GEORGIA
STATE DIVISION OF CONSERVATION

DEPARTMENT OF MINES, MINING AND GEOLOGY
GARLAND PEYTON, Director

THE GEOLOGICAL SURVEY
Bulletin Number 68

THE GEOLOGY AND MINERALOGY OF GRAVES MOUNTAIN, GEORGIA

by

Vernon J. Hurst

ATLANTA
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LETTER OF TRANSMITTAL

Department of Mines, Mining and Geology

Atlanta, December 1, 1959

His Excellency, S. Ernest Vandiver
Governor of Georgia and
Commissioner Ex-Officio
State Division of Conservation
Atlanta, Ga.

Dear Governor Vandiver:

I have the honor to submit herewith Georgia Geological Survey Bulletin No. 68, "The Geology and Mineralogy of Graves Mountain, Georgia," by Dr. Vernon J. Hurst, Geologist and Chief Mineralogist on the staff of the Survey.

The year 1959 marks the 100th anniversary of the publishing of a paper by the late Prof. Charles U. Shepard, inviting attention to the unusual variety of interesting minerals to be found at Graves Mountain in western Lincoln County, Georgia.

The finest specimens of rutile on exhibition in many of the famous private and museum mineral collections all over the world were collected at Graves Mountain and supplied by the late Dr. George F. Kunz while he was president of Tiffany and Company. In like manner, specimens of lazulite as fine as any found in this country were collected at this locality.

This publication and the accompanying geologic map constitute the first detailed report upon the geology and mineral deposits of Graves Mountain to be made available to the public generally and to geologists, mineralogists and mineral collectors in particular. It will make possible economic appraisal which very probably may result in the launching of one or more new mineral industrial enterprises.

This treatise will serve to illustrate the trend of new thought among geologists concerning the value of detailed geologic mapping as a means of locating and delimiting valuable mineral deposits.

Very respectfully yours,

Garland Peyton

Director

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THE GEOLOGY AND MINERALOGY OF GRAVES MOUNTAIN, GEORGIA

INTRODUCTION

Scope of Study

Graves Mountain has long been famous as a mineral collector's locality. For more than a century its unusually fine crystals of rutile and lazulite have attracted collectors from all parts of the world. Though still of interest primarily to collectors, some of its minerals might be in deposits of sufficient extent and grade to be economically mined.

This report deals with the geology of Graves Mountain, including the character and areal distribution of its mineral deposits. Information is provided with which to appraise preliminarily the economic potentialities of the mountain and to plan an efficient prospecting program.

This report also makes available to collectors for the first time an accurate map showing where the minerals can be found, along with brief descriptions of the 13 minerals well-known from this locality, and 5 others not previously reported.

Most of the rock-forming minerals at Graves Mountain are phases in the alumina-silica-water system; all are phases in the potash+soda-alumina-silica-water system. From published P-T-X data on these systems, physical conditions are deduced under which the mineral assemblages might have originated.

Previous Studies

In 1859 Shepard described hematite, quartz, pyrophyllite, kyanite, rutile, lazulite, barite, pyrite and sulphur from Graves Mountain. Following his paper, mineral specimens from this locality were eagerly sought by German mineralogists, who published the results of several crystallographic studies during the period 1860-1897 (Haidinger, 1860; Rose, 1862; Lasaulx, 1883; Rath, 1881; Mugge 1884, 1886, 1897).

Between 1912 and 1921 Watson published three papers, and in 1935 Johnston published a 5-page summary. An account of a trip to the mountain plus descriptive excerpts from earlier papers was published by Zodac in 1939.

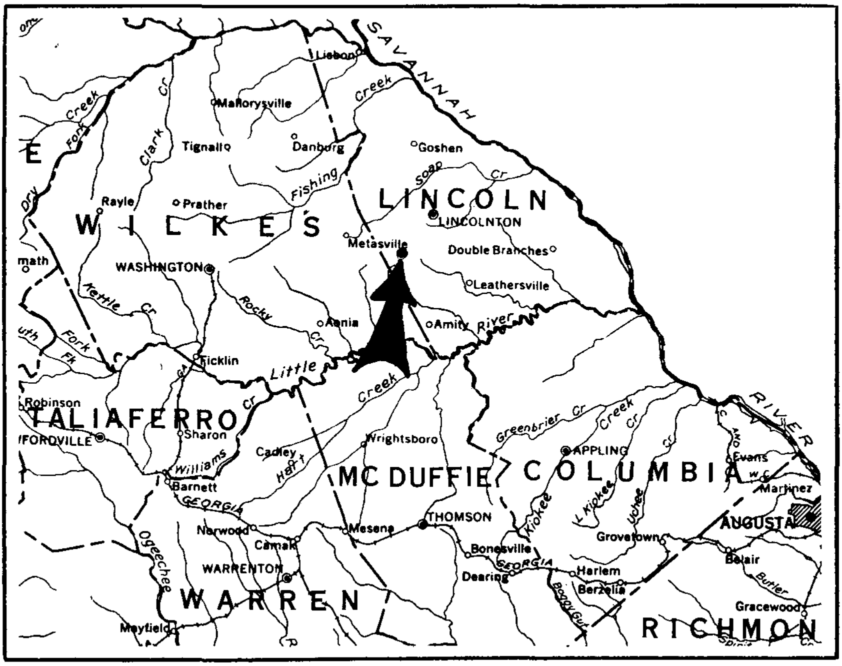

Figure 1—Location of Graves Mountain (arrow).

Location and Description

Graves Mountain is 40 miles northwest of Augusta, on the west side of Lincoln County, along U. S. Highway 378 between Lincolnton and Washington (Fig. 1).

The mountain is an asymmetric monadnock rising 400 feet above the surrounding countryside, one mile long NE-SW and ¼ mile wide. The northern slopes are gentle, the southern slopes steep. The mountain has two summits separated by a shallow saddle. The higher summit at the southwest end of the mountain is marked by conspicuous crags.

GEOLOGY

General Geology

The Graves Mountain area is underlain by the Little River Series (Crickmay, 1952, p. 31), a thick sequence of metamorphosed volcanic and sedimentary rocks equivalent to the Slate Belt rocks in North and South Carolina. The grade of metamorphism is low to intermediate, and increases toward the northwest. Unweathered rocks, which are scarce, bear well-preserved volcanic and sedimentary structures.

At Graves Mountain are three main rock types: quartz-sericite schist, sericite-kyanite-quartz rock, formerly called quartzite, and quartz conglomerate. The sericite-kyanite-quartz rock and the quartz conglomerate occupy a belt trending NE-SW along the axis of the mountain, and are flanked on both sides by quartz-sericite schist.

Abundant kyanite, pyrophyllite, rutile, and lazulite are restricted to a narrow zone striking N40°E, which cuts diagonally across Graves Mountain. The zone is marked by well-developed fractures, many of which have served as loci for the growth of kyanite, by quartz veination, and by greatly coarsened grain size.

The nearest granite is 2½ miles to the S.W. It is medium-grained, biotitic, and strongly saussuritized.

Description of the Rocks

Quartz-sericite Schist

The schist is fine-grained and well foliated. Unweathered, it is silvery white and speckled by small pyrite cubes. Deeply weathered it is also silvery white where the original pyrite content was low, but is conspicuously pitted and stained some shade of brown where pyrite amounted to ½% or more.

Though the proportion of quartz to sericite varies greatly (Table 1), these two minerals constitute at least 90% of the rock.

TABLE 1—POINT COUNT ANALYSES OF QUARTZ-SERICITE SCHIST

	1	2	3	4	5
Sericite	66.8	74.6	40.0	54.5	42.4
Quartz	32.4	24.1	56.4	41.2	48.3
Kyanite			0.5	1.7	3.8
Pyrophyllite					0.4
Opaque	0.8	1.3	3.1	2.6	5.1

1.—Road cut ¼ mile east of Graves Mountain marker on U.S. Highway 378.
2.—Large outcrop on south side of Graves Mountain, 100 yards northwest of small lake.
3.—Old shaft at northeast end of Graves Mountain.
4.—Northeast end of Graves Mountain, along County road 300 yards from U.S. Highway 378.
5.—Southwest end of Graves Mountain, along County road and about 40 yards southwest of spring.

Pyrite or its decomposition products comprise up to 5%. Microscopic kyanite is a common constituent on and adjacent to Graves Mountain, but is rare, if present, in the surrounding schists.

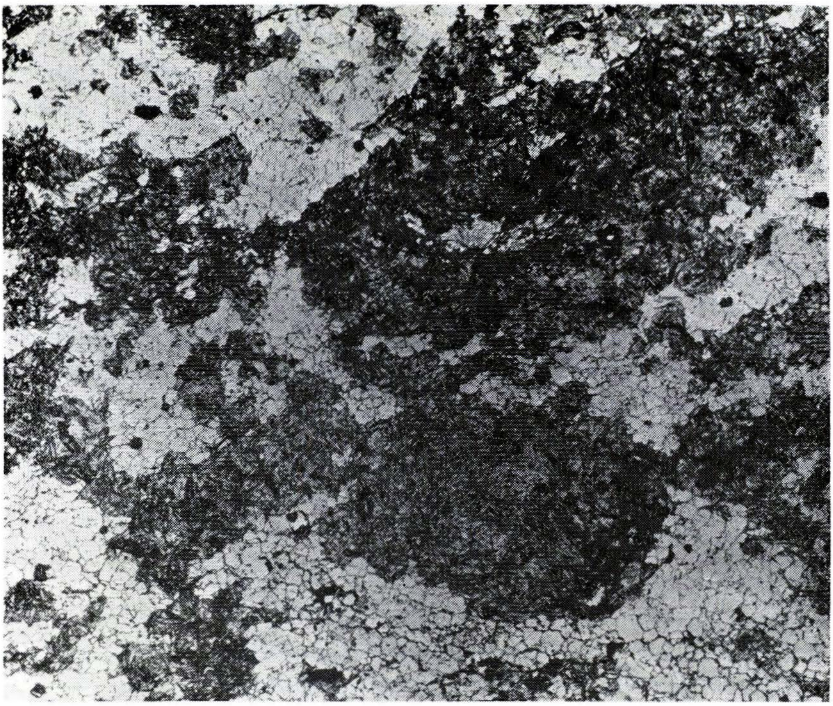

Figure 2—Sericite aggregates in fine-grained quartz matrix. Plain light, x 17.

