

THE AMERICAN MINERALOGIST

JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

VOL. 9

JUNE, 1924

No. 6

NOTE ON ANDALUSITE FROM CALIFORNIA: A NEW USE AND SOME THERMAL PROPERTIES

ALBERT B. PECK, *University of Michigan*

The andalusite here described is found at an elevation of 10,000 feet on the southwestern slope of White Mountain, in the White Mountains of the Inyo Range, Mono County, California. The deposit itself is located across a canyon about two miles east and north of an occurrence described by Knopf.¹ The andalusite reported by Knopf, however, is at present of no commercial value owing to the fact that it carries an excessive amount of quartz.

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OCCURRENCE AND PHYSICAL PROPERTIES. The main mass of the andalusite rock can probably best be described as coarse granular, and is generally of a gray or light pinkish-brown color. On exposed surfaces the color is yellow-brown due to oxidation.

The texture of the rock varies greatly. Many large fragments show a very distinctly coarse radial or columnar structure, definite rough crystals four or five inches in length being noted. At the other extreme are smaller areas which have a very fine granular texture, sugary appearance and are very friable, breaking down readily into a fine sand. While the material is generally quite compact, there are occasional large cavities and in these are sometimes found excellent groups of large coarse crystals at times reaching five inches or more in length.

The color of the material shows variation also. Crystals are generally white on the exterior portion but when broken show directly beneath the surface a pale apple-green color. Columnar or radial masses also show green or gray color but granular masses are usually white, gray, or pinkish-brown. This latter color is in reality due to inclusions of scattered rutile grains or crystals, as can readily be observed when examined microscopically.

CRYSTALLOGRAPHY. The crystals appearing in cavities are generally rather simple in form but of uncommon habit for anda-

¹ *Journ. Wash. Acad. Sc.*, 7, 549 (1917).

lusite. This probably accounts for the fact that of all those to whom a group has been shown, no one has as yet named the crystals as andalusite. The crystals are usually covered with a thin white coating which is dull and somewhat rough, so that accurate measurements of the crystal angles are impossible. Contact goniometer measurements, however, show sufficiently close agreement to the theoretical values to establish the forms present. The crystals usually occur in more or less parallel groups terminated at one end only and are also attached to each other by the prism faces so that the prism zone is generally only partially complete.

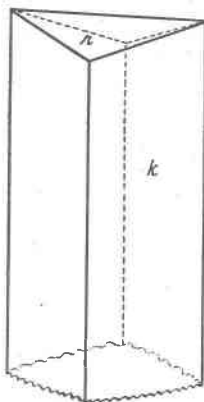


FIG. 1

Figure 1 shows the development of a typical crystal. The predominant prism is k (210) and the end of the form is terminated by the dome r (101). Measurements of the angles are as follows:

	OBSERVED	CALCULATED
kk'''	62-51°	52° 30'
rr'	72	70 56

The prism faces on the larger crystals are somewhat rounded, hence the variation in the angles noted for this form. Faces of the smaller crystals, however, give values close to those calculated for the form. Owing to the fact that the ratio of $a : b$ in andalusite is nearly 1:1, the angles for the forms (210) and (120) are very similar. It was necessary, therefore, in this case to make a thin section parallel to the base and determine the position of the optic plane. This was found to be in the short diagonal and being parallel to the a -axis, the prism then is established as k (210). It follows that

the dome is *r* (101) and not *s* (011); these two forms also possess very similar angles.

CHEMICAL COMPOSITION. On the whole the rock material is a rather pure andalusite with comparatively small amounts of several other minerals. During mining, the material is constantly checked by specific gravity determinations on a Jolly balance. Samples are taken over the face of the working and if favorable, the material is broken out, carefully hand selected and sacked. Generally the material runs at least 75-85% andalusite upon microscopic examination. A typical chemical analysis from a sample representing a carload shipment, recalculated to an Al_2SiO_5 basis, will show over 90% Al_2SiO_5 . Such an analysis follows:

ANALYSIS		EQUIVALENT TO	
SiO ₂	33.78	Al ₂ SiO ₅	94.18
Al ₂ O ₃	56.89	SiO ₂	0.22
H ₂ O	0.37	Others	5.60
Ign. loss	3.67		
Other deter.			
constituents	5.37		
	100.08		

The fact that the chemical analysis generally shows higher Al_2SiO_5 than is indicated by the microscopic examination is due to the frequent occurrence of corundum in the material. In no case do the associated minerals assume any large proportion over any considerable area, although locally they may occasionally outweigh the andalusite.

