SPHERULITIC ALKALI RHYOLITE DIKES IN THE ATSUTLA RANGE, NORTHERN BRITISH COLUMBIA[1]

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Abstract

Several alkali rhyolite dikes, generally displaying spherulitic structure, and containing riebeckite, acmite, or decomposition products of riebeckite, occur in the Atsutla Range of northern British Columbia. Spherulitic growth in one dike has been initiated at the corners or edges of phenocrysts; axiolitic growth in another dike has taken place from surfaces of contorted flow layers; elsewhere, the features that have localized spherulitic growth are not apparent. Where both the dark and felsic minerals show radial growth in the same dike, the centers of crystallization of these two groups of minerals are either separate or shared. Mechanical rejection of acmite and riebeckite by quartz but not by potash feldspar is offered as an explanation for clear crescentic masses of quartz exposed in sections of cloudy feldspathic spherulites.

Acmite crystallized before riebeckite in part of one dike, but riebeckite has been pseudomorphed by acmite in a neighboring part of the same dike. Minor and local variations in temperature or pressure may explain this reversal in sequence of crystallization. Analyses of two dikes show zirconia exceeding 0.4%. Zircon occurs with mixtures of black opaque grains, goethite, and hematite that are pseudomorphous after riebeckite but not with this mineral in its unaltered state. Riebeckite, therefore, and possibly acmite as well, may contain appreciable amounts of zirconia in solid solution.

Geological Setting

The southeastern part of the Atsutla Range of northern British Columbia (Fig. 1) is composed of granitic rocks of the Glundebery batholith which intrude sedimentary and volcanic rocks of Permian and Lower Mesozoic age exposed on the margins of the range (Watson & Mathews, 1944). The Glundebery batholith is made up mainly of granite and quartz monzonite but it also consists of minor amounts of granodiorite, quartz diorite, syenite, diorite, and gabbro. A stock of miarolitic micrographic granite is present in the central part of the batholith and may be one of the latest phases of the intrusion. The rhyolite dikes discussed in this paper, which are partly spherulitic and riebeckite- or riebeckite and acmite-bearing, occur in and adjacent to the batholith.

One dike cuts typical granitic rock in the central part of the batholith on the north fork of Nazcha Creek (locality A, Fig. 2). This dike, which is dark greenish grey and aphanitic, has a width of 3 feet, a vertical dip, and an exposed length of about 20 feet. Its margins have closely-spaced

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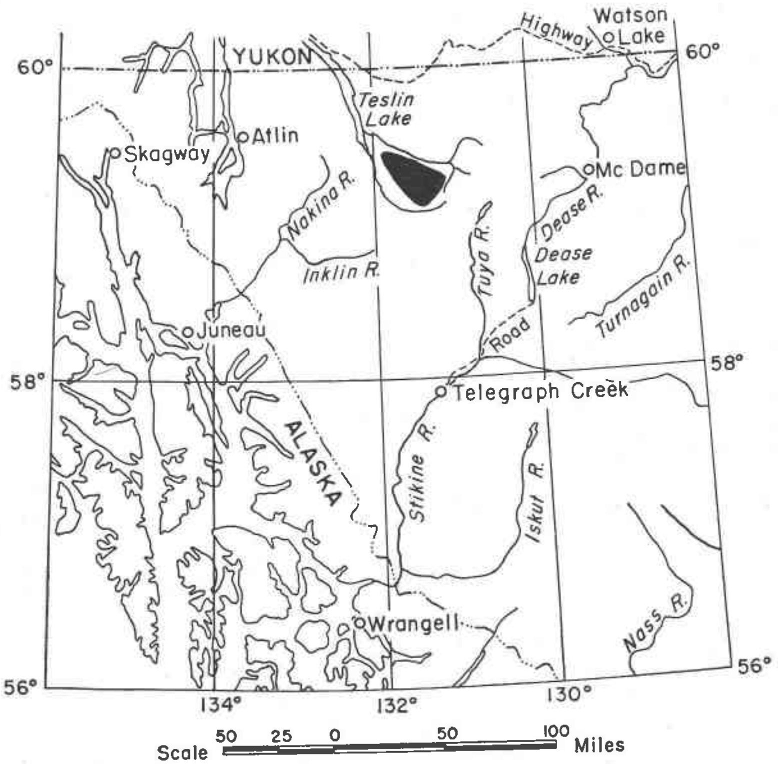


FIG. 1. Key-map of northern British Columbia showing (in black) location of Atsutla Range.

flow layers parallel to the walls; a few inches toward the center of the dike the flow layers are distinctly contorted. These zones of contorted flow layers grade, in turn, into a central zone marked by discrete to coalescent dark blue to almost black spherulites, 3 to 5 mm. in diameter. The flow layers become progressively less distinct toward the center of the zone and in places are marked only by lines of spherulites.

Fragments of similar rhyolite were found in talus at two localities, one near the southern contact of the batholith, and one near its northeastern limit.

