika (Temperley, 1944). This material included several perfectly shaped green transparent crystals two to three inches in length which, when mounted, made attractive brooches. Two or three of the crystals had streaks of blue running through their centres, a feature which is occasionally found in transparent kyanite.

2. DIAGNOSTIC PROPERTIES

(1) *Chemical Composition*

Although kyanite, andalusite and sillimanite are different minerals with different optical, thermal and other properties all three have the same chemical composition, viz. $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$. Dumortierite and topaz have the formulas $8\text{Al}_2\text{O}_3 \cdot \text{B}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$ and $\text{Al}_2(\text{F} \cdot \text{OH})_2\text{SiO}_4$ respectively. These two formulas are very similar to that of the first three members of the group except that dumortierite contains boric oxide and water in addition to alumina and silica, and topaz contains fluorine and the hydroxyl (OH) group in addition to alumina and silica. The small amount of fluorine that remains in calcined topaz may have a beneficial mineralizing action in use, while the boric oxide released into dumortierite-bearing refractories on firing is believed to have similar merit. As kyanite is often naturally accompanied by small quantities of topaz the fact that this mineral has beneficial properties is important. Mullite has the formula $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$. It will be noted that the ratio of silica to alumina is less in mullite than in kyanite, andalusite and sillimanite. The reason is that during the conversion of any of these three minerals to mullite some silica is released so that artificial mullite is in fact a mixture of mullite and a small proportion of free silica, probably cristobalite. The change of kyanite to mullite and silica may be expressed by the equation—



(2) *Ordinary Physical Properties.*

(a) *Crystalline Form and Habit.*—All the members of the group except mullite occur both as crystals, or concentrations of crystals, readily visible with the naked eye, and as microscopic crystals disseminated in rocks consisting of two or more different minerals. In the first case the ordinary physical properties usually suffice to identify the mineral but in the second it is often necessary to resort to the optical properties as seen under the microscope.

The appearance of kyanite differs considerably according to its mode of occurrence. Its most characteristic shape is developed when it occurs in quartz veins, pegmatites, or soft schists such as mica schists where, owing to its superior strength of crystallization, it has been able to force the mica aside. The commonest form is that of a blade or flattened rod which may be several inches in length but only a fraction of an inch in width and thickness. Crystals appear at first sight to have approximately rectangular outlines but measurement shows that the angle between the face of the blades and the edges is $106^\circ 04'$, between the faces and the ends $101^\circ 30'$ and between the edges and the ends $93^\circ 15'$. This departure from 90° in all three angles places kyanite in the triclinic crystallographic system and distinguishes it from all the other

members of the group, which display orthorhombic symmetry with the three crystallographic axes at right angles to one another.

In most of the kyanite occurrences which have to date been successfully exploited commercially the crystals occur in aggregates in which each crystal has interfered with the growth of its neighbours, so that none shows the characteristic form properly developed. In the Murka-Loosoi kyanite belt of Kenya the crystals are commonly short and stout, and, being orientated in all directions, form a mesh which is extremely tough and resistant to weathering. In another type of occurrence in the same deposit the crystals tend to radiate from centres in tightly packed clusters and are therefore wedge-shaped or pointed.

Sillimanite and dumortierite tend to occur more commonly in fibrous, radiating or columnar masses than does kyanite. When well-formed, crystals of sillimanite are slender with rounded cross-sections and longitudinal striations while dumortierite, though of orthorhombic symmetry, exhibits prism faces which meet at an angle of 60° . Andalusite and topaz are both found commonly in short prisms of approximately square cross-section though columnar and granular aggregates also occur. The prism faces of topaz are often vertically striated.

(b) *Colour*.—Commonly kyanite is blue in colour though occasionally colourless, green, and yellow varieties are found. Frequent impurities are graphite and magnetite, both of which give kyanite a black colour. The latter impurity causes kyanite to weather with a reddish brown crust while if manganese oxide is present it gives a purplish black crust. Rutile, which when present in kyanite occurs in disseminated grains smaller than a pin's head, gives to the mineral a reddish purple appearance. Surfaces of kyanite are occasionally sprinkled with topaz granules which also occupy interstices between the crystals. This mineral occurs as a sugary aggregate of grains. It is normally colourless but as ferriferous solutions readily penetrate between the grains it is often reddish brown. Colour alone does not suffice to differentiate kyanite from other members of the sillimanite group.

(c) *Lustre*.—All members of the sillimanite group have a vitreous (glassy) lustre. That of kyanite varies to pearly lustre while sillimanite, dumortierite and topaz are sometimes silky, dull and waxy respectively. Locally in the Murka-Loosoi kyanite belt the kyanite contains an abundance of minute grains of corundum embedded throughout the crystals. These grains roughen the reflecting surfaces and tend to give the mineral a sugary appearance.

(d) *Cleavage*.—The cleavage of kyanite is "perfect" parallel to the widest faces (100) of the crystals and "good" parallel to the narrower side faces (010). Crystals break parallel with their ends (001) only with difficulty, giving an irregular surface called a parting. The cleavage of sillimanite is perfect parallel to the length of the crystal and of topaz perfect parallel to the base. Andalusite and dumortierite have "distinct" cleavages parallel to the length in each species, as well as other less obvious cleavages.

(e) *Hardness*.—The hardness of kyanite is very distinctive since it varies according to the direction in which the test is made. Parallel to the length of the crystal on the widest face the hardness is found to be between 4 and 5 on Moh's scale, whereas across the width the hardness is between 6 and 7 and on the narrow side faces 7. This means that a piece of the common mineral orthoclase feldspar (hardness 6) or of common window glass (hardness 5) will scratch kyanite when drawn along the surface of the mineral longitudinally but will fail to scratch it and be itself abraded when drawn across the mineral. The hardness of the other members of the sillimanite group varies from 6 to 8 but is the same for different directions in each mineral.

(f) *Specific Gravity*.—The specific gravity of pure kyanite varies from 3.53 to 3.67, which places it among the heavier of the non-metallic minerals. The specific gravity of kyanite is much affected by the various impurities which it contains, a matter that is discussed on page 11.

The specific gravities of all members of the sillimanite group of minerals lie between 3.0 and 3.6 with kyanite and topaz at the top of this range, dumortierite, sillimanite and andalusite in the middle and mullite at the bottom. The figures are as follows (Winchell, 1933):—

Kyanite	..	..	..	..	..	..	3.6±
Topaz	..	..	..	..	..	..	3.52-3.57
Dumortierite	..	..	..	..	..	..	3.3
Sillimanite	..	..	..	..	..	..	3.25
Andalusite	..	..	..	..	..	..	3.1-3.2
Mullite	..	..	..	..	..	..	3.03

(3) *Optical Properties under the Petrological Microscope*

When kyanite occurs along with other minerals as a constituent of a schist, and the schist is not too fine in grain, it can generally be identified with the naked eye by its colour and form. There are, however, cases where it is difficult to distinguish. For instance in some kyanite-quartz schists where the kyanite is colourless it cannot always be identified with the naked eye, or, if identified, it is impossible to estimate even roughly the percentage of kyanite in the rock. In some other schists the kyanite and the quartz are so intimately intergrown that they cannot be separately distinguished even with a lens. Under these circumstances the rock must be examined in the form of a thin slice or as crushed material under the microscope, and the kyanite distinguished from the quartz or other minerals by its optical properties.

The optical properties of kyanite are as follows:—

(a) *Refractive Indices*.—The refractive indices are α 1.712 to 1.717, β 1.720 to 1.722 and γ 1.728 to 1.729. These values are distinctly high among rock-forming minerals and cause kyanite to stand out boldly under the microscope both in relation to the mount, clove oil or Canada balsam, and to most other species of minerals with which kyanite is commonly associated. The other members of the sillimanite group have refractive indices which vary from α 1.607 in topaz to γ 1.692 in dumortierite—values that are moderate for rock-forming minerals.

(b) *Double Refraction*.—The double refraction, or birefringence, of kyanite varies from 0.012 to 0.015 which is distinctly, but not greatly, higher than that of quartz (0.009) and gives polarization colours up to brilliant yellow of the first order in grains or thin slices 0.025 mm. in thickness. The double refraction of sillimanite is very much higher than that of kyanite giving polarization colours in red and blue of the second order in sections of normal thickness, while that of andalusite and topaz is distinctly less being only slightly higher than that of quartz. The double refractions of dumortierite and mullite are too variable to be of diagnostic value within this group of minerals.

(c) *Sign*.—The optic sign of kyanite is negative though the sign of its direction of elongation is positive, characteristics distinguishing it in suitably orientated material from sillimanite and mullite which are both positive and have positive elongation, and from dumortierite which is negative and has negative elongation. Andalusite, like kyanite, is a negative mineral but topaz is positive.

(d) *Optical Orientation*.—The acute bisectrix of kyanite is almost perpendicular to (100) with the optic plane at about 30° to the vertical axis. In topaz, sillimanite and mullite $Z=c$ and $X=a$ while in andalusite and dumortierite $Z=a$ and $X=c$.

(e) *Extinction*.—The extinction angle ($Z \wedge c$) of kyanite on the face (100) is about 30° and about 7° on the face (010), which readily distinguishes it from sillimanite, dumortierite and mullite which have straight (parallel) extinction. On basal cleavage flakes kyanite has almost straight extinction. It is rarely possible to measure extinction in the case of andalusite and topaz.

(f) *Pleochroism*.—The pleochroism of kyanite, like that of sillimanite and topaz, if exhibited at all is weak, a fact that distinguishes these minerals from dumortierite

which has strong pleochroism. The pleochroism of andalusite varies from nil to strong (X = red or yellow, Z = colourless, green or yellow), and that of mullite is strong in the natural mineral (X=Y=colourless, Z=pink) but absent in the artificial product.

(g) *Dispersion*.—The dispersions of the sillimanite group of minerals are: andalusite faint; topaz distinct; kyanite weak; sillimanite strong; dumortierite strong; and mullite strong and about twice that of sillimanite. In each case $r > v$.

(h) *Shape of grains of crushed mineral*.—When the minerals of the sillimanite group are crushed and the powder examined under the microscope kyanite is found to yield almost rectangular plates while andalusite and topaz break into irregular grains. Dumortierite, sillimanite and mullite yield either needles or laths, or both.

(4) *Associated Minerals*

Of the minerals of the sillimanite group only topaz and sillimanite have to date been found in association with kyanite in Kenya. Other minerals that are associated with kyanite at localities in this country where it is being mined are quartz, corundum, rutile, muscovite and kaolin. The only one of these that in any way resembles kyanite is corundum, which occurs at two known localities in the form of minute grains scattered within kyanite crystals. The corundum can be distinguished by the equidimensional shape of the grains, the higher refractive index (1.76) and the isotropic character of basal sections.

Distinction from Actinolite.—On several occasions Kenya prospectors have brought in actinolite in mistake for kyanite. Actinolite is an amphibole which consists of calcium, magnesium, iron and the hydroxyl group in addition to silica, and contains no alumina: it is in no way related to kyanite and has no valuable refractory properties. Actinolite is always green while kyanite may be, green, blue, black, yellow or colourless. Actinolite is a fibrous mineral while kyanite generally occurs in blades. If material crushed to -30 mesh is examined under a microscope it will be seen that kyanite breaks into almost rectangular blades or tablets with smooth flat faces while actinolite breaks into rods with longitudinal striations and oblique terminations. If a petrological microscope is available the simple extinction angle test is decisive, for in the case of actinolite the maximum extinction angle is about 15° while that of kyanite is 30° .

III—SPECIFICATION, PREPARATION FOR MARKET AND TESTS

1. SPECIFICATION

Kyanite is sold either in the raw state or, after calcining, in the form of mullite grog. Up to about the middle of 1950 all kyanite produced in Kenya was shipped in the raw state but Kenya Kyanite Ltd. then completed the erection of a rotary kiln and have been selling mullite since that date.

The price of raw kyanite depends on its alumina content. Most of the massive kyanite mined in Kenya has required little processing, but care must be taken that certain contaminating minerals are either absent or present in such small proportions that they neither bring down the alumina content of the ore below a critical figure nor seriously reduce its refractory properties.

At the present time kyanite produced in Kenya is sold to the United States Government for their national stockpile, to the United Kingdom, to European countries and for local consumption. The current specification for the American supply, which has been in force since August, 1950, is given in appendix No. 1. It covers lump kyanite and fines of a suitable quality for the manufacture of mullite refractories. The specification involves certain limitations in chemical composition and the passing of a pyrometric test for refractivity; also certain screen tests for size both before and after calcination. The ore is generally tested by chemical analysis before shipment,

The chemical composition limitations are as follows:—

Constituent	Per cent by weight on a dry basis
Al_2O_3	minimum 59.00
SiO_2	maximum 39.00
Fe_2O_3	maximum 0.75
$\text{CaO} + \text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O}$	maximum 1.00

A latitude of 0.30 per cent in the alumina is allowed to cover experimental error in analysis.

The British and European market will in general accept raw kyanite with a minimum of 58 per cent alumina, but the minimum varies somewhat among the different buyers and several lots of ore from Kenya as low in alumina as 55 per cent have been accepted for special purposes.

With regard to mullite the United States specification requires a minimum of 59 per cent alumina and a ratio of Al_2O_3 to SiO_2 of not less than 1.57. Further, the mullite must be delivered uncrushed and must pass certain screen tests. For use in refractories a hard, tough grog of low porosity from a quarter of an inch diameter downwards in size is required. For this reason refractory makers prefer massive Indian or Kenya kyanite to the coarse bladed types mined in the United States which yield a friable highly porous grog.

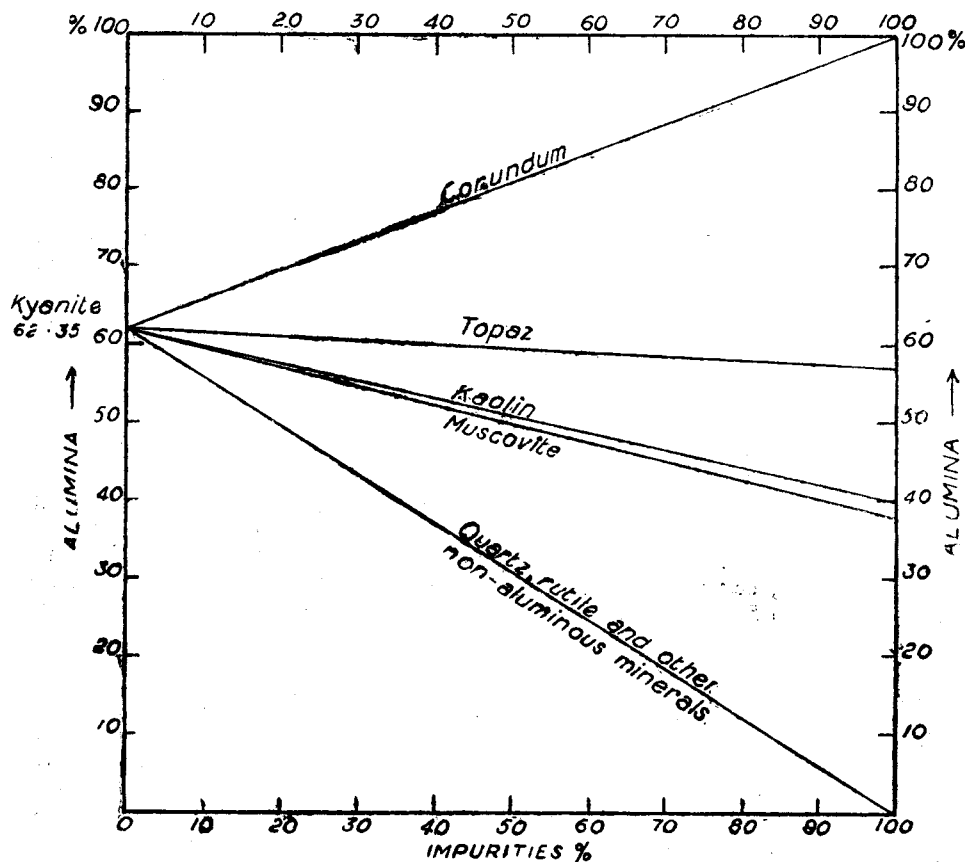


FIG. 1.—The effect of impurities on the alumina content of kyanite ore.

The chief impurities in Kenya kyanite are corundum, sillimanite, topaz, kaolin, muscovite, quartz, rutile and iron oxide. In figure 1 the effect on the alumina content

of increasing proportions of any one of these minerals separately is shown. It will be noted that corundum enriches the ore in alumina; sillimanite has no effect on it; topaz has little effect; muscovite and kaolin depress it slowly; while all non-aluminous impurities such as quartz, rutile and iron oxide rapidly reduce the alumina. The tolerable percentages of each of these minerals separately in 59 per cent alumina ore, are as follows: sillimanite 100 per cent, topaz 55 per cent, muscovite and kaolin 13 per cent, quartz, rutile and iron oxide 5.5 per cent. Corundum, owing to its melting point ($2,050^{\circ}\text{C.}$) being even higher than that of kyanite, is a beneficial constituent and is welcomed in as high a percentage as possible. In Kenya corundum occurs intimately associated with kyanite at two localities where it increases the alumina content to an average of 63.15 per cent with a maximum of 65 per cent. Some Indian kyanite has contained an average of 10 per cent corundum, which theoretically gives the kyanite-corundum rock an alumina percentage of 66. The only objectionable quality of topaz is that poisonous fluorine is evolved during calcination but, as this mineral occurs only sporadically in widely scattered pockets in the Kenya ores, its proportion is never likely to be large enough to be dangerous. Although alkali-bearing minerals adversely affect electrical and load-bearing properties, moderate amounts of muscovite may be tolerated. The maximum limit of 1 per cent for $\text{CaO} + \text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O}$ in the United States specification means that not more than 8.5 per cent of muscovite can be allowed. Nevertheless it is interesting to note that according to Riddle and Foster (1949, page 912), Champion Sillimanite Inc. mine dumortierite containing about 20 per cent of intimately intergrown muscovite which it was neither practicable nor necessary to separate. Quartz, owing to its inversions, which begin at 573°C. , should be kept as low as possible, though recent work has shown that a much larger proportion can be tolerated than was previously considered satisfactory. Rutile, a common accessory, is not a flux, but when ferri ferrous its iron content causes discoloration at high temperatures. However, a very small amount is permissible. Iron compounds are objectionable because of fluxing and discoloration and the maximum of 0.75 per cent Fe_2O_3 in the United States specification ensures that they are kept at a low figure.

2. PREPARATION FOR MARKET

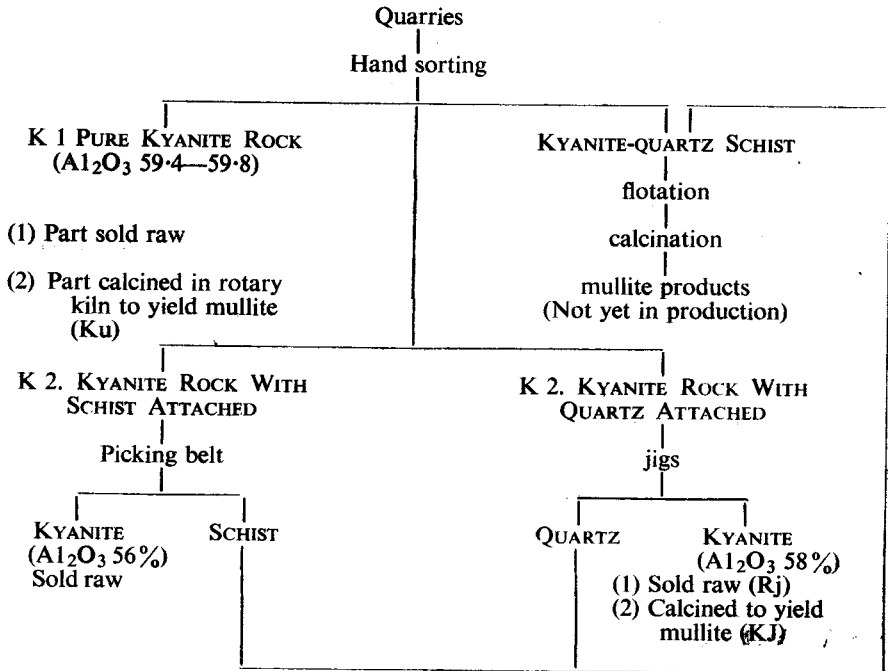
The preparatory treatment, if any, depends on the nature, extent, and intimacy of intergrowth of the associated mineral impurities. In the case of Kenya kyanite sold raw to meet the U.S.A. specification all the preparation required is careful selecting and cobbing, which is done at the foot of the working faces before the ore is thrown into the tubs that take it to the ore dump. The materials which have to be eliminated by cobbing are quartz-kyanite schist (and locally sillimanite-kyanite-quartz schist), which is the matrix in which the massive kyanite lies, and quartz and muscovite which occur here and there in pockets, lenses and stringers within the kyanite. Local patches of kyanite containing more than a minute proportion of rutile, and ore with excessive iron oxide have also to be rejected.

Much of the discarded material is in the form of lumps which, though too small for cobbing, consist of kyanite attached to schist or quartz. Kenya Kyanite Ltd. succeed in recovering some of this kyanite. Blocks in which kyanite is attached to schist are sent over a picking belt where the worst pieces are eliminated, leaving a lower grade of raw kyanite with 56+ per cent alumina. The blocks in which kyanite is attached to quartz are sent to a crusher and then to jigs which yield a product with 58 per cent alumina. East Africa Minerals Ltd. are in process of erecting jigs for separating kyanite from 80 per cent kyanite ore (K 2 grade).*

Kenya Kyanite Ltd. have developed a process for recovering kyanite from quartz-kyanite schist which consists of 30 to 40 per cent kyanite, the rest being quartz. The chief difficulty in the recovery of kyanite from schist ores arises from the intimate intergrowth of the kyanite with other minerals. Much of the kyanite occurs in the form of long, narrow blade-like crystals which penetrate the associated minerals and instead of having clean ends they are terminated by skeletal outgrowths. In consequence fine grinding is necessary and even then the separation of kyanite from the associated minerals is incomplete. Fine grinding means that gravity separation is impracticable and flotation becomes necessary.

*East Africa Minerals Ltd. ceased operations in March, 1952, and early in 1953 transferred their mining rights to Kenya Kyanite Ltd.

The various products of Kenya Kyanite Ltd. are obtained as follows:—



Some details of the processes used in recovering kyanite from some American ores are available in the pages of the technical journals.

At Celo Mountain, near Burnsville in North Carolina, the ore consists of a dissemination of kyanite in the Carolina Gneiss. The percentage composition of the ore is given by Mattson (1937) as approximately quartz 70, kyanite 15, garnet 10, and miscellaneous minerals 5 of which 27 per cent is sulphides. At first concentration was done entirely by crushing, screening and treating by air tables and magnetic separators. Two grades of material were dealt with separately in -16+28 mesh and -28+40 mesh fractions, and the products were a kyanite concentrate, a garnet concentrate and a mica concentrate.

About 1941 (Anon., 1941) Celo Mines went over to an all-flotation process for it was found that slivers of kyanite tended to go into the tailings of jigs and tables. Bureau of Mines tests indicated that table agglomeration gives better extraction than straight tabling but not as good as does froth flotation. Details of the flotation process used are given by Michell (1948). The sulphide and biotite are first removed using aero-float and laurylamine hydrochloride and then kyanite is floated with oleic acid using calgon as a modifier. The flotation feed is ground to 65 mesh and a recovery of over 90 per cent is possible from an ore carrying 15 to 20 per cent of kyanite. The final concentrate carries 97 per cent kyanite.

At Baker Mountain in south-central Virginia (Hubble, 1941) the ore is a kyanite quartzite lying among gneisses and schists of the Wissahickon formation. The ore varies from compact white quartzite flecked with kyanite to masses of kyanite crystals, large and small, that almost hide the matrix. After passing scrubbers, crushers, rolls and screens, the ore is treated by flotation and magnetic separators. The non-magnetic -35 mesh product runs 58 per cent alumina or better and contains from 92 to 94 per cent kyanite. The iron oxide (Fe₂O₃) is 1.25 per cent and free silica 2 per cent. Some of this product is calcined at 1,750° C. and the resulting mullite is screened to remove pellets of kyanite that have fused with iron oxide.

The following information is provided by Riddle and Foster (1949). Near Clarkesville, Georgia, the Georgia-Carolina Mineral Corporation worked a surface accumulation of kyanite derived from a kyanite-mica schist until it was exhausted. The kyanite-bearing top-soil was carried by a flume to a mill, where the larger crystals were screened out, and mullers rubbed off adhering mica and quartz grains. Hand-picking removed quartz and schist fragments and gave a concentrate running about 3 per cent iron oxide and 3 per cent quartz. A placer deposit in the valley was worked by first screening out the cobbles, then treating in sluice boxes by scraping the gravel back and forth with hoes to wash out the clay, sand, and fine gravel from the coarser kyanite. Hand-operated jigs recovered finer kyanite escaping with the gravel. Kyanite was also recovered from partly weathered schist by mulling, washing and screening.

The Vitrefrax Corporation developed an ingenious though not too successful method of reducing the quartz in its Ogilby, California, kyanite ore. The ore was heated to about 950° C. in a rotary kiln, which reduced the iron oxide for later magnetic separation and converted alpha to beta quartz. Quenching the calcine in water reconverted the quartz to the alpha form, the sudden contraction involved shattering the quartz free from the kyanite. After crushing the ore was washed over slightly inclined shaking screens, which retained a relatively pure kyanite concentrate. This process was later discontinued.*

Riddle and Foster make the following general remarks on the processing of kyanite ores. The only kyanite deposits generally considered practicable to work are the disseminated ores in kyanite schists, which require fine grinding to liberate kyanite. As consumers come to accept such fine-grained kyanite, commercial exploitation of these schists will become more practical. Froth flotation gives a higher kyanite recovery and concentration from such ores than any other method and considerable experimental data have been secured. Riddle and Foster give references to the source of this data, but it is in U.S.A. patents and various U.S. publications that are not available in Kenya.

3. TESTS

The principal tests used for kyanite are chemical analysis involving determinations of alumina, silica, iron oxide, titania, alkalis, etc., and various physical tests including calcination to observe fluxing, discoloration and expansion tendencies; the testing of bars made from the calcined material with suitable binders for studying high-temperature load-bearing properties; cone tests to determine refractoriness and brick tests for measurement of shrinkage, porosity, absorption and spalling. At present the only one of these tests carried out in Kenya before shipment is chemical analysis. Shipments from East Africa Minerals Ltd., are sampled at Mombasa by the shippers, the General Superintendence Co. Ltd., and the samples are assayed in the laboratories of the Mines and Geology Department in Nairobi. Shipments from Kenya Kyanite Ltd., to the U.S.A. are sampled at Mombasa by a member of the staff of the Mines and Geology Department and the samples are assayed in three laboratories, viz. Kenya Kyanite's own laboratory at Murka, the laboratory of the Mines and Geology Department and the laboratory of the Industrial Research Board in Nairobi. For every shipment the alumina, iron oxide, silica, titania and loss on ignition are determined but from time to time a fuller analysis is made involving determinations of total alkalis, lime and magnesia in addition.

In the case of raw lump kyanite there is no simple test by which the alumina content can be estimated. Sorting at the mine has to be done purely by appearance. East Africa Minerals Ltd. have, from time to time sent specimens of ore of doubtful grade to the laboratories of the Mines and Geology Department for examination by special methods. By making grain counts of graded fractions, under the microscope, a rough idea of the nature and proportions of the contaminating minerals is provided

* A similar process was used during World War II to extract kyanite from schists in the Styrian Koralpe (Anonymous, 1946). The coarsely broken schist was heated to 600 to 770°C., and then quenched and ground. The tough kyanite was then easily separated from the other minerals which had become brittle. The extraction results were, however, found to be variable.

which gives the mining staff some idea of what type of material is likely to be above and what below specification. As this is a rough method the possibility was considered of correlating alumina content with specific gravity. However, a mere review of the wide range of specific gravities of the common contaminating minerals shows that such a method is most unlikely to be successful. The specific gravities of the minerals that accompany the kyanite in the producing area in Kenya are rutile 4.2, corundum 4.0, topaz 3.6, muscovite 2.9, quartz and kaolin 2.6. Moreover, a further complication is involved in that each of these minerals contains a different proportion of alumina, the percentages ranging from 100 in the case of corundum to zero in the case of quartz and rutile.

In the case of kyanite-quartz schists the position is different. In these, quartz predominates and the proportion of any mineral other than quartz and kyanite is very small. Moreover, small errors in estimating the average specific gravity and alumina content of pure Kenya kyanite will have little effect in the case of the kyanite-quartz schists. There is, therefore, every probability that there will exist a useful correlation between the specific gravity and the alumina percentage of the schist ores. As soon as assays of such ores become available specific gravities of analysed ores should be determined and a correlation graph drawn.

A few points in this connexion should be noted. First, a difference of 1 per cent of alumina corresponds to a specific gravity difference of 0.0075 which means that specific gravities should be determined at least to the second place of decimals. The second point is that the ground material suitable for chemical analysis is much too fine to give reliable specific gravity results. Experiments done by the writer show that -60+90 mesh material will give results 0.03 to 0.04 too low and that the error on still finer fractions is very much greater. Even the -30+60 mesh fraction of a sample comes out 0.005 too low and should not be used. The reason for this is that an appreciable quantity of air adheres to the particles of the finer fractions. Consistent results were obtained using the -10+30 mesh fraction in a 50 c.c. specific gravity bottle. It is possible that the -10+30 mesh fraction taken out of an incompletely ground sample will not represent the whole sample exactly so far as chemical composition is concerned, but the error involved in this procedure is probably less than that introduced by using too fine a fraction. The third point is that distilled, or at least clear, fresh water should be used. There is, however, no need to correct for temperature since the density change of distilled water over the range 15° C.-30° C. (59° F.-87° F.) is only 0.0035.

For separating kyanite from associated minerals after crushing potassium mercuric iodide (sp. gr. 3:1) is used in the laboratories of Kenya Kyanite Ltd., and of the Mines and Geology Department. A chemical method in use at the latter laboratories for rough determinations is digestion with hydrogen fluoride. For determining the kyanite content of the mill feed at Celio Mines, North Carolina, the heavy liquid acetylene tetrabromide was used (Mattson, 1937).

IV—KYANITE IN KENYA—HISTORICAL NOTES, EXPLOITATION AND PRODUCTION

1. EARLY RECORDS

Kyanite was first recorded in Kenya by Parkinson (1913) after studying the Basement System schists near Turoka, on the Magadi branch railway-line. He found three thin beds of kyanite schist a few inches apart on the bank of one of the headwaters of the Turoka River almost 2 miles east of Turoka station. All three were felspathic schists with muscovite and quartz accompanying the kyanite. At another point in the same valley Parkinson found gneisses that were richer in kyanite than the schists. One rock consisted almost entirely of kyanite and quartz with accessory zircon and white mica.

The following year Oswald (1914) recorded kyanite as an accessory constituent in a grey gneiss of granitic appearance in the Nakanero and Angaohi Hills and in a pink granitic biotite gneiss in the Nvanchoba River below Saria, both localities lying south-west of Kisii, between that township and Lake Victoria.

In 1920 Parkinson published an account of a journey in the northern part of Kenya but, though he crossed over Basement System rocks between Rumuruti and Marsabit and again between Moyale and Wajir, he did not record any occurrences of kyanite. Nor does Gregory, in his book on the rift valleys and geology of East Africa (1921) mention any kyanite except that found by Parkinson, and one occurrence at Ulu about which he gives no details.

The next records are by Glenday and Parkinson (1926) who studied the geology of the Suk hills. They found a feldspathic quartz schist containing kyanite near the Marich Pass and kyanite-quartz schists or quartzites at two localities. The first of these was on the western flank of the Karipu Hills in the middle reaches of the Suam River where one of the schists consists almost entirely of kyanite, while another is a coarse quartzite with strongly foliated blades of kyanite up to 55 millimetres in length. At the second locality, which is at Karetuma, 7 miles east-north-east of Ka'wo, there is a quartzite of saccharoidal appearance containing small crystals of colourless or very pale-green kyanite and a little white mica. In the northern part of the Suk Hills Glenday and Parkinson (1927) found no kyanite. Kyanite gneisses were also discovered by the Geological Survey in 1938 (W. Pulfrey, unpublished report) in the valley at the foot of Rhodesian Hill, west of Tsavo.

These occurrences of kyanite have not yet led to the discovery of economic deposits, but they indicate areas that might repay prospecting.

2. RECENT DISCOVERIES

The history of kyanite as an economic mineral in Kenya begins with Parkinson's mapping of the Mtito Andei-Tsavo area. Though he began this work in 1940 his report was not published until 1947, some time after his death. It is surprising to find that in his report Parkinson mentions only kyanite-quartz schist in Murka hill, for it is hardly conceivable that he could have visited the hill without seeing at the same time the enormous boulders of massive kyanite rock that lay strewn about on its western flank and its south-western base.

