BULLETIN 47

Kyanite Occurrences in the Petaca District, Rio Arriba County, New Mexico

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Abstract

The kyanite deposits of the Petaca district, in north-central New Mexico, are approximately 55 airline miles north of Santa Fe. They occur on and near La Jarita Mesa, a part of the long, southeast-trending prong of the San Juan Mountains. The mesa surface, a dissected remnant of the Pliocene Santa Fe peneplain, ranges in altitude from 6,500 to 9,500 feet and is bordered on the east and west by the canyons of the Rio Tusas and the Rio Vallecitos, respectively.

The Proterozoic Petaca schist series, chiefly quartzites and quartz-mica schists with intercalated metavolcanic rocks, underlies the mesa and is flanked by sedimentary and volcanic rocks of Tertiary age. Numerous pegmatite bodies and quartz veins in the metamorphic terrane are related genetically to a nearby late Precambrian granite batholith. The Petaca schist series and associated younger Precambrian rocks include 10 lithologic types: quartzite, quartz schist, sericite schist, kyanite schist, metaconglomerate, garnet schist, biotite schist, amphibolite, pegmatite, and quartz (as veins).

The dominant structural feature in the district is a succession of large isoclinal anticlines and synclines with axes that strike and plunge northwestward. These folds are overturned to the northeast. Superimposed on their flanks are numerous smaller folds of varying sizes but similar attitude. Foliation, well developed in most of the metamorphic rocks, is essentially parallel to original bedding; on the limbs of folds it strikes north-northwest and dips south-southwest. Conspicuous minor crenulations in the micaceous rocks attest to reapplication of stress along the original directions related to folding. Joint sets in the competent rocks controlled the emplacement of quartz veins, and many pegmatite bodies also cut across the foliation of the host rocks.

Kyanite occurs in a major group of deposits with commercial potentialities lying within an area of 3 square miles in the north-central portion of La Jarita Mesa, and in a minor group of deposits containing very low-grade ore. The 6 deposits of the major group comprise 25 lenses of kyanite schist that are conformable with the country rock. Each lens of kyanite-bearing rock is inclosed in a shell of sericite schist that in turn grades outward into quartz schist and thence into quartzite.

The masses of kyanite schist, containing essential quartz, kyanite, and mica, were produced mainly by the progressive metamorphism of pelitic silt lenses. Lenticular or irregular masses of coarse-grained quartz-interlacing kyanite rocks and quartz-rosette kyanite rocks within the kyanite schist were formed in the absence of stress toward the end of the metamorphic period. Either metamorphic differentiation or deposition from hydrothermal solutions contaminated by dissolved kyanitic material is believed to have been responsible for the development of these bodies. Still later in Precambrian time, hydrothermal solutions with

assimilated kyanitic material formed quartz-kyanite veins along joints in the lenses of kyanite schist.

The most favorable economic features of the major kyanite deposits are: (1) the presence of kyanite schist of apparent commercial grade, (2) a moderate tonnage of exposed ore and potentially large ore reserves, and (3) the occurrence of scrap mica as a possible byproduct from the sericite schist. The most unfavorable factor is the isolated location of the deposits with respect to railroads and markets.

Introduction

LOCATION AND ACCESSIBILITY

The Petaca district of north-central New Mexico is in the eastern half of Rio Arriba County, about 35 miles south of the Colorado—New Mexico State line (fig. 1). By road the area is approximately 55 miles west of Taos, 74 miles north of Santa Fe, and 55 miles north of Espanola, New Mexico, as well as 53 miles southwest of Antonito, Colorado.

The major kyanite deposits lie on La Jarita Mesa within an area of about 3 square miles (pl. 1). The mesa is bounded on the east and southeast by the canyon of the Rio Tusas, on the west and southwest by the canyon of the Rio Vallecitos, on the north by Kiawa Mountain, and on the south by La Madera Mountain. The area of principal interest extends in a north-northeast direction for about 2½ miles from a point approximately 4 airline miles north-northeast of Vallecitos or 41A miles west-northwest of Petaca. The deposits lie in sections 22, 23, 26, 27, 28, and 34, of T. 27 N., R. 8 E., New Mexico Base Line and Principal Meridian.

All-weather, graveled roads approach to within 1 or 2 miles of all the kyanite-bearing outcrops, and unimproved branch roads, suitable for truck use, provide direct access to the deposits. The nearest railroad lines are the Atchison, Topeka & Santa Fe Railway at Santa Fe and the Denver & Rio Grande Western Railroad at Antonito, Colorado.

PHYSICAL FEATURES

La Jarita Mesa lies entirely within the Carson National Forest, and open stands of Douglas and white fir, ponderosa pine, and aspen, interspersed with broad grassy meadows, mark the rolling surface of the plateau. Relatively little underbrush is present, although locally scrub oaks and bushes form dense thickets. Kiawa Mountain, with a summit altitude of approximately 9,700 feet, rises nearly 1,000 feet above La Jarita Mesa. From the base of this mountain the mesa surface slopes gently eastward and southward to its lowest point, north of La Madera, at an altitude of 6,500 feet. Owing to its southeastward tilt, this surface is scored chiefly by east- and southeast-draining tributary canyons of the Rio Tusas.

The area is thinly populated, the inhabitants consisting mainly of Spanish-Americans who live almost exclusively in the few small settlements on the narrow strips of fertile land bordering the Rio Tusas and the Rio Vallecitos. The principal occupations are lumbering, based upon the truck delivery of logs to a sawmill near Vallecitos, and farming, which includes cattle grazing on La jarita Mesa and the raising of grain and forage crops on irrigated farmlands adjacent to perennial

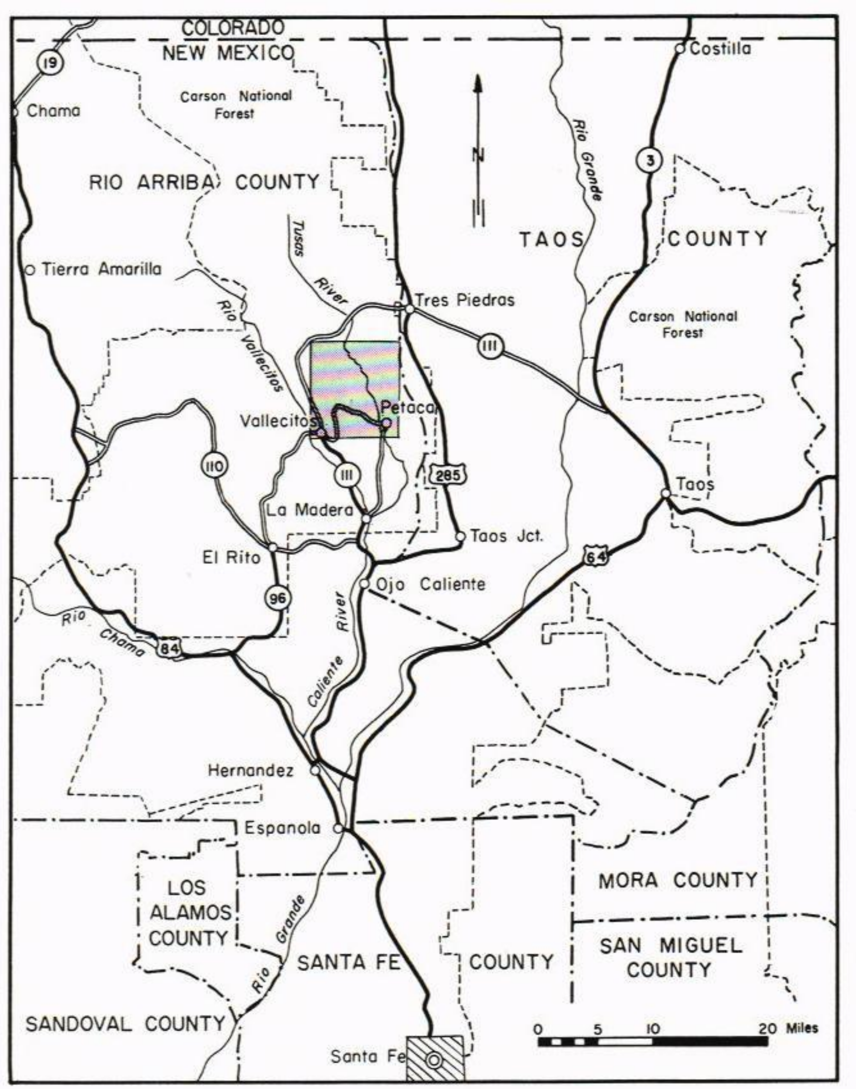

Figure 1

INDEX MAP OF KYANITE DEPOSITS, PETACA DISTRICT,
RIO ARRIBA COUNTY, NEW MEXICO

streams. Beginning as early as the 17th century, the mining of mica was an important activity in this region, but it is now confined to working dumps of the old pegmatite mines for scrap-grade material.

The summer climate in the area is rather mild, with warm days and invariably cool nights. In winter, however, temperatures from —12° to —29° Centigrade accompany the several inches to a foot of snow that covers the plateau. The average precipitation of 25 inches per year is provided chiefly by summer and fall rains and by winter snows.

Water sources on the mesa are scattered small springs, several ponds formed by the damming of intermittent streams, and Kiawa Lake, which occupies a shallow natural depression at the north end of the mesa. The springs and dams are maintained by the United States Forest Service. The only noteworthy permanent streams in the entire area are the southward flowing Rio Tusas and Rio Vallecitos, which merge at La Madera to form the Caliente River.

PREVIOUS WORK

Although the occurrence of kyanite in Rio Arriba County was recorded nearly 50 years ago (Sterrett, 1913), little attention had been given to the geology of the deposits prior to the present investigation. Outcrops of kyanite-bearing rock in the district were mentioned by Talmage and Wootton (1937), Just (1937), Northrop (1942), and Jahns (1946). The general geology of the area was described briefly by Sterrett (1923), by Atwood and Mather (1932), and more fully by Just (1937). Some additional information was furnished by Jahns (1946). A recent report by Barker (1958) presents a comprehensive and detailed treatment of geologic relationships in the Las Tablas quadrangle, which includes much of La Jarita Mesa and most of the areas where kyanite deposits are known.

FIELD AND LABORATORY WORK

In June 1951 the present writer began an investigation of kyanite occurrences in the Petaca district for the New Mexico Bureau of Mines and Mineral Resources. The field studies were continued through September 1951 and were completed during the period June-September 1952. Six large kyanite deposits were mapped with planetable and telescopic alidade at a scale of 40 feet to the inch. In addition, examinations were made of several kyanite occurrences in the quartzites of Kiawa Mountain, La Madera Mountain, and the rugged spurs south and west of Vallecitos.

Laboratory studies were made in the Department of Mineralogy of the University of Michigan during the academic years 1951-52 and 1952-53. These studies included megascopic and thinsection examination of the rocks, modal analyses, heavy-mineral separations with mineral counts, specific-gravity determinations, studies of crushed fragments, quantitative chemical analyses, and X-ray studies.

ACKNOWLEDGMENTS

The writer wishes to express his gratitude for the aid and cooperation given by the following: Dr. E. W. Heinrich, for continuous assistance and advice on the problems encountered in the field and laboratory and in preparation of the manuscript, for access to his compiled data on minerals of the sillimanite group, and for the loan of several photographs; Drs. C. B. Slawson, E. N. Goddard, F. S. Turneaure, and L. S. Ramsdell, who read the manuscript and offered constructive criticisms; Dr. L. I. Briggs, for helpful suggestions on a particular aspect of the work; Drs. Eugene Callaghan and N. L. Bowen, who visited the writer in the field during the summer of 1951 and made several valuable suggestions; Drs. Fred Barker and Harold Groom for much valuable information derived from their studies of the general geology of the Petaca district; the office staff of the New Mexico Bureau of Mines and Mineral Resources and personnel of the United States Forest Service for their kind cooperation in many ways; Mr. Tomas Chavez and Mr. Joe B. Martinez, Sr., of Vallecitos, and Mr. Joe B. Martinez, Jr., of La Madera, for many personal kindnesses; Mr. G. Dixon, of the Kyanite Mining Corp., Mr. K. W. Smith, of the Chas. Taylor Sons Co., Dr. W. R. Foster, of Ohio State University, and Mr. B. L. Gunsallus, of the United States Bureau of Mines, for statistics on the grade, production, and prices of foreign and domestic kyanite; Mr. Derwin Bell, of the University of Michigan, who drafted the index maps; and Alice Seguare Corey for continuous assistance.

The New Mexico Bureau of Mines and Mineral Resources provided financial support for the field work in 1951 and 1952. Dr. Eugene Callaghan, then director of the Bureau, took an active interest in many phases of the project. The author also is indebted to the Department of Mineralogy of the University of Michigan for use of its facilities, and to the United States Forest Service for housing during the summer of 1951.

Dr. R. H. Weber and Mrs. Glenda K. Niccum prepared the index.

Geologic Setting

The Petaca district, including La Jarita Mesa, lies in the prong of the San Juan Mountains that extends southeastward from Colorado into the northern third of Rio Arriba County, New Mexico. This prong is bounded on the east by the Rio Grande Valley, on the south by the valley of the Chama River, and on the west by the San Juan Basin.

The southeastern extension of the San Juan Mountains is composed of Precambrian rocks that are overlain in places by much younger sedimentary and volcanic rocks. The Precambrian section of the Petaca district has been divided by Just (1937, p. 10-11) into the Hopewell series of Archeozoic or Proterozoic age and the overlying Ortega quartzite of Proterozoic age. The Hopewell series is a succession of metamorphosed volcanic flows and subordinate metamorphosed sediments that are exposed in two belts. The larger belt is about 2 miles wide, trends northwestward, and crops out north of Kiawa Mountain. The other trends westward across the Ojo Caliente district, a few miles south of La Madera Mountain.

The Ortega quartzite, chiefly quartzite with interlayered metamorphosed volcanic rocks, is exposed in a north-trending belt that parallels the Rio Tusas and lies between the southern and northern belts of the Hopewell series. Within it is a subordinate unit, the Petaca schist, that is composed mainly of muscovite-bearing quartzite, quartz-muscovite schist, and micaceous metarhyolite. This unit, which is largely restricted to La Jarita Mesa, is thought by Barker (1958, p. 34, 87) to represent partial muscovitization of quartzite, metaconglomerate and metarhyolite.

Late Precambrian acidic and basic extrusive and intrusive rocks appear within both the Ortega and Hopewell series. Among these is the Tusas granite, which forms a batholith that is exposed in part along the eastern and northeastern borders of La Jarita Mesa (pl. 2).

The outstanding structural feature within the Precambrian rocks of the Petaca district is a series of large, plunging isoclinal folds that trend west-northwest to north-northwest. Several of these folds have been mapped in detail by Barker (1958, p. 65-68). Largest among them is the Kiawa syncline, which extends from La Jarita Mesa northwestward to the eastern part of the Tierra Amarilla Grant, a distance of more than 20 miles, and plunges consistently to the northwest. At a point approximately 1 mile northeast of the Kiowa View III deposit, the trend of the synclinal axis is approximately N. 45° W., and its plunge is 45 to 55 degrees to the northwest. At Kiawa Mountain the axis trends N. 70° W. and plunges 15 degrees to the west-northwest. On the west slope of Kiawa Mountain, the beds dip 80 degrees south to vertical, and to the east the dip ranges from 55 to 80 degrees southwest. The area treated in this report lies on the southwest limb of this major syncline, which here is complicated by large subsidiary folds (Barker, 1958, p. 67-68).

On the flanks of the major folds, the beds generally strike westward to northward. Dips vary from southward to westward, and inclinations from 10 degrees to vertical. Information on the attitude of the Ortega quartzite on the mountainous spurs south and west of Vallecitos and on La Madera Mountain was obtained from Harold Groom (1953, personal communication), who made a preliminary study of the geology of the southern half of the Petaca district. The strike of the quartzite south and west of Vallecitos is N. 20° to 30° W., and the dip varies from vertical to 45° SW., the average being about 60 degrees. The beds at La Madera Mountain strike about N. 70° W. and dip about 75° NE.

Foliation is essentially parallel to bedding in the metasedimentary rocks through most of the area, although local deviations occur. This interpretation of the relationship of foliation to bedding agrees with that made by Just (1937, p. 41-42), but Jahns (1946, p. 20) states that discordance of foliation and bedding is evident wherever the crests and troughs of folds can be seen.

Evidence for Precambrian faulting is meager in the Petaca district. Jahns (1946, p. 108) mentions faults, with a maximum horizontal dis-

Figure 2

TYPICAL EXPOSURES OF PETACA SCHIST IN LA JARITA CANYON

Looking east. Basalt-capped mesas in middle distance; Picuris Range and Sangre de Cristo Mountains in far background.

placement of 105 feet, within the quartzites and quartz schists 1.6 miles east-southeast of Kiawa Mountain. Slip joints and faults, trending northwest and dipping steeply southwest, also are recorded by Jahns (1946, p. 234) from an area approximately 4.5 miles due north of La Madera Mountain.

La Jarita Mesa is the largest remnant of the Santa Fe peneplain, which was developed in Pliocene time (Just, 1937, p. 17). Precambrian metamorphic rocks exposed in the central and eastern portions of the plateau are overlapped on nearly all sides by sedimentary and volcanic rocks of middle and late Tertiary age. Rejuvenation of the Petaca region, which Just (1937, p. 17) suggests took place during latest Tertiary or earliest Quaternary time, has resulted in a presently youthful stage of erosion of the plateau. Numerous steep-sided, V-shaped canyons have been cut into the undulating tableland surface by the tributaries of the Rio Tusas and Rio Vallecitos (fig. 2).

