SEQUENCE OF MINERALIZATION IN THE KEYSTONE, SOUTH DAKOTA, PEGMATITES (CONCLUDED)

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MINERALIZATION

Introduction

It is the thesis of this paper that the mineralization of the Keystone pegmatites was a continuous process, magmatic in its earliest stages and hydrothermal in the later stages, with the later minerals filling cracks in or replacing the older. The evidence for this conclusion will be given under the descriptions of the different minerals. The idea of a distinct succession of minerals in pegmatites was advanced by Brögger[25] in 1890, who distinguished four epochs of crystallization in the pegmatites of southern Norway. But during the following thirty-five years very few investigators recognized the occurrence of hydrothermal activity subsequent to magmatic crystallization in the pegmatites they were studying.[26] In recent years this conception has been revived and has been the main theme of papers by Hess,[27] Schaller,[28] Landes,[29] and Gillson.[30]

The most detailed application of the hydrothermal theory to the pegmatites of the Keystone region was by Hess in his paper on the natural history of pegmatites previously cited. Although general in its intent the majority of the illustrations depicting veining and replacement were taken in the Keystone district. In 1909 Hess described cassiterite at the Etta mine occurring in cracks in spodumene and stated that it was evidently of later crystallization.[31] Ziegler reached a similar conclusion in 1914: "Thus many

[25] Brögger, W. C.; Die Mineralien der Syenitpegmatit-gänge der Südnorwegischen Augit-und Nephelinsyenite, *Zeit. Krist. Min.*, **16**, 1890.

[26] For an account of the evolution of this idea see Hess, Frank L.; The natural History of Pegmatites, *Eng. & Min. Journal-Press*, **120**, No. 8, pp. 289–298, 1925. Also Schaller, W. T.; The Genesis of Lithium Pegmatites, *Am. Jour. of Sci.*, **10**, 269–279, 1925.

[27] *Op. cit.*

[28] *Op. cit.* Also *Am. Mineralogist*, **11**, Nos. 1 and 3, 1926.

[29] Landes, Kenneth K.; The Paragenesis of the Granite Pegmatites of Central Maine, *Am. Mineralogist*, **10**, No. 11, 353–411, 1925.

[30] Gillson, Joseph L.; The Granite of Conway, New Hampshire, and its Druse Minerals, *Am. Mineralogist*, **13**, No. 8, 307–319, 1927.

[31] *U. S. Geol. Survey, Mineral Resources*, **1909**, Vol. 2, p. 651.

of the large masses of cassiterite found in the Etta and Peerless suggest secondary growth and in many cases partly replace accompanying minerals."[32]

Ziegler was also aware of other evidences of hydrothermal activity in this district for in his paper on the differentiation of a granitic magma he says: "The main body of the Peerless and Hugo mines isᵗ of mica-spodumene type; both, however, have been faulted and brecciated in the central portion and up through the fissures so developed have arisen the amblygonite bearing solutions. Beautiful slickensided surfaces are shown in the Peerless and along these the amblygonite is found. At the Hugo there is a huge shoot of milky quartz which marginally carries much brecciated material. It is in this central portion that the amblygonite occurs."[33] In another paper he states that the giant pegmatites grade into large milky quartz masses containing amblygonite, tourmaline, and apatite enrichment which represent a slightly later stage of crystallization. These in turn grade into quartz veins.[34]

Criteria of hydrothermal activity

It is essential in studying the paragenesis of pegmatites to keep in mind the criteria of hydrothermal activity so that minerals deposited in this manner may be so recognized. Some of these are the same as the criteria of replacement. A list of the most important ones compiled and used by the writer follows:

1. The presence of veins of one mineral (or group) through another. These may be either filled fissures or replacement veins.

2. The separation of a single individual by another (cross-cutting relationship).

3. The presence of unsupported and formless minerals in others. These are considered to be replacement residuals, especially if any parallelism of structure is discernible.

4. The preservation of pre-existing textures and structures.

5. The presence of pseudomorphs in the deposit.

6. Spherical radiation of crystals. Hess[35] considers such an

[32] Ziegler, V.; The Minerals of the Black Hills, *South Dakota School of Mines, Bull.* **10**, p. 106, 1914.

[33] *Econ. Geol.,* **9**, No. 3, 264–277, 1914.

[34] Lithia Deposits of the Black Hills, *Eng. and Min. Journal,* **96**, 1053–1056, 1913.

[35] *Eng. and Min. Journal-Press,* **120**, No. 8, 289–298, 1925.

arrangement proof of replacement because the crystals must have been supported in order to so form.

7. The presence of crystal-lined cavities in the pegmatite.

8. The zoning of a deposit in such a way that the rarer mineral constituents are of greatest abundance in a shoot or pipe connecting with the deeper portions of the pegmatite. This shoot or pipe was the channelway for the upward working hydrothermal solutions.

9. The presence among the suspected hydrothermal minerals of minerals very often found in veins, such as topaz, cassiterite, chalcopyrite, and löllingite, and of minerals containing large amounts of water, such as cookeite.

10. The presence in the deposit of a mineral in two different occurrences. Points on which a mineral may vary are color, crystallographic habit, associated minerals, and chemical composition.

Geological History of the Keystone Region

The geographical and mineralogical relationships between the Keystone pegmatites and the Harney Peak granite lead to the inevitable conclusion that the former are offshoots of differentiated portions of the Harney Peak granite magma. As has already been stated, the origin of this latter mass is a subject of great interest, but of such magnitude that it could not be included in the present investigation. The Harney Peak granite is a pegmatite of batholithic proportions. It is probably an offshoot of a magma which underwent differentiation at a depth not yet reached by erosion. Its method of emplacement was both displacive, as shown by the distorted character of the schists surrounding the granite, and replacive, as evidenced by the lit-par-lit injection noted by several investigators about the margins. The crystallization of the Harney Peak magma was accompanied by the rejection of large amounts of water, boron, lithium, and the rarer elements. These substances, along with not yet crystallized granite magma, escaped upward and outward into the country rock, producing the pegmatite dikes which abound in this region.

