# Ternary Diagrams of the Quartz-Feldspar Content of Pegmatites in Colorado

*By* JAMES J. NORTON

CONTRIBUTIONS TO GENERAL GEOLOGY

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# TERNARY DIAGRAMS OF THE QUARTZ-FELDSPAR CONTENT OF PEGMATITES IN COLORADO

By James J. Norton


## ABSTRACT

Visually estimated modes of 1,803 pegmatites of the Quartz Creek district, Gunnison County, Colo., were recorded by M. H. Staatz and A. F. Trites and published by the U.S. Geological Survey in Professional Paper 265. Similar modes for 1,301 pegmatites of the Crystal Mountain district, Larimer County, Colo., were reported by W. R. Thurston in U.S. Geological Survey Bulletin 1011. Most of these modes are of homogeneous pegmatites, but many are of zones in zoned pegmatites, layers in layered pegmatites, and fracture-filling units. The modes have here been plotted on ternary diagrams representing the contents of quartz, plagioclase (albite), and perthite. Muscovite, which is the only other abundant alkali silicate mineral in these rocks, is sparse enough to be neglected in all modes except those of the zoned and layered pegmatites of the Quartz Creek district; in these, the "perthite" of the diagrams is actually perthite plus muscovite.

The modes of homogenous pegmatites of the Crystal Mountain district show a well-defined maximum at 20 percent quartz, 30 percent plagioclase, and 50 percent perthite. Homogeneous pegmatites of the Quartz Creek district also ordinarily contain about 20 percent quartz; they differ greatly in the amounts of plagioclase and perthite, but most of the modes have more than 45 percent plagioclase and less than 35 percent perthite. Similar compositions are obtained from the layered pegmatites, which are abundant in the Quartz Creek district, but the plagioclase is concentrated in footwall layers and the perthite in hanging-wall layers.

Modes of wall zones of zoned pegmatites are much like modes of homogeneous pegmatites, but tend to have somewhat more plagioclase and less perthite. Inner zones are generally on the quartz-perthite side of the ternary diagram; some of them are rich in perthite and have only a moderate quantity of quartz, and others form virtually pure quartz cores.

The modes of homogeneous pegmatites in the Quartz Creek district and many of the modes from heterogeneous pegmatites in both districts are near the ternary eutectic at high $H_2O$ pressures in the system $NaAlSi_3O_8 \cdot KAlSi_3O_8 \cdot SiO_2 \cdot H_2O$. The homogeneous pegmatites of the Crystal Mountain district contain more Or than the eutectic composition, for reasons that are not clear from available evidence.

The wide range in the plagioclase-perthite ratio in the homogeneous and

layered pegmatites of the Quartz Creek district and in the zones of zoned pegmatites in both districts is in accord with published suggestions that potassium is separated from sodium by transport through a gas during crystallization of pegmatites. The feldspathic compositions, which are gradational from plagioclase rich to perthite rich without indication of a hiatus between the two, are markedly different from the quartz-rich compositions formed at a late stage by a fluid of unknown nature that deposited quartz cores, quartz fracture fillings, and a few quartz-rich homogeneous pegmatites.

## INTRODUCTION

Staatz and Trites (1955, p. 66–107) tabulated visually estimated modes of 1,803 pegmatites of the Quartz Creek district, Gunnison County, Colo. Thurston (1955, p. 130–179) did the same for 1,301 pegmatites of the Crystal Mountain district, Larimer County, Colo. In the years since their work was done, it has become common practice to plot compositions of grantitic rocks on ternary quartz-feldspar diagrams and to interpret the results in the light of the extensive studies, especially by Tuttle and Bowen (1958), of the system $NaAlSi_3O_8 \cdot KAlSi_3O_8 \cdot SiO_2 \cdot H_2O$. The enormous number of modes obtained by Staatz and Trites and by Thurston have never been reduced to ternary diagrams of this nature. The purpose of this report is to place such diagrams in the published record and briefly discuss their meaning. For full information about the geology of these pegmatites the reader should refer to the original publications.

The modes are visual estimates rather than measurements of the composition of pegmatite. The method, though inexact, is the only feasible one by which modes of a large number of separate intrusives can be obtained. Errors seem unlikely to be of large magnitude. One hesitates even to mention the possible existence of errors without at the same time expressing admiration for the energy and patience of the persons who assembled this vast body of information.