Rock Types

METAMORPHIC ROCKS

GENERAL FEATURES

The metamorphic rocks that crop c within the area of major kyanite deposits constitute a small part of the Petaca schist, a series of quartzites and schists named by Just (1937, p. 43) and considered by him to be a facies of the Ortega quartzite. The local lithologic units have been divided by the present writer into a predominant group and a subordinate group. Quartzite, quartz schist, sericite schist, and kyanite schist are the more widespread rock types. Some of the schists represent original volcanic rocks of rhyolite composition. The subordinate types include metaconglomerate, garnet schist, biotite schist, and amphibolite.

The distinctions among quartzite, quartz schist, and sericite schist are based arbitrarily upon content of muscovite. The quartzites typically contain less than 10 percent of muscovite, the quartz schists from 10 to 20 percent, and the sericite schists more than 20 percent. The term sericite, as used in this report, refers merely to very fine-grained muscovite and not to hydromuscovite.

QUARTZITE

The typical quartzites are light gray to tan, fine to medium grained, and massive to weakly schistose. In some outcrops these rocks weather red or reddish brown, owing to the oxidation of contained magnetite and ilmenite. Although the texture generally is granular and somewhat friable, a dense semivitreous quartzite crops out near the Kiowa View V deposit. Schistosity in the quartzites is due to widely spaced, very thin layers of parallel muscovite flakes, the long dimensions of which lie in planes presumably parallel to original bedding planes. The degree of orientation of the flakes varies systematically with the amount of mica present.

Quartz, the predominant mineral, forms equant grains in the groundmass of the rocks. It also occurs as thin stringers a few inches long, and as roughly spheroidal masses one-half to about 2 inches in diameter. Pink and white spots in some of the quartzites are formed by locally abundant grains of feldspar. The irregularly distributed feldspathic parts contain abundant quartz and scant mica. The modal composition of several representative quartzites is indicated in Table I (Nos. 1 and 2).

Under the microscope the quartzites appear dominantly granoblastic in texture owing to the intergrown grains of quartz. In some places feldspar, equidimensional with the quartz, contributes to this fabric. A schistose texture, produced by the parallel orientation of mus-

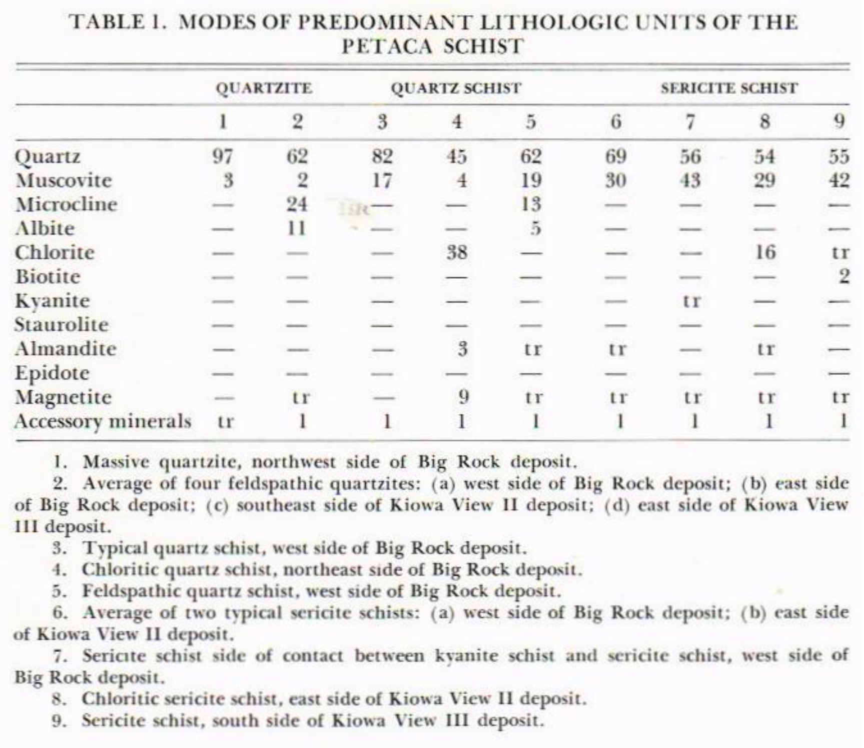

TABLE 1. MODES OF PREDOMINANT LITHOLOGIC UNITS OF THE PETACA SCHIST

	QUARTZITE		QUARTZ SCHIST			SERICITE SCHIST			
	1	2	3	4	5	6	7	8	9
Quartz	97	62	82	45	62	69	56	54	55
Muscovite	3	2	17	4	19	30	43	29	42
Microcline	—	24	—	—	13	—	—	—	—
Albite	—	11	—	—	5	—	—	—	—
Chlorite	—	—	—	38	—	—	—	16	tr
Biotite	—	—	—	—	—	—	—	—	2
Kyanite	—	—	—	—	—	—	tr	—	—
Staurolite	—	—	—	—	—	—	—	—	—
Almandite	—	—	—	3	tr	tr	—	tr	—
Epidote	—	—	—	—	—	—	—	—	—
Magnetite	—	tr	—	9	tr	tr	tr	tr	tr
Accessory minerals	tr	1	1	1	1	1	1	1	1

1. Massive quartzite, northwest side of Big Rock deposit.
2. Average of four feldspathic quartzites: (a) west side of Big Rock deposit; (b) east side of Big Rock deposit; (c) southeast side of Kiowa View II deposit; (d) east side of Kiowa View III deposit.
3. Typical quartz schist, west side of Big Rock deposit.
4. Chloritic quartz schist, northeast side of Big Rock deposit.
5. Feldspathic quartz schist, west side of Big Rock deposit.
6. Average of two typical sericite schists: (a) west side of Big Rock deposit; (b) east side of Kiowa View II deposit.
7. Sericite schist side of contact between kyanite schist and sericite schist, west side of Big Rock deposit.
8. Chloritic sericite schist, east side of Kiowa View II deposit.
9. Sericite schist, south side of Kiowa View III deposit.

covite flakes, gradually becomes dominant with an increasing content of mica.

The quartz most commonly forms a mosaic texture characterized by sharply defined grain borders. The mean dimension of the quartz grains in the groundmass has a minimum value of about 0.2 mm, and the average maximum dimension is near 0.4 mm. In many grains tiny inclusions of rutile and sericite form linear trains, some of which cross boundaries into adjoining grains. The groundmass quartz grains show little orientation of the c-axes or elongation in a specific direction. Evidences of strain, such as cracks, undulatory extinction, mortar structure, and the presence of biaxial crystals, are rare. Bands composed of finer grained quartz, averaging about 0.08 mm in diameter, appear in a few places. These bands, from 1 to 3 mm wide, are fairly continuous but have ragged and ill-defined borders.

Spherical segregations of quartz, from 1 to 4 mm in diameter, and crosscutting veinlets of quartz, from 0.08 to 2 mm thick, are common features. They are composed of interlocking quartz grains similar in size to those of the groundmass. The segregations are conspicuous because they are outlined by thin zones of muscovite and accessory minerals (fig. 3). The veinlets, generally disposed at an angle of schistosity,

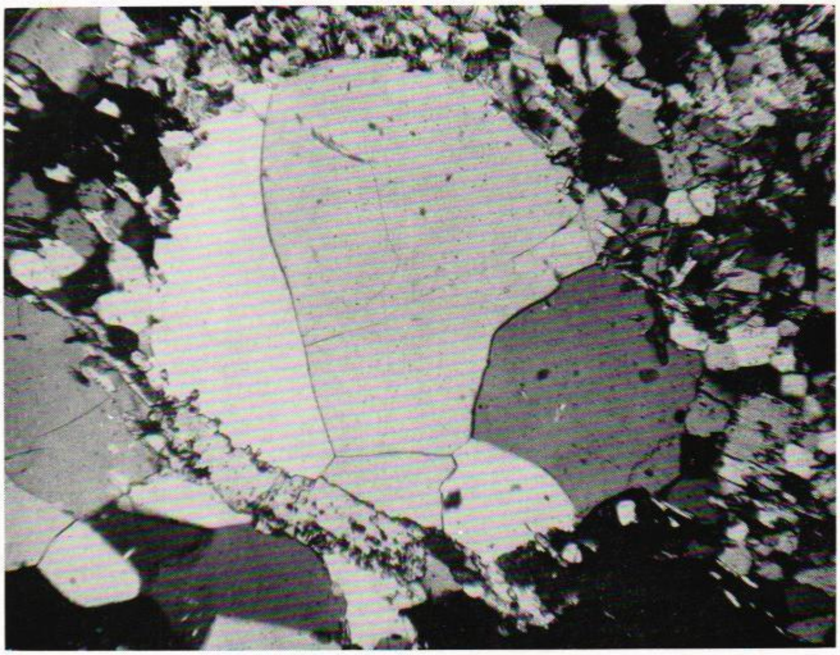

Figure 3

PHOTOMICROGRAPH OF QUARTZ SEGREGATION WITH RIM OF MUSCOVITE AND ACCESSORY MINERALS

Crossed nicols. × 40.

are likewise bordered by narrow zones of the other minerals, crystals of which are oriented with their long dimensions approximately parallel to the adjacent veinlet. Because they are independent of the schistosity, and because other minerals have not been formed across or within their borders, the veinlets and segregations are probably very late features of the quartzites.

Quartz also occurs as scattered embayed masses, each consisting of a few large anhedral quartz grains. These may represent relict pebbles of quartz. In temporal contrast to such masses is abundant fine-grained late-stage quartz that has partially replaced muscovite, feldspar, and chlorite along grain boundaries, cleavage surfaces, and twin planes.

Muscovite, although invariably present, is a minor constituent. Its average abundance in the massive quartzite is about 3 percent, in the feldspathic variety slightly less than 2 percent, and in the schistose quartzite about 8 percent. Its mode of occurrence also varies somewhat among these rock types.

In massive quartzite, unoriented porphyroblasts of muscovite are scattered throughout the quartz mosaic. Also present are a few stringers, none more than several millimeters long, that are composed of muscovite porphyroblasts laid end to end. In the schistose quartzite, a microscopic foliation is produced by layers of quartz a millimeter or so thick alternating with layers of muscovite commonly less than 0.3 mm thick. The mica flakes are strongly oriented and have a plaited or imbricate arrangement within the layers. Unoriented porphyroblasts of muscovite occur in the quartz bands but are less common than the nearby oriented flakes.

In the feldspathic quartzite, muscovite has developed chiefly through the selective replacement of feldspar grains in the quartz-feldspar groundmass. The progressive nature of this replacement can be inferred from numerous textural relationships. The process evidently begins with the sericitization of the feldspar along cleavage surfaces, twin planes, and grain boundaries, commonly continues with selective replacement of one of the sets of albite or pericline twins, and becomes complete with the coalescence of many sericite crystals to form single flakes of muscovite. Muscovite also has formed from the destruction of biotite, replacing flakes of the earlier mica mainly along their margins and cleavage planes. Associated with muscovite of this origin are chlorite and magnetite.

Feldspars are locally abundant in the quartzites. Both potash and plagioclase varieties generally are present, and each rarely appears alone. Potash feldspar dominates, although where both types are present, their abundance ratio varies within wide limits. The potash feldspar is microdine, in part perthitic; the plagioclase is calcic albite, with a composition ranging from $A13_9$. to Ab_{94}. The feldspars typically occur with quartz in mosaic intergrowths, and in younger untwinned porphyroblasts containing inclusions of quartz and, less commonly, of ilmenite, rutile, magnetite, apatite, and zircon. Many of the porphyroblasts and a few of the small grains of feldspar show incipient sericitization. A few feldspar crystals of the mosaics have been completely altered to muscovite, and some of the feldspar porphyroblasts have been partially replaced by quartz.

Accessory minerals, listed in order of decreasing abundance, are magnetite, rutile, zircon, sphene, ilmenite, apatite, almandite, and chlorite. Magnetite is idioblastic in its most common habit; it also occurs along the margins and in the cleavage planes of biotite partly altered to magnetite, muscovite, and chlorite. Rutile and sphene are present as isolated relict grains, irregular in shape, and as crystalline aggregates associated with ilmenite. Apatite and zircon appear as anhedral relict crystals. Small idioblasts of pale-pink almandite are sparingly present in some of the rocks classed as quartzite. Chlorite, least abundant of the accessory minerals, is associated with biotite in aggregates that are mottled green and brown and exhibit a random patchwork of anomalous and normal interference colors. The chlorite plainly was derived through partial alteration of the biotite.

Hematite and limonite, formed chiefly through the weathering of magnetite and ilmenite, are widespread. Leucoxene appears as a superficial alteration product on grains of ilmenite, rutile, and sphene.

QUARTZ SCHIST

The quartz schist is similar to the quartzites in many respects, but contains a higher percentage of muscovite. It is normally a nonresistant rock, but forms rare outcrops, where it also contains podlike segregations of quartz. The schist is light gray, tan, or red, and weathers to silvery tan or white. It is typically medium grained and decidedly schistose. The schistose or lepidoblastic texture results from the parallelism of numerous thin layers of muscovite flakes.

Quartz is the most abundant mineral, muscovite appears in considerable amounts, and feldspar, chlorite, almandite, and magnetite are locally abundant. Accessory minerals, listed in order of decreasing abundance, are rutile, zircon, apatite, ilmenite, and sphene. Hematite, limonite, and leucoxene are widely distributed alteration products. The modes of three representative quartz schists are listed in Table 1 (Nos. 3, 4, and 5).

Muscovite layers in the quartz schist are 0.05 mm to 1 mm thick, and alternate with 0.8- to 2-mm layers of quartz like that in the schistose quartzites. In several localities the mica layers are crumpled and highly contorted. In occurrence and textural habit the muscovite is similar to that of the quartzite, but it forms thicker and more closely spaced layers. In addition, late sericitization of feldspar has produced "shimmer aggregates." These are referred to by Harker (1939, p. 349), in his discussion of retrograde metamorphism of regionally metamorphosed rocks, as follows:

> The aluminous silicates ... often give rise to a confused mass consisting essentially of white mica, with some interstitial quartz, the "shimmer aggregate" of Barrow. Unless disturbed by subsequent shearing, the aggregate makes distinct pseudomorphs. Its appearance in this form relegates it to a somewhat late stage of cooling.

Layering is not conspicuous in the feldspathic quartz schists, and the relatively high percentage of muscovite in these rocks is due almost entirely to the occurrence of the mica as a replacement of feldspars. The characteristics of the feldspars are similar to those already described in connection with the quartzites.

In some localities chlorite is an abundant constituent of the quartz schists. The strong pleochroism (green = X and Y, colorless = Z), the anomalous interference colors, and other properties are similar to those of the pennine species. The chlorite typically forms irregularly terminated porphyroblasts, which occur in fan-shaped aggregates or in layers of varying thickness and length. The formation of additional chlorite at a later date is suggested by a few chlorite porphyroblasts that lie across the fans and layers. Associated with, or contained in, the chlorite are numerous idioblastic crystals of magnetite and almandite. Flakes of late-stage muscovite commonly transect aggregates of chlorite and muscovite, and porphyroblasts of muscovite also lie in parallel orientation with those of chlorite.

Some micaceous aggregates indicate alteration of biotite to chlorite, but a high ratio of chlorite to muscovite (as much as 9 to 1 in a few places) indicates that much of the chlorite has persisted from a stage of lower rank metamorphism rather than having been derived through alteration of biotite and almandite.

SERICITE SCHIST

The sericite schist is similar to the quartz schist in color and grain size but is markedly more schistose. It is characterized by layers of granular quartz and by layers of parallel muscovite flakes that are almost equally thick. Also present are scattered ellipsoidal masses, as much as 18 inches long, of varicolored quartz commonly surrounding cores of colorless quartz. Micaceous layers "wrap around" these zoned segregations.

Quartz and muscovite are the essential minerals of the sericite schist, although chlorite in places is a prominent constituent. The rock is similar in most respects to the quartz schist, but contains more muscovite and essentially no feldspar. The modes of representative sericite schists are listed in Table 1 (Nos. 6, 7, 8, and 9).

Quartz grains in the typical layers are commonly elongated parallel to the place of schistosity, but orientation of their c-axes is not apparent. Otherwise the quartz is similar to that already described. A well-developed lepidoblastic texture is the outstanding microscopic feature of the rock. Mica layers are either thick (several millimeters) or rather thin (0.3 to 0.5 mm), and are generally composed of very fine-grained muscovite (sericite) showing a plaited imbricate arrangement of flakes. In many places, aggregates of unoriented porphyroblastic muscovite are cut by late porphyroblasts of muscovite that rarely transect the mica layers.

In specimens from the contact between sericite schist and kyanite schist, all the kyanite crystals have been largely replaced by "shimmer aggregates," masses of small, randomly oriented muscovite flakes and interstitial quartz grains. These "shimmer aggregates" appear everywhere in the sericite schist, and probably are pseudomorphs after aluminosilicates such as feldspar (see p. 28-29). In the chloritic sericite schists, chlorite and sericite extensively replace each other. This relationship indicates overlapping periods of formation. Some dark-brown biotite also is associated with the chlorite.

Accessory minerals, listed in order of decreasing abundance, arc magnetite, rutile, almandite, ilmenite, zircon, apatite, pleonaste, and sphene. Pleonaste, a constituent of quartzose sericite schist, generally appears as small, light-green, relict grains of irregular shape.

KYANITE

Typical kyanite schists are light gray, light green, or tan, weathering to lighter tints, and are medium to coarse grained. Their complex texture is ascribable to three irregularly distributed intergradational rock types: (1) a granoblastic, medium- to coarse-grained type consisting of abundant small, randomly oriented laths of kyanite, a granular quartz matrix, and a few disseminated muscovite flakes; (2) a heteroblastic, coarse-grained type comprising large interlacing laths or rosettes of kyanite, coarse-granular interstitial quartz, and sparse, disseminated muscovite flakes; and (3) a weakly lepidoblastic, medium-grained type composed of widely spaced thin layers of muscovite oriented parallel to the foliation, and thick layers consisting of numerous small laths of kyanite in a matrix of sugary quartz. The granoblastic (1) and lepidoblastic (3) textures are the most widespread.