In all probability the pegmatite magma also both displaced and replaced the country rock in making room for itself. It metamorphosed the adjoining rock in a manner already described. At the same time it gradually crystallized, becoming a solid rock body. Due to quicker cooling near the contact differences in texture and composition occur in that zone. Adjacent to the

contact the size of grain is relatively small, being about the same as that of a normal granite. Also in the marginal zone crystallization was sufficiently rapid to cause a mineralization more typical of the original magma than of the pegmatite which finally resulted during this stage. For this reason there is a concentration of tourmaline or muscovite, or both, in the border zones of the Keystone pegmatites. Associated minerals are microcline and quartz.

As crystallization proceeded in the main portions of the pegmatite the mineralizers present did not enter in any great amount into the minerals being formed. They were again left behind and as they accumulated in successively lower levels of the pegmatite they worked upward, dissolving older minerals and depositing new. At first these hydrothermal solutions soaked through the pegmatite, producing minerals of the intermediate stage. Later, cracks developed in the earlier minerals and in these veins were formed, with, however, no fine line of demarcation between this stage and the preceding one. In some deposits the hydrothermal minerals are largely confined to one portion of the pegmatite which contained the greatest number of channelways for the solutions. This is especially true of the Hugo.

To recapitulate, four magmas are postulated to have existed in the Keystone district: (1) A hypothetical deep-seated magma which crystallized and differentiated, producing (2) the Harney Peak granite magma which crystallized into the Harney Peak "granite" and produced, by residual concentration of mineralizers, the (3) pegmatite magma, which followed a similar course and produced at successively lower levels (4) hydrothermal solutions (very dilute magma) which dissolved and replaced earlier minerals of the pegmatite. Each magma contained higher proportions of water and other mineralizers than the preceding one (from which it was derived) and hence was much more liquid.

The common primary pegmatite minerals are quartz, microcline, muscovite, black tourmaline, apatite, triphylite, and beryl. Minerals deposited during the intermediate stage are spodumene, amblygonite, and a later beryl. The greatest variety of minerals was deposited (both by fissure filling and replacement) during the third or vein-forming period. Important in this group are albite (cleavelandite), cassiterite, lepidolite, columbite, and a second generation of quartz, muscovite, and tourmaline. During the vein period precipitation of new minerals kept up with the dissolution

of older minerals so almost no cavities or pockets which are so common in the pegmatites of Maine[36] were formed. Supergene activity closed the sequence of mineralization with the formation of such minerals as purpurite, chrysocolla, and montmorillonite.

While studying the pegmatites of the Keystone district the writer found that the sequence observed in one deposit held true for the others, with, of course, some differences in the species present or in their relative abundance. Consequently in the following pages the sequence is given for the four deposits as though they were one, occasionally noting a difference, not in the order of formation, but in the relative importance of various minerals.

Chemical Considerations

The pegmatite magma expelled by the Harney Peak magma contained in greatest abundance the common oxides of a granite, namely, silica, alumina, potash, and soda. Iron oxide was unusually low. In addition to these compounds the so-called mineralizers were present in sufficient amounts to enter into some of the compounds formed during the mass crystallization of the pegmatite and to cause and maintain subsequent periods of mineralization. Tht elements lithium, boron, phosphorus, and beryllium were especially abundant, for they appear both in the accessory minerals formed during the primary crystallization of the magma and in minerals formed during later epochs.

The first, or mass crystallization, phase used up most of the potash and a good part of the small amount of iron present (in the black tourmalines of the border phase). The intermediate phase was dominated by lithium (spodumene and amblygonite), with beryllium important in a few places. The third stage of mineralization found sodium, which had previously been largely rejected, of extreme importance as a major constituent of albite. Considerable lithium still remained in the residual solutions as attested by the large quantities of lepidolite found in some of the pegmatites. The samll mount of potash not used by the microcline and muscovite of the first stage was taken care of in the third stage by a second generation of muscovite. Boron reappeared in tourmaline. Excess silica produced quartz veins. Rarer elements appeared for the first time in the minerals cassiterite, columbite, and tantalite. Iron reappeared in löllingite and the presence of this mineral implies a

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[36] K. K. Landes; *op. cit.*

dearth of sulphur, with arsenic present in its place. Water, the most important mineralizer of all, was undoubtedly present throughout the various stages of mineralization in increasing abundance, but its function was more that of a transporting medium than a mineral constituent.

In conclusion the pegmatite magma was a silica-alumina-alkali solution with water and rarer elements playing an important rôle. Of the alkalies potassium was outstanding during the first stage of mineralization, lithium during the second, and sodium (with lesser lithium) during the third. Phosphorus and beryllium were included in both the first and second stages, boron in the first and third, and the metals in th. third only (except iron).

Primary Stage

During the first stage of mineralization the pegmatite magma crystallized. The unusually abundant mineralizers had very little effect upon the composition of the minerals, but they did cause the formation of large crystals by lowering the freezing point and permitting a longer period of crystallization. As in granite, the accessory minerals were the first to complete their crystallization. The dominant minerals, microcline and quartz, usually were the very last to form.