The method of compiling the modes and drawing the contour diagrams accompanying this paper is most easily described by referring to the ternary diagram of plate 1*A*. This ternary diagram has quartz at one apex and plagioclase (mostly $An_1$ to $An_6$) at another. The third apex is for potassic feldspar or its equivalent, but there are significant differences between the figures plotted and the actual content of $KAlSi_3O_8$. The chief source of difference is that the potassic feldspar exists as perthite, which contains a substantial but undetermined quantity of Ab. Another difficulty arises from the fact that muscovite contributes significantly to the content of potassium aluminum silicate in many modes of zoned and layered pegmatites in the Quartz Creek district. For such modes, perthite and muscovite are added together to make up the "perthite" component. Henceforth in this report, where the word "perthite" is in quotation marks, it means perthite plus muscovite.

Plate 1*A* is divided into a family of hexagons whose centers are at the intersections of percentage values 10, 20, 30, and so on. Each hexagon occupies 2 percent of the area of the diagram. The first step in preparing a contour diagram is to count the number of modes falling within each hexagon. These numbers are then converted to percent, and contours are drawn which express the percentage of the total number of points that are in each hexagon—that is, in 2 percent of the area. In a ternary diagram containing, for example, a total of 500 points, any hexagon with more than 10 points lies above the contour for 2 percent; any with more than 20 points lies above the contour for 4 percent; and so on. Along each side of the diagram, in areas surrounded by half a hexagon, the percentage values are multiplied by 2; similarly, at an apex, with one-sixth of a hexagon, the values are multiplied by 6.

The diagrams are compiled from data obtained as a result of the examination of 3,104 pegmatites and reported in tabular form by Thurston (1955, p. 130–179) and by Staatz and Trites (1955, p. 66–107). Most of the pegmatites are homogeneous, consisting chiefly of quartz and feldspar uniformly distributed through the rock. They form about 94 percent of all pegmatites in the Crystal Mountain district and 78 percent of those in the Quartz Creek district. Zoned pegmatites constitute only about 2 percent of the total in the Crystal Mountain district but about 14 percent in the Quartz Creek district. In the Quartz Creek district there is also a category termed "layered pegmatites," which consists of tabular or lenticular intrusives with abundant perthite along the hanging-wall side and plagioclase on the footwall side (Staatz and Trites, 1955, p. 26–27). Some pegmatites in each district contain many thin bands of light minerals mostly feldspar and quartz, alternating with darker colored bands containing quartz, muscovite, and commonly tourmaline. These are regarded as a separate category only by Thurston (1955, p. 30–31), who called them banded pegmatites.

Unlike the homogeneous pegmatites, each of which is represented by a single mode, every zoned or layered pegmatite is represented by as many modes as there are zones or layers within the pegmatite. One consequence of this circumstance is a fundamental difference in the meaning of the ternary diagrams. The diagrams for homogeneous pegmatites show the overall compositions of these intrusives and the range in composition from one of them to another. The diagrams for zoned and layered pegmatites show only the compositions of zones and layers. The points on these diagrams are widely dispersed: they show the range over which the compositions of these units extend, but not the overall composition of the intrusives.

About 3,500 modes have been used in the preparation of this paper. An additional 100 modes reported by Thurston or by Staatz and Trites were rejected. Some were rejected because they show 10 percent or more of minerals other than quartz, feldspar, or muscovite; others because the numerical data are incomplete; and still others because they appear to contain typographical errors. Modes of a few pegmatites in the Quartz Creek district that change in composition along strikes also were not used.

## MODES OF PEGMATITES OF THE CRYSTAL MOUNTAIN DISTRICT

The modes of the homogeneous pegmatites of the Crystal Mountain district, as plotted on plate 1*B*, show a pronounced concentration around the value 20 percent quartz, 30 percent plagioclase, and 50 percent perthite. The quartz content of most of the pegmatites lies in a narrow range, from about 7 to 25 percent. The feldspathic constituents extend over broader ranges, mostly between 35 and 65 percent perthite and 15 and 55 percent plagioclase.

A subsidiary concentration lies near the quartz apex of the diagram, where Thurston (1955, p. 178–179) recorded 40 modes with 95 percent or more quartz. A few pegmatites contain between 40 and 70 percent quartz, and none contain between 70 and 85 percent quartz. Thurston's statement (1955, p. 36) that the quartz-rich pegmatites (or feldspar-bearing quartz veins, as they could be called) are gradational with the more normal pegmatites falls short of being strictly correct. Nevertheless the upward-reaching tongue formed by the zero contour, which extends toward the quartz apex but does not quite reach it, tends to support his point. Thurston (1955, p. 35, 36, and 68) assumed that the quartz-rich pegmatites are the same age as the others because there is a lack of evidence to the contrary and because most of their characteristics are compatible with this assumption.