Mica layers "wrap around" roughly spheroidal to ellipsoidal quartzkyanite pods that appear in the schistose kyanite rock. These abundant

Figure 4

KYANITE VEIN, SHOWING COMB STRUCTURE, IN KYANITE SCHIST segregations, ranging in length from about 1 inch to 1 foot, consist of large, unoriented laths of kyanite, coarse-grained quartz, and rare flakes of muscovite. Not uncommon are veinlets of kyanite or quartz and kyanite, some of which cut across the schistosity. In these veinlets, which rarely exceed a few feet in length, the kyanite blades or fibers generally are oriented with their long axes at right angles to the walls, in comb-structure fashion (fig. 4). Characteristically present in the kyanite schist are discontinuous veinlets and lenticular bodies of coarse colorless quartz. Their late formation is evidenced by their independence of the schistosity and by the usual slight enlargement of contiguous minerals within a narrow border zone. Thick quartz veins containing kyanite also are present in the kyanite schist, and are discussed farther on.

The mineral composition of representative kyanite schists is given in Table 2 (Nos. 1-8). Quartz, kyanite, and muscovite are the overwhelmingly abundant constituents.

The quartz of the kyanite schist (other than vein quartz) is similar in its characteristics to the quartz described from the other rocks. The kyanite shows a distinct tendency to be aggregated, either in clusters of unoriented twinned porphyroblasts or in swarms of small idioblastic needles whose long axes generally are parallel and lie in the plane of schistosity. Most of the porphyroblast kyanite has been replaced extensively by muscovite and quartz, especially along cleavage and twin planes

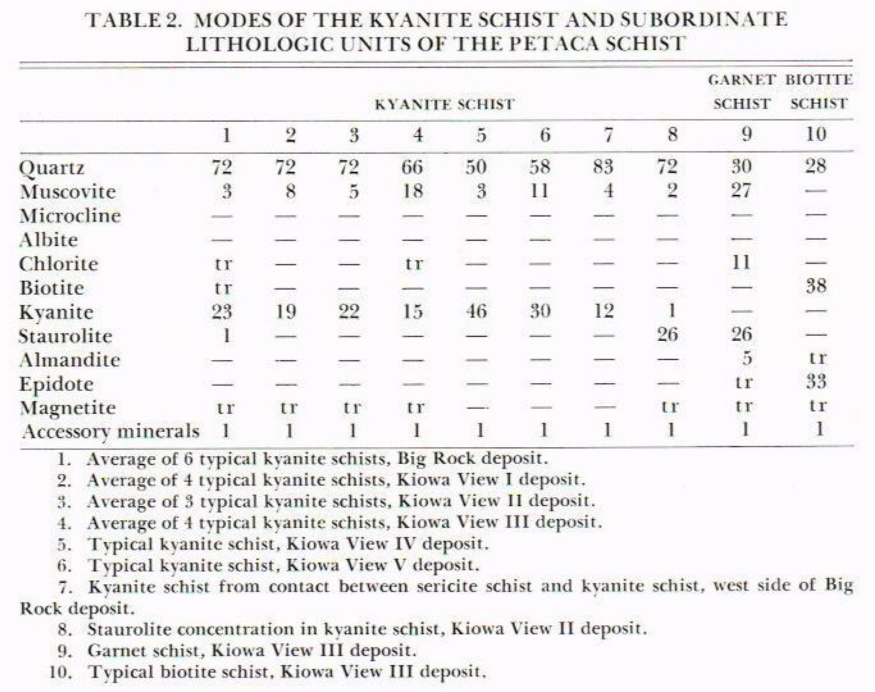

TABLE 2. MODES OF THE KYANITE SCHIST AND SUBORDINATE LITHOLOGIC UNITS OF THE PETACA SCHIST

	KYANITE SCHIST								GARNET SCHIST	BIOTITE SCHIST
	1	2	3	4	5	6	7	8	9	10
Quartz	72	72	72	66	50	58	83	72	30	28
Muscovite	3	8	5	18	3	11	4	2	27	—
Microcline	—	—	—	—	—	—	—	—	—	—
Albite	—	—	—	—	—	—	—	—	—	—
Chlorite	tr	—	—	tr	—	—	—	—	11	—
Biotite	tr	—	—	—	—	—	—	—	—	38
Kyanite	23	19	22	15	46	30	12	1	—	—
Staurolite	1	—	—	—	—	—	—	26	26	—
Almandite	—	—	—	—	—	—	—	—	5	tr
Epidote	—	—	—	—	—	—	—	—	tr	33
Magnetite	tr	tr	tr	tr	—	—	—	tr	tr	tr
Accessory minerals	1	1	1	1	1	1	1	1	1	1

1. Average of 6 typical kyanite schists, Big Rock deposit.
2. Average of 4 typical kyanite schists, Kiowa View I deposit.
3. Average of 3 typical kyanite schists, Kiowa View II deposit.
4. Average of 4 typical kyanite schists, Kiowa View III deposit.
5. Typical kyanite schist, Kiowa View IV deposit.
6. Typical kyanite schist, Kiowa View V deposit.
7. Kyanite schist from contact between sericite schist and kyanite schist, west side of Big Rock deposit.
8. Staurolite concentration in kyanite schist, Kiowa View II deposit.
9. Garnet schist, Kiowa View III deposit.
10. Typical biotite schist, Kiowa View III deposit.

and grain boundaries, but the kyanite needles are fresh. Many of the porphyroblasts contain inclusions of quartz, and in places are distinctly poikiloblastic. Also included are crystals of magnetite, ilmenite, rutile, zircon, and apatite.

Some of the large crystals of kyanite are twisted and show undulatory extinction, indicating slight late cataclasis. Commonly they form aggregates composed of randomly oriented, interpenetrating crystals, as well as subradiate groups and rosettes. Many of the crystal groups, as well as some individual crystals, are cut or disrupted by later porphyroblasts of kyanite. In the immediate vicinity of the quartz segregations and of the quartz veins, kyanite has been largely replaced by quartz, in places producing skeletal crystals. The kyanite of all types is generally very pale, but in the Big Rock and Kiowa View I deposits, kyanite pleochroic in shades of blue is present in accessory amounts.

Muscovite in the kyanite schist shows all the microscopic features described in connection with its occurrence in the other predominant rock types. Much of it is indicated by the presence of "shimmer aggregates," which may be seen, or presumed, to have resulted from the replacement of porphyroblasts of kyanite, staurolite, and possibly other aluminosilicates, such as feldspar.

Porphyroblastic staurolite is abundant in a few parts of the Kiowa View II deposit. Pleochroic (bright yellow Z, yellow = Y, pale yellow = X) and typically poikiloblastic, most of it is partially replaced by quartz and muscovite. The occurrence of idioblastic kyanite as inclusions in the porphyroblastic staurolite, as well as the reverse relationship, indicates overlapping periods of formation.

Epidote in small, pale-green to colorless, idioblastic crystals, and topaz in irregularly shaped relict grains are rare accessory constituents. Other accessory minerals, listed in order of decreasing abundance, are rutile, zircon, magnetite, ilmenite, sphene, apatite, chlorite, and biotite. Hematite, limonite, and leucoxene are widely distributed.

KYANITE-BEARING QUARTZITES

The kyanite-bearing quartzites of Kiawa Mountain, La Madera Mountain, and the two mountainous spurs that extend into the canyon of the Rio Vallecitos near the village of Vallecitos, possess many lithologic features in common. They are fine-grained, gray to blue-gray rocks with granoblastic textures produced by intergrown grains of quartz that form a mosaic pattern. Ptygmatic folds can be traced along dark magnetite-rich bands that appear in the quartzites at many places.

Kiawa Mountain

Kyanite-bearing quartzite with numerous dark-colored layers crops out extensively on the northeast and east sides of Kiawa Mountain. Under the microscope, the dominant quartz grains of the dark layers are seen to form a mosaic intergrowth and to contain numerous inclusions of magnetite, rutile, apatite, and zircon. Abundant in many layers are small grains of andalusite that are distinguished by a green color, extraordinary pleochroism (golden yellow to emerald green), and very strong dispersion ($v > r$). This andalusite is a rare manganian variety generally referred to as viridine, and its composition, optical properties, and occurrence have been detailed elsewhere (Heinrich and Corey, 1959).

The kyanite occurs chiefly as oriented porphyroblasts that contain many inclusions of quartz, magnetite, and rutile. Much of it is replaced by quartz, muscovite, and andalusite. The amount of kyanite present ranges from about 0.5 to 20 percent of the rock. Most of it is not megascopically visible.

Muscovite, in unoriented porphyroblasts and tiny idioblasts, appears in scarcely more than accessory amounts, chiefly as replacements of kyanite and andalusite. Magnetite generally is idioblastic, also occurring in irregularly shaped aggregates of xenoblastic grains. It constitutes 5 to 15 percent of the dark-colored layers. The andalusite occurs chiefly in aggregates consisting of unoriented porphyroblasts and in small disseminated idioblasts; ordinarily associated with kyanite, it replaces that mineral locally. Quartz, magnetite, rutile, and zircon are common inclusions in grains of the andalusite. The accessory minerals arc rutile, sphene, ilmenite, zircon, and apatite.

Widely scattered veins of milky quartz, some containing high percentages of kyanite, crop out in the quartzite of Kiawa Mountain. These veins are similar to those in the lenses of kyanite schist.

Vallecitos

Fractures in the quartzite that forms the spurs south and west of the village of Vallecitos are filled with quartz, muscovite, magnetite, and kyanite. The kyanite occurs in small laths whose long dimensions lie parallel to the walls of the fractures. Under the microscope the dominant quartz appears in large, xenoblastic grains with sutured, ill-defined borders. Elongate parallel porphyroblasts of kyanite are abundant, and some are almost completely replaced by quartz and sericite. Rectangular idioblasts of magnetite and ilmenite are oriented with their long dimensions parallel to the long axes of the kyanite laths. The few porphyroblasts of muscovite and the many idioblasts of sericite also share this general orientation (fig. 5). Accessory minerals are rutile, phene, zircon, and epidote.

Quartz-kyanite veins, identical in mineralogy and texture with those of Kiawa Mountain, also traverse the quartzite.

La Madera Mountain

Quartz-kyanite veins were not found in the quartzite on the south flank of La Madera Mountain. However, kyanite does occur in the

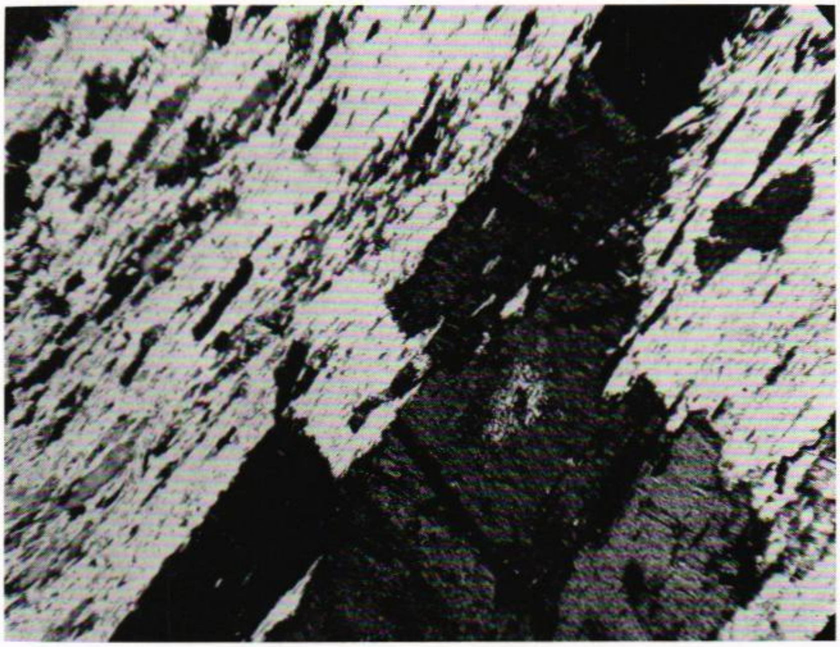

Figure 5

PHOTOMICROGRAPH OF PORPHYROBLASTIC KYANITE PARTIALLY REPLACED BY MUSCOVITE AND QUARTZ

Fracture-filling aggregate in kyanite-bearing quartzite near Vallecitos. Muscovite, magnetite, and kyanite show parallel orientation. Crossed nicols. × 130.

quartzite as disseminated crystals and as rosettes. The small laths of kyanite, averaging less than one-half inch in length, are colorless, lusterless, and somewhat weathered.

Dark bands, similar in appearance to those in the quartzite of Kiawa Mountain, occur locally in the quartzite. Microscopic examination reveals a groundmass composed of quartz intergrown in a mosaic texture, with a slight parallel elongation of many of the grains. Kyanite porphyroblasts, somewhat replaced by quartz and sericite, are suboriented with respect to the preferred direction of elongation of quartz. The long dimensions of rectangular magnetite and ilmenite idioblasts are parallel to the elongation of the adjacent kyanite crystals.

BIOTITE SCHIST

Biotite schist, interlayered with quartzite and quartz schist, crops out near the Kiowa View III deposit. It is a rusty black at the outcrop, but freshly fractured surfaces are a glistening brown black. The biotite schist is medium grained and highly schistose. The modal composition of a typical specimen is listed in Table 2 (No. 10).

Quartz and biotite form layers that range in thickness from a knife edge to 0.1 inch. Small clusters and lenticles of equant grains of quartz and epidote are encased in biotite folia. The schistosity is due to a preferred orientation of the biotite flakes in planes presumably parallel to original bedding planes. Aggregates of quartz and epidote occur in the biotite layers and appear to have forced aside the adjacent biotite flakes. Elongation or orientation of the quartz grains is not apparent.

The biotite is strongly pleochroic (brown black to buff, $X < Y$ and Z), with 2V = 0°10° and y = 1.616. The high ratio of elongation (7:1) of the biotite porphyroblasts furnishes a rough index of the rather intense recrystallization (Tyrrell, 1929, p. 267). Many of the porphyroblasts contain inclusions of quartz, rutile, and apatite. Biotite has not been replaced by other minerals except slightly by quartz.

Epidote occurs as xenoblastic, in places idioblastic, crystals in aggregates with quartz or as disseminated grains generally associated with biotite. The crystals, with an average diameter of about 0.4 mm, are colorless. They have a 2V of approximately 70° and y = 1.780, indicating a content of about 37 percent of the iron epidote member.

Ilmenite and magnetite porphyroblasts are present in some places. Hematite and limonite are widespread.

METACONGLOMERATE

In the Kiowa View II deposit a small mass of metaconglomerate is gradational into enclosing quartz schist. This rock might be regarded as a coarse-grained variety of quartz schist were it not for extensive exposures of similar and in part coarser rocks in nearby areas. Layers of metaconglomerate, for example, crop out over a considerable area northwest of the Big Rock deposit, where they are in sharp contact with the surrounding rock types and can be treated as a separate lithologic and stratigraphic unit. The larger exposed masses, conformable with the adjacent metamorphic rocks, consist of alternating layers of conglomerate and quartz schist. Generally the attitude of the foliation is parallel to that of the bedding, but locally the two features differ distinctly in trend.

The metaconglomerate is blastosephitic in structure, with numerous pebbles and cobbles, one-half inch to 6 inches in longest dimension, embedded in a matrix similar to that of the quartz schist (fig. 6). Generally ellipsoidal in shape and oriented with their long axes lying in the plane of schistosity, the pebbles and cobbles are composed chiefly of colorless vein quartz and rarely of white quartzite. In places the quartz is stained by ferric oxide or colored gray by numerous tiny interstitial grains of magnetite. Attenuation of the pebbles and cobbles is rare, and

Figure 6
METACONGLOMERATE, KIOWA VIEW II DEPOSIT

most are in sharp contact with the enclosing layers of quartz and mica. Their orientation has produced a distinct lineation in the rock.

GARNET SCHIST

Garnet schist occurs at the Big Rock deposit, where it forms a layer approximately 80 feet long and 40 feet wide. It grades into surrounding quartz schist. However, exposures as much as one-half mile long and several hundred feet thick elsewhere on La Jarita Mesa show sharp contacts with adjoining rock types.

Typical garnet schists are silvery gray, spotted with dark porphyroblasts, and weather rcd brown. They are heteroblastic in texture. Very large unoriented porphyroblasts of magnetite, ilmenite, staurolite, almandite, and chlorite appear in a schistose matrix similar to that of the quartz schist. The ratio of total porphyroblasts to groundmass and of the different porphyroblast minerals to one another varies considerably from place to place. The mode of a garnet schist unusually rich in staurolite is given in Table 2 (No. 9).

The microscopic banding of quartz and mica in the garnet schist is identical with that in the quartz schist, but it is less conspicuous than the superimposed heteroblastic texture produced by the large, randomly oriented idioblastic crystals of staurolite, chlorite, almandite, and muscovite.

Porphyroblasts of yellow staurolite have been replaced by porphyroblastic chlorite and muscovite to a moderate extent, and by quartz to a lesser degree. The replacement occurs chiefly along the crystallographic directions of the staurolite.

Numerous crystals of almandite, 1 to 3 mm in diameter, appear as inclusions within the staurolite. They are somewhat fractured and contain abundant tiny blebs of quartz. Both large and small crystals of almandite are idioblastic and exhibit the common trapezohedral outlines. In a few of the staurolite porphyroblasts, as well as in the almandite inclusions, many included elongate or rodlike grains of magnetite are oriented with their long dimensions parallel to the (010) plane of the staurolite.

The accessory minerals of the garnet schist are magnetite, ilmenite, rutile, zircon, apatite, and epidote. Magnetite and small idioblastic crystals of almandite are commonly associated with chlorite.