Table I
Paragenesis of the Keystone Minerals

	Magmatic period	Intermediate stage	Vein period
Tourmaline	——		
Muscovite	————		
Beryl	——		
Triphylite	—·—		
Apatite	——		
Microcline	————————		
Quartz	————————		
Beryl		——	
Amblygonite		———	
Spodumene		—————	
Tourmaline			——
Lepidolite			———
Muscovite			———
Albite			——
Met. minerals			——
Quartz			——

Minerals of the Primary Stage

Tourmaline. Tourmaline was one of the first minerals to complete its crystallization in the Keystone pegmatites, but it reappeared during the vein forming stage. The first generation tourmaline is confined to the border zone where it may occur in coarse, black crystals with little else present. At the Hugo mine this zone is especially prominent with some of the crystals three inches in thickness. The crystals are inclined to be stubby, with the diameter often exceeding the length. A specimen collected from the Peerless consisted almost entirely of the terminating form, a steep ditrigonal pyramid. Most of the magmatic tourmaline is jet black, but a few crystals are translucent and green or greenish blue. The commonest associated mineral is muscovite, and where tourmaline crystals are enclosed in books of mica they tend to be more transparent.

Muscovite. Muscovite of magmatic origin may be found throughout the pegmatites because the mineral was widespread in its original crystallization and also because it was fairly resistant to the chemical attack of later solutions. A concentration of mica is found, however, near the contact, for like tourmaline the chilling of the primary pegmatite magma usually caused the formation of large amounts of muscovite. The mica-rich border zones are especially well illustrated at the Etta and Hugo. The books are moderate in size, the largest approaching a foot in maximum diameter and about three inches in thickness. The color varies from yellow to silvery white. "Rulings" are common, preventing the securing of flawless sheets of any size. Of the contemporaneous mineral associates, quartz, microcline and tourmaline are the commonest. Where hydrothermal solutions have been active, muscovite or muscovite and quartz may be the only remnants left of the magmatic crystallization in which case they will be surrounded by cleavelandite, lepidolite, and other minerals of the vein stage. Many specimens were collected in which cleavelandite has replaced part of a book of mica. The plates of albite are almost invariably parallel to the cleavage of the muscovite, with many of the crystals extending some distance into the mica, replacing and merging into a similar thickness of that mineral.

Beryl. The data in regard to the position in the sequence of beryl are less conclusive than for the other minerals. It is quite definitely pre-albite, as it is veined by that mineral. It appears to be both

magmatic and intermediate in age. Usually when one mineral is formed at two different periods there are distinct differences in color, habit, and composition, but this was not true of beryl. At the Hugo mine it occurs in abundance with mica in the foot-wall zone and similar occurrences have been noted in the other pegmatites of the district. The large crystals at the Ingersoll are apparently of intermediate age and will be described in the next chapter. The color of the Keystone beryl varies between green and milky white, but is usually the latter in which case it is very similar in appearance to quartz. Well defined crystals are rare.

Triphylite. A chocolate colored mineral, locally called lithiophilite, is abundant in the Keystone pegmatites. A partial analysis of this material by Mr. Emmett Beach shows a preponderance of iron over manganese, consequently it lies toward the triphylite end of the isomorphous series and should be called by that name. Ziegler notes that sodium replaces lithium and suggests the name soda-triphylite.[37] Nowhere could the writer find entirely unaltered specimens of this material. The manganese present oxidizes very readily and changes not only the color and character of the mineral, but also stains the surrounding rock. In fact many of the specimens which seemed to be homogeneous proved upon microscopic examination to consist of an evenly stained mixture of triphylite and cleavelandite. The freshest specimen obtained was broken up and the material at the center examined both megascopically and microscopically. The color of the fresh fracture was a gunmetal blue similar to that of chalcocite, but the streak was brown. Two cleavages were noted, one good, the other (at right angles) fair. Even this material was almost opaque when viewed under the microscope. Light passed through the fine powder and the thinnest edges of the grains. The mean index of refraction was a little over 1.70. The color by transmitted light was reddish brown.

Triphylite occurs in the main portions of the Keystone pegmatites in large masses, some of them several feet across. These are without definite crystallographic form. Cleavelandite replaced triphilite readily and is consequently a very common associate. The position of triphylite in the sequence was determined by its relationship to apatite for in one specimen it was penetrated by a network of apatite veins.

[37] Quoted by J. Connolly; *Proc. S. Dak. Acad. Sci.*, **6,** 40–53, 1922.

Heterosite. A single specimen of this mineral was furnished by Mr. Hesnard. It is steel gray in color, becoming violet upon exposure. Grains examined under the microscope were black and opaque except on very thin edges. The non-opaque portions exhibited the typical pleochroism of heterosite.

Manganapatite. The apatite of the Keystone pegmatites contains 2.03 per cent of MnO[38] which is enough to classify it as a manganapatite according to Dana.[39] The mineral occurs in bluish green to green masses often several inches across. No crystal faces could be found. The commonest associates are massive quartz and cleavelandite. The latter cuts through apatite in distinct veins. Apatite is pre-spodumene as a small crystal of spodumene passes completely through and separates into two parts a single apatite individual at the Hugo mine. On the other hand apatite encloses residual masses of muscovite and replaces triphylite so it must be later than those minerals.

Microcline. Microcline and quartz were forming throughout the magmatic phase. They crystallized out with the muscovite and tourmaline of the border zone and later filled in the spaces between the accessory minerals in the central portions of the pegmatite (just as they do in a granite). However, microcline was much more readily replaced by the later minerals than was quartz, so where it happened to be situated in or near the channelways used by the hydrothermal solutions it has been largely removed. But in the less disturbed parts of the pegmatites, as in the uppermost of the three zones at the Hugo, crystals of nearly pure microcline eight to ten feet across are found.