Several dikes, which are moderately to steeply dipping and up to 20 feet wide, cut the wall rocks of the Glundebery batholith on the west side of Glundebery Valley (locality B, Fig. 2). These dikes have pale grey finely crystalline cores and white to buff microcrystalline margins that contain more or less well defined dark fibrous spherulites up to 6 mm. in diameter.

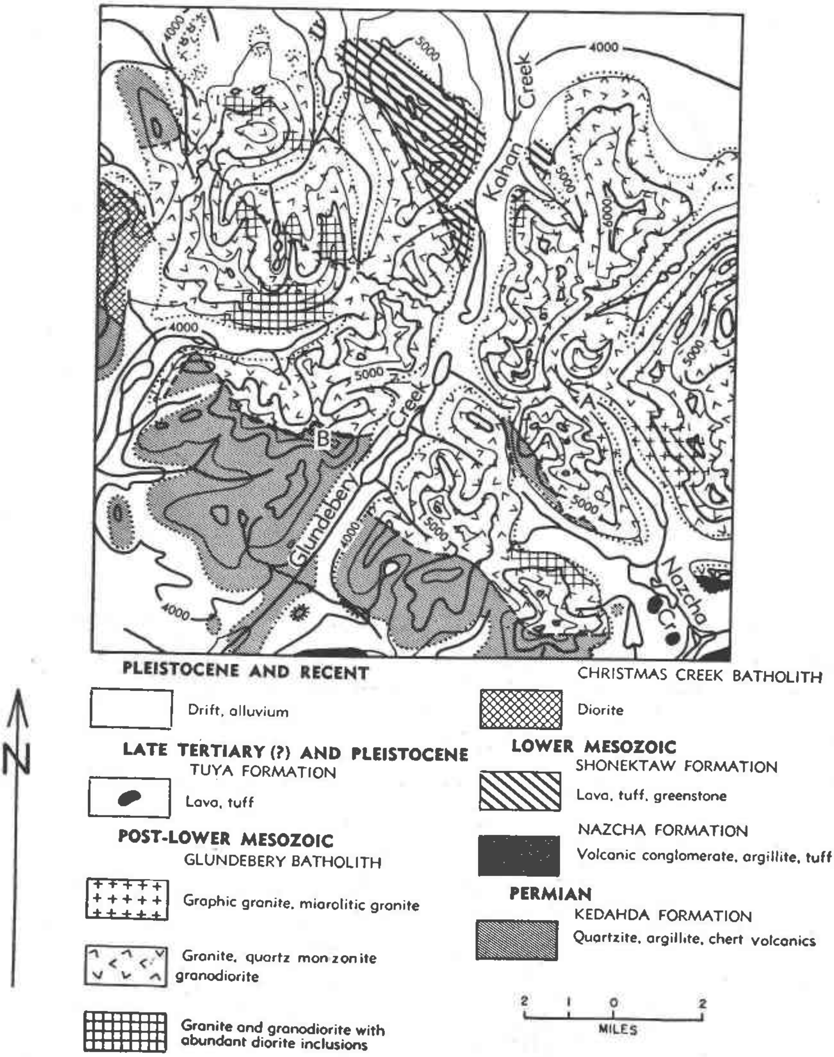


FIG. 2. Geological map of part of the Atsutla Range showing localities (A and B) at which rhyolite dikes are present.

MINERALOGY

Phenocrysts were seen in a conspicuously spherulitic zone in one of the Glundebery Valley dikes but not elsewhere. They consist of euhedral to highly corroded quartz grains of β habit up to 0.5 mm. in diameter, and euhedral feldspar crystals up to 1.5 mm. long, composed of fine grid-like microperthitic intergrowths of potash and soda feldspar (Fig.

3–5). The feldspar phenocrysts are markedly similar to those in the groundmass of much of the granite of the Glundebery batholith.

The minerals composing the non-porphyritic dikes and the groundmass of the porphyritic one are quartz, potash and plagioclase feldspars, riebeckite, acmite, zircon, black opaque grains, goethite, hematite, and sericite (?).