AMPHIBOLITE

A 6-foot layer of amphibolite, conformable with the enclosing quartz schist, is exposed in a prospect pit at the Big Rock deposit. The rock is green black and medium grained. Its foliation is caused by the parallel orientation of green hornblende needles. The predominant mineral is strongly pleochroic hornblende; Z = dark blue green, Y = X = yellow green, C A Z 21°, and y = 1.672.

Other constituents are quartz, magnetite, albite-oligoclase, chlorite, almandite, rutile, sphene, epidote, and apatite.

Amphibolites exposed near Kiawa Mountain reportedly have a similar mineralogy Uahns, 1946, p. 21; Barker, 1958, p. 25-28).

PEGMATITE AND VEIN QUARTZ

Although only one pegmatite dike or vein occurs within the mapped area, numerous small bodies of pegmatites crop out nearby. Their mineralogy is simple; the main constituent is milky quartz, accompanied by some muscovite and pink perthite. In narrow zones adjacent to the pegmatites, wall-rock mineral grains commonly are enlarged, and some pegmatitic material probably has been added. The pegmatite bodies are unmetamorphosed, and they transect the structure of the metamorphic rocks.

Quartz veins, spatially and genetically related to the pegmatite bodies, are common in the lenses of kyanite schist but are rare in the surrounding metamorphic rocks of the mapped area. Structural control over emplacement of the veins within the schist is indicated by their conformity with prominent joint sets. Sharp contacts between the quartz veins and the kyanite schist are characteristic.

Commonly the veins consist solely of quartz; a few flakes of muscovite rarely are present. Both muscovite and kyanite appear in a few of the veins within the lenses of kyanite schist. The vein kyanite is tan or blue and forms laths as much as 8 inches long. These occur as unoriented individuals, as randomly oriented crystals in aggregates, as rosettes, or as seams in which their parallel long axes are at right angles to the walls.

Specimens taken across the contact of kyanite schist and a quartz vein show, under the microscope, the following sequence of textural changes: (1) kyanite schist: unoriented porphyroblasts of kyanite and muscovite in a quartz mosiac; a few thin parallel layers of unoriented muscovite flakes in the groundmass, along with rare grains of zircon; (2) kyanite schist adjacent to the quartz vein: interlocking, xenoblastic, nonequidimensional quartz grains; mica, in greater amounts, chiefly as muscovite porphyroblasts whose long axes parallel the vein edges; kyanite porphyroblasts also suboriented parallel to the vein borders; numerous tiny grains of rutile; and (3) quartz vein: anhedral quartz grains, 1 to 3 mm in diameter, with complex sutured borders; scattered rare crystals of muscovite and kyanite.

Local Structure

PRIMARY FEATURES

Primary structural features are found in a few parts of the metamorphic terrane. Original sedimentary bedding in the large exposure of metaconglomerate near the Big Rock deposit is represented by alternating layers of fine-grained quartzite and conglomerate. In addition, channel-filling tongues of fine-grained quartzite cut across the original bedding of the conglomerate. The attitude of crossbedding in the quartzite of the Kiowa View III deposit, as well as the relationships between the metaconglomerate and channel-filling masses of quartzite near Big Rock, show that the present folds are overturned in this area.

FOLDS

The Precambrian rocks in the area of the kyanite deposits are exposed on the southwest limb of the large Kiawa syncline. Numerous subordinate flexures are superimposed on this major fold, and many outcrops are featured by isoclinal plunging folds that are overturned to the northeast. The observable and mappable folds range in crest-totrough dimension from less than a foot to many thousands of feet.

The pattern of folding is relatively simple: the fold axes trend N. 29° to 59° W., with an average of about N. 42° W. Their plunge ranges from 12° to 47° NW., with an average of about 33° NW. The traces of the axial plane are essentially parallel to the trace of foliation, and the planes themselves have an average dip of 43 degrees to the southwest. Crossbedding, channeling, and tightly compressed drag folds, present in a few exposures, serve as criteria for the determination of the upper sides of beds.

Drag folding is most pronounced in the intervals of relatively incompetent biotite schist where they are interlayered with quartzite. Although isoclinal folds having the regional orientation are present in the lenses of kyanite schist, the shapes of these lenses apparently reflect original sedimentary processes rather than the results of subsequent deformation or metamorphism.

FOLIATION

Foliation is essentially parallel to bedding wherever these two features were observed. Indeed, the foliation wraps around the noses of several folds in the quartzite and kyanite schist. Such foliation commonly is termed "bedding cleavage" or "bedding schistosity" (Billings, 1947, p. 218) and is probably of mimetic origin; thus, during recrystallization of the rock, the new platy minerals developed with a gross orientation parallel to the original bedding.

The strike of the foliation ranges from north to N. 49° W. and averages N. 27° W.; the average dip is 53° WSW. Northward from the Kiowa View III deposit the trend gradually swings from north-northwest to north at the Kiowa View I deposit, where the average strike is N. 70° W., and thence swings back again to north-northwest at the Kiowa View II deposit. A few of the pegmatite bodies, such as that at the Kiowa View II deposit, are conformable with the foliation, but in most places they are discordant.

CRENULATIONS

Crenulations, which rarely exceed I inch from crest to trough, are present in micaceous parts of all the metamorphic rocks. The axes of these slightly asymmetric open wrinkles have an average trend of N. 76° W. and an average plunge of 39° WNW. This trend is

Figure 7

QUARTZ VEIN OCCUPYING A JOINT IN LENS OF KYANITE SCHIST approximately 35 degrees more westward than that of the axes of the isoclinal overfolds, indicating that the crenulations probably were superposed upon the larger folds after overturning of the latter.

LINEATION

Linear elements are common in some of the metamorphic rocks. Within the metaconglomerate the short axes of ellipsoidal pebbles and cobbles lie normal to the foliation; their intermediate and long axes lie within the plane of foliation, and their long axes generally are in parallel alinement. In the amphibolite, lineation is shown by parallelism of the long axes of the hornblende crystals, which lie in the plane of foliation. In many of the rocks, oval-shaped flakes of mica lie with their long axes parallel.

The linear elements expressed by ellipsoidal pebbles and elongate minerals plunge in accord with the axes of the isoclinal overfolds. Still another lineation, formed by the parallel crests and troughs of the crenulations described above, plunges in a more westerly direction.

FAULTS AND JOINTS

No faults were observed in the well-exposed rocks along the several steep-sided canyons in the subject area. Elsewhere in the area, however, much of the metamorphic terrane is covered; hence faults may well be present though unrecognized.

Joint sets, which trend mainly northeastward or northwestward and dip steeply to vertically, are prominent in the competent quartzites and kyanite schists. Hydrothermal quartz veins appear in several lenses of kyanite schist, where they commonly occupy prominent joints (fig. 7).

Kyanite Deposits

The kyanite occurrences of the Petaca district can be classed as major or minor on a general economic basis. Major deposits, as here defined, contain fairly high concentrations of kyanite and low percentages of undesirable minerals, and hence may be of interest for commercial exploitation. The minor deposits, in contrast, have little economic potential because they contain kyanite in low concentrations only.

GENERAL FEATURES OF MAJOR DEPOSITS

DISTRIBUTION AND OCCURRENCE

Six major kyanite deposits are exposed on La Jarita Mesa within five adjoining sections (22, 23, 27, 28, and 34) of T. 27 N., R. 8 E. (p1. 1). They comprise 25 lenses of kyanite-bearing rock within a north-northeast-trending area about 2½ miles long and less than a mile wide. Not more than two-thirds of a mile separates neighboring deposits.

The individual bodies of kyanite-bearing rock generally form stubby lenses or thick blocky masses, but they are highly irregular in detail. Most are oval, crescentic, or roughly rectangular in both plan and inferred cross-section, and ordinarily can be referred to as pods. They are 15 to 400 feet long and 10 to 200 feet thick. Typically they form knobs and ridges that project a few feet to as much as 115 feet above the surrounding terrain. Their subsurface extent is not known.

STRUCTURAL FEATURES

Each lens of kyanite-bearing rock is enclosed by a shell of sericite schist that grades outward into quartz schist and thence into quartzite. Parallel micaceous layers in the kyanite schist are responsible for a distinct foliation that generally strikes north-northwest. Numerous quartz-kyanite segregations, around which the muscovite laminations bend, give a characteristic wavy pattern to the schistosity. In places where mica is a very minor component, the kyanite-bearing rock is so massive in appearance that the term schist becomes inappropriate.

Many isoclinal folds, overturned to the northeast, can be recognized within the bodies of kyanite-bearing rock, but their outlines are difficult to follow in detail. These flexures trend and plunge northwest, and range in crest-to-trough dimension from approximately 1 foot to several tens of feet. Another type of fold in the kyanite schist is represented by slightly asymmetrical, open wrinkles about one-half inch to 2 inches in crest-to-trough dimension. Their axes trend and plunge west-northwest. These crenulations are present only where less competent micaceous layers occur within the highly competent kyanite schist.

Numerous diversely oriented joint sets, some steeply and some flatly dipping, are present in the kyanite-bearing rocks, although only three of these sets are prominent. These strike approximately northwest, north-northeast, and northeast, and dip northeast, east-southeast, and northwest or southwest, respectively. Most of the joints extend entirely across a given mass of kyanite-bearing rock, but terminate at its contact with the enclosing sericite schist. The joint surfaces generally are planar, but in a very few places they are slightly curved.

Conspicuous against the drab background of kyanite schist are numerous veins of milky quartz, ranging in thickness from several inches to 6 feet and ordinarily in sharp contract with the schist (fig. 8). They are continuous within the kyanite-bearing lenses or pods but do not extend outward into the sericite schist. In general, the number and thickness of quartz veins increase in proportion to the size of the host lens, and veins are absent or only sparingly present within the smaller lenses. The quartz veins coincide in attitude with prominent joint sets, and within a single deposit most of them strike in only one, or perhaps two, of the three prominent joint directions.

SURFICIAL FEATURES

Most of the kyanite-bearing pods appear as distinct knobs and ridges that rise sharply above the adjacent ground. Their surfaces are grossly rounded to extremely irregular and ragged in appearance. The degree of larger scale irregularity is mainly a function of the number, spacing, and attitudes of joints that are present. Small-scale irregularity is expressed ordinarily as nodular surfaces (fig. 8); it can be correlated with rock composition and clearly reflects differential weathering of various minerals and mineral aggregates.

Huge blocks of kyanite schist and associated quartz-rich rocks, spectacularly balanced upon the surfaces of the deposits or lying scattered around their peripheries, give evidence of the effectiveness of mechanical weathering at these localities. The process is dominated by frost wedging, which not only provides the initial boulders but also contributes greatly to their subsequent comminution. Float masses of kyanite schist, ranging from pebbles to blocks 100 feet long, 50 feet wide, and 30 feet high, constitute 5 to 10 percent of the kyanite-bearing rock extending above general ground level. Most of the float is distributed as skirtlike accumulations around the bases of the knobs and ridges.

The nodular surfaces of the kyanite schist reflect differential weathering of the less resistant micaceous layers, with consequent relative elevation of the quartz-kyanite segregations. The nodes have many forms but are mainly spheroidal to ellipsoidal; they are raised from a fraction of an inch to a few inches above the mica layers wrapped around them.

Most of the kyanite-bearing rocks appear gray green on weathered surfaces, principally because of adhering lichens. The rocks themselves

Figure 8

KYANITE SCHIST AT THE BIG ROCK DEPOSIT

Typical nodular surface of weathered schist.

are extensively stained reddish and yellowish brown, owing to oxidation of the iron-bearing minerals to hematite and limonite. Reducing solutions, provided by the growth and decay of the lichens, have bleached the underlying kyanite schist to a depth of approximately one-half inch.

DESCRIPTIONS OF MAJOR DEPOSITS

BIG ROCK DEPOSIT

The Big Rock deposit is on the south rim of La Jarita Canyon in sec. 27, T. 27 N., R. 8 E. It lies a few hundred yards east of the Tres Piedras road, from which access is provided by an ungraded road that is satisfactory for truck travel. An old wagon road, in very poor condition, connects the deposit with Petaca via La Jarita Canyon.

Three large and eight small pods of kyanite-bearing rocks constitute the deposit (fig. 2; pl. 3). They are irregular in plan and have characteristic uneven, angular surface profiles. The largest pod, approximately 130 feet long, 60 feet wide, and 110 feet high, forms the prominent local landmark from which the deposit receives its name (fig. 9). The smallest pod is 15 feet long, 12 feet wide, and 10 feet high. The entire deposit trends northward, but most of the individual pods trend north-northwest and dip west-southwest at moderately steep angles. The attitude of the lenses conforms to that of the schistosity in both the constituent kyanite schist and the surrounding metamorphic rocks.

Within the kyanite schist three prominent joint sets strike northwest, west-northwest, and northeast, and dip steeply northeast, north-northeast, and northwest or southeast, respectively. In a lens at the north end of the deposit, two nearly isoclinal folds are overturned at a moderate angle to the northeast. Their axes trend northwest and plunge 14° and 20° NW. Other folds are present in the deposit, but their attitudes are obscure. Crenulations, with axes that trend and plunge west-northwest, are common in micaceous parts of both the kyanite schist and the quartz schist.

Large hydrothermal quartz veins are more abundant in this deposit than in any other within the district. Their attitudes coincide with those of the three main joint sets. A few of these veins contain kyanite in blades as much as 8 inches long. Minerals within the kyanite schist are much enlarged adjacent to about half of the quartz vein, but this effect dies out a few inches away from the contacts.

All the kyanite schist is rich in quartz, in most places so much so that

Figure 9

KYANITE SCHIST AT THE BIG ROCK DEPOSIT

Largest kyanite-bearing pod, forming prominent knob.

planar structure is faint to absent. Widely distributed is fine- to medium-grained rock that consists of little but quartz; it is very hard and compact, and typically forms angular spires, blocks, and cliffs whose surfaces are smooth in detail. Tiny flakes of muscovite and shreds and blades of kyanite are present in many places, but rarely do these minerals constitute as much as 5 percent of the rock. All types of this quartz-rich rock are grouped with the kyanite schist in Plate 3; however, they are shown separately in Plate 4, which is based upon mapping by R. H. Jahns.

Characteristically present in all the metamorphic rocks are segregations composed of large anhedral grains of quartz. In places the texture of surrounding kyanite schist has been coarsened for a distance of an inch or two away from contacts with these segregations.

The pods of kyanite schist and associated quartz-rich rocks are enclosed by envelopes of sericite schist (fig. 10), which in turn give way successively to quartz schist and quartzite. Most of the sericite schist is concealed by a thin layer of soil, but numerous prospect pits and a few natural exposures show that the width of this unit ranges from 10 feet to 40 feet.

Figure 10

ROCK TYPES AT BIG ROCK DEPOSIT

Contact of kyanite schist with sericite schist.

Quartz schist underlies most of the covered slopes in the map area, whereas the flanking massive quartzite is relatively well exposed. A feldspathic variety of the quartzite is distributed irregularly. The iron content of the quartzite at Big Rock is considerably higher than that of the quartzite in the other deposits, the percentage generally decreasing westward from the maximum reflected by the numerous thick red layers of hematite-stained quartzite on the south wall of La Jarita Canyon. Several iron-rich lenses, from 10 to 15 feet long and from 3 to 5 feet thick, also crop out at the northwest end of the Big Rock deposit. Magnetite, ilmenite, hematite, limonite, and staurolite are the dominant minerals in all these layers and lenses.

A layer of dark-green hornblende schist, 6 feet thick and conformable with the enclosing quartz schist, is exposed in a prospect pit near the northwest corner of the largest lens of kyanite schist. No other exposures of this nonresistant rock were found. Garnet schist crops out beside the southwest edge of the access road just beyond the northeast border of the map area. This rock extends northwestward along the strike for a distance of about 80 feet and forms a unit about 40 feet in exposed breadth.

Metamorphic conglomerate is present in a roughly rectangular area a few hundred yards northwest of the Big Rock deposit. The southwest border of the outcrop area is on the northeast side of the Tres Piedras road and extends parallel to it for more than a mile; the northeast border is on the south wall of La Jarita Canyon. The metaconglomerate forms a low outcrop platform more than a quarter of a mile wide; its undulatory surface lies 3 to 10 feet above that of the surrounding quartz schist and garnet schist.

Several pegmatite bodies of modest dimensions crop out along the top of a broad ridge that slopes gently southward from the southwest border of the Big Rock deposit.

Prospecting and development work are represented by numerous prospect pits and a few short trenches in the country rock around the lenses. Some commercial-grade kyanite was shipped in 1928, mainly from the Hoyt mine, an open cut and appended shaft at the north end of the largest pod. Substantial amounts of relatively high-grade material also have been obtained from the many large float blocks.

KIOWA VIEW I DEPOSIT

Five of the six major deposits in the district form a north-trending chain in which the Kiowa View I (pl. 5), in secs. 22 and 23, T. 27 N., R. 8 E., is the fourth link to the north. Access to this deposit, as well as to the Kiowa View II and Kiowa View III deposits, is provided by a rough but passable road that branches eastward from the Tres Piedras road in sec. 28, T. 27 N., R. 8 E. This circuitous ungraded road passes some 300 yards north of Kiowa View III and about 100 yards south of

Kiowa View I and II, and finally joins the Kiawa mine road slightly more than 1 mile east of the junction of the Kiawa mine and Tres Piedras roads in sec. 21, T. 27 N., R. 8 E.

From three sides gentle forested slopes lead up to the one large and two small pods that constitute the Kiowa View I deposit, which lies immediately east of a mountain meadow used as an experimental seeding plot by the U. S. Department of Agriculture. The largest lens is crescent shaped in plan and convex to the east. It is about 400 feet long, 140 feet wide in the middle, and has 40 feet of topographic relief. All the lenses strike approximately north and dip west, and hence show a 10- to 20-degree swing to the north as compared with the lenses in the other deposits. This attitude is in general conformity with that of the foliation in the kyanite schist and in the wall rocks.