Microscopic examination of a large number of feldspar specimens failed to reveal the presence of any orthoclase in the Keytone pegmatites. The variety was always microcline or microcline-albite perthite. This conclusion has also been reached by Connolly[40] who has examined a large number of specimens from this locality. Perthite is very common and in some instances the albite is so coarse that its twinning striae are visible in the hand specimen. Microcline is of much the greater quantitative importance, however, than is the perthitic albite.

Usually feldspar was sufficiently late in forming so that it did not have space available to form euhedral crystals. However, a

[38] Determined by Emmett Beach.
[39] System of Mineralogy, p. 766.
[40] *Op. cit.*

few were formed and one of these was presented the writer by Mr. Hesnard. This crystal is four inches long and $2\frac{1}{2}$ inches in diameter with a single termination. Only the prism, side pinacoid, base, and negative orthodome were present. The prism faces were equally developed with those of the side pinacoid, giving the crystal a hexagonal aspect and causing it to be called a pseudomorph after beryl.

Quartz. The quartz of the magmatic period occurs in large anhedral masses. It is the commonest mineral species in the Keystone pegmatites. The color is usually milky, but sometimes it is clear and occasionally the collector can find a specimen tending toward smoky. Rose quartz is rare in this particular locality, but it is practically the only mineral present a few miles south at the famous Scott rose quartz mine[41] where the pegmatite crops out on the side of a cliff and the exposed face measures many feet both laterally and vertically.

The quartz of the primary pegmatite in the Keystone district is found associated with all the other minerals of the same generation. It also occurs as small residual masses completely enclosed in minerals of later age, such as amblygonite, spodumene, and cleavelandite.

INTERMEDIATE STAGE

The mineralizers were largely rejected during the mass crystallization of the pegmatite magma. Those which were set free in one part of the deposit travelled through the already solidified portions and replaced the older minerals with new ones. At the very beginning of this process the residual solutions were high in lithium and the deposit was soaked with this element. Thus spodumene was formed at the Etta and amblygonite in the other pegmatites. In a few places, notably at the Ingersoll, beryllium was concentrated in the residual solutions so a second generation of beryl was formed.

Minerals of the Intermediate Stage

Beryl. At the Bob Ingersoll mine in the lowermost pegmatite there occurs a beryl crystal with a basal section measuring 45 inches across. The length is not known. Another beryl almost as large crops out in the quarry face in the middle dike. This latter crystal completely encloses a small mass of triphylite and a much larger mass of microcline. The color is white, sometimes with a pale greenish cast.

[41] Sterrett, Douglas B.; *U. S. Geol. Survey, Mineral Resources* **1908**, 2, 836–837.

Amblygonite. Amblygonite is found in all the deposits studied, but the largest amounts have been found in the Peerless and Bob Ingersoll mines. Hess[42] has described a shoot of amblygonite at the Peerless 20 feet wide by 40 feet long by at least 20 feet deep. It produced 900 tons of material. The uppermost Ingersoll pegmatite contains close to the hanging wall a nearly vertical pipe of amblygonite several feet in diameter. The pipe is largely surrounded by massive quartz and the contact between the two minerals is very uneven. Blunt points of quartz extend for short distances into the amblygonite and often out beyond such a point will lie a small isolated nearly spherical quartz mass, like an island in a submerged coastal area. On the other hand isolated masses of amblygonite do not occur out beyond the amblygonite points in the quartz area. Consequently it is believed that the amblygonite is replacing the massive quartz and is of later age. Residual masses of microcline were also observed in amblygonite. Ziegler has noted the presence in the Peerless of slickensided surfaces along which the amblygonite is found and therefore believes it to be of later age.[43] Cleavelandite and lepidolite and the other minerals of the third stage very definitely vein through amblygonite so it must lie in the intermediate class. It formed instead of spodumene when phosphorus was plentiful.

The Keystone amblygonite is white, but with a vitreous luster, and sometimes a faint bluish cast which distinguishes it from feldspar with its creamy white color. No distinct crystal forms were observed. Instead the mineral tends to a nodular habit.

Spodumene. Spodumene is found in all of the Keystone deposits, but the outstanding occurrence is at the Etta. There spodumene is one of the most important minerals and its huge elongated crystals cover the various faces of the quarry in an irregular profusion. The average crystal or "log" exposed today is from three to four feet long and from six to nine inches in diameter, but some are considerably larger and in 1904 one was uncovered with a length of 42 feet and diameters of three and six feet.[44] This is pictured and described in an article by Schaller.[45] The crystals are rectangular in cross section with truncated corners, but the terminal planes are obscure. Cassiterite is often found deposited along cracks in

[42] *U. S. Geol. Survey, Mineral Resources for* **1909**, 2, 651.

[43] *Econ. Geology*, April, **1914**, pp. 264–277.

[44] Hess, F. L.; *op. cit.*

[45] Gigantic Crystals of Spodumene. *U. S. Geol. Survey, Bull.*, **610**, p. 138, 1916.

the spodumene and is obviously of later age. The mineral decays readily, breaking down into a pink or red splintery material (due to effect of cleavage). Both Connolly[46] and Schwartz and Leonard[47] have described this alteration and determined that the end product is killinite (muscovite). The latter authors conclude "that the greater part of the alteration was the result of meteoric solutions, but the fact that some crystals in the deeper tunnels show evidence of alteration suggests the possibility of an earlier action, probably by hydrothermal solutions."

The writer believes the spodumene to be of later age than the minerals of the magmatic phase. The evidence for this is as follows:

1. The spodumene crystals exhibit cross cutting relationship to the other minerals in the pegmatites. In the Etta mine they are so huge that this characteristic is not easily observed, but in the Hugo mine a small spodumene crystal passes directly through a large apatite individual.