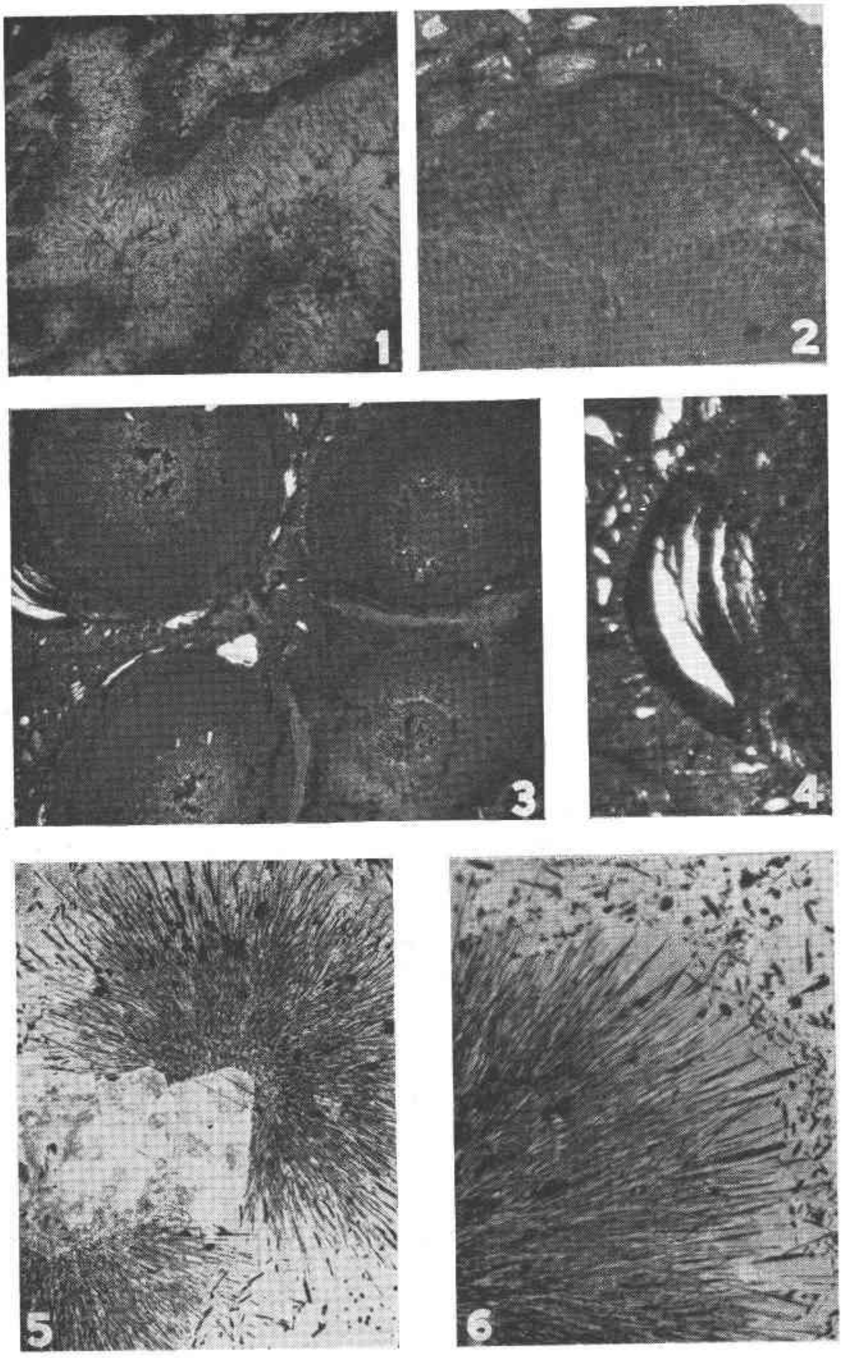
Feldspars. Where the feldspars are fine-grained and clouded with minute impurities, stain tests (after Keith, 1939, and Chayes, 1952) had to be used to distinguish the potash-rich and plagioclase-rich areas. As shown by the chemical analyses (Table 1), little or no calcium is available for anorthite and the plagioclase, therefore, approximates pure albite. The optical properties of the plagioclase in the coarser non-spherulitic rhyolite indicate this same composition.

Riebeckite. The riebeckite forms stout to acicular prisms with parallel extinction, negative elongation, low birefringence, and refractive indices of about 1.68. The pleochroism is distinct with X dark blue; Y yellow green; and Z pale yellow. The needles show well-defined amphibole cross-sections. Some needles in the spherulites of the Nazcha Valley dike cannot be identified with certainty because of their exceedingly small size, but they show the same pleochroism as riebeckite found elsewhere in the dike. Evidence presented later in this paper suggests that the riebeckite, as well as acmite, may contain zirconium.

One of the two common alteration products of the riebeckite is a pale yellowish pseudomorph with distinctly higher birefringence but the same parallel extinction and negative elongation. Scattered needles of riebeckite within a single bundle may be replaced by this yellowish mineral and adjacent needles may remain completely unaltered. A few needles are composed of riebeckite at the base and of the yellowish mineral at the distal end, the two parts being separated by a clearly defined boundary cutting obliquely across the crystal. This alteration product has been identified tentatively as acmite.

A second alteration product of riebeckite, present in the Glundebery Valley dikes, is a mixture of black opaque grains, goethite, and hematite, with closely associated zircon. In a few fibers, some of the pleochroic amphibole is preserved. Some riebeckite needles within a single spherulite show this alteration while others remain completely unaltered. In the slightly spherulitic rhyolite, fiber-like trains of black opaque grains and hematite are assumed to represent former riebeckite needles.