The modes of the few banded pegmatites in the Crystal Mountain district are plotted as a point diagram on plate 1*C*. These are concentrated in the same part of the diagram as the modes of feldspathic homogeneous pegmatites on plate 1*B*.

Modes of the individual zones of zoned pegmatites, plotted on plate 1*D*, are more diverse than modes of the homogeneous and banded pegmatites. Nevertheless, they too are clustered in or near the area occupied by the feldspathic homogeneous pegmatites on plate 1*B*, and the quartz cores of zoned pegmatites are analogous to the quartz-rich homogeneous pegmatites. The tie lines of the diagram show that zoned pegmatites tend to be separated into two categories: (1) those with horizontal tie lines, signifying a constant quartz content and a change from plagioclase-rich wall zones to perthite-rich cores; and (2) those with vertical tie lines, connecting perthite-rich wall zones and quartz cores.

These differentiation effects, expressed by the separation into plagioclase-rich, perthite-rich, and quartz-rich zones, have analogs in the homogeneous pegmatites. The horizontal tie lines correspond to the horizontal elongation shown by the contours on plate 1*B* at values of less than 30 percent quartz. The vertical tie lines correspond to the upward-reaching tongue of the zero contour on plate 1*B*.

## MODES OF PEGMATITES OF THE QUARTZ CREEK DISTRICT

In the Quartz Creek district, as in the Crystal Mountain district, homogeneous pegmatites are far more numerous than other varieties of pegmatites. Nevertheless, there also are many zoned and layered pegmatites, and these are the source of much more modal data than is obtained from the few zoned pegmatites of the Crystal Mountain district.

### HOMOGENEOUS PEGMATITES

Most of the homogeneous pegmatites contain between 15 and 25 percent quartz. The ratio of perthite to plagioclase, however, varies so greatly that, on plate 1*E*, the modes form a belt extending across the diagram, but with a concentration at high values for plagioclase (45–75 percent) and low values for perthite (5–35 percent). Modes near the quartz apex of the diagram and the upward-reaching tongue of the zero contour in the feldspathic part of the diagram are less prominent than similar features in the diagram from the Crystal Mountain district.

Muscovite is sparse in the homogeneous pegmatites, and it has been neglected in plotting the modes. Modes of the 40 homogeneous pegmatites that contain appreciable muscovite ($>3$ percent) were not used in making the diagram; however, the question of whether or not they differ from the modes of pegmatites used on the diagram is worth examining. Of these 40 pegmatites, 37 contain between 15 and 25 percent quartz. The contents of feldspar and muscovite, grouped according to the percentage of plagioclase, are:

| Number of pegmatites | Modes (in percent) | | | |
|---|---|---|---|---|
| | Plagioclase | Perthite | Muscovite | Perthite and muscovite |
| 6 | 60–75 | 0–15 | 4–5 | 5–20 |
| 8 | 50–56 | 20–25 | 4–10 | 24–35 |
| 11 | 42–49 | 25–35 | 5–10 | 30–40 |
| 8 | 30–40 | 30–50 | 5–10 | 40–55 |
| 4 | 10–20 | 50–66 | 4–15 | 60–70 |

These figures suggest that the muscovite-rich pegmatites tend to contain more potassium and less sodium than other homogeneous pegmatites. The central value lies at about 20 percent quartz, 45 percent plagioclase, and 30 percent perthite or 35 percent combined perthite and muscovite.

A few of the so-called homogeneous pegmatites are not strictly homogeneous, for they contain small fracture-filling units. Modes of 31 such pegmatites and of their fracture fillings are presented on plate 1*F*. These pegmatites are not much different from the homogeneous pegmatites of plate 1*E*, but they tend to be more silicic. The fracture fillings are much more silicic and more potassic: 13 fracture fillings consist solely of quartz; 11 consist of quartz and perthite; 6 consist of quartz, perthite, and plagioclase; and 1 consists chiefly of quartz but also accessory plagioclase. The pattern of the tie lines is similar to that of the tie lines for zoned pegmatites of the Crystal Mountain district: some are nearly horizontal, indicating constant quartz content, and others are nearly vertical, indicating a great difference in quartz content; tie lines with intermediate slopes are lacking.