2. Constancy of diameter of the spodumene crystals in the Etta mine is the exception rather than the rule. The crystals thicken and thin very irregularly and abruptly. There is no symmetry to these changes. One would expect a crystal forming from a liquid to grow outward from its axis of elongation evenly, or at least to exhibit some symmetry as do the tapering beryl crystals found at Buckfield, Maine.[48] A mineral forming by replacement of pre-existing minerals would be expected to grow unevenly due to the differences in replaceability of the earlier minerals.

3. Nearly spherical inclusions of quartz appear within the spodumene. It is the writer's idea that these are residual. ¶, as usually held, the spodumene crystals precipitated out from a liquid it is difficult to conceive how these masses of quartz could be included. If the quartz was crystallizing at the same time one wonders why it is not euhedral and how the spodumene crystals had a chance to grow to their present size.

4. Many of the spodumene crystals occur in groups with a tendency toward spherical radiation. Hess considers such an arrangement proof of replacement because the crystals must have been supported in order to so form.[49] The specific gravity of spodumene

[46] *Proc. S. Dak. Acad. of Sci.*, **6**, 42–45, 1922.

[47] *Am. Jour. Sci.*, **11**, 257–264, 1926.

[48] Landes, Kenneth K.; The Paragenesis of the Granite Pegmatites of Central Maine, *Am. Mineral.*, Vol. **10**, No. 11, Nov. 1925, p. 369.

[49] Hess, Frank L.; The Natural History of the Pegmatites, *Eng. and Min. Journal-Press*, August 22, 1925, pp. 289–298.

is 3.2, and crystals of this weight would have a constant tendency to sink in a magma which was undoubtedly of a considerable less gravity.[50]

5. Veins of spodumene along a face of massive quartz have been noted by Larsen.[51]

<center>VEIN STAGE</center>

After the lithium and beryllium bath aqueous solutions continued to work upward through solid pegmatite from the crystallizing portions at depth, but by this time contraction and earth movements had fractured the deposit so that easy channelways were available. These became filled with mineral matter. Replacement by no means ceased, however, for the veins enlarged themselves by replacing the wall rock and older minerals some distance away from the main channelways were impregnated by minerals of this stage. The very last hydrothermal solutions were those from greatest depth which on account of the distance travelled consisted mainly of water and silica. These produced the quartz veins. Usually the minerals deposited during the vein stage do not occur evenly through the entire deposit, but are more or less concentrated in one part (as in the central portion of the Hugo pegmatite). The minerals of this class are definitely later than those of the intermediate and magmatic periods, but the sequence within the class could not be worked out with precision in every instance because of the paucity of some of the mineral species. The most abundant hydrothermal mineral, albite, was not deposited until after the earlier part of the vein period.

<center>Minerals of the Vein Stage</center>

Tourmaline. The indicolite variety of tourmaline occurs with cleavelandite and lepidolite in the uppermost Ingersoll pegmatite. It is placed in the vein forming period because of its invariable association with these minerals. Complete crystals are rare, because they were encroached upon by cleavelandite. However, the characteristic striated prism faces are often discernible. The color is a dark greenish blue. At the Etta mine microscopic crystals of tourmaline are scattered through very fine sugary quartz. Dense aggregates of small cassiterite grains are also present.

[50] Connolly, Joseph; Rare Minerals in the Black Hills of South Dakota, *Proc. S. Dak. Academy of Science*, Vol. **6**, 1922, pp. 40–53.

[51] E. S. Larsen, informal communication.

Lepidolite. Lepidolite is most abundant at the Bob Ingersoll mine, where the uppermost pegmatite contains a large shoot of massive lilac lepidolite mixed with a small amount of cleavelandite. In another part of the same pegmatite the indicolite variety of tourmaline is also closely associated. At the Hugo lepidolite occurs in the middle portion of the pegmatite in large exceedingly dense masses. The mineral has also been reported from the Etta and the Peerless, but no specimens containing it were collected by the writer. Fine yellow and green mica is locally called lepidolite, but laboratory examination proved it to be muscovite. Similar results were obtained by Schwartz and Leonard[52] on specimens from the Etta mine.
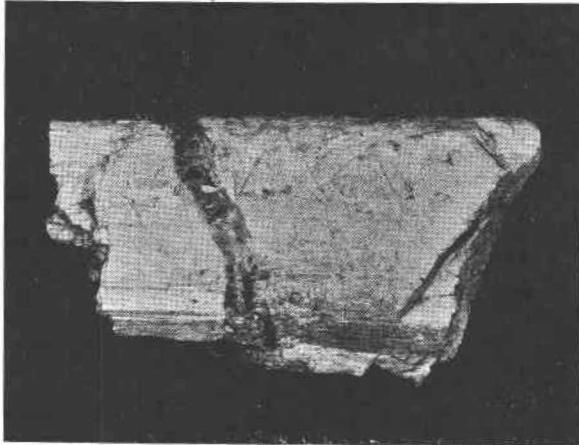

Fig. 2
Vein of quartz and dense lilac lepidolite through spodumene.
Hugo pegmatite. Specimen is 4 inches in length.

The Ingersoll lepidolite occurs in fine (but not dense) micaceous aggregates. Cleavelandite and indicolite may or may not be present. When the mineral is alone it has a beautiful deep lilac color, but when with indicolite it is usually silvery, as though the tourmaline had robbed it of its coloring matter. The Hugo lepidolite ranges in color from white to greenish gray to pink. It is at times so dense that the micaceous character is not visible in the hand specimen.[53] In that case it can be sawed into slabs and other-

[52] *Econ. Geol.*, **20,** No. 7, p. 656, 1925.
[53] Also observed by Ziegler, *Eng. and Min. Jour.*, **96,** 1053–1056. 1913.

wise worked. A specimen was secured of spodumene cut by a vein of dense lepidolite and quartz (Fig. 2). A most peculiar occurrence of the Hugo lepidolite is as a replacement of microcline. The mica flakes (which in this instance are white) oriented themselves conformably to the cleavage of the host, producing a "ghost" cleavage through the resulting aggregate. Specimens were collected showing all degrees of this replacement, from an incipient stage in which the specimen was dominantly microcline, to the final stage where the specimen consisted entirely of lepidolite, but with the microcline cleavage still visible.