It was Sir Charles Markham, in search of refractory material, who first appreciated the potential value of the massive kyanite at Murka. After making inquiries at the Mining and Geological Department for information on likely areas he visited Murka hill accompanied by Colonel Grogan in September, 1942, and pegged claims in October of the same year. Parkinson showed that the kyanite horizon that occurs in Murka is exposed again further north in Kevas and Loosoto hill, making a total strike of about 10 miles. He also discovered kyanite-graphite schist with a N.W.-S.E. strike of several miles in the hill Longalunga, which lies about 5 miles south of the point where the Mzima River joins the Tsavo River. Parkinson recorded kyanitiferous schists at several other localities as, for example, on the Tsavo River near the Mzima bend and near Manga camp at the north-western corner of the Taita hills.

Since Parkinson's work in the Mtito Andei-Tsavo area numerous quarter-degree areas on Basement rocks have been surveyed, or are in process of being surveyed by members of the Kenya geological survey. Shackleton (1946) mapped the Nanyuki-Maralal area, but although he found an occurrence of about 50 tons of sillimanite he did not discover any kyanite. Schoeman surveyed two areas, one west of Kitui and another between Embu and Meru, but again found no kyanite. Dixey did some reconnaissance surveying in northern Kenya but, like Parkinson, did not record any kyanite.

In other areas mapped, but on which reports have not yet been published, kyanite has been found in a belt of country at least 22 miles long east of Machakos, and at several localities north, south and west of Sultan Hamud (Fig. 2). None of these occurrences has yet been exploited though claims have been pegged on a kyanite-quartz schist on Mubai hill, 18 miles north of Sultan Hamud. Some details of the Mubai deposit and brief notes on the other occurrences are given in later chapters.

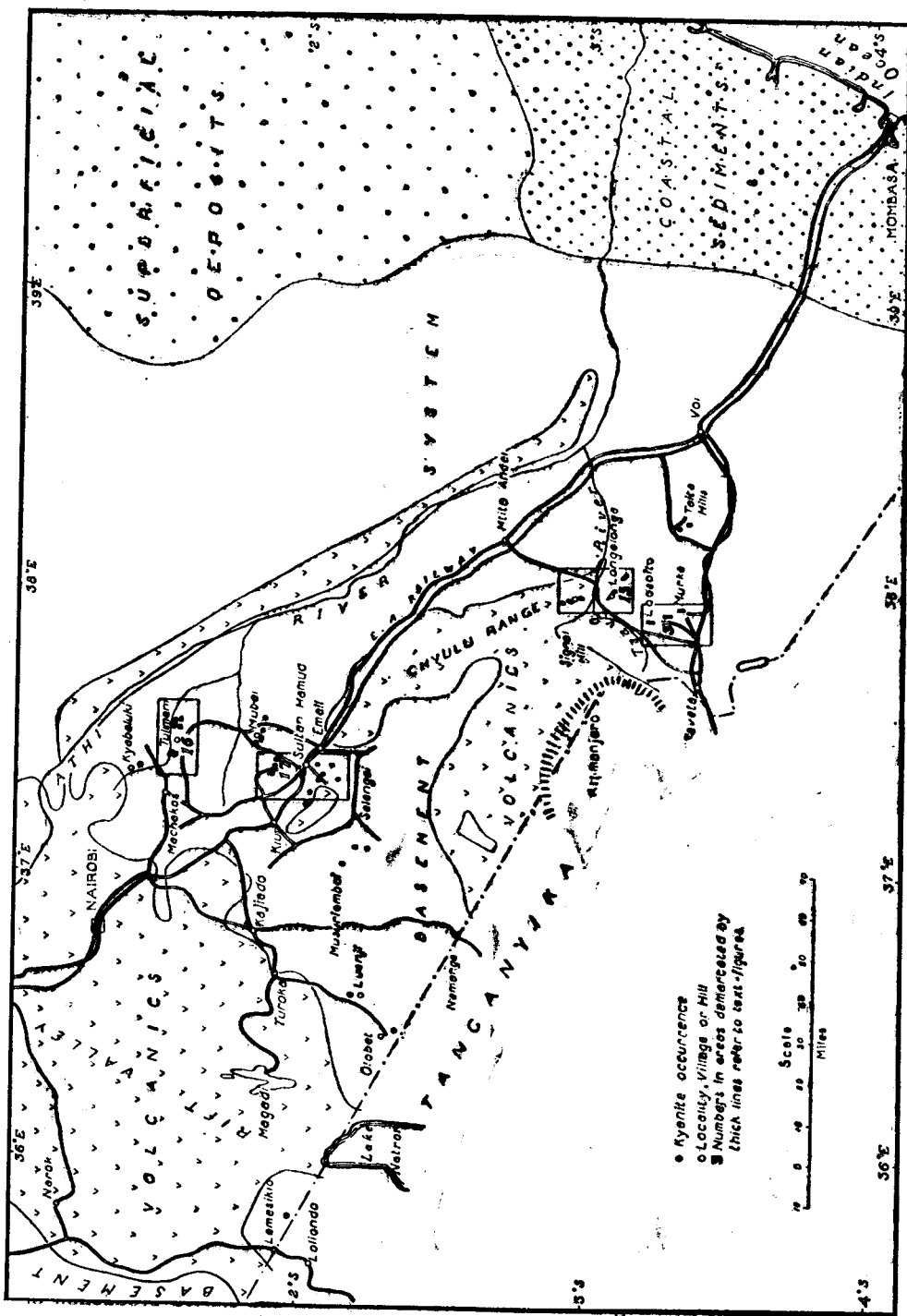


FIG. 2.—Kyanite occurrences in Southern Kenya.

3. GEOLOGICAL INVESTIGATIONS

The first geological report on Murka hill was made by the writer, who spent a few hours there in December, 1942, on behalf of the East African Industrial Research Board. The main points were established, viz. that a kyanite-bearing formation forms the crest of the hill and that here and there within this formation lie huge segregations of almost pure kyanite which vary in size up to masses of several hundred tons. Many of these masses had resisted erosion more strongly than the formation in which they lay and had been left as huge boulders on the hillsides and round the base. The writer stated that a lorry could be driven up among the boulders and at least a thousand tons collected without even climbing the hill, though it would be necessary to drill and blast the boulders. Time has shown that this was an under-estimate: altogether about 60,000 tons of massive kyanite rock have been won, mainly derived from both the level ground round about the hill and from its flanks. Only a very small proportion of this total is from segregations truly *in situ*.

In June, 1943, Dr. E. Parsons reported on Murka for Sir Charles Markham and expressed conclusions (Parsons, 1946) on the form and structure of the kyanite deposit that were totally different from those of the present writer.

In 1947 Dr. W. Pulfrey, then Senior Geologist in the Department of Mines and Geology, visited Murka and generally confirmed the views of the present writer, indicating that he believed the kyanite masses had been concentrated by hydrothermal or pneumatolytic agencies. In 1948 the writer was allocated the task of reporting on the kyanite deposits in the Murka-Loosoito belt as a first step in a survey of all the kyanite deposits of Kenya, and owing to the difference of opinion on the structure of Murka, he examined this hill with very great care and has kept it under fairly frequent observation since that date. Much of the material on the geology of the Murka-Loosoito kyanite belt in this memoir is condensed from detailed reports submitted earlier to Kenya Kyanite Ltd., and East Africa Minerals Ltd.

4. PEGGING AND EXPLOITATION

Claims on Murka were first registered by Sir Charles Markham in November, 1942. These were transferred to the newly floated company, Kenya Kyanite Ltd., in November, 1946. Claims on Kevaa and Loosoito were first registered by Mrs. Lloyd-Greame in June, 1948, but were transferred to a new company, East Africa Minerals Ltd., in November, 1949, when Mrs. Lloyd-Greame sold her mining titles.

Exploitation at Murka between 1942 and 1946 was confined to the taking of only a few hundred tons of kyanite, but the establishment of a market and overseas demands justified exploitation on a larger scale. Kenya Kyanite Ltd. was floated with the consequence that the production of kyanite in 1946 was over 2,000 tons. Work was started on the residual boulders at the south-western base of the hill and extended a short distance up the hillside and to a greater distance out onto the peneplain. By the end of 1948 nearly all the boulders of kyanite rock showing above the ground had been removed. During 1949 most of the work consisted in excavating boulders from the hillsides, though work on the lower talus slopes near the peneplain was continued with the help of an auger to locate hidden boulders and to search for deposits *in situ*. By the end of 1949 the hillside workings had reached up as far as the outcrop on the crest of the hill and segregations in place were being attacked. The maximum production of 21,775 tons was reached in 1949 after which a rapid fall took place.

The bulk of the raw kyanite shipped by Kenya Kyanite Ltd. meets the United States Government specification of Al_2O_3 minimum 59 per cent. A patch of boulders of corundum-bearing kyanite yielded just over a thousand tons averaging 63.15 per cent alumina. A few hundred tons of low-grade kyanite averaging 56 per cent alumina have also been shipped.

Kenya Kyanite Ltd. began the erection of a rotary kiln and started production of calcined kyanite about the middle of 1950.

Anticipating the rapid exhaustion of easily won massive kyanite the company has erected a flotation plant with a view to extracting the kyanite disseminated in the schist in which the segregations occur. It is stated that production from this source began in May, 1952.

Both Mrs. Lloyd-Greame and her successors East Africa Minerals Ltd., have operated in the vicinities of Kevas and Loosoito more or less simultaneously. Work was started on a patch of corundiferous boulders on the plain near the south end of Kevas and extended to a patch of normal kyanite-rock boulders at the Kopje, a small knoll lying south of Kevas. At the same time a few lorry loads of kyanite were taken from the scarp hillside of Loosoito where the more obvious boulders were soon exhausted. By the end of 1949, when Mrs. Lloyd-Greame sold to East Africa Minerals Ltd., about 800 tons of kyanite had been produced and almost all of the exposed material had been taken.

East Africa Minerals then, with great diligence and system, worked over again all the old excavations, using a power aliger to locate boulders, and opened up quarries and open-casts at the Kopje and other promising points along the outcrops. By systematic prospecting they located two new occurrences, one designated "New Claims", south of the Kopje and another "Leopold Claims", lying between Kevas and Loosoito. In both cases removal of the residual boulders led to the discovery of lenses of kyanite rock *in situ* below. At "New Claims", when the overburden became excessive, a short inclined shaft was sunk and levels driven in order to clean up a group of good segregations. In 1950 the company had a resistivity survey made over a strip of ground including both visible and concealed portions of the outcrop, but the resulting plot proved to be of no assistance in prospecting.

In 1950 the company produced over 2,500 tons of kyanite but on exhaustion of the easily won material the output fell to 600 tons in 1951. Since much kyanite of second grade that would not pass the United States Government specification was put aside during operations the company is now constructing a jigging plant for the extraction of kyanite from this material.

A brief account of the development of the kyanite industry in Kenya up to 1947 is given by Varley (1947) in the Bulletin of the Imperial Institute.

5. PRODUCTION FIGURES

The production records are as follows:—

Year		Murka	Kevas and Loosoito	Price per ton	
				£	s.
		SIR CHARLES MARKHAM			
1944	..	612		3	10
1945	..	444		3	13
1946	{	916			
		KENYA KYANITE LTD			
		1,715			
1947	..	14,447		3	15
1948	..	14,600	MRS. LLOYD-GREAME	4	5
			829		
1949	..	22,341	E.A. MINERALS	5	10
			93		
1950	..	8,926	2,543	9	0
1951	..	10,027	612	12	0

The production of calcined kyanite was started by Kenya Kyanite, Ltd., in the first half of 1950. Almost the whole production from this company in 1951 consisted of mullite which realized £24 per ton,

V—KYANITE IN KENYA—THE MURKA-LOOSOITO KYANITE BELT

1. SITUATION AND COMMUNICATIONS

The Murka-Loosoito kyanite belt is situated in the Taveta district of the Coast Province and also in the Tsavo National Park (fig. 2). The belt runs roughly north-south and, including some unexposed sections, has been traced for a distance of 9 miles. The southern end forms Murka hill which stands 4 miles north of both the Voi-Moshi branch of the East African Railways and the main road between those places (fig. 3).

2. TOPOGRAPHY AND EXPOSURES

For a long distance round the kyanite belt the country is a gently rolling peneplain. On this peneplain rise very abruptly three widely separated hills. From south to north they are Murka (350 ft.), Kevas (200 ft.), and Loosoito (1,000 ft.), the figures being rough estimations of the height of the summits above the general level of the surrounding country. The trigonometrical station on the summit of Loosoito stands 4,106 ft. above sea-level.

All three hills are long, narrow, level-crested, hog-backed hills which, owing to the steep easterly dip (30° to 40°) of the rocks, present scarp cliffs to the west and dip slopes to the east. All three have long, almost horizontal crests which descend to the peneplain abruptly at the southern, and more gently at the northern end. They are arranged slightly *en échelon*, for though all three lie in a line running N.N.W.-S.S.E. each hill is itself orientated more nearly north-south. Natural exposures of rock *in situ* are limited to the crests of the hills and to the long low ridges that extend northwards from them. The hillsides are almost completely covered with talus composed of boulders fallen from the kyanite-quartz schists which outcrop along the crests. The boulders are partly concealed by soil which supports a fairly thick deciduous scrub cover. South of Kevas there formerly stood a small rocky knoll to which the name "The Kopje" was given by the kyanite workers but most of it has been removed by quarrying. For half a mile between Kevas and the Kopje the schist outcrop can be traced almost continuously by a chain of small exposures, but elsewhere the peneplain, which is partly bush-covered and partly open grassland, is practically devoid of exposures.

Excavations on the peneplain show that a discontinuous mantle, consisting in some places of lateritic ironstone (murrum) and in others of concretionary limestone (kunkar), intervenes between the soil and the solid rock below. Nevertheless, intensive prospecting has led to the discovery here and there of clusters of kyanite-rock boulders, rising in some cases only a few inches above the soil, and at two localities, viz. "New Claims", south-east of the Kopje, and "Leopold Claims", south-east of Loosoito, these boulders were found to overlie kyanitiferous schist *in situ* bearing workable concentrations of kyanite rock.

3. ASSOCIATED ROCKS

In Kevas and Loosoito hills the kyanite-quartz schist is immediately overlain by a formation of barren, white, massive quartz schist (specimen 64/20). This is a completely recrystallized rock consisting of large grains of quartz with intricately sutured contacts. At the southern end of Loosoito this quartz schist carries pyrite and in consequence weathers reddish brown.

No formation of this kind is to be seen either in Murka or at the Kopje and its associated workings. There is not a single known exposure, natural or artificial, of any rock lying above the kyanite-quartz schist other than the barren quartz schist just mentioned. One natural exposure of a leucocratic biotite gneiss is situated about three-quarters of a mile east of the southern end of Murka, but, owing to the change in structure that occurs at the southern end of that hill it is more probable that this gneiss is one of the underlying rather than one of the overlying beds.

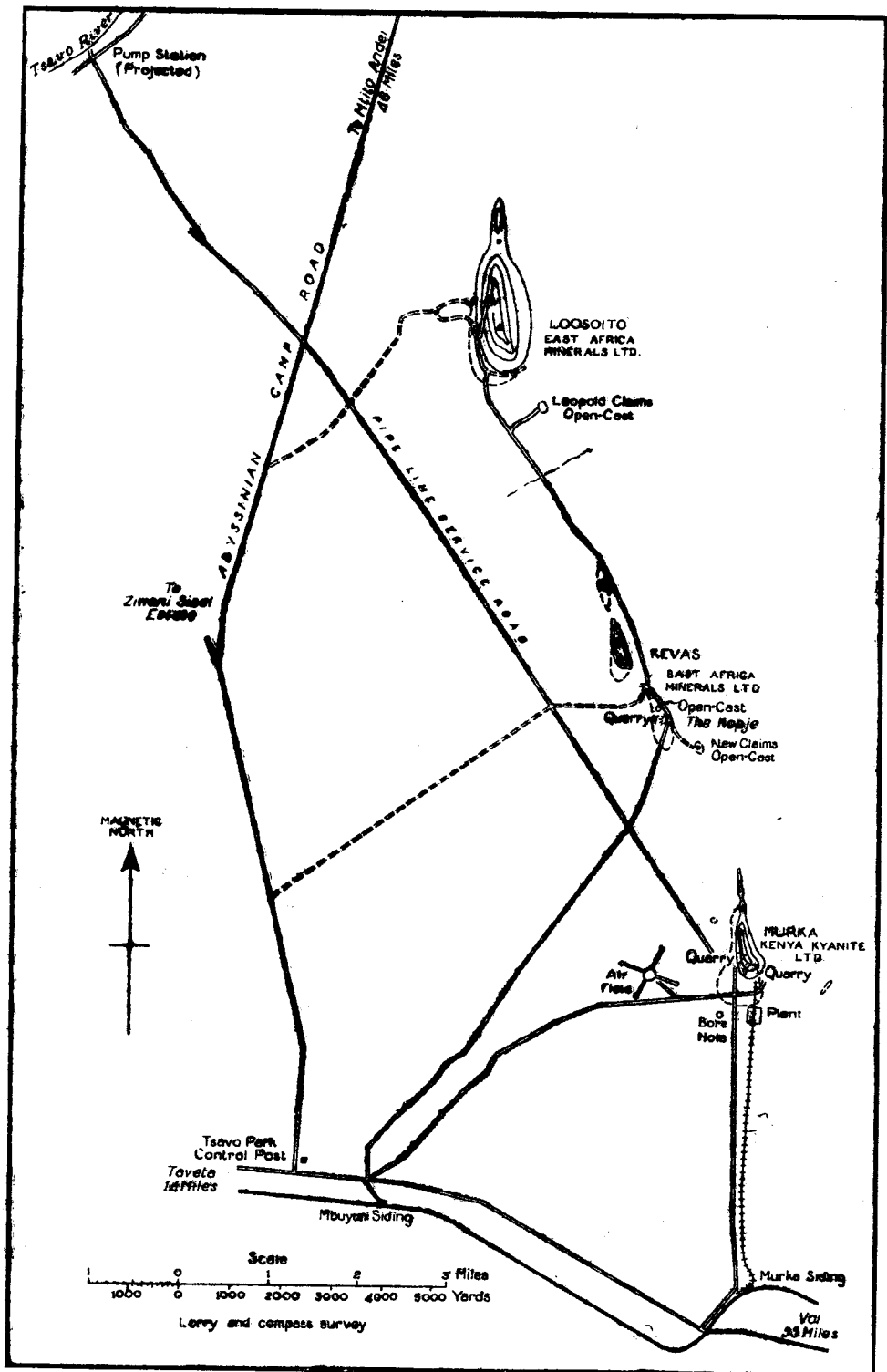


FIG. 3.—Murka-Loosito kyanite belt—Communications.

Beds immediately below the kyanitiferous formation, consisting of biotite gneiss, are exposed naturally in the low col between Loosoito and its long northern tail, but elsewhere the only exposures of the underlying rock are provided by pits and cuttings and other artificial excavations.

On the south-facing hillside at the southern end of Murka some half-dozen excavations exposed biotite gneiss, one bed of which is garnetiferous (64/6). Some leucocratic garnet-bearing gneiss with accessory biotite (64/12) was found as the spoil from a latrine 550 yards west of Murka. Hornblende-biotite gneiss (64/7) was seen in several excavations for the plant foundations south of Murka and a hornblende-biotite-epidote gneiss (64/9) in a pit about half-way between the plant and the foot of the hill. Some meso-type hornblende gneiss (64/10) was found in a pit from which corundiferous kyanite boulders had been removed 600 yards west of the northern end of Murka. Calc-silicate rocks were located at two points: one, in a cutting for a tramway at the south-western base of the hill, exhibits conspicuous green spots: it is a plagioclase-microcline-epidote-quartz rock with accessory sphene, hornblende, etc., with the epidote in large spongy granules (64/11). The second, found in a pit between the plant and the foot of the hill, is a band of epidote-hornblende-garnet-plagioclase rock about 2 in. wide (64/8).

In one of the excavations at "New Claims", south-east of Kevas, a muscovite schist with accessory kyanite and biotite (64/13) was found as a band a few inches thick immediately underlying the kyanite-quartz schist. Below it is biotite gneiss. At the Kopje a pit dug a few yards west of the scarp of kyanite-quartz schist revealed a well-foliated biotite gneiss including conspicuous quartzo-felspathic lenses (64/14).

On Kevas a few pits were found at the foot of the scarp cliff but the rocks exposed in them are so highly replaced by phosphorite (64/16) that their original nature is not clear. Mammellar incrustations of phosphorite (64/17) were found on the kyanite schists forming the lower overhanging part of the cliff at one point: they result from the action of hyrax urine upon the rocks.

At Loosoito, besides the natural exposure of biotite gneiss mentioned above, a large boulder of this rock (64/18) carrying accessory hornblende lies at the foot of the western hillside. It is well-foliated and contains long flattened rods of quartzo-felspathic material as well as masses of almandine about an inch in diameter. In a trench immediately below the scarp biotite gneiss (64/19) has been exposed. In the excavation at the hairpin bend on the motor-road up the scarp slope of Loosoito a garnetiferous hornblende-epidote-plagioclase-microcline gneiss (64/21) lying *in situ* and dipping into the hillside has been exposed.

One may conclude from the above rather meagre information that the dominant rock type among formations below the kyanite horizon is biotite gneiss in which hornblende and garnet are common accessories. Interbedded with this gneiss are some types rather richer in hornblende, while occasional thin bands of calc-silicate rock are also present.

4. THE KYANITE-QUARTZ SCHIST; EXTENT, ATTITUDE AND THICKNESS

(1) *The Schist in situ*

(a) *In the Main Part of the Kyanite Belt.*—The simple hog-backed form of all the hills in this kyanite belt and the fact that nowhere are there two parallel ridges strongly suggests that there is only one kyanitiferous quartzose formation, even though this may be locally divisible into two or more beds.* Generalized sections across the three main hills are given in fig. 4.

* Dr. Parsons of Kenya Kyanite, Ltd., states that parallel occurrences are known, and considers that they are probably a repetition of one horizon by thrusting.

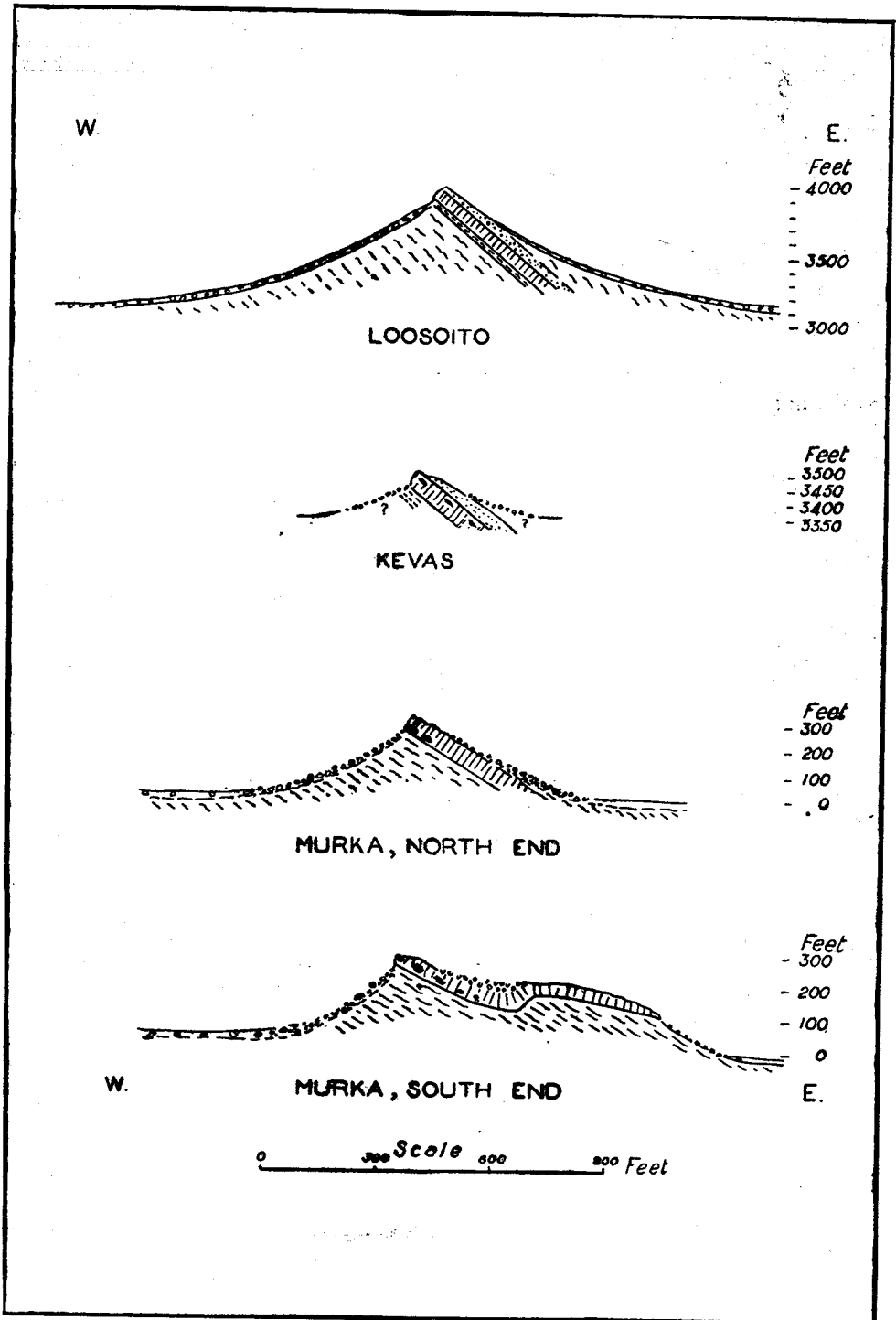


FIG. 4.—Cross-sections through Murka, Kevas and Loosoito Hills.

In Murka there is a single quartzose formation which appears to carry disseminated kyanite in varying quantities almost throughout. In the westward-facing quarries near the south of the hill (see fig. 7 and points D, E, F and G in fig. 5) the exposed thickness of the kyanite-quartz schist is about 50 ft.; but as there is probably a thickness of about 10 ft. of schist below the floors of the quarries, and because the quarries have not yet been cut back far enough to reach the true upper surface of the schist, its true thickness is likely to be nearer 70 or 80 feet.* Southwards from these quarries to the south-west corner of the crest of the hill and round to the east, where the southern quarries are situated, the thickness cannot be determined: this is partly owing to slipped material, partly to bad exposures and partly to the fact that the schist has been forced down to form the keel of a syncline;† but the kyanitiferous formation is probably much thinner here than in the first-mentioned quarries. Where the cliff appears again in the south-eastern spur of the hill the thickness is seen to diminish from 50 to 30 ft. in a west-to-east direction.

Northwards of the western quarries a thickness of about 70 ft. is maintained as far as the northern end of the high crest of the hill (point H) after which a fairly rapid thinning sets in. The kyanite-quartz schist runs the whole length of the long northern tail of Murka and it is likely that in general the thickness of the formation varies roughly with the height of the ridge that is formed by it.

The writer believed at first that the kyanite-quartz schist occurred in a series of unconnected lenses strung out in a line on the same stratigraphical horizon, and that it was probably for the most part absent on the peneplain between the hills. Subsequent discoveries of the schist at widely separated localities on the peneplain, but in the same line of strike, makes it more probable that the outcrop of the kyanite-quartz schist is continuous throughout the whole length of the kyanite belt and that the formation is merely developed into lenticular thickenings at the site of the hills. The fact that the schist is as much as 50 ft. thick at "New Claims" where there is no topographical relief shows that thickenings of this formation are not confined to the sites of hills.

North of Murka the schist is next seen at "New Claims" where, in opencast workings, it reaches a thickness of over 45 feet. The real thickness is unknown since the upper surface of the schist is not exposed. At the Kopje the size of the residual boulders and measurements in the quarry indicate a general thickness of from 6 to 10 ft. with a maximum of 14 ft., while a rather smaller thickness is suggested by the various exposures and boulders between the Kopje and Kevas.

In Kevas two distinct quartzose beds can be distinguished the lower being the kyanite-quartz schist and the upper the pure quartz schist mentioned above. The lower passes into the upper bed through a zone a few feet thick in which thin beds of the two rock types alternate. At the extremities of Kevas the ridge has a double crest due to weathering having cut back a little faster in the composite zone, than in the massive formations above and below.

No measurements of the thickness of the kyanitiferous schist were made at Kevas but it probably reaches a maximum of about 60 ft. in the southern part of the hill. In both Kevas and Loosito the lowest exposed part of the kyanitiferous schist (64/33 and 64/36) is much more fissile (along schistosity parallel to the bedding) than the upper, which is more massive, a feature that gives rise to overhanging cliffs. Some beds are highly iron-stained and some are porous at exposures due to the weathering out of quartz from a mesh of kyanite crystals (64/35).

A feature exhibited in Kevas, which has not been noted elsewhere, is a bifurcation of the kyanitiferous schist: it occurs at the southern end of the ridge. The stratigraphi-

* Dr. Parsons states that thicknesses of 70 to 80 feet have been proved, but that the thickness is variable, probably owing to repetition by thrusting within the horizon.

† Dr. Parsons considers that tear-faulting is responsible for the structures in this part of the hill.

cally higher part of it runs south-eastward to the Kopje while the lower quickly sinks below the soil surface and presumably wedges out.

After a short gap the schist is again exposed north of Kevas over a distance of about 1,000 yards with a rocky knoll about the middle. The next exposure is some 3,200 yards further on at "Leopold Claims", which lie south-east of Loosoito; but as the schist had not yet been properly exposed at the time of the writer's visit he cannot state its thickness.

At Loosoito the quartzose formation is divisible into four more or less distinct beds (see fig. 9). The three lower, which were named for reference, basal (64/37), massive (64/38) and porous (64/39) respectively, carry disseminated kyanite, but the topmost is, as at Kevas, a pure white, quartz schist. As in Kevas the basal bed is the most schistose but in Loosoito the porous bed differs from such beds in Kevas in an unexpected manner, for it is the kyanite that has been weathered out leaving a porous mass of quartz.

All four beds are present only in the central part of the high ridge (see fig. 9 (a)) for the porous bed wedges out to the southward, while northward it is displaced into an unexposed position by a dip-fault. The white bed is only exposed in the southern part of the crest of the hill for it either wedges out or is faulted back to the north. At the centre of the ridge each of the kyaniferous beds is about 25 ft. thick making a total of 75 feet. Southward the massive bed thickens and the basal bed thins while at the extremities of the hill the falling crest-line is presumed to indicate thinning of the whole quartzose formation. The writer has not made any systematic search for exposures north of the end of the Loosoito's long northern tail but prospecting by the staff of East Africa Minerals Ltd. has failed to find any.

(b) *At the South End of Murka.*—An important question, in view of the local high content of massive kyanite rock, is what becomes of the schist at the southern end of Murka. The distribution of residual boulders, a matter referred to below, led Parsons (1946) to make claims regarding the continuity and thickness of the material *in situ* at and beyond the southern end of the hill. In view of these claims the writer paid special attention to this locality and had a number of pits dug in an attempt to find concealed outcrops of schist. He failed to find any and was therefore forced to the disappointing conclusion that his first impressions were correct and that the outcrop terminates in the southward-facing scarp.

A study of the south-eastern spur of Murka shows that the schist occurs as a capping upon it with a horizontal synclinal axis running W.N.W.-E.S.E. This capping of schist presents scarps to the south, east and north-east and there is no indication whatever that the schist formation re-enters the ground anywhere in these directions. How exactly this capping of schist on the spur is connected with the main mass, with the north-south outcrop, along the crest of Murka is not clear. On the northern flank of the spur the schist outcrop stands several hundred feet above what must be the underground extension of the main body of the schist, a fact that suggests very strongly that the rocks in the spur are separated from those in the main part of the hill by a fault.