Thin sections of the schist generally show a sericite webbing flattened about individual quartz grains, or sericite-rich lenses interleaved with quartz-rich lenses. Less commonly, a groundmass of fine quartz and sericite is dotted by coarser sericite aggregates that resemble pseudomorphs (Fig. 2). The quartz grains vary in diameter from 0.01-0.2 mm and are mostly elongate. The kyanite porphyroblasts are ragged in outline, and partly altered to pyrophyllite. In weathered specimens, a red-brown material occupies mineral cleavages and intergranular spaces, lines the walls of small cube-shaped voids, and even composes microveinlets. This material is goethite or a mixture of goethite and hematite derived mainly from the breakdown of pyrite.

X-ray powder patterns reveal two varieties of sericite: muscovite and paragonite, which are hardly distinguishable by optical methods. Several thin-sections containing both micas were etched with HF and subjected to sodium-cobaltinitrite, which preferentially stains K-bearing minerals a light yellow. Though etch and stain treatments were varied, efforts to distinguish the two micas by this method were generally not satisfactory. Either the minerals did not stain, or part of the mica was already too darkly stained by iron oxide for the light yellow stain to show, or the staining solution penetrated along mineral cleavages and grain contacts, coloring the whole slide. In the few slides that stained differentially the very fine mica occurring in aggregates stained yellow, indicating that it is muscovite and the coarser mica webbing did not stain, suggesting that it might be paragonite. The relatively coarse mica in ferruginous float atop Graves Mountain a few yards southwest of the U. S. Coast & Geodetic Survey Triangulation Station is entirely 2M muscovite. Otherwise, most of the mica is paragonite or a mixture of paragonite and muscovite. Although paragonite has not been reported previously from this part of Georgia, it is probably the third most abundant mineral on the mountain.

The sericite in the schists surrounding Graves Mountain, within a 3-mile radius, is 2M muscovite. X-ray diffractometer patterns of 23 specimens revealed paragonite is only one, which was collected 2½ miles northeast of Graves Mountain along U. S. Highway 378 towards Lincolnton.

Paragonite formed abundantly at Graves Mountain, only sparingly in the surrounding schists. It appears to be a product not of regional metamorphism alone but of special conditions relating to the growth of abundant kyanite, rutile, and lazulite in the same area.

Sericite-kyanite-quartz Rock

The name quartzite used in all previous reports is a misnomer inasmuch as the rock averages less than 80% SiO_2. Its chemical composition is like that of an acidic volcanic rock. Relic texture, interbedded conglomerate, and position in a metavolcanic sequence are all compatible with origin as a tuff.

This is the resistant unit forming the heights at Graves Mountain. It crops out in a band along the length of the mountain, where it has been tightly folded and faulted, and continues away from the mountain both to the northeast and southwest. Its mineralogy and texture change from the top of the mountain towards the periphery. Without the inter-

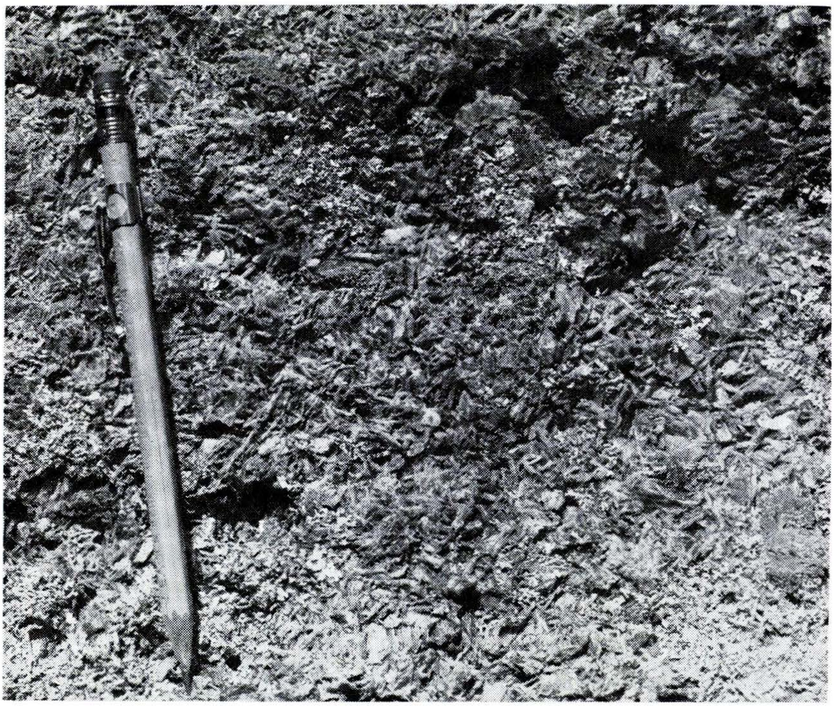

Figure 3—Coarse blue kyanite in a fine-grained quartz matrix; this is a weathered outcrop partly encrusted by lichens.

bedded conglomerate, which can be traced through the changes, the stratigraphic equivalence of different looking portions might be in doubt.

Along the top of the mountain, the rock is massive and composed mainly of kyanite and quartz. The kyanite blades are coarse, euhedral to subhedral, embedded in a matrix of fine- to medium-grained quartz. In zones several feet wide kyanite may constitute as much as 50% of the rock and may be evenly distributed (Figure 3). Generally, however, it comprises only 10-35% and is mainly in close-spaced, planar concentrations that criss-cross the rock. On weathered surfaces the kyanitic seams have been etched into relief, giving the rock its characteristic honey-combed or ribbed appearance.

Along the periphery of the mountain the rock is fine-grained and micaceous. The kyanite porphyroblasts are small, ragged, scattered through a fine-grained matrix of quartz and mica. Gradation from the coarse kyanite-quartz rock

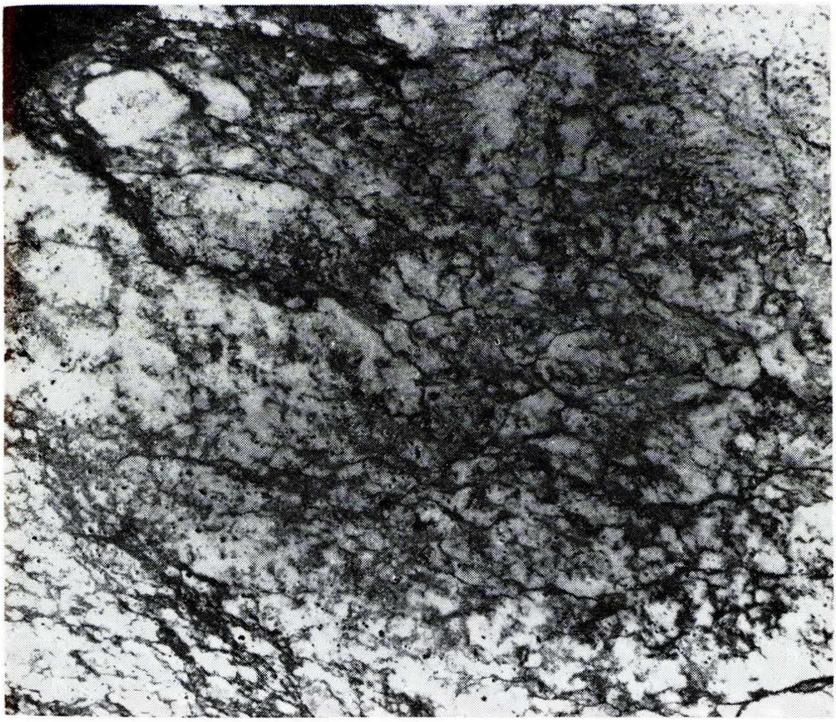

Figure 4—Sawn rock slab showing the distribution of quartz (light), mica and kyanite (dark). The black equidimensional specks are pyrite. Plain light, x 2.

atop the mountain to the fine-grained sericite-kyanite-quartz rock along the periphery is indicated by hachuring on the geologic may (Plate 1).

Coarse Kyanite-Quartz Facies. The kyanite blades are well-formed, variable in size, commonly a cm long. Generally the margins of the blades are altered to and embayed by a finely micaceous, highly birefringent mineral which is indistinguishable by optical methods from sericite. Though called sericite (Johnson, 1935, page 30), the mineral is pyrophyllite, as shown by several X-ray powder patterns. The extent of alteration is generally slight. At places, however, the kyanite has been largely replaced by pyrophyllite, and the rock is cross-cut by pyrophyllite veins up to several inches thick.

The matrix is granular quartz with individual grains mostly 0.08-0.4 mm. in diameter. Peppered through the quartz matrix and included in the kyanite are minute red rutile crystals

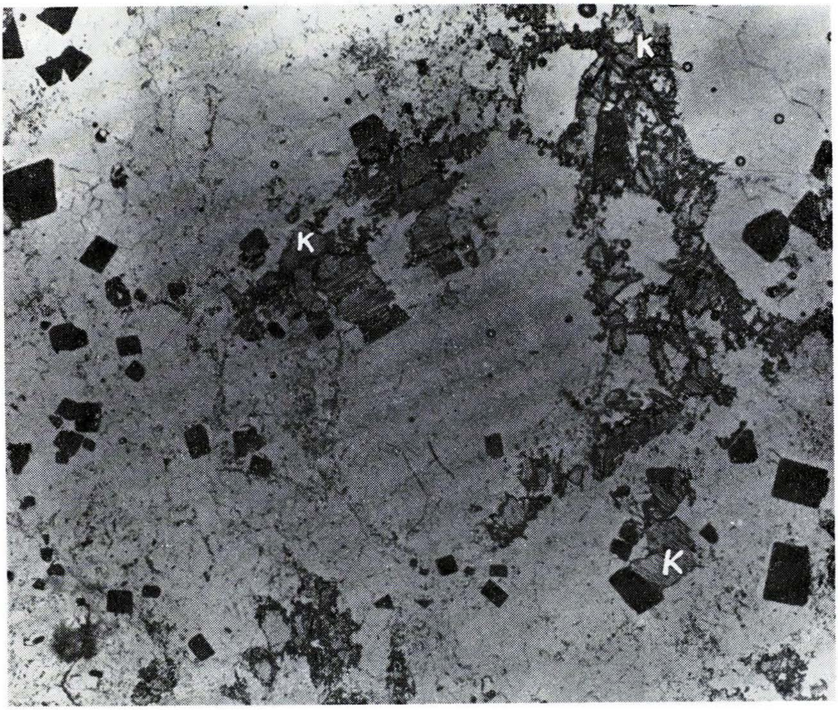

Figure 5—Ragged kyanite porphyroblasts (k) in a finer matrix of quartz and mica. The black crystals are pyrite plain light, x 14.