## LAYERED AND ZONED PEGMATITES

In many of the layered and zoned pegmatites, muscovite is so abundant that it must be taken into account, not ignored as it was in the modes discussed heretofore. On the diagrams for layers and zones, muscovite is added to perthite to form the "perthite" component. Nevertheless, the muscovite has little influence on the appearance of the ternary diagrams, for only the 125 modes listed in table 1 have more than 3 percent muscovite, and more than 5 times as many modes have 3 percent or less muscovite. Only 27 of the modes in table 1 have more muscovite than perthite.

Plate 1*G*, containing the modes of all the layers of the layered pegmatites, shows the range of composition from highly sodic layers, which are generally on the footwall, to the potassic layers, which are generally on the hanging wall. Because the layers are units of a pegmatite and their modes indicate only the composition of fractionation

TABLE 1.—*Perthite content of zones and layers containing more than 3 percent muscovite, Quartz Creek district, Colorado*

[Data are from Staatz and Trites (1955, p. 67–103). *, 2 modes. **, 3–6 modes]

| Muscovite content (percent) | Number of modes | Perthite contents (percent) | | | | |
|---|---|---|---|---|---|---|
| | | Wall zones | Intermediate zones | Cores | Hanging-wall layers | Footwall layers |
| 4 | 19 | 2 | 2 | 1 | 2 | 6 |
| | | *3 | | 20 | 30 | 7 |
| | | 10 | | 41 | 55 | |
| | | 20 | | 51 | 70 | |
| | | 25 | | | | |
| | | 40 | | | | |
| | | 41 | | | | |
| 5 | 47 | 5 | **0 | 5 | 30 | 5 |
| | | **10 | 5 | *30 | **40 | 10 |
| | | **20 | 20 | 35 | 45 | *15 |
| | | *30 | 40 | 40 | **50 | 30 |
| | | | | *45 | 60 | |
| | | | | *55 | | |
| | | | | *65 | | |
| | | | | 80 | | |
| 7 | 3 | 0 | | | 60 | 15 |
| 8 | 4 | 5 | | | 35 | 2 |
| | | 10 | | | | |
| 10 | 33 | 20 | 0 | 10 | 0 | 0 |
| | | *25 | 49 | 30 | 10 | 10 |
| | | 30 | | *35 | 20 | 15 |
| | | 40 | | *40 | 30 | |
| | | | | *50 | **40 | |
| | | | | | **45 | |
| | | | | | *50 | |
| | | | | | 60 | |
| 15 | 5 | | *0 | 55 | 5 | 10 |
| 20 | 7 | | *10 | | | 10 |
| | | | *20 | | | |
| | | | 25 | | | |
| | | | 50 | | | |
| 30 | 3 | | 0 | | | |
| | | | 10 | | | |
| | | | 50 | | | |
| 40 | 2 | | 26 | | | |
| | | | 50 | | | |
| 50 | 1 | | 0 | | | |
| 55 | 1 | | | 5 | | |

products, it is somewhat surprising to find that plate 1*G* is remarkably similar to the diagram for homogeneous pegmatites. Most of the points are at 15–25 percent quartz, and the feldspar content is similar to that of homogeneous pegmatites. The modes for layers, like those for homogeneous pegmatites, form a belt extending horizontally across the diagram, and they have a peak at high values for plagioclase. There are even fewer modes containing more than 50 percent quartz than in the diagram for homogeneous pegmatites, and the upreaching tongue in the zero contour is scarcely noticeable.

Seven of the layered pegmatites contain units called "cores" by Staatz and Trites. These are not plotted on plate 1*G* because, strictly speaking, a core is a zone, and to treat it as a layer is somewhat irregular. These "cores" have the following modes, in percent (from Staatz and Trites, 1955, p. 72, 84, 86, 87, 89, 94, and 102):

| *Quartz* | *Plagioclase* | *Perthite* |
|---|---|---|
| 100 | ---------------- | ----------------- |
| 70 | ---------------- | 30 |
| 60 | ---------------- | 40 |
| 45 | ---------------- | [1] 45 |
| 40 | ---------------- | 60 |
| 35 | 25 | 40 |
| 20 | ---------------- | 80 |

[1] Also 10 percent muscovite.

Five of these would lie above the field occupied by the modes of plate 1*G* and thus indicate a scattering of silicic representatives in modes from layered pegmatites.

The division into sodic foot wall layers (pl. 1*H*) and potassic hanging-wall layers (pl. 1*I*) is the chief feature of layered pegmatites. Plate 1*H* shows that the modes of footwall layers are concentrated in the range of 15–25 percent quartz, 60–85 percent plagioclase, and 0–20 percent "perthite." The few modes on the "perthite" side of the diagram seem anomalous, for they are in marked contrast with the very large number on the plagioclase side. Actually only four footwall layers contain 60 percent or more perthite, and the corresponding hanging-wall layer for each contains less perthite and more plagioclase, the reverse of the normal arrangement. At least one of the anomalous layered pegmatites (Staatz and Trites, 1955, p. 26), and possibly each of them, dips steeply and may have been rotated to its present position during a later tectonic event.