In the depression between the spur and the main ridge only a jumble of displaced boulders is to be seen. At the southern extremity of the main ridge, between points B and C on fig. 5, there occurred a number of enormous blocks of schists some of which enclosed the largest masses of kyanite rock found at Murka. A few of these blocks are shown diagrammatically in fig. 7. The blocks dipped in all directions and for a long time the writer was unable to decide whether they owed their orientation to tectonic forces and occurred in a crumpled zone between the spur capping and the main outcrop, or whether they owed their anomalous attitudes to slip on the hillside under gravity. Subsequent quarrying has shown that the latter view is correct, for it can now be seen that the remains of these blocks are backed by talus which still conceals the true outcrop. The nature of the junction between the schist capping the

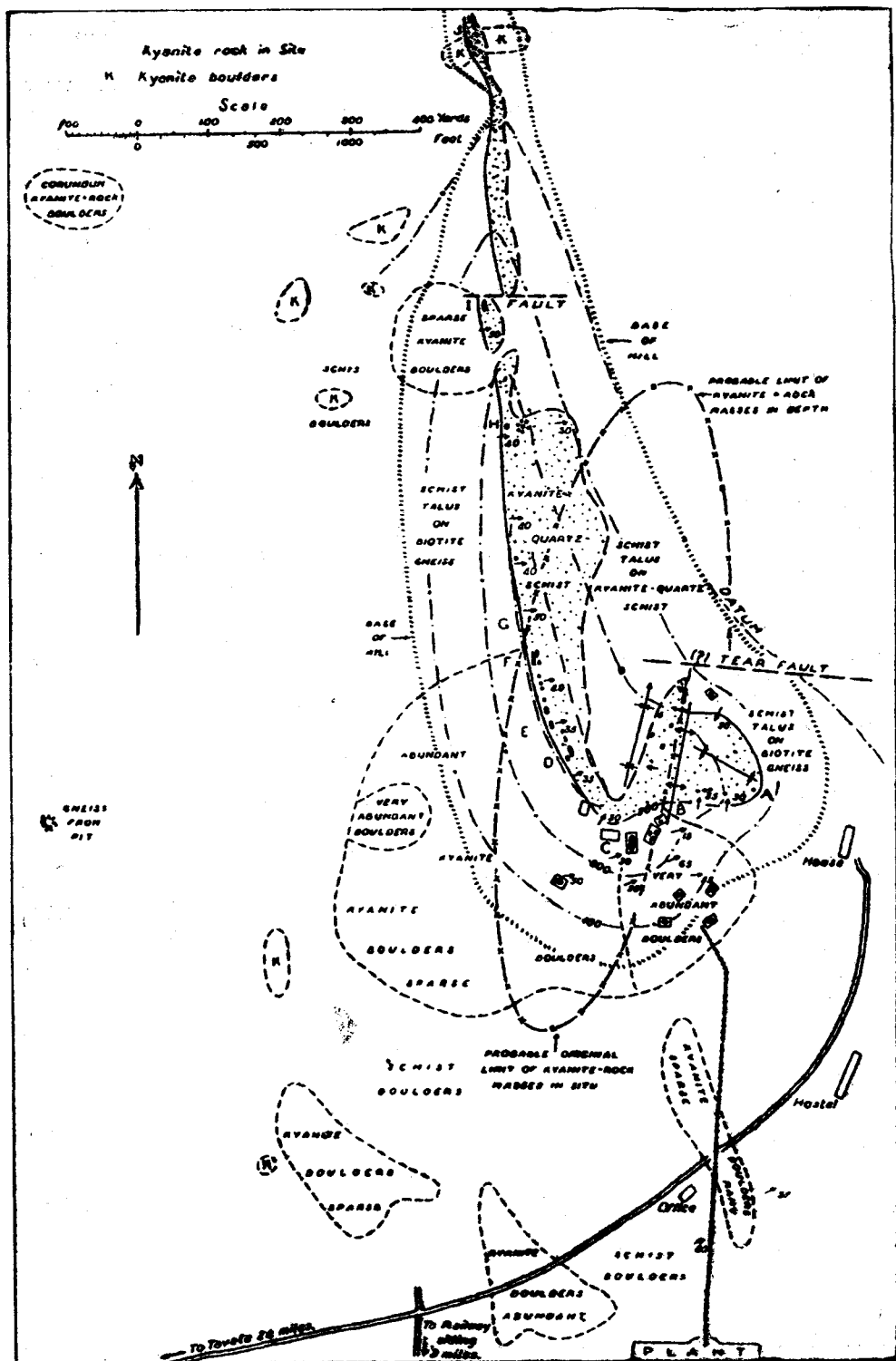


FIG. 5.—Plan of Murka Hill.

spur and the schist of the main outcrop is still obscure to the writer, but he retains his earlier opinion that there are probably a syncline and an anticline with parallel axes trending N.N.E.-S.S.W. between the two parts of the outcrop, the synclinal axis pitching steeply to the north and the anticlinal axis lying horizontally. These axes, along with the schist capping the spur, must be abruptly cut off by, or pass into, the more or less east-west fault already deduced.

The kind of dislocation that the writer has in mind is illustrated diagrammatically in fig. 6. It will be noted that the schist cannot be expected to have any outcrops or underground extension to the southward. If any concealed outcrop exists at all it is perhaps more likely to run north-eastward from the spur of Murka than in any other direction; for, should the steeply pitching synclinal axis suggested above prove to exist, it might possibly extend N.N.E. beyond the fault; in which case, an eastern limb of the syncline might crop out under the superficial deposits of the peneplain.

An observation that seems at first to be anomalous is that while the dip of the kyanite-quartz schist in the southern scarp of the south-eastern spur of Murka is to the north the dips in the gneisses on the south face of the hill are to the east. The writer believes that this is most satisfactorily explained by assuming that the two formations are here separated by a thrust-plane. He considers it probable that the rocks of the spur were partly severed from those of the main part of the hill by overthrusting from east to west and that while the schist formation behaved competently and was fractured and folded the underlying felspathic gneisses yielded plastically as incompetent material by slip along the eastward dipping foliation planes already well developed in it.

Mr. D. L. Searle, one of the writer's colleagues, believes that a thrust-plane is exposed below the schist formation in one of the quarries on the western scarp of Murka. While the writer admits that a thrust very probably exists there he cannot agree that one can be demonstrated in the exposures he has seen.

(2) *Residual Schist Boulders; with Deductions Regarding the Original Shape of the Formation.*

It has been pointed out above that all three hills, Murka, Kevas and Loosoito (and it applies also to the Kopje if the chain of small exposures to the north of it are regarded as part of it) are unsymmetrical in longitudinal section, for they all show abruptly terminating southern ends and gently declining northern ends with long tails extending still further to the north. If these hills expose cross-sections of lenticular thickenings of the kyanite-schist formation then the lenses must have their thickest parts near their southern edges.

The distribution of residual kyanite-quartz schist boulders is also asymmetrical with respect to the hills and in much the same manner as is the shape of the hills. Thus in each case residual boulders are in general more numerous and larger, and extend further from the hill, in a south-westerly direction than in any other. This has led the writer to the conclusion that each hill is an oblique cross-section of a lenticular thickening which had a long axis running N.N.E.-S.S.W. This view was in mind when fig. 6 was drawn. For clarity an outline has been drawn in this figure designated "edge of kyanite schist formation", but it is more probable that this represents the edge of a lenticular thickening of the kyanite schist. It will be shown in a later paragraph that the distribution of residual kyanite-rock masses is very similar, though not identical, with that of the schist. The reason for this apparent thickening of the schist in four elongated lenses arranged *en échelon* and with the thickest point in each lens near the southern margin is not known, but it is presumed to be a result of the mode of deposition of the sediment from which the schist is derived.

It has been mentioned on an earlier page that some of the larger residual schist boulders have been mistaken for exposures of schist outcrops. The writer recalls localities at the south-western base of both Murka and Loosoito where numerous

large boulders standing on edge and in a line have led him to contemplate seriously the possibility of their being virtually *in situ*: but he is convinced that in each case the reason for the alignment is that all the blocks concerned slipped down the hillside at approximately the same period (during one of the Pleistocene pluvial periods perhaps) and came to rest at what was then the base of the hill; and that they stand on edge because they slid down on joint planes, which were turned into a horizontal position when the blocks reached the base of the hill as explained in fig. 9 (c).

5. THE KYANITE-QUARTZ SCHIST; CONTENT OF DISSEMINATED KYANITE

(1) *Average Overall Kyanite Content*

Little is known about the distribution of disseminated kyanite within the schist in either a stratigraphically vertical or horizontal direction. Before any quarrying at the outcrop had been done the writer took 17 channel samples across the schist outcrop at Murka, the channels being distributed along 650 yards (between the points D and I in fig. 5) and spaced slightly more closely together in the southern than in the northern part. Large masses of kyanite rock were omitted during sampling but small lenses and sheets less than 1 ft. thick were included. It was hoped that these samples would provide data on the horizontal distribution of kyanite, but unfortunately they were ground up together to make one composite sample. The chemical analysis of this bulk sample was as follows:—

Per cent			Per cent		
SiO ₂	..	70.00	CaO		0.56
Al ₂ O ₃	..	23.63	MgO		5.73
Fe ₂ O ₃	..	0.11	K ₂ O		Nil
TiO ₂	..	Nil	Na ₂ O		Nil
			Loss on ignition		0.65
			TOTAL	..	100.68

Anal.: E.A. Industrial Research Board.

Assuming that all the alumina is in the form of kyanite then the 23.63 per cent Al₂O₃ represents a content of 37.55 per cent kyanite. Owing to the channels having been spaced rather more closely together where kyanite rock was most abundant, and owing to the inclusion of a small amount of kyanite rock in the samples, the above figure is probably slightly too high, the true kyanite content being near to 35 per cent.* This does not mean that this percentage of the schist is extractable in the form of pure kyanite for part of the kyanite is in very small grains intimately mixed with the quartz.

Two rough checks were recently made on the kyanite content of the schist at Murka. In No. 5 north quarry a sample bag of chips was collected by breaking off pieces of schist at intervals of a few feet along a line across the full exposed width of the outcrop. Ten chips were selected at random and their kyanite contents calculated from their specific gravities determined by suspension in water and air. The average kyanite content was found to be 33.4 per cent which agrees well with the figure previously obtained. It is noteworthy, however, that the vertical distribution of kyanite is very erratic since the kyanite content of individual chips varied from 13 to 53 per cent.

A similar check was made in the two southern quarries and their dumps at Murka No. 1 face, but as there was no exposure of the outcrop truly *in situ* here chips were taken both from the slipped blocks and from the dumps. The specific gravities of ten

*Kenya Kyanite, Ltd., state that the alumina content of the many tons of kyanite schist they have floated indicates that the estimation of 35 per cent kyanite is low.

chips taken from the bag indicated an average kyanite content of 34.2 per cent. The range among individual chips here was even greater than in quarry No. 5, viz. 0 to 61 per cent. The management of Kenya Kyanite Ltd. regard No. 1 face as yielding their best quality schist. This may be so if the poorer material is carefully sorted out.

(2) *Variation in Disseminated Kyanite Content with distance from Kyanite-rock masses*

This matter was not well investigated and the results are not conclusive, though they are perhaps worth mentioning. In No. 10 quarry at Murka chips were taken at intervals of approximately 3 in. along a line about 30 in. long drawn across the bedding where two kyanite-rock sheets 3 in. thick were situated. Specific gravity determinations on ten chips, omitting the kyanite rock, indicated kyanite contents varying from 7 to 55 per cent with an average at 32.7 per cent. The specific gravities of two other schist chips taken at contacts with kyanite rocks at other localities indicate kyanite contents of 41 and 33 per cent respectively. At the second point a second chip was taken representing schist situated from 1 to 2 in. from the kyanite rock: its kyanite content came to 43 per cent which is greater than that of the contact chip.

Although these results in themselves are of little value the general impressions gained while examining the quarries were (a) that kyanite-rock masses tend to occur in clusters and (b) that there is no impoverishment of the schist in the neighbourhood of the kyanite rock. These observations suggest that the alumina of the kyanite rock has not been drawn out of the surrounding schist but represents an excess over what is present on the average. Since the kyanite content of the schist varies up to at least 61 per cent, it is clear that segregation of the alumina into the form of kyanite rock must be controlled by other factors than the mere quantity present.

(3) *Especially rich schists of local occurrence*

In typical kyanite-rock masses the structure is decussate and there are sharp contacts between the kyanite rock and the surrounding schists. At a number of localities in Murka, Kevas and Loosito the schist was seen to be particularly coarse in texture and rich in kyanite. At some points the schist grades into what is almost kyanite rock although the sharp contacts and decussate structure are absent.

At a point about 150 yards south of the extremity of Murka's long northern tail a number of large slipped blocks close to the outcrop consist of what is virtually schistose kyanite rock (specimen 64/27), though there is clearly some quartz interfoliated with the kyanite. Restricted patches of similar coarse, rich schist have been noted in Kevas, both in the basal bed and near the top of the cliff, while in Loosito it has been found at two points in the basal and at one in the porous bed.

(4) *The sillimanitic envelope*

On the south face of Murka many of the huge slipped masses of kyanite rock had a good deal of schist still attached to them; in fact some of them consisted more of schist than of kyanite rock. Much of this schist, especially within a foot or so of the kyanite rock was seen to have a strong lineation which, in some cases, was more conspicuous than the more usual plane foliation. On slicing it was found that many specimens of this contact schist contain sillimanite in addition to kyanite and quartz and the writer came to refer to the contact schist as the sillimanite envelope.

The sillimanite is in the form of distinct separate needles, not as fibrolite, and among seven sliced specimens from Murka it is as abundant as the kyanite in one (64/42), an important constituent in two (64/44 and 64/43), a conspicuous accessory in two (64/45 and 64/46) and a rare accessory in one (64/47), while in one specimen only (64/48) was no sillimanite seen. The sillimanite appears to take the place of kyanite so that the total alumina content of this sillimanitic envelope may not differ much from that of average schist. It has been noted above that the management of Kenya Kyanite Ltd. maintain that the southern face of Murka yields their best quality schist. As all the sillimanitic envelope rock has been thrown onto the schist dumps on this face there may be an appreciable amount of sillimanite in the schist ore awaiting treatment.

Because the sillimanite occurs as needles it will be more difficult to separate from the quartz, hence a high alumina content must not be regarded as necessarily implying a high percentage of extractable kyanite. It was noted that the kyanite in this sillimanitic envelope tends to occur in more elongated, flattened and rugged crystals than in the normal schist.

Sillimanitic schist (64/44) was also found in two of the channel samples referred to in an earlier paragraph but was not examined *in situ*. The position of these channels was almost half-way between points E and F on fig. 5. Sillimanite-quartz schist (64/41) was found immediately underlying kyanite rock in the low scarp at the Kopje and other sillimanite-rich rocks were found in contact with the kyanite rock in subsequent excavations there. The sillimanite-quartz schist contains accessory kyanite and exhibits structures suggesting the derivation of the sillimanite from kyanite.

The schists of the sillimanitic envelope closely enwrap the kyanite rock masses and their plane foliation and lineation are diverted from their normal orientation to follow winding paths on the somewhat lobate and mammillated surfaces of the kyanite rock. The lineation of the schist adhering to the surface of a thin wedge of kyanite rock at the periphery of a lens is exhibited in specimen 64/49, while 64/50 is a piece of the schist itself with its plane foliation bent in adaptation to the surface of the kyanite rock. Nearly all these occurrences of sillimanitic rock were found on slipped blocks so that it was not possible to study the orientation of the lineation with reference to the points of the compass or to the structure of the kyanite belt.

(5) *The texture of the schists*

The texture of the schists varies greatly and among 17 specimens sliced four types of texture are recognizable.

The thin slices studied were cut vertically and parallel to the lineation and therefore show the least and greatest dimensions of the particles. The figures given are not intended to represent the actual particle sizes likely to be obtained on crushing to pass any particular mesh sieve but indicate the grain size of the particles seen in the thin slices.

Type (a).—Kyanite in compact crystals many of which have grown to comparatively large sizes. Representative specimens are 64/45, 48 and 59. The first two are parts of sillimanitic envelopes though the second contains no sillimanite; the third was found on a dump. In these rocks a large proportion of the kyanite is in crystals from 3 to 7 mm. in length. The crystals have smooth flat surfaces of contact with the quartz and are free from quartz inclusions. In specimen 64/45 the kyanite crystals are thin, varying from 0.1 to 0.5 mm. in thickness, but in the other two they vary in thickness from 0.3 to 2.0 mm. The proportion of kyanite in these specimens below the limits stated is small in comparison with that in the following types.

Type (b).—Kyanite in large skeletal crystals which could yield on crushing only small compact fragments. This type is represented by specimens 64/23, 25 and 26 all of which are ordinary schists, not envelope rocks. In these, much of the kyanite is in the form of crystals up to two and a half millimetres in length and half a millimetre in thickness, but owing to their skeletal form, they are unlikely to yield on crushing any kyanite fragments more than one millimetre in length and a quarter in thickness. Moreover, a substantial proportion of the kyanite would be in particles of less than a quarter of a millimetre in diameter.

Type (c).—Kyanite in highly subdivided skeletal forms which could yield on crushing only minute compact kyanite fragments. This is a fine-grained variety of type (b), the texture varying in degree of fineness rather than kind. It is represented by specimens 64/28, 29, 30 and 31 which are ordinary schists and by specimens 64/43 (1), 46 and 47 which are parts of sillimanitic envelopes. The largest compact kyanite fragments that schist of this texture is likely to yield would be half a millimetre

in mean diameter, while a large proportion of the kyanite would be in particles less than a tenth of a millimetre in diameter. Specimens 64/31 and 43 (1) are extreme examples of this textural type, part of the kyanite being in nebulae of small grains.

Type (d).—Kyanite in clusters of acicular crystals with splintery ends accompanied by sillimanite in needles, lying separately in the quartz. This type is represented by specimens 64/41, 42, 43 (2) and 44 which are all parts of sillimanitic envelopes. These schists might yield on crushing a very small proportion of particles of kyanite up to half a millimetre in diameter, but most of the aluminous material would consist of fragments of needles of kyanite and sillimanite varying in diameter from 0.1 mm. to 0.04 mm. As some of the kyanite in specimens 64/43 (2) and 44 is not completely subdivided into separate needles perhaps 0.10 mm. would be a better figure for the upper size limit for the majority of kyanite particles.

Summarizing the above textural information in terms of particle size it may be said that say 75 per cent of the kyanite in each textural type probably falls within the limits given in the following table, the figures being the mean diameters of the particles.

Type (a) 2 mm. to 0.3 mm. (8 to 50 mesh B.S.S.)

(b) 1 mm. to 0.1 mm. (14 to 150 mesh B.S.S.)

(c) 0.5 mm. to 0.05 mm. (30 to 300 mesh B.S.S.)

(d) 0.1 mm. to 0.01 mm. (150 to < 300 mesh B.S.S.)

These figures show that there is not only a great variation in particle size in a single specimen but that the range in particle size between types (a) and (d) is even greater. To get a clean kyanite concentrate from types (c) and (d) would mean grinding to -200 mesh and losing a large proportion of material in slimes; while even to include a small proportion of types (c) and (d) along with (a) or (b) ore would seriously lower the grade of the concentrate obtained. This would suggest that material from sillimanitic envelopes must be very carefully sorted if it is to be used at all. As types (a), (b) and (c) are all to be found among ordinary schists, and as they obviously vary enormously in the availability of their kyanite contents, it is clear that in order to get the most economical products out of the schists it will be essential to study the distribution of the various types and to undertake very careful selecting in the quarries.

6. MASSIVE KYANITE ROCK; MODE OF OCCURRENCE, ASSOCIATED MINERALS AND ALUMINA CONTENT

(1) *Mode of Occurrence*

(a) *Kyanite rock* generally occurs as lens-shaped masses with ellipsoidal or eye-shaped cross-sections. The range in size is great for they vary from aggregates of a few crystals to masses which weigh many hundreds of tons. The largest simple lens-shaped mass actually measured at Murka had a diameter of about 40 ft. and a maximum thickness of 10 feet. It was calculated that this lens had a volume of 8,000 c. ft. and weighed 800 tons. Recently, however, a mass was exposed in No. 5 north quarry which presented a cross-section 15 ft. thick and nearly 100 ft. long. Its outline suggested that it consisted of a number of originally separate lenses that had coalesced.

The usual internal structure is decussate, the crystals being comparatively short and thick and varying from a half to 2 in. in length (e.g. specimen 64/53). More rarely, especially in the largest segregations, part of the mass consists of crystals that are long, narrow and tapering and arranged radially round centres so as to build up spherical masses which may be 18 in. to 2 ft. in diameter (specimen 64/54). In some of the smallest masses, which often take the form of sheets a few inches thick interbedded with kyanite-quartz schist, the kyanite crystals sometimes lie with their long axes in the stratification planes and, having a slight tendency to parallel orientation, make a coarse felt with a rude lineation. A small, thin lens at Loosito consisted in part of very thin but wide blade-like crystals of kyanite lying criss-cross but mainly parallel to the stratification (specimen 64/55).

The lenses all lie with their largest dimensions parallel with the schistosity of the rocks in which they occur, which is also parallel to the interformational bedding planes. The form of their peripheral terminations varies considerably. Some masses have smooth elliptical outlines in vertical cross-section, while in others the convex changes to a concave outline, which gives rise to a keel-like periphery. In yet others the outer margin is ragged, the kyanite rock passing into the schist through a zone of wedge-shaped intercalations. A close watch on the quarries would have to be kept in order to decide which is the most characteristic form. In the first two cases the foliation of the enclosing schist is deviated around the lenticular kyanite mass but in the third case divergence may or may not be exhibited. All gradations occur between the three forms.

It is probable that the kyanite rock masses are elliptical in plan, parallel with the bedding, but the quarries have not been watched carefully enough to ascertain whether this is so or not. The masses may also have a parallel orientation with regard to their longest axes, but again this has not been established. A few observations of a rude lineation in the enclosing schists suggest that a N.N.E.-S.S.W. orientation may exist.

(b) *Kyanite-Corundum Rock*.—A patch of residual boulders lying 600 yards west of the northern end of Murka yielded over 100 tons of kyanite averaging 63.15 per cent alumina. A small patch of similar boulders near the southern end of Kevas yielded a few hundred tons of kyanite also higher in alumina than pure kyanite rock. This type of rock has not been found anywhere *in situ* in the schist. The rock consists of two ingredients (a) balls of deep blue but opaque, radiating, bladed kyanite up to about a foot in diameter in (b) a matrix consisting of grey-blue corundiferous kyanite with a decussate structure and a rather finer grain than that of normal kyanite rock. The corundum is in the form of tabular crystals of sand-grain size included within the kyanite. Small pockets of topaz crystals also of sand-grain size are conspicuous on account of the granular form of this mineral and its lack of colour (specimens 64/56 and 64/57).

(2) *Associated Minerals*

(a) *Common Minerals*.—The following minerals are usually to be found in every mass of kyanite rock though generally in very small proportions:—

(i) *Rutile*.—Almost all specimens of kyanite rock (e.g. 64/58) and kyanite-quartz schist (e.g. 64/23) contain rutile. Rutile in large quantities gives the kyanite rock or schist a purplish colour. If this colour is absent the rock is unlikely to give more than 1 per cent TiO_2 on analysis.

(ii) *Iron Oxide*.—This substance, occurring as red, translucent films between the kyanite crystals, is fairly common and gives the rock a reddish-brown colour (specimen 64/59). Specimens of this colour probably contain over 1 per cent Fe_2O_3 , but if they are allowed to form only a very small proportion of the ore they are not likely to raise its iron oxide content above that allowed by the specifications.

(iii) *Muscovite and Quartz*.—These two minerals, which generally occur together, are found here and there in irregular nests within or adjacent to masses of kyanite rock. They are generally as coarse in grain as in a pegmatite, with mica books up to 1 or 2 in. across. They are never accompanied by feldspar in such situations. The muscovite-quartz bodies are very irregular in form and appear to occupy interstices between the centres of concentration and radial growth of kyanite. In the schists of Kevas and Loosoito pockets of coarse quartz and muscovite are associated with the small developments of kyanite rock that occur in those hills. When kyanite-quartz schists are partly replaced by the growth of kyanite rock a small amount of this quartz-muscovite material seems to be a normal by-product which is shouldered aside, or sometimes entrapped, by the growing kyanite (specimens 64/61 and 64/60). Quartz without muscovite and in finer-grained aggregates also occurs as irregular veins and masses within kyanite rock. Muscovite without quartz occurs sparingly as partings between the crystals in kyanite rock:

it is often more or less altered to kaolin. Rather surprisingly muscovite is almost entirely absent from the kyanite-quartz schist.

(iv) *Kaolin*.—A little kaolin is generally present at the crystal contacts where it is derived from muscovite. In crushed material flakes of muscovite in all stages of alteration to kaolin can generally be seen. Occasionally kaolin is unusually abundant as in specimen 64/62. A rock which appears to consist of kaolin after sillimanite is represented by specimen 64/63 from Kevas.

(b) *Local Minerals*.—The following minerals are usually absent from kyanite rock but are present locally. Sillimanite and topaz are sometimes sufficiently concentrated locally to give sillimanite rock and topaz rock.

(i) *Sillimanite*.—The occurrence of this mineral in the form of sillimanite-kyanite-quartz schist envelopes round the kyanite-rock masses in certain localities has already been described. Locally, at contacts between the kyanite rock and its envelope there occur pockets of sillimanite rock. One from Murka (specimen No. 2882), the exact locality of which was not recorded, consists of a felt of sillimanite in the fibrolite condition which includes abundant, but irregularly distributed small corundum grains; it is a sillimanite-corundum rock. No true corundum rock has been found in association with the kyanite. A specimen from the Kopje (64/64) consists partly of kyanite rock and partly of sillimanite rock. In the latter the sillimanite is in two conditions, one as sheaf-like aggregates of fairly well-defined tapering prisms and the other as fibrolite. Corundum in short prismatic grains is very abundant in this specimen, both forming closely packed mosaics and disseminated through the sillimanite sheafs. Specimens in which kyanite rock and sillimanite rock are fairly intimately mixed are also to be found (64/65 and 64/66).

(ii) *Topaz*.—This occurs as small pockets, rarely larger than the fist, in kyanite rock. Sometimes it constitutes topaz rock (64/67) and in other cases is mixed more or less intimately with kyanite (64/68 and 64/69). The topaz crystals are always fine-grained and granular.

(iii) *Tourmaline*.—This mineral is rare, its principal locality being at the southern base of Loosoito. It is sometimes associated with quartz and muscovite in contact with kyanite rock (64/70) and sometimes occurs in the interstices between the kyanite crystals in kyanite rock (64/71).

(iv) *Pyrite*.—This is also a rare mineral so far as association with kyanite is concerned. One of the localities at which it has been found is the Kopje, where it is irregularly disseminated in small grains within a limited volume of kyanite rock (specimen 64/72). It was also found in rare fist-sized pockets in residual boulders at Murka. Pyrite in the quartz schist overlying the kyaniteiferous formation in Loosoito hill has been mentioned in an earlier section.

(v) *Wad*.—Occasionally wad takes the place of red iron oxide as films between the kyanite crystals in kyanite rock. This gives the rock a purplish-black appearance (specimen 64/73).

(vi) *Chlorite* (?).—Small patches of the kyanite rock are sometimes found that are green instead of blue. Under the microscope it is seen that the greenness is not due to the kyanite itself but to films of a green mineral, presumed to be chlorite, in crystal contacts and cleavage planes (specimens 64/75 and 64/74).

(vii) *A prismatic mineral* several inches long that was found on one of the schist dumps at Murka has not yet been identified (64/76). It is completely pseudomorphosed by muscovite and quartz, but judging from its hexagonal cross-section it may have been corundum.

(3) *The Alumina Content of the Kyanite Rock*

The following analyses have been extracted from the files in the Mines and Geology Department:—

CHEMICAL ANALYSES OF KYANITE FROM THE MURKA-LOOSOITO BELT

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
SiO ₂	38.28	37.51	35.20	37.38	35.88	38.07	37.67	37.84	58.83	58.68	58.80	60.30	33.44	38.48	37.14	35.05	34.65	35.99	34.29	33.64	39.34	38.27
Al ₂ O ₃	59.90	60.69	62.22	59.65	61.00	61.23	59.66	60.42	58.83	58.68	58.80	60.30	63.76	59.60	60.03	62.90	64.06	60.79	62.41	63.57	58.98	59.57
Fe ₂ O ₃	0.96	tr	0.64	0.56	0.30	0.59	0.57	0.70	0.84	0.95	1.07	1.02	0.65	0.32	0.40	0.25	0.43	1.25	1.96	0.87	0.93	0.75
TiO ₂	0.60	1.52	1.25	1.09	1.48	1.00	1.05	1.07	0.65	—	—	—	1.61	1.94	1.37	1.10	1.01	1.78	1.10	1.50	1.05	1.17
CaO	0.40	—	—	0.27	0.12	0.18	0.29	0.24	0.48	0.60	0.56	0.54	0.54	—	—	—	—	—	—	—	—	—
MgO	tr	—	—	0.07	0.08	Nil	tr	Nil	0.14	0.60	tr	0.16	tr	—	—	—	—	—	—	—	—	—
K ₂ O	0.46	—	—	0.12	0.12	—	—	—	0.24	0.18	0.10	0.13	—	—	—	—	—	—	—	—	—	—
Na ₂ O	tr	—	—	0.24	0.24	—	—	0.08	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Moisture	—	0.02	0.10	—	0.60	0.80	0.04	0.08	—	—	—	—	1.78	—	—	—	—	—	—	—	—	—
Ignition Loss	—	0.41	0.55	0.60	—	0.80	0.69	0.85	—	—	—	—	—	—	—	—	—	—	—	—	—	—

	Sample No.	Locality	Analyst	Remarks
A	M/2155/100	Loosoito	A. F. R. Hitchins	Representative of 300 tons consignment.
B	M/2018/145A	Murka	M. G. Edwards	Hand sample analysed in London.
C	M/2018/140A	Murka	M. G. Edwards	Method of American Society for Testing
D	M/1941/A/64	Murka	A. F. R. Hitchins	Materials.
E	M/1941/A/64	Murka	W. P. Horne	Method of American Society for Testing
F	20,898	Murka	W. P. Horne	Materials.
G	20,954	Murka	W. P. Horne	Method of American Society for Testing
H	20,897	Murka	W. P. Horne	Dried at 105/110° C.
I	21,305	E.A. Minerals Ltd.	W. P. Horne	Representative of 300 tons consignment.
J	21,362	E.A. Minerals Ltd.	W. P. Horne	Representative of 300 tons consignment.
K	21,060	E.A. Minerals Ltd.	W. P. Horne	Representative of 300 tons consignment.
L	21,393	E.A. Minerals Ltd.	W. P. Horne	
M	21,845	Murka	W. P. Horne	
N	M/2018/176	Murka	A. F. R. Hitchins	
O	CA/7/143	Murka	M. G. Edwards	Calced kyanite.
P	3217	Murka	M. G. Edwards	
Q	3218	Murka	M. G. Edwards	
R	3219	Murka	M. G. Edwards	
S	22,073	Murka	W. P. Horne	Analysis on ignited sample.
T	22,493	Murka	W. P. Horne	
U	7,818	Murka	W. P. Horne	

7. DISTRIBUTION OF MASSIVE KYANITE ROCK

(1) *General Remarks*

As the distributions of residual boulders and of masses *in situ* are closely related it is convenient to discuss them together, working northwards from Murka to Loosoiito. The kyanite-rock masses generally occur in clusters within the schists. At any one locality they tend to be concentrated at a particular horizon with the largest in the centre and small masses round about. The central masses often have an irregular mammilated surface as though formed by the amalgamation of several smaller masses. The smaller bodies round about, though most numerous at the same horizon as the central masses, are usually a little above or below the plane of maximum concentration. Kyanite-rock clusters appear in general to occur more commonly near the base than elsewhere in the schist, but there are many exceptions. There are no leaders running from one body to another, but it is often possible to locate unseen masses by noting the direction in which the foliation of the schist diverges. As the deviation of the schist takes place only within a few feet of the kyanite-rock masses this method is generally, however, only helpful within the confines of a cluster of bodies.

The sillimanitic envelope finds its greatest development at the south end of Murka, but it has also been noted at the Kopje. Elsewhere the massive kyanite is in direct contact with the normal kyanite-quartz schist, and sillimanite is absent.

(2) *In Murka Hill—Kenya Kyanite, Ltd.*

Figure 5 shows the distribution of kyanite rock (black spots) as it was seen before any quarrying took place. Almost all masses of kyanite rock *in situ* discovered by the writer are indicated but only the very largest of the slipped masses are shown individually.

In figure 7 the principal workings of *in situ* or nearly *in situ* material are shown, rather diagrammatically, up to September, 1951. Kyanite rock visible on the 4th September is distinguished from kyanite which was seen at the outcrop before quarrying started.

It will be noted that the principal sections of the outcrop that have yielded kyanite rock are the south face between points B and C, where No. 1 quarries are situated, and the west face between points D and G, where Nos. 5 and 10 quarries have been opened. The quarries in the south face when last seen were still mainly in slipped material, work having stopped in the talus behind the slipped blocks. Only in one corner of the most eastern quarry was any rock exposed that is possibly *in situ*. In view of the large tonnage of kyanite won from these slipped blocks and from those which had slipped further down the hillside below this face, it is expected that more kyanite rock is present in the schist behind these quarries. As this face is probably on, or close to, the keel of a syncline, and as the kyanite is likely to be concentrated at a low horizon in the schist, it may be necessary to work downwards as well as northwards to get at it.