Joints are poorly developed and widely spaced in this deposit, although two prominent nearly vertical sets are present in the large lens; one strikes approximately west and the other northwest. In the northern part of the large lens, folds in the kyanite schist are conspicuously outlined by ferric oxide staining. They are nearly isoclinal and are moderately overturned to the north. Their axes trend north-northwest and plunge in the same direction at low to moderate angles. Crenulations are rare in all the rocks.

Short spires of kyanite schist feature the top of the largest pod, and are the result of vigorous erosion of hematite-rich layers in adjacent parts of the kyanite schist. Also present are remarkably large float blocks of kyanite schist. The largest of these is 80 feet long, 40 feet wide, and 20 feet high.

The reddish hue of the kyanite schist in the northern end of the large lens reflects an unusual concentration of ferric oxide in the form of closely spaced hematitic streaks that delineate folds or follow planes of schistosity and jointing. Conspicuous blue streaks in the kyanite schist at the southeast end of the deposit mark the positions of veins rich in faintly pleochroic blue kyanite. In general, the kyanite of the Kiowa View I deposit is finer grained than that in any of the other large deposits except the Kiowa View III.

The two small pods of kyanite schist, which project only a few feet above the surrounding terrain, appear to be of good quality and exhibit most of the characteristics of the larger lens.

Contacts between sericite schist and quartz schist are poorly exposed, but there is some evidence of the typical sequence of rock types outward from kyanite schist into sericite schist, thence into quartz schist, and finally into quartzite. Small conformable seams of hematite, in general discontinuous, are present in the quartz schist; a rare variety contains abundant chlorite. A few quartz veins transect the kyanite schist; they coincide in attitude with the prominent joint sets of the large lens.

Prospecting and development work on this deposit have been limited to the excavation of three small elongate pits.

KIOWA VIEW II DEPOSIT

The Kiowa View II (pl. 6), northernmost in the belt of major deposits, is in sec. 23, T. 27 N., R. 8 E. Three kyanite-bearing lenses are exposed. The largest, rectangular in plan, is about 170 feet long by 220 feet wide and reaches a height of 40 feet above the adjacent ground. It strikes north-northwest and dips moderately steeply to the west-southwest; thus it is generally conformable with the schistosity of the contained kyanite schist and that of the surrounding rocks. Only one major set of joints, with a northwest strike and steep northeast dip, is visible in the kyanite-bearing rock. Folds are rare, and crenulations occur in only a few places.

Differential weathering, besides forming the usual nodular surfaces, has carved the top of the main lens into many large spires or tapering slabs 10 to 15 feet high and approximately 20 feet wide and 5 feet thick at the base. In addition, the top of the lens is marked by a rectangular sunken platform 16 feet long, 8 feet wide, and 3 feet deep; this depression was formed through rapid weathering of iron-rich rock containing abundant staurolite (table 2, No. 8).

Numerous large float blocks near the main lens increase the total volume of kyanite schist exposed above the ground by approximately 10 percent.

Immediately southeast of the large pod is a relatively thin shell of kyanite schist about 240 feet long, 30 feet wide, and 5 feet in topographic height. It is elongate parallel to the southeast side of the main lens, and is separated from it by 50 to 60 feet of sericite schist. It contains kyanite schist of good quality. On the southwest end of this elongate body, curved crystals of kyanite as much as 10 inches long, associated with segregations of quartz, are exposed in a prospect pit.

A small pod of kyanite schist, containing curved crystals of kyanite as much as 18 inches long, crops out northwest of the main lens. The formation of these unusually large crystals may have been related to the intrusion of a nearby pegmatite dike.

Several pits have been dug in sericite schist around the perimeter of the largest lens. These excavations show that a ring of sericite schist of unkrown width encircles the lens and grades outward into quartz schist. The quartz schist crops out wherever it contains resistant segregations of coarse-gra'ned, varicolored quartz, but in general this metamorphic rock is covered by thin surficial deposits. Iron-rich parts of the schist in several places contain almandite garnet and chlorite. Numerous crenulatiors are present in nearly all exposures.

The quartzite in the area is typically white and gray, and massive to thinly layered. In addition, a feldspathic variety appears in many places. Major folds are common, and minor crenulations are rare in the massive quartzite, but this relation is reversed in the thinly layered parts of the section.

About 200 feet north of the main lens is a transition from normal quartz schist into metaconglomerate. The pebbles and cobbles of the conglomerate range from one-quarter of an inch to 4 inches in diameter and are red, tan, gray, black, or white. They are composed almost entirely of medium-grained quartz.

From a point slightly northeast of the main lens, a pegmatite dike extends northwestward for nearly half a mile. Milky quartz, the dominant mineral, is accompanied by muscovite and rare pink microcline. Quartz veins are rare throughout the area.

KIOWA VIEW III DEPOSIT

The Kiowa View III deposit (pl. 7) is in the N½ sec. 37, T. 27 N., R. 8 E., about one-half mile north of the Big Rock deposit. It consists of six lenses of kyanite schist, most of which form dip slopes on the north wall of La Jarita Canyon and jut short distances upward from its rim. Northeast of the deposit an excellent spring is maintained by the U. S. Forest Service.

The individual pods of kyanite schist are roughly rectangular in plan, and project 5 to 25 feet above the surrounding terrain. The largest is about 80 feet long and 140 feet wide, the smallest 25 feet long and 15 feet wide. The percentage of kyanite in the smaller lenses appears to be somewhat lower than in the larger ones, probably because of a greater degree of alteration of kyanite to sericite in the smaller lenses. Folds are present in the lenses, but their attitudes are obscure; crenulations are uncommon. Quartz veins are rare.

An estimated 30 percent of the visible kyanite schist in this deposit is represented by numerous float blocks in the immediate vicinity of the lenses, on the slopes below the lenses, and along the bottom of La Jarita Canyon.

Each pod of kyanite schist is ringed by sericite schist, which grades outward into typical quartz schist. Ellipsoidal masses of coarse-grained transparent quartz, some as much as 12 inches in diameter, occur in the sericite schist. In the north-central parts of the area a thick layer of massive quartzite appears to have been converted extensively into a mica-rich quartz schist. This occurrence suggests that either a lens of kyanite schist lies a short distance beneath the surface in this area, or that the mica-rich schist is a remnant of an envelope around a kyanitebearing lens that has been entirely removed by erosion. Feldspathic quartzite. with microcline dominant over calcic albite, is not uncommon, and abundant chlorite and garnet appear in a few parts of the quartzite.

Many overturned isoclinal folds can be observed in the massive quartzite. Three main sets of joints were noted: one with a northeast strike and steep northwest dip, one striking north and dipping steeply cast. and the third with a northwest strike and a moderately steep northeast or southwest dip.

Biotite schist is exposed on the steep southwest wall of a southeast-draining tributary to La Jarita Canyon. The fold pattern in this rock is shown in the east-central sector of the map (pl. 15). Other layers of biotite schist crop out on the gentle slopes near the bottom of the canyon southeast of the map area.

Several hundred feet northwest of the deposit, garnet schist crops out on the south side of La Jarita Canyon some distance above the stream bed. This large exposure, which is bordered on the southwest by metaconglomerate, can be traced along strike for a distance of nearly half a mile.

A pegmatite dike is exposed about halfway up the north wall of La Jarita Canyon approximately a quarter of a mile east of the map area. The pegmatite appears to contain a considerable amount of muscovite, chiefly in small books that are heavily ruled.

KIOWA VIEW IV DEPOSIT

The Kiowa View IV deposit (pl. 8) is in sec. 34, T. 27 N., R. 8 E., about one-quarter mile south-southwest of the Big Rock deposit and a few hundred feet northeast of the Petaca-Vallecitos road. It comprises two smaller lenses of kyanite schist 10 to 15 feet in diameter, along with numerous float blocks of the same rock. The schist is light green, massive in appearance, and somewhat micaceous. Megascopically it seems to be of good quality and uniform mineralogy. The abundance of kyanitebearing float suggests that a considerably larger deposit was formerly present.

Quartz schist surrounds the pods but is very poorly exposed. Low rounded outcrops of quartzite, similar to those described from the other deposits, appear to the east, northeast, and northwest.

KIOWA VIEW V DEPOSIT

The Kiowa View V deposit (pl. 9) is in sec. 28, T. 27 N., R. 8 E., approximately two-thirds of a mile west of the Big Rock deposit and about 400 yards west of the Tres Piedras road. The kyanite schist crops out on a broad-crested northwest-trending ridge. It forms a pod, about 150 feet long and 50 *feet* in maximum width, that projects 1 to 5 feet above the level of the ridge.

The kyanite-bearing rock is predominantly light green, massive in general appearance, and has a foliation that trends northwest and dips southwest. It is cut by steeply dipping joints that strike northwest and northeast. Small blocks of float are present east and south of the deposit.

The quartz schist surrounding the kyanite-bearing pod is covered with a thin layer of soil and vegetation, but its presence is attested by numerous loose blocks. Outcrops in the vicinity of the pod consist of massive, blue-gray, vitreous quartzite, shown in the northeast sector of the map. Two prominent steeply dipping joint sets appear in this rock, one striking northwest and the other northeast.

An accumulation of kyanite-bearing float, in blocks several inches to 6 feet in diameter, occupies a strip about 100 yards wide and more than a quarter of a mile long both north and south of the Tres Piedras and Eureka mine roads in sec. 28, T. 27 N., R. 8 E. This float concentration suggests the former presence of an adjacent kyanite deposit, as the nearest exposed deposit is on lower ground more than half a mile away.

DESCRIPTIONS OF MINOR DEPOSITS

Low-grade deposits of kyanite that are present on and near La Jarita Mesa differ in details of their geology and genesis from the Big Rock and Kiowa View deposits already described.

KIAWA MOUNTAIN DEPOSIT

The Kiawa Mountain deposit, in sec. 4, T. 27 N., R. 8 E., is roughly triangular in plan, with one apex of the triangle pointing to the east. It is large and rather ill defined, and occurs in a resistant, black-banded, gray to blue-gray, vitreous quartzite. This rock forms part of the Ortega quartzite of Just (1937) and has been assigned to the upper quartzite member of the Kiawa Mountain formation by Barker (1958). It underlies rugged terrain in the axial region of the northwest-plunging Kiawa syncline.

The quartzite is traversed by numerous veins of milky quartz, some of which contain kyanite. These veins range from a few inches to a few feet in thickness and from a few feet to several hundred feet in length. They arc distributed irregularly, at least over the northeast and east sides of the mountain. Kyanite also appears in the dark layers of the quartzite, where it is associated with quartz and magnetite. Many of these layers are involved in ptygmatic folds. Although the total amount of kyanite in the deposit is very large, the grade of the rocks is too low to be of present economic interest.

VALLECITOS DEPOSITS

Kyanite occurs in two mountain ridges near Vallecitos. These ridges emerge as spurs into the canyon of the Rio Vallecitos where this stream and one of its eastward flowing tributaries have cut deeply into the general terrain. One deposit is about half a mile south of Vallecitos in sec. 17, T. 26 N., R. 8 E., apparently the locality mentioned by Just (1937, p. 70) and Jahns (1946, p. 261). The other is approximately half a mile west of the same village in sec. 8, 1'. 26 N., R. 8 E.

The spurs are composed of Ortega quartzite similar in appearance to the rock exposed on Kiawa Mountain. Some of the kyanite appears in veins of milky quartz as colorless, tan, or blue laths 6 inches in maximum length. Many of these laths are unoriented individuals, others are clustered in sprays and rosettes. The remainder of the kyanite occurs in simple fracture fillings as oriented blades about one-quarter of an inch long. It is associated with magnetite and quartz.

The veins of milky quartz are widely spaced and cross the quartzite ridges in many directions. They range in thickness from a few inches to several feet and in length from several yards to a hundred yards or more. Only about 5 or 10 percent of these veins contain kyanite. Ilmenite and muscovite are typical accessory constituents.

LA MADERA MOUNTAIN DEPOSIT

La Madera Mountain, approximately 1½ miles wide, extends south-southeastward for about 3 miles from sec. 17, T. 25 N., R. 8 E. The Caliente River and the Ojo Caliente-La Madera highway parallel the steep west flank of the mountain, which is underlain by quartzite similar to that exposed on Kiawa Mountain.

The kyanite occurs in the quartzite as concentrations of small laths about one-half inch in length, either in rosettes or in groups of unoriented crystals. It also appears in dark layers that are locally prominent in the quartzite.

Origin of the Kyanite Deposits and Associated Metamorphic Rocks

NATURE OF THE ORIGINAL SEDIMENTS

Most of the metamorphic rocks are thought to represent original sedimentary types, despite the known occurrence of acid and basic igneous rocks within the section. This view is based upon the layered structure of the metamorphic rocks, as well as the presence of widely distributed metaconglomerate. Further, the mineral assemblages and corresponding chemical composition (table 3) are characteristic of regionally metamorphosed quartzose-feldspathic-argillaceous sediments. Finally, relict sedimentary structures, exemplified by bedding planes and channeling, are present in a few places.

The structure, mineralogy, and spatial relationships of the various metamorphic rock types provide evidence concerning the general conditions of formation of the Precambrian sediments. The presence of metaconglomerate and mica schist suggests derivation from shallow-water marine and/or terrestrial clastic deposits rather than from deeper water sediments. The metaconglomerate is locally more than 1,000 feet thick, which is more suggestive of terrestrial than of littoral deposition (e. g., Barrell, 1909, p. 620).

The predominant metamorphic rocks, quartzites and quartz-mica schists, evidently were formed from quartz sands containing varying amounts of impurities. The irregularly distributed feldspathic sections of these crystalline rocks represent metamorphosed arkoses, although some may well have been derived from rhyolitic volcanic rocks. The thickness of these quartzose sediments, estimated by Just (1937, p. 11) to

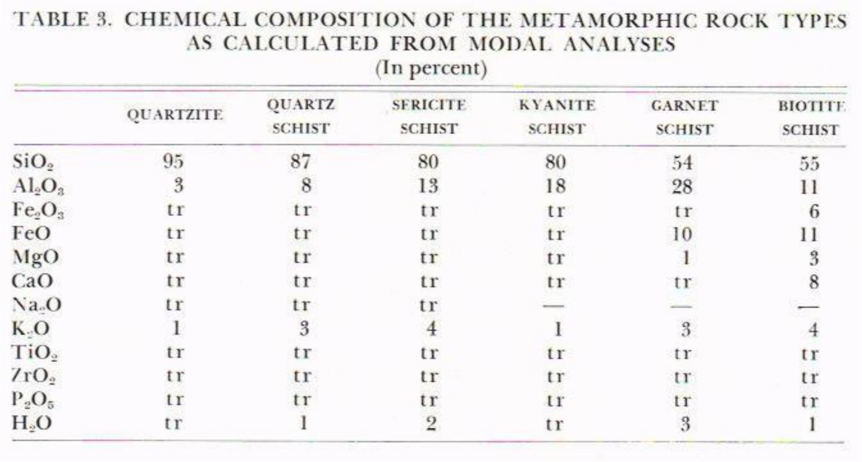

TABLE 3. CHEMICAL COMPOSITION OF THE METAMORPHIC ROCK TYPES AS CALCULATED FROM MODAL ANALYSES

(In percent)

	QUARTZITE	QUARTZ SCHIST	SERICITE SCHIST	KYANITE SCHIST	GARNET SCHIST	BIOTITE SCHIST
SiO_2	95	87	80	80	54	55
Al_2O_3	3	8	13	18	28	11
Fe_2O_3	tr	tr	tr	tr	tr	6
FeO	tr	tr	tr	tr	10	11
MgO	tr	tr	tr	tr	1	3
CaO	tr	tr	tr	tr	tr	8
Na_2O	tr	tr	tr	—	—	—
K_2O	1	3	4	1	3	4
TiO_2	tr	tr	tr	tr	tr	tr
ZrO_2	tr	tr	tr	tr	tr	tr
P_2O_5	tr	tr	tr	tr	tr	tr
H_2O	tr	1	2	tr	3	1

range from 10,000 to 25,000 feet, suggests a marine rather than terrestrial environment. Quartz sands, in combination with pelitic silt (later metamorphosed to kyanite schist) and conglomerate, constitute the typical sedimentary rock assemblage of the mildly unstable shelf, as described by Dapples, Krumbein, and Sloss (1948, p. 1935-1936):

> Sandstones designated as the quartz-potash feldspar type are arbitrarily differentiated from the pure quartz type with which they are intergradational. ... if they represent sediments of one cycle of deposition the sorting is poor, the heavy-mineral suite contains minerals unstable to weathering, and interstitial clay, silt, and mica are more abundant than in other shelf sandstones. The local areal distribution of sandstones belonging to this type suggests the limited occurrences of unstable shelf areas in a region of dominant stability. . . .
>
> Subgraywacke (quartz-muscovite) sands differ from the quartz-muscovite sands of the stable shelf in several features.... Appreciable quantities of clay and micaceous minerals appear in the matrix between the larger quartz and muscovite grains.... Feldspars are present to a moderate degree....
>
> . . . the shale of the slightly unstable shelf is siltstone. These are micaceous and feldspar is one of the common minerals in the silt fraction....They are, however, closely associated with subgraywackes...

Lithologic repetition is a prominent feature in the metamorphic rocks of the Petaca district. A possible explanation for these repetitions is given by Dapples, Krumbein, and Sloss (1948, p. 1924):

> . . . repeated associations are implied when a section is referred to as typical shelf facies . . . they connote the development of certain lithologic types within limited conditions of accumulation. The concept of rock facies implies that when a source area delivers a unique type of debris to a depositional basin, a special type of rock is produced as a result of the integration of the source and depositional environment. It also implies that when the same combination occurs in another locality or at a later geologic time, a similar deposit results.