0.01-0.03 mm. across and occasional irregularly-shaped masses of fine rutile up to 0.2 mm. across. The fine rutile generally makes up 0.5% of the rock, or less, but in some specimens constitutes ½-1%. Large black rutile crystals occur sparingly and erratically. They are stubby, prismatic, the larger about one inch long. Where in contact with kyanite, they interlock, and rarely, invade the kyanite along cleavages. Both the large and small rutile crystals are most abundant where the rock has been strongly pyrophyllized.

Small pyrite cubes comprise ½-2% of the rock. In the zone of weathering they have decomposed to hematite-geothite which discolors the rock. At a few places the hematite-goethite composes small cross-cutting veinlets, or botryoidal masses several inches across.

Blue lazulite crystals constitute 1-5% of large masses of the kyanite-quartz rock, and as much as 15% of a few narrow zones. The crystals are scattered, apparently at random,

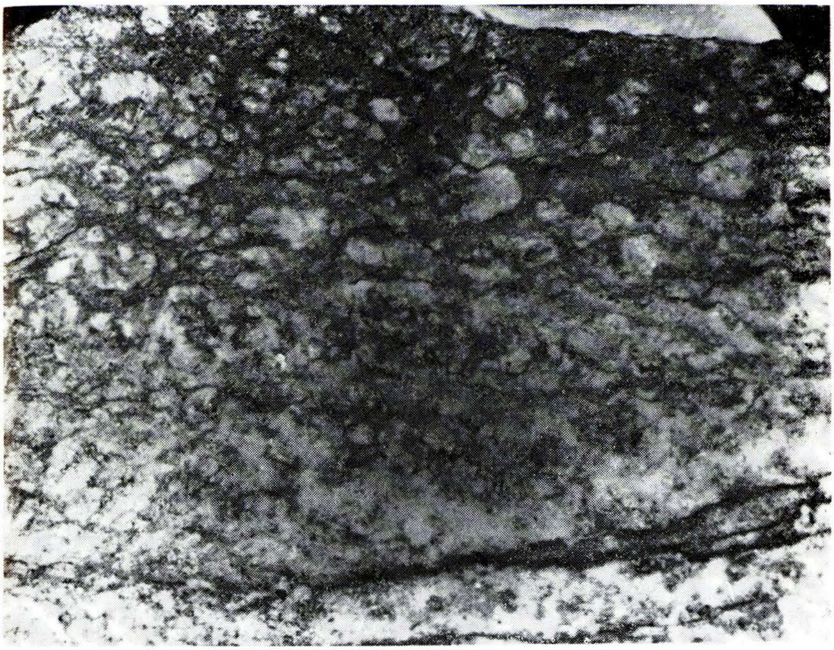

Figure 6—Sawn slab showing a typical texture of the sericite-kyanite-quartz rock. Plain light, x 3.

within the quartz-rich bands. They are mostly euhedral, average a little less than 1/4″ across, and are commonly twinned. The largest are about 1 1/2″ across.

The lazulite crystals have inclusions of quartz and rutile. The quartz grains are anhedral and about the same size as those in the rock matrix; the rutile crystals are minute, equant and red-brown. Less common inclusions are mica, kyanite, pyrophyllite, and andalusite. Many of the small lazulite crystals are plastered by coarse sericite or pyrophyllite, a single book of mica against each crystal face. Many of the crystals are altered along internal fractures to a fine-grained material with moderate birefringence, part of which is gibbsite.

In thin section the lazulite is seen to be anhedral where in contact with kyanite and euhedral where in contact with pyrophyllite. Kyanite porphyroblasts are ragged near lazulite or irregularly terminated against it. These textural relations suggest that the lazulite might have crystallized after the kyanite and with or before the pyrophyllite.

East of the highest summit the kyanite-quartz rock contains scattered colorless to white barite crystals, the largest about 1″ long. They are inconspicuous where little altered. Many of them have been corroded, even completely removed, leaving cavities which are now lined or partially filled by minute crystals of colorless quartz and pale yellow alunite.

Transecting the kyanite-quartz rock are thin veinlets of pyrophyllite, gibbsite, alunite, and occasionally small amounts of andalusite.

Fine-grained Sericite-Kyanite-Quartz Facies. Fine grain size and intergranular stain render the sericite-kyanite-quartz rock hard to distinguish from the quartz-sericite schist in the field. At places they appear to be completely gradational.

Figure 4 illustrates a typical texture. The light-colored masses are fine granular quartz. The dark colored masses are iron-stained muscovite-paragonite and minor kyanite. The kyanite porphyroblasts are typically small and poorly formed (Fig. 5); the black specks are weathered pyrite.

Figure 6 illustrates another typical texture. The light-colored masses, while superficially resembling the granular quartz in Figure 4, are composed instead of kaolin, pyrophyllite and kyanite. The pyrophyllite is in the form of small seams and patches which are either co-mingled with or surrounded by kaolin. Mainly within the pyrophyllite are oriented patches of kyanite. The texture suggests breakdown of kyanite to pyrophyllite and further alteration to kaolinite.

In the sericite-kyanite-quartz rock are occasional coarse quartz grains and a little quartz conglomerate (Fig. 7). Also, there are sericite aggregates pseudomorphing some previous constituent similar to the quartz grains in size and shape (probably feldspar). No feldspar is found in any of the rocks on the mountain.

TABLE 2—POINT COUNT ANALYSES OF SERICITE-KYANITE-QUARTZ ROCK

	1	2	3	4
Quartz	69.0	33.9	72.8	65.2
Kyanite	16.1	59.5	24.6	2.1
Micaceous minerals*	14.0	5.6	1.2	31.4
Opaque	0.9	1.0**	1.4	1.3

1.—Near spring, southwest end of Graves Mountain.
2.—Near dragstrip, northeast end of Graves Mountain.
3.—Prominent crags 500′ S.W. of B.M.
4.—Promontory 400′ N. of spring at S.W. end of mountain.

*Mostly mica but includes pyrophyllite and kaolin.
**Mostly rutile.

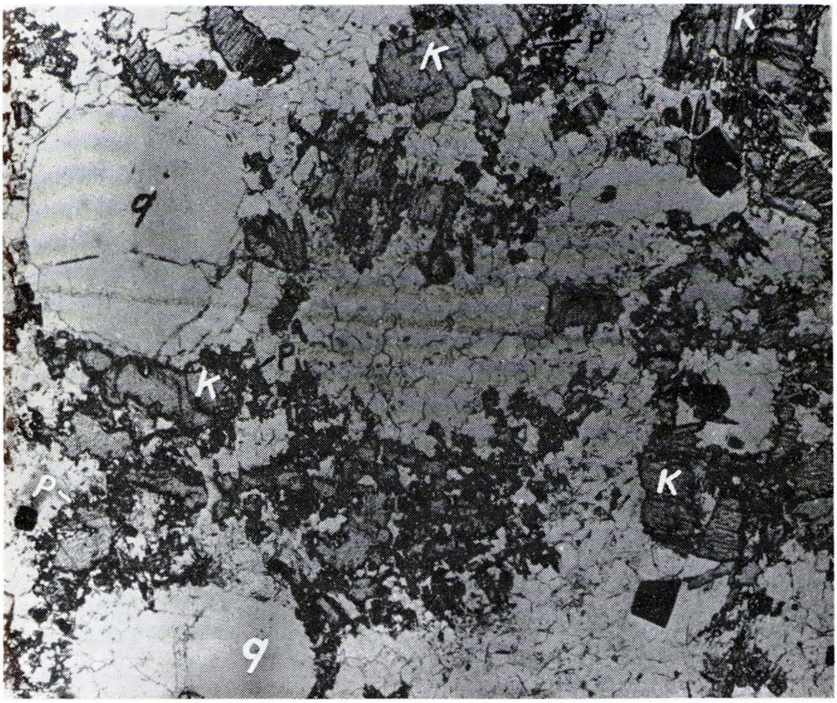

Figure 7—Coarse, rounded quartz grains (q) in the sericite-kyanite-quartz rock. Plain light, x 20. The kyanite porphyroblasts (k) are incipiently altered along margins to pyrophyllite (p).

Quartz Conglomerate

A conglomeratic zone up to 15 ft. thick is found along one stratigraphic horizon in the sericite-kyanite-quartz rock. The zone is almost continuously traceable from a point ½ mile northeast of Graves Mountain to the dirt road at the southwest end. Farther to the southwest are exposures which are probably the same horizon.

The zone varies in thickness, number of conglomeratic layers, and percentage of pebbles but is everywhere well-defined. The pebbles constitute less than 30% of the zone and range from ½ inch in diameter down to sand size. The conglomeratic layers are interbedded with the sericite-kyanite-quartz rock, from which they differ only in texture.

The pebbles are a single species, quartz. The former presence of another pebble-size constituent is shown by pseudomorphing aggregates of sericite. In conglomerate southwest of Graves Mountain are pebbles of both feldspar and quartz, though mainly quartz.