ASSOCIATES. The associates of the andalusite are also deserving of mention, especially since several are considered among the less common minerals.

Lazulite is perhaps the most unusual mineral associated with the andalusite. It occurs in small blue-green veinlets or masses scattered through the mass. Optically it shows a distinct light blue pleochroism. Chemical analysis usually shows small amounts of P_2O_5 present in the rock.

Pyrophyllite is another uncommon mineral found with the andalusite. It occurs in crusts of radial fibers on the walls of cracks or as radial masses in small cavities. Owing to its chemical composition, as soon as its water is lost it takes on nearly the same composition as andalusite and hence can hardly be considered as an impurity.

Muscovite also occurs in much the same manner as pyrophyllite and is somewhat more abundant but at no time reaches large proportions. It occurs in distinct plates, usually in divergent groups.

Corundum is a rather common associate of the granular andalusite and is usually deep sapphire-blue in color. It is generally in small scattered plates or grains but occasionally may form lenses two or three inches in size. According to observation thus far it is always blue in color. In a few instances crystals of andalusite with blue corundum centers have been noted. For manufacturing purposes a small amount of corundum is favorable to the neutralization of the effect of any excess quartz in the rock.

Rutile is a rather constant associate, largely as microscopic inclusions in the andalusite. At times small free crystals can be found. The constant association of rutile and the blue color of the corundum would seem to confirm the theory that the color of sapphire is due to the presence of TiO_2 .

Pyrite is sometimes found locally, especially near open veins. When near the surface it has often weathered leaving a stained and porous rock.

The absence of quartz is very noticeable. It is almost never found in the andalusite proper but is confined to veins crossing the mass.

Barite also has been noted a number of times; one large right angled twin having been found.

Lazurite also has been found, not in the andalusite but in veins of milky quartz adjacent to the mass. It is of interest to note that Knopf points out that the occurrence examined by him across the canyon and to the southwest, was first staked as a silver mine, the bright blue lazurite being mistaken for AgBr. After an assay showed silver to be absent the claim was dropped. Later the brown andalusite mass was staked again, this time under the impression that it was apatite. This in turn proved valueless and was relinquished.

USE

This deposit of andalusite serves as an extremely good example of a comparatively useless, rare, or "museum" mineral becoming common enough to be available on a commercial scale. Heretofore it has been observed only in small scattered masses or crystals. At the same time it has found a commercial use, until at present about 70 tons per week are being mined. Both of these

developments have been the result of patience and thorough scientific research.

For some years the manufacture of the porcelain core of the most modern type of automobile spark plug has tended toward the formation during the burning process of an increasingly higher content of a crystalline compound, thought to be an "artificial sillimanite." Bowen² has recently shown, however, that in artificial melts consisting of Al_2O_3 and SiO_2 in varying proportions the compound $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$ corresponding to natural sillimanite does not form as has been stated in an earlier work on the subject, but that the compound formed has a composition $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$. Not only is this compound similar chemically to sillimanite but its physical and optical properties are remarkably similar as well.³

This "artificial sillimanite" produced in ceramic ware results from the molecular changes taking place in clay under the influence of heat and various fluxes. The highest content of "sillimanite" has been developed by introducing into the unburned body artificially prepared "sillimanite" in the form of a calcine, a mixture of clay, alumina, and fluxes, heated to a high temperature of about 1500°C . This was of course an expensive method to obtain the desired end although it has been used for several years in the manufacture of spark plugs.

In order to eliminate the necessity of making an "artificial sillimanite," the logical procedure was to turn to one of the natural Al_2SiO_5 compounds, namely, sillimanite, andalusite, or cyanite, but here the difficulty of obtaining any of these in sufficiently large quantities and in a pure state presented itself, until the California andalusite deposit was discovered.

Careful research was then able to substitute this natural material for the "artificial sillimanite" with the result that not only was the manufacture less expensive but also the resulting article was better than the previous one.

² N. L. Bowen and J. W. Greig, *J. Am. Cer. Soc.*, 7, 238-54 (1924).

³ In the original manuscript of the present paper the writer regarded the crystalline compound formed by the inversion of andalusite and cyanite and the crystals formed in porcelain as sillimanite, following the earlier work of the Geophysical Laboratory on the system $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$. Since the announcement of the work of Bowen and Greig it has been necessary in several cases to change "sillimanite" to the new compound " $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$." This statement is made so that full credit may be given to them for the facts they have discovered and the writer's sincere thanks are due Dr. Bowen for his kindness in allowing this use of his manuscript before its actual publication.