Ordinary variations in the major sedimentary fades, within the same framework of deposition, adequately explain the development of the biotite and garnet schists. The biotite schist probably represents an original slightly calcareous, argillaceous sand or silt in which the available calcium ultimately was consumed in the formation of epidote, and biotite ultimately evolved from the argillaceous material, in a middle-grade metamorphic environment (Harker, 1939, p. 263; Turner, 1948, p. 94). The presence of abundant almandite, staurolite, biotite, chlorite, and quartz in the garnet schist suggests a primary quartzose-argillaceous sediment rich in ferrous iron (Harker, 1939, p. 225).

The assumption that basic extrusive rock was the parent material of the amphibolite rests in part upon conformable relationships between the amphibolite and the enclosing quartz schist, and in larger part upon the similarity of the present mineral assemblage (blue-green hornblende, epidote, and acid plagioclase) to mineral associations of metamorphosed basic igneous rocks, as described by Turner (1948, p. 98) and Harker (1939, p. 280-281).

The lenticular shape of the kyanite-bearing pods can be explained in terms of known depositional processes. Sediments analogous in composition and particle size to those now represented by the kyanite schist are being laid clown off the coast of California at the present time, and within what may well be equivalent depositional environment. In their report on this sedimentation, Revelle and Shepard (1939) detail a mechanism whereby narrow troughs and basins alined parallel to the shore, as well as submarine canyons normal to the shore, act as sedimentary traps for silts and clays. The normal lateral and vertical transitions from coarse to finer and finer particle sizes in the original sediments, culminating in lenses of silt, can be accounted for satisfactorily by the presence of such sedimentary traps in a mildly unstable shelf environment.

In summary, a general and progressive spatial variation in size and composition seems to have been characteristic of the original sediments within the area studied. These sediments ranged from conglomeratic material through coarse sand and fine sand to silt. In terms of composition, the transition was from pure quartz sands to arenites containing feldspars and argillaceous material. Feldspars normally appeared in all the sediments within the inferred depositional environment. The argillaceous material probably appeared chiefly as white mica, clay minerals, hydrated oxides of alumina, and iron-magnesium minerals, such as chlorite. A factor to be considered is the probable formation of illite through the absorption of potassium by the clays in a marine environment (Rankama and Sahama, 1950, p. 203-206, 431-436; Noren, 1935). Fine-grained authigenic orthoclase also may have been formed from the argillaceous material of the sediments (e. g., Gruner and Thiel, 1937, p. 846). Small percentages of the resistates, rutile, zircon, apatite, topaz, magnetite, ilmenite,and sphene,evidently were distributed rather evenly through the sediments, decreasing in amount in the reworked sands.

An essentially normal sequence in particle size and composition of the sediments within the suggested framework of deposition, together with the mineralogical and chemical composition of the present metamorphic rocks, permits the inference that the distribution, shape, and mineralogy of the metamorphic formations have been directly controlled by the composition and structure of original sedimentary units. Thus the present rock series, comprising quartzite, quartz schist, sericite schist, and kyanite schist, probably represents an original sedimentary series composed of coarse quartz sands, coarse quartz-muscovite sands, fine-grained quartz-illite sands, and clay silts, respectively.

DEFORMATION AND METAMORPHISM

Prominent among the physical factors controlling the metamorphism of the rocks within the map areas were hydrostatic pressure, stress, and temperature. The action of stress in producing overturned isoclinal folds is everywhere manifest. Widespread drag folds and schistosity indicate a semiplastic yielding of the rock to directed pressure. Less evident, though possibly of major importance, was the effect of stress in governing the orientation of some of the kyanite crystals. On the whole, stress seems to have been of moderate intensity throughout the subject area.

The large size of some of the folds, the semiplastic yielding of the rocks to stress, the lack of cataclasis, and the moderate grain size of the mineral constituents suggest at least a moderate depth of burial and hence a moderate lithostatic pressure during deformation and metamorphism. Corresponding temperatures are best indicated by the mineral assemblages produced in rocks of given initial composition. The highest temperature assemblage found in the metamorphic rocks is the middle-grade kyanite-staurolite-almandite association; thus the maximum temperatures indicated for these rocks appear to have been moderately high in the metamorphic scale.

PROGRESSIVE METAMORPHISM

Under conditions of stress and progressively increasing temperature, ferruginous arenaceous beds with a small content of calcium were converted to biotite-epidote-quartz schist representing a middle grade of metamorphism. Associated basic extrusive rocks were metamorphosed to amphibolites containing the critical mineral association hornblende-epidote-acid plagioclase. According to Turner (1948, p. 89), this mineral assemblage "embraces a grade of metamorphism that corresponds approximately to the almandite zone of regional metamorphism as defined for pelitic schists."

In the sedimentary sequence of coarse- to fine-grained arenaceous clastic rocks, progressive metamorphism produced numerous changes. Pure quartz sands were transformed to massive quartzites containing a few porphyroblasts of muscovite. Muscovite is one of the first minerals to form during metamorphism and probably remains stable throughout all the metamorphic grades (e. g., Barth, 1936, p. 779-780). Quartz-muscovite sands were recrystallized to micaceous quartz schist and to foliated quartzites. Almandite-staurolite schists with varying amounts of biotite and iron oxides were developed through metamorphism of quartz-muscovite sands containing concentrations of ferruginous and argillaceous impurities (Harker, 1939, p. 214, 219, and 248; Chapman, 1939, p. 171-173).

Fine-grained quartz-illite sediments were metamorphosed to sericite schists. Abundant clay minerals in numerous lenses of silt provided excess alumina for the crystallization of much disseminated kyanite. Many of the kyanite crystals are twisted and exhibit undulatory extinction, features that may indicate formation under higher stress and at an earlier time relative to accompanying unstrained crystals of staurolite.

Staurolite and biotite, which are locally abundant, represent iron-magnesium impurities in the original quartz-clay sediment; the iron probably was present as limonite, and much of the magnesium may have been adsorbed by clays.

The feldspars in the quartzites, quartz schists, sericite schists, and kyanite schists are believed to have been essentially unaffected by progressive metamorphism. Both potash feldspar and acid plagioclase normally show no changes beyond simple recrystallization in metamorphic rocks of moderate to moderately high grade (e. g., Harker, 1939, p. 247).

Among the common accessory minerals not already mentioned are magnetite, ilmenite, limonite, rutile, sphene, leucoxene, zircon, and apatite. Limonite and leucoxene are secondary minerals. Some of the magnetite may be a relict constituent, and some may have evolved through reduction of ferric compounds or through progressive metamorphism of muscovite and chlorite to biotite and magnetite (Harker, 1939, p. 64, 214, and 237; Chapman, 1939, p. 171-172). The ilmenite also may have been preserved as a relict mineral, or it may have been produced from the elements of rutile and magnetite during metamorphism (Harker, 1939, p. 46). Zircon and apatite are present only as relict minerals. Grains of spinel occur locally in the sericite schist and are believed to be relicts.

RETROGRESSIVE METAMORPHISM

The association of strained crystals of kyanite with unstrained crystals of staurolite indicates that peak stress probably was attained before maximum temperature was reached during metamorphism. Both these and other metamorphic minerals gradually became unstable under subsequent conditions of diminishing temperature and stress; thus was begun a series of retrogressive changes that probably continued throughout the remainder of the period of deformation. The reactions took place very slowly, so that many of the regressive mineral transformations never were completed.

Under conditions of retrogressive metamorphism, kyanite, staurolite, and almandite, in the presence of water, could react with potash feldspar to form a mica (Turner and Verhoogen, 1951, p. 452). This reaction would result in the total destruction of any potash feldspar in the lenses of kyanite schist, and in partial sericitization of the staurolite and kyanite. A similar interaction probably took place in the envelopes of sericite schist, where feldspar, staurolite, and almandite are now essentially absent. Lesser amounts of water may have been present in the feldspathic parts of the quartzites and quartz schists, where sericitization is highly incomplete.

Retrograde transformation of biotite to chlorite and sericite occurred in all the metamorphic rocks, probably at somewhat lower temperatures. Examples of the changes involved in such alteration of biotite to chlorite arc cited by Harker (1939, p. 350), Billings (1937, p. 474, 548, and 552), Chapman (1939, p. 175-176), and Read (1934, p. 650).

FORMATION OF QUARTZ BODIES AND QUARTZ-ROSETTE KYANITE BODIES

Aluminum and silicon must have been highly mobile during metamorphism, probably in the form of Al • OH and Si • OH complexes transported by liquid or gaseous solution. These postulated fluids are referred to in this report as "aluminum-silicon solutions," and the problem of their origin is discussed farther on.

During the general episode of deformation and metamorphism, stresses evidently produced numerous openings through which the aluminum-silicon solutions could move. Where many narrow, closely spaced, intersecting fissures were present, conditions were especially favorable for replacement on the adjacent minerals to form the coarse-grained quartz-unoriented kyanite rock and the quartz-rosette kyanite rock (fig. 11). Where larger openings were provided, the invading solutions formed either masses of quartz and larger kyanite rosettes or veinlets of kyanite and quartz.

Subsequent to the last deposition from the aluminum-silicon solutions, openings probably continued to form. These were filled with quartz deposited from residual silicon solutions. Thus stringers and irregular masses of quartz locally transect kyanite-quartz bodies formed earlier. Within the sericite schist, quartz schist, and quartzites the same

Figure 11

ROCK TYPES AT BIG ROCK DEPOSIT

Quartz-rosette kyanite rock.

interplay of deformation and deposition occurred, but here only siliceous solutions were available. Veinlets, pods, and irregular masses of quartz therefore were the only products.

FORMATION OF CRENULATIONS AND JOINTS

Crenulations in the more micaceous rocks represent a later reapplication of pressure, probably from the northeast and southwest. They are deformed by no porphyroblasts and evidently were formed after the period of recrystallization and semiplastic yielding of the metamorphic rocks. Joints also were developed during a later period, but they cannot be dated with respect to the crenulations because the two features are not present in the same rock types.

INTRUSION AND INJECTION

Intrusion of pegmatitic magma and injection of siliceous hydrothermal solutions followed the period of deformation and metamorphism. Pegmatite bodies in the quartz schist are both conformable and crosscutting in their relations to the metamorphic structures. Emplacement of the quartz veins, which are most abundant within the kyanite-bearing lenses, was controlled by joints. Their larger size, greater continuity, straight borders, and sharp contacts distinguish these quartz veins from the masses of quartz formed during metamorphism. Criteria for determining the age relationships of the pegmatite bodies and quartz veins were not recognized in the region investigated. However, Jahns (1946, p. 52), in a report on the complex pegmatites of the Petaca district, concludes that the quartz veins appear to be contemporaneous with, or slightly later than, the nearby pegmatites.

Intrusion of pegmatites and injection of siliceous solutions were accompanied by some addition of silica and by enlargement in grain size of the minerals in immediately adjacent quartz schist. Minor amounts of potassium, aluminum, and water from the pegmatite fluid probably were also added to the invaded rocks. Some quartz veins in the lenses of kyanite schist contain scattered kyanite crystals or large aggregates of bladed kyanite. The texture of the kyanite schist has been distinctly coarsened along the margins of many quartz veins.

COMPARISON WITH OTHER KYANITE OCCURRENCES

Several other occurrences of kyanite are similar in major features to those of the Petaca district, although they differ in some details of mineralogy and metamorphic sequence. Examples of these are described in the following paragraphs, along with a sampling of deposits in which the kyanite is considered to be of magmatic origin.

Argillaceous Paleozoic sediments in southeastern New York have been modified profoundly by magmatic intrusions and orogenic processes. The Hudson River slate has been metamorphosed and exhibits three facies: (1) muscovite slate, (2) kyanite schist, and (3) sillimanite gneiss. Regarding the formation of kyanite, Barth (1936, p. 789) states:

> Porphyroblastic cyanite is found, but tiny needle-like crystals in the groundmass of the material of the shear zone are quantitatively more important. This occurrence has special significance. The material deposited along shear zones has crystallized from relatively water-rich silicate solutions, and cyanite has, therefore, also crystallized directly from a solution, and apparently in this case did not depend on the action of shearing stress for its formation.

Upper Precambrian sediments and intercalated basic igneous rocks have been metamorphosed to mica schist, slates, quartzites, amphibolites, and crystalline limestone in the Fukushinzan district, Korea. The metamorphic rocks have been intruded by alkaline plutonic masses. Kyanite-quartz veins, found only in the mica schists, contain druses into which crystals of kyanite, quartz, and muscovite project. An explanation of the veins and druses is presented by Miyashiro (1951, p. 62-63), as follows:

> These kyanite-quartz veins were deposited from an aqueous fluid, circulating along the schistosity planes of mica-schist, at a certain stage of regional metamorphism....
>
> The mode of occurrence of kyanite, projecting into druses in the veins, is especially interesting. The empty druses appear to have been filled with fluid during metamorphism. Kyanite and other crystals must have grown in these cavities under hydrostatic pressure. Evidently any conditions of shearing stress did not prevail there during the formation of the druses.

A pelitic facies of the Moine sediments, in eastern Ross-shire, Scotland, has been thermally metamorphosed by a granitic pluton and later regionally metamorphosed. Hornfels and mica schists have resulted from this polymetamorphism. Quartz-kyanite veinlets cut alternating layers of siliceous and argillaceous composition in the hornfels. Tilley (1935, p. 96-97) discusses the origin of these veinlets, as follows:

> The quartz-kyanite veins cutting the banding of the hornfelses represent a special case of metamorphic differentiation; probably quartz and kyanite represent material segregated from the groundmass of the rock. That migration of kyanite substance in addition to silica is involved seems to be demanded by the occurrence of kyanite in the veins opposite siliceous bands and not confined to the proximity of argillaceous layers where fine needles of kyanite are commonly present. The kyanites have, however, no constant orientation in the veins.

On Unst, in the Shetland Islands, pelitic schists composed mainly of muscovite, quartz, kyanite, chloritoid, staurolite, and iron ores contain veinlike bodies of quartz and kyanite. The rock immediately adjacent to these bodies generally contains no quartz and is much enriched in kyanite, which forms large interlaced or subradiate blades. The constituents of the veins themselves are glassy quartz and rosettes of kyanite as much as 2 inches long. Concerning the origin of these veins, Read (1933, p. 324) states:

> It is concluded, therefore, that these quartz-kyanite rocks were formed by a process of endogenous secretion during metamorphism, and that their complementary portion is indicated by the silica-poor country-rock immediately adjacent to them.

In the Luisha copper mine in Katanga, Belgian Congo, the country rock is a red, highly altered schist containing quartz, chalcopyrite, and andalusite. It is cut by veinlets of chalcopyrite, malachite, and white kyanite in groups of radiating crystals. Buttgenbach (1925, p. 119) concludes that the material of the veins was transferred from the country rock.

Karpoff (1946, p. 1154-1155) describes a pegmatite occurrence on the Algeria-Sudan frontier, where the country rocks are a two-mica gneiss and a kyanite-muscovite schist with amphibole and garnet. Numerous pegmatite bodies containing quartz, feldspar, muscovite, garnet, and tourmaline cut the metamorphic rocks. One of these bodies, enclosed by the kyanite-muscovite schist, contains a quartz mass 2 to 3 meters in diameter, which is traversed by a vein consisting of chlorite, muscovite, and kyanite crystals as much as 40 cm long. Karpoff holds that the kyanite is not of magmatic origin but is due instead to assimilation of kyanitic material from the country rock by the pegmatite solutions.

Among the metamorphosed sediments of the Post Pond volcanic series in the Mascoma quadrangle, west-central New Hampshire, are quartzite, mica-quartz schist, mica schist, and kyanite schist. The quartzite is feldspathic, and the micaceous schists contain feldspar, biotite retrogressive to chlorite, and garnet. The kyanite schist consists of muscovite, poikiloblastic or sericitized kyanite, and quartz, with or without chlorite. Chapman (1939, p. 134) says:

> The mineralogical composition of these rocks and their association with quartzite and mica-quartz schist strongly favor the idea that the kyanite schist was derived from sediments rich in alumina ...

The purpose of this brief review is not to try to prove, by analogy, any theory of origin for the Petaca kyanite deposits. Rather, it is the writer's intention to show that the outstanding features of the Petaca deposits are duplicated in several, and perhaps many, kyanite deposits throughout the world. These features include the formation of kyanite under essentially nonstress conditions in tensional openings during the metamorphism of sedimentary rocks, along with formation of the same mineral in some associated quartz veins. Metamorphic differentiation, which can be invoked to explain the quartz-kyanite segregations of the Petaca deposits, has been suggested by Tilley and Read as the process responsible for the small quartz-kyanite bodies in Ross-shire and in the Shetland Islands. In addition, the formation of kyanite-bearing rock in the lenses or pods of the Petaca district through assimilation of kyanitic material from the country rock and later recrystallization is akin to the origin suggested for the occurrences in Katanga, Belgian Congo, and on the Algeria-Sudan border. Finally, the association of quartzite, quartz schist, sericite schist, and kyanite schist in the Petaca area is nearly duplicated by the sequences of quartzite, mica-quartz schist, mica schist, and kyanite schist described from New Hampshire. The kyanite schist in both regions has been interpreted as metamorphosed pelitic sediments.

Many occurrences in which kyanite is considered to be of magmatic derivation are described in the literature. For example, the kyanite at Graves Mountain, Lincoln County, Georgia, occurs in quartz-kyaniterutile-ilmenite veins and is associated with lazulite in the country rock. Johnston (1935, p. 201) concludes that it is of hydrothermal (indirect magmatic) origin. According to Taber (1913), kyanite in gold-bearing veins of the James River Basin, Virginia, is of magmatic origin. Jonas and Watkins (1932, p. 1) state that the kyanite found in the quartz-muscovite-microcline-rutile-kyanite pegmatite near Galax, Carroll and Grayson Counties, Virginia, is a high-temperature mineral of igneous origin.