The modes of hanging-wall layers on plate 1*I* are spread out over a greater part of the diagram than the modes of footwall layers. The spread mainly reflects a wide range in the perthite-plagioclase ratio.

The diagram containing modes of all zones in zoned pegmatites (pl. 1*J*) shows many characteristics that were noted in the previous diagrams. It also has one new characteristic: the large number of modes in the silicic part of the diagram. There is a concentration near the quartz apex and a lesser concentration along the quartz-"perthite" side line, and the area bounded by the zero contour is reduced to a very small part of the diagram near the quartz-plagioclase side line. Otherwise, however, this diagram is reminiscent of the diagrams for homogeneous and layered pegmatites (pl. 1*E*, *G*). It shows a concentration that forms a belt across the diagram at 15–25 percent quartz, and the peak value in this belt is on the plagioclase side. The modes of this belt are largely from wall zones, which are shown separately in plate 1*K*. Their greatest concentration is about 70 percent plagioclase, 20 percent quartz, and 10 percent perthite and muscovite. Scarcely any of the modes of wall zones contain more than 40 percent quartz.

Silicic and potassic modes of zoned pegmatites are mainly from inner zones (pl. 1*L*), and thus are in striking contrast with modes of wall zones. The areas above the 4-percent contour on plate 1*L* are mostly at 40 percent or more quartz, and all are on the "perthite" side of the diagram. The maximum at the quartz apex is separated from the maximums in the more feldspathic parts of the diagram, but not so clearly that one can confidently deny the existence of a gradation between the quartz field and the "perthite" field.

There is a clearcut contrast between intermedite zones and cores, though many more modes are available for cores than for these zones. The modes of the intermediate zones, plotted as points on plate 1*L*, are widely scattered. The areas above the 4-percent contour contain only six intermediate zones; all other modes of these areas are cores. Furthermore, the cores of pegmatites containing these 35 intermediate zones are highly silicic or potassic; 19 of the intermediate zones are in pegmatites with quartz cores, 12 are in pegmatites with cores that lie on the quartz-"perthite" side line, and only 4 are accompanied by cores that have plagioclase as well as perthite and quartz. In general, the compositions of the intermediate zones lie between the plagioclase-rich wall zones and the plagioclase-poor cores.

In bulk composition the zoned pegmatites seem to be generally more silicic than the homogeneous and layered pegmatites. This difference is probably slight, for quartz-rich inner zones are ordinarily of much smaller volume than feldspathic outer zones. If one had enough data to calculate the volumes of all the zones and then calculate the average composition of each zoned pegmatite, he might well find that few of the bulk compositions have more than 30 percent quartz.

Overall, however, the modes for zoned pegmatites confirm those for other varieties of pegmatites in the Quartz Creek district by showing that plagioclase-rich assemblages predominate, even though perthite-rich and quartz-rich assemblages also formed during the course of crystallization.

## DISTRIBUTION OF BERYL

The chief purpose of the field studies in both the Crystal Mountain and Quartz Creek districts was to determine the distribution of beryl, and during the examination of each pegmatite a particular effort was made to find beryl. One might well expect a correlation between the presence or absence of beryl and the overall composition as expressed by the quartz-feldspar ternary diagrams. Three ternary diagrams, constructed to test this possibility, show the composition of beryl-bearing pegmatite (pl. 1 *M–O*).

It is somewhat surprising to find from the diagrams that the beryl-bearing pegmatites are not much different from those without beryl. Plate 1*M*, for the Crystal Mountain district, contains virtually no modes near the quartz apex of the diagram, but otherwise it resembles plate 1*B–D*. The beryl-bearing homogeneous pegmatites of the Quartz Creek district (pl. 1*N*) lack highly silicic representatives and include very few that are rich in perthite. Modes of zones and layers that contain beryl (pl. 1*O*) are widely distributed through the feldspathic part of the diagram and along the quartz-perthite side line, but they extend over less of the silica-rich part of the diagram than the zones on plate 1*J*.