Acmite. Acmite occurs chiefly as small equant grains and stout prisms disseminated throughout the spherulites of the Nazcha Valley dike and it is also present as stout radiating fibers in a few interspherulitic parts of this rock. It has pale yellow color, scarcely noticeable pleochroism, high


1
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birefringence, and refractive indices ranging from 1.76 to more than 1.79. The prisms have negative elongation and parallel extinction. Although the indices of the acmite (?) psuedomorphous after riebeckite have not been determined, its other optical properties correspond to those given above.

Zircon. Zircon occurs as fine crystals adjacent to the black opaque grains, goethite, and hematite after riebeckite but it was not seen in the vicinity of unaltered riebeckite.

Black Opaque Minerals, Goethite, and Hematite. Black opaque grains, goethite, and hematite are common as alteration products of riebeckite needles. In one section of non-spherulitic rhyolite, however, black opaque grains and goethite occur together as interstitial grains up to 0.4 mm. in diameter making up about 5 per cent of the rock and distributed fairly uniformly throughout it. *X*-ray analyses of magnetic concentrates show that the magnetite content of the three analyzed rocks is less than 0.17, 0.10, and 0.04 per cent respectively.[1]

Petrography

Feldspathic Spherulites of the Nazcha Valley Dike

Feldspathic spherulites are well developed only in the central part of the Nazcha Valley dike (locality A, Fig. 2). They are clearly distinct from spherulites or axiolites composed of radiating fibers of riebeckite which occur not only in the Glundebery Valley dikes but also locally in the margins of the Nazcha Valley dike. These feldspathic spherulites display several concentric zones with fairly distinct structure and mineral

[1] Chief Analyst and Assayer, B. C. Department of Mines. Personal communication, February 7, 1947.

Fig. 3-1. Contorted flow layers in Nazcha Valley dike. Layers of cloudy, finely-crystalline riebeckite and potash feldspar alternating with more coarsely-crystalline quartz and riebeckite needles. ×15.

Fig. 3-2. Secondarily branching fibers of potash feldspar at outer edge of second zone of feldspathic spherulite in Nazcha Valley dike. ×40.

Fig. 3-3. Closely packed feldspathic spherulites in central part of Nazcha Valley dike. Clear crescentic areas are composed of radiating fibers of quartz and minor plagioclase. ×15.

Fig. 3-4. Clear crescentic areas composed of fibers of quartz and minor plagioclase with acmite-rich rims on their convex surfaces. Nazcha Valley dike. ×40.

Fig. 3-5. Riebeckite needles and pseudomorphs after riebeckite radiating from corners or edges of microperthite phenocryst. Glundebery Valley. ×25.

Fig. 3-6. Rim of spherulite showing ends of radially-arranged needles of riebeckite and tangentially-arranged stouter prisms of riebeckite in quartz and potash feldspar. Glundebery Valley. ×40.

content (Fig. 3-3). Where the spherulites are widely spaced, all zones may be present, but where they are closely packed, only the innermost two or three zones are developed. The successive zones, from the center of the spherulites outward are as follows:

First (Innermost) Zone. This relatively clear zone has an ill-defined roughly polygonal to circular outline with a radius of 0.25 to 0.45 mm. It is made up of irregular grains of potash-rich feldspar containing abundant clusters of minute elongate grains of acmite and, around the margins of the zone, a few prisms of riebeckite.

The acmite granules range from 2 to 10 μ in length in the center of the zone but are 10 to 15 μ long toward the margins; the riebeckite prisms reach 10 by 30 μ.

Second Zone. This zone, 0.60 to 1.25 mm. in width, is composed of radial fibrous growths of potash-rich feldspar containing scattered granules of acmite and a felted mass of minute needles having the pleochroism of riebeckite.

The acmite has a fairly uniform grain size throughout the zone. The riebeckite (?) needles, on the other hand, which average about 5 μ in length at the inner edge of the zone, become progressively smaller toward the outer edge where they average 1 to 2 μ in length, and merge into a general cloudiness characteristic of the outer zones. The inner limit of the felted mass of needles lies at the polygonal to circular border of the innermost zone and corresponds approximately to the inner limit of fibrous feldspar. Stain tests show that the matrix of the second zone is composed chiefly of potash feldspar, although some narrow sectors may be composed of plagioclase feldspar and quartz. The fibers have parallel or slightly oblique extinction and may have either positive or negative elongation. Rare sectors of secondarily branching fibers similar in form to those described and illustrated by Iddings (1891, p. 458 and Fig. 6) are present. These secondary branches apparently grew faster than or developed in advance of the primary fibers, for in their sectors the fine regular cloudy growth line that marks the outer limit of this zone is bowed outward (Fig. 3–2). Elsewhere, this growth line is nearly circular.

Third Zone. This zone, which reaches 0.70 mm. in width, consists mainly of potash feldspar clouded with submicroscopic crystallites of riebeckite (?) and widely scattered grains of acmite. The acmite in the matrix of this zone forms granules up to 20 μ in diameter. Radiating fibrous growth is shown by the potash feldspar though it is less well-developed than in the two adjacent zones.