ORIGIN OF THE PETACA DEPOSITS

Any theory of origin for the Petaca kyanite must account for these features of the deposits:

1. Strain effects exhibited by some of the kyanite crystals, indicating formation under stress conditions.
2. The presence of quartz-rosette kyanite masses, suggesting crystallization under essentially nonstress conditions.
3. The occurrence of kyanite, evidently also under nonstress conditions, in some of the quartz veins.
4. Veinlets, pods, and irregular masses of quartz that appear both in the lenses of kyanite schist and in the other metamorphic rocks.
5. Constant proportions of the relict minerals present in the major rock types.
6. The restriction of kyanite to the podlike bodies of kyanite schist, whether it occurs in the schist or in quartz veins.

Theories of origin that might be applied to the lenses of kyanite schist in the Petaca district include the following:

I. The lenses originally consisted of sedimentary rock containing a high percentage of detrital kyanite. The specific gravity of kyanite (3.5 to 3.7) suggests that heavier detrital minerals which normally would be present in such a sedimentary concentration should be more abundant as relicts in the kyanite schist than in the other metamorphic rocks. This is not the case. Further, the relict minerals that are present point to igneous, rather than metamorphic, rocks as the sources of the original sediments.

2. Metamorphic solutions or emanations of local derivation assimilated kyanitic material from rock units other than the kyanite schist and transported it laterally or upward to form the lenses of kyanite schist. Chemical analyses of the metamorphic rocks over a wide area surrounding the kyanite-bearing lenses might demonstrate such abstraction of alumina and silica, but available petrographic data do not. There is no visible increase in the amount of alumina and silica in rocks some distance away from the lenses over that in the rocks immediately adjacent to the lenses. Leaching and transportation of kyanite-forming materials over much greater distances appear to be even less likely. Localization of the kyanite in lenses implies either strong structural control of the inferred solutions or a highly favorable chemical environment, but no observed evidence indicates that either one of these conditions obtained.

3. Magmatic emanations (solutions) rich in aluminum and silicon were responsible for the concentrations of kyanite. Any effects of such emanations upon the sediments prior to metamorphism presumably would have been effaced or substantially transformed during the subsequent deformation. Inasmuch as some of the observed kyanite is strained, it must have been formed prior to the close of the period of deformation and metamorphism.

The aluminum and silicon carried by the emanations could have been derived either from the source magma or from the overlying rocks that were traversed. Elements indicative of a magmatic origin, such as boron and fluorine, are not present in the existing metamorphic mineral assemblage. Except for the kyanite schist, all the known rocks with a large alumina content also contain substantial amounts of potassium. Magmatic emanations abstracting alumina from any of these rocks might be expected to abstract potassium as well; yet the percentage of potassium in the kyanite schist is relatively low as compared with that in the surrounding metamorphic rocks. Moreover, although some structural or chemical control of the magmatic emanations seems necessary to explain the lensoid shape of the kyanite deposits, no evidence of such control was observed.

There appears to be no real support for the theory that entire lenses of kyanite schist were formed through the action of aluminous magmatic emanations, although such solutions could have accounted for other, smaller scale features. The unique occurrence of kyanite in quartz veins that are confined to the kyanite-bearing lenses suggests that aluminous material was extracted from the kyanite-bearing rock during upward migration of magmatic solutions and was subsequently deposited as kyanite under essentially nonstress conditions. The extrusion of basic lavas prior to metamorphism, and the emplacement of quartz veins following the metamorphism, may indicate that magmatic activity continued in this area throughout the entire period of diastrophism. Thus the kyanite-bearing lenses may have been permeated by magmatic solutions during the middle stage of metamorphism, when both the quartz-rosette kyanite masses and the irregular masses of quartz were formed by a combination of open-space filling and replacement.

4. The kyanite was formed through metamorphic differentiation of aluminous sediments. It seems very unlikely that entire lenses of kyanite schist were formed in this manner, as other kyanite-bearing formations are not present in the area. However, the aggregates of interlacing kyanite crystals and the quartz-rosette kyanite masses, as well as the veinlets, pods, and irregular bodies of quartz, may have developed through metamorphic segregation.

The term "metamorphic differentiation," denoting the migration and segregation of material under metamorphic conditions, was introduced by Stillwell (1918, p. 58-65, 76-79, 200-209). Eskola (1932, p. 68), in discussing the principles of this process, advanced the following classification of metamorphic changes of composition:

1. Differentiation within a rock mass, due to:
    a. The growth of crystals or aggregates of crystals (the concretion principle).
    b. The concentration of the least soluble substances (the principle of enrichment in the stablest constituents).
    c. The extraction and redeposition of the most soluble substances (the solution principle).
2. Transfer of substances into and from a rock mass, effecting:
    a. Addition.
    b. Metasomatism.
    c. Extraction of substances.

The quartz-rosette kyanite masses and the small, irregular bodies of quartz appear to illustrate 1c of Eskola's classification.

Read (1933, p. 324-328) discussed the subject of metamorphic differentiation and the formation of quartz masses by this process. Citing several European occurrences of quartz segregations, he concluded that such masses effectively illustrate the principles of metamorphic differentiation.

Turner (1948, p. 144) has stated:

> Growth of veins and laminae of simple mineralogical composition during metamorphism of initially homogenous rocks is now generally attributed to metamorphic differentiation governed by the solution principle.

Concerning the origin of quartz veins in staurolite schist in New Hampshire, Chapman (1950, p. 708) has commented as follows:

> It is generally agreed that the degree of mobility (solubility) of silica is high...It would seem . . . that the role of silica in the formation is a passive one; and that silica was probably forced into new positions.

The principles governing the segregation of material during metamorphism have been discussed by Rankama and Sahama (1950, p.

250-255). They postulate that with increasing temperature during metamorphism the kinetic energy of some of the ions in mineral structures will be increased to the point where these ions will be liberated from their coordination. The liberated ions form a "dispersed phase," which may be a liquid or a gas and which increases in volume with increasing temperature. With decreasing temperature, the ions from the old structure, collected in the dispersed phase, are released to form new structures.

It is suggested that the quartz-rosette kyanite masses and the small, irregular quartz bodies formed in fissures within the kyanite schist through the agency of metamorphic aluminum-silicon solutions moving under relaxed-stress conditions. The action of these solutions is considered to have been in accord with the "solution principle" of Eskola, the "endogenous secretion" of Read, and the "dispersed phase" mechanism of Rankama and Sahama.

5. Regional metamorphism of pelitic sedimentary lenses accounts for the major occurrences of kyanite. Available evidence strongly favors the theory that the kyanite schist was produced by middle-grade metamorphism of pelitic silt. Modal analyses of the schist show several features verifying this hypothesis: (a) Identical relict mineral assemblages, present in similar proportions in kyanite schist and surrounding rock types, indicate contemporaneous sedimentary formation. (b) If it is assumed that silica was not introduced in significant amounts, the dominance of quartz suggests a primary quartzose sediment, an origin in harmony with that of the associated country rocks. (c) The kyanitestaurolite-biotite association duplicates the critical mineral assemblage of middle-grade regionally metamorphosed argillaceous sediments, as defined and described by Harker (1939, p. 226), Turner (1948), Barth (1936), Chapman (1939), and numerous others. (d) The major mineral components and their respective abundance are typical of metamorphosed impure arenaceous sediments (Harker, p. 249). (e) The irregular distribution and erratic proportions of the metamorphic ferromagnesian minerals reflect the usual irregular distribution of ferromagnesian material in argillaceous-quartzose sediments.

Vestigial bedding, channeling, and the presence of metamorphic conglomerate leave little doubt as to the sedimentary origin of the other metamorphic rocks. Their spatial relationships strongly suggest original cyclical deposition of fine- to coarse-grained arenaceous sediments. With decreasing grain size, a progressively greater content of argillaceous material appears to have been deposited in this sedimentary section. The interpretation of the kyanite schist as metamorphosed silt-clay lenses fits naturally into the theory of a regional sequence of impure quartzose sediments and interlayered basic extrusives as the progenitors of all the metamorphic rocks in this area.

Stress features characteristic of regional metamorphism, such as folding, secondary foliation, and strained crystals, are widespread and abundant in the kyanite schist.

6. A combination of the above theories accounts for the kyanite deposits. The process of simple regional metamorphism does not explain the formation of the quartz-rosette kyanite bodies and the large kyanitebearing quartz veins. Metamorphic differentiation and injection of siliceous hydrothermal solutions containing assimilated aluminous material have been suggested by the writer as mechanisms responsible for development of these features. A combination of regional metamorphism of argillaceous-arenaceous sediments, later metamorphic differentiation or injection of contaminated siliceous hydrothermal solutions, and still later injection of more siliceous hydrothermal solutions is thought by the writer to explain most satisfactorily the origin of the kyanite deposits.

Economic Features

KYANITE AND MULLITE

COMPOSITION AND PROPERTIES

Kyanite, crystallizing in the triclinic system, and andalusite and sillimanite, in the orthorhombic system, form a trimorphous group with the composition Al_2Si0_5. Although these three minerals have the same chemical composition, they differ distinctly from one another in their physical and optical properties, as well as in their modes of occurrence. All three are converted to mullite ($3A1_20_3 \cdot 2Si0_2$) and silica glass on heating to high temperatures, and mullite has properties that are of considerable industrial and commercial importance.

Kyanite typically forms long-bladed crystals and medium- to coarse-grained aggregates of interlocking or radiating blades or fibers. Much less common is the massive variety, composed of randomly oriented and interlocking small crystals. Kyanite exhibits excellent cleavages parallel with the (100) and (010) planes, as well as basal (001) parting. It has a Mohs hardness of 4 to 5 parallel with the c-axis and 6 to 7 normal to the c-axis. The specific gravity ranges from 153 to 3.67. Optically it is biaxial negative, with the following indices: α = 1.7124.717, ß = 1.720-1.722, and γ = 1.728-1.729. The chemical composition is $A1_20_3$, 62.92 percent, and SiO_2, 37.07 percent.

Calcination of kyanite to mullite is accompanied by an increase in volume ranging from 16 to 200 percent; consequently, the product is highly porous. This is particularly true of mullite derived from coarse domestic kyanite, which therefore has high shrinkage capacity and is difficult to bond in use. In contrast, massive imported kyanite yields a coarse, tough product of considerably lower porosity. The microstructure of mullite obtained from kyanite is an interlacing aggregate of needles, which promotes mechanical strength (Riddle and Foster, 1949, p. 895-900).

The commercially desirable properties of mullite are high refractoriness, stable to 1,810°C; low thermal expansion, with resultant resistance to heat shock; intermediate thermal conductivity; good load-bearing ability from low to high temperatures; and resistance to chemical corrosion, particularly acid slags (Riddle and Foster, 1949).

USES

Kyanite is processed generally into mullite, which is employed almost entirely in the manufacture of so-called superduty refractories. These refractories are used in the metallurgical, enameling, glass, ceramic, chemical, electrical, and cement industries, chiefly in the form of bricks and shapes, and as cements, mortars, plastics, and ramming mixtures. The metallurgical industry consumes about 50 percent of the output of mullite refractories, and the glass industry about 40 percent; the remaining 10 percent is used for miscellaneous products, mainly in the ceramic industry. The metallurgical industry requires large amounts of mullite refractories for electric induction furnaces and for zinc-smelting and gold-refining furnaces. Large amounts also are used in glass tanks, plungers, feeders, and other glasshouse refractories, and smaller amounts are employed in the manufacture of kiln furniture and in the construction of ceramic kilns. Recently mullite has been used for the ceramic lining in the jets of jet engines and for gas-turbine rotor blades.

Minor use is made of kyanite itself as a source of alumina in glass and as an ingredient of electrical and chemical porcelains and pyrometer tubes.

STRATEGIC IMPORTANCE

The Munitions Board, as of September 1952, included kyanite and mullite among the materials listed as strategic and critical. However, provision was made to stockpile only massive kyanite, which is not produced commercially in the United States. In addition, both synthetic mullite and mullite obtained from massive kyanite are stockpiled (United States Tariff Commission, 1952, p. 5-6). The United States Government specifications for kyanite ore include a maximum of 39 percent $Si0_2$, a maximum of 0.75 percent Fe_20_3, and a minimum of 59 percent $A1_20_3$.

SUBSTITUTES

Substitutes are available for nearly all applications of mullite refractories. Among these substitutes are superduty fire clay, silica, high-alumina clay, fused alumina, magnesite, chrome, magnesia-alumina, and fused alumina-silicate. In general, efficiency is lowered through the use of these materials; moreover, some are difficult to obtain or are relatively expensive.

SYNTHETIC MULLITE

Synthetic mullite is not produced from minerals in the sillimanite group. It is made instead from a blend of other highly aluminous and siliceous materials, either by means of the electric furnace or by sintering. Electrically fused mullite is said to be equal or superior in quality to that made from massive imported kyanite. Sintered mullite is reported to be of slightly lower quality than the electrically fused variety.

PREPARATION FOR MARKET

The treatment of kyanite ore depends upon the nature, abundance, and intimacy of intergrowth of the associated mineral impurities and upon the degree of expansion on calcination. Diaspore, corundum, and pyrophyllite add to the alumina content and therefore are desirable. Alkali-bearing minerals adversely affect electrical and load-bearing properties, but a small percentage of muscovite may be tolerated. Because of inversions, free quartz must be reduced to a minimum, and iron minerals, such as magnetite, limonite, and pyrite, are objectionable because of their fluxing and discoloration action. Owing to its excessive expansion on firing, kyanite usually is calcined before use as near to 1,500°C as is practicable. There is no fixed decomposition temperature, and the rate of breakdown for a given type of kyanite varies with grain size and heating rate.

Disseminated kyanite must be concentrated through elimination of undesirable constituents. Such ore is ground to 35 mesh or finer for treatment by froth flotation and for magnetic separation. In contrast, most ores from massive or segregated deposits need no processing beyond crushing the larger pieces and removing the obvious impurities by handsorting.

PRODUCTION AND PRICES

The kyanite industry in the United States is a relatively new one, and was still in an early stage of development as recently as the late 1930's. In the early 1950's only two companies were mining and marketing kyanite. Commercialores, Inc., was working a deposit near Glover, South Carolina, and the Kyanite Mining Corp. was producing kyanite ore from a property, known as Baker Mountain, in Prince Edward County, Virginia.

The deposit at Baker Mountain is large and contains about 20 percent kyanite. The major gangue constituents are clay, iron ores, and quartz. The Kyanite Mining Corp. also owns a deposit at Willis Mountain, in Buckingham County, Virginia. Here the ore contains approximately 35 percent kyanite, 1 percent rutile, and a small amount of iron. The principal gangue mineral is quartz. This deposit may consist of more than 50 million tons of working ore (G. Dixon, 1953, personal communication).

Kyanite also has been produced in varying amounts from deposits near Spruce Pine, North Carolina, as well as from deposits in Georgia and California. The mining of kyanite in the United States is less important than the manufacture of mullite refractories from both domestic and imported kyanite. About 10 companies are engaged in the manufacture of such products.

Kyanite has been imported chiefly from Africa and India. The main producing districts in 1953 were the Lapsa Buru and Madras areas, India; Kenya, Africa; and several districts in South Africa.

Official statistics on United States production of kyanite represent shipments to the market only, and are available for the periods 1939-43 and 1948-51 (table 4). The production of synthetic mullite is reported to have increased in recent years, and is estimated to have been 10,000 to 12,000 tons in 1951.

The price data shown in Table 5 indicate a substantial upward trend for kyanite between 1940 and 1951 This commodity is not under price control at the present time.

FUTURE NEEDS IN THE UNITED STATES

Domestic consumption of mullite, both synthetic and that derived from kyanite and related minerals, is expected to increase in the future because of defense-program needs and large civilian requirements. Nearly all the strategic or coarse-grained mullite is produced from Indian and Kenyan kyanite, but the reserves of this high-quality material have been somewhat depleted. In addition, political unrest in Kenya and export controls in India have limited shipments of kvanite to the United States for long periods of time.

Calcining of domestic kyanite produces a fine-grained product that supplies an important but noncritical need in the field of mullite refractories. A recently developed process, in which domestic kyanite is heat treated with highly aluminous material, makes it possible to manufacture coarse-grained or strategic mullite. As yet, this process is not widely used commercially.

To meet the *need* for an assured supply of strategic mullite, the United States Government has undertaken a program to expand domestic capacity for producing synthetic mullite. This program is expected to result in an additional output of about 20,000 tons of strategic mullite per year.

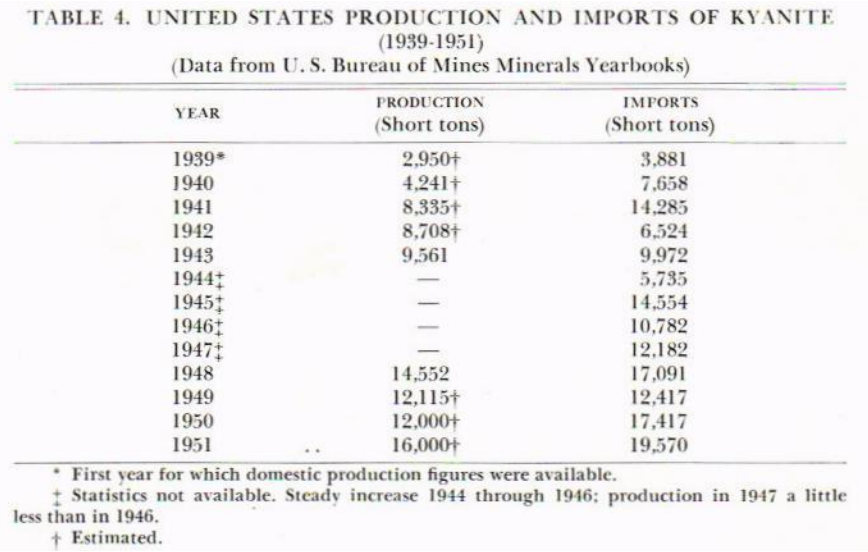

TABLE 4. UNITED STATES PRODUCTION AND IMPORTS OF KYANITE
(1939-1951)
(Data from U. S. Bureau of Mines Minerals Yearbooks)

YEAR	PRODUCTION (Short tons)	IMPORTS (Short tons)
1939*	2,950†	3,881
1940	4,241†	7,658
1941	8,335†	14,285
1942	8,708†	6,524
1943	9,561	9,972
1944‡	—	5,735
1945‡	—	14,554
1946‡	—	10,782
1947‡	—	12,182
1948	14,552	17,091
1949	12,115†	12,417
1950	12,000†	17,417
1951	16,000†	19,570

* First year for which domestic production figures were available.