Quartz Veins

In the area of coarsened grain size quartz veins and lenses are numerous. They are mostly a few inches thick but range in width from ⅛″ to several feet. Their contacts with the country rock are mostly sharp. The vein-quartz is white, translucent, and typically barren. A few of the veins contain coarse stellated pyrophyllite, rutile crystals, or euhedral transparent kyanite blades. Adjacent to several of the veins are

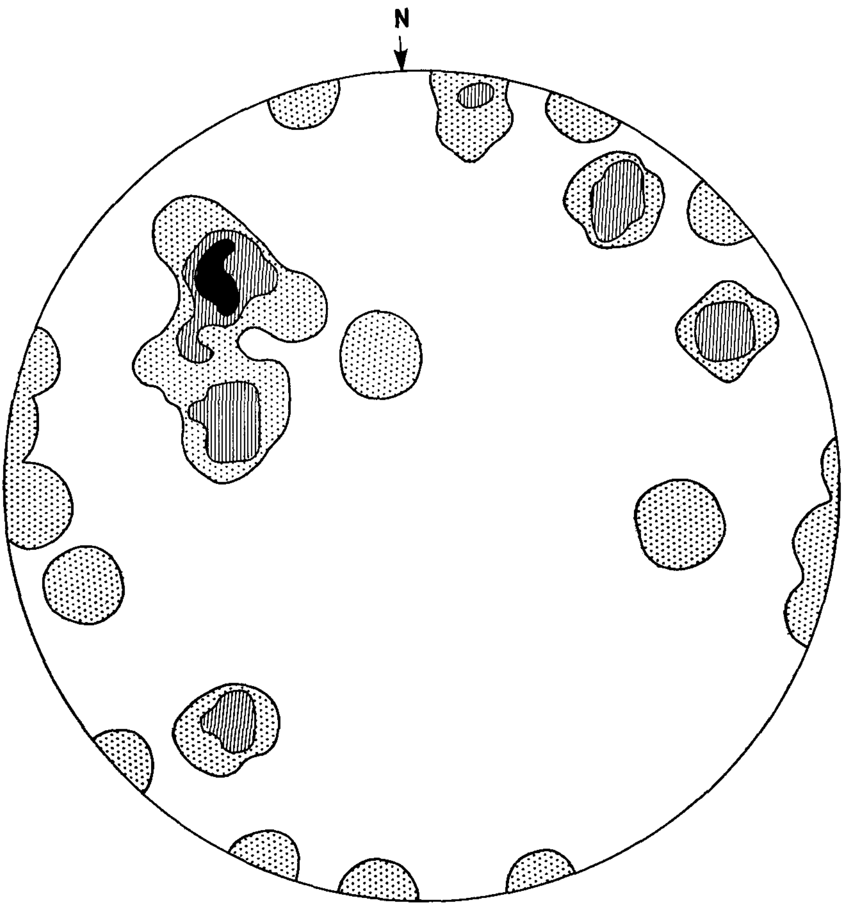

Figure 8—Poles of quartz veins. Lower hemisphere projection on equal-area net. Contour counter 1% of total area; distance between counts 0.5 cm. 27 measurements. Contours 3-6-12%.

what appear to be concentrations of kyanite and/or pyrophyllite. In most instances these minerals are only coarser adjacent to the veins, not more abundant.

Most of the veins strike NE-SW and dip steeply to the SE (Fig. 8). Their orientation does not coincide with that of the kyanitic seams, the cross fractures, or the pyrophyllite veins (compare Figs. 9, 10, 11).

Some of the veins are concordant with the early foliation and are deformed, while others cleanly transect all early structures; therefore, they are not all the same age.

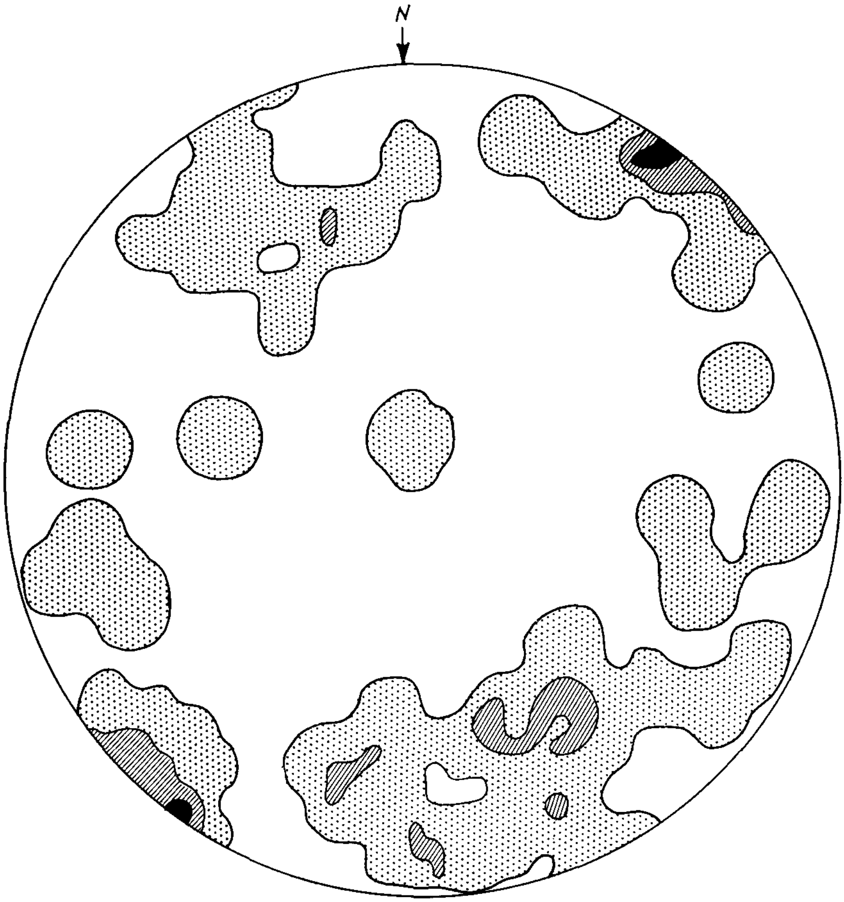

Figure 9—Poles of fracture cleavage planes along which kyanite is concentrated. Lower hemisphere projection on equal-area net. Contour counter 1% of total area; distance between counts 0.5 cm. 63 measurements. Contours 1-4-8%.

Structures

Primary Structures

Bedding is well preserved in the sericite-kyanite-quartz rock except in the area of coarsened recrystallization atop Graves Mountain. The thickness of the beds varies from a few inches to several feet, and at one horizon is fine enough to approach lamination.

Rough sediment grading involving fine conglomerate and sand is discernable at four places (for location see Plate 1).

Secondary Structures

A regional schistosity marked by preferred orientation of mica and quartz is impressed on the rocks, being best developed in those which are fine-grained and very micaceous. Generally the schistosity can be distinguished from fine bedding but there are places where the two are hard to separate. They are often parallel.

A system of shear fractures or fracture cleavages is developed locally. The planes are a fraction of an inch to several inches apart and traceable for a few feet. They are generally seen as planar concentrations of kyanite in the massive coarse-grained rocks on top of the mountain. Toward the periphery of the mountain they become faint fractures, along which kyanite has only begun to form, transecting schistosity. The fracture cleavages have two principal attitudes: N52W, nearly vertical and N65-70E, 55NW (Fig. 9). Where both sets are clearly discernable, the latter is best developed. The area where the fracture cleavages are well-developed coincides with the area of coarsened recrystallization, where rutile and lazulite are found.

Cross-cutting both schistosity and fracture cleavages is a conspicuous set of fractures which are widely spaced (1-100 ft.), and often traceable for several tens of feet. They do not have concentrations of kyanite along them but are commonly occupied by pyrophyllite veins.

The outcrop pattern shows several small folds at Graves Mountain, but a unique structural interpretation is prevented by partial obliteration of textures and limited exposure.

MINERALOGY

Barite, goethite, gold, hematite, ilmenite, kyanite, lazulite, muscovite, pyrite, pyrophyllite, quartz, rutile and sulphur have been reported from Graves Mountain. Other minerals which occur there but have not been reported previously are alunite, andalusite, gibbsite, kaolinite and paragonite.

Alunite

Small cavaties in the weathered kyanite-quartz rock are lined or partly filled by pale yellow masses of alunite in which there are minute colorless quartz crystals and, usually, porous masses of gray barite. Although a few of the alunite-bearing cavities have the shape of kyanite blades, most of them have the shape of barite crystals. All stages of decomposition of barite are represented. Apparently the sulphate released by the break-down of barite has reacted with the aluminous minerals, notably kyanite and lazulite, to form the alunite.

Shepard (1859) did not recognize alunite in the Graves Mountain rocks but did report minute yellow sulphur crystals. Inasmuch as both minerals are soft and give a positive reaction for sulphur, the alunite might have been misidentified as sulphur.

The best exposures are 150 ft. south of the saddle.

Andalusite

Andalusite has been recognized at two places: (1) 100 ft. due east of the highest summit and (2) N45°E about 400 ft. from the old adit.

At the first place it exists as small white to gray inclusions in lazulite crystals, associated with 2M muscovite and greenish to colorless kyanite.

At the second place it is a minor constituent of thin flesh-colored veinlets—composed mainly of alunite, gibbsite, pyrophyllite, and one or more additional minerals—transecting the kyanite-quartz rock.

Barite

Stubby, euhedral, barite crystals up to ½ inch long are in the kyanite-quartz rock 150 feet south of the saddle and at several other places in the coarse kyanite zone. Being colorless like the quartz matrix, the crystals are not easy to see except where they have been etched or altered sufficiently for crystal outlines to show.

Most of the exposed barite crystals are in the quartz-rich layers. They are scattered, generally several inches apart, without apparent orientation. Many of them have been partly altered to alunite or even removed, leaving small cavities in which there are crusts of yellow alunite and drusy colorless quartz crystals.

Gibbsite

Gibbsite is found in small quantities in the veinlets which contain andalusite and in the weathered lazulite crystals.

Goethite-hematite

The brown stain which discolors most of the weathered rocks is goethite or goethite-hematite. These minerals also line the walls of small cubic voids and compose microveinlets.

Botryoidal masses of goethite-hematite up to a foot across are found in the float on the east side of the highest summit, in the saddle, and in the old field northwest of the highest summit.

Most if not all of the iron in the goethite-hematite has come from decomposing pyrite.

Gold

Shepard (1859) reported gold in the kyanite-quartz rock "especially near the southern extremity of the formation, where it becomes more schistose and embraces minute crystals of pyrites. It has here been worked to some extent for the precious metal".

Ilmenite

Several specimens of vein quartz containing large tabular ilmenite crystals have been found on the north slope of the mountain in float, but none have been observed in place (Johnston, 1935, p. 28).