Ziegler[54] states that caesium and rubidium are present in some of the Black Hills pegmatites. The specimens collected by the writer have not yet been analyzed for these elements.
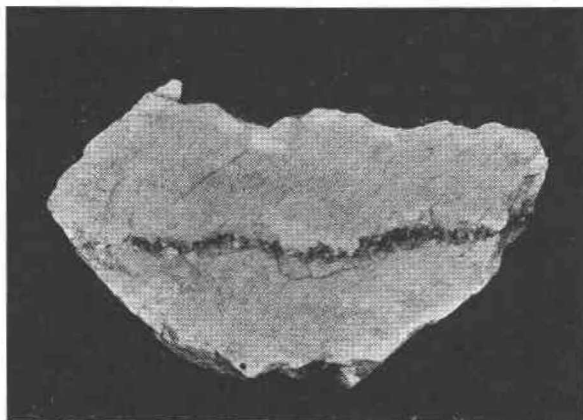

Fig. 3

Vein of quartz and green muscovite through microcline. Ingersoll mine. Total length of specimen, $5\frac{1}{2}$ inches.

Muscovite. Muscovite of the vein period is found in all of the Keystone pegmatites. It differs from the mica of the magmatic period in habit, for it never forms books of any size, but instead composes fine grained aggregates. The color is yellowish green or greenish yellow. As has already been noted this mica is locally known as lepidolite and its occurrence is very similar. A specimen collected from the Hugo showed vein muscovite replacing a cleavable mineral (probably microcline) in exactly the same manner

[54] *Op. cit.*

as does lepidolite. A specimen from the Peerless contained yellow masses of very dense muscovite.

Cleavelandite is a practically universal associate of green muscovite. Cassiterite is also often present and the mixture of the three minerals is referred to as greisen. The replacement of microcline by vein muscovite is well illustrated in a picture published by Hess.[55]

Albite. Albite is the most abundant mineral of the vein stage. It is found in each of the four deposits studied and in every instance is definitely later than the minerals listed in the first two groups and tourmaline, lepidolite, and muscovite of the third group. The most striking occurrence is where it replaces milky quartz belonging to the magmatic period. In that case the albite cuts through the quartz in a multitude of distinct veins ranging in thickness from 1/32 of an inch to several inches. The veins ramify in such a manner as to make the aggregate a typical replacement breccia (see Fig. 5). Hess has pictured a similar specimen from the Black Hills in his article on the natural history of pegmatites.[56] Such quartz-albite replacement breccia is especially common at the Etta and Peerless and at the uppermost Ingersoll pegmatite it composes most of the southern part of the outcrop.

Quartz is by no means the only mineral replaced by albite. Veins and apophyses of the latter mineral extend into microcline, apatite, amblygonite, spodumene, and many other minerals. The sheet-by-sheet replacement of muscovite has already been described. The commonest associates of albite are lepidolite, green or yellow muscovite, indicolite, cassiterite, and columbite-tantalite.

All of the albite of this period is the lamellar variety known as cleavelandite. Each crystal is tabular and thin and has a tendency to join with others in a sheaf-like aggregate. The color is white except where stained by manganese solutions from the triphylite in which case the mineral may be brown or black on the surface.

Cassiterite. Cassiterite occurs in all of the Keystone pegmatites and many years ago was the cause of much unsuccessful mining activity at the Etta. One mass found in this deposit was said to have weighed between 50 and 60 pounds.[57] No such amounts have been found in recent years and the statement made in 1894 that

[55] *Eng. and Min. Journal-Press,* **120,** No. 8, p. 294, 1925.

[56] *Op. cit.,* p. 293.

[57] W. P. Blake; quoted by C. C. O'Hara, *South Dakota School of Mines, Bull.,* **6,** 1903.

"tin apparently decreases in quantity with depth"[58] was probably true. At any rate one can see little excuse for a tin stampede in the present exposures of the Etta, for cassiterite is not in the least abundant. The collector can expect greater success in searching for this mineral in the Hugo pegmatite.

Cassiterite occurs in the Keystone district in a number of ways. One occurrence is in small grains scattered through cleavelandite. A second is with vein quartz, but this is of greater importance outside of the pegmatites as at Hill City where there are a number of abandoned tin mines. A third occurrence is in a greisen, which may be composed of green or yellow muscovite only, or mica and quartz (both belonging to the vein stage), or these two minerals
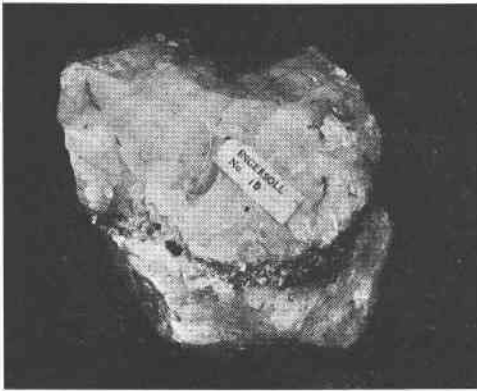

Fig. 4

Vein containing yellow muscovite, albite, and cassiterite passing through massive milky quartz. Ingersoll mine. Length of specimen 3 inches.

plus albite. The last named is common, and was called albitic greisen in the early reports. At the Ingersoll indicolite may also be present. A sugary greisen at the Etta contained minute grains of cassiterite in a fine quartz groundness in which microscopic crystals of tourmaline were also present. A vein containing yellow mica and cassiterite is shown in Fig. 4.