The third zone is characterized in section by numerous clear crescentic areas reaching dimensions of 2.5 by 0.6 mm., composed of radiating fibers of quartz and minor plagioclase, and rather sharply defined from the cloudy groundmass. Almost all of these areas are concave toward the center of the spherulite, their inner edges being concentric with or more sharply curved than the growth line marking the inner edge of the third zone. Some irregularities in their shape may be attributed to partial merging of adjacent crescents. The crescents are not uniformly distributed but are as a rule least common where spherulites are most closely packed.

The quartz fibers of the crescents show a strong preferred orientation with both their greatest lengths and optic axes normal to the inner walls of the crescents. Acmite, which is about uniformly distributed throughout the surrounding cloudy feldspathic groundmass, is absent from the central part of the clear crescents, but is concentrated in a narrow rim on their outer convex surfaces. The width of the acmite-rich rim in any sector of the crescent is roughly proportional to the width of the crescent, and approximately the same amount of acmite is present in any one sector as in an equal area of the adjacent cloudy matrix. The submicroscopic riebeckite (?), like the acmite, is concentrated on the outer surfaces of the crescents where it forms a dark rim approximately equal to the width of the crescent and about twice as cloudy as the surrounding feldspathic matrix.

With few exceptions the crescents lie in the third zone outside the fine cloudy circular line marking the outer limit of the second zone. Where, however, they lie within the second zone near its outer limit, this bounding line is bowed outward.

Fourth Zone. This zone, which reaches 1.25 mm. in width, consists of clouded potash-rich feldspar having distinct radial growth, and widely scattered acmite. The inner edge of the zone is not well-defined, but its outer edge is clearly marked by a deeply lobed contact against the much more densely clouded plagioclase-rich interspherulitic areas. The acmite granules reach diameters of 10 μ. The zone is characterized by numerous, small, radially-elongate areas up to 0.2 mm. long composed of clear quartz and plagioclase. These areas, like the crescents of the third zone, are bounded by dark cloudy rims, but none is large enough to possess distinct lateral or terminal concentrations of acmite. It is probable that they have the same origin as the crescentic areas and that their shapes have been determined by the radial growth of isolated quartz crystals.

A few oval to nearly circular clear areas, up to 0.8 mm. in diameter, consist of relatively coarse equigranular quartz. These areas are rimmed by dark borders of dense cloudy material and some acmite, and differ only in size, shape, and lack of fibrous habit from the structures described above.

Interspherulitic Areas. These cuspate areas range in width from about 2 mm. where the spherulites are widely spaced, to thin lines where they are closely packed. These areas are composed chiefly of densely clouded feldspathic material lacking distinct radial growth, and of small central areas rich in granular quartz. Stain tests show that the clouded matrix is made up almost entirely of plagioclase, but that potash feldspar is locally present in the vicinity of the quartz. The central cuspate areas consist of quartz in interlocking grains up to 0.1 mm. in diameter together with small fibers of plagioclase and, in a few places, large radiating fibers of acmite. Densely clouded rims are characteristic of these quartz-rich patches. More or less circular clear areas, similar to those occurring in the fourth zone, may also be present.

General Observations. Several observations regarding the character and distribution of the minerals of the feldspathic spherulites follow. The paragenesis is shown diagrammatically in Fig. 4.

1. Acmite, which is most abundant in the first zone, decreases abruptly in concentration at the contact with the second zone, and is present in only minor amounts in the outer zones except at the margins of the quartz areas. Locally, however, it is abundant in masses of quartz in interspherulitic areas. The average size of the acmite granules increases between the center and the margin of the first zone and then declines gradually in outer zones. The radiating fibers of acmite of the interspherulitic areas are different in habit from the granules in the spherulites.

2. Riebeckite (?) is present in an amount apparently inversely proportional to that of acmite. It is absent in the central part of the first zone where acmite is abundant, and present in considerable amounts in the second zone where acmite is scarce. Change in riebeckite content from the second to the outermost zone is not determinable. Two generations can be recognized: relatively large prisms in the outer part of the first zone, and minute to submicroscopic needles in the other zones. Al-

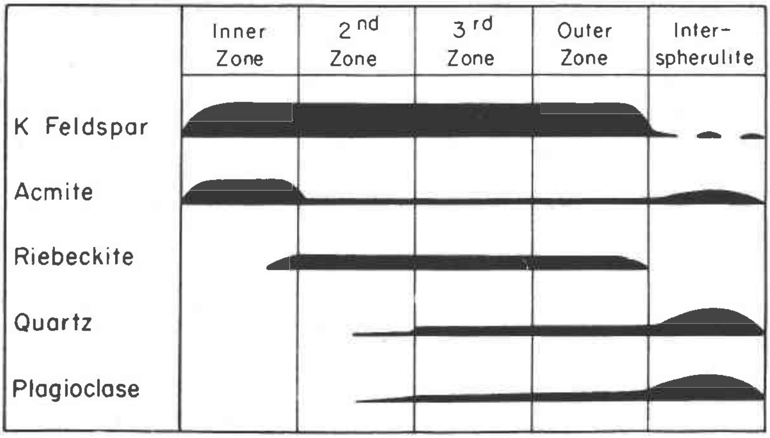

FIG. 4. Diagram showing paragenesis of minerals in central part of Nazcha Valley dike.

though the decline in grain size from the first to second zone is abrupt, the decline in size of the needles from the inner edge of the second zone to the outermost zone is gradual.