Kaolinite

Though a minor constituent, kaolinite is widespread.

Typically it forms thin white coronas about kyanite porphyroblasts, either mingled with pyrophyllite or enclosing pyrophyllite which in turn encloses kyanite.

Fist-size chunks of massive white kaolinite have been collected from a "stratum" in a well on the Dessie R. Kennedy property at the southern edge of Graves Mountain.

Kyanite

An estimated 10% of the coarse-grained rock on Graves Mountain is kyanite. Wide zones contain 20-40%.

The kyanite is distributed in three ways:

(1) Along foliation and fracture planes, i.e., in planar concentrations criss-crossing the rock;

(2) In zones marginal to quartz veins, less commonly in quartz veins;

(3) And as crystals and groups of crystals disseminated without apparent systematic arrangement.

In the fine- to medium-grained rocks along the periphery of the mountain the kyanite porphyroblasts are small, poorly formed, and generally distributed along foliation planes. In the coarse-grained rocks on top of the mountain the kyanite is subhedral to euhedral and occurs as single crystals or groups of crystals partly disseminated through the rock but mainly concentrated along fracture planes. The margins of some of the quartz veins are marked by conspicuous concentrations of coarse kyanite. Along most of the veins, however, the kyanite is only coarser, not more abundant. A few of the veins contain large, especially well formed blades.

The fresh kyanite is pale blue except in lazulite-rich zones where it may be colorless to pale green. The weathered blades are some shade of brown.

Much of the kyanite is incipiently altered along crystal margins and cleavages to fine pyrophyllite. The extent of alteration varies greatly from one outcrop to another. Alteration is greatest along cross-fractures on the main summit and just north of the saddle.

Lazulite

Blue lazulite crystals are locally abundant in the sericite-kyanite-quartz rock. Where they are present, they constitute 1-5% of the rock; zones 1-2 feet thick on the southeast side of the mountain average as much as 15%.

The lazulite crystals are distributed within a wide zone running northeast-southwest across the mountain. They are not restricted to a single bed or group of beds, but are mainly in the silica-rich bands. They are not found in the quartz veins.

The crystals are pyramidal to tabular, commonly twinned, and average less than ¼″ across. The largest are about 1½″ across. Fresh crystals are dusky blue (5 PB 3/2); weathered crystals azure blue, grayish blue, or mottled blue and white.

Most of the crystals contain visible inclusions. These are generally colorless quartz grains or minute red-brown rutile crystals. Less common inclusions are sericite, pyrophyllite, and andalusite. Many of the crystals are plastered by coarse sericite or pyrophyllite, a single book of mica against each crystal face.

The weathered lazulite crystals have transformed along margins and fractures to a fine-grained material of moderate birefringence, part of which is gibbsite.

Paragonite

The sodium-analogue of muscovite, paragonite, is one of the common rock-forming minerals. It is fine-grained and generally associated with muscovite from which it cannot be distinguished visually.

The micaceous rocks surrounding Graves Mountain contain very little paragonite.

Pyrite

The percentage of pyrite is very variable. Most of the rocks contain ½-4%, but there are zones which may contain as much as 10%.

The pyrite is scattered through the rocks as small cubes. Where the rocks are weathered, the pyrite has decomposed and its former presence is indicated by a brown discoloration and numerous cubic voids.

Pyrophyllite

Stellated clusters ¼-1″ in diameter of pearly gray pyrophyllite, iron-stained to yellow or red-brown at weathered outcrops, form veins up to at least one foot thick cross-cutting the kyanite-quartz rock. Nearly all of the veins strike N60-

70W and dip steeply. Coarse pyrophyllite clusters are also in and along many of the quartz veins.

In addition, pyrophyllite is found as a fine-grained alteration product along the margins of most of the kyanite blades.

Rutile

Rutile is the most sought mineral at Graves Mountain, where crystals up to 5 inches long and weighing as much as a pound have been collected. Some of the world's finest museum specimens have come from this locality.

The zone wherein the crystals can be collected, in place, is shown on Plate 1. Loose crystals may be found in the colluvium in the saddle and on the slopes north of the saddle, particularly after heavy rains.

Several prospect trenches have been dug in the saddle. Lustrous sharp-faced crystals of small size were obtained from the old trench highest in the saddle. On the steep slope due south of this trench black crystals up to 1¼" long can still be collected. They are in pyrophyllitized kyanite-quartz rock and in small quartz veins or pods.

Large rutile crystals are well exposed on the steep slope 200 feet due east of the highest summit, scattered through relatively unaltered kyanite-quartz rock. The adit driven into the mountain directly underneath these exposures did not encounter much rutile because it was driven below the southeast-dipping rutile zone.

Most of the coarse rutile occurs as scattered crystals or groups of crystals in the kyanite-quartz rock, both in the unaltered and in the pyrophyllitized rock. The best concentrations are in the strongly pyrophyllitized rock and in some of the pyrophyllite veins. Quartz blebs and veins contain isolated crystals. Contrary to what has been reported, the deeply weathered kyanite masses that are highly charged with secondary iron minerals are not the favored host rocks, though they do sometimes contain fine specimens. The coarse rutile crystals are dark red-brown to black, stubby prismatic and commonly intergrown or twinned.

Minute red-brown rutile crystals mostly less than 0.1 mm long are included in all the major minerals within the pyrophyllitized zone. This fine-grained rutile is locally abundant enough to make up ½% or more of the rock.

Developmental Stages at Graves Mountain

The present mineralogy is a result of several developmental stages whose sequence is revealed by textural and structural relations. Little can be deduced about the time intervals separating the stages. Possibly some of them followed so closely as to merge.

First Stage

The earliest decipherable episode is the deposition of tuffaceous(?) sediments and intercalated gravels along a zone passing through Graves Mountain. These belong to the Little River Series (Crickmay, 1952), a thick sequence of metamorphosed pyroclastic rocks, other sediments, and lavas.

Second Stages

Low to intermediate grade regional metamorphism followed. The rocks were folded and recrystallized, mainly to quartz-sericite schists.

Third Stage

Following metamorphism, a system of fracture cleavages developed along a zone striking N40E across what is now the top of Graves Mountain. They might have been the result of a couple acting in a plane N40E, 40SE whereby the southern part of the mountain moved SW relative to the northern part. This interpretation accords with their orientation and with the better development of the N65-70SE, 55NW set.

Where cleavages developed, the rocks recrystallized and new minerals appeared. Foremost in abundance was kyanite. It grew along fracture planes and to less extent along schistosity and bedding planes. Its concentration along foliation planes connotes at least small-scale mobilization of the rock's constituents. Probably there was concomitant large-scale transfer of phosphorus, titanium, sulphur, and barium into the fractured zone and alkali out because lazulite, rutile, pyrite, and barite formed there in higher percentages than could be expected from the rock's original composition. The lazulite, rutile, barite, and andalusite formed after the kyanite had crystallized.

Within the zone of coarsened recrystallization, where fracture cleavage had developed, original textures were largely obliterated.

Fourth Stage

Postdating the growth of kyanite, widely spaced cross-fractures devloped. Their orientation (Fig. 10) is the same as that of the pyrophyllite veins (Fig. 11), and many are loci of pyrophyllitization.

Pyrophyllitization succeeded the development of the cross-fractures and was largely controlled by them. The thin veinlets which contain andalusite cross-cut the kyanite-quartz rock and might have formed during this stage.

Fifth Stage

Kaolinite crystallized locally.

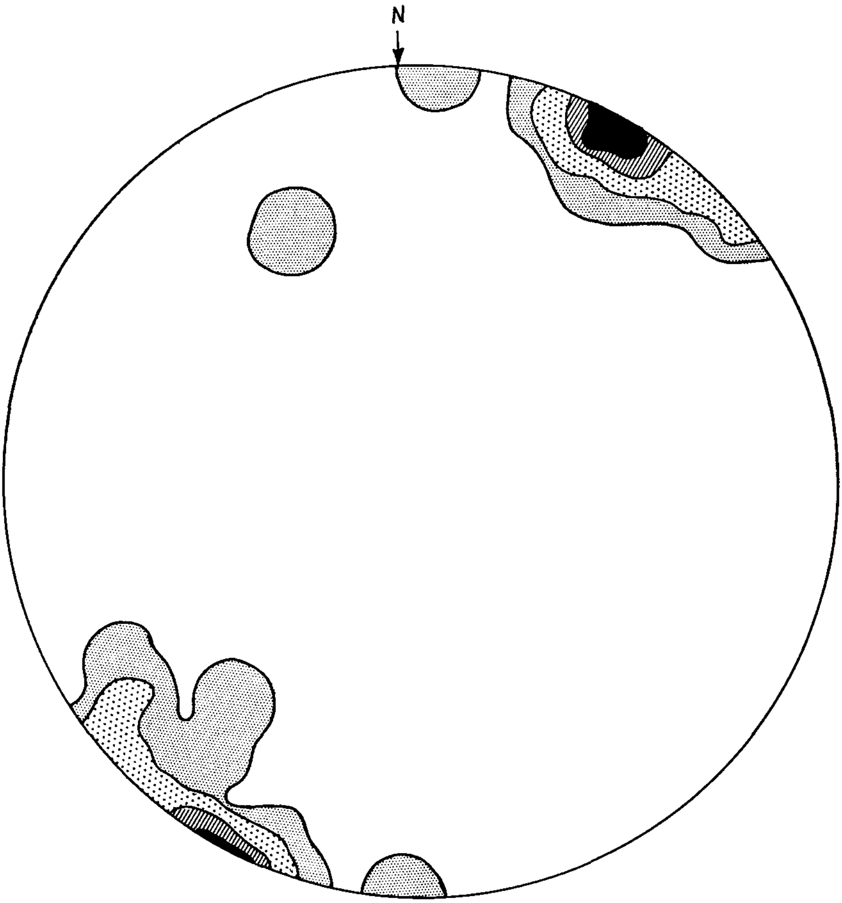

Figure 10—Poles of prominent, widely spaced cross-fractures. Lower hemisphere projection on equal-area net. Contour counter 1% of total area; distance between counts 0.5 cm. 31 measurements. Contours 3-6-20-32%.