Thurston (1955, p. 69) noted that 78 of the pegmatites contain 1 ton or more of beryl, and the rest contain only trace amounts. To ascertain if these 78 pegmatites differ from the others, a plot of their modes was made, but it is not published here because its only important difference from plate 1*M* is that it lacks the 24-percent contour. Staatz and Trites (1955, p. 50) reported that only 42 pegmatites have more than trace amounts of beryl, and these are not numerous enough to demonstrate meaningful differences from plate 1*N*, *O*.

## SUMMARY OF OBSERVATIONS

To establish a background for discussion of origin, it is desirable to sum up what the modal data tell about the chemical composition of the Quartz Creek and Crystal Mountain pegmatites. About 85 percent of the pegmatites in these two districts are homogeneous, and thus are the main basis for estimating average composition of the rock. The modes from layered and zoned pegmatites, though of less value in determining bulk composition, show the nature of differentiation products and the chronologic sequence of changes in composition.

The chemistry of granitic rocks is most readily examined in terms of the content of Q, Ab, and Or, which are about the same as the quartz, plagioclase, and perthite (or perthite plus muscovite) of the ternary diagrams. The quartz may be regarded as substantially pure $SiO_2$, and the plagioclase (at $An_1$–$An_6$) may be taken as virtually equivalent to $NaAlSi_3O_8$. Chemical composition at the third apex of the ternary diagram is not so easily inferred, for the perthite consists of both albite and microcline, and the muscovite probably contains sodium as well as potassium. Staatz and Trites (1955, p. 32) found that in one sample of perthite the ratio of Or to Ab is 4.5 : 1, and this ratio will be used here in estimating the compositions of both the Crystal Mountain and Quartz Creek pegmatites.

The modes of homogeneous pegmatites of the Crystal Mountain district (pl. 1*B*) cluster around a value of 20 percent quartz, 30 percent plagioclase, and 50 percent perthite, and the modes of the banded and zoned pegmatites are about the same. This modal composition suggests that the average pegmatite in the Crystal Mountain district contains 20 percent Q, 40 percent Ab, and 40 percent Or.

The diagrams for the Quartz Creek district clearly indicate an average of about 20 percent quartz, but the ratio of plagioclase to perthite varies so greatly that more guesswork is involved in assigning average values to them. In the diagram for homogeneous pegmatites (pl. 1*E*) the 12-percent contour surrounds a maximum at 60 percent plagioclase and 20 percent perthite, but the centers of the 6- and 3-percent contours are at values somewhat higher for perthite and lower for plagioclase. An adequate estimate for an overall average is 20 percent quartz, 55 percent plagioclase, and 25 percent perthite, which converts to 20 percent Q, 60 percent Ab, and 20 percent Or. The diagram for layered pegmatites (pl. 1*G*) suggests a similar average value. Even the diagram for zoned pegmatites (pl. 1*J*) does no great violence to this estimate if one allows for the probability that the quartz-rich zones are of much smaller volume than the feldspathic units.

These values for average composition are plotted as points A and B on plate 1*P*. Each of these points is surrounded by a dashed line that is equivalent to the 6-percent contour from the diagrams for homogeneous pegmatites but recast in terms of Q, Ab, and Or. About 70 percent of the homogeneous pegmatites in each district fall within the areas bounded by these lines. Most granites are in or near these same parts of the system according to Tuttle and Bowen (1958, fig. 42, p. 79), but ordinarily the granites have a higher content of normative quartz than plate 1*P* shows for the pegmatites.

The chief compositional difference between the pegmatites and granite is that many of the pegmatite modes—especially modes of layers and zones—are highly sodic, highly potassic, or highly silicic. The separation of sodic from potassic materials is gradational, and, because the quartz content generally remains unchanged at about 20 percent, the result is a pattern characterized by horizontal belts in the contour diagrams and horizontal tie lines in other diagrams. Between feldspathic and quartz-rich pegmatite, however, there is ordinarily a hiatus: nearly all the modes of the various diagrams have either less than 50 or more than 90 percent quartz. The only evidence of gradational phases is from the quartz-perthite inner zones of the Quartz Creek district and from upward-reaching tongues of the zero contour on several diagrams.

Quartz cores and quartz fracture fillings crystallized after the feldspathic units of pegmatites. Where a difference in age between plagioclase-rich and perthite-rich units can be demonstrated, the perthite-rich unit is younger, as shown by perthite-rich fracture fillings that cut plagioclase-rich pegmatite and by perthitic inner zones surrounded by plagioclase wall zones. On the other hand, where perthite is concentrated in the upper part of a layered or zoned pegmatite and plagioclase in the lower part, the two may be largely contemporaneous, or the perthite-rich material may even have crystallized first.