In the westward-facing scarp the main concentration of kyanite-rock masses exposed before quarrying was in a length of 500 ft. between the points D and F. Some rough calculations based on the size and number of exposed masses were made in order to get an idea of the percentage of kyanite rock in the schist. As the kyanite rock appeared to be concentrated mainly in the lower 50 ft. of schist this thickness was used in the calculation; and as the kyanite rock seemed to be more densely distributed in the southern than in the northern part of this 500 ft. of outcrop it was divided into two parts each 250 ft. long, and a calculation made for each part separately. The result

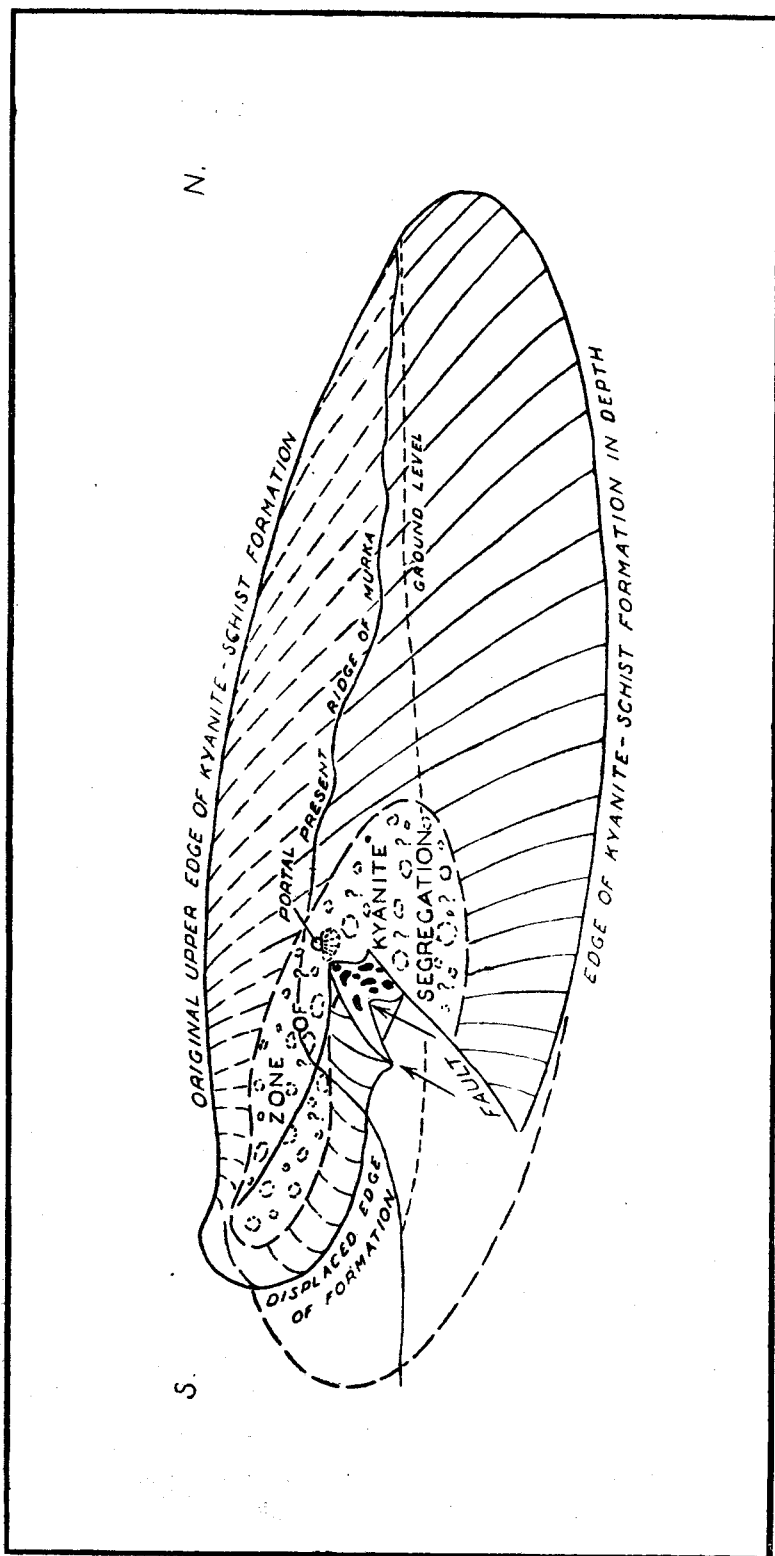
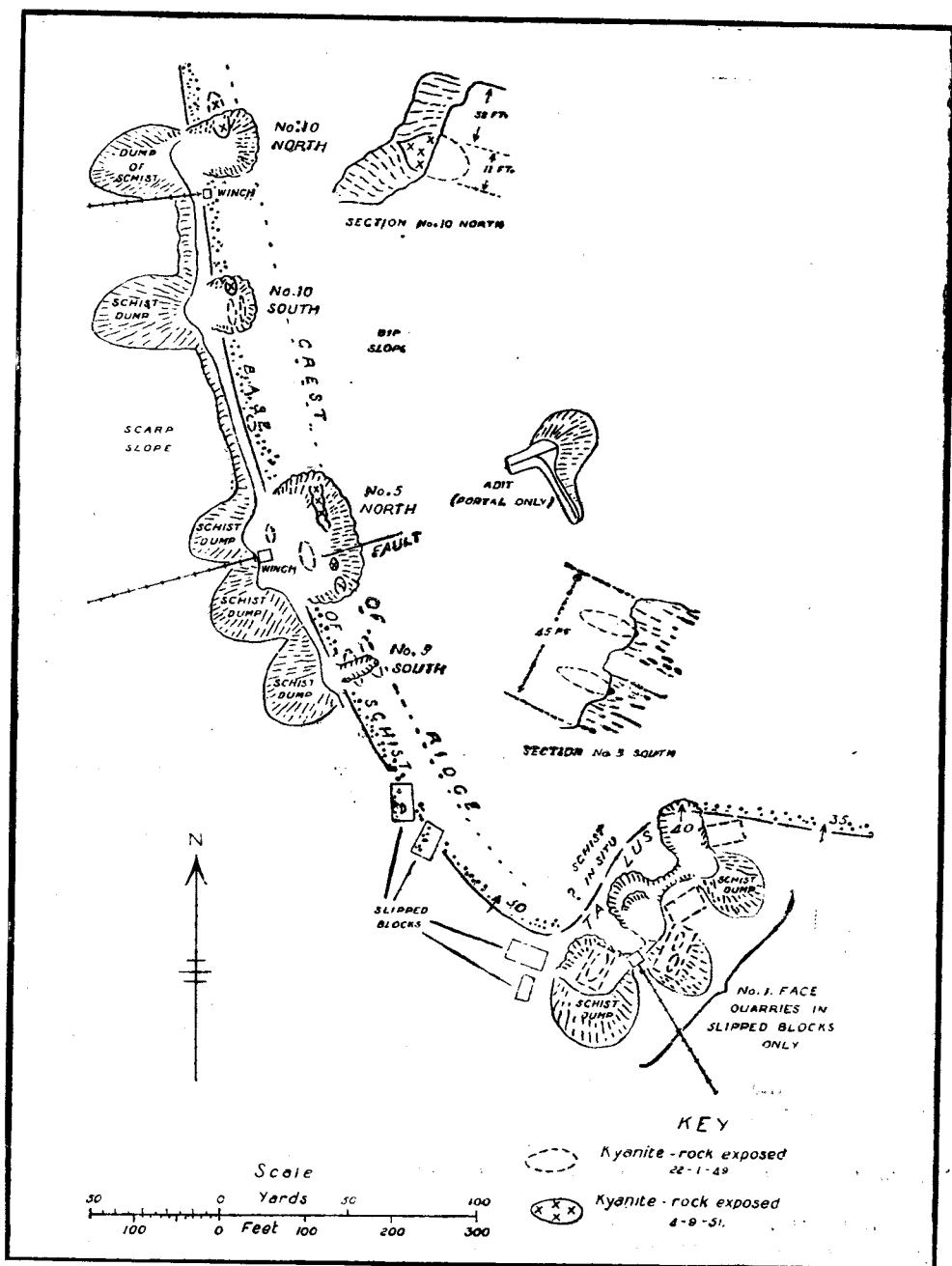


FIG. 6.—Diagrammatic representation of Murka Hill.



was that the schist within the southern 250 ft. of outcrop was found to carry 6.3 per cent of kyanite rock and that within the northern 250 ft. of outcrop 1.4 per cent kyanite rock. The kyanite rock masses measured for these calculations were estimated to weigh from 40 to 800 tons each.

On the peneplain at the south end of Murka patches of residual kyanite-rock boulders extend to a maximum distance of 500 yds. from the base of the hill in directions from south to south-west, which suggests that the original distribution of kyanite rock in the schist was in an area elongated from N.N.E. to S.S.W. A line has been drawn in figure 5 to indicate such original limits of kyanite rock both in the schist, which is now represented by residual boulders, and in the schist that still remains underground. It is obvious, however, that the distribution of kyanite rock within the underground part of this area is likely to be as erratic as it is at the exposed outcrop, and as erratic as the irregularly distributed patches of residual boulders suggest it was in the part that has been disintegrated by erosion. While the distribution of residual kyanite rock is a poor foundation on which to base conclusions regarding underground distribution it is the only indication that the writer has been able to find. In a report on Murka written in March, 1950, the writer recommended the covering of the underground part of the area indicated by a grid of diamond drill-holes spaced 100 ft. apart along lines running down the dip at 400 ft. intervals. No drilling has been done because the management anticipate winning all the kyanite-rock masses in the course of quarrying the schist for its content of disseminated kyanite.

At point H, near the northern end of the high ridge, some small kyanite-rock masses occur at a high horizon on the dip-slope but unless they indicate a cluster of larger bodies below they are not likely to yield much raw lump kyanite.

A little further north at point I there is a small lens at a low horizon in the schist and, to judge from the occurrence of slipped blocks on the slope below and of clusters of residual boulders on the peneplain, there must have been a small concentration of kyanite-rock masses in the schist of this locality. Whether any more exists underground remains to be discovered.

On the northern tail of Murka kyanite rock has been worked at the point J but was of poor quality. The writer found kyanite rock at four different points further north along the tail, but the size of the bodies was very small.

Of considerable interest is the cluster of corundum-kyanite boulders that lay 600 yds. west of the northern end of Murka. The writer counted 86 boulders showing above the surface and, by estimating their size, calculated that they would yield 400 tons of kyanite. Actually over 1,000 tons was won from this patch. The management of Kenya Kyanite Ltd. expected to find an outcrop of corundiferous kyanite under these boulders, but did not. The only rock that the writer saw in the excavations there, when the work was finished, was a meso-type hornblende gneiss. It is not certainly known whence these corundiferous kyanite residuals are derived but as similar boulders occur close to the line of the schist outcrop south of Kevas it is presumed that they came from the same kyanite-quartz schist formation as all the other kyanite.

(3) *In the Workings of East Africa Minerals, Ltd.*

(a) *At "New Claims".*—Here there was no exposure of the schist outcrop whatever nor any topographical indication of its existence. The outcrop was located solely by the finding of a few residual kyanite-rock boulders which just broke the surface of the soil sufficiently to expose a few square inches.

When the writer last visited these workings (6th September, 1951) the outcrop had been opened up for a distance of 120 yds. along the strike. At the north end of this section an open-cast 40 by 20 yds. and 45 ft. deep had been excavated, a cross-section of which is shown in figure 8. This working was the site of a cluster of kyanite-rock lenses all of which lay at or close to the base of the schist. Owing to the thickness of overburden it was decided to win the remaining masses in the cluster by underground work and an incline was being sunk from which drives were projected to get at the back of the kyanite bodies. Along the rest of the opened-up section of the strike the kyanite bodies were so small and scattered that at only one point had any kyanite been followed down the dip and there only for ten yards.

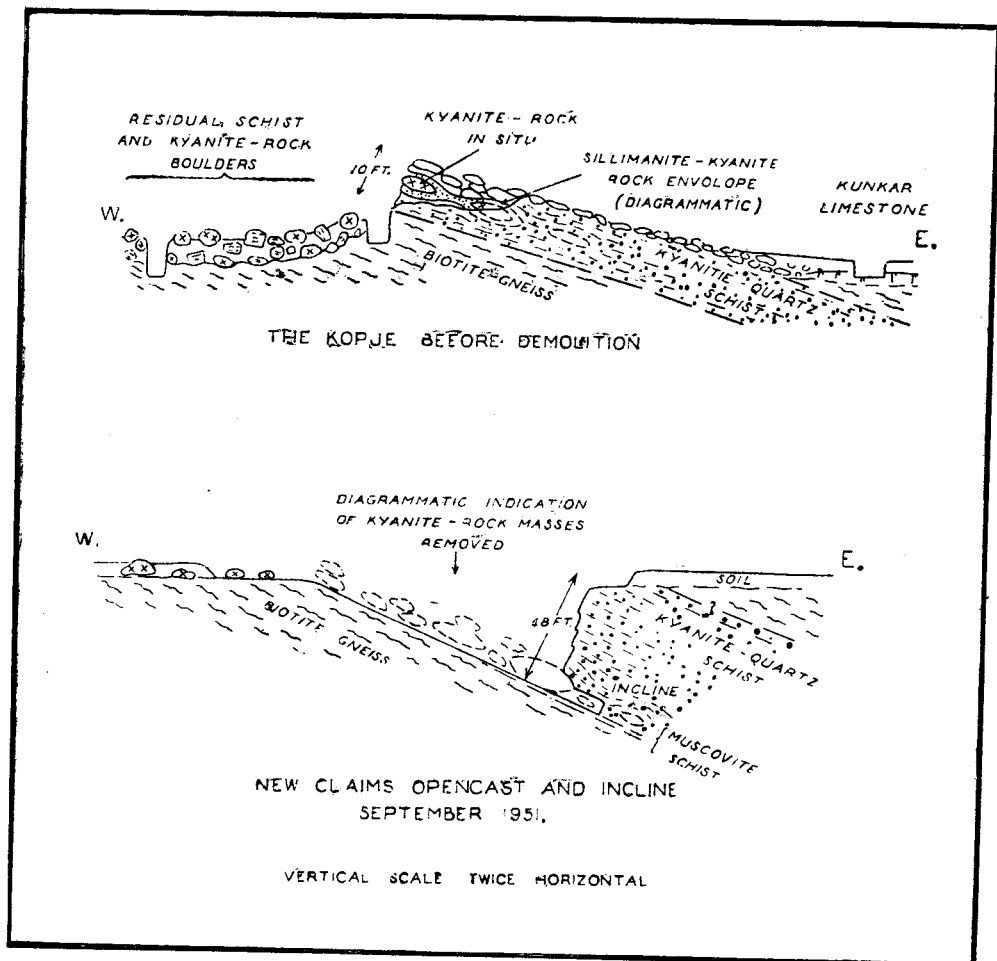


FIG. 8.—Workings of kyanite rock, East Africa Minerals, Ltd.

(b) At "the Kopje".—The Kopje was a rocky knoll (see fig. 8) standing about 15 ft. high and extending some 50 yards along the strike. It presented a low scarp to the south-west in which some kyanite rock was exposed, but most of the kyanite in this locality was won from a patch of residual boulders that lay immediately adjacent

to, and to the south of, the scarp. In the course of operations about half the Kopje was demolished but the kyanite proved to be of rather poor quality and in small widely-scattered bodies, so that the excavation was not taken below ground level. Some of the kyanite-rock masses *in situ* in the Kopje were enclosed, or partly enclosed, in a sillimanite-kyanite schist envelope.

Thinly scattered and small kyanite-rock masses, for the most part enclosed within residual blocks of schist, extended 400 yards south of the Kopje and 250 yards west of it.

(c) *Between the Kopje and Kevas*.—The outcrop of the schist runs north-westwards from the Kopje to Kevas and for the first 800 yds., which is about two-thirds of the distance, its position is revealed by a chain of small exposures rising a few feet above the peneplain. Here and there small masses of kyanite rock, usually only a few pounds in weight, show themselves embedded in the schist but at one point only, in "Musa's Hole" 250 yds. from Kevas, was any cluster of kyanite-rock bodies found that was worth opening up. Here a small open-cast was excavated. A narrow strip of ground, about 150 yds. wide, adjacent to, and south-west of this line of exposures has yielded a considerable tonnage of kyanite from scattered clusters of residual boulders. A large proportion of the residual boulders excavated from this area did not show above the soil; they were located by systematic probing with a power-driven earth-auger. One cluster, situated 550 yds. from the Kopje and from 30 to 130 yds. from the probable position of the outcrop, yielded high-alumina corundum-kyanite boulders identical with those found near Murka. Between this point and Kevas no workable kyanite has been located.

(d) *In Kevas Hill*.—Although some of the schist of Kevas appears to be unusually rich in disseminated kyanite true kyanite rock is exposed only in a very few thin lenses which are not large enough to be worth working. The largest, which is 6 in. thick, occurs about half-way along the scarp near the base of the cliff. There is a larger lens but it is much contaminated with quartz and iron oxide. Although Kevas is accompanied by a well-developed field of residual schist boulders which extends 300 yds. in a south-westerly direction from the scarp at the southern end of the hill, the boulders are completely devoid of kyanite rock.

(e) *At "Leopold Claims"*.—Although the kyanite-quartz schist outcrop is exposed for a distance of 1,200 yds. north of Kevas no kyanite rock has been found in it, nor have any residual boulders been seen in the vicinity. The next exposure is at "Leopold Claims" 1,000 yds. south of the southern end of Loosoito. Here a few kyanite-rock boulders were found just breaking the surface as at "New Claims", but at the time of the writer's last visit (7th September, 1951) only a few square yards of soil had been stripped and it was still uncertain whether these masses were in place or not. The schist outcrop has subsequently been located and a useful tonnage of kyanite rock won from this locality.

(f) *In Loosoito Hill*.—Kyanite rock *in situ* has been observed at about a dozen points widely distributed along the total length of exposed strike of 3,400 yds. including the northern tail of the hill. At only four points are the lenses over a foot thick, and possibly worth investigating from an economic point of view. These all lie in the basal schist bed. The most promising occurs about half-way along the base of the high crest of the hill; it is exposed at two points 60 yds. apart but it is not known whether it is continuous between these points or not. Its thickness is 2 ft. and 3 ft. at the two exposures respectively and it is much contaminated with quartz and muscovite. East Africa Minerals Ltd. intend sinking an incline on this lens to find out if it is worth working. In the rocky knoll that lies in the col between Loosoito and its northern tail there is a kyanite-rock lens about 1 ft. thick and 20 ft. long. Most of the smaller bodies are sheet-like with scattered lenticular thickenings.

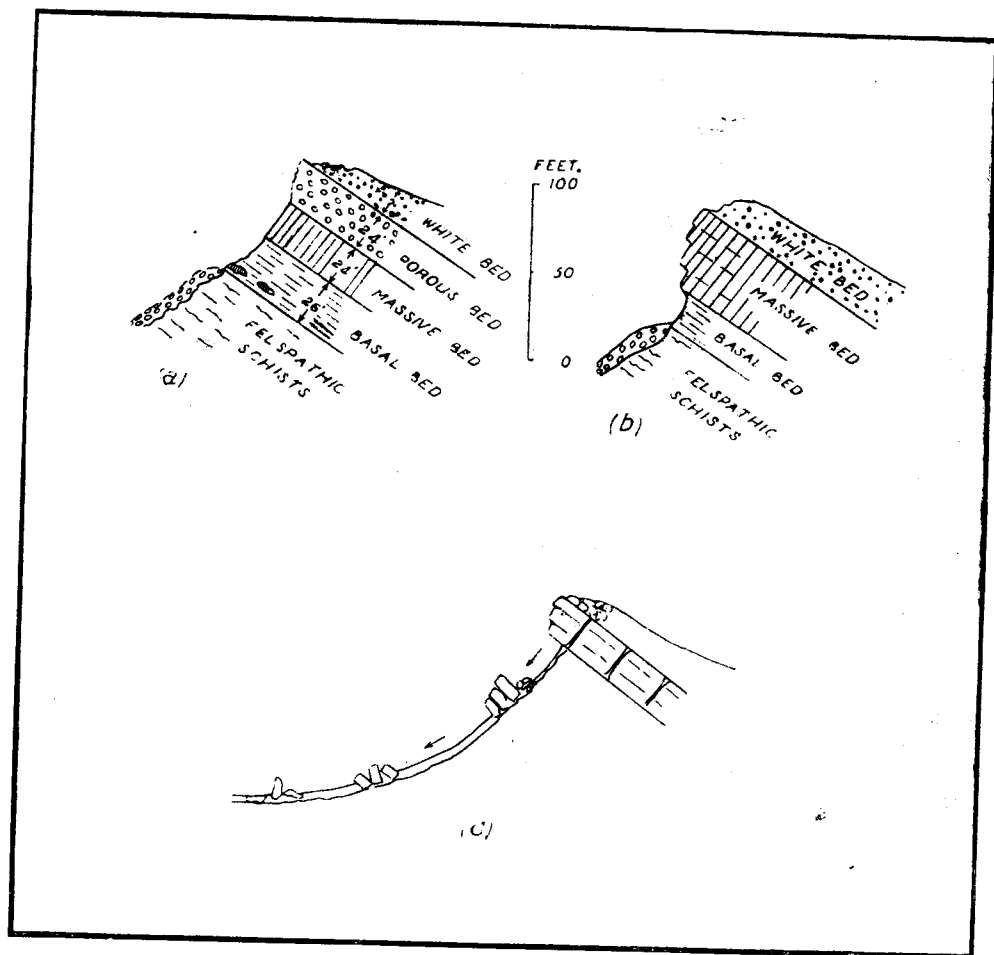


FIG. 9.—Cross-sections through Loosoito Hill: (a) Middle of hill crest; (b) near southern end of hill crest; and (c) diagrammatic explanation of standing residual blocks.

The central section of the steep scarp face of the hill, along a strike length of 500 yds., has yielded to diligent search a considerable tonnage of kyanite rock from slipped blocks, though none has been found on the gently sloping pediment of the hill nor on the peneplain beyond. The occurrences *in situ* mentioned above are very probably all that remains of a cluster of lenses that were represented by these slipped blocks. East Africa Minerals Ltd. have cut a well-graded, zig-zag motor-road up the face of Loosoito for the purpose of taking out the kyanite won from this hillside.

At the southern base of Loosoito some large blocks of schist, which include small masses of kyanite rock, stand up on their edges in rows as though they were *in situ*. On general grounds it is, however, much more probable that they are slipped blocks which have come to rest with their peculiar orientation and alignment as explained in figure 9. They have yielded a few tons of kyanite.

8. THE ORIGIN OF THE KYANITE IN THE MURKA-LOOSOITO KYANITE BELT

The following observations probably have some significance with respect to the origin of the kyanite in the Murka-Loosoito belt.

(1) The content of disseminated kyanite in the schists certainly varies from nil to 60 per cent and almost certainly rises locally to 100 per cent without the development of distinct segregations. In the vicinity of quarries where kyanite-rock masses are situated the schist though very variable from bed to bed, averages over a substantial part of its width about 33 per cent kyanite. The occurrence of corundum disseminated in kyanite rock at two localities only, suggests that though the concentration of alumina did not normally exceed 63 per cent, which is the alumina content of kyanite, there were points where the concentration of alumina reached 68 per cent. The kyanite content of the schists distant from kyanite-rock concentrations has unfortunately not been investigated, but its great variation from bed to bed, where it has been determined, suggests that the alumina content has not remained unchanged from the time of the schist's origin as a sedimentary rock. This matter is discussed further in the chapter on the origin of kyanite (page 77).

(2) The kyanite-rock masses are not segregations of alumina which impoverish the surrounding schists. They apparently occur where the schist had more than its average alumina content, but as they are not present everywhere when the schist is rich in disseminated kyanite there is evidently another factor involved in the development of segregations.

(3) Exposures in the surrounding country are so few that it is impossible to be certain that no plutonic igneous rock underlies the area but there is no reason to believe that there is any. The association of quartz, muscovite, topaz and, rarely, tourmaline suggests the activity of volatile fluxes though there is no evidence that they were of magmatic origin.

(4) The lenticular form of the kyanite-rock masses and the occurrence of linear structure in the sillimanitic envelopes that surround them suggests that the kyanite-rock masses grew in the schist while deformation under regional metamorphism was taking place. In thin slices of the sillimanitic envelope rocks the sillimanite tends to be most abundant round the periphery of somewhat augen-shaped crystals of kyanite, as though it had developed from the kyanite under strong deformation. In these rocks some of the kyanite crystals seem to have been in process of breaking up into bundles of acicular kyanite crystals. It is suggested that where the kyanite-rock masses grew to the largest sizes, that is at the south end of Murka, the rupture of the rock under deformation was greatest and that the sillimanite developed where the foliation of the schist was most disturbed by being forced to flow round the kyanite-rock masses. Because the kyanite-rock masses grew to a large size at the south end of Murka, where a dislocation has been proved to exist, one is tempted to conclude that tectonic disturbance was a factor in localizing the development of segregations. This often seems to have been the case where quartz-felspathic pegmatites in other formations are concerned. However, the juxtaposition of large segregations and a dislocation at the south end of Murka may be a coincidence and along the whole schist strike there is little to suggest any connexion between dislocation and segregation. The only points where location of kyanite segregations might be connected with tectonic forces are at the Kopje, and possibly at "Leopold Claims", where the strike swings 45° or more from the expected direction. There is thus no clear evidence of any connexion between location of kyanite-rock masses and tectonic disturbance.

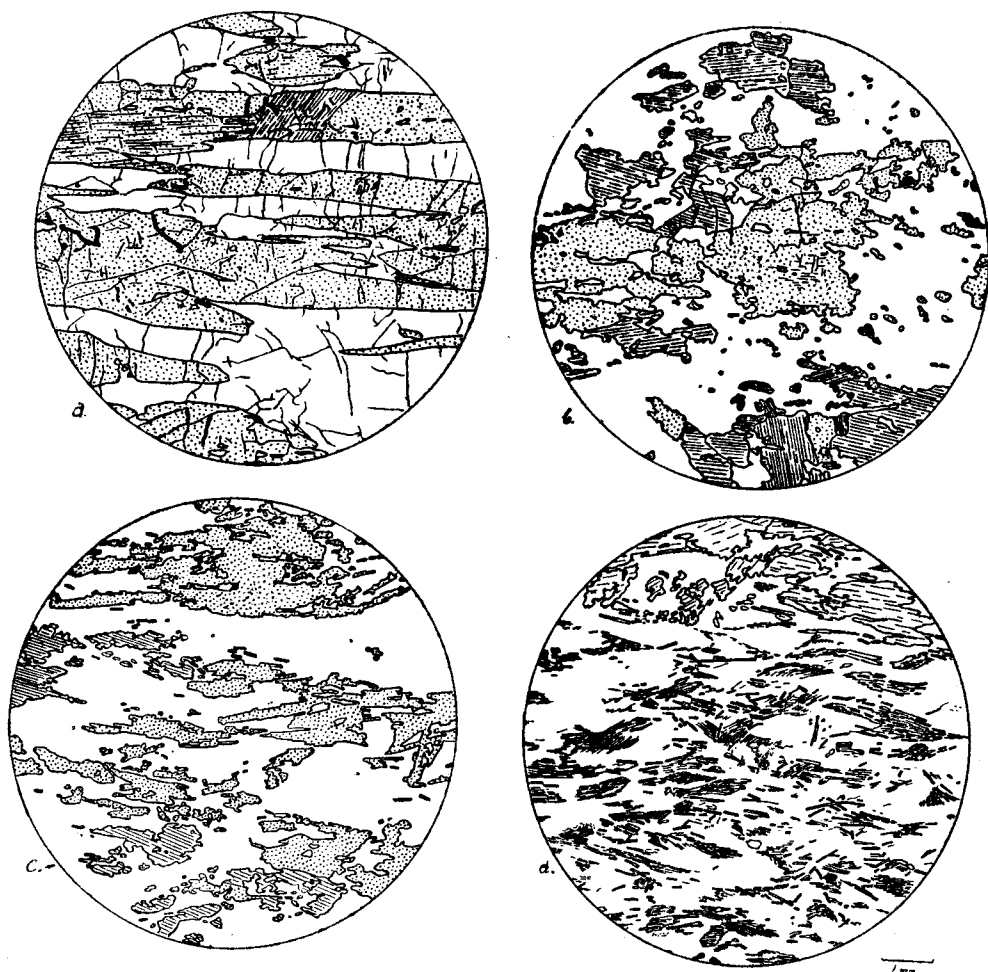


FIG. 10.—Micrographs showing textural varieties of the kyanite-quartz schist of the Murka-Loosointo kyanite belt:—

- (a) Specimen 64/59, Type A.
- (b) Specimen 64/26(i) Type B.
- (c) Specimen 64/28, Type C.
- (d) Specimen 64/42, Type D.

(Note.—In these and micrographs illustrated in later text-figures, the outlines of the kyanite crystals have been traced as faithfully as possible using a camera lucida, but the stippling and hatching that distinguish crystals cut at different angles by the thin section have been drawn diagrammatically. The mosaic produced by the traces of the quartz grain contacts have been omitted for clarity. All the drawings were made from thin section cut normal to the bedding, and in fig. 10 all are on the same scale.)

VI—KYANITE IN KENYA—THE MUBAI AND THE MUSURIAMBOI KYANITE-QUARTZ SCHIST

The alluvial part of the deposit can be reached by either of two footpaths, viz. an easy route two and a quarter miles long which follows the valley of the Ndolo River, or a more hilly track one and three-quarter miles long which climbs over a spur projecting southwards from Mubai hill. If the alluvial part of the deposit proved to be workable a road of access about 6 miles long could easily be constructed from the Emali-Nziu road. The distance to rail at Emali would then be about 21 miles. The Sultan Hamud-Okia road includes a mountain pass with many sharp bends and several drifts that are impassable during and shortly after heavy rain. The Emali-Nziu road traverses more level country but is also liable to be impassable during the rains.

(b) *Topography and Geological Setting*.—The summit of Mubai hill stands about 800 ft. above the Ndolo River at the alluvial boulder concentrations and the schist outcrop runs along a ridge estimated to stand about 180 ft. below the summit. The main concentrations of alluvial boulders nearest to the Ndolo River lie on spurs, separated from one another by tributary stream-beds, and extend from about 20 to 150 ft. above river level. Another concentration was found higher up one of the spurs; it extends from about 200 to 300 ft. above river level.

All rocks in the vicinity are gneisses and schists of the Basement System including quartz veins and pegmatites. According to recent geological mapping by B. H. Baker of the Mines and Geological Department, the lower part of the south-western slope of Mubai consists of rocks belonging to an association which he has distinguished as "principally unbedded, massive, homogeneous granite gneiss with biotite". The rocks of the upper part of the slope, which include the kyanite-quartz schist belong to a group distinguished by Baker as "banded gneisses consisting of interbedded light and dark granitoid and biotite gneiss with subordinate hornblende-bearing rocks". All the rocks in the vicinity dip to the north-east at angles commonly lying between 20 and 50°. The kyanite-quartz schist dips at 30°. A few feet above the kyanite-quartz schist there is a bed of coarse muscovite-rich gneiss which is exposed at several places and serves as a marker bed where the kyanite-bearing schist is either absent or not exposed.

The concentrations of kyanite-quartz schist boulders are distributed in such a way as to indicate that they are derived from the schist bed at the crest of the hill and deposited on lower ground to the south-west. The deposition took place when the valley floor was 200 to 300 ft. higher in relation to the present river bed than it is now, for the concentrations are restricted to the crests of spurs isolated by denudation, resulting from river rejuvenation. In the Murka-Kevas-Loosoito kyanite belt the greatest distance at which residual kyanite or schist boulders lie from the outcrop is only 600 yards. Some of the boulders of the deposit here described lie more than 2,000 yards from the present position of the parent outcrop. This suggests either that the denudation of the kyanite-bearing schist began much earlier at Mubai than in the Murka belt or that at Mubai the transport of boulders was assisted by fluvial action while in the Murka belt slip on steep slopes was the only movement with a horizontal component that took place.

On a casual inspection of the samples taken it appears that the overall kyanite content of the alluvial boulders is higher than that of the schist in place. If this is a fact it is one to be expected and can be attributed to the greater resistance to weathering and, therefore, the longer survival of the more kyanite-rich portions of the schist formation. In this connexion it is interesting to note that at Murka, Kenya Kyanite Ltd. have found that the alumina content of the kyanite rock from segregations so far available in place in the schist is lower than that of the residual boulders lying on the hill slopes and on the surrounding peneplain.

The mode of origin of the schist is not precisely known. Like the rocks with which it is associated it was originally a bedded sedimentary deposit, but it is uncertain how much, if any, material has been added or taken away during the process of metamorphism which all these rocks have been through. No segregations of kyanite rock

were found in the schist. The usual presence of a little muscovite along with the kyanite and quartz suggests that some fluxes were present for this mineral is frequently associated with the kyanite-rock segregations in the Murka belt. It is possible that the comparatively small thickness of the formation, which averages about 5 ft., did not permit the segregation of kyanite to take place.

(c) *The Kyanite-quartz Schist in place*

(i) *Length of outcrop and thickness.*—So far as mining possibilities are concerned the schist has a strike 600 yds. long,* which is continuous except for one small gap. Thicknesses cannot be measured accurately on account of the displacement of blocks at the exposures but the figures given on the plan, which vary from 3 to 12 ft., can be regarded safely as minimum estimates. The formation probably averages about 5 ft. in thickness over the 600 yards. The gap referred to is a break of about 50 yds. in the continuity of the exposures near the south-eastern end of the outcrop, but immediately adjacent to this break on one side of it a thickness of 12 ft. was measured. The reason for this break and thickening was not ascertained but so far as tonnage is concerned the thickening probably compensates for the loss by the gap.

The approximate horizon of the schist can be traced north-westwards for a further 600 yds. by means of an intermittently exposed bed of muscovite gneiss, but the kyanite-quartz schist is only exposed at one point in this distance, i.e. at 600 yds. N.W. of the main exposure. Whether the kyanite-quartz schist is continuous but unexposed in the intervening ground or is only developed here and there in small lenses was not determined, but the fact that alluvial boulders on the lower slopes of Mubai hill west of the summit are few and far between suggests that the latter is the true alternative.

In the opposite direction, i.e. south-eastwards, the schist outcrop rapidly descends the scarp face of the mountain. It appears to thin out in this direction, but in view of the rapidly increasing overburden the schist horizon was not explored by the writer beyond the point shown on the plan.