Well terminated cassiterite crystals are not common, but an occasional grain will contain a few faces, usually in the prism zone. Copper stain, such as malachite, may coat a part of a cassiterite

[58] Morse, A. J.; The Harney Peak Tin Mines, *Eng. and Min. Journal*, **58**, p. 463, 1894.

specimen, in which case the mineral is locally referred to as cupro-cassiterite. This name was given by Ulke[59] to a light yellowish to malachite green mineral with an earthy fracture found at the Etta. The supposed formula was $4SnO_2$ plus $Cu_2Sn(OH)_6$. Headden[60] later showed that the composition of this material varied widely and concluded that it was an oxidation product of stannite. It is highly probable that the copper stain found on the Keystone cassiterite did not come from the cassiterite, but from minute grains of intergrown chalcopyrite. The latter mineral occurs in visible
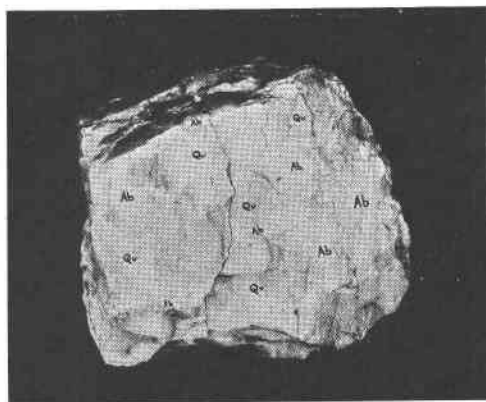

Fig. 5

Replacement breccia from Etta pegmatite. Quartz and vein albite. Total length of specimen 8 inches.

amounts in stannite. A yellowish powder found on one specimen of cassiterite from the Hugo was highly suggestive of uranium, but it did not give a definite bead test for that element.

Stannite. One specimen of stannite was secured by the writer through the kindness of Mr. Hesnard. This was originally taken from the Etta pegmatite. A single crystal of the mineral one inch long by one-half inch wide is embedded in massive milky quartz. The presence of tin and sulphur was verified by a qualitative analysis by Mr. Beach. Within and around one end of the crystal is chalcopyrite in very fine veins.

[59] Ulke, T.; A New Tin Mineral in the Black Hills, *Trans. Am. Inst. Min. Eng.*, **21**, 240–241, 1892.

[60] *Am. Jour. Sci.*, **45**, 105, 1893.

Stannite from the Peerless has been analyzed and described by Headden.[61] He determined the formula to be 2RS plus SnS_2 in which R represents copper $\frac{1}{2}$, iron $\frac{1}{2}$, and zinc and cadmium $\frac{1}{4}$.

Chalcopyrite. The occurrence of this mineral has just been described. It is apparently later than stannite, as it occurs along the stannite-quartz contact, and in thin veins within the tin mineral. Chalcopyrite is one of the very rare minerals of the Keystone pegmatites.

Löllingite. Löllingite is fairly common at the Peerless. It is one of the late minerals of the vein stage, as it cuts directly through plates of cleavelandite, its usual associate. The mineral is steel gray, crystallizing in long thin tabular crystals which vein through the rock joining with other crystals to produce a dendritic effect.

The analysis of a specimen of löllingite from the Peerless mine by Mr. Emmett Beach follows:

Fe	26.30 per cent	
Co	none	
Ni	none	Fe:As = 1:2
As	74.01	
S	slight trace	
Total	100.31	

Geyerite. A specimen from the Etta furnished by Mr. Hesnard consisted of a steel gray metallic mineral surrounded by cleavelandite. Its physical properties were the same as those of löllingite, but instead of a tabular, vein-forming habit the mineral was massive. It was called leucopyrite, but due to the presence of sulphur it is more nearly geyerite. An analysis by Mr. Beach along with the analysis of geyerite from Geyer, Saxony,[62] follow:

	Geyer, Saxony	Etta mine, S. Dakota	
Fe	32.92	33.62	
Ni	—	none	
Co	—	none	
Sb	1.37	none	Fe:As = 3:4
Sn	—	none	
Mn	—	none	
As	58.94	56.58	
S	6.07	6.27	
	99.30	96.47	

[61] *Op. cit.*

[62] Dana's System of Mineralogy, 6 ed., p. 97.

Columbite-Tantalite. This mineral is common in all the Keystone pegmatites. A mass found at the Ingersoll measured 20 inches square by 24 inches long and weighed close to one ton.[63] Hess[64] describes a mass at the Etta which weighed 600 pounds and it is possible that failure to distinguish this mineral from cassiterite caused the over-valuation of the Etta as a tin deposit. The commonest associate of columbite-tantalite is cleavelandite. The former is scattered through the albite in the same way as cassiterite. But columbite-tantalite is rarer in greisen than is cassiterite. Very often the mineral occurs wedged into milky quartz or beryl.