In short, the main points to note in the modal diagrams are that granitic compositions predominate but that some pegmatite units are anomalously rich in either Ab, Or, or Q. The chief difference in composition between granite and the homogeneous pegmatites, which form the bulk of the rock, is the lower quartz content of the pegmatites. In the homogeneous pegmatites and, more strikingly, in the layered and zoned pegmatites, the ratio of Ab to Or is highly variable, but the Q content is constant. Where the age sequence can be demonstrated, the Or-rich units generally formed after the Ab-rich units. The youngest units in these pegmatites are nearly monomineralic quartz cores and fracture fillings, in which the compositions stand in sharp contrast to those of feldspathic varieties of pegmatite.

## ORIGIN

Staatz and Trites (1955, p. 47–49) and Thurston (1955, p. 63–68) concluded that the pegmatites crystallized from magma, and they attributed such units as layers, zones, and fracture fillings to fractionation processes. If so, the bulk compositions of these pegmatites can profitably be examined in the light of the work on the sytem $NaAlSi_3O_8$–$KAlSi_3O_8$–$SiO_2$–$H_2O$ by Tuttle and Bowen (1958). Tuttle and Bowen showed that the compositions of most natural granites are near the thermal minimum of this system, as they should be if formed from a magmatic liquid. Pegmatites also contain $NaAlSi_3O_8$, $KAlSi_3O_8$, and $SiO_2$ in proportions that are near the granite minimum, and their peculiarities have led virtually all investigators to conclude that $H_2O$ is important in their development. Recent literature particularly emphasizes the role of a hydrous gas in the differentiation process that yields the sodic, potassic, and silicic compositions of the different units of zoned and layered pegmatites (Jahns and Burnham, 1958, 1962; Jahns and Tuttle, 1963, p. 90–91; Norton and others, 1962, p. 118–123).

Plate 1*P* shows the main characteristics of the granite system as presented by Luth, Jahns, and Tuttle (1964, fig. 4), and it also shows the positions of the most common pegmatite compositions (presumably equivalent to the magma composition) of the Quartz Creek and Crystal Mountain districts. The positions of the isobaric minimum and the isobaric eutectic on this diagram indicate that the intersection of the feldspar solvus and solidus is at a pressure between 3 and 5 kilobars $H_2O$ pressure. Stewart and Roseboom (1962, p. 285) have shown that the intersection may be at somewhat lower pressure.

The pegmatites are two-feldspar rocks, thus of subsolvus origin and formed under conditions of moderate to high $H_2O$ pressure. Though the average compositions of pegmatites of the Quartz Creek and Crystal Mountain districts are near the granite minimum, they are at anomalously low $SiO_2$ values, and in addition the Crystal Mountain compositions are in the field of primary crystallization of potassic feldspar. Published plots of pegmatite compositions more commonly indicate a much higher content of quartz (for example, Orville, 1960, figs. 9, 10; Redden, 1963, fig. 94; Jahns and Tuttle, 1963, fig. 10; Luth and others, 1964, fig. 6).

The low-silica compositions require either improbably high $H_2O$ pressure or some other effect, perhaps causing loss of silica from the system, that cannot be explained within the framework of currently available experimental data. There is at least some loss of silica during the crystallization process. The Quartz Creek district, for example, has a few homogeneous pegmatites that, though otherwise of undistinctive composition, generated fracture fillings consisting solely of quartz. At Crystal Mountain the quartz-rich counterparts of the feldspathic homogeneous pegmatites presumably formed from a fluid abstracted from the source magma. Furthermore, at Crystal Mountain all zoned pegmatites with quartz cores contain wall zones similar in composition to the homogeneous pegmatites.

The modes of the homogeneous pegmatites at Crystal Mountain suggest that the rocks originated from a potassic magma, perhaps generated by anatexis, that was dry enough to yield bulk rock compositions controlled by factors other than the position of the isobaric eutectic (Luth and others, 1964, p. 770). The Crystal Mountain pegmatites contain little mica, and few are zoned; thus they may have formed in a relatively water-poor environment, though they are not hypersolvus granites nor dry granites in any normal sense.