Physical Conditions under which Mineralogy Developed

Only during the third, fourth, and fifth stages did physical conditions different from those in the region as a whole prevail at Graves Mountain. During the third stage the mineral assemblage quartz-kyanite-muscovite-paragonite developed. During the fourth stage part of the kyanite and quartz transformed to pyrophyllite. During the fifth stage kaolinite appeared locally.

All these minerals except the micas are phases in the ternary system Al_2O_3-SiO_2-H_2O. All are phases in the K_2O+

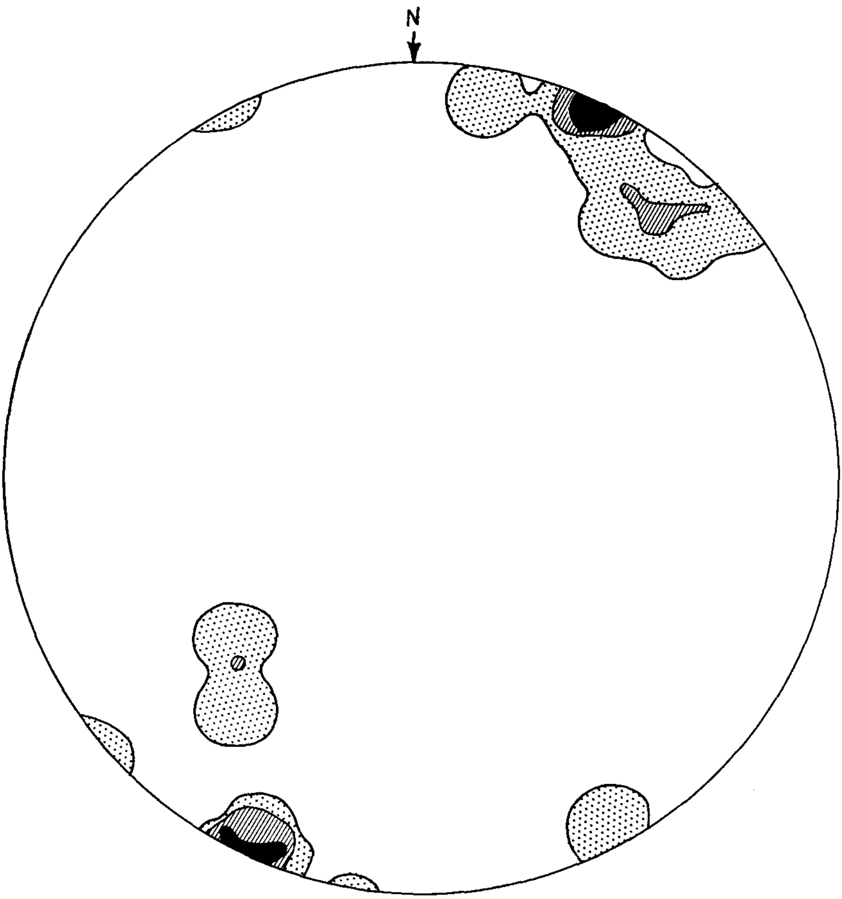

Figure 11—Poles of pyrophyllite-bearing veins at 13 localities. Lower hemisphere projection on equal-area net. Contour counter 1% of total area; distance between counts 0.5 cm. Contours 7-15-30%.

Na_2O-Al_2O_3-SiO_2-H_2O system. Experimental data bearing on the physical conditions required for the formation of these mineral assemblages are reviewed below.

The Al_2O_3-SiO_2-H_2O system was investigated over the temperature range 100-930°C at pressures up to 2069 bars by Roy and Osborn (1954). They delimited the stability fields of quartz, kaolinite, pyrophyllite, and the other phases in the system except those of the composition Al_2SiO_5 (mullite, andalusite, sillimanite, and kyanite). Their efforts to synthesize the Al_2SiO_5 polymorphs produced only mullite and possibly andalusite. Subsequent work has shown that kyanite can be readily synthesized at pressures greater than those used by Roy and Osborn; andalusite can crystallize below 1000 bars, as well as higher pressures (Roy, 1954; Hemley, 1959); sillimanite as low as 3000 bars (Kennedy, 1955).

Mullite is stable at atmospheric pressures and high temperatures. Andalusite appears to be stable at water pressures of 690-2069 bars within the temperature range 450-650°C (Roy, 1954), and to be unstable in the presence of excess water below 425°C (Roy and Osborn, 1954).

Kyanite decomposes at moderate water pressures below 450°C (Roy and Osborn, 1954). It is stable in the presence of excess water only at very high temperatures and pressures. Under water-deficient conditions, however, and high confining pressures, it can be grown at temperatures as low as 550°C (Kennedy, 1955).

Clark, Robertson, and Birch (1957) experimentally determined the kyanite-sillimanite equilibrium curve within the temperature interval 1000-1300°C and extrapolated the curve over the temperature range of regional metamorphism (curve 1 in Fig. 12). Their work verifies Miyashiro's deduction (1949) that kyanite is the high-pressure polymorph, but the extrapolated portion of their curve indicates much higher pressures than could have affected most rocks during metamorphism.

The natural occurrence of kyanite-andalusite-sillimanite, as described by Heitanen (1956), suggests a triple point for the Al_2SiO_5 composition within the pressure-temperature range of metamorphic rocks. The scarcity of this type of occurrence suggests that the triple point is at a higher pressure than is commonly realized by rocks undergoing metamorphism.

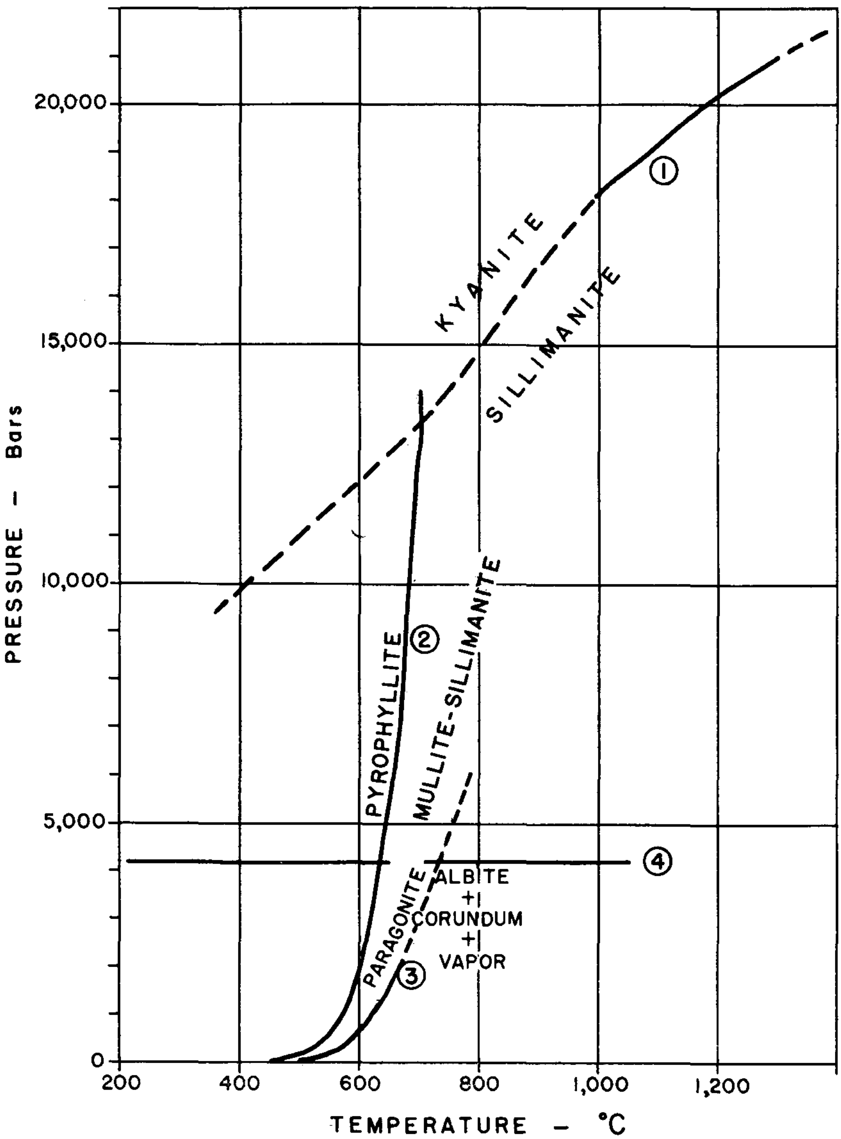

Figure 12—*Curve 1 — Kyanite-sillimanite equilibrium relations, dashed where extrapolated (Clark, Robertson, and Birch, 1957). Curve 2—Hydrothermal break-down of pyrophyllite to mullite-sillimanite (Kennedy, 1955). Curve 3—Hydrothermal decomposition of paragonite (Eugster and Yoder, 1954). Curve 4—Load pressure at a 10 mile depth, assuming an average specified gravity of 2.7.*

Although published experimental data on the stability fields of the Al_2SiO_5 polymorphs are not entirely consistent, they are compatible enough to permit some refinement of the phase diagram suggested by Miyashiro (1949) and Thompson (1955) (see Fig. 13). The hydrothermal decomposition curve for pyrophyllite is from Kennedy (1954), as well as its intersection with the sillimanite-mullite curve and with the kyanite-sillimanite curve (point x). The solid portion of the kyan-