3. The potash feldspar of the first zone forms irregular interlocking grains, whereas that of the outer zones forms radial fibers. Although potash feldspar makes up the greater part of the spherulites, it is absent from interspherulitic areas except in halos around patches of quartz.

4. Quartz is found almost exclusively in the interspherulitic areas and in clear areas of crescentic, radially elongate, and oval to circular shapes in the third and fourth zones of the spherulites. It tends to form relatively coarse crystals of either fibrous or equigranular interlocking habit.

5. Plagioclase, which generally is fibrous, is found almost exclusively in the interspherulitic areas and in or adjacent to the clear quartz-rich areas in the outer zones of the spherulites.

Flow Layers of the Nazcha Valley Dike

The flow layers of the Nazcha Valley dike (locality A, Fig. 2) are made up of cloudy, finely-crystalline layers alternating with more coarsely-crystalline layers of quartz and conspicuous riebeckite needles (Fig. 3-1). The cloudy layers, 0.035 to 0.8 mm. in width, are composed of minute needles of riebeckite up to 10 μ in length in a colorless weakly birefringent matrix with an index close to that of balsam. Stain tests show this to be mainly potash feldspar. The clear intervening layers, 0.04 to 1.40 mm. in width, are composed of quartz and needles of riebeckite, or of acmite (?) pseudomorphous after riebeckite, forming narrowly radiating bundles extending from both walls toward the center of the layers. Most of these needles are straight, but in a few of the wider layers they apparently tended to bow slightly to one side during their growth and they meet in a central zone in which needles of acmite (?) and minor riebeckite are arranged parallel to the layers. A few spherulites composed of radiating fibers of acmite (?) and riebeckite in a quartz-rich matrix may be present in the central parts of some of the wider layers, and hemispherical aggregates of similar composition are present locally along their walls. Neither the quartz nor the delicate needles of riebeckite in the clear layers shows any strain even at points where the flow layers are markedly contorted; hence it seems that these minerals crystallized after injection of the dike had been completed.

Spherulitic Dikes of Glundebery Valley

The spherulites of the Glundebery Valley dikes (locality B, Fig. 2) range from 0.4 to 3.5 mm. in diameter. They consist of radiating needles of riebeckite, or its alteration product composed of black opaque grains, goethite, and hematite, in a matrix of fine radiating fibers of feldspar which is mainly potash-rich. Many of the larger spherulites have grown around quartz or microperthite phenocrysts, but most of the smaller more closely packed spherulites lack such nuclei. Where phenocrysts have served as centers of crystallization, needles of riebeckite and fibers of feldspar tend to radiate from some of the corners or edges of the phenocrysts rather than from their faces (Fig. 3-5). The outer rim of a typical spherulite consists of micrographic quartz and potash feldspar together with ends of the radially-arranged riebeckite needles and additional stouter prisms of riebeckite similar to those of the interspherulitic areas (Fig. 3-6). These stouter riebeckite prisms show a preferred orientation parallel to the rim of the spherulite and may have been rotated into this position prior to engulfment in the growing spherulite.

Another dike in this locality contains indistinct spherulites composed mainly of intergrowths of quartz and radiating feathery feldspar. These irregular coalescent spherulites rarely exceed 6 mm. in diameter. Mixtures of black opaque grains and hematite pseudomorphous after riebeckite needles tend to have a rough radial arrangement in some places and in one place, a tangenital arrangement, but in most parts they are oriented at random. The radiating clusters of pseudomorphs after riebeckite needles commonly transgress fibers of the quartz and feldspar intergrowths. Although in the highly spherulitic rhyolite from this locality both the riebeckite and feldspar fibers radiate from a common center, this rule does not necessarily apply to the imperfectly spherulitic dike.