(ii) *Dip, ore-overburden ratio and tonnage.*—The dip is about 30° to the north-east. The schist-overburden ratio is shown diagrammatically at a point about the middle of the strike by the cross-section on the plan. From a point 150 yds. north of this cross-section to a point 350 yds. south of it the situation with regard to overburden is favourable. Thus, over a length of outcrop of 500 yds. the overburden increases down the dip from nil to 60 ft. in 250 feet. In other words over an area of 500 by 80 yds. the overburden averages 10 yds. in thickness and amounts to 400,000 cubic yards. Assuming that the average thickness of the schist is 5 ft. (1.66 yds.) this overburden covers 66,400 cu. yds. of ore, leading to an overburden to ore ratio of about 6:1. Assuming the schist carries 20 per cent† kyanite and has a specific gravity (calculated on kyanite content) of 2.84 there will be 12.64 cu. ft. per ton. This gives 142,000 tons as the amount of schist covered by overburden where the average overburden-schist ratio is six to one. Further down the dip the thickness of the overburden rapidly increases so that underground mining methods would have to be employed. The overburden will probably consist mainly of felspathic gneisses, more or less kaolinized and friable near the surface, but harder below.

* Since this report was written three new strikes of similar schist have been found by prospecting organized by Mr. P. H. Cull. They are situated respectively three-quarters of a mile north, three miles and a half east and eight miles and a half east-south-east of the summit of Mubai. Their positions are roughly indicated on Fig. 11, but they have not yet been geologically surveyed. Mr. Cull believes that the tonnage of kyaniteiferous schist in these new strikes taken together is at least equal to that of the occurrence described here.

† Subsequent heavy medium tests and chemical analysis have shown that the kyanite content is about 30 per cent (see page 44).

If it is assumed that the kyanitiferous schist was originally circular in plan, with a diameter of 700 yds., and averaged 3 ft. in thickness, and that half of it has been removed by denudation and half remains available for mining, then the total quantity remaining works out at about 400,000 tons.

(iii) *Sampling and Variations in Kyanite Content.*—The eight points at which samples were taken and the grouping of the samples into three lots (D1, D2 and D3), representing the N.W., centre and S.E. sections of the outcrop respectively are shown on the plan. Each sample consisted of numerous pieces of rock broken off salient edges of schist blocks on the scarp side of the exposure. Schist blocks *in situ* or as nearly so as possible, were selected and edges chosen which most nearly represent the whole thickness of the formation. As the overlying and underlying formations are not exposed it is uncertain whether or not the whole thickness of the schist has been seen and sampled. The weights of the samples taken were as follows:—

	<i>Lb.</i>
D1 North-west	27
D2 Centre	45
D3 South-east	20

(d) *The alluvial boulder concentrations*

(i) *Distribution and tonnage of boulders.*—The concentrations of schist boulders on spurs at low levels on the north-east bank of the river are largely covered with dense thorn thicket. The three concentrations investigated can each be divided into two parts, one in which boulders are thickly distributed and another in which they are sparsely distributed. The total measured area of thickly distributed boulders is about 43,000 sq. yds., but as there is another patch at a higher level that was not surveyed the total area might amount to 70,000 square yards. As many boulders are more or less buried in soil it is difficult to estimate the effective depth of schist if it were evenly spread out over the area given. Few boulders are more than 2 ft. thick and except in very restricted areas they do not seem to cover the ground completely. Perhaps 3 in. would be a safe estimate of the effective thickness, giving a tonnage of 12,500. There are however, also the boulders in the areas of sparse distribution to be taken into account, and there are also large numbers of boulders in the dry stream-beds which descend from the outcrop at the crest of the hill to the bed of the Ndolo River in the immediate vicinity of the alluvial concentrations. One might therefore, count on a total of about 20,000 tons of schist from the alluvial boulders.

(ii) *Sampling and kyanite content.*—Samples were taken along three lines AA, BB and CC cut through the thicket on each of the three concentrations examined. Each sample line was about 200 yds. long. The samples consisted of numerous pieces knocked at random off the corners or edges of boulders chosen along or near the sample lines. Possibly angular boulders are better represented than rounded ones but this is unlikely to invalidate seriously the representative character of the samples.

In most parts of the areas of boulder concentrations no boulders of any kind of rock other than kyanite-quartz schist are present, as the underlying gneisses are deeply weathered. At the N.E. end of sample line CC, however, there is a small area where rapid erosion has taken place, in consequence of which some blocks of vein quartz lie among the schist boulders. As such blocks are very easily distinguished from the schist boulders they were excluded during sampling.

The weights of the samples taken were as follows:—

	<i>Lb.</i>
A.—Western concentration	80
B.—Central concentration	90
C.—Eastern concentration	190

An impression was gained during sampling that the average kyanite content of the alluvial schist boulders is higher than that of the schist in place at the crest of Mubai Mountain. It is obvious from an examination of the samples taken that this schist varies greatly in kyanite content and grain size from one lamina to another, so that many thin slices would have to be examined before much could be stated regarding the variations in these characteristics. One specimen (52/457), in which the kyanite is particularly green and conspicuous, was sliced and one of the fields is illustrated in figure 13 (a). The dimensions of the majority of the kyanite crystals are 10 by 2.5 by 1.25 mm. but these crystals are skeletal and include much quartz embedded in them or lying between their ragged elongated prongs. Measurements made on two thin slices under the microscope show that portions of crystals that consist of solid, pure kyanite rarely exceed 2 by 0.5 by 0.5 mm.

(2) *Ore dressing report (A. L. Stewart)*

The object of the ore-test was to determine the amenability of the material to standard ore dressing methods.

The samples as received were reduced in particle size and bulk to about 1 lb. of -25 mesh material each. These were assayed by separating the heavy and light fractions with potassium mercuric iodide (sp. gr. 3.0). The light fractions contained some kyanite and the quartz had rutile inclusions, but the only impurities in the heavy or kyanite fractions, were small quantities of rutile and ilmenite. The results obtained for the six samples were:—

<i>Sample No.</i>	<i>Heavy Minerals</i> <i>wt. per cent</i>						
A	..	..	..	..	..	..	27.0
B	..	..	..	..	..	..	31.5
C	..	..	..	..	..	..	31.2
D1	..	..	..	..	..	..	28.0
D2	..	..	..	..	..	..	29.2
D3	..	..	..	..	..	..	27.5

The sample No. C was assayed chemically with the following result:—

	<i>Per cent</i>						
Al ₂ O ₃	..	..	..	..	..	..	18.87
TiO ₂	..	..	..	..	..	..	0.42
Fe ₂ O ₃	..	..	..	..	..	..	1.39

Anal.: W. P. Horne.

The alumina content is equivalent to 30.3 per cent of kyanite.

All six samples were mixed together and used for the feed for the ore-test. This feed was crushed to -16 mesh and then sized. The various size fractions were separated with potassium mercuric iodide, and the products examined microscopically. It was observed that the kyanite and quartz were almost completely free when crushed below 30 mesh, but that the rutile and ilmenite were not freed above 72 mesh.

Gravity concentration on a Wilfley table was tried but it was found that in order to obtain a suitable concentrate it would be necessary to have the feed very closely sized and the concentrate would have to be cleaned several times before it was up to grade.

It was then decided to try flotation. Taggart (1947, page 12/127) suggests using an acid wash followed by flotation by oleic acid with some gangue depressant such as sodium silicate. This was carried out and it was found that by floating with 3 lb. of

oleic acid and half a pound of sodium silicate per ton of ore after de-sliming, acid washing and then adjusting the pH to 6.5, it was possible to obtain concentrates containing less than 4 per cent of quartz. It was considered that although the acid washing was beneficial it would not be practical owing to the number of operations required to re-adjust the pH. In view of this a rougher cleaner operation using similar quantities of reagents was tried and gave similar results.

It was noted that although the flotation concentrates contained less than 4 per cent of quartz, they contained about 1 or 2 per cent of rutile and it would be necessary to clean this out. This was done with a Wilfley table but it is not considered to be suitable as even when a depressant such as Teepol is used some of the concentrate continues to float. This trouble however, might be overcome by using a dry method of gravity concentration such as pneumatic tabling; alternatively it might be possible to separate the kyanite and rutile by flotation.

It may be suggested that the following flow-sheet would be a suitable method of treating this material:—

1. Comminution to -50 mesh producing a minimum of fines. Probably rolls and a rod mill would be most suitable.
2. De-sliming.
3. Rougher flotation with oleic acid and sodium silicate, the tailings being discarded.
4. Cleaner flotation.
5. Drying.
6. Removal of rutile by pneumatic tabling.

It should be noted that the tests carried out are not conclusive and that further work is required both on batch and continuous testing scales before a flow-sheet is decided on. The samples used for these tests came from a very small portion of the deposit as it is now known to exist, so that in order to obtain a reliable result the methods indicated should be tried out on samples from newly-found ore-bodies to the east. This report only suggests a method by which this material might be separated but it is not implied that a quartz-kyanite schist with only 30 per cent of kyanite can be treated economically.

2. THE MUSURIAMBOI DEPOSIT

The following details have been extracted from a report by D. L. Searle and A. L. Stewart of the Mines and Geology Department of Kenya, dated May, 1952. The deposit was discovered by Searle while geologically mapping the area south-west of Sultan Hamud. No titles had been registered at the date this report was written.

The deposit is situated about 7 miles west of Selengai which lies 28 miles south-west of Sultan Hamud. Its latitude is $2^{\circ} 12' S.$ and its longitude $37^{\circ} 03' E.$ From Nairobi, Selengai can be reached by road from Kiu on the Nairobi-Mombasa railway (20 miles), and from Mombasa it can be reached by road from Emali (about 20 miles). The deposit can be reached from Selengai by going 4 miles along the Selengai-Namanga road and then proceeding 4 miles north-westwards through the bush towards Musuriamboi ridge which bears 320° magnetic from the deposit. The deposit is half-way from the road to the hill. The country is gently undulating with a few widely scattered small hills, on one of which kyanite schist is exposed on the northern slope. The bush is thin and it is easy to make a way through it in a vehicle.

One exposure of quartz granulite was found near the deposit, but owing to the general paucity of exposures in the vicinity the strip of country in which the schist lies was mapped as superficial deposits resting on undifferentiated Basement System rocks. The Musuriamboi ridge itself was mapped as granitoid gneiss. The lie of the

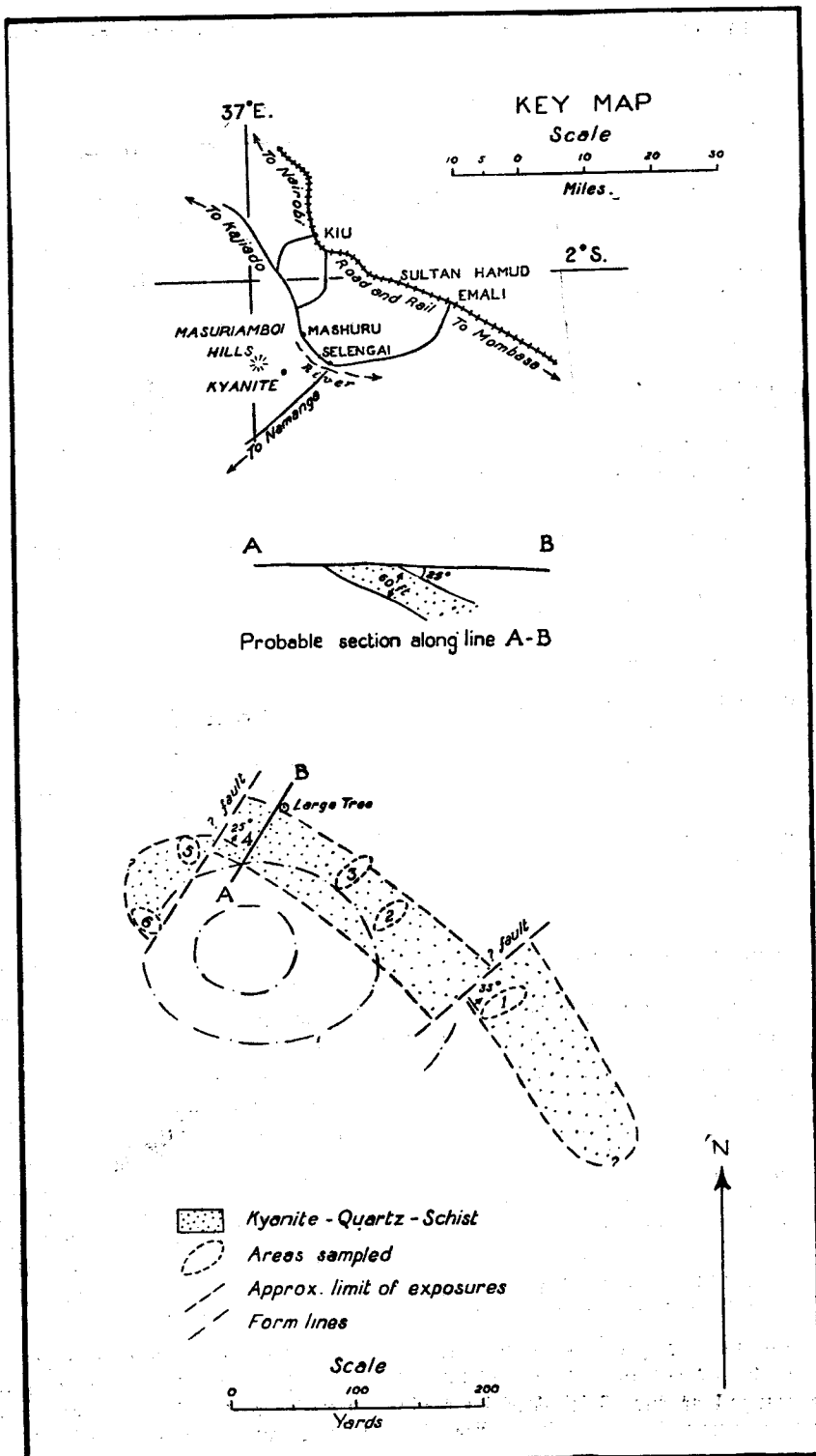


FIG. 12.—Plan of the Musuriamboi kyanite-quartz schist deposit. After D. L. Searle and A. L. Stewart.

outcrop of the kyanite-quartz schist is shown in fig. 12. Exposures suggest an outcrop 60 yds. wide and at least 400 yds. long, but owing to the large number of detached boulders lying on and about the outcrop, it is not possible to define its limits precisely. Observations at two exposures which appeared to be in place gave dips of 25° and 33° respectively. If the above measurements represent truly the size and attitude of the deposit then some 500,000 tons of schist are available by open-cast working without the removal of any overburden. About four times this tonnage would be available by open working before the ratio of overburden to schist reached unity. But before any of these estimates can be relied upon enough excavation must be done to confirm the validity of the measurements on which they are based.

Offsets of the strip of ground in which the exposures occur suggest that the schists are cut by two dip faults. The outcrop of the kyaniteiferous schist is unlikely to terminate abruptly at the ends, as the limits of the exposures suggest, but rather to wedge out gradually at distances which can only be determined by excavation.

Samples were taken from the six localities numbered, each being a grab sample of chips selected at random and making up 20 to 30 lb. each.

Heavy mineral separations (using potassium mercuric iodide $G'=2.9$) were made on the six samples after crushing to pass a 25-mesh screen. The heavy fractions were found to consist of kyanite with from 1 to 4 per cent of rutile, and the grains of these minerals were almost completely free from adhering quartz. About 1 per cent of ilmenite was present in the heavy fraction from two of the samples. The percentage of heavy minerals varied from 32 to 56 per cent with an average at 46 per cent.* This is a distinctly higher average than that found in the Murka-Loosito kyanite belt and is very much higher than the average kyanite content at Mubai. An analysis of the combined heavy fractions yielded the following figures:—

	<i>Per cent</i>							
Al_2O_3	..	..	..	..	..	..	..	58.16
Fe_2O_3	..	..	..	..	..	..	..	0.79
TiO_2	..	..	..	..	..	..	..	1.53

Anal.: W. P. Horne.

It was found that in each sample the rock chips varied considerably from one another in their kyanite content as judged by the naked eye, indicating that the variation from bed to bed within the formation at any one cross-section is greater than the variation in the formation as a whole along the exposed portion of the strike. In this respect, therefore, this kyanite-quartz schist formation is very similar to those of the Murka-Loosito and Mubai occurrences.

Thin slices were cut from six pieces of schist taken during sampling. They show a very considerable variation both in kyanite content and grain size. A field in one of these slices is illustrated in figure 13 (b), but must not be regarded as indicating the average texture of the schist. Another occurrence of very similar schist (specimen 59/217) was discovered by Searle on the northern flank of a knoll situated 2½ miles south of that just described.

Searle has reported a third occurrence of kyanite-quartz schist in the same quarter-degree area. This one is situated in Kasebe hill which lies 1 mile north-west of Mr. Cull's house at Mutini, and is shown on figure 17. This schist contains approximately 70 per cent of kyanite with blades measuring up to 2 in. in length. The schist has been seen only as float on the eastern side of the hill but there is every possibility that a narrow band up to 10 ft. in width dips into the hillside at this locality.

*Later work by P. Joubert, after extensive excavation by a Government prospector, suggests that the average kyanite content is about 14.5 per cent.

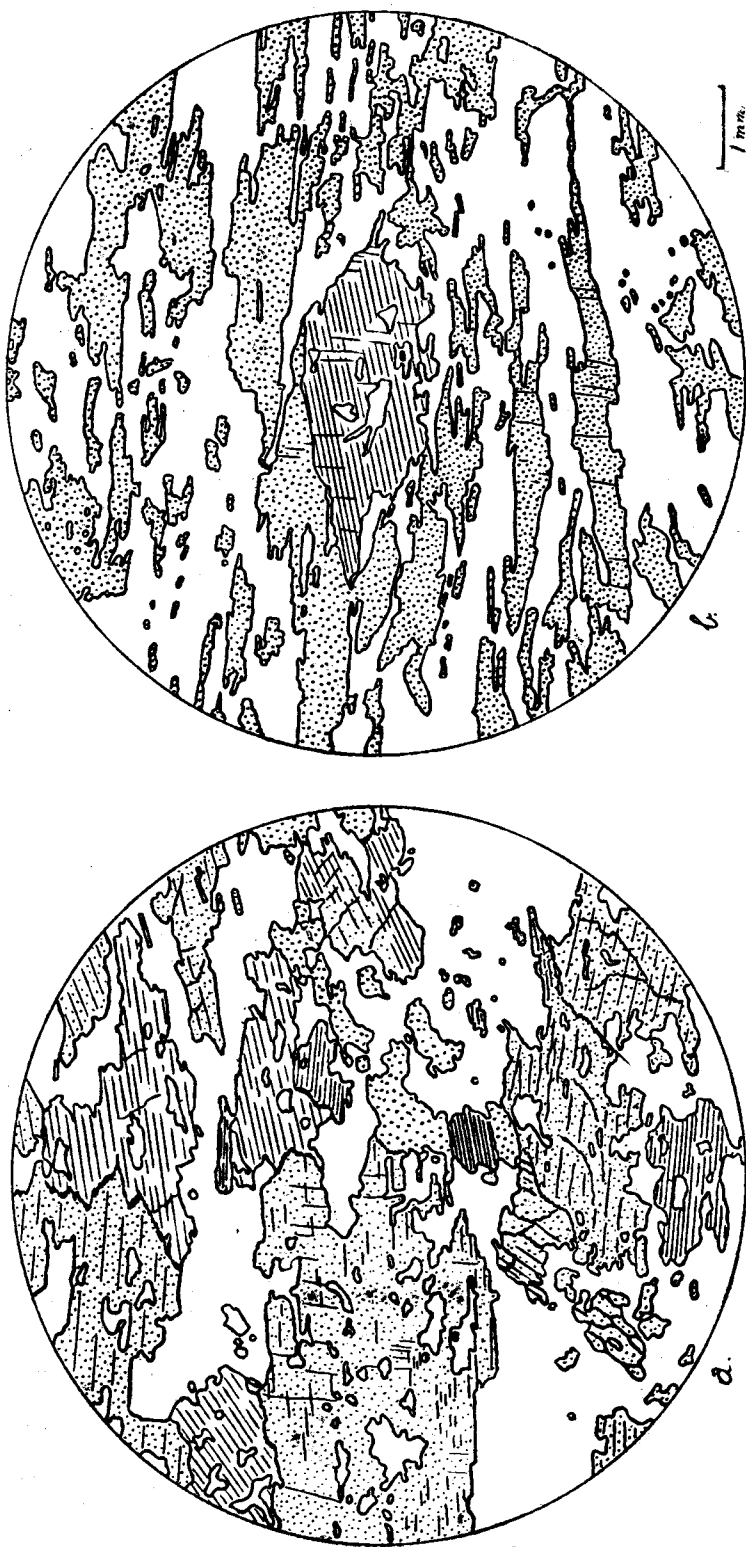


FIG. 13.—Micrographs of quartz-kyanite schists from: (a) Mubai; and (b) Musuriamboi.
 (Note.—The drawings do not portray average textural types, and must not be regarded as providing a comparison between the two deposits.)

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Anal.: W. P. Horne.

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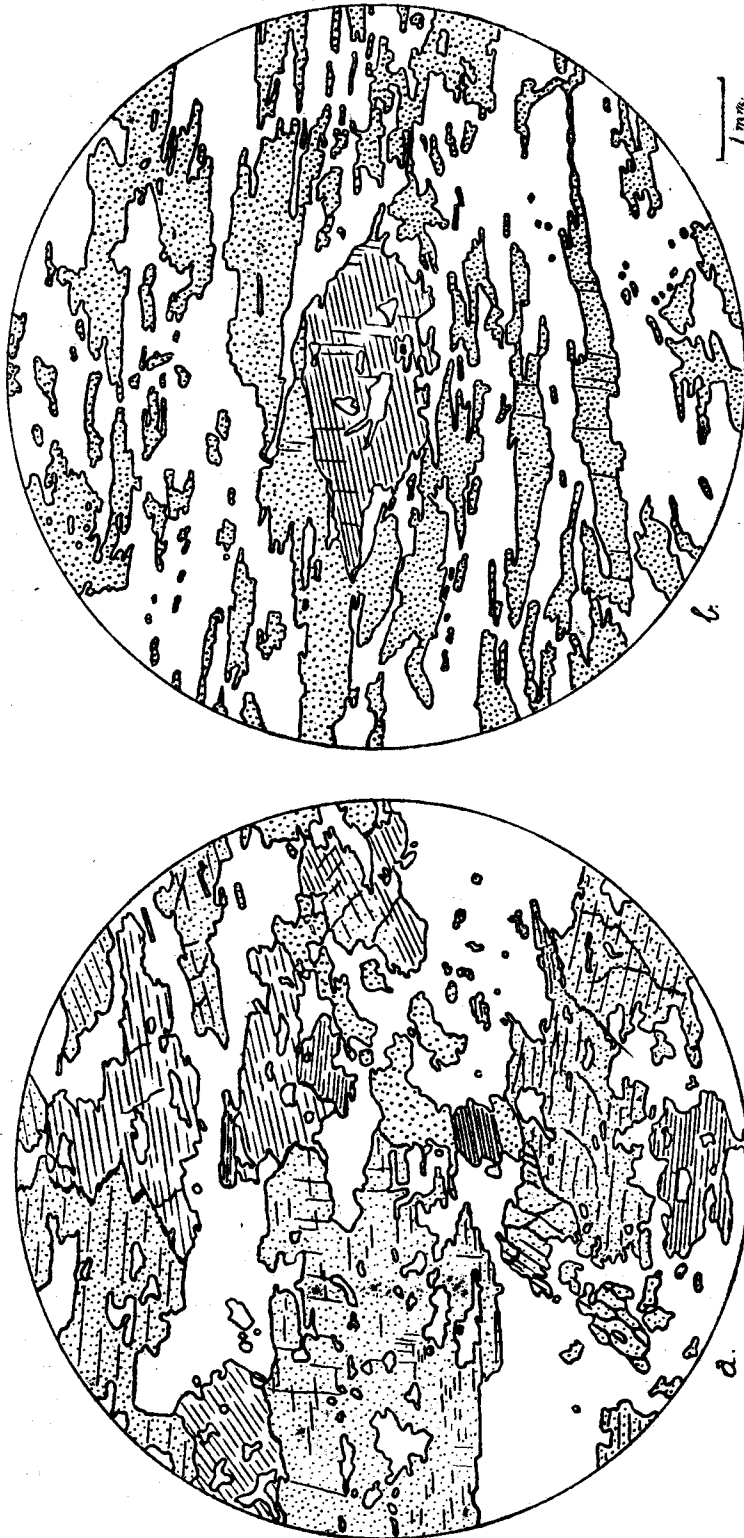


FIG. 13.—Micrographs of quartz-kyanite schists from: (a) Mubai; and (b) Musuriamboi.
 (Note.—The drawings do not portray average textural types, and must not be regarded as providing a comparison between the two deposits.)

A muscovite-kyanite-quartz schist which should perhaps be classified along with the kyanite-quartz schists, occurs in Kemioso ridge 6 miles south-west of Sultan Hamud. This occurrence was also found by Searle and is shown in fig. 17. He reports the following model analysis of the schist by volume.

	<i>Per cent</i>
Quartz	50.7
Muscovite	39.3
Kyanite	9.3
Rutile	0.7

VII—KYANITE IN KENYA—LONGALONGA-SIGNAL HILL AND THE TULIMANI-KYABALUKI KYANITE BELTS

1. GENERAL

The chief characteristic of the deposits described in this section is the occurrence of graphite, (a) as inclusions in the kyanite crystals themselves, and (b) as disseminations in both the kyanitic schists and in many other types of schist (fig. 14). The graphite in the kyanite crystals makes them appear to the naked eye either black and opaque, or dark blue and translucent. The graphite, which occurs in many types of schist, has such a darkening effect upon them than they have quite an abnormal appearance, so that care has to be exercised in identifying them in the field.

In the Tulimani-Kyabaluki kyanite belt and also at Soysambu (p. 61) the kyanite schists are closely associated with crystalline limestones; in the Longalonga belt the association is not so close though limestones occur in the series 2 or 3 miles from the kyanite, across the strike.

The kyanite crystals in these kyanite schists commonly reach a length of a quarter of an inch, while locally they may be as much as 2 in. long and half an inch thick. The kyanite often contains transparent inclusions as well as those of graphite which are opaque. Such inclusions have not been positively identified, but they have a refractive index and birefringence equal to those of quartz, though they are slightly purplish in colour and when elongated have inclined extinction. As their elongation may be related to the symmetry of the enclosing kyanite, and not their own, these inclusions probably are quartz. When abundant the transparent inclusions seem to contribute to the opacity of the kyanite, for some crystals remain dark even after the graphite has been decomposed by heating. Although some crystals are so densely packed with such inclusions as to be almost spongy there is no intergrowth of quartz and kyanite such as gives rise to the skeletal crystals so common in the kyanite-quartz schist of Murka, Mubai and Musuriamboi. When the graphitic kyanite crystals are heated to 1,100° C. in air much of the graphite is driven off by oxidation, the proportion depending on the size of the crystals. In the case of large crystals only the graphite at or near the surface is affected, but after grinding to -60+90 mesh, well over half the graphite is removed. With finer preliminary grinding almost all the included graphite is oxidized.

The kyanite-graphite schists consist mainly of quartz though variable proportions of plagioclase feldspar are also sometimes present. Accessory minerals are muscovite and, in the Longalonga belt, the chrome mica fuchsite. Occasionally garnet is present.

Up to the present the only serious attempt to work this type of kyanite has been at Longalonga where Kenya Kyanite Ltd. have tried to recover it from the soil at the foot of the hill. So far they have not produced any kyanite from this source, the difficulties being the low percentage of kyanite and the occurrence in the soil of limonitic and manganiferous concretions which have approximately the same specific gravity as kyanite and cannot therefore be successfully or cheaply separated from it. As the sources of massive kyanite become exhausted the possibility of recovering kyanite from these graphitic schists or their residual deposits will have to be further investigated.

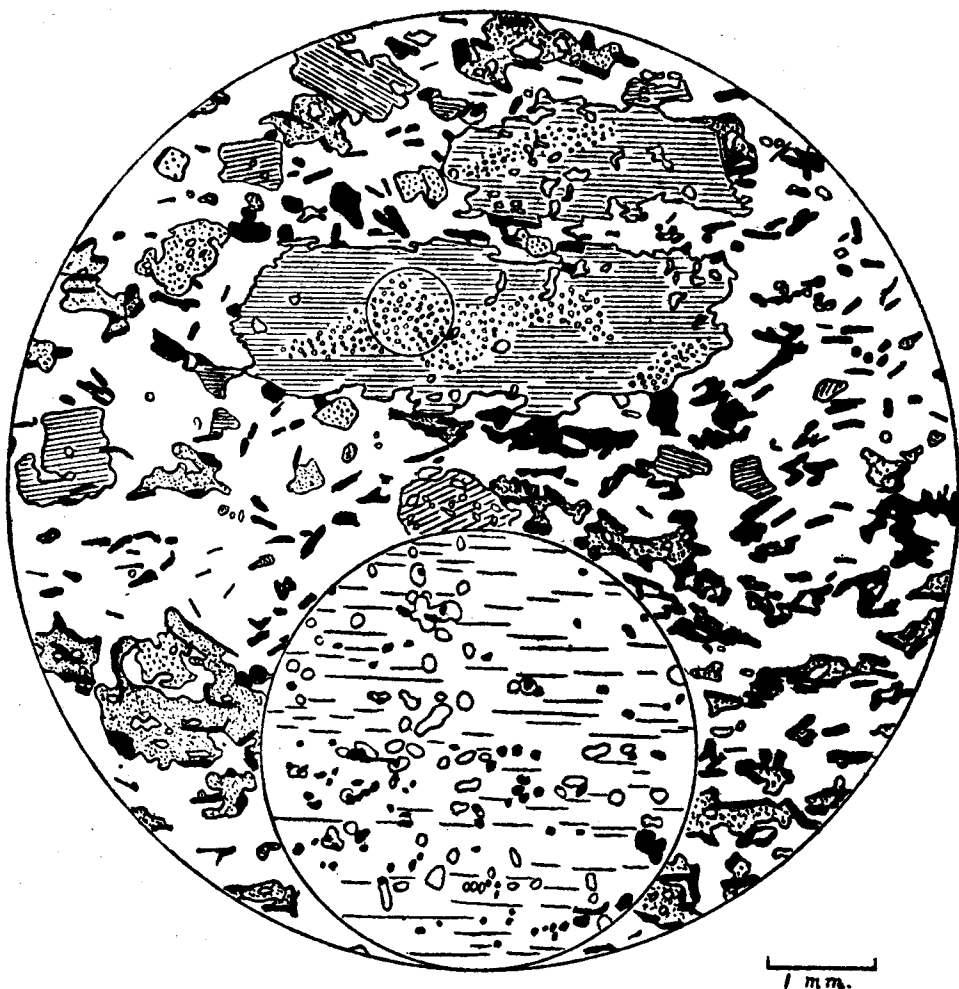


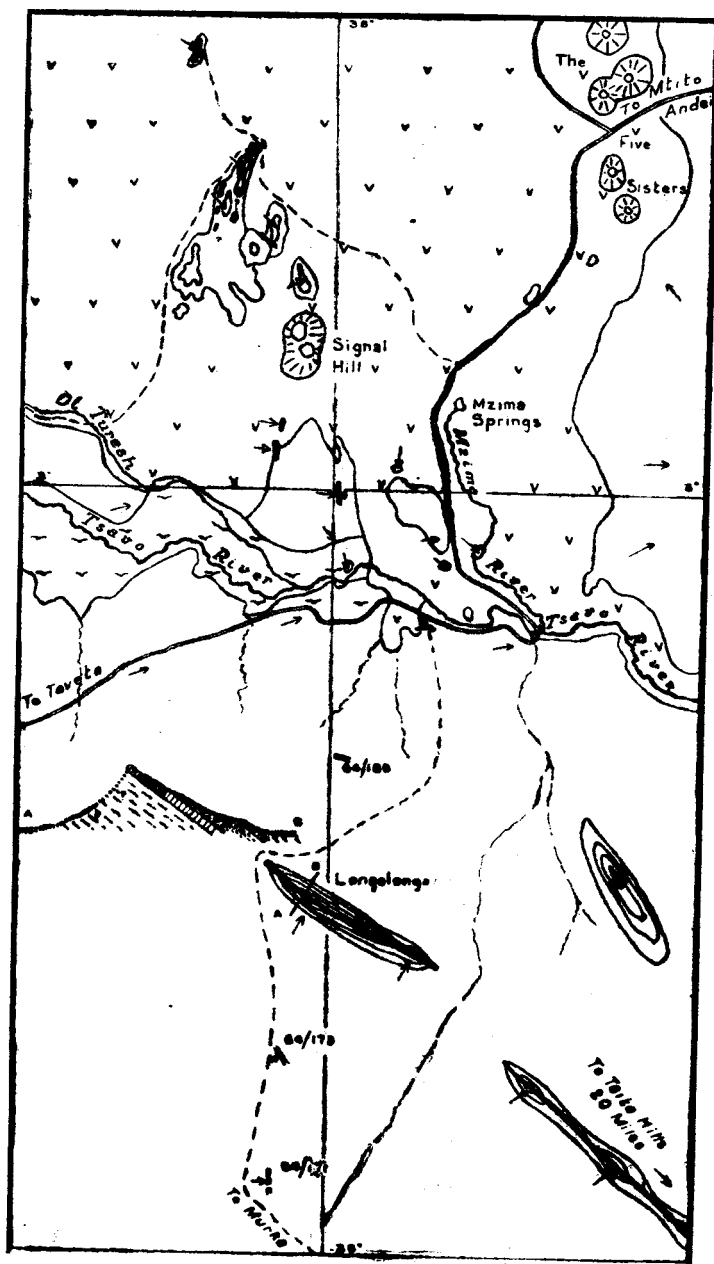
FIG. 14.—Micrograph of a graphitic-kyanite schist from Longalonga. Inset is part of a large kyanite crystal, more highly magnified showing graphite and quartz inclusions.