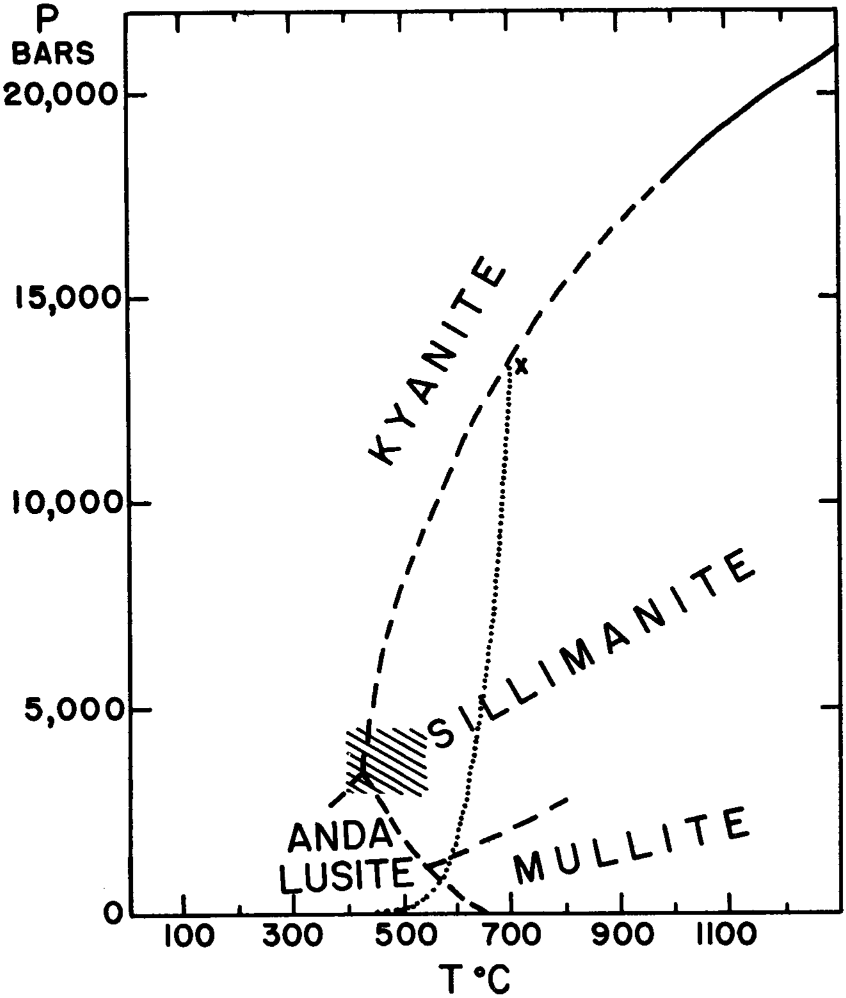

Figure 13—Tentative phase diagram of the composition Al_2SiO_5 (solid and dashed lines). The dotted line is the hydrothermal decomposition curve of pyrophyllite. Data sources are given in the text.

ite-sillimanite curve is from Clark, Robertson, and Birch (1957). The low-pressure portion of the andalusite-mullite curve is suggested by Roy's work (1954). The location of the triple point, assuming that it exists, is the most uncertain part of the diagram; the field relations of andalusite, sillimanite, and kyanite indicate that it lies within the temperature interval 400-550°C and within the pressure range 3000-4500 bars (cross-hatched area in Fig. 13).

Probable phase relations in a portion of the system K_2O-Al_2O_3-SiO_2-H_2O from 450-650°C at 1000 bars water pressure (Fig. 14) are reproduced from Yoder and Eugster (1955), after slight modification suggested by Fig. 13. Higher pressures, as might have prevailed at Graves Mountain, shift the stability field of pyrophyllite to higher temperatures (see curve 2 of Fig. 12) and cause kyanite or sillimanite to form rather than andalusite.

The kyanite at Graves Mountain must have crystallized at high pressure, i.e., while the rocks now exposed were still several miles below the earth's surface (extreme depth is ruled out by the existence of fracture cleavage, along which part of the kyanite grew). The kyanite formed during the third stage as part of the assemblage quartz-kyanite-paragonite-muscovite. Paragonite is not stable above 700°C at high pressure (curve 3 of Fig. 12). It follows from the experimental data

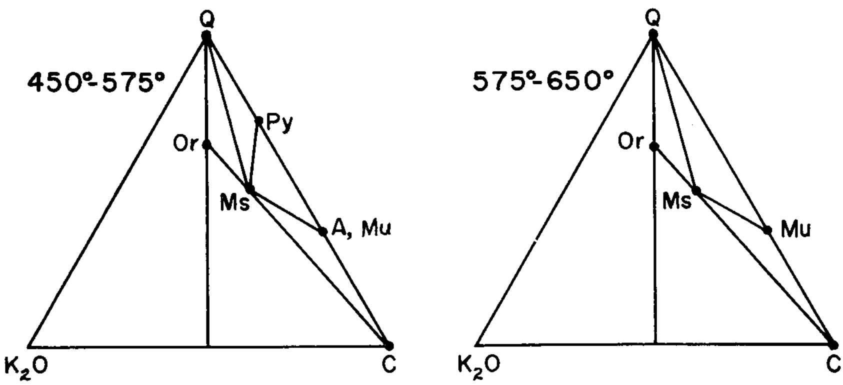

Figure 14—Probable phase relations in a portion of the system K_2O-Al_2O_3-SiO_2-H_2O from 450°-650° C at 1000 bars water pressure (slightly modified from Yoder & Eugster, 1955, p. 271). A = andalusite, C = corundum, Ms = muscovite (sericite), Mu = mullite, Or = orthoclase, Py = pyrophyllite.
Or = orthoclase, Py = pyrophyllite.

mentioned above and summarized in Figs. 12 and 13 that the Graves Mountain kyanite must have grown under water-deficient conditions at temperatures considerably less than 700°C, probably within the temperature range 400-500°C.

If this interpretation is correct, the partial transformation of kyanite to pyrophyllite during the fourth stage required no change in pressure or temperature, only the ingress of water. The concentration of pyrophyllite along a set of cross-fractures which postdate the crystallization of the kyanite is compatible with this conclusion.

The andalusite might have formed simultaneously with the pyrophyllite but at points where water was still deficient.

The transformation of pyrophyllite to kaolinite, which took place locally during the fifth stage, required excess water and temperatures below about 400°C.

Summary of Crystallization Sequence

Kyanite crystallized subsequent to regional metamorphism, during the third stage. Rutile and lazulite crystallized during the fourth stage, barite during the fourth or fifth stage. Pyrophyllite formed during the fourth stage, and probably also the andalusite. Kaolinite crystallized during the fifth.

Summary of Physical Conditions

The kyanite probably grew under water-deficient conditions at 400-500°C and high pressure. Pyrophyllite probably formed as a consequence of ingress of water along fractures as the rocks began to cool, the supply of water determining the amount of pyrophyllite that formed. Andalusite could have crystallized simultaneously where water did not penetrate. As the temperatures dropped below about 400°C, kaolinite formed where excess water was still available.

Gibbsite and alunite, the youngest minerals, probably crystallized at or near atmospheric temperatures and pressures.

Because the phase equilibrium relationships of relatively simple, pure systems might not apply, strictly, to naturally-occurring minerals which are phases in a more complicated system, the pressure-temperature conditions deduced above must be regarded only as approximations, probably close to the actual conditions that once existed at Graves Mountain.

Figure 15—Typical distribution of kyanite (dark) along fracture planes and foliation planes. The light gray matrix is mainly quartz, partly fine mica (< 5%).

Cause of Kyanite Localization

The kyanite grew in and along a fractured zone which transects bedding, therefore localization was not caused by original rock composition so much as by special physical conditions. Kyanite growth within the fractured zone was controlled mainly by fracture planes and, to less extent, by foliation planes. The most apparent difference between the fractured zone and the bounding rocks was its greater permeability. The special conditions that induced kyanite growth might have been created by permeating (water-deficient?) gases either at a higher pressure than the country rocks or of special chemistry.

ECONOMIC GEOLOGY

Three economic minerals are exposed in sufficient quantities to be considered potential ore minerals; kyanite, rutile, and pyrophyllite. The distribution of each is shown on Plate 1.

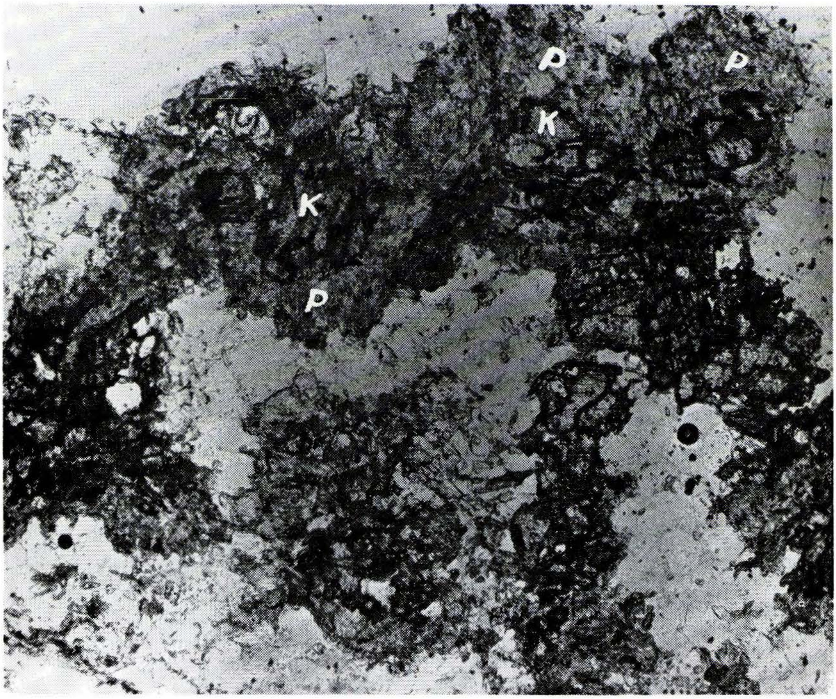

Figure 16—Advanced stage of marginal alteration of kyanite (k) to pyrophyllite (p). Plain light, x 55.

Kyanite

The coarse kyanite is in a zone 200′ wide x 600′ long trending N40°E across the top of the mountain. The zone dips steeply SE and is exposed for a vertical distance of nearly 200′.

Within this zone coarse kyanite, concentrated mainly along fracture planes and foliation planes (Fig. 15), constitutes 15-20% of the rocks. Rock masses up to 10′ thick contain as much as 50% kyanite (see Fig. 3). The zone averages 15-25%, and contains at least ½ million tons of kyanite down to the base of the mountain (a vertical distance of nearly 200′).