The interspherulitic parts of the dikes of Glundebery Valley described above and the non-spherulitic rhyolite at this locality are made up of

TABLE 1

	1	2	3	4
CHEMICAL ANALYSES*				
SiO_2	74.42	77.29	75.83	72.80
TiO_2	0.21	0.15	0.26	0.33
Al_2O_3	8.58	9.27	10.35	13.49
Fe_2O_3	3.44	2.07	4.35	1.45
FeO	3.07	1.36	0.54	0.88
MnO	0.11	0.04	0.05	0.08
MgO	0.34	0.09	0.26	0.38
CaO	trace	0.34	0.18	1.20
Na_2O	4.33	4.01	2.66	3.38
K_2O	4.75	4.54	4.59	4.46
H_2O+	0.29	0.37	0.92	1.47
H_2O-	0.10	0.08	0.07	—
P_2O_5	n.d.	n.d.	n.d.	0.08
ZrO_2	0.46	0.41	0.14	n.d.
Total	100.10	100.02	100.20	100.00
NORMS				
Apatite	—	—	—	0.20
Ilmenite	0.40	0.29	0.49	0.61
Zircon	0.68	0.61	0.21	—
Orthoclase	28.15	26.90	27.20	26.69
Albite	17.63	22.36	22.57	28.45
Anorthite	—	—	0.89	5.28
Corundum	—	—	0.66	1.12
Acmite	9.97	6.00	—	—
Sodium metasilicate	1.81	1.13	—	—
Magnetite	—	—	1.16	2.09
Hematite	—	—	3.55	—
Diopside	—	1.46	—	—
Hypersthene	6.36	1.78	0.65	0.95
Quartz	34.71	39.03	41.83	33.18
Water	0.39	0.45	0.99	1.47
Total	100.10	100.01	100.20	100.04

* 1, 2, and 3 analyzed by Chief Analyst and Assayer, British Columbia Department of Mines.

1. Zone of contorted flow layers, Nazcha Valley.
2. Spherulitic zone, Glundebery Valley.
3. Non-spherulitic zone, Glundebery Valley.
4. Average rhyolite, including 24 liparites (Daly, 1933, p. 9).

equigranular interlocking quartz and feldspar. The riebeckite in the interspherulitic areas differs from that in the spherulites by having a distinctly stouter habit and by being much more highly altered to trains of black opaque minerals and hematite. In the non-spherulitic rhyolite, no riebeckite is present and not even psuedomorphs were seen. Instead, more or less equant interstitial grains of black opaque minerals and goethite are scattered throughout the rock in abundance.

Chemical Composition

Analyses of three samples of the rhyolites are given in Table 1 and an average composition of rhyolite (including liparite) computed by Daly (1933, p. 9) is included for comparison. The rhyolites from the Atsutla Range are clearly deficient in alumina and lime, but abnormally rich in ferric iron, and to a lesser extent, in ferrous iron.

Each of the three analyzed rhyolites contains modal albite, potash feldspar, and quartz, which are abundant in their norms (Table 1). In samples 1 and 2, riebeckite, acmite, and decomposition products of riebeckite can account for most of the excess soda and iron indicated by the normative acmite, sodium metasilicate, diopside, and hypersthene.

Conclusions

Crystallization of the groundmass of the rhyolite dikes occurred after the dike-magma came to rest; otherwise, the delicate fibers of the spherulites and axiolites would show damage from contact with one another. To preexisting inhomogeneity in the magma of the Nazcha Valley dike can be ascribed the layering in its marginal zones; this layering was contorted by viscous drag against the dike walls during emplacement of the melt. The Glundebery Valley dikes seem to have been homogeneous at the time of intrusion except for scattered phenocrysts.

Pressure did not necessarily remain uniform once the magma had reached its final position, nor did temperature necessarily decline continuously. Minor changes in gas content, vapor pressure, and confining pressure could take place with time. Heat supplied by crystallization might locally and temporarily balance loss of heat to the walls of the dike and if appreciable supersaturation of some constituents existed, some excess heat might be evolved on rapid crystallization which could bring about a local rise in temperature. Such changes in conditions during cooling might account for the reversal in the sequence of crystallization of acmite and riebeckite and for the sharp breaks in conditions of crystallization in the spherulites of the Nazcha Valley dike.

A close relationship between riebeckite and acmite is shown in the rhyolites described above and in many other rocks bearing these minerals.

The stability ranges of these two minerals are, however, not well known. The transformation of riebeckite to acmite can be expressed by the equation:

$$\underset{\text{Riebeckite}}{(OH)_2Na_2Fe_3''Fe_2'''(Si_4O_{11})_2} = \underset{\text{Acmite}}{2NaFe'''Si_2O_6} + \underset{\text{Ferrosilite}}{3Fe''SiO_3} + SiO_2 + H_2O$$

Assuming densities of 3.40, 3.60, 3.95, 2.65 for riebeckite, acmite, ferrosilite, and quartz respectively, we find that the molecular volume of riebeckite (275) slightly exceeds the total of those of its solid decomposition products (251). The molecular volume of water vapor, itself a function of both temperature and pressure, is, therefore, critical in determining the effect of pressure on this transformation. It is apparent from data on the specific volume of water vapor (Birch, 1942, p. 211) that at depths of less than some tens of kilometers and temperatures of some hundreds of degrees or more, increasing pressure favors the development of riebeckite and vice versa. Such a conclusion is in accord with that deduced from petrographic studies of hornblende and pyroxene in volcanic rocks in which hornblende is considered to be a deep-seated mineral, and pyroxene one capable of crystallizing at shallower depths. The effect of temperature on the riebeckite—acmite transformation is not known.