Every kind of pegmatite in these two districts exhibits a wide range in the proportions of Or and Ab, rather than the approximately uniform composition ordinarily supposed to exist in a magma. The results of whatever process separates the sodic and potassic materials are most evident in zoned and layered pegmatites. Many wall zones in both the Crystal Mountain and Quartz Creek districts are rich in plagioclase. Their compositions, though widely scattered (pl. 1*D*, *K*), are mostly near the eutectic and may be in part controlled by it. Perthitic inner zones, on the other hand, are far afield from the eutectic. Jahns and Burnham (1958, 1962) pointed out that a feasible means to separate the potassic from the sodic materials is through a hydrous gas, which presumably becomes increasingly abundant as the magmatic history advances. If the gas phase carries and deposits more potassium than sodium, it can account for the high perthite content of many inner zones. In layered pegmatites the concentration of potassic feldspar along the hanging wall and sodic feldspar along the footwall indicates a process that acts under the influence of gravity. A gas phase, which would be likely to rise upward through the pegmatitic fluid, is especially attractive as a means of transporting potassium. A hydrous gas with a temperature gradient is known to concentrate potassium relative to sodium in its cooler parts (Orville, 1963), which in a pegmatitic fluid would presumably be the upper part of the chamber.

The homogeneous pegmatites also fit the supposition that pegmatite minerals were deposited by a gas as well as by a liquid and that potassium can migrate upward in a pegmatitic fluid, as both the layered pegmatites and perthite hoods of zoned pegmatites indicate. The differentiation of a body of fluid so that the upper part has more potassium than the lower part can have either of two results. On the one hand, this body of fluid can divide into several smaller bodies that ultimately crystallize as homogeneous pegmatites; the pegmatites thus formed would contain different amounts of sodium and potassium and would plot in correspondingly different places on the ternary diagrams. On the other hand, the original body of fluid can crystallize in place, so that its upper part contains more potassic feldspar than the lower; if the top of the pegmatite is exposed at today's erosion surface, the mode recorded on the ternary diagrams will be high in perthite; and if the lower part of the pegmatite is exposed, the mode will contain correspondingly less perthite and more plagioclase. One or both of these processes seem fully satisfactory to explain the range in the ratio of Or to Ab in these pegmatites. To go further and suggest that the Crystal Mountain homogeneous pegmatites acquired their potassic character from a potassium-rich differentiate formed near the top of a magma chamber, and that there are concealed sodic counterparts at depth, places a strain on the evidence. The small range in the ratio of Or to Ab in these pegmatites and their modest content of hydrous minerals indicate that any hydrous gas had a small part in their origin.

The bearing that a gas phase may have on the origin of quartz cores and other forms of quartz-rich pegmatite is not clear. One of the most striking characteristics of quartz cores is their almost total lack of gradation—in fact, virtually knife-edge contacts—with the feldspathic units surrounding them. At Crystal Mountain the zoned pegmatites in which participation by a gas seems likely are those with albite-rich wall zones and perthite-rich cores, but without quartz-rich units. The zoned pegmatites with quartz cores contain perthite-rich wall zones of approximately the same composition as homogeneous pegmatites but generally more silicic. Apparently the wall zones crystallized in much the same way as the homogeneous pegmatites, and the cores represent a residue of silica that was separated by some means after the feldspathic constituents were used up. The Crystal Mountain district also contains many quartz-rich homogeneous pegmatites that are lithologically the same as quartz cores, and may well have formed from a fluid that was expelled from the parent body and crystallized elsewhere. Zoned pegmatites in the Quartz Creek district show more evidence than those at Crystal Mountain of a transition rather than a hiatus between perthite-rich and quartz-rich inner units. In homogeneous pegmatites of the same district, the fracture fillings, which lithologically correspond to inner zones, are mainly either quartz rich or feldspar rich, not transitional between the two. The few quartz cores in layered pegmatites are in sharp contrast with the feldspathic outer units.

Regardless of whether the medium that gave rise to these quartz units was a liquid or a gas, it was apparently very dense, for around the quartz cores there is no evidence of cavities or of structural collapse to fill preexisting cavities. Though this fluid deposited virtually nothing but $SiO_2$, it must have been derived from the fluids that precipitated feldspathic units, for occasional modes are transitional between the feldspathic and highly silicic compositions. Why a presumably gradual change in the nature of the fluids should be accompanied by a marked change in the crystalline products cannot be explained with currently available experimental data.

However important the differentiation products of pegmatites may be, they must not be allowed to overshadow the homogeneous pegmatites, which predominate over all other varieties of pegmatites discussed in this report. The homogeneous pegmatites probably formed largely by crystallization from a subsolvus magmatic liquid, but some of their compositional peculiarities seem to be effects of a coexisting gas. Many of the modes from zoned and layered pegmatites suggest that normal magmatic processes were dominant in these also, but with greater participation by a gas phase. The remaining modes, which did require specialized processes, represent only a minute percentage of the pegmatite in these districts.

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