‡ Statistics not available. Steady increase 1944 through 1946; production in 1947 a little less than in 1946.

† Estimated.

TABLE 5. PRICES OF DOMESTIC AND FOREIGN KYANITE BY TYPES
(Data from U. S. Bureau of Mines Minerals Yearbooks)

	1940 AVERAGE	SEPT. 30, 1943	SEPT. 30, 1950	SEPT. 30, 1951	OCT. 2, 1952	MAY 8, 1953
DOMESTIC KYANITE (F.O.B. POINTS OF SHIPMENT, PER SHORT TON, IN CARLOAD LOTS)						
35-mesh						
Raw, in bulk	$15.00	$19.00	$29.00	$32.00	$29.00	$35.00*
Raw, in bags	17.50	21.50	32.00	35.00	32.00	
Calcined, in bags	22.50	26.50	40.00	44.00		
48-mesh						
Raw, in bags	19.50	23.50	34.00	37.00		
Calcined, in bags	24.50	28.50	42.00	46.00		
100-mesh						
Raw, in bags	19.50	23.50	35.00	38.00		
Calcined, in bags	24.50	28.50	43.00	47.00		
200-mesh						
Raw, in bags	22.50	26.50	40.00	43.00	40.00	
Calcined, in bags	27.50	31.50	48.00	52.00		
INDIAN KYANITE (F.O.B. ATLANTIC PORTS)*						
Crude, in bulk	$20-$25	$50-$55	$55-$65	$55-$70	$55-$70	$55-$90
SYNTHETIC MULLITE (F.O.B. PLANT)*						
Bulk (lump)						$75-$100

* Approximate.

KYANITE DEPOSITS OF THE PETACA DISTRICT

DEVELOPMENT AND PRODUCTION

Although claims were filed on the major kyanite deposits as early as the mid-1920's, exploration and development have been limited to small prospect pits and trenches in the kyanite schist and surrounding rocks. Probably the most extensive and systematic program of exploration was conducted in 1948 and 1949 by Gladding, McBean & Co., of Los Angeles, California.

In 1928 Philip S. Hoyt is reported to have shipped 1,500 tons of kyanite ore to a St. Louis firm for use in high-grade refractories. This constitutes the only known production from the Petaca deposits. The material was obtained from boulders and from the large central knob at the Big Rock deposit, where an open cut was excavated. A vertical shaft, 8 feet by 8 feet at the collar and reportedly 128 feet deep, was sunk from this cut or from a point nearby.

TONNAGE AND GRADE

The tonnage of each kyanite-bearing lens in the major deposits was estimated on the basis of measurements made in the field, and within the framework of the following assumptions:

1. In general the down-dip extension of each lens below the general level of the surrounding terrain is approximately equal to the along-strike dimension of its outcrop.
2. The applied tonnage factor, 11.20 cu ft per ton, is the same in all deposits.
3. The volume of kyanite-bearing-float is approximately one-tenth that of the upward projection portion of the lens or pod from which the float was derived.
4. Pods less than about 900 square feet in exposed area could not be mined profitably; such bodies, therefore, can be neglected in the calculations.

The estimated and inferred volumes and tonnages of the principal kyanite deposits are listed in Table 6.

To determine the approximate grade of typical kyanite-bearing rock, the two largest lenses in the Big Rock deposit were sampled. Chips were collected at 3-foot intervals on a line across each lens and perpendicular to its strike. Chip samples also were obtained from exposures of the coarse-grained quartz-kyanite rock. Chemical analyses of the samples (table 7) were made in the Mineralogical Laboratory of the University of Michigan, and a corresponding mineral composition was calculated from the results of each analysis. These theoretical values are compared, in Table 8, with the averages of many modal analyses of typical kyanite schist and of coarse-grained quartz-kyanite rock. Comparisons also are made with the results of quantitative studies of several heavy-mineral separations.

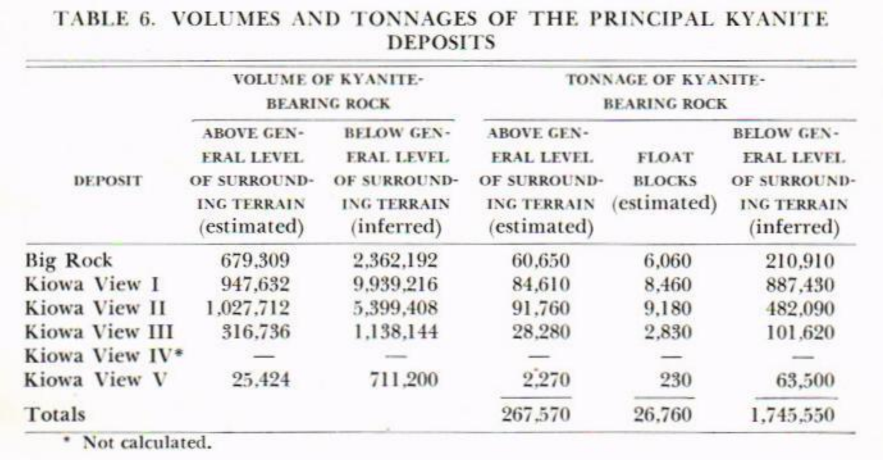

TABLE 6. VOLUMES AND TONNAGES OF THE PRINCIPAL KYANITE DEPOSITS

DEPOSIT	VOLUME OF KYANITE-BEARING ROCK		TONNAGE OF KYANITE-BEARING ROCK		
	ABOVE GENERAL LEVEL OF SURROUNDING TERRAIN (estimated)	BELOW GENERAL LEVEL OF SURROUNDING TERRAIN (inferred)	ABOVE GENERAL LEVEL OF SURROUNDING TERRAIN (estimated)	FLOAT BLOCKS (estimated)	BELOW GENERAL LEVEL OF SURROUNDING TERRAIN (inferred)
Big Rock	679,309	2,362,192	60,650	6,060	210,910
Kiowa View I	947,632	9,939,216	84,610	8,460	887,430
Kiowa View II	1,027,712	5,399,408	91,760	9,180	482,090
Kiowa View III	316,736	1,138,144	28,280	2,830	101,620
Kiowa View IV*	—	—	—	—	—
Kiowa View V	25,424	711,200	2,270	230	63,500
Totals			267,570	26,760	1,745,550

* Not calculated.

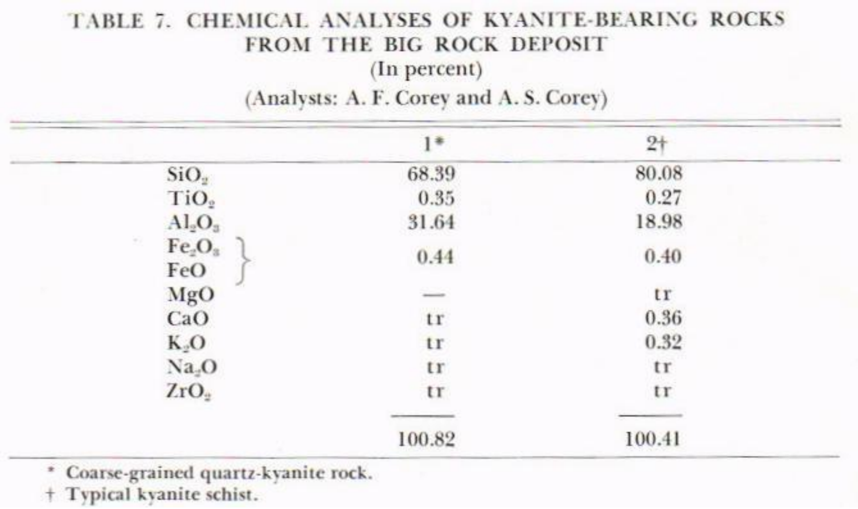

TABLE 7. CHEMICAL ANALYSES OF KYANITE-BEARING ROCKS FROM THE BIG ROCK DEPOSIT
(In percent)
(Analysts: A. F. Corey and A. S. Corey)

	1*	2†
SiO_2	68.39	80.08
TiO_2	0.35	0.27
Al_2O_3	31.64	18.98
Fe_2O_3 FeO	0.44	0.40
MgO	—	tr
CaO	tr	0.36
K_2O	tr	0.32
Na_2O	tr	tr
ZrO_2	tr	tr
	100.82	100.41

* Coarse-grained quartz-kyanite rock.
† Typical kyanite schist.

The specific gravity of the typical kyanite ore is 2.86 (average of 40 determinations), and that of the coarse-grained kyanite ore is 3.10 (average of 10 determinations). These values for specific gravity are not corrected for moisture content or for voids.

Estimated tonnages (table 6) of the principal kyanite deposits, though based in substantial part upon inferred relationships at depth, are regarded by the writer as reasonably sound factors for economic appraisals. On the other hand, the suggested values for grades of kyanitebearing rocks (table 8) should be applied with caution, as they are

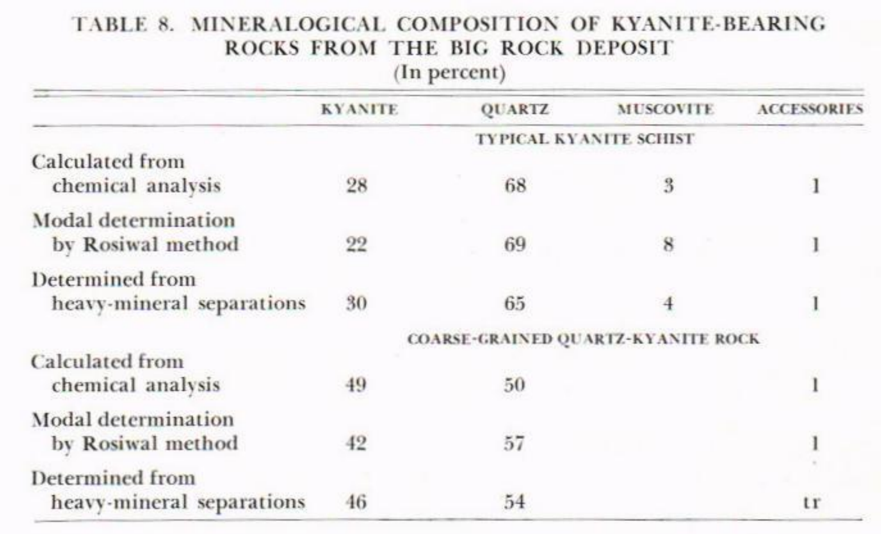

TABLE 8. MINERALOGICAL COMPOSITION OF KYANITE-BEARING ROCKS FROM THE BIG ROCK DEPOSIT
(In percent)

	KYANITE	QUARTZ	MUSCOVITE	ACCESSORIES
		TYPICAL KYANITE SCHIST		
Calculated from chemical analysis	28	68	3	1
Modal determination by Rosiwal method	22	69	8	1
Determined from heavy-mineral separations	30	65	4	1
		COARSE-GRAINED QUARTZ-KYANITE ROCK		
Calculated from chemical analysis	49	50		1
Modal determination by Rosiwal method	42	57		1
Determined from heavy-mineral separations	46	54		tr

founded upon a program of sampling confined to one deposit and upon an assumption that the relatively rich coarse-grained quartz-kyanite rock constitutes approximately 10 per cent of the total volume of the deposit. Further, standard sampling procedures would require considerably more than just one collecting traverse across a given pod in order to provide an estimate of average grade that properly could be compared with estimated tonnage of the pod, owing to known compositional irregularities of the kyanite-bearing rocks.

A detailed economic appraisal of the Big Rock deposit was made in 1947 and 1956 by R. H. Jahns, who has furnished the following summary statement:

> The quartz-kyanite rock of economic interest constitutes only small parts of the large, podlike bodies in which it occurs. The casual observer is tempted to regard each knob-forming mass of quartz-rich rock as possible kyanite ore, especially when he notes the many large, kyanite-rich boulders and blocks that plainly have fallen from Big Rock and nearby knobs. Each knob, however, is composed mainly of rock that contains less than 5 percent kyanite. and at least half of the rock is essentially barren of this mineral.
>
> The deposits were sampled by collecting chips of exposed rock at points 12 inches apart along lines essentially normal to the elongation of the pod under investigation. The lines of traverse were spaced 5 *feet* apart. Each sample, weighing 18 to 40 pounds, was crushed, quartered down in a Jones-type splitter, and analyzed modally under the microscope. For two of the largest samples the analytical technique was checked by complete physical separation into mineral fractions in the laboratory; the respective fractions were weighed, and the results were found to be in good agreement with those obtained from the measurements under the microscope.
>
> Estimates of reserves were based upon measured areas of exposure. including reasonably inferred exposure in intervening areas where no outcrops are present, of rocks containing at least 5 percent kyanite. If it is assumed that the aggregate area of such material remains constant at successively lower levels beneath the outcrop, approximately 5,250 tons of potential kyanite ore is present per 10 feet of depth. The kyanite content of this ore ranges from 5 to about 75 percent by weight, and its average grade is near 18 percent. The grade undoubtedly could be held at a minimum of 25 percent kyanite by selective mining, with attendant reduction in output and reserves.

Although the above-quoted estimate is cast in a different form, it is plainly more conservative than any estimate based upon a direct combination of the data presented in Tables 6 and 8 of this report.

OTHER ECONOMIC FACTORS

As already noted in the introduction of this report, the climate on La Jarita Mesa is mild during much of the year. Precipitation, averaging about 25 inches a year, occurs mainly as fall rains and winter snows. Although temperatures commonly are low for short periods during the winter season, previous mining and lumbering operations in this area were essentially continuous throughout the year. Several sources of water are present within about a 1-mile radius of the kyanite deposits, but some pipeline and storage facilities would be necessary to assure sufficient water for mining operations.

The district is served by all-weather roads, and either the present ungraded access roads to individual deposits could be used for truck hauling, or new roads could be constructed quickly and easily with a bulldozer. The soil and small rock fragments that form a thin but extensive layer over the quartzites and schists should serve as excellent roadbed material.

Concentration of the ore before shipping would be necessary to assure a satisfactory market. One of the largest manufacturers of mullite refractories produced from kyanite, the Chas. Taylor Sons Co., has expressed interest only in purchasing ore that contains not less than about 96 percent kyanite (K. W. Smith, 1953, personal communication). Chemical analyses of representative concentrated kyanite ores of the trade are given in Table 9 (K. W. Smith, 1953, personal communication).

Many experienced miners live in the Petaca district, and competition for manpower is not severe, as the few small farms and minor industries in the area cannot employ all the able-bodied men.

ECONOMIC SUMMARY

Many aspects of mining and marketing are beyond the scope of this geologic report, but the results of the present investigation warrant the following summary of factors that are basic to an economic appraisal of the Petaca kyanite deposits:

1. Substantial quantities of kyanite-bearing rock are present; most of this material occurs as bodies of minable size.

TABLE 9. CHEMICAL ANALYSES OF REPRESENTATIVE CONCENTRATED KYANITE ORES
(In percent)

	1*	2†	3‡	4§	5 ‖
Al_2O_3	61.42	67.05	60.11	58.50	58.72
SiO_2	34.96	26.39	34.14	36.93	37.65
Fe_2O_3	0.74	0.75	0.55	1.49	1.17
TiO_2	1.44	2.79	3.50	0.10	1.25
CaO	0.14	1.15	tr	0.02	tr
MgO	0.20	1.30	tr	0.20	tr
Alkalies	0.40	0.59	0.20	1.70	0.59
Ignition loss	0.53	0.04	1.50	1.06	0.38

* Lapsa Buru, India. May contain as much as 10 percent corundum; the best kyanite ore obtainable.

† South Africa. May contain 25 percent corundum and numerous impurities; not very desirable ore.

‡ Madras, India. May contain 25 percent corundum and high percentages of mica; not very desirable ore.

§ Madras, India. Contains a large percentage of mica and other impurities; very friable after calcining and therefore not desirable.

‖ Average of many domestic kyanite ores.

2. Ore containing about 20 percent kyanite apparently is necessary for commercial operations. The grade of ore in the principal kyanite deposits appears to be high enough to permit the mining of such material on a commercial scale.
3. The concentrations of mica in envelopes of schist that enclose the kyanite-bearing pods are sufficiently high to permit recovery of byproduct scrap mica from mining operations for kyanite.
4. Open-cut methods of mining would be feasible at most of the deposits, and would require the removal of little overburden.
5. The kyanite ore might command a premium price if it were to yield a calcined product similar to that obtained from imported kyanite.
6. The deposits are readily accessible, and climatic factors are generally favorable. Some development of an adequate water supply would be necessary. The deposits are at a considerable distance from rail transportation, and at much greater distances from centers of processing and demand.

It can be concluded that the Petaca deposits have sufficient economic promise to justify a program of exploration aimed at a much more definitive appraisal of tonnage and grade.

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Numbers in **boldface** indicate main references.