2. THE LONGALONGA-SIGNAL HILL GRAPHITIC KYANITE BELT

(1) *Situation and Extent of Belt*

This belt, which has been traced for a distance of about 12 miles, is most easily examined in Longalonga Hill on the 38th meridian of east longitude, $4\frac{1}{2}$ miles south of the Tsavo River (fig. 15). Longalonga can be reached by motor tracks both from Murka Hill to the south and from the Taveta-Mtito Andei road on the north, the northern track leaving the road $1\frac{1}{2}$ miles west of the Tsavo drift.

In a south-easterly direction the writer has followed the kyanitic schists as far as the south-eastern corner of the sketch map with a break in exposures between Longalonga and the next hill. The strike is directed towards the Taita Hills, which are distant about 20 miles and the appearance of a small dip and scarp hill on the line of strike, about half-way between Longalonga and the Taita Hills, suggests that the kyanitic schist may continue with a broken chain of exposures at least 10 miles in that direction.



KEY

- [V] Volcanic rocks and lake beds [hatched] Graphite-Kyanite schists
 [white box] Basement system [horizontal lines] Kyanite-Garnet rocks
 [dashed line] Silimanitic rock

Scale

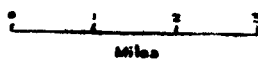


FIG. 15.—Sketch-map of part of the Longalanga-Signal Hill graphitic kyanite belt.

To the north-west there is a break in the exposures and the schist is not seen again till it appears striking north-south in three small hills, north of the Tsavo and between Signal Hill and that river. North of these exposures the Basement System is almost entirely obscured by lava flows, cinder cones and ash fields, but north-north-west of Signal Hill rocks of that system protrude through the volcanics in several parallel and arcuate ridges. Three of these ridges at least contain bands of similar kyanitic schist. Still further to the north-west, beyond the margin of the sketch map another chain of Basement System hills rise through the volcanic rocks that form the western base of the Chyulu range. These hills, which include Kalulu, Kathui Chande (or Soit Sambu) and Itolwe have been examined by the writer and do not contain any kyaniferous rocks.

South of the Tsavo River the rocks of this kyanite belt dip north-eastwards, while north of the river the dip is to the east.

(2) *Associated Rocks*

That part of the kyanite belt lying south of the Tsavo occurs within the area of Parkinson's (1947) reconnaissance map. According to this map the kyanitic schists extend along the axis of a N.W.-S.E. striking belt of argillaceous sedimentary rocks about 12 miles wide, which lies in a field of paragneisses. The belt includes crystalline limestones, kyanite schists, graphite schists containing both kyanite and graphite, muscovite and biotite schists including migmatites in the Taita Hills, garnet schists, pyroxene-garnet schists and quartz schists which are sometimes ferri-ferous, garnetiferous and kyanite-ferous. The belt also includes a series of epidote-hornblende schists with scapolite and garnet which Parkinson refers to as the "Volcanic Group", and, north-east of Maktau, an arenaceous facies which includes quartzites or quartz schists and types that have undergone penetration soaking. Parkinson suggests that these metamorphosed sedimentary rocks formed part of a gigantic roof pendant in a concealed granite batholith.

The country west of the 38th meridian and south of the third parallel which includes the western half of Longalunga, has recently been surveyed by L. M. Bear, geologist in the Mines and Geology Department, whose report is in preparation. The present writer has made a few reconnaissance traverses in the vicinity of Longalunga and east of the 38th meridian. Here the dominant rock type is muscovite-quartz schist which is occasionally kyanitic. South of Longalunga the series contains a band of crystalline limestone, a kyanite-garnet rock (64/173) and a quartz-felspathic rock containing sillimanite (64/171). North of Longalunga a kyanite-garnet-muscovite schist (64/186) and a hornblende pyroxenite (65/53) were found, and north of Signal Hill a black graphitic garnet-quartz granulite.

Longalunga itself consists of quartz schists which contain muscovite, or graphite, or, more commonly both (65/44). There is often fuchsite (chrome muscovite) in place of ordinary muscovite (65/42) and generally some albite, much decomposed, is present. Garnet (65/43) occurs in some beds and kyanite (65/35) in others. A characteristic feature of Longalunga is the abundance of wad. This mineral occurs as narrow veins and replacements* in many of the rocks (64/41) and gives rise to a shining black veneer (64/40) on exposures and float blocks. The anthills are black due to impregnation of the soil with wad.

Longalunga rises about 450 ft. above the immediately surrounding country and at its north-western end there are two formations of kyanitic schist which form salient features in the profile (see section on fig. 15). Both formations consist of kyanite-graphite-albite-quartz schist with accessory fuchsite. The beds between contain little or no kyanite and are more micaceous. Among them are some garnet-rich rocks and the

* Dr. Parsons queries whether some of the manganese oxide replacements may not lie along fault-lines.

beds impregnated with wad. It is not known what kind of rock underlies the main kyanitic formation and forms the scarp slope of the hill, as the rock in place is here obscured by blocks slipped from above. At the south-eastern end of the hill, however, pegmatite and quartz-mica schists occur among the talus on the scarp face.

(3) *The Kyanitic Schists*

The kyanite-graphite-albite-quartz schist formation that forms the crest of Longalunga is 50 to 60 ft. thick and massive, giving rise to a cliff. The porphyroblasts of kyanite are most conspicuous in two rather ill-defined beds, 3 ft. thick and 3 ft. apart, lying at about the middle horizon of this formation. The formation exposed near the base of the dip slope is about 30 ft. thick and consists of the same rock. The kyanite porphyroblasts are unevenly distributed within it. On the long ridge south-east of Longalunga kyanite porphyroblasts are not so abundant but they are conspicuous at a point 200 yds. beyond the second peak from the west traversing in a south-easterly direction.

In the small hills between Signal Hill and the Tsavo there are again two parallel formations of graphitic kyanite schist but they are thinner than at Longalunga. Two rock types were collected here, a kyanite-muscovite-graphite-quartz-felspar schist (65/25) and a kyanite-graphite-quartz-felspar schist (65/26).

North of Signal Hill the first group of ridges were visited only at their northern extremities. The same types of rock were found with the addition, at the end of the northern ridge, of a non-graphitic rock with large pale blue kyanite crystals. The most northerly ridge of all consists of the usual graphitic kyanite schist.

(4) *Colluvial and Alluvial Kyanite*

Colluvial kyanite occurs in the soil nearly all round Longalunga and is particularly conspicuous along the foot of the dip slope. In some places there is a thin sprinkling of loose kyanite crystals and other mineral fragments on the surface of the soil, deposited by sheet rain-wash from the slopes of the hill. The kyanite in this material makes up well over 50 per cent and, if there were enough, it would be workable. Unfortunately it is very thinly scattered, nowhere fully obscuring the soil surface. Most of this kyanite is in crystals which vary in length from one-eighth to a quarter of an inch.

The soil itself contains loose kyanite crystals. Kenya Kyanite Ltd., who, at the time of writing hold an Exclusive Prospecting Licence covering 21 square miles with Longalunga near its south-western corner, have investigated the possibility of recovering kyanite from the soil. They have sunk a number of pits in the soil near the south-eastern base of the hill. The kyanite content of the soil was found to be of the order of 1 per cent and the kyanite to be accompanied by granules of wad and concretions of manganiferous limonite which, having specific gravities very close to that of kyanite, could not be satisfactorily separated by simple gravity methods. Up to the present no kyanite has been produced from this source.

Some kyanite crystals picked from the soil surface were analysed with the following results:—

	Per cent
Al ₂ O ₃	55.54
Fe ₂ O ₃	0.32

Anal.: J. Furst

On traversing the sand-rivers east of Longalunga the writer noticed here and there patches of river sand containing well over 50 per cent kyanite, but on digging he found that these patches were mere veneers or laminae scarcely more than a few crystals deep, so that the volume of material present is negligible.

(5) *Prospecting*

The whole of this kyanite belt lies in the Tsavo National Park in which prospecting can only be done under licence obtainable from the Trustees of the Royal Kenya National Parks through the Commissioner of Mines and Geology. Prospecting is not easy owing to the distraction occasioned by rhinoceros, which are extremely abundant.

3. THE TULIMANI-KYABALUKI GRAPHITIC KYANITE BELT

(1) *Situation and Extent of Belt*

This belt passes through the village Kaani, which lies on the Thwaki River 7 miles east of Machakos (see inset map on fig. 16). The belt extends northward from Kaani, first following the Thwaki River and then passing east of Kyabaluki, a conspicuous isolated hill. North of this hill it has been traced by a prospector, who reports that it extends at least as far as Kangundu, a hill lying five miles north of Kyabaluki.

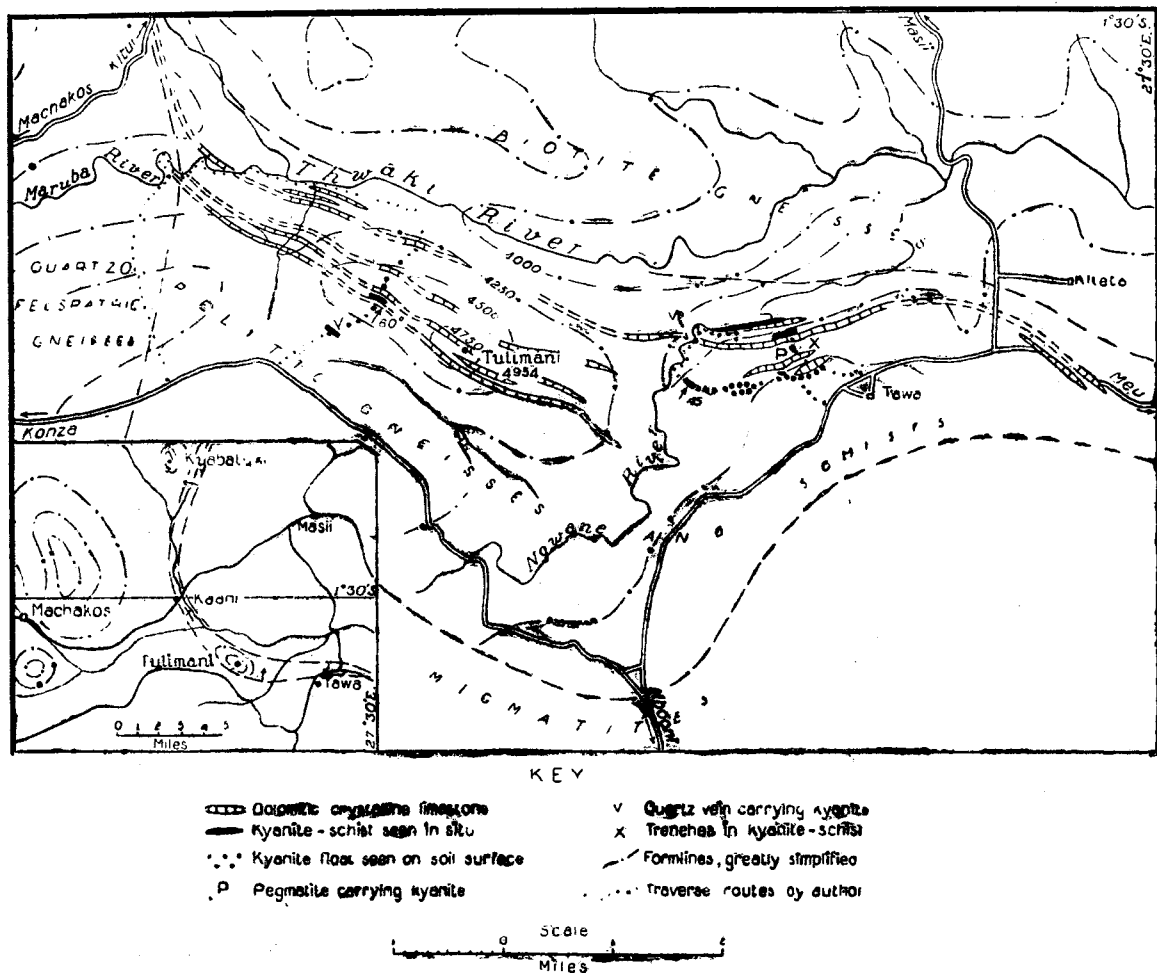


FIG. 16.—Sketch-map of the south-eastern part of the Tulimani-Kyabaluki kyanite belt.

In the opposite direction the kyanite belt swings to the south-east, and after crossing the Maruba River, a tributary of the Thwaki, it includes the conspicuous ridge Tulimani. It continues to curve eastward, crosses the Ngwane River and passes north of Tawa village. East of Tawa it rapidly thins out and is last seen crossing the road 2 miles east of that village. The distance from Kangundu to the end of the belt east of Tawa is 22 miles.

(2) *Associated Rocks*

The south-eastern part of the belt, from Kaani to beyond Tawa, lies in a quarter-degree square that has recently been surveyed by Mr. B. H. Baker, a geologist in the Mines and Geology Department of Kenya, though his report is not yet published. The northern part of the belt lies in an area that has not yet been geologically surveyed. The quarter-degree area east of Tawa, and into which the kyanite belt might be expected to extend, has been surveyed but no trace of the belt was found.

According to Baker the kyanite schists lie in a series which he has designated "Undifferentiated banded pelitic gneisses and schists". In the area which he has mapped this series is flanked on the north by biotite gneiss and on the south and south-west by migmatites and undifferentiated quartzo-felspathic gneisses respectively. The kyanitic schists are closely associated with a number of dolomitic crystalline limestones which run the whole length of the kyanite belt and lie close to the northern edge of the pelitic schist series. The limestones are flanked on the south by a band of plagioclase-amphibolite and hornblende.

In Tulimani the limestones and kyanitic schists form a belt about a mile wide and the rocks dip at about 30° to the north. North-westwards the dip steepens and the belt narrows until at the crossing of the Maruba River and near Kaani the rocks are vertical and the limestone-kyanite belt is only half a mile wide. From Kaani northwards the dips become gradually less and less steep but are directed to the west instead of the east as would be expected. The width of the belt also increases northwards corresponding to the reduction in the dip.

The writer paid a short visit to the area and made four traverses, two of which are shown in fig. 16, the other two being at Kaani and east of Kyabaluki respectively. The rock types encountered included the following:—

Dolomitic crystalline limestone; 52/444.

Dolomitic crystalline limestone, black with graphite; 52/443.

Actinolite-epidote schist (and other calc-silicate rocks); 52/431.

Talc schists; 52/440 and 445.

Quartzite, graphitic (grey, massive); 52/442.

Quartz schist, graphitic (grey, flaggy); 52/452.

Tremolite-quartz schist; 52/454.

Tremolite-quartz schist, graphitic (black); 52/447, 448, 453.

Biotite-quartz schist, graphitic (flaggy); 52/437.

Biotite-quartz-felspar granulite, graphitic, with accessory calcite (massive); 52/446, 450.

Muscovite-biotite schist, garnetiferous; 52/441.

Muscovite-albite schist (porphyroblastic albite); 52/438.

Kyanite rock with accessory ilmenite; 52/434.

Kyanite-graphite-quartz vein.

Kyanite-quartz vein; 52/436.

Kyanite pegmatite.

(3) *The Kyanitic Schists*

The kyanite schist occurrences in this belt are not encouraging. The kyanitic beds appear to be most numerous in the vicinities of Tawa and Tulimani. The writer found none in the Maruba River nor near Kaani, though his search was far from exhaustive. Near Kyabaluki one exposure was found near the left bank of the Thwaki River, at a point close to the position of the dip arrow on the map (fig.16). Tremolite is fairly abundant in the schists near the foot of Kyabaluki but kyanite was not seen there. A prospector has brought in large pieces of schist, rich in kyanite, from a locality between Kyabaluki and Kangundu but the writer did not find the occurrence.

Near Tawa a kyanite-schist is present, at least locally, along the high ridge between that village and the Ngwane River. Black graphitic kyanite crystals up to $1\frac{1}{2}$ in. in length were found lying on the soil at two localities though the quantity available is very small. An analysis of some of these crystals from the west end of the ridge is as follows:—

	Per cent
Al_2O_3	56.84
Fe_2O_3	0.75

Anal.: J. Furst

About two-thirds of the way down the western end of this ridge a bed of kyanitiferous mica schist at least 20 ft. thick is exposed in a donga, just above the point where it is crossed by a crystalline limestone. Here and there in the schist are lenticular masses a few inches thick consisting almost wholly of kyanite, but the exposures do not show what quantity of this material is likely to be available. The kyanite lenses contain an opaque mineral, probably ilmenite, disseminated among the kyanite crystals.

In the bed of the Ngwane River where it is flowing from west to east there runs a bed of kyanite-muscovite-quartz schist which is exposed in the river banks here and there. Traversing back towards Tawa from the S-bend in the Ngwane River kyanitiferous muscovite-albite schist was seen in a small gully. In all these schists the kyanite occurs as porphyroblasts. Prospecting pits have been dug on a bed of schist lying about three-quarters of a mile north-west of Tawa but the writer was not aware of their existence at the time of his visit and did not see them.

In the vicinity of Tulimani kyanite was seen only on the traverse closest to that hill. At the head of one of the streams the first exposure to be seen is a kyanitiferous schist while on the down-stream side of the first limestone band exposed in the gully there is a bed of garnetiferous kyanite schist. In neither bed is the kyanite either abundant or in large crystals.

(4) *Kyanite in Quartz Veins, Pegmatites and other Rocks*

An interesting feature of this belt is the occurrence of kyanite and graphite, two characteristic schist minerals, in quartz veins and pegmatites. In the northward-flowing part of the Ngwane River, west of Tawa, a loose boulder of vein quartz about a foot in diameter containing about 10 per cent of kyanite in blades up to 3 in. in length, was found in the river-bed. The kyanite was very pale green and entirely free from black or coloured inclusions.

A quartz vein about 2 ft. thick bearing small quantities of both kyanite and graphite was seen *in situ* near the head of a valley west of Tulimani. Quartz veins of about the same thickness are common in this schist belt but only at the single locality mentioned has kyanite been found in them.

Pegmatites are rare in the schist belt as compared with their occurrences in the felspathic gneisses on either hand. A piece of pegmatite float, seen in a gully north-west of Tawa, was found to contain a few large blue kyanite crystals.

Mr. B. H. Baker who has surveyed this area reported the occurrence of a number of boulders of kyanite-quartz rock on the top of Thathaeine Hill, half a mile north of Tawa village. He has also reported kyanite crystals about one cm. in length in contact with, or protruding from, a boulder of crystalline limestone on the eastern slope of Tulimani Hill.

VIII—KYANITE IN KENYA—OCCURRENCES IN THE VICINITY OF SULTAN HAMUD

1. GENERAL

Kyanite has been found at the following localities (fig. 17) in the general vicinity of Sultan Hamud, mainly through the prospecting activities of P. H. Cull, a resident of Sultan Hamud, and by D. L. Searle and B. H. Baker who have made geological surveys of the surrounding area. The localities are listed from north to south together with their distances from rail.

	<i>Miles</i>
Mubai, kyanite-quartz schist	20
Kiu station turn-off, crystals in soil	7
Kianini, crystals in felspathic mica schist	10
Kilimandui, crystals in felspathic mica schist	10
✓ Kioo, crystals in pegmatite	10
✓ Sultan Hamud borrow pit, crystals in soil and schist ..	2
Masembene, garnet-kyanite schist	10
Kemioso, crystals in muscovite-quartz schist	6
Emali summit, crystals in soil	3
Kasebe, kyanite-quartz schist	7
Mutini, crystals in schist	7
✓ Manone, crystals in felspathic schist	9
Soysambu, crystals on limestone	14
Musuriamboi north, kyanite-quartz schist	20
Musuriamboi south, kyanite-quartz schist	20

The occurrences at Mubai, Kemioso, Kasebe and the two near Musuriamboi, have been described in Chapter V of this memoir which deals with kyanite-quartz schists. The remaining ten occurrences are described in this section.

None of these ten occurrences has been adequately prospected, some of them being known only by a sprinkling of kyanite crystals on the surface of the soil; but it is probable that none of them is large enough by itself to be economically exploited. It is possible, however, that taken altogether they might yield enough kyanite to warrant the erection of jigs at the kyanite sites, and flotation and calcining plants at Sultan Hamud. Samples have been taken by the Mines and Geology Department from the Sultan Hamud borrow pit occurrence for beneficiation tests and if the results of these are promising this deposit will be opened up and others sampled.

2. ASSOCIATED ROCKS

Sultan Hamud lies about a mile south of latitude $2^{\circ} 00' S$. The country for a distance of 30 miles north of this latitude has been surveyed by B. H. Baker and that for the same distance south by D. L. Searle. The following notes on the associated rocks are taken from the maps of both geologists and from Mr. Searle's report.

Though the regional strike of the Basement System in this part of Kenya is north and south there is an area extending from Machakos to Sultan Hamud in which this regular strike direction is severely disturbed by the existence of domes of massive granitoid gneiss 3 or 4 miles in diameter, round which are deflected the more banded gneisses and schists. In the mountainous country north of Sultan Hamud it has been possible to map these domes and their enveloping banded rocks in some detail and it is seen that the group of kyanite occurrences at Kianini, Kilimandui and Kioo are all situated in a belt of meta-sedimentary schists and gneisses that are sweeping round the southern edge of a granitoid gneiss dome.

South of Sultan Hamud, where the country consists of inselbergs scattered about on a peneplain, and exposures are consequently more limited, the dome structure is not so clear. The strikes, however, are exceedingly curvilinear and the structure obviously highly disturbed. The inselbergs consist for the most part of bands of meta-sedimentary rocks including crystalline limestones, quartzites, muscovite quartzites and amphibolites together with their partly feldspathized representatives lying in a field of quartzo-feldspathic and granitoid gneiss.

3. DETAILS OF THE OCCURRENCES

(1) Kiu Station turn-off

This occurrence lies in the north-western angle formed by the roads at the turn-off to Kiu Station from the Nairobi-Mombasa road. It lies on the farm of Mr. R. Stanley. Baker reports that a sprinkling of kyanite crystals on the surface of the soil is all that is to be seen. The schist from which this kyanite is derived is apparently closely associated with a band of crystalline limestone. The writer did not visit this occurrence and no samples are available.

(2) Kianini

The kyanite-bearing beds occur on a steep hillside above the Kasikiu-Kilome road and can be approached by an old mica-miner's track which branches off that road up the hillside. The situation as indicated on the plan is not exact as the writer had no large-scale map on which to plot it at the time of his visit. He was guided to the occurrence by an African employed by Mr. P. H. Cull. The kyanite appears to be confined to a coarse-grained band in a biotite gneiss (52/459) which consists of biotite, quartz and feldspar. The kyanite crystals, which are up to $1\frac{1}{2}$ in. in length, are blue and transparent. Several small masses of the rock are to be seen protruding from the soil on the steep hillside and it is uncertain without excavation whether they are *in situ* or not. The total quantity of kyanitiferous rock to be seen amounts to a few hundredweight only but the occurrence may perhaps indicate the presence of a kyanitic horizon. Half an hour spent prospecting in the vicinity failed to reveal any further exposures.

(3) Kilimandui

This occurrence is a band of schist that crosses the neck of a spur running south-westwards from the hill Nduluni. It is easily accessible by a footpath from the Kasikiu-Kilome road at Wathini. The schist outcrop, which strikes east-west and dips 45° south, is exposed for about 100 yds., eastwards from an African hut on the neck of the spur. The schist, like that of Kianini, consists of biotite, quartz and feldspar, and the kyanite, which occurs in crystals up to $1\frac{1}{2}$ in. in length, is scattered unevenly throughout

a thickness of about 15 feet. The crystals that have weathered out and lie sprinkled over the exposure are clean internally apart from some quartz inclusions, but most of them have some quartz and biotite grains attached to their surfaces. An analysis of a few of the cleaner crystals picked from the surface (52/460) is as follows:—

	Per cent
Al ₂ O ₃	49.87
Fe ₂ O ₃	0.72

Anal.: J. Furst

Mr. Cull's African prospector had found no further exposures of kyanitiferous schist to the west, while to the east, between the spur and valley bottom, the same line of strike appears to be occupied by five bands of vermiculite schist. If trenching should prove a strike of kyanite schist several hundred yards long and a zone of friable rock beneath the soil several yards thick, then this occurrence might profitably yield a small tonnage of kyanite.

(4) *Kioo*

A kyanite-bearing pegmatite has been quarried on the northern slope of Kioo Hill just above the neck separating it from Nduluni. Besides kyanite the pegmatite contains vermiculite, garnet, tourmaline and pale green oligoclase. It is a very irregular body which in some places sends tongues and stringers into the country rock and in others displays a gradational contact. The contact-rock at most exposures is massive vermiculite, which grades through vermiculite-felspar rock into micaceous felspathic schist, but at others the contact is direct with schist. Some of the schists contain kyanite. The kyanite, which is irregularly distributed in the pegmatite, grows into well-developed crystals, the largest found being as much as a foot in length and several inches in thickness. Some hundredweight of these crystals have been sold to dealers in mineral specimens and recently several tons have been excavated for sale on the industrial market. This occurrence is covered by claims registered by P. H. Cull.

(5) *Sultan Hamud Borrow Pit*

This kyanite occurs in a large borrow pit on the north-eastern side of the Nairobi-Mombasa road at a point 2½ miles on the Nairobi side of Sultan Hamud. It lies on the farm of Mr. Thompson (now deceased) and was pegged by P. H. Cull in 1948, but the claims have since been abandoned. The occurrence was first described in May, 1948, by W. Pulfrey in an unpublished report, and later in February, 1950, by B. H. Baker.

Pulfrey stated that kyanite crystals up to half an inch in length occur abundantly in a matrix of murram which also contains in places abundant small ironstone balls. The murram is covered by quartz rubble and, on the north side of the pit, decomposed micaceous quartz schists lie underneath it. At the western corner of the pit, where the dip is about 5° to the north, Pulfrey recorded the following section:—

	ft. in.
Brown soil	6
Quartz rubble	2 0
Murram carrying kyanite and quartz veins (therefore representing decomposed rock) and decomposed layers of mica-schist	4 0
Band with many quarter-inch to half-inch ironstone balls	1 0
Quartz vein	2
Kyanite-rich rock (not bottomed)	6

Pulfrey concluded that the deposit was eluvial. The ironstone balls mentioned are weathered garnets.

Baker estimated 75 per cent of kyanite in a band of kyanite gneiss *in situ* at the north-western corner of the excavation and suggested that here there may have been some recrystallization due to the action of a pegmatite, which runs east-west a few feet to the north of the pit.

With regard to the size of the deposit Baker states that, walking round the low hill on which it occurs, it is difficult to say what the extent may be, but up to a distance of 150 yds. along the north side of the main road in the direction of Sultan Hamud there are many traces of kyanite float. A 4-ft. deep prospecting pit dug some 100 yds. north of the working shows murram soil without trace of kyanite. Any further exploration of the deposit will entail extensive trenching.

Recently Mr. Stewart of the Mines and Geology Department has taken bulk samples of the kyaniteiferous decomposed rock and soil at this occurrence for beneficiation tests.

It was found that by screening it was possible to obtain a concentrate containing quartz, kyanite and decomposed garnet, and that the kyanite could be separated from this concentrate by jigging. However, it was found that even an apparently clean concentrate only assayed 55.62 per cent Al_2O_3 and 0.36 per cent Fe_2O_3 (Anal. W. P. Horne). Hand-picked crystals previously taken by B. N. Temperley, assayed 53.96 per cent Al_2O_3 and 1.43 per cent Fe_2O_3 (Anal. J. Furst). When some of these crystals were examined in thin section under the microscope and it was observed that they contained inclusions of quartz, varying in size from 0.1 mm. to 0.01 mm., it was considered that it would be uneconomical to remove this quartz, and in view of this the deposit as a whole was considered uneconomical, and no further test work was done. [A.L.S.]

(6) *Musembeni*

A kyanite-garnet-mica schist was found by Searle near the summit on the south-west side of Musembene Hill which lies about 9 miles west of Sultan Hamud. The rock (specimen 59/215) is rich in greenish black biotite and contains large scattered crystals of porphyroblastic garnet and blades of greenish white kyanite. No details regarding the size of the occurrence are available.

(7) *Emali*

An occurrence of kyanite crystals on the surface of the soil near the summit of Emali, the high ridge south of Sultan Hamud, has been reported but no details are available.

(8) *Mutini*

Mr. P. H. Cull has reported the occurrence of a kyanitic schist close to his house on Mutini Hill. No details are yet available.

(9) *Manone*

This hill, which can be reached most easily from Emali, consists of biotite gneiss which is locally either kyaniteiferous or garnetiferous, or both (59/231). The kyanite is neither abundant nor evenly distributed and there appears to be no associated eluvial or colluvial material or any appreciable zone of disintegrated rock.

(10) *Soysambu*

Ten miles south-south-west of Sultan Hamud there is a group of five exposures of crystalline limestone which are about to be made the basis of a Portland cement

industry. The most easterly of these five exposures is the nearest to a conspicuous mountain called Soysambu and may be conveniently referred to as the Soysambu limestone (fig. 17). The exposure of the limestone is about 350 yds. by 140 yds. in extent, though it is not continuous throughout that area. Its surface is sprinkled with kyanite crystals up to half an inch in length which shows that the limestone is divided into several sheets interbedded with kyanitiferous schist.

The quantity of kyanite on the surface is small and it is most unlikely that the schist would be workable for its kyanite; but when the limestone comes to be quarried for cement the interbedded schist will have to be extracted at the same time and separated from the limestone. Under these circumstances it might pay to recover the kyanite.

An analysis of some crystals picked from the surface of the soil on this limestone is as follows:—

	Per cent
Al ₂ O ₃	56.67
Fe ₂ O ₃	0.29

Anal.: J. Furst

IX—KYANITE IN KENYA—OCCURRENCES IN SOUTH, CENTRAL AND WESTERN KENYA AND THE TAITA HILLS

1. OCCURRENCES SOUTH OF TUROKA

(1) Olobet

The following description was written in collaboration with A. L. Stewart who has visited the occurrence and is working on some samples from it.

It was discovered by S. J. Merrit and lies 27 miles south-south-east of Magadi and 36 miles north-west of Namanga, that is, at latitude 2° 15' S., longitude 36° 23' E. It is about 4 miles from the Tanganyika border near boundary pillar No. 37, and is most conveniently reached from Turoka station on the Magadi branch line. The route south from Turoka is first by a fuel lorry track which is followed for about 5 miles as far as a P.W.D. borehole (No. 875). At this point the track forks and the right branch is taken to a second borehole (No. 1523) about 15 miles further on. A disused track continues to Olobet, a hill (4,107 ft.) at the foot of which there used to be a native shop, but this track is overgrown and it is better to reach Olobet by driving southward through the bush for 8 miles and then south-westward for five. To reach the kyanite occurrence from Olobet it is necessary to go south-easterly (150°) for 3 miles, crossing the Turosei sand-river.

The kyanite schist occurs in a hill called Olesilwa which is elongated east-west and rises about 700 ft. above the surrounding country. The dip is low, about 10° eastwards, and the kyanitic schist occurs as slipped boulders almost all over the northern flank of the hill. The southern flank has not been explored. The length of strike indicated by the boulders is at least 700 yds., but nothing is known of the width of the bed *in situ* except that the largest boulders are at least 5 ft. thick. The kyanitiferous schist apparently underlies a thick quartzite which caps the hill.

The schist (58/195) consists of biotite, quartz, kyanite and a little feldspar and graphite. The kyanite occurs in crystals up to half an inch in length, clear blue and opaque black kyanite occurring both in the same rock and even in the same crystal. The kyanite appears to be fairly evenly distributed throughout the schist.

Two holes a foot or so in depth dug in the soil at the foot of the hill revealed an eluvial concentration carrying 5 to 10 per cent of kyanite.

Some grab samples of both schist and soil were taken and ore-dressing tests are in progress.

A prospector has reported the occurrence of similar schist at a point 4 miles east of Olesilwa Hill and local Africans state that still more occurs somewhere to the south-west.

(2) Luanji

This occurrence lies about 15 miles north-east of Olobet and 16 miles south of Turoka, and was found by P. Joubert of the Mines and Geology Department while mapping in that area. The following notes have been extracted from a report by this geologist. The kyanite occurrence is reached from Turoka by following the Olobet track as far as a point 6 miles south of the first borehole (No. C.875) and then turning eastward. The kyanite lies in the foothills to the north of Luanji, which rises about 1,000 ft. above the surrounding country.