Columbite-tantalite is one of the few minerals of the Harney Peak pegmatites to occur in well formed crystals. A large crystal in the possession of Mr. Hesnard is completely terminated. Detailed crystallographic descriptions of columbite from the Ingersoll and Etta have been published by Blake.[65] The habit is usually tabular, parallel to the (100) face. This aids in distinguishing columbite-tantalite from cassiterite. But the most infallible test is the streak which for the former mineral is dark brown while the Keystone cassiterite gives a very light brown streak. Headden[66] has published twelve analyses of columbite-tantalite from the Etta, Peerless, Ingersoll, and Sarah (Hugo) pegmatites. The atomic ratios of columbium to tantalum vary from 6 to 1 to 1 to 1. In other words all the specimens examined were either toward the columbite end of the isomorphous series or they were midway between columbite and tantalite. Schaeffer[67] analyzed a single specimen from the Etta and found no columbium, but Headden has pointed out discrepancies in his results.[68] A crude relationship exists between the specific gravity of columbite-tantalite and the columbium-tantalum ratio. The specimens collected by the writer have not yet been analyzed, but according to their specific gravities they are all toward the columbite end of the series, except one from the Etta which was a little beyond the midpoint toward the tantalite end. One specimen from the Peerless was not tested because the mineral was distributed through a cleavelandite-green muscovite gangue in such fine grains that a specific gravity deter-

[63] Blake, W. P.; Columbite in the Black Hills, *Am. Jour. Sci.*, **28**, 340–341, 1884.

[64] *U. S. Geol. Survey, Bull.*, **380**, 131–161, 1909.

[65] *Am. Jour. Sci.*, **41**, 403–405, 1891.

[66] Headden, Wm. P.; Columbite and Tantalite, *Am. Jour. Sci.*, **41**, 89–102, 1891.

[67] Schaeffer, C. A.; Note on Tantalite, *Trans. Am. Inst. Min. Eng.*, **13**, 231–233, 1884.

[68] *Op. cit.*

mination was not feasible. It was supposed, however, to be nearly pure tantalite. In breaking up the one ton mass of columbite at the Ingersoll, Blake[69] found cavities filled with yellow powder pellets that consisted of hydrous uranium oxide.

Strüverite. A single specimen from the Etta pegmatite containing this mineral was secured through Mr. Hesnard. The strüverite is in small black opaque grains scattered through a cleavelandite-microcline-muscovite-spodumene aggregate. It is indistinguishable from columbite except by its crystal form, which is tetragonal. Hess and Wells[70] have described the occurrence of this mineral at the Etta in detail. It is found where columbite crystals are sprinkled especially thickly through the pegmatite. It contains titanium, tantalum, columbium, and iron. The name strüverite is applied to the tantalic acid end of an isomorphous series while the columbium end is known as ilmenorutile. What is probably the same mineral was described by Headden and Pirsson under the name black rutile.[71]

Uraninite. A large specimen from the uppermost Ingersoll pegmatite was supplied the writer by the owner, Mr. Denis Henault. It consisted of amblygonite and quartz in part replaced by lepidolite. Within the lepidolite (and of the same period of mineralization) are several small masses of uraninite or pitchblende. Surrounding the black uraninite are yellow and orange oxidation products, probably the minerals uranophane and gummite. The uranium-lead ratio of this material was determined by Davis,[72] which when calculated in terms of age gives the figure 1,667 million years. Connolly[73] believes such extreme age to be inconceivable for these rocks and suggests that the alteration which is quite apparent on the uraninite specimens may be responsible for a change from the true uranium-lead ratio because of the much greater solubility of salts of the former element.

Quartz. Quartz veins can be found cutting through minerals of the magmatic and intermediate phases in all of the Keystone pegmatites. They were especially abundant at the Ingersoll and Hugo mines. They are on the whole small, rarely exceeding one-

[69] *Am. Jour. Sci.*, **28**, 340–341, 1884.

[70] *Am. Jour. Sci.*, **31**, 432–442, 1911.

[71] *Am. Jour. Sci.*, **41**, 249, 1891.

[72] Davis, C. W.; The composition and age of uranium minerals from Katanga, South Dakota, and Utah. *Am. Jour. Sci.*, **11**, 201–217, 1926.

[73] Connolly, Joseph P.; The Tertiary Mineralization of the Northern Black Hills, South Dakota, *School of Mines, Bull.*, **15**, p. 14, 1927.

half inch in thickness, but some can be traced for long distances. A number of specimens were collected showing veins of pure quartz cutting through microcline, amblygonite and black tourmaline. At other times the quartz was accompanied by fine yellowish green muscovite and cassiterite, or by dense purple lepidolite (Fig. 2).

Pockets are rare in the Keystone pegmatites, so crystals are not common.   One specimen, originally secured from the Peerless, consisted of clear quartz crystals under one-fourth inch in length lining a small vug.   The crystals were prismatic with only the common forms visible.   The remainder of the specimen consisted of a dense muscovite-quartz aggregate, with a little residual amblygonite here and there.

Supergene Stage

With the uncovering of the pegmatites by the agencies of erosion the primary minerals were subjected to supergene alteration. The scarcity of iron prevented the formation of any appreciable limonite gossan. The most active staining agent was manganese oxide, derived from the weathering of triphylite.

Supergene minerals

Small amounts of purpurite can occasionally be found coating triphylite. Schaller[74] has published a description of the occurrence of this mineral near Hill City, including an analysis and sketch of a crystal. Manganese oxide coats both triphylite and surrounding minerals.

Microcline and amblygonite in the zone of oxidation tend to alter to the clay minerals. One clay specimen collected by the writer from the Hugo was derived from spodumene, for a number of residual fragments of this mineral could be detected under the microscope. The main mass, which was yellowish white and powdery, was montmorillonite. It was practically isotropic, with an index of about 1.55. However, the principal alteration product of the Keystone spodumene is killinite, according to Schwartz and Leonard.[75]

Yellow and orange oxides of uranium coat uraninite and columbite and occasionally other minerals. Copper present in chalcopyrite and stannite has been oxidized to malachite and chrysocolla in the exposed portions of the pegmatite.

[74] *Am. Jour. Sci.*, **29**, 152–158, 1907.
[75] *Am. Jour. Sci.*, **11**, 257–264, 1926.