Thin sections show that most of the kyanite blades have quartz inclusions 0.08-0.2 mm in diameter, and that the blades are irregularly interlocked with the quartz matrix. Thus fine grinding will be required for complete separation. Much of the kyanite is incipiently altered to pyrophyllite (see Fig. 7). An advance stage of this alteration is illustrated by Fig. 16. Scattered through the kyanite-bearing rocks are varying amounts of fine mica (muscovite and paragonite), pyrite, lazulite, and rutile.

In 1940, an adit was driven by the owners into the southeast slope of the mountain for about 75 feet to obtain unweathered kyanite-quartz rock for flotation tests. A 300 pound sample was sent to the Stamford ore-testing laboratory of the American Cyanamid Company. Their tests show that the quartz, pyrophyllite, and kyanite can be readily and cheaply separated to yield a -40 mesh concentrate containing 96-97% kyanite with very low iron content (Watkins, 1942).

On the southeast side of the mountain a quarry with a face 100′ high can be quickly opened with no stripping, hoisting, or pumping required.

Pyrophyllite

Masses of pyrophyllitized kyanite-quartz rock and thin pyrophyllite veins are common within an area 250′ wide x 1000′ long which includes the coarse kyanite zone and the high-rutile zone. About half the area is covered.

Whether a minable body of pyrophyllite can be developed depends on what might be encountered at depth and on what underlies the covered areas.

Rutile

Megascopic rutile is largely restricted to the coarse kyanite zone.

The rutile occurs in crystals of all sizes from minute red-brown prisms less than 0.01 mm long to black stubby prisms 2″ long, and even longer. The microscopic crystals are included in kyanite and lazulite, as well as peppered through the quartz matrix. They generally constitute 0.01-0.5% of the rock, exceptionally ½-1%. The larger rutile crystals are scattered erratically through the kyanite-quartz rock, often concentrated in pyrophyllitized masses (Fig. 17). Because of erratic distribution and the masking effect of lichens and stain the percentage of rutile cannot be reliably estimated from present exposures.

Most of the rutile is found in a zone 100′ wide x 500′ long striking NE-SW and dipping 40-60°SE. This zone overlies the

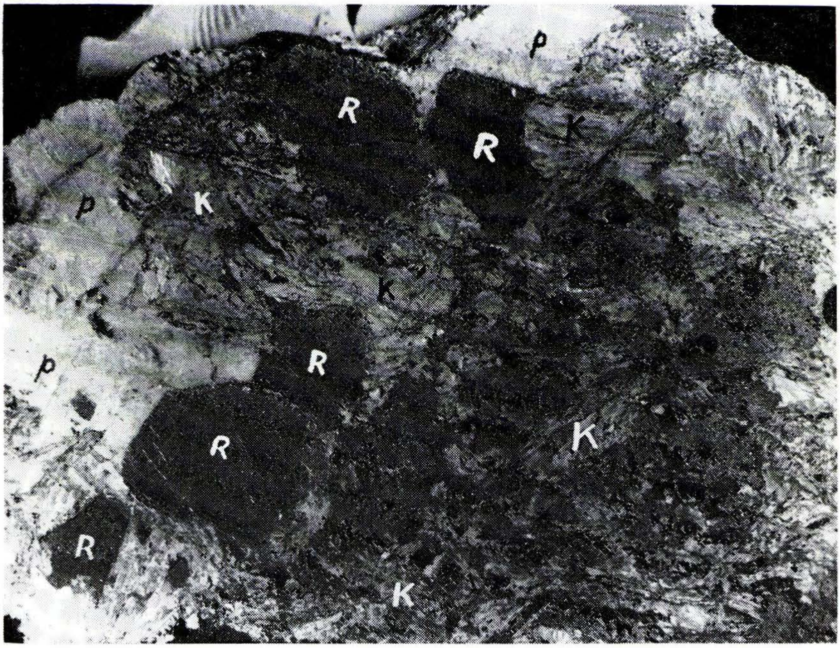

Figure 17—Coarse rutile in pyrophyllitized kyanite. R = rutile; P = pyrophyllite; K = kyanite. Photograph of sawn rock slab x 2.

old adit, passes just east of the U. S. Coast & Geodetic Survey Triangulation station, and passes through most of the trenches in the saddle. Most of the rock in this zone probably contains less than 2% TiO_2, but there are high-grade rutile concentrations which, if numerous, might make the entire zone of minable grade.

Systematic cross-trenching augmented by a few diamond drill holes across the zone can provide samples on which to base reliable estimates of tonnage and grade.

ACKNOWLEDGEMENTS

Dr. Hatten S. Yoder reviewed the parts of the manuscript that deal with the interpretation of physical conditions at Graves Mountain and made several important suggestions and corrections which have been incorporated in the report. Dr. E. F. Osborn discussed the application of phase studies in the alumina-silica-water system (by Roy and Osborn) to the interpretation of physical conditions. Mr. Willis Holland assisted with part of the field work. Dr. A. S. Furcron read the manuscript and made numerous typographical corrections.

BIBLIOGRAPHY

Clark, S. P. Jr., Robertson, E. C. & Birch, F., (1957) Experimental Determination of Kyanite-Sillimanite Equilibrium Relations at High Temperatures and Pressures: Amer. Jour. Sci. vol. 255, p. 628-40.

Crickmay, Geoffrey W., (1952) Geology of the Crystalline Rocks of Georgia: Ga. Geol. Surv. Bull. 58.

Eugster, Hans and Yoder, H. S. (1954) Carnegie Institution of Washington Yearbook No. 53, p. 112 (Fig. 7).

Haidinger, M. W., (1860) Die Rutilkrystalle von Graves Mount in Georgia U.S.N.A.: Akad. Wiss. Wien, vol. 39, p. 5-9.

Heitanen, Anna, (1956) Kyanite, andalusite and sillimanite in the schist at Boehls Butte Quad., Idaho. Amer. Min., vol. 41, p. 1-28.

Hemley, Julian J., (1959) Some Mineralogical Equilibria in the System K_2O-Al_2O_3-SiO_2-H_2O: Amer. Jour. Sci. vol. 257, p. 241-70.

Johnston, W. E., (1935) Kyanite at Graves Mountain: Ga. Geol. Surv. Bull. 46, p. 26-30.

Kennedy, George C., (1955) Pyrophyllite-sillimanite-mullite Equilibrium Relations to 20,000 bars and 800°C. (Abstract): Geol. Soc. Amer. Bull. 66, p. 1584.

Lasaulx, A., (1883) Optisch-Mikroskopische Untersuchung der Krystalle des Lazulith von Graves Mountain, Lincoln County, Georgia, U.S.A.: Niederrhein, Gesell.

Miyashiro, A., (1949) The Stability relation of kyanite, sillimanite, and andalusite and the physical condition of metamorphic process: Geol. Soc. Japan, Jour., vol. 55, p. 218-223.

Mügge, O., (1884) Bemerkungen uber die Zwillingsbildung einiger Mineralien: Neues Jahrb., Bank 1, p. 221.

——————, (1886) Zur Kenntnis der Flachen veranderungen durch Secondare zwillingsbildung Neues. Jahrb. Band 1, p. 147-154.

——————, (1897) Mineralogische Notizen: Neues Jahrb. Band 2, p. 82-84.

Rath, G., (1881) Ein neuer Beitrag zur Kenntniss der Krystisation des Cyanit: Zeitschrift fur Krystallographie, Band 5, p. 17-23.

Rose, Gustav, (1862) Ueber eine neue kreisformige Verwachsung des Rutils: Annalen der Physik und Chemie, vol. 115, p. 643-649.

Roy, D. M., (1954) Hydrothermal Synthesis of Andalusite: Am. Min., vol. 39, p. 140-143.

Roy, Rustum and Osborn, E. F., (1954) The System Al_2O_3-SiO_2-H_2O: Amer. Min., vol. 39, p. 853-885.

Shepard, C. U., (1859) On Lazulite, Pyrophyllite, and Tetradymite in Georgia: Amer. Jour. Sci., vol. XXVII, p. 36-40.

Thompson, J. B., Jr., (1955) The Thermodynamic basis for the mineral facies concept: Amer. Jour. Sci., vol. 253, p. 65-103.

Watkins, Noel H., (1942) Kyanite in Graves Mountain, Georgia: Amer. Cer. Soc., Bull. vol. 21, p. 140-141.

Watson, T. L., and Watson, J. W., (1912) A Contribution to the Geology and Mineralogy of Graves Mtn., Ga.: Virginia Univ. Philos. Soc. Bull., Sci. Series, vol. 1, p. 200-221.

Watson, T. L. (1915) The Rutile Deposits of the Eastern U. S.: U. S. Geol. Surv. Bull. 580, p. 391-392.

——————, (1921) Lazulite of Graves Mtn., Ga., etc.: Wash. Acad. Sci. Jour., vol. 11, p. 386-391.

Yoder, Hatten S. and Eugster, H. P., (1955) Synthetic and Natural Muscovites: Geochimica et Cosmochimica Acta, vol. 8, p. 225-280.

Zodac, Peter, (1939) Graves Mountain, Georgia: Rocks & Minerals, vol. 14, No. 5, p. 131-141.

INDEX


GEOLOGIC MAP of
GRAVES MTN., LINCOLN CO., GA.
APPROXIMATE SCALE
0 100' 200' 300' 400'
1959
Vernon J. Hurst
N
US Hgwy 378
GA Hgwy 47
To Washington
To Lincolnton
CEM
CEM
Vernon J.Hurst
EXPLANATION
ROCKS
Sericite-kyanite-quartz rock
The sericite is 2M muscovite or paragonite, or both. In the stippled areas the kyanite is fine-grained & generally not visible to the unaided eye; in the coarse random-hatched areas, the kyanite blades are more than a quarter-inch long, and may be longer than one inch.
Conglomeratic sericite-kyanite-quartz rock
Quartz-sericite schist
Quartz-muscovite schist (solid color); quartz-muscovite-paragonite schist (hachures).
MINERAL CONCENTRATIONS
Pyrophyllite
Rutile
Lazulite
SYMBOLS
Lithologic contact, dashed where approximate
Strike and dip of bedding
Strike and dip of schistosity
Top of beds, as indicated by graded bedding
Prospect pit and trench
Prospect shaft
Adit
House
Service station
Church
Cemetery
Orchard
Dam and lake
Spring
Sawdust pile
Power transmission lines
Triangulation station