The kyanitic schist occurs at the base of quartzitic horizons which are topographically prominent in this area. The quartzite is underlain by migmatites and schist, in places also kyanitiferous. There has been much repetition of the series by isoclinal folding, the quartzites forming small ridges north of Luanji beacon. The kyanite crystals increase in size and abundance both along the strike towards Luanji and across the strike to the south-west. The kyanite schist was traced in one horizon for a distance of over 1,000 ft., never exceeding 1 ft. in width.

The schist consists of kyanite, muscovite, biotite, feldspar and quartz and the kyanite crystals attain their maximum size just below the quartzite, where they are sometimes from 2 in. to 3 in. in length. The kyanite decreases rapidly in size as the rock becomes more pelitic but abundant small kyanite crystals occur in the pelitic types. The kyanite crystals in a representative specimen (58/190) are clear and transparent and free from opaque inclusions: they are colourless except for a median streak of pale blue which occurs in some of them.

Similar schists in the same stratigraphical position have been found for a distance of 10 miles south of Luanji and in Lositait Hill about 20 miles south-east of Luanji, as well as in the neighbourhood of the Ingito Hills. None of the schists examined, however, contain as much kyanite as that at Luanji.

North-east of Luanji, kyanite occurs with graphite close to crystalline limestones which are also repeated by isoclinal folding. In this association the development of kyanite has been very erratic and the crystals have remained small.

(3) Turoka River

Kyanite schist occurrences were found by Parkinson (1913, page 538) and lie somewhere in the vicinity of the workings of Kenya Marble Quarries, Ltd., which are situated a few miles above Turoka station, and were mentioned in chapter IV (page 11) of this memoir. They have not been relocated.

2. AN OCCURRENCE SOUTH OF NAROK

A. J. Stevens, formerly chemist with the Magadi Soda Company, and R. A. Wilkinson, one-time District Commissioner at Narok, made a *safari* in 1949 westward from Magadi up the Nguruman escarpment to the Narok-Oldeani road. At the top of the escarpment and on the right bank of the Bagasi River they located an occurrence of kyanitic schist. It lies about 15 miles east-south-east of Lemesikio where the Narok-Oldeani road crosses the Kenya-Tanganyika border. Its exact position is marked in red on a copy of air photo 82D.162/5142 in the possession of the Mines and Geology Department.

No information is available regarding the extent of the schist but to judge by the photograph it occurs in a well-defined ridge and may have a long strike,

A single specimen (50/19) is available which shows clear greenish kyanite crystals up to about 1 in. in length concentrated in the foliation or bedding planes in a quartz schist and accompanied by a rather abundant iron ore mineral which is probably ilmenite.

3. OCCURRENCES IN SUK

The early records of kyanite in Suk by J. Parkinson have been mentioned in chapter IV of this memoir. The areas in which they occur are being surveyed by the Mines and Geology Department at the time of writing but no reports on the kyanite are yet available.

4. OCCURRENCES IN THE TAITA HILLS

Parkinson found graphitic kyanite schist at the north-west corner of the Taita Hills. The locality is marked on his map (1947) of the Mtito Andei-Tsavo area near Mganga Camp which is named Mwameru on the topographical map, East Africa, 1:125,000, Voi. The schist is exposed in some trenches on the roadside a few hundred yards south-west of the drift over the Kishusi River. The rock is a garnetiferous kyanite-hornblende schist and is graphitic like the schists at Longalunga, which suggests that the Longalunga kyanitic horizon enters the Taita Hills in this neighbourhood.

Two other kyanite occurrences are known to the writer in the Taita Hills though they are not likely to be more than of academic interest. One is a kyanite-bearing pegmatite, float blocks of which occur in a small valley joining the Kishusi River about a mile up-stream from Mwameru. The locality is most easily reached from the road to the Makinyambu asbestos mines. The kyanite has a brilliant blue colour but is in thin blade-like crystals which are not readily extractable from the pegmatite. No kyanite schists were seen in the neighbourhood though an exhaustive search was not undertaken. The pegmatite blocks lie close to a conspicuous mass of tremolite-rock which occurs on the adjacent valley side.

The other kyanite occurrence lies on a col between two peaks somewhere in the hills 3 or 4 miles south-south-east of Mwameru. Its exact locality was not recorded as the writer had no map with him when he was taken to it by an African prospector working for Father J. Grennan of Voi. The rock, which is very poorly exposed, is a quartz-sillimanite rock carrying a good deal of kyanite and some accessory dumortierite (specimen 65/85).

X—MODES OF OCCURRENCE OF KYANITE IN GENERAL

1. GENERAL STATEMENT

The principal modes of occurrence of kyanite are as follows:—

- (1) Disseminated in schists in association with various assemblages of the minerals muscovite, staurolite, almandine, biotite, plagioclase and quartz.
- (2) Disseminated in quartzites, quartz schists and quartz-muscovite schists.
- (3) As kyanite-rock masses within kyanitiferous schists, the principal deposits of this kind occurring in the quartzose schists.
- (4) In pegmatites and quartz veins occurring concordantly within kyanitiferous schists, or discordantly either within or in the neighbourhood of kyanitiferous schists.
- (5) In high-alumina eclogites.
- (6) In injection gneisses.
- (7) As an alteration product of andalusite.
- (8) Residual boulders of kyanite rock and kyanite-quartz schist, and residual concentrations of kyanite crystals in the soil.

Most of the deposits of economic value are concentrations of kyanite in quartzites and quartz schist though in a few cases disseminations in both quartz schists and polymineralic schists are worked. Occurrences of kyanite in quartz veins and pegmatite are insignificant in size but are important with respect to the mode of origin of kyanite. As a general rule, though not without exceptions, kyanite concentrations are confined to quartzose schists, and kyanite-bearing pegmatites to the polymineralic schists. Kyanite-bearing quartz veins occur in association with both types of schist. In the account that follows concentrations, veins and pegmatites are considered under the head of the type of schist in which they occur. The modes of occurrence in eclogites, steatites and injection gneisses, and as replacements after andalusite, are of academic interest only.

In about half the number of kyanite deposits described granites either occur close at hand or in the general vicinity, and in most of such cases the authors attribute to the kyanite a magmatic origin. In a few cases the alumina of the kyanite is believed to have been derived from metamorphosed sediments but to have been concentrated to form kyanite rock through the agencies of magmatic solutions.

Residual deposits do not constitute a mode of occurrence fundamentally different from the others. All occurrences of residual boulders of kyanite rock or of kyanite crystals concentrated in soil or alluvium have been derived from some kind of schist or quartzite whether or not the outcrop of the source rock can be found. This mode of occurrence is not treated separately here and it suffices to say that in Kenya residual boulders of kyanite-quartz schist have been found as much as 2 miles distant from the outcrop of the parent rock.

2. DISSEMINATIONS IN POLYMINERALIC SCHISTS AND OCCURRENCES IN ASSOCIATED QUARTZ VEINS AND PEGMATITES, AND AS MASSIVE CONCENTRATIONS

The kyanite content in polymineralic schists varies from nil to practically 100 per cent. There is no data as to the average kyanite content but it appears that schists with over 15 per cent kyanite are rare and that rocks with higher percentages occur only as local patches and lenses within lower-grade rocks.* Up to the present very few deposits of this kind have been exploited. Segregations of kyanite rock in polymineralic rocks are extremely rare, unless the Indian kyanite deposits are placed in this category, and none have been found workable.

(1) *The Staurolite-Kyanite Subfacies*

The association of kyanite with various combinations of the minerals muscovite, staurolite, almandine, biotite, plagioclase and quartz is so common in schists in regionally metamorphosed areas that it has been given the status of the type assemblage of the staurolite-kyanite subfacies of the amphibolite facies in the facies classification of metamorphic rocks. The subfacies was originally named the staurolite-amphibolite subfacies (Eskola, 1939), but has more recently been referred to by Turner (1948) as the staurolite-kyanite subfacies. It is in general characteristic of rocks which have suffered medium- to high-grade regional metamorphism involving strong deformation under high pressure and shearing stress, and kyanite appears in the mineral assemblage when the alumina content of the original rock is high and the potash low. If the alumina is low then hornblende makes its appearance in the mineral assemblage and kyanite is absent while, if potash is high, microcline and epidote take the place of kyanite and plagioclase. In many cases of assemblages which contain kyanite, staurolite is absent. In the mapping of metamorphic zones the staurolite zone is often relatively narrow or wanting, from which it is concluded

* The kyanite gneisses and schists of the Styrian Koralpe are reported to include large reserves of rock containing 15 to 20 per cent of kyanite, with local developments containing up to 40 to 50 per cent (Anonymous, 1946).

that staurolite has a limited field of stability under regional metamorphism. Chemically staurolite and quartz are equivalent to almandine, kyanite and water so that almandine and kyanite often take the place of staurolite in rocks of this type.

The above facts make it clear that the paragenesis of kyanite in the staurolite-kyanite subfacies is well understood. The question of whether temperature, pressure, stress or chemical composition is the dominant factor in the development of kyanite is discussed in the chapter on the origin of kyanite.

Most pelitic schists belong to the low potash section of the staurolite-kyanite subfacies and carry kyanite where the alumina is high. Such pelitic schists are well represented among the Dalradian and Moinian of Scotland (Harker, 1950, page 224 and Read, 1931, pages 33, 40, etc.) and in the United States (Barth, 1936 and Billings, 1937). Kyanite in this association is common in the Basement System in Tanganyika (e.g. near Iringa, Mpwapwa, Idibo and Handeni) and in Kenya (e.g. south-west of Kisii, near Turoka, near Sultan Hamud and in the Marich Pass). Savage (1935) records two bands of kyanite gneiss a mile apart and some 10 miles long in the Kirk Mountains in southern Nyasaland. The country rocks are garnetiferous, felspathic and quartzitic gneisses with occasional epidotic and amphibolitic beds and concordant quartz and pegmatite veins. The kyanite is sometimes graphitic.

(2) *Exploited Deposits in the United States*

Up to the present few occurrences of kyanite of the staurolite-kyanite subfacies type have proved to be of economic value; this is due to the relatively small percentage in which kyanite is commonly present, and to the difficulty of separating it from the considerable variety of minerals with which it is associated. But as deposits of other kinds become exhausted and methods of separation become perfected more occurrences of this type will come under exploitation.

Examples of such polymineralic schists which have been, or are being, worked for kyanite are found in America. At Celo Mountain, North Carolina (Mattson, 1937), a band of gneiss is worked which contains approximately 15 per cent kyanite, 10 per cent garnet, 30 per cent mica and 40 per cent quartz, the remainder consisting of miscellaneous minerals of which 27 per cent are sulphides. Riddle and Forster (1949) mention two more occurrences of this type. At Cullen, Virginia, kyanite is recovered from a complex schist by equally complex, but highly efficient, modern mineral dressing methods; and near Clarkesville, Georgia, kyanite has been recovered from detrital accumulations and the weathered mantle of kyanite-mica schist.

(3) *Kyanite-bearing Quartz Veins and Pegmatites associated with Polymineralic Schists*

The occurrence of kyanite-bearing quartz veins and pegmatites in association with kyanite-bearing schist has been noted by many writers. Read (1933) has described kyanite-bearing quartz veins in a kyanite-chloritoid-muscovite-quartz schist in Unst, Shetland Islands. Quartz-kyanite rocks form veins up to several yards in thickness and vein-complexes with the country-rock. The kyanite in the veins forms rosettes, the crystals reaching a length of 2 in.; and the country rock in contact with the veins is enriched in kyanite. Read regards this occurrence as an example of "metamorphic differentiation" and in no way connected with igneous activity. He refers to Eskola's (1932) discussion of the principles of metamorphic differentiation and considers that the concentration of quartz and kyanite in Unst is governed by the concretion principle, the principle of enrichment in the stablest constituent and the solution principle. Read also refers to records by Heddle (1901) of kyanite-bearing quartz veins in nodules or "concretions" in kyanite-bearing country rocks in Scotland. Barrow (1893) had also noted that the most beautiful crystals of kyanite occur in quartz segregations.

Tilley (1935) described an occurrence of kyanite in quartz veins and as replacements of chistolite and cordierite in Ross-shire rocks which had suffered superimposition of regional on thermal metamorphism. Like Read he regarded the kyanite as derived from material segregated from the ground mass and therefore an example of origin by metamorphic differentiation.

Stuckey (1932), describing kyanite deposits in North Carolina, stated that the "pocket or bunchy" deposits are confined to quartz veins and pegmatite dykes which are associated with, and occur in, Archæan, Algonkian and Cambrian rocks. In the Carolina gneiss they consist of small lenses 3 to 8 ft. wide and 10 to 100 ft. long. In some lenses kyanite occurs in crystallized pegmatitic material consisting of quartz, orthoclase, albite and mica, in others it is associated with fine-grained pegmatitic material composed of granular quartz and feldspar and small sheets of mica, or in massive white vein quartz. The three varieties pass by gradations from one to another and, according to Stuckey, doubtless represent stages in pegmatite formation. Other minerals observed in the pegmatites and quartz veins were garnet, tourmaline, corundum, graphite and sericite. Stuckey believed that all types of kyanite occurrences in North Carolina were derived by replacement under the action of residual solutions from pegmatite and granitic magmas.

Taber (1935) noted kyanite in a quartz vein, cutting schist derived from argillaceous sediments in Virginia, and concluded that it was derived from an altered inclusion of wall-rock. Kyaniteiferous schists had been noted as the wall-rocks of veins elsewhere in the same area.

Noakes (1946) records the occurrence of concentrations of kyanite on the hanging-wall of quartz veins in the Strangways Range, Northern Territories, Australia. Kyanite-biotite schists occur in the same area.

Kyanite in a pegmatite cutting kyaniteiferous mica-schist was observed by Karpoff (1946) at a locality on the Algeria-French Equatorial Africa border and Heinrich (1950) has described a pegmatite in North Carolina carrying kyanite, staurolite and graphite, and cutting a rhodolite(garnet)-hypersthene-anthophyllite-biotite-sillimanite gneiss. Heinrich also mentions quartz veins carrying staurolite and kyanite in a staurolite-kyanite schist in Montana.

An occurrence of kyanite in quartz veins in the Ajmer-Merwara District of Rajputana has been described by Chhibber (1949). The veins cut biotite schists and Chhibber believes that the alumina of the kyanite was derived from the biotite schists as a result of igneous activity, while the silica was furnished by the quartz veins.

Kyanite, pseudomorphosing large andalusite crystals in pegmatite has recently been described from the Styrian Koralpe (Anonymous, 1946).

In Kenya, the writer has seen quartz veins carrying kyanite and graphite in an area which included kyanite-graphite schists and he has seen kyanite-bearing pegmatites at two localities in one of which kyaniteiferous schist occurred close at hand.

(4) *Massive Kyanite Concentrations in Polymineralic Schists*

Barrow (1893) noted that kyanite occurred in aggregated masses, sometimes as large as a man's head, in kyaniteiferous schists at Bulg in north-east Forfarshire. More recently Alderman (1942 and 1950) has described an occurrence of massive kyanite-quartz and sillimanite-quartz rocks in biotite schists, marbles and quartzites of Proterozoic age and low degree of metamorphism near Williamstown, South Australia. The aluminous rocks cut directly across the strike of the metamorphosed sediments and field evidence suggests that they were derived from them. The kyanite and sillimanite rocks show a rough zonal arrangement. At the centre is massive sillimanite-quartz rock with subordinate rutile and in some places a little kyanite. Round

this centre is an ill-defined zone of massive kyanite-quartz-(rutile) rocks. These pass outwards into red-stained biotite schists in which shimmer aggregates almost certainly represent former kyanite crystals.

The massive sillimanite-quartz rocks frequently contain small patches of quartz and kyanite and are cut by veins of kyanite or its alteration products. Some of the quartz-kyanite veins carry a little oligoclase and seem to be a link with normal pegmatites, which are abundant in the surrounding rocks. Some massive kyanite segregations occur directly in the biotite schist. Small corundum crystals are frequently associated with kyanite and its degradation products. Much of the kyanite has been converted into damourite and the sillimanite into clay.

Alderman considers that the kyanitiferous masses are segregations produced by metasomatic processes in which alumina-rich fluids played a leading part and that they were formed by replacement of the schist minerals during rising temperature. The kyanite disseminated in the schists was formed he believes by permeation, and that in the veins and pegmatites by precipitation during falling temperature. The sillimanite was formed from the kyanite when the temperature was at a maximum. At the time of writing his first paper Alderman believed that the aluminous solutions were magmatic, but in the second paper he regards them as derived from the surrounding metamorphosed sedimentary rocks. He attributes the special concentration of kyanite, quartz and rutile to the mobility of Si, Al and Ti (along with B, which appears in tourmaline in the pegmatites). The greater mobility is accounted for by the small ionic radii of these elements in comparison with those of Fe^{11} , Fe^{111} , Mg, Na, K and OH which are required in the formation of the feldspars and micas.

In contrast with the numerous occurrences of kyanite rock concentrations in silicious formations as described below, the two just referred to are the only cases of kyanite concentrations in biotite schists that the present writer has discovered in the literature available to him.

3. DISSEMINATIONS IN QUARTZOSE ROCKS AND ASSOCIATED MASSIVE KYANITE CONCENTRATIONS AND KYANITIFEROUS QUARTZ VEINS

In the majority of economic kyanite deposits the kyanite occurs either as disseminations or as concentrations in quartzites, quartz schists or quartz-muscovite schists. These rocks are sometimes associated with polymineralic schists. They do not grade laterally into polymineralic schists but into non-kyanitiferous quartzites and quartz schists. The kyanite content is extremely variable ranging from nil to almost 100 per cent, and the variation occurs both laterally and vertically. Concentrations of kyanite rock are much more common in quartzose rocks than in polymineralic schists. As in the case of the polymineralic schists, however, low percentages are much more prevalent than high, and the figures available suggest that the average value in formations large enough to be workable lies between 20 and 33 per cent. About half a dozen deposits of disseminated kyanite in quartzose rocks have been exploited and it is likely that more of this type will be developed in future. A large one in Kenya is under investigation at the present time. The origin of the disseminated kyanite in the quartzose rocks is uncertain, and is discussed in a later chapter. It will be noted that although series in which the kyanite-bearing rocks occur have often been described as aluminous, and that in several cases reference is made to the occurrence of polymineralic schists in the vicinity, the workable kyanite generally occurs in the more quartzose members of the series.

Among the described examples there are only three cases where kyanite in quartzose rocks is not accompanied by kyanite concentrations, viz. at Henry Knob, South Carolina and at Mubai and Musuriamboi, Kenya. The concentrations of kyanite generally take the form of masses of kyanite rock devoid of stratification and with crystals orientated

in every direction. In these concentrations there may be a certain amount of included quartz or muscovite which brings down the alumina content to about 55 per cent, but on the other hand, in some concentrations the kyanite contains so much disseminated corundum that the alumina content is raised to 68 per cent. The massive kyanite-rock concentrations are not surrounded by a zone depleted in kyanite; in general the schists appear to be richer in kyanite in the vicinity of the kyanite-rock concentrations. In most cases the kyanite-rock concentrations occur in kyanitiferous schists, but in the Indian and Uganda deposits described the enclosing schists are barren or almost barren of kyanite. In Uganda the kyanite occurs in concordant quartz veins so that the deposit is not quite comparable with other massive concentrations.

Pegmatites are not characteristic of kyanite deposits in quartzose rocks but quartz veins are closely associated with half the number of described deposits.

(1) *Exploited Deposits in India*

The Indian kyanite deposits are placed first on account of their importance, but there is in fact some doubt as to whether they should be included in this category. In a communication recently received from Dr. J. A. Dunn, who has worked extensively on the Indian kyanite deposits, he comments on the writer's classification. He maintains that there is a close connexion between occurrences in polyminerale schists and in quartzose rocks and that in his experience the large segregations of kyanite rock and kyanite-quartz rock normally occur in the polyminerale schists. He writes that although the quartzites and quartz schists are veined in places by kyanite and sometimes contain small segregations, the larger massive kyanite segregations (which range to kyanite-quartz rock) occur in adjacent mica schists.

The classification of the Indian deposits seems to hinge on the question whether the mica schists are polyminerale schists or quartzose rocks. In his original memoir Dunn states that the mica schists consist mainly of muscovite and quartz with subordinate felspar, and mentions staurolite and biotite as occurring abundantly only at certain localities. One should therefore perhaps conclude that the Indian deposits constitute a link between the polyminerale and quartzose types of occurrence.

In his 1929 memoir Dunn described the kyanite, sillimanite and corundum deposits in Northern India. Massive kyanite rock occurs at seven localities along a strike of 70 miles in the Singhbhum district and along a parallel strike of 8 miles in the Manbhum district, the two strikes being about 23 miles apart. The largest occurrence of kyanite rock is at Lapsa Buru at the western end of the Singhbhum belt where a reserve of 214,000 tons of surface boulders was estimated. At three other localities on this strike about 20,000, 10,000 and 8,000 tons respectively was estimated. In the Manbhum belt the kyanite rock contains much muscovite and the available tonnage is insignificant.

The country-rock throughout the Singhbhum kyanite belt consists of hornblende schist and mica (mainly muscovite) schist which belong to the Iron Ore Series. Most of the mica schist underlies the hornblende schists though there is much interdigitation of outcrops. The rocks are tightly folded and in some cases mica schists are folded into the hornblende schists, but in others there is interbedding. At Lapsa Buru the mica schist contains innumerable lenticles of hornblende schist. The hornblende schists are metamorphosed basaltic lavas and Dunn believed that the mica schists were metamorphosed clays, derived by the weathering of the lavas in Archæan times. Some of the clays consist of transported material deposited among the lavas but others were derived by weathering *in situ*. According to this view the hornblende schist lenticles in mica schist represent kernels of fresh dolerite in residual clay. The schists are mainly muscovite-quartz schists but they contain subordinate felspar. At two localities staurolite is very abundant in the schists, at another biotite is present. Kyanite is not a normal ingredient of the schists except close to the kyanite-bearing formations mentioned below, but at one locality coarse kyanite crystals occur with coarse quartz

in small concordant segregation veins. Rutile is almost everywhere present in the schist and topaz and tourmaline occur locally. Veins of fluorite were seen at one locality. At three places quartzites are associated with the schists and at another a magnetite-quartz schist occurs. At one point the country-rock is described as a muscovite-biotite-plagioclase-quartz schist. A quartz-garnet rock occurs there also.

Kyanite-quartz rock occurs at all localities where massive kyanite rock is found. This kyanite-quartz rock occurs as lenticular formations and grades into the surrounding schists. At two localities it merges into the quartzites already mentioned. The kyanite-quartz rock is variably massive or schistose. At one locality it is cleaved with muscovite developed on the cleavage planes; at another it is bedded due to variable amounts of quartz in different layers. Dunn gives chemical analyses of two specimens of kyanite-quartz rock, but they differ so greatly from one another that one cannot conclude anything as to the general composition of the rock. They indicate contents of 10 per cent and 89 per cent of kyanite respectively.

Kyanite-rock masses *in situ* in the Singhbhum belt always occur in the kyanite-quartz formations. They are generally grey, coarse-grained rocks which sometimes display a radial arrangement of long crystals, but at one locality the kyanite rock is unusually fine in grain and is faintly banded due to abundant rutile in certain layers. The alumina content of the kyanite rock in some cases reaches as much as 68 per cent which shows that corundum is present, included in the kyanite crystals. At one locality four types of kyanite rock are listed, viz. a dark grey variety containing corundum, a pink variety consisting mainly of corundum, a rose-coloured type containing dumortierite, and a type black with tourmaline. At one point staurolite, and at several others a green mica, probably euphyllite, occur in the kyanite rock.

The passage from kyanite rock to kyanite-quartz rock is through muscovite-kyanite rock at one place, through massive damourite (partly decomposed muscovite, superficially resembling talc) at another, and through chlorite-muscovite schist at a third. In the case of the damourite occurrence the cleavage of the schists bends round the kyanite-damourite mass. At one locality the muscovite-quartz schist contains lenticular bands of massive rock consisting of kyanite and muscovite. At another, masses of hornblende schist in the mica schist are bordered with a narrow irregular zone of kyanite rock from nil to 6 ft. in width.

At several places the kyanite rock is penetrated by veins and patches of coarse kyanite and by veins of quartz. At one locality the kyanite veins are 6 in. wide and the kyanite crystals are arranged across them with or without interstitial quartz. At another point kyanite rock passes laterally into topaz rock and topaz occurs as veins and patches in the kyanite rock. At still others tourmalinization and brecciation have taken place giving tourmaline-kyanite rock.

The kyanite belt runs parallel with the Rakha copper lode and at one locality only 150 yds. from the lode small vugs in a kyanite vein are lined with a copper-aluminum phosphate similar to torquiose.

In the Manbhum belt field relations are slightly different. The mica schists occur along the boundary of the Chota-Nagpur granite-gneiss, some of the kyanite occurring in schists, which are actually included in the granitic rock. Locally the schists are tourmalinized and quartz veins are very abundant. The schists are the same muscovite-quartz schists as in the Singhbhum belt but the kyanite-rock segregations occur directly within the muscovite-quartz schists without the intervention of kyanite-quartz rock as is characteristic of the main belt. The kyanite rock has the form of irregular masses up to 6 ft. in length. Their outer parts are schistose and Dunn suggests that much of the mica schists is derived from kyanite rock by crushing, with the addition of alkalis through the hydrothermal action of the adjacent granite. Nearly all the kyanite rock in this belt contains muscovite.

Concerning origins Dunn suggested in his 1929 memoir that the muscovite-quartz schists were metamorphosed pure white clays derived by the weathering of basalt in Archæan times, the clays having been in part residual and in part transported. The kyanite-quartz rock he described as a variant of the mica schists and referred to the kyanite rock as an ultimate form of the kyanite-quartz rock. He believed that segregation by "metamorphic migration" was only of secondary importance and that the kyanite-rock masses represented portions of the clay that were bauxitic. In a later memoir (1937), however, Dunn considers the possibility that concentration of alumina may have taken place at two stages in the geological history of the deposits. The occurrence of leaching during the Dalma volcanic period, throughout a zone of tuffs associated with the iron ore and kyanitiferous deposits, suggested to Dunn that the clays from which the kyanite deposits were derived might have had their alumina content increased by leaching out of other constituents. He also suggested that solutions from the adjacent soda-granite might not only have assisted in the segregation of kyanite but might have removed certain constituents, such as MgO and FeO, from the mica schists and thereby enriched them still further in alumina.

In the letter mentioned earlier Dr. Dunn states that not all the kyanite deposits in Bihar are directly associated with basic igneous rock and that only some of the lavas were subjected to contemporaneous Archæan decomposition. Many of the widespread mica schists, he writes, were tuffs, in addition to normal sediments. The aluminous character, he continues, may have been inherent in the original rocks; on the other hand, appreciating the great part played by solutions in the metamorphism of the rocks of Southern Bihar, he would not rule out the redistribution of alumina to form alumina-enriched zones of mica schist, followed by the segregation of kyanite under favourable metamorphic conditions.

Looking at the Singhbhum picture as a whole, writes Dunn, a clear-cut feature stands out: the distribution of the kyanite segregations, like the distribution of the copper and the apatite deposits, is related to the soda granite of the thrust belt, as is best shown on Plate I of Mem. Geol. Survey, India, vol. LXIX, part I. The solutions responsible for the segregation of kyanite from the alumina of the adjacent schists appear to be related to the soda granite.

(2) *Exploited Deposits in Quartzose Rocks in the United States*

Near Ogilby in California (Campbell and Wright, 1950) the Vitrefax series is described as dominantly pelitic and consisting chiefly of muscovite and quartz-muscovite schists with subordinate quartzites. The principal concentrations of kyanite are confined to the more quartzose portions of the formation, though a kyanite-quartz-muscovite-biotite-staurolite-garnet assemblage is known. In the concentrations the texture approaches decussate, and muscovite and magnetite in minor amounts accompany the dominant kyanite and quartz. Tourmaline and apatite are locally concentrated. The association of unusually large crystals of kyanite with vein quartz and the growth of crystals along fractures athwart the regional schistosity is regarded by Campbell and Wright as evidence of local hydrothermal concentration of kyanite. The series has not only been regionally metamorphosed but invaded by tonalite, adamellite and granite.

At Baker Mountain, Virginia, the Wissahickon formation comprises gneisses, schists and micaceous quartzites the chief constituents being oligoclase, biotite, muscovite, and quartz with varying amounts of garnet, staurolite and kyanite (Hubble, 1941). Kyanite ore found there is a quartzite "enclosed in schists" which "varies considerably from place to place, consisting now of masses of kyanite crystals, large and small, that almost hide the matrix and at others a compact white quartzite flecked with kyanite in smaller blades. Between the two extremes there are all gradations". The schists occur as an "island" surrounded by granodiorite. According to Riddle and Foster (1949) the quartzite averages 20 to 30 per cent kyanite.

In Johnston County, North Carolina, the bedrock of the region consists of acid schistose volcanics and slates of Algonkian age which have been strongly silicified (Stuckey, 1932). The kyanite occurs in a rock which ranges from almost pure quartzite to quartz-mica schist, and contains concordant veins and lenses of massive white quartz from a few inches to 5 or 6 ft. in width. "Kyanite associated with pyrophyllite occurs irregularly disseminated through these rocks in lens-like masses that vary from almost pure kyanite to barren rock. The kyanite crystals are light-grey to colourless, have a maximum length of 2 in., and lie in every position." Owing to the occurrence of kyanite in pegmatites and quartz veins cutting the kyanitiferous formations and for various other reasons Stuckey believed that the kyanite was deposited by replacement from residual solutions of magmatic origin.

At Henry Knob, South Carolina, the kyanite occurs disseminated in a Cambrian quartzite interbedded with chlorite-sericite schist (Smith and Newcome, 1951). The average kyanite content of the quartzite is 20 per cent though locally it varies from nil to 80 per cent. On account of the occurrence of kyanite in quartz veins, in seams along formational contacts, and as euhedral crystals lining vugs, as well as on account of pyrite being associated with the kyanite and for reasons connected with variations of grain size, Smith and Newcome attribute the origin of the kyanite to the introduction of aluminium. They give reasons for believing that the aluminium cannot be derived from the adjacent schist and conclude that it originated from the neighbouring Yorkville granite of late Carboniferous age, being introduced by hydrothermal solutions. The higher proportion of kyanite in the quartzite than in the adjacent schist was attributed to the greater permeability of the quartzite. Smith and Newcome refer to an occurrence of kyanite in quartz veins cutting kyanitic quartzite at Graves Mountain, Georgia, described by Pindle (1935) as further evidence of a hydrothermal origin.

Riddle and Foster (1949) refer to the occurrence of large and rich deposits in Lincoln County, Georgia, in which kyanite makes up 30 per cent of a quartzite.

(3) *Deposits in Western Australia, Uganda and Kenya*

At Yanmah in the Bridgetown area of Western Australia (Noakes, 1946, and communications from the Geological Survey of Western Australia and the Ministry of National Development, 1952) about 4,000 tons of kyanite has been won from residual boulders of kyanite rock, but production ceased in 1948. The mineral composition of the boulders was kyanite 90 per cent, limonite 4 per cent, rutile 3 per cent and other minerals which included corundum, kaolin, hornblende and zircon, 3 per cent. The chemical composition revealed 65.4 per cent alumina and 3.2 per cent titania: the high alumina indicated that the kyanite contained a considerable percentage of included corundum.

The residual boulders lay upon a series that includes kyanite-quartz schist, muscovite-kyanite schist and garnetiferous quartzite. Kyanite rock occurs in thin bands along the bedding planes in the kyanite-quartz schist. The kyanite bands range in thickness from a fraction of an inch to 6 in., and in places widen into segregations of massive kyanite. The report in Noakes' publication of a lens of kyanite rock 600 ft. long and 15 to 70 ft. wide has, however, proved to be erroneous. The most important beds of kyanite-quartz schist have a length of outcrop of 400 to 450 ft. and a width of 15 to 70 ft., with a steep dip. Lateritization is deep. The extraction of kyanite from the schists has not yet been undertaken.

In the Kamera Hills in south-west Uganda, Combe (1932, page 39 and briefly re-described 1946) reported a large development of kyanite, staurolite and garnet occurring at intervals in a belt of mica schists in contact with a granite. The most prominent occurrence of kyanite is in a schist composed of alternate laminæ of muscovite and of muscovite and quartz. The kyanite is either associated with irregular concordant quartz veins, in which it occurs as single blades entirely enveloped in

white quartz, or as coarse bladed aggregates which measure as much as 5 ft. in diameter. Exceptional specimens consisting of aggregates of blade-like crystals, in which single crystals 18 in. in length occurred, were collected. Kyanite was not observed to occur as an essential constituent of the mica schists themselves. Muscovite occurs with the kyanite as intergrown masses, and in crystallographic intergrowths with alternating paper-thicknesses of both minerals. In his later paper (1941) Combe considered that not more than 20 per cent by volume of kyanite was present and that probably its extraction would not be profitable.

The most prominent kyanite zone covers a width of 75 yds. and is situated within 200 yds. of the edge of a mass of granite, while further from the granite the schists contain chistolite. The field relations described suggest to the writer that temperature-pressure conditions characteristic of regional metamorphism had been locally superimposed on contact metamorphism, though all Combe writes on the matter of origin is that the formation and localization of the deposits seems to have been controlled by certain other conditions, in addition to the factor of the varying chemical composition of the indurated rocks. He does not suggest what the certain conditions were.