THERMAL CHANGES

Although the material is introduced into the clay body of the unburned porcelain core as andalusite, certain changes take place during the burning process and as a result of these no andalusite is present in the finished product but all of it undergoes a molecular change to a compound of the composition $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ with excess of a glass highly siliceous in composition.

This change is quite definite, taking place sharply and at a definite temperature. Under manufacturing conditions this temperature is in the neighborhood of cone 13 on the Seger scale (theoretically equal to 1390°C but actually probably considerably lower).⁴

Of interest from the microscopic standpoint is the behavior of andalusite during this change. Up to the inversion point andalusite retains all of its original optical properties except for the formation of small glass-like inclusions which apparently represent the fusion of included impurities. At the inversion point the clear homogeneous grains of andalusite give way to grains composed of fibrous or columnar crystals, each crystal parallel to the adjacent one with a narrow strip of glass between. The result is instead of a clear grain, a grain composed of a group of parallel crystals having all of the optical properties of $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$, with glass between each. Traces of the remains of such structures can sometimes be seen in a section of a finished spark plug core.

Cyanite also changes to $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ and glass under heat but at a temperature of about cone 11 (theoretically 1350°C). The structure developed is also different from that shown by the change in andalusite. Cyanite yields a "sillimanite body" consisting of groups of interlocking fibers of $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ which are not parallel over any considerable length. Along with these are areas of glassy matter, generally more abundant than in the andalusite and due no doubt to the fact that cyanite is less pure as a rule than andalusite.

The fact that andalusite changes to $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ at a temperature considerably below the final temperature to which the porcelain is burned has a very practical value because in this change from andalusite to $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ and excess siliceous glass there is an increase in specific gravity and a consequent decrease in volume. This volume change tends to produce strains in the porcelain,

⁴The statements made here are purely provisional. The writer expects to investigate the changes with temperature in more detail at a later date.

which can be absorbed if the inversion takes place well below the final burning temperature. If this were not true and the change took place near the final temperature, a decidedly weaker porcelain might result.

Incidentally, during this inversion the andalusite does not outwardly break down and lose its original form, so that good artificial pseudomorphs of this mixture of $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ and glass after andalusite are readily obtained by simply heating for a sufficiently long period above the inversion temperature. This can not be done with cyanite because the expansion at the inversion point is so great that the cyanite breaks down into a chalky, friable mass.

The writer here wishes to acknowledge his sincere thanks to Dr. J. A. Jeffery, President, and Mr. F. H. Riddle, Research Director of the Champion Procelain Company, whose interest and co-operation have made this note possible.

AN UNUSUAL OCCURRENCE OF CYANITE

R. C. WALLACE, *University of Manitoba*

In the Reed-Wekusko Map-Area in Northern Manitoba a series of sediments has been mapped by Dr. F. J. Alcock of the Geological Survey of Canada as the Wekusko series, which he describes as follows:

The Wekusko series consists of gneisses and mica schists most of which are believed to be of sedimentary origin. The paragneisses are finely banded rocks locally showing distinct bedding and crossbedding and with conglomeratic horizons. They vary from light gray to dark gray in colour. They consist of quartz, feldspar, biotite and usually garnet. The mica schists vary considerably depending on the kind of secondary silicates developed in them: garnet, staurolite, and garnet-staurolite types are the common varieties and in one locality a cyanite-bearing schist is associated with the other types. Five distinct areas of these rocks occur in the Reed-Wekusko sheet. . . . Immediately east of the outlet of Anderson lake a ridge approximately 1500 feet long and from 100 to 200 feet wide extends in a northeast direction. The ridge is bordered on the west by low, swampy land facing Anderson lake and on the east by a stretch of muskeg 150 feet wide, to the east of which runs a ridge of red granite-gneiss. The ridge of schist is well exposed throughout: it has been heavily glaciated and shows big grooves and furrows, one of which is 8 feet in width and 6 feet in depth. Like the paragneiss many varieties are met with and all gradations from the garnet gneiss to micaceous schists containing abundant staurolite crystals are encountered. The commonest variety is a biotite schist containing both staurolite and garnet. Towards the northeast end of the ridge a garnetiferous mica schist is developed in which garnet rhombic dodecahedrons, varying in size up to $2\frac{1}{2}$ inches in diameter in places, comprise most of the rock.