The relationship between riebeckite and acmite and the black opaque minerals, goethite, and hematite is also close, although again little is known of the stability ranges of the minerals. Experimental work shows that acmite melts incongruently at 990° C. to form hematite and a liquid richer than acmite in silica and soda (Bowen & Schairer, 1929). It has been found that hornblende and pyroxene of lavas become unstable under conditions of diminished pressure and slow cooling from a relatively high temperature and tend to break down into pseudomorphs of iron ores (MacGregor, 1938, p. 54, p. 56). In lavas, the reduction of pressure is caused by extrusion and temperature is maintained, or even increased at the surface, until the change takes place. It is difficult to see how pressure could be markedly reduced during crystallization in the dikes of the Atsutla Range before they became cold.

The origin of the clear crescentic areas of quartz and minor feldspar in the sections of the third zone of the Nazcha Valley dike presents an interesting problem. At first glance, they might be regarded as the fillings of open concentric cavities like those of lithophysae. Such, however, does not seem to be the case. Quartz crystals have not grown from opposite walls to meet in an irregular sutured boundary midway between them; instead, most of the individual crystals extend from wall to wall. The concentration of acmite at the outer side of the crescents can best be explained by the mechanical displacement of acmite crystals, previously disseminated through the cooling magma, by the force of growing crystals of quartz which began their growth on what is now the inner margin of the crescents and became extended normal to these surfaces. This mechanism accounts for the similarity in size, shape, and optic characters of the acmite grains at the edges of the crescents to other grains of that mineral scattered through the adjoining parts of the spherulites. The fact that the ratio of the width of the acmite rim to the width of the entire crescent conforms closely to the ratio of acmite to matrix in neighboring areas is likewise in accord with the postulated mechanism. The cloudy concentrations of riebeckite (?) immediately outside the crescents may be accounted for in the same way although the grains of this mineral are too fine to show similarity in shape and optic characters to those farther from the crescents. The mechanism presumes that within the third zone quartz developed on the surfaces of the growing spherulites which had hitherto been composed principally of potash feldspar. The potash feldspar, apparently incapable of forcing aside the granules of acmite and needles of riebeckite, had engulfed these impurities; needles of quartz, on the other hand, apparently were able to push the solid particles ahead of their growing tips. The work of Becker & Day (1905, 1916), Correns (1926), and others, (see Buckley, 1951, pp. 468–479) has shown not only that forces of repulsion between a growing crystal immersed in a supersaturated liquid and an adjoining solid can exist, but that the forces can vary with the surface characters of the two solids in contact with one another. Growth of individual quartz masses on the spherulites may have become effectively retarded when their outer surfaces had become thoroughly encrusted with granules of acmite and mats of riebeckite. Up to this stage, however, growth of quartz may have exceeded that of feldspar, for in one place where quartz has developed immediately inside the cloudy growth line marking the outer limit of the second zone, this line shows a distinct bulge.

The zirconia content of the dikes attains unusually high though by no means unprecedented values. The average content of zirconia in 80 German occurrences of "granite" is about 0.034% according to v. Hevesy & Würstlin (1934, p. 308), less than one tenth that of the two analyzed spherulitic dikes of the Atsutla Range. According to these authors (1934, p. 309), "soda granites and soda syenites" have an average content of 0.067% zirconia (26 occurrences from various sources) and "potash granites and potash syenites" have an average of 0.084% zirconia (24 occurrences from various sources). Appreciably higher amounts of zirconia, however, have been reported elsewhere. A sample of rockallite analyzed by Washington (1914, p. 297) contains 1.17% zirconia and samples of granite from the Ampasibitika area of Madagascar contained from 0.50 to 3.71% zirconia according to Lacroix (1903, p. 235).

It is of interest that these zirconia-rich rocks from British Columbia, Rockall, and Madagascar are rich in riebeckite and aegirine, acmite, or arfvedsonite. The zirconia content of the Madagascar granites was attributed by Lacroix (1903, p. 236) to the presence of abundant zircon. Since zircon is rare in the sample from Rockall, however, Washington concluded that the zirconia is present in the acmite and calculated that it contains 2.67% zirconia (1914, p. 300). He suggested that the distinction between the yellow-brown pyroxene referred to as acmite and the greenish kind called aegirine may be connected with the presence of zirconia or oxides of rare earths in the former and their absence from the latter (1914, p. 301; 1927, p. 233, 248). In the spherulitic rhyolite dikes of the Atsutla Range, zircon occurs only with intensely altered riebeckite but not with this mineral in its unaltered state, and the pyroxene is a pale yellow variety. For these reasons, it is suggested that the riebeckite and acmite of the rhyolites may contain appreciable amounts of zirconia in solid solution.

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