Other occurrences in Uganda are kyanite schists near Murchison Falls and garnetiferous kyanite-quartz schists associated with meta-calcareous rocks at Moroto (Uganda Geological Survey, *in litt.*). At the latter locality the thin kyanite schists are interbedded with marbles and amphibolitic schists, and the kyanite, occurring in blades up to 2 mm. long, is impure, containing numerous inclusions of the ground-mass.

In the Murka-Loosoito kyanite belt of Kenya the kyanite is apparently confined to quartz schists lying within a great thickness of dominantly felspathic schists and gneisses which are not kyaniteiferous. Masses of kyanite rock are certainly confined to the quartzose formations. Kyanite-quartz schists occur elsewhere in Kenya, e.g. at Mubai, but no kyanite rock concentrations have yet been found in them, and they all occur within series which are dominantly felspathic.

(4) Nyasaland

A deposit consisting of lenticular segregations of massive kyanite rock in kyanite-quartz gneiss, which is apparently very similar to those in the Murka-Loosoito kyanite belt of Kenya, occurs at Kapiridimba in the Kirk Mountains in the southern part of Nyasaland. Alexander (1938) calculated that there was probably about 12,000 tons of kyanite *in situ* per ten yards depth along a strike of three-quarters of a mile, and that there was about 3,500 tons of residual kyanite rock available. In 1939 Alexander reported that a South African mining firm had pegged claims on the deposit, but as nothing has been heard since about development it is presumed that remoteness of the deposit (36 miles of earth road, then 430 miles by rail to the port of Beira) has prevented its economic exploitation.

Two small hills rise 125 ft. and 50 ft. above the general level. A formation of kyanite-quartz gneiss dipping 40° to 70° runs along their crests, and both crests and upper slopes are strewn with boulders of kyanite-quartz gneiss and kyanite rock. The kyanite-quartz gneiss occurs in bodies that are lenticular in form and which appear to grade into quartzite when followed along the strike. They are intercalated in variable quartzitic and micaceous gneisses and schists which, in turn, grade into mesotype garnetiferous and hornblendic types.

The kyanite rock occurs in massive lenticular segregations, examples of which *in situ* up to 5 ft. in diameter were recorded, while one in boulder-form measured 12½ ft. by 6 ft. by 4½ ft. and was estimated to weigh 30 tons. The segregations appear to be arranged *en échelon* within the kyanite-quartz gneiss. The kyanite is pale to deep blue and occurs in radiating columnar aggregates of medium to coarse grain with blades up to a maximum length of 6 inches. The associated minerals are a little mica (damourite or muscovite) and, rarely, a little tourmaline. The greater part of the kyanite appears to be reasonably free from ferruginous impurities. Some mica-kyanite-quartz schist is present locally.

(5) *Bechuanaland*

An account of a newly discovered kyanite deposit in Bechuanaland had recently been given by W. A. Campbell (1951). It occurs about 9 miles south-east of Francistown in the Tati Concession in the north-eastern part of the Protectorate. It gives rise to a ridge called Halfway Kop, trending N.N.W.-S.S.E. and having a length of over 500 ft., and an altitude of about 65 ft. above the surrounding plain.

The spine of the ridge is formed of hard kyanite schists which grade on either side into quartz-kyanite schists that are flanked by chloritic schists. The general dip is 40°-60° to W.S.W. The kyanite-rich zone has a width of at least 5 ft., but tapers off to either end of the ridge though it is still present at plain level. Other occurrences of kyanite rocks both further north and further south indicate extensions of the horizon. The crest of the ridge is covered by large residual boulders of kyanite rock of shipping grade. Similar boulders occur in abundance under a cover of 3 ft. of soil on the surrounding plain, where they have been found as much as 500 yds. distant from the hill.

Three types of kyanite-bearing rock have been recognized:—

- (1) Massive kyanite rock consisting of radiate crystals of kyanite up to 3 in. in length, together with interstitial flakes and minute rosettes of pyrophyllite.
- (2) A limited development of a schistose variety with smaller kyanite crystals in a matrix of pyrophyllite, quartz and sericite.
- (3) A pale pinkish brown compact quartz-kyanite schist that generally flanks the massive kyanite rock, in bands up to 10 ft. or more in width. Kyanite blades and plates are scattered throughout the rock, and associated with minor amounts of sericite, dumortierite and rutile.

An analysis of the kyanite rock included the following:—

									Per cent
SiO ₂	..	..	..	..	..	..	..	..	35.45
Al ₂ O ₃	..	..	..	..	..	..	..	..	61.19
Fe ₂ O ₃	..	..	..	..	..	..	..	..	0.88
TiO ₂	..	..	..	..	..	..	..	..	1.12

Anal.: R. O. Roberts.

It will be seen that the Bechuanaland occurrence has a striking resemblance to the deposits of the Murka-Loosito belt in Kenya.

4. OCCURRENCES IN ECLOGITE, STEATITE, AND INJECTION GNEISSES, AND AS PSEUDOMORPHS AFTER ANDALUSITE

(1) *Kyanite in Eclogite*

Kyanite is an essential constituent of some eclogites and Tilley (1936) has shown that, when the alumina content of eclogites is greater than the amount that can be absorbed into the composition of the pyroxene and garnet, kyanite makes its appearance. Eclogites are characteristic of the deepest zones in the earth's crust of which the products are open to inspection, zones in which directional stress is believed to give place to high hydrostatic pressure. It therefore appears that while the crystallization of kyanite may be aided by stress this factor is not essential in its genesis.

Tilley (1937) has described an interesting occurrence of kyanite in an amphibolite at Glenelg, Scotland. The amphibolite was apparently derived from a non-kyaniferous eclogite by retrogressive metamorphism in which stress was an important factor. Although the unaltered eclogite was non-kyaniferous, kyanite developed in shear-

planes running through it. The kyanite amphibolite proved on analysis to be exceptionally aluminous and could not have been derived from the unaltered eclogite by isochemical change. Tilley therefore attributed the kyanite veins in the eclogite and the kyanite in the amphibolite to migration and local concentration of alumina derived from the eclogite during its retrogressive alteration. He refers to the known capacity of kyanite substance to migrate during stress metamorphism.

(2) *Kyanite in Steatite*

After describing some steatite occurrences in the neighbourhood of Choma Hill in the Kirk Mountains in the southern part of Nyasaland, Savage (1935), states that associated with the steatite and talcose belt in several parts of the area is a rock consisting of kyanite with amphibolitic, talcose and asbestiform minerals having a coarsely acicular and radiating texture, and that sometimes the rock consists of practically massive kyanite. No more details are given. This is the only reference that the present writer has found to the occurrence of kyanite in this association.

(3) *Kyanite in Injection Gneisses*

Du Rietz (1938) has found kyanite in injection gneisses in the Muruhatten region of Sweden. The injection gneisses were formed by the injection of granitic material into mica schists. The unaltered mica schists do not contain kyanite. The composition of the schists is not that of an extremely argillaceous sediment but of an almost saturated rock as compared with ordinary mica schists. The mica schists that carry kyanite are localized in the injected zone and the kyanite, according to Du Rietz, was formed by the combined action of stress and metasomatism, some alumina having been supplied by metasomatic-magmatic solutions.

Miss Wyckoff (1952, page 46) has described kyanite in granitized rocks of the Wissahickon schists near Philadelphia. She finds that in such rocks kyanite is more commonly needly than in the non-granitized schists, and considers that it may be a by-product of the granitizing process.

(4) *Kyanite after Andalusite*

The origin of kyanite by the alteration of andalusite has been described by a number of writers. One instance has already been cited, viz. in a hornfels in Ross-shire (Tilley, 1935, page 93). The kyanite in the Kamera Hills, Uganda, may also have been derived from andalusite (Combe, 1932, page 39). Another example, from Pennsylvania, has been described by Dike (1951). Here andalusite formed in quartz-sand lenses in shale of the Wissahickon formation by the action of diabase magma. Later regional metamorphism altered the andalusite to kyanite, which sometimes occurs as large nodules up to 60 lb. in weight.

Kyanite pseudomorphs after andalusite have also been described from the Koralpe, south-west of Graz in Southern Austria (Anonymous, 1946). They occur in pegmatites inter-layered in gneissic rocks, and in quartz-felspar two-mica gneisses and schists. In the pegmatites the kyanite is in densely entangled fine prisms and fibres, pseudomorphosing original andalusite crystals that were 20 cm. by 4 to 5 cm. in size. The kyanite is remarkably pure except at the surfaces of the pseudomorphs, where there is a dense coating of small muscovite flakes. The pegmatites are believed to have been locally enriched in alumina, the muscovite skins being attributed to deuteric hydrothermal action. The pseudomorphs in the gneisses and schists are large and similar to those in the pegmatites.

The occurrence of kyanite as pseudomorphs after andalusite in the Ross-shire hornfelds which show no signs of deformation, and the destruction of the kyanite further from the granite by stress metamorphism, suggest that when andalusite has already been formed kyanite may appear much sooner than when no aluminosilicate mineral is present.

XI—THE ORIGIN OF KYANITE

In this chapter it is convenient to divide kyanite rocks into the following classes, viz:—

- (a) Disseminations of kyanite in polymineralic schists.
- (b) Occurrences of kyanite in quartz veins and pegmatites.
- (c) Disseminations and massive concentrations of kyanite in quartzose rocks.

The origin of kyanite in eclogites, injection gneisses and as pseudomorphs after andalusite has already been discussed.

1. ORIGIN OF KYANITE DISSEMINATED IN POLYMINERALIC SCHIST

In the previous chapter it was explained that disseminations in polymineralic schists are commonly produced by the regional metamorphism of argillaceous sediments of a particular chemical composition. The principal question that remains to be discussed, so far as this mode of occurrence is concerned, is what factor in regional metamorphism is critical for the development of kyanite. The discussion of this subject by Turner (1948, page 81, and Turner and Verhoogen, 1951, page 452), already referred to, illustrated by triangular ACF, and AKF diagrams* suggests that the chemical factor is the most important; the sediment must be comparatively high in alumina and low in potash. Another consideration which lends support to this conclusion (also discussed by Turner, 1948, pages 36-38) is that studies of metamorphic zones shows that kyanite is not confined to a high grade of metamorphism; in other words, a definite temperature and clearly defined stress conditions are not as critical in the development of kyanite as is chemical composition. Turner refers to the following four papers of significance in this connexion. Sugi (1935) noted in Japan a complete absence of kyanite and staurolite although sillimanite was well developed in a zone of injection gneisses surrounding granite intrusions. Vogt (1927) mapped in Norway biotite, garnet and oligoclase zones and found that kyanite and staurolite were typically absent. In both these cases the absence of kyanite was attributed by the authors to the chemical composition of the sediments concerned, which were abnormally low in alumina. In two papers dealing with zoning in the eastern United States the range of kyanite is considerably wider than it is in the Dalradian of Scotland. Thus, Barth (1936) found in New York State that the biotite zone was followed by one in which almandine, staurolite and kyanite appeared simultaneously in rocks of appropriate composition. In New Hampshire, Chapman (1939) found that kyanite was present throughout the pelitic rocks of a "middle grade" zone characterized by garnet and staurolite.

The case of replacement of andalusite by kyanite studied by Tilley in Ross-shire (1935) suggests that, provided the chemical composition of a rock or mineral is exactly right, kyanite can develop at a very low grade of metamorphism where no sign of stress is to be seen. Alderman (1942) describes massive quartz-kyanite and quartz-sillimanite rocks near Williamstown in South Australia as occurring in biotite-zone schists and gneisses. If Alderman is correct this occurrence again indicates that grade of metamorphism is not a critical factor in the development of kyanite.

The occurrence of kyanite in eclogite has been shown by Tilley (1936) to depend on an excess of alumina over what can enter into the composition of pyroxene and garnet, while the presence of kyanite in a very deep-zone rock suggests that stress was an unimportant, if not negligible, factor. The association of cordierite, an anti-stress mineral, with kyanite in South Harris, Outer Hebrides, is considered by Davidson (1943) to indicate also that kyanite can be formed without the influence of high shearing stress.

* ACF diagrams = triangular plots with $A = \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 - (\text{Na}_2\text{O} + \text{K}_2\text{O})$; $C = \text{CaO}$; $F = \text{MgO} + \text{FeO} + \text{MnO}$ at the apices; AKF diagrams use $A = \text{Al}_2\text{O}_3 - (\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$; $K = \text{K}_2\text{O}$; $F = \text{FeO} + \text{MgO} + \text{MnO}$ at the apices.

The conclusion is therefore reached that in argillaceous sediments of the right composition (high alumina and low potash) kyanite can develop under a wide range of temperature, pressure and stress conditions. Provided the chemical composition is within certain limits stress does not appear to be a necessary factor in the crystallization of kyanite in a solid rock, though it cannot be denied that, as Harker (1950, page 151) contended, stress may extend the field of stability of kyanite and that, as Eskola (1939) maintains, shearing stress may have an important catalytic effect in facilitating low velocity reactions of which the crystallization of kyanite is probably one.

2. ORIGIN OF KYANITE IN QUARTZ VEINS AND PEGMATITES

The numerous occurrences of kyanite in quartz veins and pegmatites, cited in the previous chapter, show that under the circumstances in which these rocks are formed kyanite does crystallize from aqueous solutions, in which stress cannot operate. It is evident that where alumina is present in silica-saturated aqueous solutions it may crystallize as kyanite in quartz veins, and when it is present along with alkalis, and is in excess of the alkalis required to form feldspar, then kyanite may also appear in pegmatites.

The proximity of granites has led Stuckey (1932), Smith and Newcome (1951) and Pindle (1935) to believe that all the kyanite of the deposits they describe, both disseminated in schists and quartzites and occurring in veins and pegmatites, was of magmatic origin. Du Rietz (1938), who found kyanite in injection gneisses, considered the kyanite due, in part at least, to magmatic alumina, while Heinrich (1950) describing kyanite in pegmatites regarded this mineral as pyrogenic. On the other hand Dunn (1933), Chhibber (1949) and Karpoff (1949) believe that, though the pegmatites and veins are (or in some cases may be) of magmatic origin, the kyanite in them is derived from the alumina (sometimes already in the form of kyanite) of the wall-rocks or from adjacent aluminous formations. Alderman first considered that kyanite-quartz concentrations and kyaniteiferous veins and pegmatites were derived by the activity of aluminous solutions of magmatic origin (1944) but later (1950) also regarded the alumina as derived from the surrounding metamorphic rocks.

Read (1933) and Tilley (1935) believe that kyaniteiferous veins can develop by metamorphic differentiation without any form of magmatic activity.

Opinion, therefore, seems to be equally divided on whether the alumina of kyanite in veins and pegmatites is magmatic or derived from the adjacent schists.

The facts, first that kyanite is not a mineral characteristic of granites, and second, that kyanite is only found in veins and pegmatites in areas where disseminated kyanite is known to occur, appear in the writer's opinion to point clearly to the non-magmatic origin of kyanite in any form. There is much evidence that excess alumina can be moved about within schists and be extracted from schist and crystallized as kyanite in quartz veins and pegmatites. There is, on the other hand, nothing to suggest that the excess alumina is magmatic unless it be the occurrence of kyanite in injection gneisses described by Du Rietz (1938). But this is a single case and some other explanation may be possible. For instance the injected material may have been derived by the mobilization of feldspathized sediments of a highly aluminous type or the injected material may contain, still unabsorbed, the last remnants of a kyanite zone engulfed in its advance.

It seems clear with regard to pegmatites and quartz veins that, whatever their origin may be, the kyanite in them is probably derived from excess alumina in the wall-rock or in other rocks in the vicinity.

3. ORIGIN OF KYANITE DISSEMINATED AND CONCENTRATED IN QUARTZOSE ROCKS

(1) Preliminary Considerations

It is evident that the origin of kyanite both as disseminations and as concentrations in the quartzose rocks is much more uncertain than that of kyanite in the

previously discussed associations. All accounts of kyanite deposits show that there is a great variation in both disseminated and concentrated kyanite, laterally and vertically, in every kyanite-bearing formation. The main difficulty is to account for the variation. Variation in alumina content might be due to a number of causes, e.g.:—

- (a) Variation in the composition of the original sediment at the time of its deposition.
- (b) Non-uniform leaching out of non-aluminous material before regional metamorphism—
 - (i) by weathering in Archæan times;
 - (ii) by magmatic solutions.
- (c) Non-uniform metasomatic changes during regional metamorphism causing—
 - (i) introduction of alumina of magmatic or deep-seated origin;
 - (ii) redistribution of alumina derived from argillaceous rocks;
 - (iii) partial removal of non-aluminous material from aluminous sediments.

(2) *The Composition of the Sediment at the time of Deposition*

In spite of the fact that kyanite-quartz schists vary in kyanite content from nil to 100 per cent, any kyanite schist formation taken as a whole probably averages from 20 to 33 per cent kyanite. This conclusion is based on meagre data as follows:—

- (a) Murka-Loosito kyanite belt, Kenya. In the neighbourhood of concentrations schist beds vary from nil to 60 per cent kyanite with an average about 33 per cent.
- (b) Mubai kyanite-quartz schist. Where thick enough for exploitation samples well-distributed along the strike show variation from 27.0 to 31.2 per cent of kyanite.
- (c) Baker Mountain, Virginia. Riddle and Foster (1949) state that the kyanite content of the schist varies from 20 to 30 per cent.
- (d) Henry Knob, South Carolina. Smith and Newcome (1951) state that the kyanite content ranges from nil to 80 per cent, but averages about 20 per cent.
- (e) Lincoln County, Georgia. Riddle and Foster (*op. cit.*) give 30 per cent as the kyanite content of the kyanite-quartz schist.

Dunn believes that the variation in kyanite content is so great that an average value has no meaning and certainly, if any alumina has been introduced, or other constituents leached out of the formation as a whole, then the average is meaningless. If there has, however, been merely a redistribution of alumina within the formation then the average kyanite content might indicate the original alumina content of the sediment. In view of this possibility it is perhaps worth while considering what type of sediment would give, on isochemical metamorphism, a quartz-kyanite schist containing 20 to 33 per cent kyanite.

Tomkeieff's statistical study of clays (1933) is convenient for this purpose. He plotted the $H_2O:Al_2O_3:SiO_2$ ratios by weight of 689 clays on a triangular diagram and derived a chemical classification of clays based on their dominant constituent mineral, the types being divided from one another by convenient values of the molecular ratio $SiO_2:Al_2O_3$. This classification is incorporated in the diagram in figure 18. Tomkeieff found that clays with an $SiO_2:Al_2O_3$ molecular ratio greater than 5.5 were very rare. It will be seen from the figure that kyanite-quartz schists with 20 to 33 per cent kyanite have $SiO_2:Al_2O_3$ molecular ratios that vary from 12 to 6.5. One half of this range, viz. from 12 to 9, lies outside the range of clays while the other half corresponds to rare types of Fullers Earth.

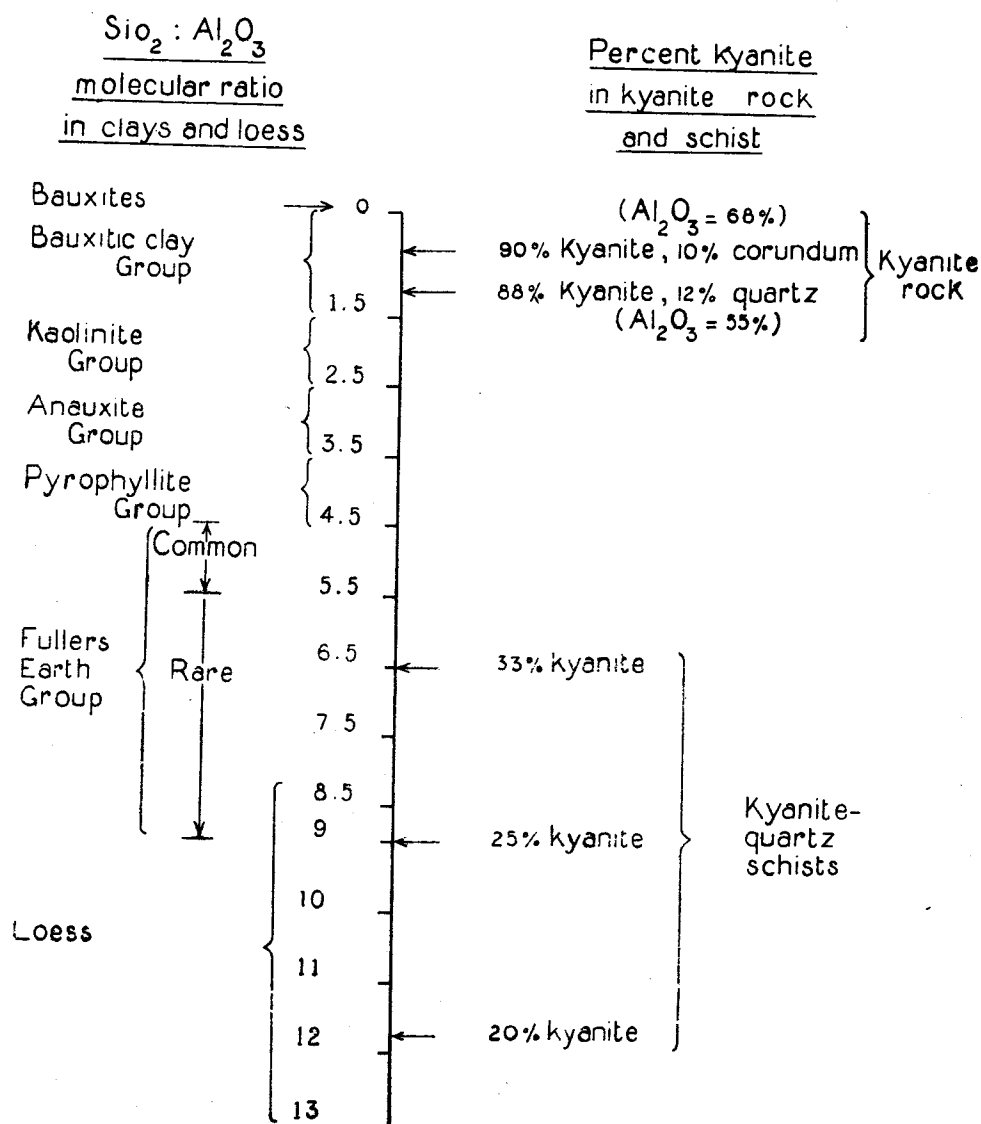


FIG. 18.—Diagram to show the equivalence of the kyanite content of quartz-schists and kyanite rock to the $\text{SiO}_2 : \text{Al}_2\text{O}_3$ molecular ratios of clays and loesses. Classification of clays after Tomkeieff.

If, therefore, the average kyanite content of a kyanite-quartz schist formation should indicate the chemical composition of an original sediment then that sediment was evidently not an ordinary clay. A search in Clarke's Data of Geochemistry (1924) shows that loesses have $\text{SiO}_2 : \text{Al}_2\text{O}_3$ molecular ratios varying from 8.5 to 13, and are thus equivalent to $\text{SiO}_2 : \text{Al}_2\text{O}_3$ ratio to the lower half of the kyanite-quartz schist range under consideration. In other words kyanite-quartz schists with average kyanite contents varying from 18 to 26 per cent might have been derived from loess without change in the $\text{SiO}_2 : \text{Al}_2\text{O}_3$ ratio, though most of the small amounts of basic oxides and alkalis that occur in loesses would have had to be removed.

The following analyses of loesses are quoted in an abridged form from Clarke (1924, page 514) only those constituents over 1.0 per cent being given.

	A	B	C	D	E	F	G
SiO ₂	64.61	72.68	60.69	74.46	67.10	69.27	60.97
Al ₂ O ₃	10.64	12.03	7.95	12.26	10.26	13.51	15.67
Fe ₂ O ₃	2.61	3.53	2.61	3.25	2.52	3.74	5.22
MgO	3.69	1.11	4.56	1.12	1.24	1.09	1.60
CaO	5.41	1.59	8.96	1.69	5.88	2.99	2.77
Na ₂ O	1.35	1.68	1.17	1.43	1.42	1.70	0.97
K ₂ O	2.06	2.13	1.08	1.83	2.68	31.4	2.28
H ₂ O	2.05	2.50	1.14	2.70	5.09	4.19	9.83
CO ₂	6.31	0.39	9.63	0.49	3.67	Tr	0.31

Twenhofel (1932) has suggested that loesses may be found more extensively in the geological column than previously suspected, particularly in the pre-Cambrian and early Palæozoic when there was no protecting land vegetation.

If the kyanite-quartz schists were originally loesses or water-laid, wind-blown silts and if the pure quartz schists into which they often grade, or with which they are often associated, were derived from cherts, then the climatic conditions under which they were deposited were probably similar to those in the Magadi area of Kenya in the middle Pleistocene when lake silts alternating with cherts were deposited.

(3) *Changes in Composition before Regional Metamorphism*

In his first memoir Dunn (1929) suggests that the kyanitic rocks were formed from aluminous clays derived by the weathering of basic volcanics in Archæan times. In his second memoir (1937) he suggests that the clays from which the kyanite deposits were derived might have had their alumina proportion increased by the leaching out of other constituents by solutions of magmatic origin. In a letter recently received he writes that although some lavas in Singhbhum were subjected to contemporaneous Archæan decomposition, it is not asserted that this was the origin of widespread mica schists. Many of the schists were formerly tuffs, in addition to normal sediments. Apart from the associated beds of quartzite and quartz schist, he writes, the zone in which the kyanite deposits occur was one of aluminous schists. The aluminous character may have been inherent in the original rocks; but on the other hand, appreciating the widespread part played by solutions in metamorphism in the rocks of Southern Bihar, he would not rule out the redistribution of alumina to form alumina-enriched zones of mica schists, followed by the segregation of kyanite under favourable metamorphic conditions.

Thus Dunn seems now inclined to give at least as much weight to redistribution of alumina during metamorphism as to leaching in pre-metamorphic times. As the opportunity for the differential migration of rock constituents is so great during regional metamorphism it is much more probable that this is the principal cause of the rapid variation in alumina content than some weathering or leaching process that may or may not have occurred in an earlier period.

(4) *Changes in Composition during Regional Metamorphism*

The introduction of alumina unaccompanied by alkalis either from a magmatic source, or as "emanations" from depth, is not a recognized geological process. Moreover, many kyanite deposits appear to be independent of any granite from which alumina might have been derived. The redistribution of alumina already present, however, by the agency of magmatic solutions is a different matter.

If the alumina is not magmatic or juvenile then it must be derived from argillaceous material and its erratic distribution in the kyanitiferous formations must be due either to—

- (a) redistribution of the alumina present in the original siliceous sediment;
- (b) non-uniform introduction of alumina into the siliceous sediment from adjacent aluminous sediments;
- (c) non-uniform removal of silica from an aluminous schist.

So far as the development of the kyanite-rock concentrations is concerned there is little doubt that redistribution of alumina within the siliceous sediments has taken place. It is true that the concentrations are not surrounded by zones deficient in kyanite, but if migration has occurred freely through considerable thickness of rock the development of a deficiency zone is not an essential concomitant of this process.

Which of the three processes stated above was dominant in producing the variation in alumina content within the kyanite-quartz schist formations is uncertain. The kyanitic quartzose schists generally contain so little alkalis and basic oxides that from whatever parent rock they were formed, except perhaps chert, those radicles must have been removed. It is therefore not impossible that quantities of silica might also have been removed at the same time and that the variation in silica content might be due to the process failing to reach completion. There seems to be no way of either ruling out or establishing the importance of this process.

The choice evidently lies between processes (a) and (b) above. Either the siliceous rocks were loesses in which original small variations in alumina content have been accentuated by some process included under the general term metamorphic differentiation, or the rocks were pure sandstone or cherts into which alumina migrated from adjacent aluminous sediments during metamorphism. As the kyanite-quartz schists occasionally grade laterally into quartzites free from kyanite it seems rather more probable that all the alumina has been introduced from aluminous rocks in the series. If the alumina had been introduced into sandstones or quartzites during regional metamorphism the great variation in kyanite content might perhaps find a reasonable explanation in variations from bed to bed in the porosity of the original sediment.

This is admittedly a most indefinite and unsatisfactory conclusion but until more is known of the variations in chemical composition within the schists little more can be said.

The origin of kyanite should not in fact be discussed without far more reference to sillimanite, a mineral to which the writer has not paid adequate attention. In the letter referred to above Dunn writes as follows on this subject:—

“In discussing the kyanite deposits, the sillimanite deposits must not be ignored. They differ in their relationships only in the type of metamorphism. Again the associated quartzites grading to sillimanite-quartz schists are comparable with the beds of quartzite grading to kyanite-quartz schists commonly found in the vicinity of kyanite deposits . . . It is of interest to bear in mind that massive corundum may be associated with the sillimanite deposits, but apparently not with kyanite (where corundum is only associated as a disseminated mineral). The rocks associated with the sillimanite deposits, particularly in Assam, are identical with the khondalites, even to the associated charnockitic or hypersthene-bearing types. What the exact metamorphic conditions are which form on the one hand kyanite deposits, and on the other sillimanite, remain problematical; to my mind the degree of dryness (influence of water) of the metamorphic conditions is a likely factor.”

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APPENDIX 1

Specification for kyanite purchased by the United States Government for the national stockpile

MATERIAL PURCHASE SPECIFICATION—KYANITE

1. DESCRIPTION

This specification covers lump kyanite and kyanite fines of a quality suitable for the manufacture of mullite refractories. It also covers mullite produced from any suitable raw material.

2. QUALITY REQUIREMENTS

(a) *Kyanite*

(1) *Chemical analysis*.—Each lot of lump kyanite or kyanite fines shall meet the following chemical analysis requirements:—

						<i>Per cent by Weight (Dry Basis)</i>
Al ₂ O ₃	..	..	..	..	..	Minimum 59.00
SiO ₂	..	..	..	..	..	Maximum 39.00
Fe ₂ O ₃	..	..	..	..	..	Maximum 0.75
CaO + MgO + K ₂ O + Na ₂ O	..	..	..	..	..	Maximum 1.00

(2) *Pyrometric cone equivalent test*.—Each lot shall exhibit a pyrometric cone equivalent value of 37 or better as determined according to A.S.T.M. procedure C-24-42 with tentative revisions of 1944.

(3) *Physical requirements*.—Each lot of lump kyanite shall contain, as loaded into railroad cars in the United States, not more than 10 per cent by weight passing a one-half inch screen.

Each lot of kyanite fines shall contain, as loaded into railroad cars in the United States, not more than 60 per cent by weight passing a 16 mesh U.S. standard screen and not more than 5 per cent by weight shall be retained on a one-half inch screen.

A sample from each lot shall, after being calcined, crushed and screened, exhibit not more than 60 per cent passing a 16 mesh U.S. standard screen and not more than 20 per cent passing a 100 mesh U.S. standard screen. The grains of the grog shall be strong (not chalky) and suitable for the manufacture of refractory brick and large shapes.

(b) *Mullite*

(1) *Chemical analysis*.—Mullite shall contain not less than 59 per cent Al₂O₃, in the calcined condition, and shall have a ratio of Al₂O₃:SiO₂ of not less than 1.57.

(2) *Physical requirements*.—Mullite shall be delivered in the calcined but uncrushed condition. A sample from each lot shall, after crushing and screening, exhibit not more than 60 per cent passing a 16 mesh U.S. standard screen and not more than 20 per cent passing a 100 mesh U.S. standard screen.

APPENDIX 2

MELTING POINTS AND INVERSION TEMPERATURES OF SOME REFRACTORY MINERALS

Sege Cone	TEMP.	Melting Point	Inversion Point
	°C.		
	2800	magnesia	
	2050	corundum	
42	2000		
41	1960		
40	1920		
39	1880	forsterite	
38	1850		
37	1825		1810 mullite
36	1790	quartz	
35	1770	kaolin	
34	1750		
33	1730		
32	1710		
31	1690		
30	1670		
29	1650		
28	1630		
27	1610	rutile	
26	1580		
20	1530	anorthite	sillimanite
19	1520		
18	1500	common glass	
17	1480		
16	1460		
15	1435		
14	1410		
13	1380	muscovite	andalusite
12	1350		
11	1320		
10	1300		
9	1280		
8	1250		kyanite, dumortierite
6	1200	alkali felspars	

APPENDIX 3
WORLD PRODUCTION OF KYANITE
(in tons)

Year			Kenya	India	Australia	U.S.A.
1935	..	..	—	20,000*	—	†
1938	..	..	—	22,385	20	†
1940	..	..	—	10,270‡	—	4,000*
1944	..	..	612	13,099	—	†
1945	..	..	444	13,497	—	†
1946	..	..	2,631	14,487	140	†
1947	..	..	14,447	14,351	2,931	†
1948	..	..	14,600	12,605	1,125	†
1949	..	..	23,263	12,824	—	†
1950	..	..	11,469	35,488‡	—	†
1951	..	..	10,639	42,301‡	—	†

*Figures from W. R. Jones' *Minerals in Industry*, 1943,

†Figures not available.

‡Figures supplied by the Geological Survey of India.